A 500 WATT(e) RADIOISOTOPE THERMOELECTRIC GENERATOR FUELED WITH STRONTIUM-90 FLUORIDE FROM THE DEPARTMENT OF ENERGY'S WASTE ENCAPSULATION AND STORAGE FACILITY

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ABSTRACT

A 500 watt(e) radioisotope thermoelectric generator (RTG) is being designed and fabricated by Teledyne Energy Systems for the Department of Energy. The BUP-500 RTG has a five-year design life and consists of the following components: multiple strontium-90 fluoride heat sources (three different types can be used), a tungsten shield, six series-connected thermoelectric conversion assemblies, thermal insulation, and a finned cylindrical housing. The generator will be mounted on isolators within an expanded metal cage to reduce shocks and vibration incident to transportation and handling. A separate power conditioner will allow a user to adjust the RTG's output voltage between 24 and 32 volts.

INTRODUCTION

Teledyne Energy Systems is building a 500 watt(e) radioisotope thermoelectric generator (RTG) for the Department of Energy's Office of Defense Waste and Byproducts Management. The RTG will be fueled with strontium-90 fluoride from DOE's Waste Encapsulation and Storage Facility (WESF) and then it will be made available to the Department of Defense for test and evaluation.

The BUP-500 RTG is a result of DOE efforts to find beneficial uses for selected byproduct materials and to develop secure and highly reliable power sources for national defense needs. One of the byproducts targeted for beneficial applications is strontium-90, which is processed, encapsulated, and stored at WESF. It is an excellent radioisotope heat source for both static and dynamic electrical power sources and has been used extensively in RTGs. RTGs fueled with strontium-90 have been used in many remote applications where high reliability is required and unattended operation is necessary. None, however, have been designed to produce more than 100 watts(e). Most systems either needed a small amount of power or they needed so much power that RTG technology was inappropriate. There were few applications in between. Recently though, applications have surfaced which require extremely reliable, long-life, maintenance-free power sources that produce up to 500 watts(e) or a small multiple thereof. These applications provided much of the incentive to build the BUP-500.

Applications for the BUP-500 generally involve DOD command, control, and communications systems but they also include relatively large scientific data collection and telemetry systems, and small earth stations. One of these appplications involves emergency shelters at unmanned and extremely remote sites in the proposed North Warning System. A single BUP-500 RTG could provide enough electricity and heat to insure the survival of visiting maintenance and repair crews who are unable to use the site's primary facilities.

This paper discusses the heat sources which were considered for the BUP-500 and summarizes its final design.

HEAT SOURCE CONSIDERATIONS

The initial objective in designing the BUP-500 was to use strontium-90 fluoride as encapsulated at WESF. It was soon discovered, however, that this objective could not be accomplished. The thermal inventories of existing WESF capsules are too low and the encapsulation itself is inadequate. These problems led to an RTG design which allows the use of existing strontium-90 fluoride, but in a new fuel capsule, and "fresh" strontium-90 fluoride in a capsule similar to the one now used at WESF.

Strontium-90 has been used as a source of heat in terrestrial RTGs for over twenty-five years. Teledyne Energy Systems alone has built more than sixty generators with strontium-90 heat sources. None of these, however, uses strontium-90 as originally encapsulated. All have uniquely designed fuel capsules. This complicates RTG fueling and increases cost. For these reasons, one of the initial goals of the BUP-500 project was to use strontium-90 fluoride as encapsulated at WESF.

The current practice at WESF is to cold-press strontium-90 fluoride in a Hastelloy C-276* liner and then place the liner in an outer container of Type 316L stainless steel. The stainless steel container was evaluated using the criteria in IAEA Safety Series No. 33[1], and was found to be inadequate for RTG use. Furthermore, the thermal inventory of existing WESF capsules averages less than 700 watts(t). Since the BUP-500 must be fueled with approximately 7500 watts(t), that means at least eleven capsules would be required. This number of capsules results in an RTG which is too large and too heavy. Because of these problems, the goal of using existing WESF capsules was abandoned and a new goal was established: design the BUP-500 to use (1) existing strontium-90 fluoride (38% strontium-90), but in a new fuel capsule and (2) "fresh" strontium-90 fluoride (55% strontium-90) in a WESF-type capsule modified to meet RTG heat source design criteria. In that way generators could be built now, and when fresh fuel became

* ® Cabot Corp., Kokomo, IN.

available, the RTG's design would not have to be changed. Also, WESF encapsulation for fresh strontium-90 fluoride could be designed with RTG service in mind. This goal was achieved and, as a result, the BUP-500 can use three different types of heat sources:

(1) A Sentinel (Teledyne's commercial line of RTGs) type fuel capsule, capable of holding about 2500 watts(t) of existing, hot-pressed, strontium-90 fluoride.

