THIRTEEN-WATT ISOPOE-POWERED THERMOELECTRIC GENERATORS
FOR SPACE AND LUNAR IMPACT MISSIONS*

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ABSTRACT

Two small thermoelectric generators which derive their power from the radioactive decay of Curium-242 have been designed.

The first is intended for use in space and is capable of delivering an essentially constant power output of 13 electrical watts over a 6-month operational life. It weighs 16.6 lb and occupies a volume of 230 cu in.

The second generator is designed to operate for 2 months, both in lunar day and night, after a hard (500 ft/sec) impact on the moon. The principles of design are described. The complete power supply weighs 6.2 lb and occupies a volume of 350 cu in., including allowances for mounting structure and radiator surfaces.

In both cases, external radiation levels may be reduced to the point where personnel exposure in ground handling and photon dosage to neighboring instrumentation are minimized.

Thermal-to-electrical conversion principles, properties of the radioisotope fuel, method of encapsulation of the fuel and techniques for obtaining constant power output are discussed. Safety considerations in the event of accidents during launch-to-operation sequence are presented briefly.

INTRODUCTION

History

As part of a program sponsored by the AEC and aimed at


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the development of radioisotope-fueled auxiliary power units for space applications, The Martin Company, in October 1959 undertook the development of a conceptual design of a Cm-242 powered thermoelectric generator suitable for a 6-month space mission. Later, NASA and the Jet Propulsion Laboratory of the California Institute of Technology requested that the specifications for the generator be changed to permit its application to a lunar mission in which an instrument capsule containing the generator would impact on the surface of the moon at a velocity of approximately 500 ft/sec and would survive to produce power for a period of at least 30 and preferably 60 earth days. This necessitated a radically different approach to the design. Both conceptual designs were completed by July 1960, (Refs. 1 and 2).

Mission Requirements

The generator designed to operate in extraterrestrial space was required to satisfy the following specifications:

1. Electrical Power: The generator must deliver 13 watts at 3 volts dc of continuous unregulated electrical power for a period of at least 6 months following launching into space.

2. Weight: The integrated power supply, consisting of generator, d-c to d-c converter and voltage regulator, must not exceed 18 lb in weight, of which 15 lb is allocated to the generator itself. (The scope of this study did not include design of the voltage converter or regulator.)

3. Environment: The unit must operate in normal fashion in an undefined space trajectory (for example, a circumlunar probe) following its subjection to missile-induced conditions typical of the Vega launch vehicle.

   a. Acceleration - Rotation about any axis at 700 rpm.
   b. Vibration - 15 g of white Gaussian noise from 20 to 2000 cps for 10 minutes in each of 3 mutually perpendicular planes.
   c. Shock - 4 axial shocks of 25 g, each lasting 20 m sec with a rise time of 1 m sec.

Development of the Vega vehicle was cancelled during the course of the program, and these conditions were then held to be illustrative only.
External Radiation: Because of the presence of radiation-sensitive equipment in the JPL payloads, external gamma radiation emanating from the generator must not exceed 7 photons/sq cm-sec above 100 kev at a point 10 cm from the surface. (In the case of an anisotropic radiation field, it was permissible to orient the generator with respect to the rest of the payload so that the minimum radiation level would be seen by the payload. No restriction was placed on neutron fluxes external to the generator during its operational life.)

For purposes of safe ground handling, external radiation levels were to be reduced to at least 60 mrem/hr at a distance of 1 meter. Design of a suitable shipping cask to achieve this figure was included in the scope of the work, so that the generator itself did not pay the attendant weight penalty.

The conceptual design of the lunar impact generator was to be based on the same specifications with the following exceptions:

1. A maximum weight of 18 lb, excluding a d-c to d-c voltage converter.
2. A continuous output of 13 watts at 3 volts dc for a period of 60-days after impact.
3. Ability to withstand the decelerative forces resulting from lunar impact at 500 ft/sec.
4. Reduction of external radiation level to 60 mrem/hr at 1 meter for ground handling purposes, and to the following levels in operation for protection of radiation-sensitive equipment in the instrument capsule.

On a circular area of 100 sq cm located 5 meters from the generator, not to exceed

a. 1 photon/cm$^2$ sec in the energy range 0.4-3.0 mev.

b. 0.5 photon/cm$^2$ sec in the energy range 3.0-10.0 mev.

The Atlas-Agena B rocket system was selected as being typical of the vehicle capable of delivering a 300-lb payload to the moon at the specified 500 ft/sec impact velocity, thereby fixing accelerations at launch, flight trajectories, abort conditions and missile-induced vibrations during firing of the engines. Flight trajectories and abort conditions were of principal interest in the safety analysis performed concurrently, (Ref. 3). Maximum launch acceleration was assumed to be 20 g,
and vibrations induced in the generator during flight were taken to be 10 g rms accelerations in any direction at frequencies in the range of 20 to 2000 cps.

Design Approach

The principle of thermoelectric conversion has been studied extensively on a theoretical basis by Ioffe, (Ref. 4), and others. Practical thermoelectric generators have been made possible by the development of semiconductors with large Seebeck coefficients and low thermal conductivities and electrical resistivities. Furthermore, the use of the decay energy of radioisotopes as a source of heat at high temperatures permits the design of compact, lightweight and dependable thermoelectric power supplies exceptionally well suited for space applications. The feasibility of employing radioisotopes as heat sources for thermoelectric generators has been proven in other AEC-sponsored projects conducted by The Martin Company, (Refs. 5 and 6), as part of the SNAP Programs.

The primary point of departure from earlier designs was the selection of Cm-242 as the isotope to be employed as the heat source in the two designs.

