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OPERATIONAL AND SYSTEM TESTING OF SNAP 3 THERMOELECTRIC GENERATOR

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ABSTRACT

SNAP 3 was the first of several auxiliary power systems developed under the SNAP* program sponsored by the Atomic Energy Commission.

The electrical performance of the SNAP 3 generator in a variety of environments has been accurately defined through test. A total of 2593 hours has been amassed, during which these units have been subjected to the shock, acceleration and vibration fields anticipated in the boost phase of a satellite launching.

Additional performance tests have provided voltage-amperage relationships, with thermal input as the parameter, under simulated space conditions. Ambient temperatures ranged from +70° to -100°F, with the unit suspended in an evacuated chamber.

A method developed to change the insulation conductivity with time provides a constant thermal input to the thermoelectric conversion unit. A constant electrical output is produced, although the total thermal energy available decreases with time as a function of the isotope half-life.

An essential adjunct to performance definition has been the determination of the safety of a radioisotope power unit in combination with a vehicle system. A brief summary covers the results of tests simulating the critical situations encountered in typical missions.

The next step will be actual flight tests, in which generator components (but no radioactive fuel) will be ejected from ballistic missiles. By monitoring the re-entry of the components, it will be possible to determine the validity of heating rate assumptions and dispersal calculations. These tests should remove all technical reservations concerning the safety of these units in association with a vehicle system.

*SNAP--Systems for Nuclear Auxiliary Power, AEC Contract
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INTRODUCTION

SNAP 3 was the first device to produce a practical amount of electrical power by direct conversion of the heat resulting from radioisotope decay. It was demonstrated at the White House in January 1959. The characteristics of this unit follow:

Physical dimensions	4.75 in. diameter; 5.5 in. height
Weight	5 lb
Source	Po-210, 1495 curies
Half-life	138 days
Thermal power	48 watts
Electrical power	2.4 watts
Efficiency	5%
Thermoelectric material	Doped lead telluride
Hot junction temperature	720° F
Cold junction temperature (outer skin)	175° F
Dose rate at surface	350 mr/hr
Dose rate at 1 meter	3.5 mr/hr

Polonium-210 was selected as the radioisotope heat source for this unit on the bases of ready availability and high power density. Its thermal energy results almost entirely from the emission of a 5.3-mev alpha particle. A low-gamma emission coincident with a 4.5-mev alpha particle occurs in 0.0012% of the disintegrations. Mound Laboratory has provided the polonium for all generators fueled to date. Double stainless steel capsules are inserted in a heavy-walled heat source cylinder. This cylinder is then closed with a threaded plug and sealed by fusion welding. In this unit the thermoelements support the central source.

The Minnesota Mining and Manufacturing Company designed and fabricated the thermal-to-electrical conversion section. The lead telluride elements, approximately an inch long, have diameters of 0.210 inch (N-type) and 0.225 inch (P-type). These are paired to form 27 couples, which are mounted in six vertical rows with a radial arrangement of nine elements per row.

Each element is loaded axially against a hot shoe by a two-pound force provided by a spring and adjustment screw located in an aluminum cold junction ring. The hot shoe is made of iron, flame-sprayed with aluminum oxide. The shoe makes the electrical connection between element pairs at the hot junction, while the oxide coat prevents current flow through the supporting hot junction cylinder. The couples are connected in series by copper wires at the cold junction and insulated electrically from the cold junction ring. Insulation is provided by an oxide coating (Martin hardcoat) on the aluminum bearing caps, located between the element end cap and the pressure spring.

The hot junction cylinder supports the elements through the hot shoes and contains a tapered internal hole to receive the fuel capsule previously described. Mica sleeves are placed on the hot junctions of the elements to provide additional protection and insulation.

The remaining void inside the generator shell is filled with Johns Manville Min-K-1301 insulation. This material is formed into solid pieces in the hemispherical ends, and is in powdered form in the thermoelectric area. The internal arrangement is illustrated by the artist's concept (see Fig. 1). After the first unit, a spun copper shell was used instead of the brass case illustrated. Other improvements in construction details decreased the weight to four pounds.

Three additional units have been fueled with various amounts of polonium, ranging upward to 2320 curies. A maximum output of 4 watts at 4 volts has been obtained with an efficiency of 5.75%. The last two units were subjected to over 2000 hours of severe environmental testing prior to fueling. Their operation, so far, has been satisfactory.

