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RADIOISOTOPE THERMOELECTRIC GENERATOR

by

R. J. Campana

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SNAP-15A
RADIOISOTOPE THERMOELECTRIC GENERATOR*

by

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and Electronic Engineers 12th Nuclear Science Symposium,
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ABSTRACT

In the output power range below one electrical watt, the combination of an isotope heat source with a metallic thermoelectric converter yields characteristics that are superior to systems employing other kinds of energy sources or conversion methods. When the output power is to be delivered at a high impedance, the metallic thermocouple shows a substantial advantage over the semiconductor thermocouples. The isotope-metal thermocouple system can be designed to yield other important power source characteristics such as the ability to withstand severe mechanical vibration and shock and to produce constant output power over a very wide range of temperature ambients. The design for the present (SNAP-15A) device allows for an ambient range of from -65° to $+165^{\circ}\text{F}$, but a much wider range can be accommodated. Transient response to ambient temperature change can be tailored to specific requirements for uniform power output. Finally, the device can operate under water, in air, or in vacuum.

The device characteristics support a wide range of potential applications. Following are some of the applications under consideration:

1. Provide a steady reference voltage for long life applications.
2. Supply a network of radio beacons for the lunar landing area.
3. Power transmitters for remote weather and detection data.
4. Provide fail-safe ultrareliable long-life power in space satellites.
5. Power miniaturized communication sets.

The degree to which the new device is competitive with other power sources for such applications depends on the detailed requirements. As the requirements become extremely severe, the range of superiority is usually broadened. Thus, if the requirement is for voltage outputs of from 5 to 20 volts without power conditioning equipment, then superiority

can usually be demonstrated. If the ambient requirements are severe, such as the extremes from desert to arctic conditions, then the device shows strong advantages over chemical batteries. The device is adaptable to the much wider ambients, such as the temperature extremes of the lunar nights and days. Finally, the advantage of isotopic-powered sources generally holds for very long life applications. The SNAP-15A device is designed for a minimum life of 5 years.

I. INTRODUCTION

This paper describes the design, development, and potential uses of SNAP-15A, a radioisotope thermoelectric generator with a power output of about 1 mw. The generator was developed for the U. S. Atomic Energy Commission under contract AT(04-3)-167, Project Agreement No. 21, by the General Atomic Division of General Dynamics Corporation. [1, 2, 3, 4] As developed, the generator is a Pu-238-fueled, metal thermocouple generator capable of producing about 1 mw of power output at >4.5 v for at least 5 years, with very high reliability even under extreme environmental conditions.

In a fifteen month period starting from a conceptual design, 16 generators of the prototype SNAP-15A were built and were submitted to an extensive environmental test program. The test program is continuing with generators that have been on test in excess of two years using electrical heat to simulate the isotope, and in excess of sixteen months using isotope-heated devices. Test results demonstrate that SNAP-15A is a highly reliable generator.

The technology and techniques of wire thermocouple and thermopile construction developed for SNAP-15A are adaptable to generators of smaller volume and higher power to meet the requirements of various applications. Some of the uses envisioned for SNAP-15A and SNAP-15A-type generators are: long-life reference voltage, microelectronic devices, fail-safe ultrareliable long-life power sources, cardiac pacemakers, etc.

This paper describes the generator design and performance and compares semiconductor and metal thermocouples. It includes test results to date, a safety and hazards evaluation, and a description of uses and applications.

II. GENERATOR DESCRIPTION

The SNAP-15A generator is shown in Fig. 1; its performance data are given in Table I and its I-V curve in Fig. 2. Heat is supplied by the decay of radioactive Pu-238 contained in a fuel capsule, which, in turn, is held in place by a capsule holder. The capsule holder is recessed at one end into which the hot junctions of the thermocouples are potted with a silicone rubber to form one end of the thermopile. The thermopile consists of 1300 thermocouples made of 2-mil-diameter Tophel Special and Cupron Special^{*} wire with twisted and dip-brazed junctions. Twenty-five couples are wound in series and are bundled together to form a thermobundle. Bundles are subsequently connected as parallel pairs, and then 26 pairs are connected in series to complete the circuitry. The result is a series-parallel grid of thermocouples that enhances the reliability of the generator.

The cold junctions of the thermobundles are potted to a stainless steel ring in a manner similar to that used at the hot junctions. The hole in the ring is somewhat larger than the hot well of the capsule holder because two 10-mil-diameter lead wires have been potted onto the thermobundles to facilitate their interconnection. After interconnection is accomplished, the wires are potted and covered by a stainless steel disk held together by a set of four studs.

The comparatively large mass of the stainless steel ring and disk incorporates thermal capacitance which, in conjunction with the resistance of the thermal insulation surrounding the thermopile, provides a means of dampening transient changes in load voltage that occur when the ambient temperature is suddenly changed. The four mounting studs form a thermal shunt through the thermal insulation; such shunting is minimized by the length-to-area ratio chosen and the low thermal conductivity of stainless steel.

^{*}Tophel Special is 10 Cr-90 Ni and Cupron Special is 0.5 Mn-40 Ni-59.5 Cu.