Curium-242 is a high-energy alpha emitter produced artificially by the neutron bombardment of Am-241. Although it has been available only in research quantities in recent years, its potential usefulness as a heat source has led to an extensive program which will result in the production of gram quantities within the next year, (Ref. 7). It is characterized by a half life of 163 days and a very high specific thermal power of 122 watts/gram, making it suitable for use in generators of minimum size and weight with operational lives of 3 to 6 months. Shielding problems resulting from external radiation are minimized with this isotope because of the relatively low level of penetrating radiation emanating from it. It has the further advantage of being much less costly to produce than its principal competitor, Po-210.

Special pains must be taken to ensure that the integrity of the fuel capsule is maintained under all plausible conditions for long periods of time, when exposure of humans to the released isotope is possible. This problem is common to almost all areas of the atomic energy industry, and is peculiar to isotope-powered generator technology only from the viewpoint of the unusual environments that are experienced in space applications.

Other aspects of the generator concepts discussed in the following sections are based on technologies already developed.
SPACE POWER SYSTEMS

and well understood, and the resulting designs are unusual solely in that novel combinations of materials and physical principles have been employed. As a result, it is contemplated that operating generators of the types described can be constructed with a minimum of further analytical treatment, but with a fairly extensive experimental program designed to prove those areas of uncertainty not readily susceptible to theoretical analysis.

GENERATOR FOR SIX-MONTH SPACE MISSION

In approaching this study, several alternative designs were evaluated in light of the specifications established. They included:

1. Several units of the SNAP III design, fueled with curium instead of polonium and connected electrically. In SNAP III, heat is conducted directly from the source to the thermoelectric elements.

2. An enlarged version of SNAP III.

3. A generator in which heat is transferred from the fuel container to a surrounding spherical collector shell by radiative processes. Thermoelectric elements are mounted normal to the shell and are, in turn, enclosed within a spherical radiator shell (Fig. 1).

4. A modification of Item 3 to the extent that the spherical shells are replaced by 28-sided polyhedrons so that the thermoelectric elements can be joined to flat rather than spherical surfaces (Fig. 2).

5. A radiative-type generator consisting of concentric right circular cylindrical surfaces, with the cylindrical heat source mounted on the axis (Fig. 3).

Detailed preliminary analyses of the various types of generator designs may be found in other Martin Nuclear Division reports, (Refs. 8 and 9).

Heat transfer analyses performed during evaluation of the various design concepts indicated that a spherical configuration utilizing radiative heat transfer would have optimum weight and performance characteristics. Practical considerations from a manufacturing and assembly aspect, however, suggested that modifications of the spherical configuration would be necessary if these areas of difficulty were to be minimized. In particular, the making and retention of good physical contact
between the thermoelectric elements, their connectors, and heat collector or radiator surfaces for purposes of electrical or thermal continuity appeared particularly troublesome. In addition, access to the central void region for purposes of assembly, disassembly or repair was obviously restricted, and addition of equipment for mounting the generator or for providing a thermal bypass was made more complex.

As a compromise between the conflicting requirements of manufacturing ease, minimum weight and maximum performance, the cylindrical radiative design was chosen for further study.

Fuel Capsule and Heat Source

At first, consideration was given to fabricating the curium source in the form of oxide pellets, but this approach was discarded because of concern over radiation damage to the compound and increased external radiation caused by alpha-neutron reactions on oxygen. Consequently, a fuel form consisting of an alloy of gold and curium (5 Au:1 Cm) was selected because of its potential ease of fabrication and good heat transfer characteristics; the gold also serves to dilute the specific power of curium to a more appropriate level.

The shape of the fuel—a right circular hollow cylinder—was arrived at as a compromise between heat transfer and mechanical or fabrication concerns. It is desirable to place the fuel at the end of the heat source close to the area where surplus heat is to be dissipated for purposes of flattening the electrical power output so that a large temperature gradient over the length of the heat source is avoided. At the same time, a solid cylinder—while preferable from a fabrication viewpoint—raises objections due to the excessive axial temperatures which result. A hollow cylinder is more difficult to manufacture but permits the internal void space to be used as a reservoir for the storage of helium gas which accrues from the alpha decay of curium; it also eliminates the centerline temperature problem.

Because Cm-242 decays to Pu-238, it is necessary to enclose the curium in a thin tantalum outer liner to prevent corrosive attack of the primary encapsulation material by the plutonium. Tantalum is essentially inert to plutonium at the temperatures to be experienced by the heat source.

An inner liner of tantalum is provided for the Cm-Au mixture to support it in the event of unpredictable deterioration of the alloy. Very small holes drilled in the liner permit escape of helium to the central void region.
Based on a final overall conversion efficiency of 4.8%, 6.3 grams of Cm-242 are required to give an initial thermal output (at the time of encapsulation) of 755 watts. It is expected that the curium will not be separated in pure form, but as an alloy, principally, Am-241 containing 45% by weight of curium. Thus, the weight of the Am-Cm mixture required is 14 grams, and another 70 grams of gold diluent bring the weight of the fuel to 84 grams in a volume of 0.284 cu in. The pressure buildup of helium in the void space can be expected to rise to 7670 psi at the end of the useful life of the generator (240 days after encapsulation). The resultant unsupported hoop stress induced in the tantalum container (1/32 in. wall thickness) would approach 110,000 psi, a factor of about 10 times the ultimate stress for this metal at operating temperatures. The tantalum vessel cannot be made thicker because of problems which then arise in assuring that it would burn up upon re-entry to the earth's atmosphere at the end of an earth satellite mission or upon final stage failure at near-orbital velocities. The tantalum is therefore backed up by an outer container of Hastelloy C, a material with excellent high temperature strength properties and resistance to corrosive attack by sea water, and yet readily burnable under re-entry conditions. Indeed, the outer container must be installed within a few days after encapsulation of the curium in the tantalum, or distortion and ultimate failure could occur in the 60-day period elapsing between encapsulation and launch.