ENVIRONMENTAL TEST PROGRAM⁽¹⁾

Environmental tests were conducted in the Dynamic Test Facility at the Martin plant on four thermoelectric generators designated 1G4, 1G5, 1H2 and 1H3 by the manufacturer. The radioisotope heat source was simulated by an electrical resistance heater located in the central cylinder. The configuration of these units is basically as described above. The main differences are the thermoelectric element diameters (see Table 1).

Fig. 1 Low Power Radioisotope Thermoelectric Generator
REF: RP-61-2-37

TABLE 1
Basic Generator Comparison Data

Generator No.	Element Diameter (inches)		Interior Atmosphere (%)	Insulation Material	Average Output (watts)
	N-Type	P-Type			
1G4	0.210	0.225	85 N ₂ , 15 H ₂	Min-K-1301	3.0
1G5	0.210	0.225	85 N ₂ , 15 H ₂	Min-K-1301	3.0
1H2	0.149	0.158	95 Ag, 5 H ₂	*Diatomaceous earth and Min-K-1301	1.5
1H3	0.149	0.158	95 Ag, 5 H ₂	*Diatomaceous earth and Min-K-1301	1.5

*Diatomaceous earth is used in place of powdered Min-K-1301 around the elements in the hot junction area.

The units were subjected to vibration, acceleration and shock inputs in each of the three principal orthogonal planes. Test specifications were submitted by Jet Propulsion Laboratories (JPL) for the Vega booster and by Lockheed Missile Systems Division (LMSD) for the Discoverer, Midas and Sentry programs⁽²⁾. Each unit--to assure reliability--was initially tested to one of the specifications and then completely retested to the other specification. A total of 2593 hours of generator operation was amassed during these tests.

Vibration tests were conducted with a Calidyne Model No. 177A vibration system. A magnetic tape, furnished by JPL, consisted of a sinusoidal vibration of 5 g rms from 15 to 500 cps, superimposed on a random signal of 5 g rms, band-limited between 15 and 1500 cps for five minutes. The second portion consisted of a sinusoidal vibration of 8 g rms from 500 to 1500 cps, superimposed on a random signal of 5 g rms, band-limited between 15 and 1500 cps for five minutes. Two test cycles, each 10 minutes in duration, were conducted in each of the three principal orthogonal planes, with the generator mounted as shown in Fig. 2.

Before each test, the generator power input, power output and hot and cold junction temperatures were stabilized for ten minutes. A parallel system of recording enabled visual observation as well as permanently recorded data. The tape signal was played into the Calidyne shaker head through the console by an Ampex Model 307-2 recorder.

Fig. 2. Test Specimen with Fixture Mounted on Calidyne Vibrator

Vibration tests showed the maximum efficiency drop to be 5% of the overall performance in the Y plane. This drop in efficiency, after reaching its maximum, remained constant until the vibratory force was discontinued. The generator recovered its original level of efficiency in a maximum time of ten minutes (see Fig. 3).

Output voltage, monitored to determine if any ripple existed, showed a constant rms oscillation level of 1.20 mv to be superimposed on the d-c output of 2.80 volts in the X and Z planes. In the Y plane, a sharp peak in the oscillations was observed, equivalent to an rms level of 3.60 mv. A constant 2 g rms sinusoid from 15 to 1500 cps was applied in all planes. This peak occurred at a frequency of 700 cps.

The JPL specification for acceleration testing called for a 15 g static acceleration for five minutes in each of the three principal orthogonal planes. The LMSD specification required a maximum of 10 g for 10 minutes. A Genisco accelerator with a maximum force of 75 g was used. The tests were conducted in 5-g steps in all three orthogonal planes.

Oscillograph records taken before, during and after each test show the generator to be stable in operation and efficiency under the specified conditions. The external resistance load, used to match the generator load, increased due to the power-consuming slip-ring instrumentation within the centrifuge. This explains the lower pretest efficiencies apparent in Fig. 4.

JPL specifications for shock testing the SNAP 3 generator called for four shocks of 50 g with a 1-ms rise time in each of the three principal orthogonal planes. LMSD specifications required a 40-g shock with a 2-ms rise time, a dwell time of 3 and a decay time of 0.4 ms. Since the hammer-type shock machine was not capable of meeting the dwell requirements, two 40 g shocks with a 1-ms rise time were substituted.

