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Uses of radio-active (nuclear) materials by the United States of America for space power generation

Working paper submitted by the United States of America

Summary

The first United States use of Nuclear Power Systems in space occurred in June 1961 on a small, 2.7 electrical watts, Navy Navigation System Satellite. This technology has been developed; so that each of the Voyager spacecraft launched in 1977 was provided approximately 475 watts of power by the Nuclear Power Systems. The use of Nuclear Power Systems has been carefully controlled, and in all applications, the safety of programme personnel and the world population has been emphasized. An active development programme has provided the technology necessary to significantly improve the thermoelectric conversion efficiency and at the same time provide much safer systems.

The early systems, through SNAP-9A, were designed to contain the fuel during launch pad or early ascent aborts and to burn-up during re-entry and disperse the radio-active plutonium-238 as very small particles in the stratosphere. With improved technology, since 1965, the nuclear fuel has been contained; so there will be no capsule rupture for normal and most abort conditions. Containment prevents dispersal of the radio-active material.

The containers are hot and an individual is not likely to handle or keep them and thus receive serious radiation exposure. The radiation exposure rate at approximately one metre from the individual fuel spheres is only a few mrem per hour. The individual fuel capsules are large enough to be recognized and recovered if they re-enter on land near people.

Attachments* 1 and 2 illustrate the size and construction of the multihundred

* All the attachments in this paper are issued in English only. Reprints of photographs in attachments 6 and 7 as provided to the Secretariat could not be reproduced; they will be distributed separately during the meetings of the Committee on the Peaceful Uses of Outer Space in New York, 26 June-7 July 1978.

watt (MHW) radio-isotope thermoelectric generators (RTG), which were used on the DOD Lincoln Experimental Satellite (LES) 8/9 and NASA Voyager spacecraft. Although the plutonium-238 power systems to date have all used relatively low, 5 to 6.7 per cent, efficient thermoelectric conversion systems, we have a programme to develop more efficient thermoelectric designs and also to develop much higher efficiency dynamic systems. Space use of these systems is not anticipated until the 1980s.

Of the 22 spacecraft which have been launched with nuclear power systems since 1961 (attachment 5), only the Snapshot launch on 3 April 1965 used a reactor system. An orbit with a lifetime of approximately 4,000 years was achieved before the reactor was started. It operated 43 days before it developed a voltage regulator problem and shut itself down.

Failures during the early phases of three missions (Transit 5BN-3, 21/4/64; Nimbus B-1, 18/5/68; and Apollo 13, 11/4/70) prevented normal operations and the spacecraft returned. The Transit/SNAP-9A (System for Nuclear Auxiliary Power) successfully vapourized, as designed, and the plutonium-238 was dispersed at high altitude. The Nimbus/SNAP-19 system contained the plutonium-238 and the fuel was recovered from the Santa Barbara channel off the California coast. The Apollo 13/SNAP-27 unit survived re-entry and sank in the deep South Pacific ocean.

The development of safe, compact nuclear generators to power scientific experiments and communications systems has contributed much to the exploration of space. A brief description of the uses, progress and developments, trends in technology and systems, and the safety and review policies and procedures is presented below.

Department of Defense (DOD)

DOD has used and is using nuclear power supplies for navigation and communication systems. With the exception of the Transit navigation systems launched 6/61 and 9/72 (Flight Nos. 1 and 14 listed in attachment 5), these units are in greater than 1,000 year orbits. The Transit 4-A launched 6/61 is in an orbit greater than 500 years, and the Transit launched 9/72 is in an orbit greater than 100 years. Recovery of and return to earth by the Space Transportation System (STS) appears to be feasible. The DOD uses nuclear power units for those missions which require survivability and which may encounter particularly adverse environments. In some instances, the launches were development and/or test missions leading to future operational requirements.

National Aeronautics and Space Administration (NASA)

NASA normally uses nuclear power supplies for special missions where solar or other power sources are not applicable. With the exception of the Nimbus III satellite, which used two radio-isotope thermoelectrical generators (RTGs) in an orbital mission (1969), NASA has not used RTGs in earth orbit. The normal uses of these systems are for missions which do not have sufficient sunlight to operate solar cells or where the environment would limit the lifetime of solar cells. For

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missions on the Martian surface, where dust storms occur, and on the Lunar surface, where debris could be blown around as the Lunar Module (LM) upper stage departed the Lunar surface, RTGs were used. Other NASA missions, such as the Pioneer 10 and 11, which went to Jupiter and then beyond and will go out of the solar system, and the Voyager 1 and 2, which are scheduled for Jupiter then Saturn fly-bys and then will eventually go out of the solar system, have solar fluxes sufficiently small that it would be extremely difficult or impossible to fly these missions using solar cells for power. Therefore, nuclear power supplies were used. The same requirements led to the decision to use radio-active power supplies for the Jupiter Orbital Probe (Galileo) mission in 1982.

There may be other types of missions which, because of their specific nature, require other than solar cells for power, and each of these will be evaluated on its own merit.

In addition to using RTGs for power, the DOD Transit (9/72) and the NASA Pioneer 10 and 11, Viking 1 and 2, and Voyager I and II each used small radio-isotope heater units (RHUs) to keep critical equipment warm. The Galileo mission in 1982 will probably require RHUs. These units contain one thermal watt (30 Ci) of plutonium-238 oxide. They are designed to survive normal as well as abort conditions. They have been tested in explosion, re-entry, and impact environments, and they survived. The RHUs operate at approximately 110° F in 70° F air, and the radiation dose rate is approximately 1 mrem/hr. at 10 cm. from their surface. Attachment 3 is descriptive material from the "Safety Analysis Summary Report for the (Voyager) MJS - Radioisotope Heater Unit" prepared by Mound Laboratory for the United States Energy Research and Development Administration.

Many spacecraft require small radio-active sources as part of the scientific instruments. These sources are evaluated for safety and reported to appropriate organizations. A typical report is included as attachment 4.

<u>Department of Energy</u> (DOE)

In the 20 years of the Space Age, the DOE and its predecessors, the Energy Research and Development Administration (ERDA) and the Atomic Energy Commission (AEC), have had a growing role in the United States exploration and exploitation of space. From a few early Earth orbital missions through Lunar landings to long-term outer-planetary journeys, the compact, reliable, and long life nuclear isotope power supplies have been essential to mission success. A primary goal continues to be support of the Nation's civilian space exploration efforts with particular orientation toward missions which depend upon delivery of adequate electrical power while operating in a remote, hostile, or specialized environment. A corollary goal of equal significance is support of the national security interests of the Department of Defense (DOD) in its deployment of satellite systems for navigation, communication, or general uses in Earth orbit.

The Atomic Energy Commission provided the technical base for production of plutonium-238 in suitable quantities for space power applications. This radio-isotope is the workhorse heat source for these systems. Its 87.7-year half

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life and its alpha emission decay scheme combine to enable design and development of space power supplies with light weight, little shielding, and long-term, operational reliability.

Commercial contractors provide the development, fabrication, and support functions needed to deliver safe and efficient systems to convert the radio-isotope decay heat into electrical energy.

The so-called static conversion systems, attachments 1 and 2, use solid state thermoelectric couples to provide up to 500 watts of stable direct current to the spacecraft. Development of static converters is continuing and is pointed toward higher efficiency and greater modularity. Dynamic conversion systems transfer the isotopic decay heat to a working fluid, which actuates a generator through either a piston or turbine system. Two such systems, with expected efficiencies in the range of 18 to 30 per cent, are currently under development and will be suitable for power requirements in excess of 1,000 watts. These can be used with isotope heat sources.

Progress in system safety

As indicated in attachment 5, during the 1961-1977 period, the United States launched into earth orbit or deep space 22 spacecraft carrying nuclear power sources. Beginning with SNAP-3, a 2.7 watt power source, on board a Navy Navigation System Satellite, power system capability has evolved to a point where approximately 475 watts of electrical power was provided to each of the Voyager spacecraft launched in late 1977 on deep space missions to Jupiter, Saturn, and Uranus. Entry 17 of attachment 5 refers to two spacecraft launched on one booster, and each spacecraft had two MHW RTGs. The Voyagers each have three RTGs. All of the radio-isotope generators utilized the decay heat of plutonium-238 to power the thermoelectric converters. One nuclear reactor, SNAP-10A, using uranium-235 as the fission heat source was launched as a test system in 1965. This unit was boosted to a 4,000 year orbit before startup of the reactor was permitted.