With dimensions of the Hastelloy C vessel set at 15/16 in. ID and 1-1/4 in. OD, the maximum hoop stress induced in it by evolution of helium after 6 months of operation is 27,900 psi, as compared to the ultimate strength of 43,000 psi and yield strength of 36,000 psi at 1600°F for this material. The mean operating temperature of the Hastelloy C is expected to be about 1450°F; while this gives an additional small factor of safety, any inadvertent temperature rise much above 1600°F would cause rupture of the container, since the strength of the material decreases rapidly with increased temperature in this region.

At 60 days after encapsulation (the anticipated time of launch), the maximum hoop stress is computed to be 9770 psi. Maximum permissible capsule temperature at this time would be about 2000°F. The remainder of the heat source is comprised primarily of tungsten metal, because its good thermal conductivity ensures that the temperature gradient along the surface in the axial direction is less than 50°F and because it acts as a highly efficient gamma radiation shield. A detailed drawing of the heat source assembly is shown in Fig. 4.
Thermal Bypass Mechanism (Heat Dump)

As implied earlier, it is desirable to provide some means of diverting heat from the thermoelectric converter region of the generator throughout the life of the unit. This flattens its electrical output, since the thermal output of the heat source decays at the same rate as the radioactivity, and the hot junction temperature of the conversion apparatus (which determines the conversion efficiency and the electrical output) drops accordingly with time. Also, the use of the thermal bypass concept enables the use of constant hot junction temperatures approaching the maximum permissible without damage to the generator and hence results in a higher conversion efficiency averaged over the life of the generator than would be otherwise attainable.

The device employed consists of a fixed radiator attached conductively to the heat source at the end containing the fuel capsule. Covering the radiator is an insulated shutter which is actuated by the thermal expansion of molten metal contained in a loop situated in the hot junction region. The size of the loop and the type of linkage connecting it to the shutter are such that the latter is fully open (exposing maximum radiator surface to space) at the beginning of life and is fully closed at the end of life (reducing parasitic heat losses to a minimum). A sodium-potassium mixture (NaK) is the molten metal employed.

The mechanism is shown in detail in Fig. 5, the assembly drawing of the generator. It is capable of radiating at least 312 watts of thermal power to space at the beginning of the operational life of the unit, the value necessary to ensure that the hot junction temperature over the 6-month life will be constant. It should be noted that such a device need not be calibrated throughout the open-shut sequence, since it is self-compensating in maintaining a uniform hot junction temperature.

Thermoelectric Converter

Details of this portion of the generator are almost self-evident in Fig. 5.

The P- and N-type lead telluride thermoelectric elements are designed to be inserted into the generator from the outside, so that individual elements may be replaced if necessary. Silicone rubber O-rings on the element follower caps permit charging the converter region with an inert gas to alleviate sublimation of the lead telluride. The method of bonding the
hot ends of the elements to the electrically connecting shoes is not stipulated in this conceptual design because of the frequent changes in thought occurring over this aspect of the technology.

All electrical connections at the colder ends of the elements are made externally for ease of assembly and repair.

Generator Characteristics

The overall mechanical design of the generator is depicted in Fig. 5, and the resulting characteristics of the unit are listed in Table 1.

Table 1
Generator Characteristics
For 6-Month Space Mission

<table>
<thead>
<tr>
<th>Operational life (months)</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td></td>
</tr>
<tr>
<td>Diameter (in. )</td>
<td>7-1/2</td>
</tr>
<tr>
<td>Height (in. )</td>
<td>8-3/8 (shutter closed)</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>Thermodlectric</td>
<td>6.51</td>
</tr>
<tr>
<td>Thermal</td>
<td>73.5</td>
</tr>
<tr>
<td>Overall</td>
<td>4.8</td>
</tr>
<tr>
<td>Temperatures (°F)</td>
<td></td>
</tr>
<tr>
<td>Hot junction</td>
<td>1000</td>
</tr>
<tr>
<td>Cold junction</td>
<td>370</td>
</tr>
<tr>
<td>Heat loss (watts)</td>
<td>36</td>
</tr>
<tr>
<td>Insulation thickness</td>
<td>1.25</td>
</tr>
<tr>
<td>Thermoelectric elements</td>
<td></td>
</tr>
<tr>
<td>Output voltage (volts)</td>
<td>3</td>
</tr>
<tr>
<td>Number of pairs</td>
<td>30</td>
</tr>
<tr>
<td>Cross-sectional area (in.²)</td>
<td></td>
</tr>
<tr>
<td>P-type</td>
<td>0.1300</td>
</tr>
<tr>
<td>N-type</td>
<td>0.1089</td>
</tr>
<tr>
<td>Doping (%)</td>
<td></td>
</tr>
<tr>
<td>P-type</td>
<td>1.0 Na</td>
</tr>
<tr>
<td>N-type</td>
<td>0.05 Pbl</td>
</tr>
<tr>
<td>Length (in. )</td>
<td>0.75</td>
</tr>
<tr>
<td>Fuel</td>
<td></td>
</tr>
<tr>
<td>Isotope</td>
<td>Cm-242</td>
</tr>
<tr>
<td>Purity (%)</td>
<td>45</td>
</tr>
<tr>
<td>Dilution (Au:Cm by wt)</td>
<td>5:1</td>
</tr>
<tr>
<td>Weight of isotope (gm)</td>
<td>6.3</td>
</tr>
<tr>
<td>Thermal power (watts)</td>
<td></td>
</tr>
</tbody>
</table>
At encapsulation  752
At launch          582
At end of life     270

