Space isotopic power systems

With the technology sound and growing, and units already built for missions ranging from 120 days to 5 years, the designer can and should plan appropriate space application of isotopic systems

BY CAPT. R. T. CARPENTER, USAF
U.S. Atomic Energy Commission

A new space power system technology —isotopic power—has developed to the point where it can and should be considered by the space-vehicle designer for use in many types of missions.

The Atomic Energy Commission's isotopic space power program dates back to several years before Sputnik I, but the program suffered a severe setback in 1959 when the Snap-1A generator development program was cancelled.[1] This pioneer program was not completed because it may have been too ambitious for its day. The need for isotopic power had not yet become apparent to space program planners; its place and full significance in the nuclear space power program were not clearly established; its applicable thermoelectric energy conversion technology was still very new; large quantities of isotopic fuel materials were not readily available; and the operational safety of large quantities of radioactive material in space vehicles was a brand new unknown in a space program already full of unknowns.

That the demise of the Snap-1A program was not due to a lack of technical soundness is evident when one looks at the thermoelectric generator fabrication technology, isotopic-fuels technology, and aerospace nuclear safety technology contributed by the program and used as a foundation for follow-on space isotopic power-system developments.

Because of this sound technical basis, the Commission's space-oriented isotopic power development program has made a steady, although sometimes slow, comeback through a series of events since 1959, so that today a program technically comparable to Snap-1A could once more be undertaken with a high probability of successful completion. This series of events can help demonstrate the status of today's space isotopic power program. Details of the various systems have been described many times and will not be repeated here. For reference purposes, the characteristics of several space isotopic power systems are given in the table appearing on page 70.

While efforts were being made to interest space power-system users in isotopic systems, the first practical radioisotope-fueled thermoelectric generator—Snap-3—was being subjected to exhaustive electrical tests; shock, vibration, acceleration and thermal-vacuum environmental tests; and fire, explosion, impact and re-entry burnup nuclear safety tests.[2,3]

Concurrently, the terrestrial applications—the Snap-7 programs—sustained the isotopic power development program and promoted the fission-product separations and processing capability that exists within the Commission today.[4] The interest among terrestrial power users—the Navy, Weather Bureau, and Coast Guard—was sufficiently strong to support this fuels production program, whereas the interest in Snap-1A had been inadequate. At the same time, significant quantities of the long-lived alpha-emitter fuel, plutonium-238, were being produced so that it could be allocated to low-powered space systems. Relatively little direct radiation hazards are associated with alpha-emitter fuels compared to beta-emitter fission products.

Because of these background efforts, it was possible to fabricate, fuel, test, and get approval to use the first plutonium-238 fueled Snap-3 generator on the Navy's Transit-4A navigation satellite in June 1961, with a lead time of only five months. The launches of the 2.7-w, Pu-238-fueled Snap-3s on Transit-4A and Transit-4B (in November 1961) were not just "firsts in space."[5] The experience gained in integrating these units into satellites, the flight-test data obtained from

CAPT. R. T. CARPENTER is Deputy Chief of the AEC's Isotopic Power Branch in the Division of Reactor Development. He has been manager of space and terrestrial power development projects with the Commission's isotopic power program since April 1959. Capt. Carpenter's previous assignments include responsibilities as R&D project engineer at the Chemical Corps Biological Labs and at Wright Air Development Center. He holds a B.S. in chemical engineering and an M.S. in nuclear engineering.

orbit, and the interagency procedures and policies established prior to their launch produced in a matter of months a state of the art for isotopic space power which probably would have taken several years with a much larger unit, such as Snap-1A.

The generator on the Transit-4A satellite continues to produce enough power to transmit the low-powered Doppler navigation signals to earth after being in orbit almost two years. Because of a failure in the satellite's telemetry system a few weeks after launch, quantitative data on the performance of the generator are no longer available.[6] Qualitative performance of the unit is still being monitored by the Transit tracking stations.