The generator, test fixture and mounting plate were bolted to the impact plate of the shock machine as shown in Fig. 5. Two accelerometers were mounted to monitor input and response accelerations. Oscillograph records of typical outputs from the accelerometer mounted on the outer shell of the generator, as well as typical input pulses, are shown in Fig. 6. Oscillating d-c signals show a peak rms value of 5 mv in the Y plane. Generator efficiency during the shock tests (see Fig. 7) is typical for all planes.

PERFORMANCE TEST PROGRAM

In addition to the extensive tests discussed above, numerous parametric tests have accurately defined SNAP 3 performance under a variety of conditions. Generator output has been determined for various condi-

Fig. 3. Efficiency Versus Time--Y-Plane Vibration Test

Fig. 4. Efficiency Versus Time--Y-Plane Acceleration Test

Fig. 5. Test Specimen Mounted on Shock-Test Rig

Fig. 6. X-Plane Shock Test

Fig. 7. Efficiency Versus Time--X-Plane Shock Test

tions of thermal input and load resistance, both in air and in an evacuated bell jar.

Several internal gas mixtures have been evaluated as to heat loss and effect on thermoelectric element life. Internal gas pressure was varied from two atmospheres to a fully evacuated condition. However, the most interesting results were obtained when the temperatures and pressures anticipated at orbital altitudes were simulated as nearly as possible.

For these tests, the unit was suspended within a sealed spherical shell, 24 inches in diameter, which later was evacuated to simulated space pressures. The shell internal surface was coated with a flat black lacquer to simulate the absorptivity of the space void. This arrangement is illustrated in Fig. 8.

After sealing, the assembly was placed in an environmental test chamber. Chamber pressure was maintained at one atmosphere to allow continuous control of the evacuated shell temperature. Voltage-versus-amperage data were obtained, with thermal input as a parameter for ambient shell temperatures of +70, +50, 0, -40 and -100° F. Three generator surface conditions were tested: polished copper, copper painted with two coats of black lacquer and copper heavily coated with black copper oxide.

Maximum generator output was obtained for all generator surface conditions at minimum shell temperature. Due to the low emissivity of the polished copper, output was minimum with this surface condition since heat transfer was primarily radiative in nature. A painted surface proved to be slightly superior to the oxide coating. The voltage-amperage data are plotted in Fig. 9, with surface condition as the parameter.

Figure 10 illustrates a typical voltage-amperage relationship with input power as the parameter. In the previous figure, the output is given as 3.8 watts--not 4 watts, as given in the Introduction. This is because in a space environment the isotope load must be slightly reduced to avoid overheating. Since radiation is the only method of heat transfer from the cold junction, its temperature increases slightly over that in air. This causes a corresponding increase in hot junction temperature when the same thermal input is provided.

Using the decay-versus-time relationship for any selected radioisotope, the data provided by Fig. 10 may be used to predict the performance of the generator at any time after its initial loading. Applying Polonium-210 characteristics, the electrical output--in the absence of some method of power flattening--would fall off to approximately 1.8 watts over a 90-day period.

Fig. 8. Altitude Chamber Test Arrangement

Fig. 9. Snap III Chamber Test Results, Painted Generator Surface

Fig. 10. Snap III Chamber Test Results

A method of obtaining a constant output has been devised through tests in Martin laboratories. Conductivity of the Min-K insulation decreases rapidly at pressures less than one atmosphere. Thus, by introducing a conductive gas mixture of helium and hydrogen into the shell, the conductivity may be increased initially and then decreased by allowing the gas to leak to space.

This conductivity change may be controlled by proper selection of a fixed orifice, so as to be inversely proportional to the thermal energy decrease. Initially, with a gas charge of one atmosphere, heat losses through the insulation are high and generator output is decreased to approximately 2.8 watts. As this gas charge leaks out, generator efficiency improves, so that a constant output is produced for a 90-day period.

The ideal relationship of internal pressure, input power and output power resulting from parametric tests is shown in Fig. 11. Fabrication of a fixed orifice with the desired leak rate was a tedious process--and a procured orifice was used for a life test. Its characteristics differed somewhat from those sought and the life test was halted after 24 days of operation. Although the internal pressure deviated from the optimum, sufficient data were obtained to indicate the practicality of the method.