<table>
<thead>
<tr>
<th>Estimated Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell insulation                                         1.178</td>
</tr>
<tr>
<td>Collector                                                1.286</td>
</tr>
<tr>
<td>Thermoelectric elements and bosses                       4.80</td>
</tr>
<tr>
<td>Radiator                                                1.766</td>
</tr>
<tr>
<td>Internal gamma shield                                    3.88</td>
</tr>
<tr>
<td>Actuator reservoir                                       0.491</td>
</tr>
<tr>
<td>NaK                                                      0.077</td>
</tr>
<tr>
<td>Actuator and hinge                                       0.033</td>
</tr>
<tr>
<td>Shutter cover and liner                                  0.500</td>
</tr>
<tr>
<td>Shutter insulation                                       0.170</td>
</tr>
<tr>
<td>Fuel capsule                                             0.529</td>
</tr>
<tr>
<td>Radiator                                                 1.857</td>
</tr>
<tr>
<td>Reservoir supports                                       0.043</td>
</tr>
<tr>
<td>Fuel                                                     0.031</td>
</tr>
<tr>
<td><strong>Total</strong>                                                <strong>16.241 lb</strong></td>
</tr>
</tbody>
</table>

Photon and Neutron Shielding

In the early stages of this study, it was believed that the JPL specifications for external photon fluxes could be met completely by use of an internal shield. While this was perhaps true for primary gamma rays produced during the decay of curium and its daughters and during the spontaneous fission of curium, more comprehensive calculations performed later indicated that significant photon dosages resulted from inelastic scattering of the neutrons produced by curium fission and from \((n, \gamma)\) reactions. Since this gamma radiation was produced both within the internal shield and in the surrounding generator structure, it became impractical to provide enough shielding over an entire end of the generator to attenuate the radiation without excessively penalizing the weight of the generator. Therefore, only enough shielding (roughly 60%) of the total thickness required, was placed within the generator, since this proportion did not compromise generator performance or design. In an actual mission, it would be necessary to provide about the equivalent of 1.5 in. of tungsten externally to reduce the photon dose to the requisite 7 photons/cm² sec 10 cm from the surface. The weight of the latter increment is not computed since it will be a function of the radiation-sensitive area to be protected. Two and one-half inches of tungsten shielding are provided within the generator.

Based on the amount of fuel remaining after the 2-month period between encapsulation and launch, the shielding required...
for purposes of safe ground handling of the generator is 1.6 in. of water. This amount reduces the radiation level to the prescribed 60 mrem/hr at 1 meter. The relative contribution of various types of radiation and the effect of the water shield thereon is given in Table 2.

Table 2

Ground Handling Radiation Dose Rates

<table>
<thead>
<tr>
<th>Type of Radiation</th>
<th>Dose Rate, mrem/hr at 1 meter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No shield</td>
</tr>
<tr>
<td>Neutron</td>
<td>110</td>
</tr>
<tr>
<td>Decay gamma</td>
<td>12.6</td>
</tr>
<tr>
<td>Fission gamma</td>
<td>2.7</td>
</tr>
<tr>
<td>Capture gamma</td>
<td>0.03</td>
</tr>
<tr>
<td>Inelastic scattering gamma</td>
<td>0.015</td>
</tr>
<tr>
<td>Total</td>
<td>125.3</td>
</tr>
</tbody>
</table>

GENERATOR FOR HARD LUNAR IMPACT MISSION

Design Assumptions

Since details of the launch vehicle, impact vehicle and instrument capsule were not available during the course of this study, it was necessary to make some arbitrary assumptions concerning them so that the generator design would at least reflect representative conditions which might occur during launch, abort or lunar impact.

As stated before, the Atlas-Agena B rocket system was assumed to be the launch vehicle. The impact vehicle was assumed to consist of a retrorocket attached to a spherical instrument capsule roughly 3 feet in diameter, consisting primarily of a crushable structure to cushion the impact forces on the instruments contained therein. Since the crushable material might possess thermal insulation properties, the generator was conceived to be mounted on the exterior of the capsule at a point farthest removed from the retrorocket. In the event of a successful mission, the retrorocket case would probably impact first. Uniform deceleration of the payload was assumed to occur over a distance of 1 foot, leading to a figure of about 4000 earth g deceleration. To be conservative, the generator design was based on an impact angle varying a maximum of 15 degrees from the axis of the vehicle. The design that evolved was symmetrical about a linear axis which coincided with the axis of the impact vehicle, and maximum stresses were taken to be compressive in nature along the axial direction.
Failure of the retrorocket, which could lead to impact velocities of the order of 10,000 ft/sec, or impact of the generator preceding the rest of payload, were excluded from consideration in this study, except that the generator was made as rugged as possible to give some assurance that the fuel capsule would retain its integrity under these extremely adverse conditions. These conditions do not lend themselves to analytical treatment, and an extensive knowledge of the lunar surface--plus a detailed experimental program--would be required before any assurances in these respects could be made.

Design Considerations

The resulting generator configuration is depicted in Figs. 6 and 7. It is comprised of a fuel block in the shape of a rectangular parallelepiped, containing the curium fuel in four sealed canisters. Two modular arrays of thermoelectric elements are mounted on opposite sides of the fuel block, and the remaining internal volume of the generator is filled with a solid thermal and electrical insulation. The rigid outer shell, in the general shape of an ellipsoid of revolution, conducts rejected heat to radiator surfaces and is attached to a shock absorbing bellows structure which, in turn, is fastened to the impact vehicle. Simplicity of the design and the lack of moving parts are apparent. Following is a more detailed description of the constituent parts.

1. Housing: Beryllium metal was selected for the structural casing material for several reasons. It has a relatively high thermal conductivity and an emissivity coefficient of 80 Btu ft/ft² hr °F and 0.61, respectively, which make it desirable from heat transfer aspects.

   For impact stress conditions, the yield strength at 500° F is 40,000 psi. For minimum weight, the density is only 0.066 lb/in³ (Al= 0.1 lb/in³).

   For minimum deflection or bowing, it is desirable for a material to possess a high modulus of elasticity. The value for beryllium is E = 40 x 10⁶ psi (Al,E = 10 x 10⁶ psi).