(2) A modified WESF capsule, capable of holding about 1100 watts(t) of fresh, cold-pressed, strontium-90 fluoride.

(3) A modified WESF capsule, capable of holding about 1400 watts(t) of fresh, melt-cast, strontium-90 fluoride.

A "universal" shield was designed to accept the required number of each type of heat source. RTG components outside the shield are identical regardless of the heat source used. The only aspect of the RTG that changes as the type of heat source is changed is the configuration of the heat source cavities in the shield. This is illustrated in Fig. 1.

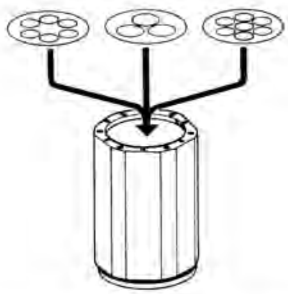

Fig. 1. BUP-500 RTG Universal Shield Concept

There was concern that the universal design would result in an RTG which was heavier than one designed to use existing fuel exclusively. However, it was found that the universal shield's size and hence the RTG's size was set by the three Sentinel-type capsules containing existing strontium-90 fluoride and not one of the other options. It was also discovered that the existing design for liners within WESF capsules could probably be retained if fresh strontium-90 fluoride is melt-casted, but the design would have to be changed if the strontium-90 fluoride was cold-pressed. The reason for this is poor compatibility between the cold-pressed fuel and the Hastelloy C-276 liner at anticipated operating temperatures. Compatibility problems exist because of impurities introduced in the fluoride during processing. Melt-cast strontium-90 fluoride, however, is essentially free of impurities because they are removed during the casting process.

DESIGN SUMMARY

The BUP-500 consists of multiple strontium-90 fluoride heat sources, a tungsten shield, six series-connected thermoelectric conversion assemblies, thermal insulation, and a finned cylindrical housing. The arrangement of these components is shown in Fig. 2. The RTG will be mounted on isolators within a cage to attenuate shocks and vibration incident to *transportation* and handling. It is designed to produce a minimum of 500 watts(e) at 28 volts DC at the end of its five year design life. Beyond that, its power output will decrease by approximately 4% per year. The BUP-500 weighs approximately 7100 lbs; its height is 46.3 inches; and its diameter is 59.8 inches. All applicable regulations for safe transport and use will be met 1-4. The following is a description of key components.

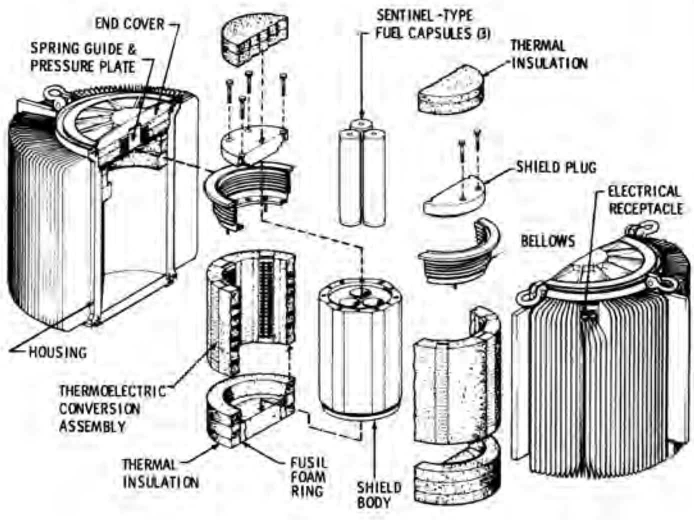

Fig. 2. BUP-500 RTG Exploded View

Heat Source

(Although the BUP-500 is designed to use three types of heat sources, this discussion will be limited to the Sentinel-type heat source which contains existing strontium-90 fluoride.)