Telemetry data from Transit-4B indicated the radioisotope thermoelectric generator (RTG) performed precisely as expected for about eight months. In early June 1962, an abrupt drop in generator output voltage was observed. During the next week, the voltage came right back up to the normal operating value of 2.1 v, dropped again to millivolts, came back up and then dropped to and stayed at practically zero voltage. This cyclic behavior is not characteristic of an RTG failure. Upon analysis of the data, it was concluded that a capacitor across the input to the DC-to-DC voltage converter had shorted out. The solar power supplies aboard Transit-4B failed soon after the high-altitude nuclear test of July 9, 1962, and signals are no longer being received from the satellite.[7]

One of the lessons learned from these early flight tests was the importance of integrating the nuclear unit into the payload as soon as possible. Because the Snap unit was substituted for a solar-cell panel at the last moment, only a limited number of telemetry channels were available to monitor the generator. Only the output voltage and surface temperature were monitored. Knowledge of the output current at the time of failure probably would have confirmed the failure mode.[7]

These successful flight tests of experimental RTGs led to the early initiation of the Snap-9A program to develop a 25-w RTG to deliver all of the power for the Navy's operational prototype Transit-5 navigation satellites. The unit is shown on page 70. Snap-9A, the first isotopic power system developed for a specific space application, uses technology gained from Snap-1A thermoelectric module developments and the experience of the launches of the Pu-238 fueled Snap-3 in vehicle integration, ground-handling, and aerospace nuclear-safety aspects. The first electrically heated Snap-9A generator was operated six months after go-ahead from the Navy and award of the contract to Martin Co. by AEC. The first flight-acceptable generator was fueled with Pu-238 nine months after go-ahead. It is scheduled for use this year.

During the past year, a substantial amount of data has been obtained from ground tests of the electrically heated and fueled generators. Important results were obtained from long-term thermal-vacuum tests of the units under simulated space operating conditions. The generators were found to be very stable power sources when subject to sunlight and shadow conditions for a 600-mi. polar orbit. The high heat capacity of the compact generator allowed a gradually changing surface temperature and power output under these conditions, indicating the solar input had little effect on the system. The Pu-238 fuel provides an unalterable source of heat far more stable than an electrical heater. Power degradation was observed during tests of the fueled generators that was too small to detect with the variations in line voltage, etc., experienced with electrically heated units. Although extremely small, these changes would be significant over the five-year design lifetime of the generator.

The cause of this power degradation was quickly diagnosed because similar but more easily detected power losses had been observed in the Snap-7 generators a few months earlier. The materials used in the generators were outgassing in a time-temperature dependent manner, causing a greater heat loss to bypass the thermoelectrics. To counteract this, the generators have been baked at higher temperatures and filled with inert gases at higher pressures to reduce the effect of the outgassing on generator performance.

The temperature cycling experienced by the generators during these ground tests was far more frequent and severe than that which would occur in space. This thermal cycling increased internal impedance of the generators and consequently resulted in a mismatch between the RTG and the payload. The fix for this problem came from the more advanced thermoelectric fabrication technique used for Snap-11 which had been developed and tested since the design for Snap-9A was frozen. This new technique provides a lower internal impedance for RTG, and makes it less subject to change during prelaunch handling. Snap-9A was reworked to incorporate these improvements. Thus, in effect, two generations of RTGs have been developed under the Snap-9A program without an intervening flight test.

Snap 11, a 25-w RTG being developed for use on NASA's Surveyor soft lunar-landing missions, has also contributed significantly to isotopic space power systems technology.[8] After a design study and a preliminary safety analysis had been completed, NASA established a requirement for the Snap-11 generator development program late in 1961. During the past year, a detailed design was completed that would meet all the interface requirements of the Surveyor spacecraft. These included the electrical, physical, nuclear radiation, and thermal interface specifications.[9] The electrical output can be easily matched to the payload through a DC-to-DC voltage converter similar to that used with conventional power supplies.

