New Developments in the Space Isotope Power Program

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An adequate source of electric power is, of course, essential to all space missions. As these missions become more ambitious, the power needs will increase. It is the job of the Atomic Energy Commission to assure that the unique capabilities of nuclear power sources are available for use as needed for these missions. The missions requirements that must be considered involve both the NASA and the military, and the AEC works closely with both NASA and the DOD in the conduct of this program. The space isotopic power program is the responsibility of the Space Nuclear Systems Division of the AEC. Sandia Laboratory, working under the aegis of the Space Nuclear Systems Division of the AEC, is responsible for the technical management of this expanding development program.

Let us first look at the need for isotopic power generating systems for space applications. Radioisotope thermoelectric generators (RTG's) have been developed which provide the desired reliable power output for the required long lived satellites. Figure 1 indicates that isotopic power systems and solar systems are both useful in the low powered (few watts to a few kilowatts) long operating life region. In the higher powered region, reactor power appears more applicable. Isotope powered systems would be selected over solar powered systems where specialized environments or operating conditions of a particular mission indicate superiority for the isotopic powered system. Examples of these specialized environments are regions of low incident sunlight, high-flux Van Allen radiation belts, and orbits of high atmospheric drag. Isotopic power systems appear particularly attractive for space probes being sent to the outer planets, space landers on the moon or any of the planets which would result in a day-night cycle, or for extremely long life missions.

Past systems, representative of the first generation SNAP isotopic power systems, which have been launched in actual space application include the SNAP 3 with a 2.7-watt electrical output and the SNAP 9A with a 25-watt electrical output. Both were launched aboard Navy navigational satellites. The SNAP 3 is shown in Figure 2 on an experimental navigation satellite. This isotopic power generator continues to power radio beacons on this satellite after more than six years. This is the oldest operating satellite in space today.

The SNAP 9A is shown in Figure 3 attached to the TRANSIT 5BN satellite. Three of these satellites were launched in 1963-64.

Present isotopic power systems for which the development is essentially complete include the SNAP 19B and the SNAP 27.

Two SNAP 19B generators, mounted in tandem, will be flown aboard the NIMBUS-B NASA weather satellite in the spring of 1968. These generators will supply 50 watts of power to supplement the solar power aboard the satellite. Figure 4 shows the two SNAP 19B generators mounted aboard the NIMBUS-B spacecraft.

Figure 5 shows a cutaway of the SNAP 19B radioisotope thermoelectric generator (RTG) which has been developed for the AEC by Martin Marietta. The generator is fueled with plutonium-238 which decays by alpha emission with a half life of 87 years. These alpha particles produce the heat by being trapped within the fuel itself or contained by the capsule. Low level neutron and gamma photons are also emitted but the levels are so low that no special shielding is required.

The plutonium fuel is contained within the intact reentry heat source (IRHS) which was developed as part of the SNAP 19B system and is shown in Figure 6. The intact reentry heat source is completely enclosed within a graphite heat shield. This heat shield provides the necessary thermal protection for the plutonium fuel in the event that a reentry occurs as the result of an aborted mission.

The heat developed within the plutonium fuel is converted into usable electrical energy by maintaining a temperature difference across the thermoelectric elements. The plutonium fuel maintains a high temperature at the hot junction and the radiator fins attached to the outer case reject the excess heat and maintain the cold junction temperature at the outer end of the thermoelectric elements. The SNAP 19B thermoelectric elements are made of lead telluride (produced by the 3M Company) which has been doped to provide both negative and positive elements. These N and P elements are then assembled together to provide thermoelectric couples which are in turn connected in a series parallel network for reliability.

The SNAP 19B generator has been completely qualified by Martin Marietta for its application to the NIMBUS-B spacecraft mission. This qualification testing has included subjecting prototype generators to environmental levels at least one and one-half times greater than those which will be encountered during the actual space mission. The environments to which this generator has been subjected include vibration, accelerometer thermal vacuum, and operating life tests. The actual flight system, consisting of the two flight SNAP 19B generators mounted in tandem, have been subjected to flight qualification environmental tests. These tests include vibration, acceleration, and thermal vacuum at the actual levels which will be encountered during launch and space operation.