Each heat source (Fig. 3) consists of a sealed strength member containing three sealed liners with each liner containing four hot pressed strontium-90 fluoride pellets. The heat source is designed to meet the criteria specified in IAEA Safety Series No. 33[1]. A prototype capusle will be subjected to the complete set of IAEA tests. These tests meet or exceed those specified in 10 CFR Part 71 for special form radioactive material.

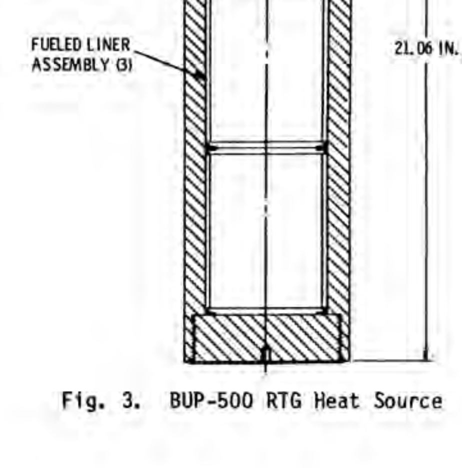

Fig. 3. BUP-500 RTG Heat Source

Strontium-90 fluoride within WESF capsules will be removed, pulverized, and hot pressed in a graphite die to a pellet about 4.0 inches in diameter and 1.3 inches thick. The pellet's density will be between 3.7 and 4.0 g/cc. Based on the average specific power of the 60 WESF capsules with the highest thermal inventories and the minimum pellet density, a minimum power density of .78 w/cc (July 85) will be obtained. Hot pressing and reencapsulation of the fuel will be accomplished at Oak Ridge National Laboratory.

The liner is made from Haynes-25* and consists of a tubular housing with two welded end caps. It adds nothing to the strength of the heat source and serves only to isolate the fuel from the strength member. Selection of the liner material was based on extensive materials compatibility work done at Battelle's Pacific Northwest Laboratory[5]. Test results support the use of Haynes-25 at temperatures up to at least 1,000 °C . The liner's maximum, worst temperature is approximately 950°C and its wall thickness (0.20 inch) exceeds the depth of chemical attack which is estimated to occur over a 20 year period.

The strength member is made of Hastelloy-S*and consists of a tubular housing with a threaded and welded end cap on each end. Each end cap is machined with a threaded hole to facilitate transfer of the assembly between adjoining hot cells and final installation of the heat source into the RTG. The selection of Hastelloy-S was also based on work done at Battelle's Pacific Northwest Laboratory[6].

Shielding

The shield used in the BUP-500 consists of a shield body and a shield plug which is attached to the body with twelve high strength alloy steel bolts. Its diameter is 20.4 inches and its height is 28.6 inches. The shield plug is designed with a "stepped" lower end which fits into a mating cavity in the body. This arrangement serves as a guide for the plug as it is lowered into position in a hot cell following the fueling operation, and it precludes excessive shear loads on the attaching bolts during the hypothetical thirty-foot drop test prescribed for the RTG in 10 CFR 71 packaging standards. The shield body is fabricated with six flat faces around its circumference to provide mating surfaces for the thermoelectric conversion assemblies.

Each shield component is cold pressed and sintered. The material selected is a tungsten alloy consisting of 92% tungsten, 4% nickel, and 4% iron. Its minimum density is 17.0 g/cc. The shield is designed so that the RTG, in its shipping container, will not produce radiation levels which exceed the limits specified in 49 CFR 173 and 10 CFR 71.

Thermoelectric Conversion Assembly

The thermoelectric conversion system contains 336 thermoelectric couples. These couples are divided equally into 12 thermoelectric modules. Two modules and an associated heat sink form a thermoelectric conversion assembly. Each assembly bears against one of the six flats machined on the shield body in an arrangement that can be seen in Fig. 2.

A typical thermoelectric couple is shown in Fig. 4. The base of the couple is a 0.18 inch thick nickel "hot shoe" to which n and p-type thermoelectric elements with iron "cold shoes" are bonded. TE 1006, a lead-telluride alloy, and TAGS-85, an alloy of tellurium, silver, germanium and antimony, will be used for the n and p-type elements, respectively. Both materials were developed by Teledyne. A tin telluride wafer is included between the TAGS-85 element and the iron "cup" so the p-type leg is actually a segmented assembly.