The operational philosophy, which has been adopted for orbital missions, requires the normal orbital lifetime to be long enough to allow for radio-active decay of the radio-isotope fuel or reactor fission products to a safe level prior to re-entry to earth. This philosophy recognizes, however, that missions use parking orbits from which to launch the spacecraft on deep space or high orbit trajectories. If the Snapshot spacecraft had not achieved a sufficiently long lived orbit to meet safety requirements, it would not have been started up, and as a result, no fission products would have been produced.

Since its inception, the U.S. space nuclear power programme 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 operating and potential accident conditions.

The earlier systems, through SNAP-9A, were designed to contain the isotope fuel during a launch pad or early ascent abort and to permit complete vaporization

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of the fuel source in the stratosphere during re-entry. World-wide dispersion and dilution of the fine nuclear fuel particles would preclude high contamination in any localized areas. The SNAP-9A Transit 5BN-3, launched in April 1964, failed to achieve orbit, re-entered the atmosphere over the ocean east of Africa, and burned up on re-entry as it was designed to do. High altitude atmospheric sampling confirmed that the nuclear fuel did vaporize during re-entry and was dispersed world-wide.

Recognizing that limitations must be placed on dispersal of particulate nuclear material in our environment, an extensive materials development programme made it possible for space isotope power systems, following SNAP-9A, to be designed to contain the nuclear material through normal and accident conditions and prevent dispersal of respirable particles.

In support of this requirement, rigorous quality assurance and ground testing activities were pursued for each mission, on which radio-active power systems were to be used. To verify the accomplishment of such safety-related efforts, a comprehensive interagency safety review, involving some of the best experts available in the United States, is conducted prior to soliticing launch approval for each mission.

Attachment 6 is a series of pictures showing the RTGs response to a possible explosion environment during a pad abort of a Voyager booster. This information was included in the "Final Safety Analysis Report". The RTG case was damaged, but the fuel source assemblies were still intact.

Attachment 7 is a series of pictures showing a fuel capsule impact test at 281 ft/sec on granite. The fuel spheres were deformed but they did not break. This information was included in the "DOD LES 8/9 Mission Safety Analysis Presentation".

Extensive testing is accomplished for each system design. In those tests where failures occur, the crack sizes are measured, potential fuel release is determined, and potential exposure of people is estimated. This information is included in the previously mentioned safety reports and provides the basis for estimating the probability of fuel release and the potential for exposing people to ionizing radiation.

During launch, experienced personnel from co-operating agencies and their specialized contractor staffs, in the disciplines of operational safety and health physics, are on standby at the launch site as an added precaution. They can respond to any potential radiological emergency which might result from a malfunction.

In further support of safety considerations, a world-wide atmospheric sampling programme is maintained to evaluate changes in airborne radionuclide levels. This is accomplished with high altitude aircraft which measure background radiation which includes materials due to weapon testing and the SNAP-9A burn-up. This will verify that no dispersal of nuclear fuel particles has resulted from new missions.

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The significance and value of the safety assurance measures adopted early in the programme were substantiated in three instances.

The SNAP-10A reactor was successfully launched on the Snapshot demonstration mission in April 1965. As planned, the system was placed in a 4000 year orbit and was not started up until the safe altitude was confirmed. The reactor operated for 43 days before shutdown due to a voltage regulator malfunction. Upon shutdown, the system contained a 2 x 10^5 curie inventory. After 15 years the inventory would decay to less than 100 curies and after 100 years, to less than 1/10 curie. At re-entry, the fission product radio-activity will be insignificant.

The NASA Nimbus B-1 spacecraft was launched in May 1968 but was aborted due to a guidance error. It was destroyed by the Range Safety Officer at an altitude of 100,000 feet and the spacecraft with the RTGs fell into the Santa Barbara channel. Since these generators were designed to survive the conditions, the fuel capsules were recovered intact and were returned to AEC fuel processing facilities for recovery of the plutonium-238 fuel. No nuclear fuel was released to the atmosphere or the ocean.

The NASA Apollo 13 mission aborted on the way to the moon after a successful launch in April 1970. The lunar module, with the fuel cask attached, re-entered the atmosphere over the South Pacific. Post-re-entry surveys were made at all levels of the atmosphere downwind of the re-entry area and confirmed that no nuclear fuel was released. The nuclear fuel cask re-entered intact, as designed, and is at the bottom of the Tonga Trench in approximately 20,000 feet of water.

Progress has been made in the space programme to virtually eliminate the release of radio-active fuel during normal operations and most launch aborts. As future trends require larger systems with higher electrical power levels and larger fuel inventories, more stringent system safety requirements, greater hardware quality and reliability requirements, and more sophisticated analytical and test methods to improve the quality of risk assessments and source term evaluations are being developed and enforced.

Current status

All systems launched to date have fulfilled numerous programme objectives and, in certain cases, have indicated areas for design improvements. All accident occurrences have been properly handled in accordance with planned safety philosophy and objectives.

The Apollo Lunar Surface Experiments Package (ALSEP) units were placed by the Apollo explorers in five different locations on the Moon. Specifications called for a one-year operating life for the first four ALSEPs and two years for the Apollo 17 station. They exceeded this requirement and delivered power until the official termination date of 30 September 1977. As a consequence of the reliable performance of both the power supplies and the scientific instrumentation, NASA has

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accumulated evidence of approximately 10,000 moonquakes and 200 meteorite impacts. In addition, NASA has obtained data on charged particles in the Moon's atmosphere and on the magnetic environment and interior Lunar structure. These data have been made available to interested, participating scientists in many parts of the world.

Twenty months after its launch in March 1972, Pioneer 10 encountered Jupiter, performed close-up studies of the planet, its moons, and its environment, and transmitted these data for use by United States and other participating scientists. The four RTGs on this spacecraft continue to report their own power output and scientific data after 5.6 years of service and from a distance exceeding 1.2 billion miles from the earth. System performance is following an expected trend, while the spacecraft follows a Solar System escape trajectory.

Pioneer 11, technologically a twin but programmatically different, performed a Jupiter fly-by manoeuvre and then was targeted for a Saturn encounter in 1979. Power system performance data, reported in flight from a distance of 600 million miles from Earth, again indicated a stable, predictable output after 4.5 years of operation.

The Viking landers were successfully positioned at two selected sites on the planet Mars on 20 July and 3 September 1976, after launch on 20 August and 9 September 1975, respectively. The soil sampling apparatus, the complex sensors, and analytical laboratories on board the landers, and the telemetry and television equipment transmitting information to earth were dependent upon the RTGs for continuing power supply. These units remained viable throughout the diurnal and seasonal temperature variations characteristic of the Mars weather patterns. In fact, some heat from the generators also was diverted periodically to keep certain lander equipment warm during the colder periods. Latest reports from the lander telemetry systems indicate stable performance at a predictable power output level, after more than a year on the Martian surface.

The Lincoln Experimental Satellites (LES 8/9) were launched in March 1976 as units of a communications system designed for crosslink as well as satellite to Earth transmission. The RTGs on board not only provide necessary operating power but also are to demonstrate the dependability and survivability of a satellite powered in this manner for long-term operation in a hostile environment. The nuclear supplies are delivering power slightly in excess of expectations, and performance is very satisfactory. The record of LES 8/9 generator performance lends encouragement to use of the Multi-Hundred Watt (MHW) units in other applications where earth orbital power supplies are required.

The Voyager spacecraft (formerly designated Mariner Jupiter/Saturn) were launched from the Kennedy Space Center on 20 August and 5 September 1977. Each spacecraft was powered by three MHW RTGs having a combined output of approximately 475 watts per spacecraft. The total nuclear electric power for the Voyager missions is nearly equal to all other nuclear-powered United States missions currently in space. Reports telemetered from the Voyagers indicate stable operation of the MHW generators and favourable prognosis for data retrieval at Jupiter encounter in 1979 and Saturn encounter in 1980-1981. It is anticipated that the generator

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lifetime will be adequate to return information from the approach to Uranus in 1986 and possibly from Neptune in 1989. Attachments 1 and 2 are cutaway views of the MHW RTGs.

Trends in technology

Materials technology and generator designs have steadily improved as the space nuclear power programme advanced to meet the challenges of more stringent mission requirements. Initially, fuel material was limited to plutonium-238 metal or an alloy with zirconium; these materials yielded 6 to 7 thermal watts per cubic centimeter of fuel, but were not compatible with typical capsule metals at elevated temperatures.