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In addition to the development and qualification test program, Martin Marietta and the AEC provided a complete safety analysis including a test program to provide data inputs for this safety analysis. As a result of this complete safety review, launch approval has been obtained for this flight. The flight system, consisting of two generators, a power conditioning system, and a telemetry conditioning system, along with ground handling and testing equipment, has been delivered by the AEC to NASA for this flight. A summary of the SNAP 19B generator characteristics is shown in Table I.

**TABLE I**

<table>
<thead>
<tr>
<th>SUMMARY OF GENERATOR CHARACTERISTICS</th>
<th>SNAP 19</th>
<th>SNAP 27</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Generator Performance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(One Generator)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Power (Max. - Beginning of Life)</td>
<td>30 watts</td>
<td>73 watts</td>
</tr>
<tr>
<td>Output Power (Min. - After 1 yr. Operation)</td>
<td>22 watts</td>
<td>63.5 watts</td>
</tr>
<tr>
<td>Hot Junction Temperature</td>
<td>900°F</td>
<td>1100°F</td>
</tr>
<tr>
<td>Cold Junction Temperature</td>
<td>400°F</td>
<td>525°F</td>
</tr>
<tr>
<td><strong>Heat Source Characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Source O.D.</td>
<td>3&quot;</td>
<td>2.5&quot;</td>
</tr>
<tr>
<td>Heat Source Length</td>
<td>6.5&quot;</td>
<td>16.9&quot;</td>
</tr>
<tr>
<td>Thermal Output (Nom.)</td>
<td>570 watts</td>
<td>1460 watts</td>
</tr>
<tr>
<td>Fuel Form</td>
<td>PuO₂</td>
<td>PuO₂</td>
</tr>
<tr>
<td><strong>Generator Design Characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter over Fins</td>
<td>21&quot;</td>
<td>15.7&quot;</td>
</tr>
<tr>
<td>Overall Length</td>
<td>11&quot;</td>
<td>18.1&quot;</td>
</tr>
<tr>
<td>No. of Fins</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Fin Radial Length</td>
<td>7.75&quot;</td>
<td>5.0&quot;</td>
</tr>
<tr>
<td>Weight (Fueled)</td>
<td>28.5 lbs.</td>
<td>42.3 lbs.</td>
</tr>
</tbody>
</table>

The SNAP 27 isotopic power generator is being developed by the General Electric Company under contract to the AEC for use in the APOLLO program. The SNAP 27 generator has been designed to provide the electrical power source for the APOLLO Lunar Surface Experiment Package (ALSEP) which is being developed by NASA. The ALSEP is a series of instruments and supporting subsystems that will be deployed on the lunar surface by the astronaut and will transmit lunar environmental information for a period of at least one year. The SNAP 27 generator assembly will be transported to the moon in the lunar module's scientific equipment bay along with ALSEP. The fuel capsule assembly will be transported in the graphite lunar module fuel cask attached to the exterior surface of the lunar module. After landing, the astronaut removes the generator assembly as part of the ALSEP. Using the flight handling tool, the astronaut extracts the fuel capsule assembly from the graphite lunar module fuel cask and inserts it into the generator assembly. The astronaut then sets up the scientific experiments contained in the ALSEP package which are powered by the SNAP 27. Figure 7 shows the astronaut making final adjustments to the directional antenna prior to returning to earth via the lunar module. These instruments will continue to telemeter data from the lunar surface for a period of at least one year being powered solely by the SNAP 27 generator.

Figure 8 shows a cutaway of the SNAP 27 generator. The central fuel capsule contains the plutonium fuel which provides the thermal power input from the alpha decay. The fuel capsule radiates its heat to the hot junction of the lead telluride thermoelectric couples produced by the 3M Company. The cold junction is maintained by rejecting waste heat to space from the beryllium finned outer case. A summary of the characteristics of the SNAP 27 is shown in Table I.