   The geometry of the case was selected to minimize heat losses from the fuel block, i.e., to shape the internal dimensions to the isotherm of the fuel capsule.

2. Thermoelectric Elements: Sixty-four individual thermoelectric elements of square cross section are bonded into a
rigid square module approximately 2 in. x 2 in. x 1 in. high with a thin separator of adhesive insulation cured in place as matrix filler (Fig. 8). The most suitable material to use appears to be Temporell 1500. This arrangement will yield several important advantages. Elements of long slender geometry, which contribute to optimum thermal efficiency and higher output voltage, can be used in place of short, squat elements (where previously a short squat geometry was considered as the best possibility of eliminating columnar failure).

The end surfaces of the modules can be machined parallel to very close tolerances after assembly to obtain uniformity of length and to ensure good thermal and electrical contacts.

The module arrangement also results in a generator of minimum size and weight. The axes of the elements are oriented coincident with the axis of maximum thrust to provide maximum strength at impact, i.e., direct compression.

To further enhance the impact characteristics, cobalt silicide (Transitron Corporation) was selected for use as the thermoelectric semiconductor material because of its superior mechanical properties. Cobalt silicide does not have as high a thermoelectric figure of merit (Z) as lead telluride, but this deficiency is offset by its ability to operate at much higher hot junction temperatures and thus at a higher Carnot efficiency.

3. Junction Connectors: A flexible copper printed circuit backed with silicone rubber sheet is used to obtain electrical series contact at the cold junctions. For the radiation level anticipated, the useful life of silicone rubber is in the neighborhood of 1 year. This arrangement results in simplicity of construction and assembly and minimum weight. Due to the relatively good thermal conductivity of silicone rubber (60 Btu ft/hr ft²) and high conductivity of copper, the cold junction temperature drop should not exceed 20° F at rated input. The combination of resiliency and ability to yield offers additional benefits in absorbing possible differential expansion between the P and N elements and in providing maximum reliability on impact.

4. Fuel Block: Hastelloy C was selected as the material for the fuel block because of its impact strength at high temperatures (at 1600° F, US = 36,000 psi). Figure 9 depicts the fuel block geometry.
The thin-walled tantalum fuel canisters provide a corrosion barrier between the Hastelloy and the Pu-238 resulting from decay of Cu-242 and permit handling of smaller quantities of the isotope prior to encapsulation.

A minimum block thickness is desired to eliminate large lateral heat losses and yet sufficient wall thickness must be available to provide structural strength for abort conditions and helium pressure buildup during radioisotope fuel decay.

Linear scoring on the fuel block surfaces is employed to prestress these local areas. In the event of a vehicle abort impact, energy is absorbed deliberately in the fracture at predetermined areas, thereby greatly decreasing the possibility of random or unpredictable fracture of the block or tantalum containers.

5. Insulation: Temporell 1500 or equivalent insulation is contemplated. After final testing and assembly of the generator, the insulation will be injected through the filler plug to form a rigid, shock-resistant encapsulation of the fuel capsule and thermoelectric modules. An alternative arrangement is to pot the modules in the case with a dummy fuel block and a temporary Teflon parting sheet to provide fuel block accessibility and a refueling capability.

It is of interest to note that due to the minimum thermal insulation cross section area and sizing of the case, the heat leakage is reduced to a very attractive 7% of heat input.

6. Assembly Flange: Preloading of element modules for good thermal and electrical contacts is essential and is obtained by uniform torquing of the flange bolts. Belleville spring washers under the bolt heads provide a simple, lightweight method of maintaining uniform stresses when thermal excursions and expansions occur.

The properties of beryllium at high temperature make it difficult to predict burnup on re-entry to the earth's atmosphere in the event of final stage abort. It is conceivable that intact re-entry may be obtained. Additional experimental studies will be required. Therefore, at this time it has been decided to assemble the housing with aluminum bolts. On re-entry, the bolts should melt preferentially, thus permitting separation of the two halves of the housing and exposing the Hastelloy fuel block to aerodynamic heating and subsequent burnup.
7. Support Structure: A conical-shaped aluminum alloy bellows, filled under pressure with helium gas, constitutes the lower radiator and impact absorber. For purposes of maximum heat transfer, it will be desirable to highly polish the bottom surface of the generator assembly and to oxidize the inner wall of the bellows.

The cone configuration is utilized for stability both under launch and impact conditions.

At impact, the load is carried into the bellows structure and absorbed simultaneously in the compression of the gas and yield of the bellows walls.

8. Radiator Fin: The upper radiator fin is mounted on the top attachment threads of the generator casing and is fabricated of soft annealed aluminum alloy. Maximum heat transfer is realized due to the high thermal conductivity and emissivity coefficient.

Under abort conditions, the soft aluminum will readily yield at impact, thus absorbing a large portion of the shock energy.

The fin cross section is of tapered geometry. The root thickness is several times greater than the tip thickness to obtain maximum fin efficiency.

9. Internal Circuitry: For reasons of maximum reliability, the generator internal electrical circuitry is subdivided into two individual circuits which feed an external voltage converter. Thus, if one module circuit should fail, half power will remain available.

ANALYSIS OF PERFORMANCE

One of the most important factors in the early stages of the analytical effort associated with the design study was determination of the feasibility of eliminating a mechanism for flattening the electrical power output over the design life of 60 days by rejecting surplus heat to the environment directly from the heat source. Such a device is ordinarily required when the mission life is equal to or greater than the half life of the isotope employed, as in the case of the space mission generator.
By studying the effect of changes in the lunar ambient temperature over a period of 60 days on the operation of a hypothetical generator similar in geometry to the actual design, it was determined that if a design point of 1400°F hot junction temperature at the end of life coincident with the worst ambient condition of lunar daytime were selected, the hot junction temperature would not exceed 1800°F at any time prior to the end of life. Cobalt silicide is limited to a maximum operating temperature of 1800°F. It should be recalled here that the lunar surface is estimated to vary in temperature from +250°F in the daytime to -250°F in the night-time.