Plutonium-238 oxide microspheres, fused to high density with a plasma torch, were more stable in contact with containment metals at elevated temperatures, but they suffered from a low power density of 2.5 to 3.0 watts per cubic centimeter. Significant improvement was achieved with molybdenum-coated particles, hot-pressed into a disk. This fuel form was more stable toward its environment and had a power density in excess of 4.0 watts per cubic centimeter. Further advantages were achieved with a hot-pressed sphere of plutonium-238 oxide, welded into an iridium capsule and cushioned in a protective fibrous graphite impact shell. These fueled units not only operate at high temperatures but are designed to withstand re-entry heat and impact and to resist corrosive action in any environment.

Throughout the design history of space nuclear power systems, competitive trends in specifications are evident. Increasing power demands have been tempered by constraints on payload weight; as a consequence, engineers used beryllium and specialized graphites to reduce power system weight. Increasing safety requirements for launch and possible re-entry situations resulted in multiple encapsulation with resistant metals and graphites; in response, fuel specialists developed fuel forms with higher power density and improved mechanical and chemical stability.

Similarly, the development of thermoelectrical converter materials has been responsive to the demands for additional power without weight penalties. The lead telluride modules of earlier systems were improved in efficiency by use of a tellurium-antimony-germanium-silver leg; by this expedient, the conversion factor rose from 5.0 to 6.3 per cent. An additional increment in efficiency was achieved by adoption of silicon-germanium couples; conversion rose to 6.7 per cent and the higher operating temperature enabled greater wattage output. Attachment 8 illustrates the increase in output power.

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Representative materials and their performance parameters are tabulated to show the steady progress to date:

	1961	1969-72	1972-75	1976-
Generator	SNAP-3	SNAP-27	SNAP-19	MHW
Mission	Transit-4	Apollo	Pioneer	LES 8/9
Fuel Form	Pu-metal	PuO_2 micro-spheres	PuO_2-Mo cermet	Pressed PuO_2
Thermo-element	PbTe	PbSnTe	PbTe-TAGS	SiGe
Specific Power, watts/lb	0.67	1.06	1.36	1.90
Conversion efficiency, %	5.0	5.0	6.3	6.7

Trends in systems

In the programme to date, the static thermoelectric conversion systems have satisfied requirements for up to 500 watts of electrical power, delivered reliably for mission durations of up to 10 years. Conversion efficiencies in the range of 5 to 7 per cent, however, may limit payload weights, and therefore scientific opportunities may not be realized. Research has proceeded on a class of selenide thermoelement materials which have shown 8.5 per cent conversion efficiency in the laboratory, and appear to be capable of development toward 10 or even 15 per cent efficiency.

In anticipation of near-term requirements for nuclear electric power supplies capable of delivering 500-2,000 watts, DOE has coupled its nuclear expertise with NASA and industry in the development of both a Brayton cycle engine and an organic Rankine cycle engine. It is expected that either of these systems, when chosen for flight development, will have efficiencies approaching 30 per cent. In the summer of 1977, Congress approved and began funding the Jupiter Orbiter/Probe (Galileo), a NASA mission scheduled for launch in 1982. Its objective is to further explore the environment, atmosphere, topography, and structure of that fascinating planet. In support of this endeavour, DOE has undertaken to develop the selenide isotope generator, incorporating the higher efficiency selenide conversion materials and the flight-qualified MHW heat source. Two generators delivering 240 watts each comprise the nuclear power complement.

Additional NASA missions proposed as FY 1979 "new starts" include the Solar-Polar mission for launch in 1983; this mission is sponsored jointly by NASA and the

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European Space Agency. In anticipation of this requirement, DOE has initiated design and materials studies on a general-purpose heat source, which would be coupled with a selenide thermoelectric converter. Improved performance and safety benefits are expected from this combination.

On the horizon are DOD requirements which indicate a need for systems supplying electrical power in the 1 to 2 kilowatt range. To support this need, DOE is actively exploring the relative merits of two candidate dynamic systems, the Brayton isotope power system and the kilowatt isotope power system. The latter system employs an organic Rankine cycle engine. Development and engineering are progressing in each area, ground demonstration tests are scheduled for early 1978, and detailed evaluation will enable selection of that system best fulfilling its functional specifications and best suited to the conditions of shuttle launch. A demonstration flight test in 1982-1983 is contemplated as part of the DOD space test programme. Affirmative results from that demonstration flight test would be a significant input to the selection of the power system for the Global Positioning Satellite, Communications Satellite System and General Purpose Satellite.

Review procedures

Since 1971, Environmental Impact Statements (EISs) have been required for those activities which may have an adverse effect on the environment. Each space system is included in the requirement. Beginning with the Pioneer 10 and 11 missions, an EIS was prepared and published for general distribution. These analyses evaluated the over-all mission impact and specifically the potential problems related to the use of RTGs. A more rigorous review, however, is required for special abort conditions. The procedures to accomplish these reviews have been followed since 1964.

A special interagency review panel has been established to assure the adequacy of system designs and to further assure the safety of the general public as a result of the use of radio-active power supplies on United States spacecraft. This panel has been named the Interagency Nuclear Safety Review Panel (INSRP), and it consists of members from the Department of Defense (DOD), the Department of Energy (DOE), the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), and the Nuclear Regulatory Commission (NCR). Appropriate technical support is provided by the Federal agencies and their contractors.

It is the responsibility of this panel to carefully review the technical aspects of the systems and missions and to prepare a report which is used by management in going forward to request Presidential approval for the use of any nuclear powered spacecraft. This panel is made up of personnel not responsible for the application, and thus it provides a third party evaluation. Hardware design, abort environments, normal operational environments, and any potential accident or operation is considered. If modifications of the designs are required, as a result of the reviews, they are accomplished by programme personnel and contractors. The design changes are then further reviewed by the panel.

In those instances where systems have aborted, the review panel has gone back and evaluated the results to determine if anything happened contrary to the original assessments. This review procedure is anticipated for all future launches

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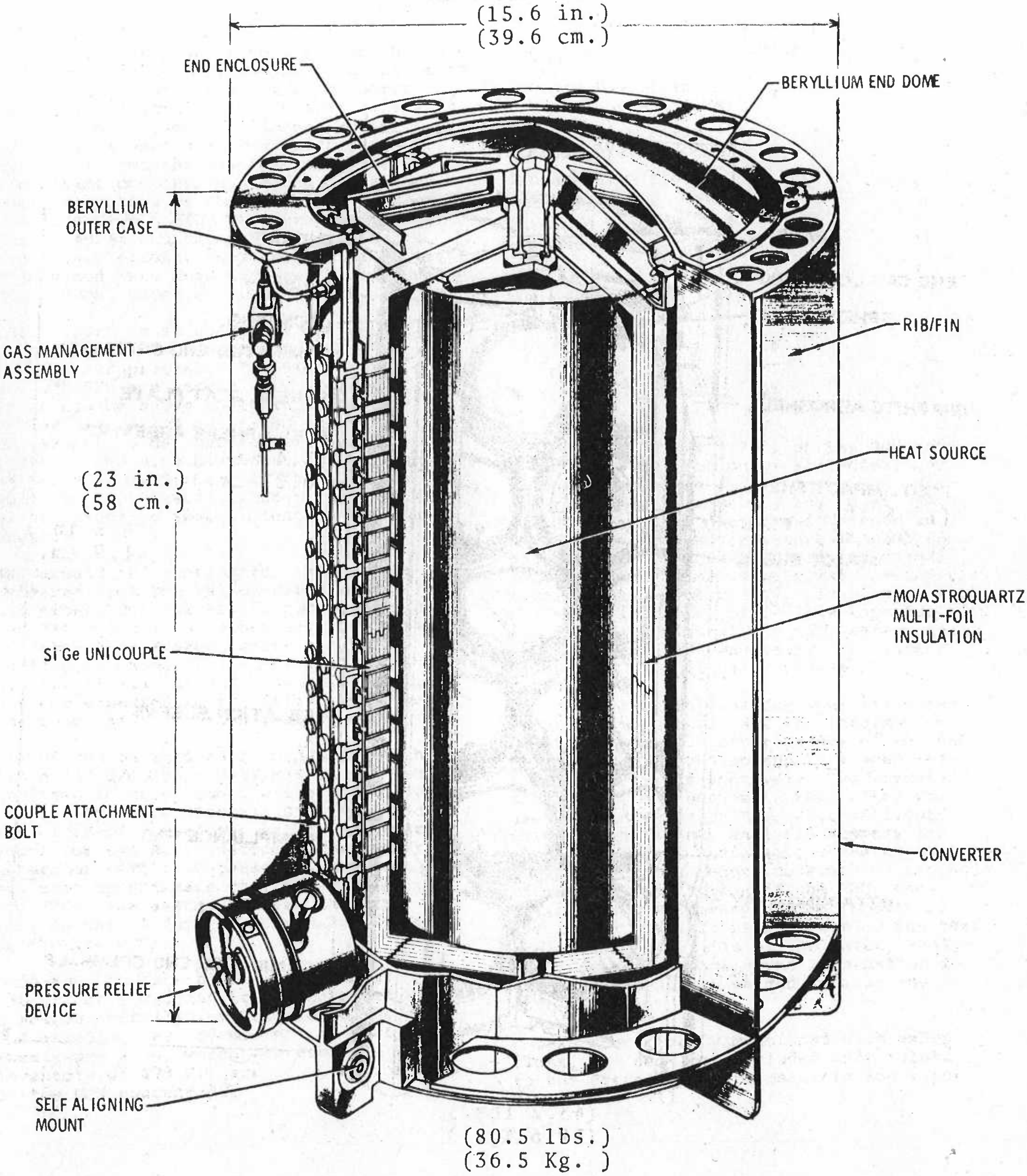
which involve the use of radio-active power supplies. The operational aspects of the Space Transportation System (STS) and its supporting subsystems will be carefully evaluated as preparations are made for the Galileo launch in 1982, future DOD missions, and possible Space Transportation System (STS) problems associated with recovery and return of nonfunctioning or short-lived nuclear systems.