FIG. 1 -- SNAP-15A generator

Table I
TYPICAL DATA FOR SNAP-15A GENERATORS^a

Power output	1.55 mw
Open-circuit voltage	8.12 v
Load voltage	5.90 v
ΔV_L during ambient transient	0.55 v
Load resistance	22.5 k Ω
Generator resistance	8.66 k Ω
Thermal input	1.46 w
Overall efficiency	0.106%
Bypass heat loss	58%
Geometry	Cylinder
Diameter	2.5 in.
Length	5.0 in.
Weight	0.85 lb
Thermopile	
p-leg wire	Tophel Special
n-leg wire	Cupron Special
Wire diameter	2.0 mils
Couple length	1.5 in.
Hot-junction temperature	400 ^o F
Cold-junction temperature	100 ^o F
Number of couples	1300
Number of circuits	2
Materials	
Radioisotope	Pu-238
Thermal insulation	Min-K-503
Electrical insulation	Pyre-ML + RTV-60
Canister	Al-epoxy sealed
Capacitor	316 stainless steel

^aStart-of-life conditions.

Fig. 2--I-V curve of SNAP-15A generator

The thermopile is embedded in Min-K-503, the best available thermal insulation which does not depend on vacuum to achieve its low conductivity value. It minimizes the heat lost by flow paths other than through the thermopile and mechanically supports the thermopile and canister envelope. A cylindrical plug of thermal insulation permits insertion and withdrawal of fuel capsules through the port in the canister.

An aluminum canister provides mechanical protection for the thermal insulation and excludes oxygen and water vapor. The thermal insulation and the canister are filled with argon and sealed with epoxy resin to a leak rate of $<10^{-8}$ cc/sec.

III. CHOICE OF THERMOELECTRIC MATERIAL

A comparison of generator efficiencies using metal and semiconductor thermocouples is shown in Fig. 3 as a function of power output and load voltage. The curves are based on metal thermocouples of Tophel Special and Cupron Special wire and semiconductor thermocouples of p-PbSnTe and n-PbTe. The load voltage affects the efficiency only when the cross-sectional area/length of the thermocouple legs (A/L) required to match the generator to its load is not practically achievable. Thus the efficiency of generators made from metal thermocouples is independent of load voltage since $A/L \leq 10^{-7}$ cm is practical, while the semiconductor is limited to $A/L \geq 10^{-3}$ cm. The metal-based generators, therefore, are matched to their load in all cases, while the semiconductor-based generators are not. The crossover from metal to semiconductor superiority as a function of power and load voltage corresponds to a load current of about 15 ma.

While efficiency was an important criterion for selection of metal thermocouples, the reliability of metal thermocouples and the technology upon which they are based were equally important and were considered superior to those of the semiconductors.

Fig. 3--Comparison of metal and semiconductor thermocouple generators

IV. TEST PROGRAM AND RESULTS

Five experimental generators were built to determine the basic design and fabrication processes. Then three demonstration generators of a single design using electrical heat source simulation to determine performance and isotope requirements were fabricated, and sixteen Pu-238-heated prototype generators are now undergoing life and environmental testing.

As a final step in the fabrication of prototype generators, an initial performance test was made in which the generator resistance, open circuit voltage, load voltage when connected to a 22.5 kohm load, and voltage loss during sudden change of ambient temperature from -65° to $+165^{\circ}$ F were measured for a given heat input. Subsequently, the generators were operated at room ambient temperature for several days prior to being subjected to the environmental tests shown in Table II. Early in the test program, constant acceleration, humidity, and irradiation tests were conducted but were found to be somewhat trivial for this generator and therefore were discontinued.

The life and environmental testing are conducted by dividing the generators into three groups and operating them at each of three ambient temperatures. -65° F, room, and $+165^{\circ}$ F, for an extended period (about two months). The generators are then subjected to vibration, mechanical shock, and thermal cycling tests and returned to steady operation at their respective ambient conditions. In this manner a comparison of generator performance before and after the tests is obvious. After a second extended period of steady operation following the environmental tests, each group of generators is rotated to a new ambient temperature condition and the whole process is repeated. Thus, each generator is exposed to each ambient condition for an extended period with interruption for environmental testing. A typical life performance curve is shown in Fig. 4. The performance curve of a typical generator subjected to environmental testing is shown

Fig. 4--Life test curve, generator 32

in Fig. 5, in which the first triangular marker at the bottom of the figure indicates the vibration test, the next two markers define the duration of the thermal cycling test, the fourth marker indicates the mechanical shock test, and the last marker a leak check.

The test results are too extensive to discuss in detail in a summary paper. Life testing of Pu-heated generators is in excess of 14 generator-years and with the addition of testing with electrical simulation of isotope heat amounts to more than 30 generator-years. The longest test on a single generator is more than two years while the shortest is about one year. In summary, the test program has confirmed the validity of the SNAP-15A concept and has demonstrated the basic performance and reliability of the SNAP-15A generator.