The physical limitations of the vehicle naturally dictate the size, weight, and shape of an RTG. For the Surveyor program, it was decided to extend Snap-11 out from the spacecraft (because of overriding thermal considerations) so that an optimized RTG configuration could be used. The separation distance and provisions for shielding in the design of the curium-242 fuel capsule will allow Snap-11 to meet the extremely stringent background radiation levels specified for the sensitive radiation detectors aboard the spacecraft. Thermal integration problems were most severe and caused abandonment, for the present, of a design for conducting heat to the sensitive payload instruments during the cold lunar night.

A thermal mockup of the Snap-11 has been fabricated and is undergoing tests. Electrically heated prototype generators will be available for integration tests later this year. Because of launch vehicle problems, Snap-11 is not scheduled to fly before 1965, unless the results of earlier solar-powered Surveyor spacecraft dictate otherwise.

The significant differences between Snap-11 and Snap-9A are due primarily to the different mission lifetime requirements (120 days vice five years) and, therefore, the different fuels employed. The short-lived Cm-242 fuel requires a power-flattening feature to remove excess heat generated early in the mission. Thus Snap-11 incorporates a temperature-controlled, liquid metal-actuated heat-dump shutter which starts open and then gradually closes as the isotope decays in order to maintain a constant temperature on the hot junction of the thermoelectric generator and a constant power output. This technique

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Designation	Use	Power Output, (W)*	Weight, (lb)	Size (in. OD × in. ht.)	Isotopic Fuel	Design Life	Operational Date
Snap-1A	Air Force satellite	125	175	24 × 34	Cerium-144	1 year	Cancelled in 1959
Snap-3	Thermoelectric demonstration	3	4	4.75 × 5.5	Polonium-210	90 days	Demonstrated in 1959
PU-238 Fueled Snap-3	Transit 4A & 4B satellites	2.7	4.6	4.75 × 5.5	Plutonium-238	5 years	Launched in 1961
Snap-9A	Transit 5 satellites	25	27	20 × 9.5	Plutonium-238	6 years	1963
Snap-11	Surveyor soft lunar landing	21–25	30	20 × 12	Curium-242	120 days	1965
Snap 13	Thermionic demonstration	12.5	4	2.5 × 4	Curium-242	120 days	Demonstration in 1964
500-w Generator (Thermionic)	Design study only	500	100–175	—	Curium-242	6 months	—
		500	175–225	—	Plutonium-238	1–5 years	—
		500	250–300	—	Cerium-144	1 year	—
IMP Generator (Thermoelectric)	IMP satellite (design only)	25	21	22 × 11 × 10**	Plutonium-238	1–3 years	1964***
Sr-90 Generator (Thermoelectric)	Communications satellites	30	20–25	—	Strontium-90	5–10 years	1965***
		60	40–50	—	Strontium-90	5–10 years	1965***
		120	70–80	—	Strontium-90	5–10 years	1966***
		300	150–175	—	Strontium-90	5–10 years	1966***

* Raw power from generator. Voltage converter efficiency 75–85% not included.
** In. length × in. width × in. height.
*** First use in space for planning purposes.

is similar to the one developed under the Snap-1A program. The other difference is in the safety criteria used for designing the Snap-11 fuel capsule. In the event the unit should reenter the earth's atmosphere, it will be designed to remain intact instead of burning up. The short-lived fuel will decay to practically nothing before re-entering from the parking orbit. The fuel capsule is designed to prevent widespread contamination of the lunar surface in the event of a vehicle malfunction leading to high-velocity impact on the moon.