Potential for personnel injuries

Although there is a remote potential for some level of injury to some individual(s), that potential is considered to be small. The probability of some individual receiving an exposure equal to or greater than that permitted for radiation workers has been considered to be about one chance in a thousand launches during the prelaunch and the initial orbital phase. Once the spacecraft achieves its pre-assigned orbit, the lifetime will exceed two or three hundred or perhaps a thousand or more years. For long-lived orbits and interplanetary flights, the probability of injury is considered to be essentially zero. The probability of injuries, while using the Space Transportation System (STS) as the booster, is considered to be less probable than for the unmanned booster systems; since the STS has the capability to return and land with the spacecraft.

With the containment design being used in the isotope systems, the safety measures being applied for operations, and the detailed review conducted by the INSRP, the likelihood of injury is considered acceptably small. Future systems will continue to receive stringent reviews. The review requirements consider those factors necessary to avoid earth contamination or injury of people. Each mission must be evaluated on its own merits, including safety, mission necessity, and cost effectiveness.

Attachment 1



MHW Radioisotope Thermoelectric Generator

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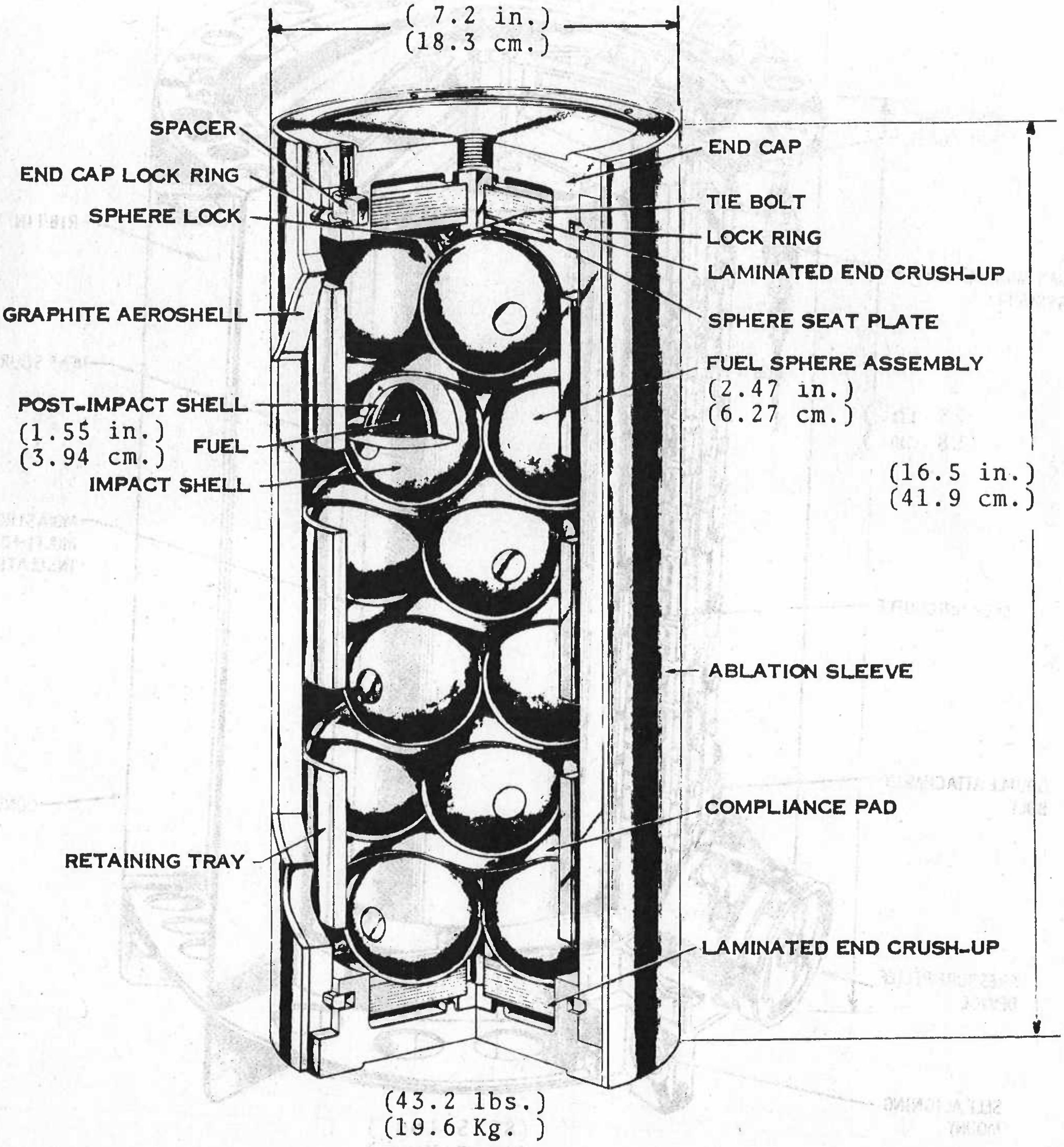
Attachment 2



MHW Heat Source

Attachment 3

Introduction

In October 1969, under contract to the NASA Ames Research Center, TRW Systems initiated the design, fabrication of piece parts, final unit assembly, and nuclear safety evaluation of the Radioisotope Heater Unit (RHU) to be used on the Pioneer F and G spacecraft for thermal control of selected spacecraft components. Mound Laboratory, under direction of the AEC's Division of Isotopes Development, was responsible for fuel loading and encapsulation. During the safety effort, continuous liaison was maintained with Headquarters, Atomic Energy Commission, through Mr. William S. Holman.

This report is an update of the report [1] that TRW Systems prepared for NASA during the Pioneer program. The Pioneer-RHU and the MJS-RHU are essentially identical. If it can be shown analytically and/or by comparison with Pioneer-RHU tests that the MJS-RHU would be expected to survive any probable MJS mission abort, the approval of the MJS-RHU for use in the MJS mission would be facilitated without the necessity of an extensive requalification testing program.

Background information for this report was gathered from General Dynamics (Convair Division), General Electric Company and the Jet Propulsion Laboratory as well as from the Pioneer-RHU report previously mentioned. Some of the information gathered was not final, but additional information was not expected to significantly affect the conclusions of this report.

All of the background information on the Titan III E/Centaur D-1T/MJS launch vehicle included in this report was prepared by General Dynamics (Convair Division) and was directed toward the safety considerations for the Radioisotope Thermoelectric Generator (RTG). Because the RHUs are in the same approximate station position as the RTGs, the assumption was made that the risk potential for the RHUs was the same as the the RTGs.