Since the fuel capsule assembly is transported to the lunar surface external to the generator, it is mounted in a graphite fuel cask which incorporates heat shielding material to assure intact reentry of the fuel capsule in the event of a flight abort. Should an abort occur, the fuel cask remains attached until the lunar module breaks up due to reentry heating. The graphite heat shielding material attached the fuel throughout the reentry sequence to earth impact. After the reentry heating phase, the fuel cask will cool and slow down until it impacts at terminal velocity. The graphite lunar module assembly is shown in Figure 9. The General Electric Company has subjected the SNAP 27 to a complete series of prototype qualification environmental tests as well as flight qualification tests for the generators which will be flown to the moon. Life testing of thermoelectric couples, subsystem modules, and full scale generators has indicated the capability of meeting the requirements of at least one year operation on the lunar surface. In addition, a complete safety analysis has been performed to provide the necessary information to obtain flight approval.

All generators, fuel capsule assemblies, ground handling and test equipment are available and ready for delivery to NASA when desired to meet the revised APOLLO flight schedule.

A number of new systems are under development to meet the requirements of both NASA and the DOD. These include the development of the SNAP 29 isotopic power generator, the development of the heat source to be coupled with the NASA Brayton cycle system power converter, and the development of a generator for the Navy's new navigation satellite program (NAVSAT).

In the SNAP 29 program, the technology is being developed for isotope generators at the 500-watt level for missions of 90 to 120 days duration. The SNAP 29 concept is shown in Figure 10. This generator uses the alpha emitting fuel polonium-210 with a half life of 138 days to provide the thermal input to the system. The fuel capsules are contained in the flat plate heat source shown at the right in Figure 10. A reactor arrangement provides the necessary power flattening to compensate for the change in thermal flux over the period of the mission as the fuel decays. The heat rejection to space from the cold side of the thermoelectrics is accomplished by a series of parallel heat pipes using water as a working fluid. The SNAP 29 program is now concentrating...
primarily on fuel and component technology. The present goal is to perform a fueled ground demonstration test in 1969. If results appear promising, flight system development could be scheduled to meet user requirements. The SNAP 29 is designed to adapt to various DOD and NASA missions. An artist’s conception of using the SNAP 29 in an AGENA type mission is shown in Figure 11 and in a SATURN type mission in Figure 12.

NASA has requested the AEC to develop a large isotope heat source system to provide the thermal input power to the Brayton cycle power converter being developed by Lewis Research Laboratory. Figure 13 schematically shows the total Radioisotope Gas Turbine Electric Power System (Brayton Cycle System). The AEC is responsible for the large isotope heat source system which includes the plutonium-238 fuel inventory to provide 25 thermal kilowatts, the necessary encapsulation, and reentry protection to provide safety in the event of an abort. NASA has scheduled a ground demonstration test of the entire system to be run in 1971 in the vacuum chamber at the Plum Brook facility.

The DOD has requested the AEC to develop a generator for the Navy’s navigation satellite program (NAVNAV). This generator will take advantage of the lightweight thermoelectric technology now under development. With this technology, we hope to achieve a system weight of about 1/2 pound per watt in this fairly low power region.

In addition to the system development work for specific applications, the AEC space isotope power program is charged with the responsibility of providing the new technologies necessary to provide improved future systems. For improved systems one would desire a reduced weight, cost, and size along with improved reliability and increased lifetime. Most of these characteristics can be improved with higher power conversion efficiency. For isotope systems, the amount of fuel required is a major element in determining the cost of the system. Obviously, the amount of fuel could be reduced in proportion to the increase in system efficiency. The weight of the system is also decreased by higher efficiency. Efficiency may be increased in two main ways: (1) increase in heat source temperature to improve the Carnot efficiency, and (2) the development of more efficient power conversion technology. In general, the cold side temperature cannot be reduced without causing an unacceptable increase in radiator area. Thus, the only way to increase the temperature difference across the system is to increase the hot side temperature. In terms of technology this requires an increase in the fuel surface temperature and in the power conversion system capability.