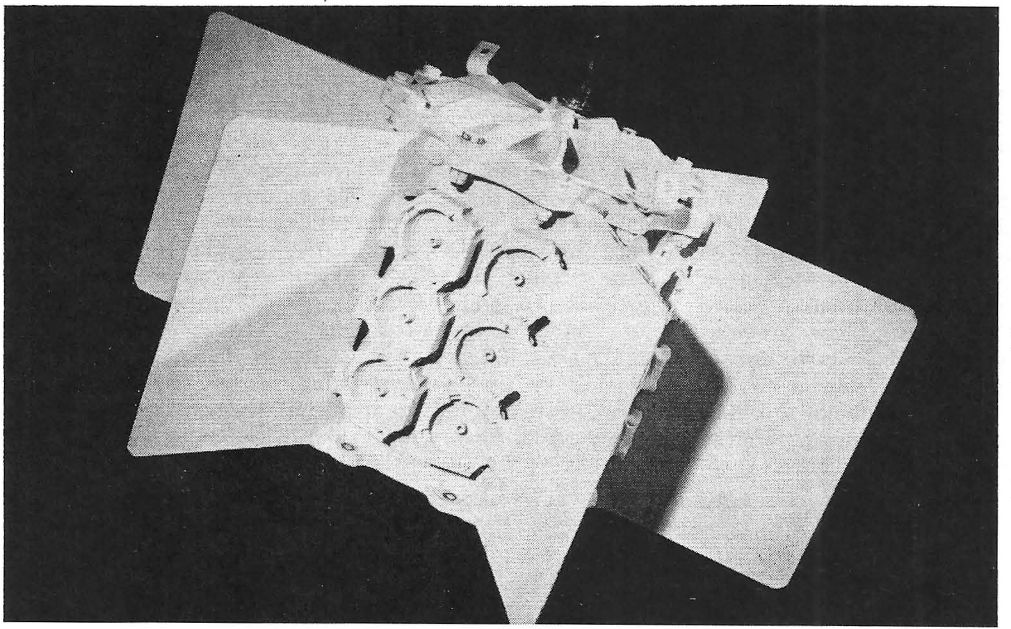
Because of the Snap-11 fuel requirement, a Cm-242 production capability has been established at Oak Ridge National Laboratory. The first fuel-load quantities of this extremely high power-density material will be produced later this year. This Cm-242 development program is also contributing supporting technology applicable to a curium-244 (long-lived alpha emitter) fuel production program for space power needs.

Recently, a design effort was undertaken for an isotopic power system for use on the Interplanetary Monitoring Probe (IMP) satellite being developed by NASA's Goddard Space Flight Center, shown on page 71. This program also involved vehicle integration problems since the RTG had to fit on a spacecraft designed to use a solar power supply. The power system, if adopted by NASA, will include two RTGs placed on opposite sides of the spacecraft to maintain proper weight and balance for stabilization. The IMP generators will each produce approximately 25 w and will be fueled with Pu-238 because of the longer than one-year mission lifetime. These RTGs incorporate design improvements over Snap-9A which provide for easier fabrication and lower system weights. The number of seals required in the generator has been reduced to improve long-term reliability, and the shape of the generator and radiator fins has been tailored to fit into the existing vehicle design.

For the most part, the IMP generator uses proven materials and techniques, the only changes made being those required for system integration. For example, one of the primary objectives of the IMP satellite is to map the magnetic field between the earth and the moon, so a very sensitive magnetometer is included aboard the vehicle. Therefore, some of the materials used in the RTG and the electrical circuitry of the generator had to be changed to reduce the generator's effect on the magnetic field.

The purpose of this brief review has been to review the current state of the art of space isotopic power systems. It can be summarized as follows:

To date, low-powered systems (up to 25 w) have been developed and



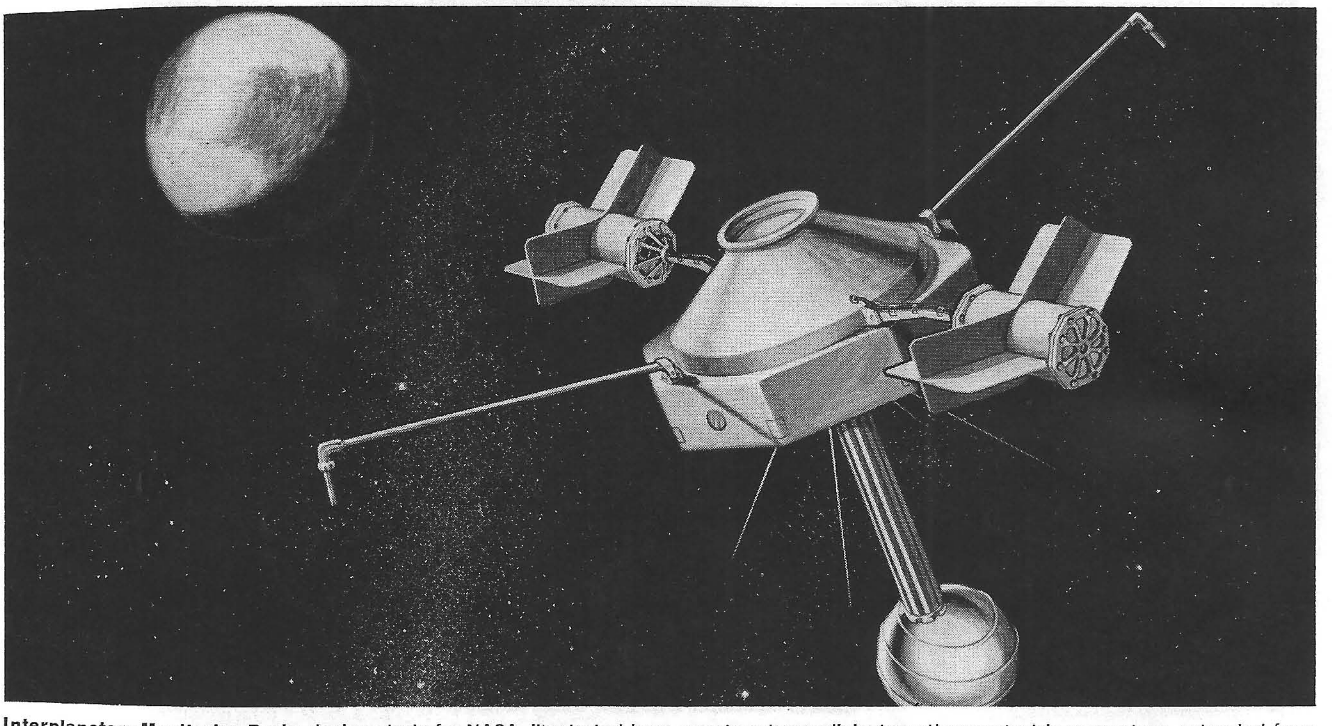
25-watt radioisotope thermoelectric generator for use on the Navy's operational prototype Transit-5 navigational satellite. The first flight-acceptable generator was fueled with Pu-238 nine months after go-ahead, and is scheduled for launch this year.

qualified for operational use. Only the "safest" alpha-emitter fuels have been used. Present RTG's display a power-to-weight ratio of about 1 w/lb. Isotopic-fueled static thermoelectric conversion systems exhibit a high degree of reliability. The lifetimes to be expected are a function of the isotope fuel used. Units have been designed and built for mission lifetimes ranging from 120 days to five years. The systems are flexible and can be integrated into almost any type of space vehicle. Lead times have been extremely short in many cases, but launch schedules have been met. Interagency cooperation and support have been successfully demonstrated.

4. *Thermionic power conversion technology*—to demonstrate the capabilities of radioisotope-fueled thermionic power systems.

5. *Aerospace nuclear safety technology*—to provide for safe employment of larger and more powerful nuclear devices in space.

Now how does the current technology relate to future isotopic power system developments and applications. Radioisotope fuel properties and availability determine, to a large extent, the fuel selected for a given application.[10] Because the supply of alpha-emitter fuels will be limited for the next few years, their use in high-powered systems, or for missions re-



Interplanetary Monitoring Probe design study for NASA, illustrated here, employs two radioisotope thermoelectric generators, extended from opposite sides of the spacecraft to maintain proper balance for its stabilization.

quiring a large number of satellites, will be limited. Alpha-emitter fuels are best used for planetary probe missions or on other spacecraft where low radiation levels are mandatory. They can also be used for low-altitude satellite missions where lifetime and weight are prime considerations and radiation effects of the artificial belts make it impractical to use solar cells. The short-lived alpha emitters—polonium-210 and curium-242—are good for mission lifetimes up to six months which justify the use of isotopic systems over competitive systems.[11]