Each RHU consists of one thermal watt (30 Ci) of PuO_2, and it is contained within a sealed, metallic, multilayered capsule and graphite reentry protection system. Twenty-one RHUs, which represent a fuel inventory of 639 Ci, are required for each of the MJS spacecraft.

Subsystem	RHUs	Housings
Inboard Low Field Magnetometer (ILFM)	3	1
Outboard Low Field Magnetometer (OLFM)	3	1
Inboard High Field Magnetometer (IHFM)	2	1
Outboard High Field Magnetometer (OHFM)	2	1
Boom Dampers	3	3
Hydrazine Quick Disconnect	2	2
Sun Sensors	6	6
Total	21	15

The nuclear safety effort on the RHU consisted of a definition of all normal and potential accident environments that may occur during the mission, and an assessment of the effects of these environments on the RHUs. For those environments in which some potential of fuel release was indicated, conservative estimates were made of the risk magnitude and probability. In keeping with the small inventory of radioisotope fuel and the design margins of the RHU, safety analyses for MJS (RHU) and tests for Pioneer (RHU) were intentionally conservative.

The purpose of this safety analysis summary report is to present all the information pertinent to the nuclear safety of the RHU for a review by the appropriate agencies leading to flight approval. The format of this report has been patterned after that used for the Pioneer RHU, which followed that for the safety analysis summary for the Apollo Lunar Radioisotope Heater (ALRH), except that this report consists of a single volume. A description of the RHU, the mission, and a summary of the results of the safety analysis is presented. The text presents such details of the safety analyses, tests, and background information for the Pioneer RHU [1] as needed to make the report complete.

Unless specifically mentioned with exceptions, the sections included that relate to the Pioneer RHU are meant to apply for MJS-RHU as well.

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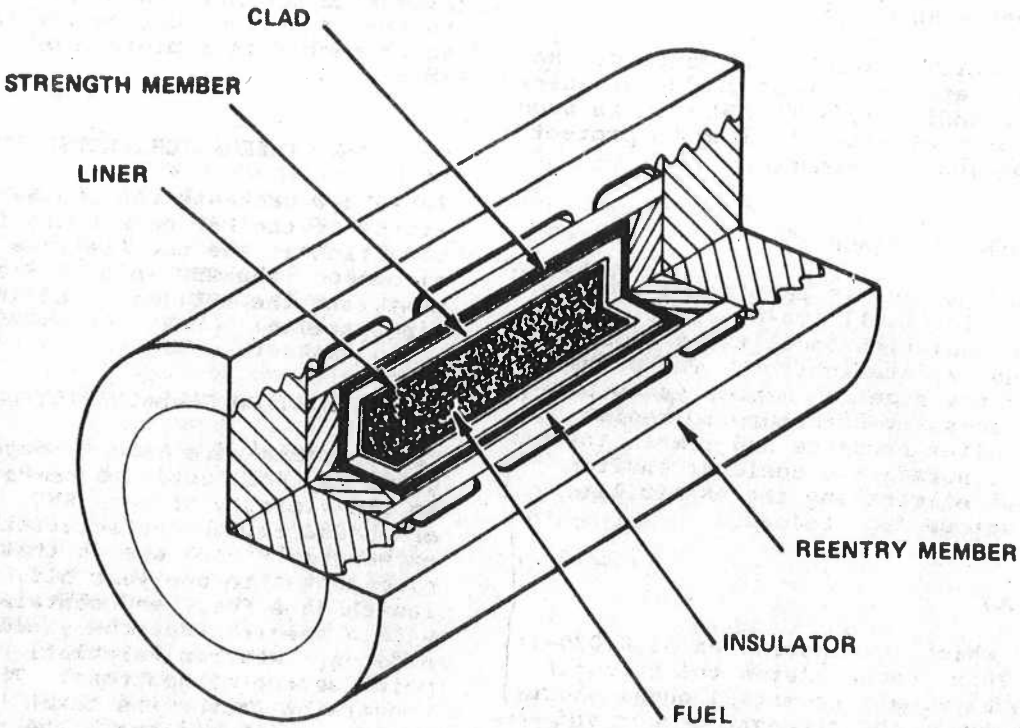

FIGURE 2-1 - One watt Radioisotope Heater Unit.

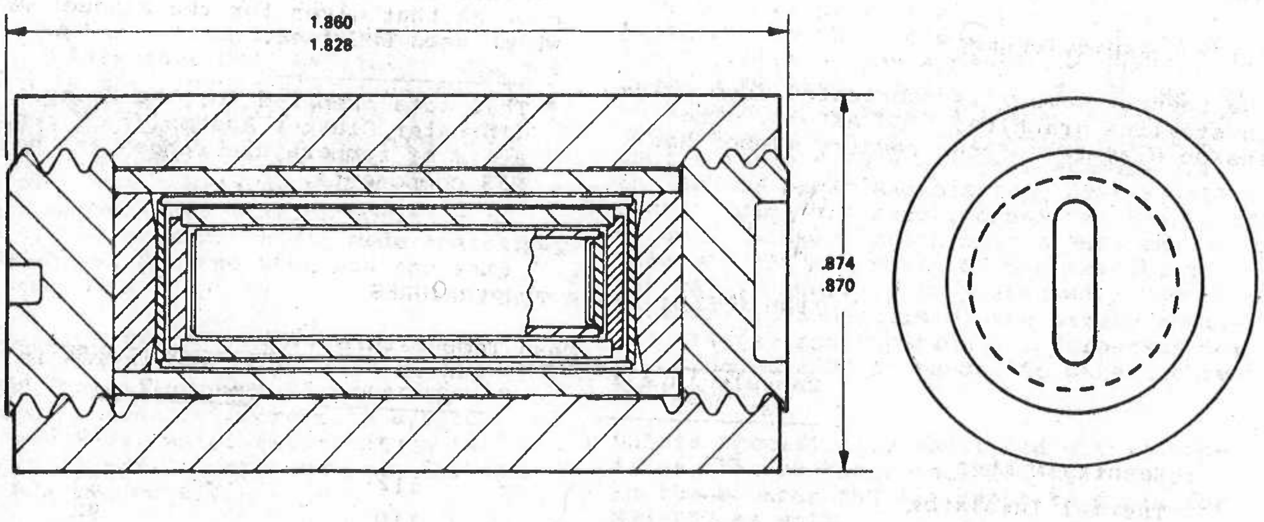

FIGURE 2-2 - RHU assembly drawing.

2.1.3 LINER - SHIM

The liner, which contacts and contains the isotope, is fabricated from 0.020-in. thick Ta-10W. In addition, a Ta-10W shim is used to cover the fuel after loading to protect the weld during the closure.

2.1.4 STRENGTH MEMBER

The strength member is fabricated from 0.040-in. thick T-111 (Ta-8W-2Hf). The double encapsulation facilitates capsule fueling and decontamination. The primary purpose of the strength member is to provide the necessary structure to resist internal helium pressure and remain intact through all normal and accident environments, thus eliminating the possibility of radioisotope fuel release.

2.1.5 CLAD

The clad, which is constructed of 0.020-in. thick Pt-20Rh, encapsulates the strength member to eliminate potential chemical reactions between the strength member and external environments.

Note: This is a design change from the Pioneer RHU which used a 0.010-in. Pt-20Rh clad.

2.1.6 THERMAL INSULATOR

The thermal insulator is pyrolytic graphite, 0.050-in. thick. The purpose of the thermal insulator is to minimize capsule temperature during reentry.

2.1.7 REENTRY MEMBER

The reentry member is fabricated from polychystalline graphite, POCO AXF-5Q. The inside diameter of the reentry member has ridges to minimize the heat transfer to the thermal insulator during reentry. The reentry member is a minimum of 0.157 in. thick.

2.2 THERMAL CHARACTERISTICS

Table 2-2 presents the steady-state temperatures of the RHU components for three conditions: the capsule in a 70°F air environment, the RHU in a 70°F air environment, and the RHU installed in the TCA* (in space).

2.3 RADIATION CHARACTERISTICS (MJS-RHU)

Calculations were made to determine the gamma ray and neutron dose rates expected in the vicinity of each RHU. The analyses are based on the characteristics of ^{16}O-exchanged $^{238}PuO_2$ shards that are within nine months to one year old, approximating launch date fuel, and contain 80% ^{238}Pu with a specific neutron yield of 4×10^3 n/sec-g. Neutron calculations assume a point source of neutrons. The flux-to-dose conversion factor was taken to be 0.12 mrem/hr per N/cm^2-sec. The neutron fluence-to-dose equivalent conversion factor is 3.3×10^{-5} mrem/n-cm^2.