V. SAFETY AND HAZARDS

The dose rate at the surface of the SNAP-15A generators resulting from neutrons and gamma radiation emanating from the Pu-238 source has been measured to be typically ~ 10 mrem/hr maximum. When compared to the normal AEC whole-body tolerance of 7.5 mrem/hr/8-hr day for laboratory workers, the SNAP-15A generator is a negligible hazard.

The safety factor of the SNAP-15A generator is primarily dependent on the fuel capsule. The extreme toxicity of Pu-238 in inhalation or ingestion requires encapsulation of the isotope and control of the capsules under all conditions.

Analysis of the accidents that may occur indicates that those during transportation are the most serious consideration, both in probability of occurrence and in severity. Fire, impact, and loss are considered to be of greatest concern. The capsules have been designed and tested to withstand fire and impact under maximum credible accident conditions. The test results indicate that the SNAP-15A fuel capsule is safe under all

Fig. 5--Environmental test curves, generator 32

conditions but may be marginal when exposed to impact on a granite surface after free-fall from an altitude of 10,000 feet or more. Thus, the present capsule is restricted to terrestrial applications. Nothing inherent in the design, however, would preclude the application of the generator to non-terrestrial missions.

VI. APPLICATIONS

Although the SNAP-15A generator is designed to deliver 1.75 milliwatts with a hot junction of less than 370°F , the power output may be increased considerably without change in overall size, operating temperature, or materials. As the power output is increased, holding the operating parameters and output voltage fixed, the efficiency increases rapidly. Typical operating efficiencies at three power levels are:

Power Output (mw)	Conversion Efficiency (%)
1	0.12
10	0.37
100	0.47

Increased output requires an increase in isotope loading. The increase in isotope loading is less than proportionate to output because of the gain in efficiency. Higher efficiencies can be obtained with wire generators if higher hot junctions are used; for example, at 100 mw an efficiency of 1% is obtained with 900°F hot junctions.

The size of generators may be decreased to a minimum value while maintaining the power output, operating temperatures, materials, and output voltage fixed. Adjustment of wire diameter and length permits the volume to be reduced to nearly the minimum with only a small effect on the conversion efficiency. Approximate minimum volumes are:

Power Output (mw)	Minimum Volume (in. ³)
1.0	<1.0
10.0	1.5
100	5.0

Power output in excess of 100 mw(e) may be considered. Because efficiency is an important consideration in isotope power units, more efficient converters, as they become applicable at higher power levels, supplant the wire thermoelectric converter. The power levels at which a semiconductor converter, optimized for high voltage output, overtakes and equals the efficiency of a metal converter are as follows for a series of three generator output voltages:

Power Output (mw)	Voltage (v)
70	4.5
105	10.0
155	30.0

At power levels below those listed, metallic thermocouples exhibit a substantial superiority in efficiency. At higher power levels, semiconductor thermocouples demonstrate higher efficiency.

Voltage Reference

The generator can provide a voltage reference or a series of reference voltages for a high impedance system. Voltage reference is used for provision of accurate bias voltages or for accurate comparison with a received signal. Reference voltage applications generally fall in the power range from microwatts to milliwatts.

Communications

The higher power versions of the generator can be used as source power for transistorized equipment, particularly where remoteness is

essential or accessibility for maintenance or replacement is difficult or hazardous. Intermittent communications, where the power source is combined with an accumulator, can be performed at high power levels. Isotope power sources are particularly applicable for very long life operations, for long shelf life, or for standby operations. The SNAP-15A device may be used under extreme ranges of environmental conditions, for example, for high stability interrogation receivers for oceanographic research and for low-drain, long-life space vehicle telemetry.

Fail-safe Power

Because of its extremely high reliability, the low-power unit may be used for reserve power when the primary sources fail. The fail-safe unit can provide power continuously at its rated level or intermittently at higher power outputs in conjunction with an accumulator.

Position Indicating

Long-life power capability can be utilized to energize position-indicating radiators, such as r-f beacons dropped along the course of a lunar excursion and xenon light flasher beacons.

Instrumentation and Data Procurement

Where remote location makes maintenance costs significant, the low-power unit may be useful in providing long-life instrument power. Examples are oil well instrumentation systems and research submarine data collection systems without hull penetrations.

Other Applications

A large number of devices classified as "microelectronics" may utilize long-lived and highly stable power sources of the SNAP-15A type to advantage.

REFERENCES

- [1] Baker, F. S., R. J. Campana, and W. S. Sargent, "SNAP-15A Thermoelectric Generator , Final Summary Report, " USAEC Report GA-5317, General Atomic Division, General Dynamics Corporation (to be issued) (C/RD).
- [2] Campana, R. J., "Design of the SNAP-15A Generator, " USAEC Report GA-5296, General Atomic Division, General Dynamics Corporation, June 19, 1964.
- [3] Campana, R. J., et al. , "Final Safety and Hazards Report for the SNAP-15A Generator, " USAEC Report GA-4554 (Rev.), Vols. I, II, and III, General Atomic Division, General Dynamics Corporation, October 30, 1964.
- [4] Campana, R. J., F. S. Baker, R. Leedy, "Test Evaluation of SNAP-15A Generator, " USAEC Report GA-5781, General Atomic Division, General Dynamics Corporation, November 30, 1964 (C/RD).