The entire analysis was predicated upon the availability of both P- and N-type cobalt silicide elements. At the present time, P-type material is not available commercially, and the assumption is therefore made that its thermoelectric properties would be equivalent to the N-type material. The use of all N-type elements, although feasible, would result in a generator of markedly decreased performance because of excessive heat losses through the electrical connections required to complete the series circuit. It is believed that high temperature thermoelectric materials, with physical and thermoelectric properties superior to cobalt silicide, will be on the market in the near future.

Laboratory tests indicate that cobalt silicide may be difficult to bond to the hot and cold junction connectors. Therefore, provision has been made in the analysis for a contact resistance loss equivalent to 25% of the element resistance. This necessitates an increase in the cross-sectional area of the elements and a corresponding increase in the thermal power input because of the resulting decrease in conversion efficiency.

The approximate temperature distribution computed in the analysis is shown in Fig. 10.

Enough curium fuel must be provided at encapsulation to give 265 watts of thermal power 120 days later. This is found to be the equivalent of 445 watts at the time of encapsulation. Since the specific power of pure Cm-242 is 122 watts/gram, 3.65 grams of the pure isotope are required at the time of loading into the fuel canisters. It is anticipated that the curium actually produced will be diluted with Am-241 and other isotopes of much longer half life, so that the resultant power density of the mixture is about 50 watts/gram.
The use of a shock-absorbing bellows structure was found to reduce the deceleration on impact to 2750 g, imposing a load of 16,500 lb on the bellows. The corresponding compressive stress on the lower thermoelectric array was 7000 psi, which would result in an elastic deformation of less than 1 mil. The silicone rubber backing deflects about 7 mils. Maximum impact stress induced in the lower beryllium housing is 22,000 psi. All of these figures are considered to be well within the elastic limits of the materials involved.

The resonant frequency of the system is calculated to be 55 cycles/sec, which is within the frequency range of interest. Damping to overcome the resonance may be necessary if the launch vehicle exhibits this vibration frequency for any appreciable length of time.

Thermal stresses induced in the generator are found to be negligible, since the Belleville washers employed in assembling the generator permit differential expansions and contractions in the axial direction to take place. Lateral stresses are not significant because of the uniform temperature distribution in this direction.

The estimated weight breakdown of the generator and mounting structure is given in Table 3.

TABLE 3

<table>
<thead>
<tr>
<th>Estimated Weights of Components</th>
<th>(lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>1.04</td>
</tr>
<tr>
<td>Fin</td>
<td>0.72</td>
</tr>
<tr>
<td>Elements</td>
<td>1.10</td>
</tr>
<tr>
<td>Fuel capsule</td>
<td>1.0</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.6</td>
</tr>
<tr>
<td>Bellows assembly</td>
<td>1.5</td>
</tr>
<tr>
<td>Thermal gaskets</td>
<td>0.08</td>
</tr>
<tr>
<td>Bolts and springs</td>
<td>0.06</td>
</tr>
<tr>
<td>Hot and cold shoes</td>
<td>0.10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>6.2</td>
</tr>
</tbody>
</table>
SHIELDING ANALYSIS

The specifications for external radiation dose rate laid down at the inception of the program can be met for ground handling purposes without the use of any shielding, based on the following contributions to the dose rate from the 3.6 grams of Cm-242 present at the time of encapsulation:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>mrem/hr at 1 meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission neutrons</td>
<td>49.8</td>
</tr>
<tr>
<td>Gammas from spontaneous fission</td>
<td>0.39</td>
</tr>
<tr>
<td>Gammas from neutron capture</td>
<td>0.04</td>
</tr>
<tr>
<td>Gammas from Cm-242 decay</td>
<td>0.009</td>
</tr>
<tr>
<td>Gammas from inelastically scattered neutrons</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>50.2</strong></td>
</tr>
</tbody>
</table>

To meet the JPL requirement for the dose rate to sensitive instruments, 1.2 in. of tungsten or equivalent would be required between the generator and the payload. Weight of the shield would be determined by the geometry employed.

SAFETY CONSIDERATIONS

Both designs have been evaluated on a preliminary basis by the Martin Nuclear Safety Analysis Group. Hazards specifically attendant to impact on the moon by the lunar generator have not been studied; they will be given special attention in a future analysis.

Curium-242 is primarily an alpha emitter which exhibits only a small proportion of gamma and neutron radiation. The principal radiobiological hazard is therefore a result of ingestion or inhalation, and the problem of protection against whole-body penetrating radiation is therefore not present. The fundamental design objective in isotopic power of assured containment or harmless dispersal of the radioactive source must be met for all likely environmental conditions before a generator is fielded for an operational mission.

It is assumed that the generators would be launched by the use of a typical ICBM vehicle combined with a final orbital or trajectory injection stage from the Cape Canaveral launch site. Vehicle failure in the latter part of the final stage thrust would result in high altitude burnup of the curium from aerodynamic heating on re-entry. The fallout, assumed to take place between 30 and 60 degrees latitude in
one hemisphere, would be insignificant. Failure during most of the ascent phase would result in intact impact of the fuel capsules in the ocean. Failure during the last part of the ascent phase or early part of final stage thrust could result in incomplete burnup, followed by dispersal of the remainder of the fuel in the ocean; the ensuing concentration of radioactivity in sea water would drop quickly to a value considered safe for public exposure. Aborts in the early part of the launch phase might conceivably result in impact of the generators on land at velocities of less than 500 ft/sec; the lunar impact generator is expected to withstand the impact without violation of the integrity of the fuel capsule, although the space mission generator is marginal in this respect and would have to be evaluated further by experimental means.