The results of the radiation calculations are shown in the graph in Figure 2-3. There is very little difference in the gamma and neutron values obtained. However, some ^{236}Pu is present in all fuel, ion exchanged or not, and ^{208}Tl (an intense gamma emitter) grows in, thereby gradually increasing the gamma dose rate. Neutron radiation for the MJS-RHU is, as initially calculated, is approximately one-half as much as that given for the Pioneer RHU, which used PMC fuel.

* This data prepared for the Pioneer TCA (Thruster Cluster Assembly) is representative of temperature ranges for heated MJS components.

Table 2-2

RHU STEADY-STATE TEMPERATURES

	Mean Temperature (°F)		
	Capsule in Air at 70°F	RHU in Air at 70°F	RHU in TCA in Space; T_{sink} = 65°F
Reentry Member	---	110	70
Thermal Insulator	---	112	76
Clad	160	115	92
Strength Member	164	119	96
Liner	170	125	101
Fuel	172	127	102

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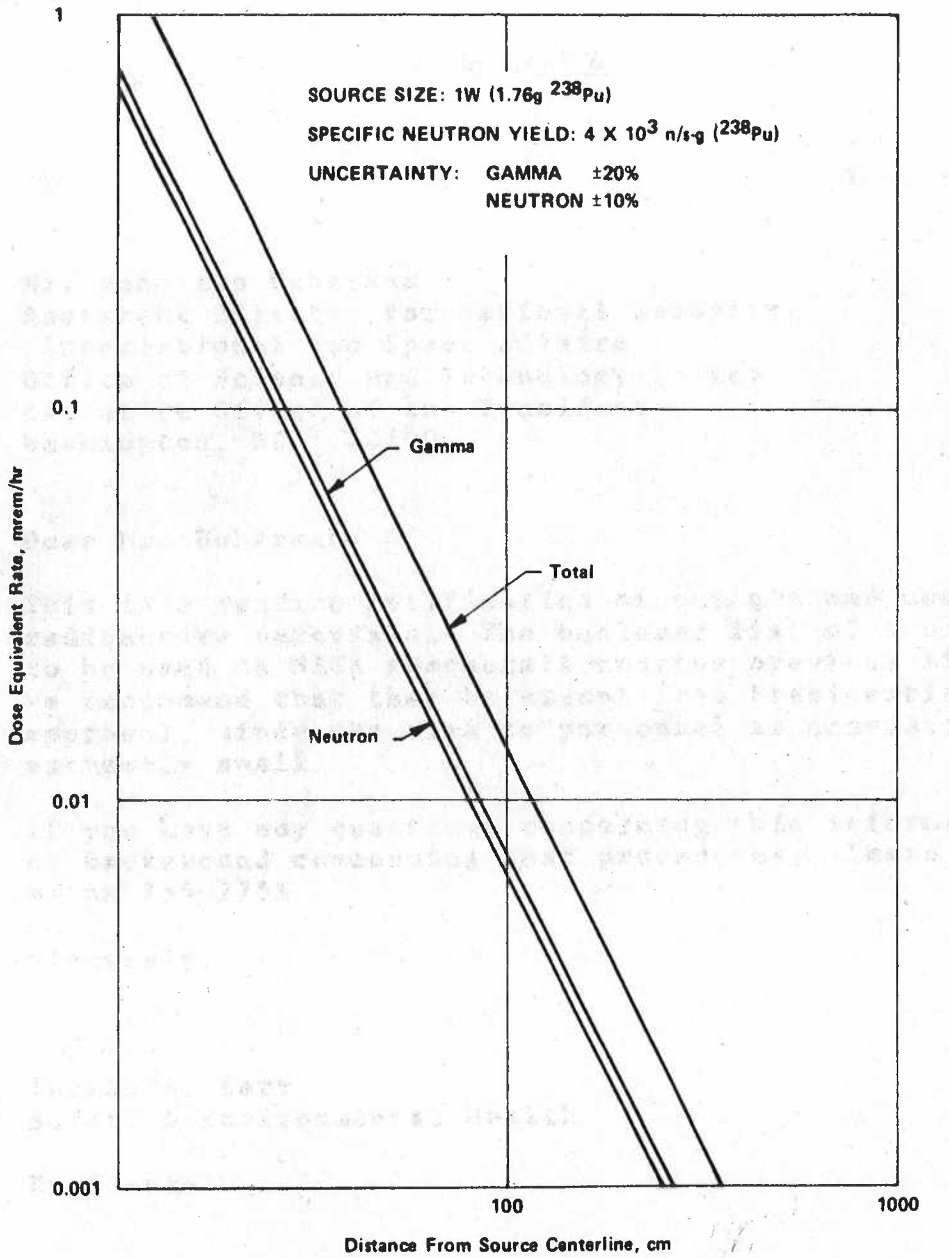

FIGURE 2-3 - Calculated neutron and gamma dose rates for MJS/RHU.

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Attachment 4

YZ October 14, 1977

Mr. Benjamin Huberman
Assistant Director for National Security,
International and Space Affairs
Office of Science and Technology Policy
Executive Office of the President
Washington, DC 20500

Dear Mr. Huberman:

This is a routine notification of our planned uses of radioactive materials. The enclosed list of sources to be used on NASA spacecraft updates previous lists. We recommend that they be exempt from Presidential approval, since the risk to personnel is considered extremely small.

If you have any questions concerning this information or background concerning past procedures, please call me on 755-2751.

Sincerely,

Thomas B. Kerr
Safety & Environmental Health

Enclosure

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

NASA

FILE21304
SEP 23 1977

Reply to Attn of: 205

TO: NASA Headquarters
Attention: Office of Systems Management
Mr. Thomas B. Kerr--YZ

FROM: Administration and Management Directorate
Health and Safety Engineering Office

SUBJECT: List of Radioactive Sources to be Launched Within NASA/GSFC Spacecraft and Payloads

Enclosed are two copies of the above subject list which contain current information regarding spacecraft or payloads containing sources scheduled to be launched during the next twelve months.

We feel the enclosed list and supporting information should meet the requirements concerning the use of minor radioactive sources in space operations.

Please call Mr. Joseph Olivito on 982-6295 if you have any further questions concerning this matter.

Eugene M. Sober
for Leven B. Gray

Enclosure

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LIST OF RADIOACTIVE SOURCES BE LAUNCHED WITHIN NASA/GSFC
SPACECRAFT PAYLOADS

SPACECRAFT	LAUNCH SCHEDULE	LAUNCH SITE	NO. OF SOURCES	ISOTOPE	TOTAL ACTIVITY	CATEGORY	REMARKS (ORBIT DURATION ETC.)
ISEE-A+B	OCT '77	Air Force Eastern Test Range, FL (ETR)	3 1 1 1 1	241 Am 133 Ba 137 Cs 148 Gd 228 Th	320µCi 200µCi 200µCi 0.1µC 0.1µC	B	Elliptical orbit Apogee 2. Earth radii Perigee 280 K Inclination 28.50 Period 2.3 days
ASTROBEE	NOV '77	White Sands Missile Range (WSMR), NM	2	210 Po	6mCi	A*	Sources will be recovered with payload
ISEE-C	JULY '78	ETR	4 1 1 1 1 1 2	241 Am 244 Cm 36-Cl 14-C 207 Bi 106 Ru 90 Sr	122µCi <0.01µCi <0.01µCi <0.01µCi <0.01µCi <0.04µCi 70µCi	B	Heliocentric

*Refer to previous memorandums, Safety Analysis Summary (SAS) reports to Headquarters, dated 7/17/70 and 12/16/70, it is felt that a detailed SAS is not necessary due to previous reports.

/...