The second approach to greater efficiency and reduced weight is to develop those power conversion concepts which offer higher efficiency of converting thermal energy to electricity. As a first step in providing better converters, we are working toward improved thermoelectrics. In addition to the lead telluride thermoelectrics, silicon germanium thermoelectrics are being developed for the AEC. Figure 14 shows the system efficiency in percent that can be attained with presently used thermoelectric materials for various hot junction temperatures. In all cases, the cold junction temperature is 200°C. By cascading silicon, silicon germanium, and lead telluride materials to take advantage of the high temperature capability of silicon germanium at the hot end of the cascade and the higher Seebeck coefficient of the lead telluride at the low end of the cascade, generator efficiencies in the 7% to 10% region can be attained in lieu of the present PbTe generator efficiency of about 5%. The efficiency of such a cascaded system is also shown in Figure 14.

Another thermoelectric improvement is the so-called compact converter. Figure 15 shows a schematic representation of a compact converter being developed by Westinghouse for the AEC. In this design, heat is transferred to the hot junction by flowing a hot working fluid in pipes from the heat source to the hot junction of the thermoelectrics through the central pipe. A second working fluid loop transfers the waste heat from the outside or cold junction to a radiator. Heat pipes may also be incorporated for transferring the heat to the hot junction. The curve in Figure 16 shows the improvement in efficiency that this compact converter has attained during development from 1965 to 1968.

Gulf General Atomic has developed for the AEC a lightweight thermoelectric converter panel called Isotec. This panel has been optimized to take advantage of the properties of lead telluride for low weight while still employing a low temperature fuel. The panel, shown in Figure 17, which receives and disposes of heat by radiant heat transfer, uses miniaturized thermoelectric lead telluride elements and the latest insulation techniques to reduce weight. For relatively low powered generators, this panel should provide a lighter weight generator and still operate at the relatively low temperatures best suited for lead telluride thermoelectrics.

New thermal insulations are being developed for various temperatures and environments of interest to the space isotope power program. The AEC has placed a contract with Johns-Manville to develop an optimized bulk type insulation for temperatures up to 1800°F. This insulation would be applied to systems using sealed thermoelectrics of the lead telluride type. Johns-Manville is investigating the removal of fillers from the Min-K 2000-type insulation to minimize any outgassing from the insulation during the operation of an isotope generator. The mechanical strength of this insulation has been shown to be more than adequate and its insulation properties have been improved.

The AEC has placed a contract with the Linde Division of Union Carbide Corporation to develop vacuum foil type insulations for temperatures up to 1800°F. These insulations perform best in the space vacuum environment. Extremely low thermal conductivity values have been obtained in this program.

The Thermo Electron Engineering Corporation has an AEC contract to develop vacuum foil type insulations for temperatures up to 3200°F.
application to the isotopic thermionic program. This development has been very successful in obtaining low conductivity in vacuum systems at extremely high temperatures. This represents a necessary accomplishment for the ultimate development of an isotopic thermionic system.

The AEC is also extremely interested in the development of fuel capsules to operate at higher temperatures. An AEC contract has been placed with Atomics International to develop the technology necessary for an isotopic fuel capsule with a surface temperature of 2000°F. A capsule of this temperature could be used with the large heat source program to power the Brayton cycle system and could also be used with a silicon germanium thermoelectric converter system. Figure 18 shows one of the early fuel capsules being developed under this program.

The above capsule represents an unvented design approach to a high temperature capsule, i.e., a capsule which contains the pressure within the capsule due to the release of helium from the fuel. The AEC also plans to place a contract with industry for the development of a vented capsule approach for the same temperature level of 2000°F. As these two development programs progress, capsules will be developed that can be used in various systems depending on whether a particular system design can better use a vented or an unvented capsule.