Explosion or fire on the launch pad, although much less probable than other kinds of vehicle abort, create severe conditions under which there is a remote possibility that the fuel capsules might rupture. The principal effects of concern are the very high temperatures (1700 to 200°F) which exist for a few minutes and the corrosive attack on the fuel capsules by the acid component of the hypergolic fuel. Any release of curium would take place within the controlled area and would be well localized.

A much more detailed evaluation may be found in a Martin report, (Ref. 3).

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The following engineers made substantial contributions to the design and analysis of the concepts described:
Thomas Bustard, Marion Furrow, Lester Lee, Merle Peiffer, James Peters, Cecil Riggs, Adolph Spamer, and Raymond Stankiewicz.

REFERENCES

APPENDIX

SELECTION OF ISOTOPES FOR USE IN SPACE POWER

The purpose of this Appendix is to provide a general insight to the problem of selecting a given isotope for use as a power source in space applications. As will be seen, no trivial solution to the problem exists because of the complex array of factors which influence the decision.

Useful Radioisotopes

Of the several hundred radioisotopes known to man, only a handful are suitable for isotopic power. The first elimination may be made on the basis of half life, since only those isotopes with half lives of from 100 days to perhaps 100 years may be employed usefully.

Those isotopes with very short half lives cannot be stored economically or used efficiently, since substantial initial inventories must be carried along to provide the desired thermal power at the end of the useful life of the heat source. In turn, problems are introduced in dissipating the unproductive decay heat before the end-of-life condition is reached, as can be seen in the evolution of the curium-fueled generator for a six-month space mission described earlier. The upper limit on the half life is somewhat arbitrary, imposed principally by the fact that nature has provided only one or
two isotopes with half lives in the range of 100 to 1000 years, and these isotopes are of no practical value for other reasons.

The second characteristic of the remaining isotopes which reduces the number of useful ones still further is the kinetic energy level and type of emitted radiation, since it is this energy that is converted to heat by absorption in the surrounding material. The maximum energy of useful alpha emitters meeting the half-life criterion is in the range of 4 to 6 Mev and that of the beta emitters is in the range of 0.2 to 3 Mev. As an example of how a low energy level may eliminate an isotope, the case of tritium (H-3) may be used. Although its half life of 12.26 years at first appears to make it most attractive, its maximum beta energy of only 0.018 Mev eliminates it as a source of thermal power.

The next factor that affects the choice of isotopes is a complex one involving cost and availability. Two sources of radioisotopes are available: from the fission process in nuclear reactors and by neutron irradiation of more stable materials. Ordinarily the first group is plentiful, and the cost per unit of radioactivity is inversely proportional to the demand for a given isotope. Since this group is the by-product of an existing nuclear process and must be stored as waste if not utilized, the cost of maintaining the fission reaction is not charged directly to the cost of the isotopes. The second group is inherently more expensive, since the target materials for neutron bombardment prove to be expensive in themselves and, in addition, the cost of performing the irradiation and subsequent chemical separation is borne directly by the isotope produced.

Still another characteristic which must be considered is the type and level of penetrating radiation which escapes from the heat source and which therefore determines the nature and amount of shielding required. In some cases, gamma radiation is emitted by the radioactive daughters of the original isotope or in conjunction with the primary decay reaction, while in others the primary energetic particles cause secondary reactions which emit radiation quanta. The energetic beta particles, for example, produce substantial levels of X radiation (bremsstrahlung) as they are slowed down by the surrounding material. Alpha particles induce secondary reactions in materials of low atomic number which result in the emission of neutrons. Some alpha emitters also undergo spontaneous fission, resulting in production of both neutron and gamma radiation. As a general rule, however (and there are a few significant exceptions), the
beta emitters require considerably more shielding than do the alpha emitters. It thus becomes clear that the choice of an isotope for use in a power plant for a space application will be determined to a large extent by the weight allocated to the power supply and by the degree of shielding required for protection of personnel or sensitive instrumentation.

Taking all of the foregoing characteristics into consideration, the radioisotopes listed in Table 1 are presently feasible for use in space power applications.

Since the attainable power density of the isotope is a rough measure of the overall weight and size of the power supply, it can be seen that the alpha emitters (and C-144 of the beta emitters) are the only isotopes worthy of initial consideration for minimum weight systems of the type which will probably make the first journeys into space. Po-210 is much more expensive than Cm-242, and thus only the curium and the Pu-238 are left as candidates for short- and long-lived missions, respectively. Even then, these isotopes may be ultimately replaced by the less costly beta emitters when the cost and availability of the isotope becomes a more significant factor than the weight of the power supply.

Encapsulation Materials

Selection of the material employed to encapsulate the isotope is an important consideration since the isotope must be contained in the event of fire, explosion or impact resulting from rocket vehicle abort at any time prior to the approach of orbital velocities. Still another almost contradictory limitation imposed is that the fuel capsule burnup as a result of aerodynamic heating upon re-entry of the capsule to the atmosphere from orbit and that the radioactive material be dispersed in micron-sized particles at altitudes above 100,000 feet. A substantial proportion of the total effort expended in developing isotopes for power supplies in space applications has been devoted to meeting these criteria. As a result, superalloys such as Hastelloy C, Haynes 25, Inconel X and others are ordinarily employed because of their high temperature strength, extremely low corrosion rate in water and resistance to oxidation or attack by fire and hypergolic fuels.

Fuel Form

The chemical and physical characteristics of the form in which the isotopic fuel is prepared must be evaluated in terms of the following criteria:
1. Desired proportion of radioisotope required to meet power density specification (usually maximized).