SAFETY TESTS⁽³⁾

Although performance and environmental tests have defined the behavior of these generators under normal flight conditions, an essential adjunct has been the determination of the safety of these units in combination with a vehicle system. For logical planning of a test program to simulate the critical situations of any mission, the vehicle trajectory was divided into three phases: launch, ascent and orbital injection--or re-entry. Each phase was then analyzed to establish test criteria encompassing the greatest hazards to the integrity of the unit.

Prior to initiation of the test program, selection of a material for the radioisotope container was made, based on a study of published data and conferences at Battelle Memorial Institute. The first two SNAP 3 units delivered to the AEC for demonstration purposes used molybdenum capsules.

For a unit whose final disposition is re-entry, the use of a high melting-point refractory metal would significantly delay and possibly prevent destruction of the capsule through aerodynamic heating. Investigation of the super alloys resulted in the selection of Haynes 25 material, manufactured by Haynes Stellite Company. This alloy is made up primarily of cobalt, with chromium, nickel, tungsten, iron and other materials present in small amounts. Its properties are available in literature published by the manufacturer and in reports published by Martin⁽⁴⁾⁽⁵⁾.

Fig. 11. Snap III Power Flattening Test

Capsule design was revised from the original pressed plug closure to incorporate a threaded plug and fusion-welded to provide a positive seal. Simulation of the generator structure was accomplished as shown in Fig. 12. Heating of the capsule required the use of a cartridge heater in lieu of a welded plug. Thermoelectric materials were not included in the specimens, since their contribution to the structural integrity of the unit was not considered significant. Void spaces were filled with powdered Min-K insulation before soldering the copper cover to the lower shell.

Critical situations existing on the launch pad arise from the explosive potential of a completely fueled missile. This potential is not fully realized, unless a mass spill occurs through tank rupture due to fallback after liftoff, inadvertent actuation of the destruct system or structural failure. The general nature of the phenomena depends on the type of fuel.

Reports published by Space Technology Laboratories⁽⁶⁾ and personal contacts there were very helpful in defining these phenomena, which, by their very nature, are difficult to analyze. For test purposes, the overall reaction was divided into two basic effects: shock overpressure and high temperature.

Ignition of a mixture of LOX and RP-1 will produce a significant shock wave. Although the impulse characteristics are slightly different, a TNT equivalent was computed with the assistance of Dr. W. Baker of the Ballistics Research Laboratory at Aberdeen Proving Ground⁽⁷⁾.

Specimen size, quantity of explosive and distance from the center of explosion to specimens were scaled one-third size to reduce the requirements. Generator and capsule specimens were arranged at a 12-foot distance around 1650 pounds of TNT. The measured shock overpressures created by the detonation exceeded those measured in actual missile failures by 125%. Effects on the isotope capsules were negligible, although the external generator shells were destroyed (see Fig. 13).

Mixing of hypergolic propellants produces extreme temperatures around 6000° F without significant shock. This situation was created with 165 gallons of aniline and 244 gallons of nitric acid. These liquids were supported on the top platform of a wooden tower, under which 20,000 pounds of scrap metal was stacked to simulate missile structural materials.

Explosive charges were used to simultaneously rupture the liquid containers. Temperatures ranged downward from 5100° F, decreasing to 1200° F after 20 minutes. Development of the fireball one second after ignition is shown in Fig. 14. Generator and capsule specimens, all full size, were suspended in the fire zone. Capsule integrity was maintained in all specimens (see Fig. 15).

Fig. 12. Generator Specimen Assembly

Fig. 13. Shock Test Specimens

Fig. 14. Fireball One Second After Ignition

Fig. 15. High Temperature Test Specimens

The second critical phase occurs during ascent of the vehicle. Propulsion failure or command destruction will result in impact of the generator on the earth's surface at various velocities and at various distances downrange. For test purposes, a terminal velocity of 500 fps for the isotope capsule and 350 fps for the generator assembly was assumed to be the maximum attainable.