Enclosure

SUMMARY OF SPACE NUCLEAR POWER SYSTEMS

LAUNCHED BY U.S.A (1961-1977)

Radioisotope Power Systems

Flight No.	System	Mission	Launch Date	Launch Site	^{238}Pu Fuel	Amount (Curies)	Disposition
1	SNAP 3	TRANSIT 4-A	6/61	ETR	Metal	1,800	In > 500 Year Orbit
2	SNAP 3	TRANSIT 4-B	11/61	ETR	Metal	1,800	In >1,000 Year Orbit
3	SNAP 9A	TRANSIT 4-BN-1	9/63	WTR	Metal	17,000	In >1,000 Year Orbit
4	SNAP 9A	TRANSIT 5-BN-2	12/63	WTR	Metal	17,000	In >1,000 Year Orbit
5	SNAP 9A	TRANSIT 5-BN-3	4/64	WTR	Metal	17,000	Aborted Downrange, Burned Up on Reentry
*	SNAP 10A	SNAPSHOT	4/65	REACTOR SYSTEM - See end of table			
6	SNAP 19	NIMBUS B-1	5/68	WTR	Microspheres	34,400	Aborted at Launch, Recovered From Ocean
7	SANP 19	NIMBUS III	4/69	WTR	Microspheres	37,600	In ~3,000 Year Orbit
8	SNAP 27	APOLLO-12	11/69	KSC/ETR	Microspheres	44,500	On Lunar Surface
9	SNAP 27	APOLLO-13	4/70	KSC/ETR	Microspheres	44,500	Aborted after TLI. Deep Ocean Burial-South Pacific
10	SNAP 27	APOLLO-14	1/71	KSC/ETR	Microspheres	44,500	On Lunar Surface
11	SNAP 27	APOLLO-15	7/71	KSC/ETR	Microspheres	44,500	Lunar Surface
12	SNAP 27	APOLLO-16	4/72	KSC/ETR	Microspheres	44,500	Lunar Surface
13	RTG	PIONEER F (10)	3/72	CKAFS/ETR	Cermet	80,000	Jupiter/Deep Space
14	RTG	TRANSIT	9/72	VAFB/WTR	Cermet	24,000	In <1,000 Year Orbit
15	SNAP 27	APOLLO-17	12/72	KSC/ETR	Microspheres	44,500	Lunar Surface
16	RTG	PIONEER G (11)	4/73	CKAFS/ETR	Cermet	80,000	Jupiter/Deep Space

/...

Summary of Space Nuclear Power Systems (Cont'd)
Launched by U.S.A. (1961-1977)

Flight No.	System	Mission	Launch Date	Launch Site	^{238}Pu Fuel	Amount (Curies)	Disposition
17		LES 8/9	3/76	CKAFS/ETR	Oxide Spheres	280,000	In > 4000 yr orbit
18		VIKING-1	8/75	CKAFS/ETR	Cermet	42,000	Mars Surface
19		VIKING-2	9/75	CKAFS/ETR	Cermet	42,000	Mars Surface
20		MJS-1 (VOYAGER)	8/77	CKAFS/ETR	Oxide Spheres	210,000	Jupiter/Saturn
21		MJS-2 (VOYAGER)	9/77	CKAFS/ETR	Oxide Spheres	210,000	Jupiter/Saturn

Reactor Power Systems (1 only)

System	Mission	Launch Date	Launch Site	Fuel	Amount	Disposition
SNAP 10A	SNAPSHOT	4/3/65	WTR	^{235}U Fully Enriched	≈ 4.5 Kgs	In > 1000 yr orbit

/...

NUCLEAR SPACE LOG

NUMBER OF LAUNCHES (RTG's)	- 21 SINCE JUNE 1961
TOTAL ACTIVITY (CURIES OF $^{238}PuO_2$)	- 1,361,600
DEEP SPACE	- 580,000 (43%)
ORBIT	- 379,200 (28%)
LUNAR SURFACE	- 222,500 (17%)
MARS SURFACE	- 84,000 (6%)
PACIFIC OCEAN	- 44,500 (3%)
RECOVERED	- 34,400 (2%)
ATMOSPHERE	- 17,000 (1%)
NUMBER OF LAUNCHES (REACTOR)	- 1, ON 4/3/65
IN ORBIT	4.5 KG ^{235}U

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U. S. SYSTEM ABORTS WITH RADIOISOTOPE THERMOELECTRIC GENERATORS (RTGs) ABOARD

1. DOD--TRANSIT-5BN-3-(SNAP 9A)-4/21/64

   Failure on launch, reentered over Indian Ocean and burned up. RTG heat source was metal and was designed for burnup. Was detected by air sampling of atmosphere.

2. NASA--NIMBUS-B-1-(SNAP 19)-5/18/68

   Booster guidance failure on launch- range safety destroyed booster. Spacecraft with RTGs (2) fell into Santa Barbara Channel off coast of California. Heat sources recovered from 300 feet of water and fuel reused.

3. NASA-APOLLO 13-(SNAP 27)- 4/11/70

   Service Module failure-LEM used for survival facility during circumlunar flight and return to earth. RTG heat source reentered with LEM into South Pacific (10-20,000 feet of water) after command module was separated for astronaut recovery. No attempt to recover because exact location is unknown and water is too deep.

Although first systems (RTGs) had fuel capsules designed to burn up on reentry, improvements in fuels and containment materials have permitted designs for intact reentry and potential recovery of the fuel on land. Future systems are being designed with same philosophy.

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SUMMARY
TRANSIT 5BN-3
SNAP 9A ABORT

RADIOISOTOPE POWER SYSTEMS

LAUNCHED APRIL 1964
DID NOT REACH ORBIT DUE TO CONTROL FAILURE.
*REENTERED ATMOSPHERE AT 400,000 FEET AND BURNED-UP, OVER THE WEST INDIAN OCEAN NORTH OF MADAGASCAR.

DESCRIPTION

THERMOELECTRIC POWER SYSTEM
POWER - 510 WATTS (THERMAL)
27 WATTS (ELECTRIC)
FUEL - ^{238}Pu METAL
17,000 CURIES

RESULTS - A GLOBAL SAMPLING PROGRAM CONDUCTED BY THE AEC HEALTH & SAFETY LABORATORY (HASL) SINCE 1964 HAS ACCOUNTED FOR THE SNAP 9A ^{238}Pu AND CONFIRMS THAT THE FUEL DID BURNUP AND DISPERSE IN THE UPPER ATMOSPHERE.

*NOTE: THE SNAP 9A FUEL CONTAINMENT WAS DESIGNED TO BURNUP ON REENTRY. THIS IS THE LAST RADIOISOTOPE SYSTEM SO DESIGNED-ALL RADIOISOTOPE SYSTEMS SINCE ARE DESIGNED FOR INTACT REENTRY AND RECOVERY.

/...

SUMMARY

TRANSIT 5BN-3

SNAP 9A ABORT

Radioisotope Power Systems

Launched April 1964

Did not reach orbit due to control failure.

*Reentered atmosphere at 400,000 feet and burned-up, over the west Indian Ocean north of Madagascar.

Description

Thermoelectric Power System

Power - 510 watts (thermal)
27 watts (electric)

Fuel - ^{238}Pu metal
17,000 curies

Results - A Global Sampling Program conducted by the AEC Health & Safety Laboratory (HASL) since 1964 has accounted for the SNAP 9A ^{238}Pu and confirms that the fuel did burnup and disperse in the upper atmosphere.

*NOTE: The SNAP 9A fuel containment was designed to burnup on reentry. This is the last radioisotope system so designed-all radioisotope systems since are designed for intact reentry and recovery.

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SUMMARY SHEET

SNAP 10A SPACE NUCLEAR REACTOR SYSTEMS

SNAP SHOT FLIGHT TEST

LAUNCH - APRIL 1965 FROM VAFB/WTR ABOARD AN ATLAS/AGENA VEHICLE - > 1000 YEAR ORBIT

POWER SYSTEM - WEIGHT - 960 LBS.
SIZE - 11.5 FEET X 4.3 FEET D (AT BASE)
NaK COOLANT
THERMOELECTRIC CONVERSION SYSTEM
OUTPUT - ~ 500 WATT (ELEC.)

REACTOR - WEIGHT - 250 LBS.
SIZE (CORE VESSAL) - 15" HEIGHT X 9" DIAMETER
NUCLEAR FUEL - ~ 4.5 KGS URANIUM-235
FUEL ELEMENTS - U/ZR HYDRIDE, 37 ELEMENTS, 12" LONG X 1.25" DIAMETER
BERYLLIUM REFLECTED AND CONTROLLED

STATUS - OPERATING TIME IN ORBIT - 43 DAYS
ACCIDENTLY SHUT-DOWN BY SPURIOUS ELECTRONIC SIGNALS; RESTART NOT POSSIBLE.

FISSION PRODUCT ACCUMULATION:

AT SHUTDOWN - ~ 2×10^5 CURIES
AT 15 YEARS - ~ 100 CURIES
AT 100 YEARS - ~ 10^{-1} CURIES

/...