2. Ease of preparation.

3. High melting point and thermal stability.

4. Radiation stability.

5. Compatibility with encapsulation material.

6. Ability to be dispersed when aerodynamically heated.

The first five criteria can be determined in laboratory investigations. The sixth can be evaluated only qualitatively without actual re-entry experiments involving inert substitutes for the radioactive components.

The cost of preparing the fuel form is not as significant as might be imagined, since it is often less than the cost of separation or formation of the isotope itself. The cost of preparation is also an inverse function of the quantity of isotope being processed. The fuel forms listed in Table 1 represent the latest thinking in this area, but development work is being continued to improve the fuel characteristics.
### TABLE 1
Potentially Useful Radioisotopes for Heat Sources in Space Applications

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Mode of Decay</th>
<th>Half-Life</th>
<th>Fuel Form</th>
<th>Density (gm/cc)</th>
<th>Power (thermal) (watts/cc)</th>
<th>Estimated Costs Current ($/watt)</th>
<th>Projected ($/watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Po\textsubscript{210}</td>
<td>Alpha</td>
<td>138 days</td>
<td>Po</td>
<td>9.3</td>
<td>1320</td>
<td>600\textsuperscript{(1)}</td>
<td>300\textsuperscript{(1)}</td>
</tr>
<tr>
<td>Cm\textsubscript{242}</td>
<td>Alpha</td>
<td>162 days</td>
<td>Cm\textsubscript{2}O\textsubscript{3}</td>
<td>11.75</td>
<td>1169</td>
<td>80\textsuperscript{(2)}</td>
<td>45\textsuperscript{(2)}</td>
</tr>
<tr>
<td>Pu\textsubscript{144}</td>
<td>Alpha</td>
<td>86.4 yr</td>
<td>PuC</td>
<td>12.5</td>
<td>6.9</td>
<td>--</td>
<td>1600\textsuperscript{(3)}</td>
</tr>
<tr>
<td>Ce\textsubscript{147}</td>
<td>Beta-Gamma</td>
<td>285 days</td>
<td>CeO\textsubscript{2}</td>
<td>6.4</td>
<td>12.5</td>
<td>87</td>
<td>14\textsuperscript{(3)}</td>
</tr>
<tr>
<td>Pm\textsubscript{137}</td>
<td>Beta-Gamma</td>
<td>2.6 yr</td>
<td>Pm\textsubscript{2}O\textsubscript{3}</td>
<td>6.6</td>
<td>1.1</td>
<td>3000</td>
<td>1630\textsuperscript{(3)}</td>
</tr>
<tr>
<td>Cs\textsubscript{90}</td>
<td>Beta-Gamma</td>
<td>33 yr</td>
<td>CsCl</td>
<td>3.9</td>
<td>1.27</td>
<td>500</td>
<td>54\textsuperscript{(3)}</td>
</tr>
<tr>
<td>Sr\textsubscript{60}</td>
<td>Beta-Gamma</td>
<td>28 yr</td>
<td>SrTiO\textsubscript{3}</td>
<td>4.8</td>
<td>0.54</td>
<td>455</td>
<td>23\textsuperscript{(3)}</td>
</tr>
<tr>
<td>Co\textsubscript{59}</td>
<td>Beta-Gamma</td>
<td>5.3 yr</td>
<td>Co</td>
<td>9.0</td>
<td>2.7\textsuperscript{(4)}</td>
<td>100\textsuperscript{(5)}</td>
<td>100\textsuperscript{(5)}</td>
</tr>
</tbody>
</table>

---

1) Personal communication from Mount Laboratory.

2) Radiation cost not included (increase is at $100/watt).

3) AEC estimates based on construction of major separation facility.

4) Based on irradiation to specific activity of 30 curies/gram and self-absorption of 80% of the gamma energy.

5) Based on AEC published price of $1.00/curie in quantities greater than 100 kilocuries.
This area for heat dump mechanism

Symmetrical about $\mathcal{C}_L$

Fig. 1. Spherical 13-Watt Generator
Fig. 2. Polyhedral 13-Watt Generator
Fig. 3. Cylindrical 13-Watt Generator Concept
Fig. 4. Fuel Capsule Space Mission Generator
Fig. 5. Mechanical Design of Generator
Fig. 6.
Isotope Powered Thermoelectric Generator--Lunar Impact Mission
1. CONNECTOR SHOES  GL010 IN. COPPER 
2. BACKING--0.010 IN. 
3. SI LI CONE RUBBER 
4. RADIATOR FIN--AL ALLOY 
5. THERMOELECTRIC MODULE--COBALT SILICIDE--32 PAIRS 
6. FUEL CAPSULE--HASTELLOY C 
7. BELLEVILLE SPRING--C RES STL 300 (TYP 8 PLACES) 
8. AL 0.010 IN. 
9. SHIM SET--LAMINATED AL ALLOY 
10. SELF-LOCKING BOLT (TYP 8 PLACES) 
11. SEAL--SILICONE RUBBER (OPTICAL) 
12. FILLER PLUG 
13. INSULATION--TEMPORELL NO. 1500 INJECTED 
14. OXIDIZED 
15. BELLOW SUPPORT--AL ALLOY 
16. IMPACT ABSORBER, RADIATOR 
17. HELIUM GAS--100 PSI 
18. POLISHED 

Fig. 7. Generator Configuration
Printed circuit, cold junction shoes ~ 0.010 copper

Printed circuit, backing ~ 0.010 silicone rubber

Output lugs

Aluminum oxide ~ 0.050

Hot junction shoes ~ 0.050

Adhesive type insulation--1/16 layer

Full scale

Fig. 8. Thermoelectric Module Arrangement
Score (typical 6 places)

Fuel block (Hastelloy C)

Fuel canister (tantalum)

Plug fusion weld seal

Fig. 9. Fuel Capsule

470° F

450° F

500° F

450° F

1400° F

1410° F

650° F

800° F

1400° F

Fig. 10. Approximate Temperature Distribution