Generator and capsule specimens were impacted against targets ranging in hardness from granite to water. Tests were conducted on the ballistic track at Aberdeen Proving Ground, where FFAR rocket motors accelerated the specimens to the desired velocities. Although considerable abrasion and deformation occurred in some specimens, pressure tests proved that capsule integrity had been maintained.

Figure 16 shows capsule specimens after impact on granite and concrete, with the former target causing the greatest deformation. This specimen was sectioned and photographed at 10 times magnification. Figure 17 illustrates the ability of the Haynes 25 material to deform without failure. The welded area also exhibited this characteristic, with only slight cracks apparent at the juncture of the weld bead and the threaded area.

After impact, the isotope container will be exposed to a variety of corrosive media on the earth's surface. The most common of these were considered to be an oxidizing atmosphere, salt water and salt spray. Heated specimens and unheated control samples of capsule materials were exposed to these environments.

Testing was halted after 720 hours, since the Haynes 25 specimens developed an oxide coat which, once formed, appeared to inhibit further oxidation. The maximum corrosion rate measured was 0.7 mg per square decimeter per day. Extrapolated, this is less than 0.0001 inch per year. Adequate containment of the radioisotope is thereby assured for 10 half lives, which, in the case of Polonium-210, is approximately four years.

SAFETY DEVICES

Although the tests have demonstrated the ability of this unit to survive the most severe environments conceivable, a method of reducing generator exposure would be a desirable backup to the basic system. This may be accomplished by incorporating a cartridge-actuated device to eject the unit clear of the vehicle. Ejection will separate the generator from the debris resulting from a vehicle failure on the pad, and facilitate recovery.

Fig. 16. Capsule Impact Test Specimens

Fig. 17. Section of Impact Specimen

A preliminary reusable ejection gun has been fabricated and tested. This device has ejected generator specimens with a horizontal range of over 260 feet, using two M-48 squibs. Deformation of the copper case was slight, although the initial shock exceeded 400 g.

Normal operation of the vehicle system will place the payload and generator in orbit, but in the present state of the art predicted orbital lifetimes are difficult to achieve or control. Therefore, re-entry must be assumed at any time during the planned operational life of the generator. In addition, malfunction of the final stage could result in velocities less than adequate for orbit or for misaligned thrust vectors causing immediate re-entry.

The prevalent choice is to design the unit for aerodynamic burnup and consequent dispersal of the radioisotope at the earliest time, highest altitude and smallest particle size attainable. The temperature, velocity and heat input calculated for typical trajectories were simulated in the plasma jet facility at the General Electric Aerospace Laboratory. These determined the destruction characteristics of the generator and isotope capsule. Analyses of these data were correlated to the vehicle trajectories to determine dispersion altitudes and locations⁽⁸⁾.

A positive control of isotope dispersal may be obtained by destroying the containment capsule in orbit or early in the re-entry phase. This can be done by using a shaped charge to vaporize the central portion of the container and expel the isotope as minute particles in the high temperature gas stream. The shaped charge will be locked in a safe misaligned position to prevent inadvertent release of the isotope. The arming operation will take place only after a safe dispersal altitude has been reached.

Tests have demonstrated that 33 grams of RDX explosive are adequate to assure complete penetration of the generator shell and capsule. Figure 18 illustrates the effect of this explosive contained in one 34A jet perforator, manufactured by E. I. duPont de Nemours. The reliability associated with explosive devices is also inherent in this system.

SUMMARY

The SNAP 3 generator has been exhaustively studied under the most extreme conditions of missile operation, including missile abort. It has successfully met all of the safety criteria that have been discussed. In addition, it is sufficiently rugged to operate satisfactorily under the extreme environments imposed by normal missile flight.

Fig. 18. Destruct Test Results

SNAP 3 is now considered to be a flight-operational system, qualified for space application. The thermoelectric converter portion of this system is "off the shelf" hardware readily available from the Minnesota Mining and Manufacturing Company. The test data presented are also applicable to similar systems being fabricated or proposed. The extensive test program is also indicative of the measures sponsored by the Atomic Energy Commission to dispel the initial reservations associated with the use of these devices in space.

The next step will be actual flight tests, in which generator components (but no radioactive fuel) will be ejected from ballistic missiles. By monitoring the re-entry of the components, it will be possible to determine the validity of heating rate assumptions and dispersal calculations. These tests should remove all technical reservations concerning the safety of these units in association with a vehicle system.

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