As mentioned in the SNAP 29 discussion, heat pipes using water as the working fluid are already being applied to this system to provide heat rejection. The AEC has also initiated programs to develop heat pipes using alkali metals as the working fluids. The principle of the heat pipe is shown in Figure 19. Heat is added in the boiler region of the pipe and removed in the condenser region of the pipe. The working fluid is vaporized due to the heat addition in the boiler region and passes down the axis of the pipe as a vapor which is then condensed in the section where heat is being removed. In the case of the SNAP 29, heat pipes of about 3/8" diameter and 15' long are being employed. The heat pipe appears to provide a very efficient method for transferring heat from one place to another. The AEC has continued life tests on heat pipes using potassium as the working fluid and operating at 6000°C at RCA. Two heat pipes were removed from test for disassembly and investigation after successfully completing 6000 hours, one pipe has been removed after successfully completing 10,000 hours, and one pipe will be continued on life test to 20,000 hours. These tests indicate that alkali metal heat pipes may be operated reliably for long periods of time.

The AEC expects to continue placing contracts with industry for advanced development of new converter systems, of improved fuel and capsule systems, and to develop other technologies which are necessary for future isotope power generator systems. This technology development is important so that when new system requirements appear, these developments will allow the use of state-of-the-art technologies for application to new systems.
Figure 1  Power vs Life for Various Space Power Systems
Figure 2    SNAP 3 Mounted on Experimental Navy Satellite
Figure 3  SNAP 9A System Attached to TRANSIT 5BN
Figure 4  NIMBUS Satellite (SNAP 19 Installed)
SNAP-19 GENERATOR

FUEL CAPSULE
Pu-238

FINS

Pb-Te THERMOELECTRIC ELEMENTS

GRAPHITE HEAT ACCUMULATOR BLOCK

Weight 30 Lbs.
Power Output 30 Watts

Figure 5 SNAP 19 Generator
Figure 6  SNAP 19 Intact Reentry Heat Source
Figure 7  SNAP 27 and ALSEP on Lunar Surface
Figure 8  SNAP 27 Radioisotopic Electric Generator
Figure 9  Fuel Capsule Assembly in Fuel Cask Assembly (SNAP 27)
Figure 10  SNAP 29 RTG Exploded View
Figure 11  SNAP 29 and AGENA
Figure 12  SNAP 29 and SATURN

COURTESY MARTIN MARJETTA
Figure 13 Radioisotope Gas Turbine Electric Power System (Brayton Cycle)
THERMOELECTRIC SYSTEM EFFICIENCY

FOR $T_c = 200^\circ C$

![Graph showing system efficiency for different materials and temperature.]
Figure 15  Schematic Compact Converter Design
COMPACT CONVERTER TUBULAR
MODULE PERFORMANCE SUMMARY

EFFICIENCY - %

1968

1967

1966

1965

ELAPSED TIME ON TEST - 1,000 HOURS

0 2 4 6 8 10 12 14 16 18

COURTESY WESTINGHOUSE
D67-15039

Figure 16 Compact Converter Tubular Module Performance Summary
CROSS SECTION OF LIGHTWEIGHT PANEL CONVERTER

Heat Rejected to Space

Semiconductor Element
Radiator
Core Cover Sheet
End Cap
Insulation
Collector

Heat Input from Source

Isotec Panel

Figure 17 Lightweight Panel Converter

D68-11011
LARGE RADIOISOTOPE HEAT SOURCE CAPSULE

Figure 18  Large Radiolisotope Heat Source Capsule
HEAT PIPE
EFFICIENT HEAT TRANSFER DEVICE

THE HEAT PIPE IS CAPABLE OF TRANSFERRING 500 TIMES THE HEAT ENERGY PER POUND OF WEIGHT OF A HIGH CONDUCTING ROD

Figure 19  Heat Pipe