SUMMARY

NIMBUS B-1 - SNAP 19 ABORT

DESCRIPTION

FUEL: RADIOISOTOPE FUEL CAPSULE, 34,400 CURIES PLUTONIUM-238 OXIDE MICROSPHERES

CONTAINMENT: HAYNES-25

DESCRIPTION: THERMOELECTRIC POWER SYSTEM

POWER - 1030 WATTS (THERMAL)

60 WATTS (ELECTRIC)

ABORT CONDITIONS: GUIDANCE FAILURE AT LAUNCH. RANGE DESTRUCT WITH SPACECRAFT AND RTGS LANDING IN SANTA BARBARA CHANNEL OFF CALIFORNIA COAST.

RESULTS: THE FUEL CAPSULES WERE RECOVERED AND THE FUEL REUSED. NO FUEL RELEASED DURING ABORT.

/...

SUMMARY
APOLLO 13 - SNAP 27 ABORT

DESCRIPTION

FUEL: RADIOISOTOPE FUEL CAPSULE, 44,500 CURIES PLUTONIUM-238 OXIDE MICROSPHERES

CONTAINMENT: HAYNES-25 CAPSULE CONTAINED IN A GRAPHITE FUEL CASK ATTACHED TO THE LUNAR LANDING MODULE (LM).

ABORT CONDITIONS: REENTERED WITH THE LM AT 400,000 FEET ABOVE THE SOUTH PACIFIC OCEAN AND IMPACTED INTACT IN DEEP OCEAN SOUTH OF FIJI ISLANDS.

RESULTS: AIR MONITORING AT SEVERAL HIGH AND LOW ALTITUDES IN AREA CONFIRMED THAT NO NUCLEAR FUEL WAS RELEASED.

LOCATION: NEAR TONGA TRENCH IN 20,000 - 30,000 FEET OF WATER.

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Attachment 6*/

Explosion Parameters Recorded on Magnetic Tape

Type Transducer	Transducer Distance (ft)	Shock Arrival Time (msec)	Measured Overpressure (psig)	Estimated Duration (msec)	Estimated* Impulse (psi-sec)
Static	11.5	2.30	260	14	0.60
Static	13.5	2.80	94	12	0.55
Static	15.5	3.30	121	14	0.46
Stagnation	15.5	3.30	790	3	0.32
Static (A)	17.5	3.85	110	16	0.38
Static (B)	17.5	3.90	118	16	0.42
Stagnation (A)	17.5	3.78	540 (380)	2	0.28
Static (A)	19.5	4.47	105	16	0.31
Static (B)	19.5	4.49	108	15.5	0.25

* Impulse read at time when pressure profile first returned to zero amplitude (i.e., positive phase impulse).

Calculated Explosion Parameters
(Based on ideal gas Rankine-Hugoniot Equations)

Shock Tube Station (ft)	ΔP (psig)	ΔP_{stag} (psig)	ΔP_r (psig)	q (psi)	M_s	M_2	$\frac{\rho_2}{\rho_1}$	$\frac{T_2}{T_1}$	$\frac{U_2}{C_1}$
15.5	121	398	669	178	3.09	1.38	3.94	2.79	2.31
17.5	118	385	648	172	3.06	1.37	3.91	2.75	2.28
17.5	110	351	593	155	2.97	1.35	3.83	2.64	2.19
19.5	108	342	579	151	2.94	1.34	3.80	2.61	2.17
19.5	105	330	559	145	2.90	1.33	3.77	2.52	2.13

ΔP = Static overpressure

ΔP_{stag} = Stagnation overpressure

ΔP_r = Peak reflected overpressure

q = Dynamic pressure

M_s = Shock Mach number

M_2 = Flow Mach number

ρ_2/ρ_1 = Density ratio across shock

T_2/T_1 = Temperature ratio across shock

U_2/C_1 = Flow velocity to initial sound speed ratio

*/ Photographs for this attachment to be distributed separately.

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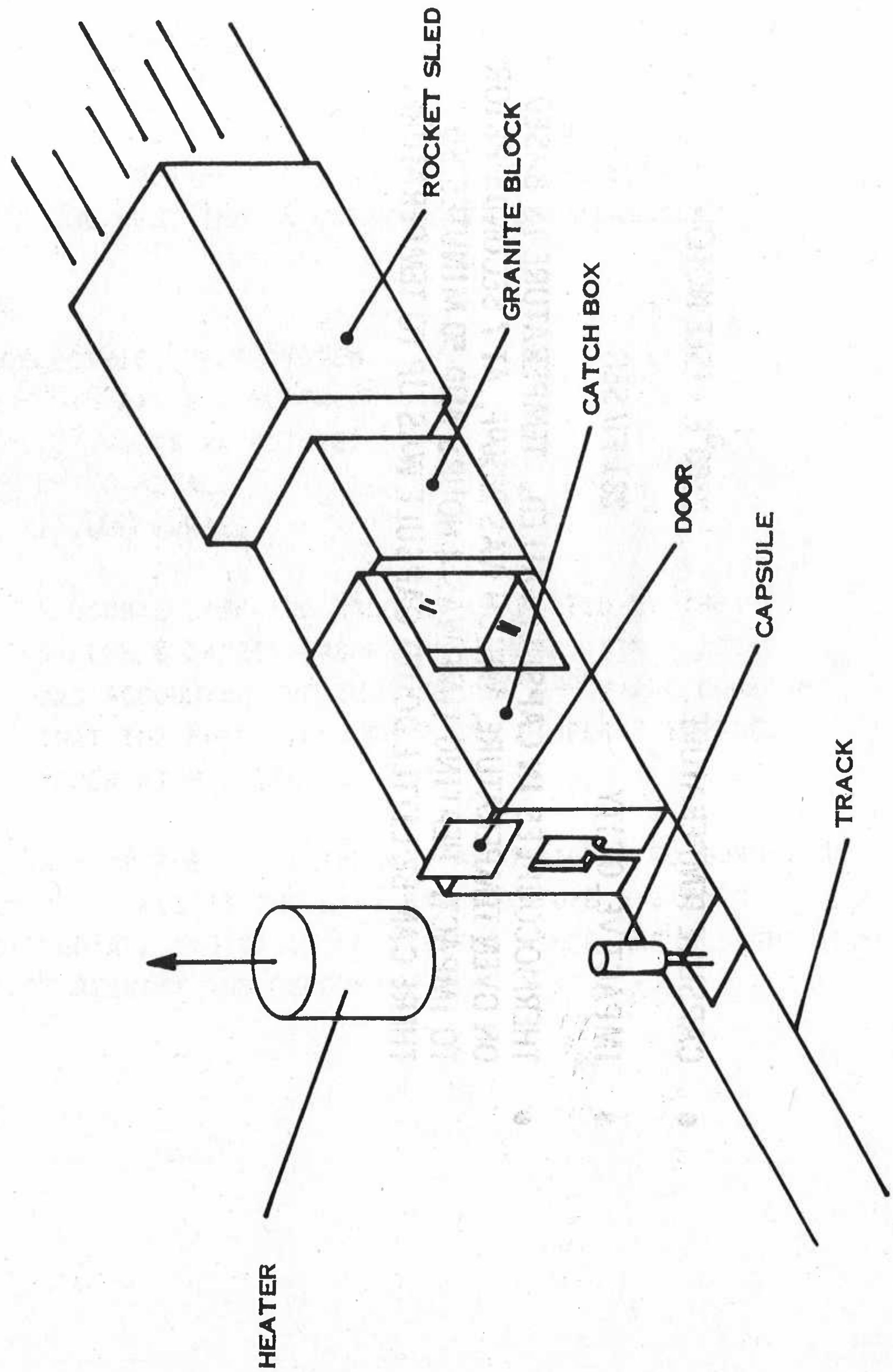
Attachment 7 */

TEST SETUP



*/ Photographs for this attachment to be distributed separately.

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TEST CONDITIONS

- CAPSULE TEMPERATURE 2500°F + (SEE NOTE)
- IMPACT VELOCITY 281 FT/ SEC
- THERMOCOUPLES IN CAPSULE FAILED. TEMPERATURE IS BASED ON OVEN TEMPERATURE, WHICH WAS 2530°F, AT 7 SECONDS PRIOR TO IMPACT. HEATING TIME WAS 4 HOURS AND 50 MINUTES SO THERE CAN BE LITTLE DOUBT CAPSULE WAS UP TO TEMPERATURE.

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Attachment 8