The long-lived alpha emitters—curium-244 and plutonium-238—should be used only for missions with a lifetime of one year or longer, except where they can be recovered and reused, as in a manned space capsule. Long-lived alpha emitters can also be used over and over for prelaunch checkout of systems designed to use beta emitters. As alpha emitters become more abundant in the last half of this decade, they can be considered for use in more or larger power systems.[4]

For those unmanned missions which do not include sensitive radiation detectors, it seems advisable to use the fission product, beta-emitter fuels—cerium-144 (for mission lifetimes up to one year) and strontium-90 (for mission lifetimes greater than one year). These isotopes are being produced in large quantities today, are relatively inexpensive to process, and can be compounded in high-temperature fuel forms which can be readily dispersed at high altitudes during reentry into the earth's atmosphere.

The disadvantages of the beta-emitter fuels, compared to the alpha emitters, are their low power density and the direct radiation emitted as X-rays, or bremmstrahlung, which given off as the beta particle's energy is transformed into heat and gamma rays. Low power density means the system will be larger and somewhat

In addition to the prototype generator developments already described, supporting R&D efforts are being pursued by AEC in the following areas:

1. *Isotopic fuels technology*—to provide fuel forms with higher melting points and higher power densities which still meet aerospace nuclear safety criteria.

2. *Isotope production and processing capability*—to improve the availability and lower the cost of isotopic fuels.

3. *Thermoelectric power conversion technology*—to provide higher temperatures, more efficient and/or lighter weight thermoelectric systems.

heavier. The direct radiation requires consideration during ground handling and launch operations.

An AEC program is underway to demonstrate safe ground handling and launch procedures of a beta-emitter fueled unit. Procedures of this kind were developed under the Snap-1A program, and have been improved to be more compatible with launch pad operations and different launch vehicles. Generally, if proper consideration is given to self-shielding of payload components and to the use of separation techniques, if necessary or possible, the radiation from these beta-emitter fueled power sources requires little or no additional shielding to protect electronic instruments during operation in space. Use of these more abundant beta emitters permits consideration of isotopic power for higher powered applications, for example, some scientific satellites, and operational systems requiring many satellites in orbit, such as communication and meteorological satellites.[10,12]

Power-to-weight ratios for RTGs are being improved. For alpha-fueled systems, 2 to 3 w/lb is achievable with 25 to 250 w generators within the next two to three years, by using thermoelectric materials and fabrication techniques already under development in the supporting R&D programs cited above. Beta-fueled systems will weigh 1.5 to 2 w/lb for comparable power levels. These gains are expected with no loss in reliability, and with some improvement in conversion efficiency of the thermoelectric generators.

Developments in the thermionic R&D programs indicate that, by the time the high power-density alpha emitters become more available in the 1966–67 period, thermionic isotopic power systems will also offer improvements in specific power ratios and conversion efficiencies. Thermionic systems are farther away because of the higher operating temperatures involved and because systems fueled with beta emitters are not competitive with thermoelectric systems in weight, efficiency, or reliability. However, thermionic systems will be smaller than thermoelectric systems at comparable power levels.

There is no magic limit to the power levels for isotopic power systems. There is, however, an optimum power-to-weight ratio for each power level for a given generator concept. Therefore, it might be desirable to use two or more optimum units for higher power requirements. For a few rather unique missions, such as manned lunar exploration or Mars and Venus orbiters or landers, where power levels in excess of 500 w will be required, there may be some advantages in considering the use of isotopic power systems, providing that adequate lead time is allowed for AEC to make the necessary fuels available.

The time to factor an RTG into a payload is during the design phase. Then one can take advantage of the unique characteristics of isotopic power systems, such as making use of the predictable heat source to positively control the payload temperature. Space isotopic power systems are still considered very much in the R&D stage, but so is the space program. Since there are many variables in the selection of an isotopic system; since the development cycle is short (two to three years); and since development costs are relatively low, there are obvious advantages in developing an optimized power system for a given application and making use of this rapidly advancing technology.

Isotopic power will not answer all the problems facing a space power system designer. However, it stands ready to be used for those many space missions where it is applicable and where other systems cannot or should not be used.

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