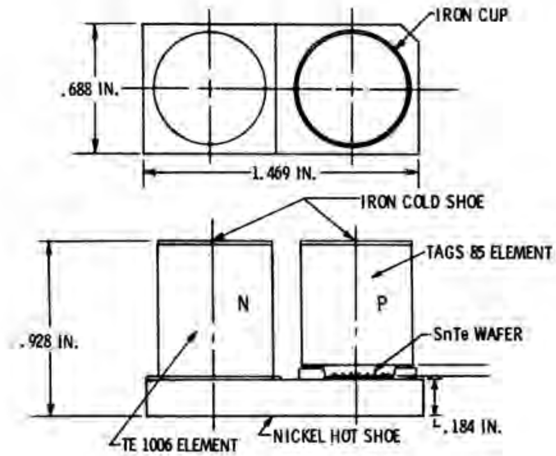

Fig. 4. BUP-500 RTG Thermoelectric Couple

A thermoelectric module is fabricated by inserting 28 couples into holes in a block of thermal insulation such that the cold shoes are minimally exposed. Copper straps, arranged to connect the couples in series, are soldered in place using a fixture which positions the straps over the cold shoes.

Two thermoelectric modules are mated with "cold end hardware" to provide a path for heat flowing through the thermoelectric couples to the finned RTG housing. The cold end hardware consists of spring loaded pistons, each aligned with a thermoelectric element, which fit into cavities in a "module bar" or heat sink. The arrangement of these components is shown in Fig. 5. The springs keep the pistons in contact with the copper straps and the module bar in contact with the housing. The spring pressure also produces a good thermal interface between the hot shoes and the shield. The pistons and piston hole bores in the module bar are designed for very close sliding fits to minimize thermal resistance between the cold shoes and the housing. The pistons and module bars are both fabricated from an aluminum alloy and hardcoated to provide electrical isolation from the copper straps.

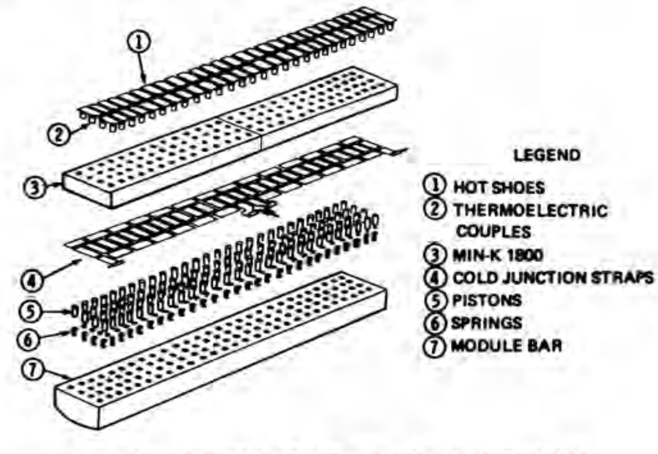

Fig. 5. BUP-500 RTG Thermoelectric Modules & Cold-End Hardware

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Thermal Insulation

Two types of thermal insulation are used to minimize parasitic heat losses. One is a rigid foam fabricated from pure fused silica. This type is used to support the shield and the shield pre-load force. (This force is applied through the spring guide/pressure plate assembly as the RTG's lid is bolted to the housing and is used to keep the shield from moving relative to the rest of the RTG during transportation and handling.) The second type of insulation is formed from fibrous media and very fine particulate matter and is used strictly for its extremely low thermal conductivity.

The rigid type of insulation is produced by Harbison-Walker Refractories and is designated as Fusil Foam 50. This material has good thermal insulating properties and better compressive strength than other insulations. The fibrous types of insulation are Min-K TE 1400 and Min-K TE 1800, both produced by Johns-Manville Corporation. Min-K TE 1400 is used above the shield. Min-K TE 1800 is used between thermoelectric elements, between the thermoelectric conversion assemblies, and beneath the shield inside the Fusil Foam ring. These insulations consist primarily of submicron silica particles, an opacifier and fibrous reinforcement. TE 1400 has a fairly even balance of coarse and fine fibers which makes it suitable for some load bearing applications. TE 1800 has a slightly lower thermal conductivity and is designed for non-load bearing applications.

Bellows Assembly

When thermoelectric materials are exposed to air at near operating temperatures, they suffer degradation due to oxidation and sublimation. The bellows provides a sealed chamber for the thermoelectric conversion assemblies and therefore protects them during fueling. The assembly is fabricated by welding a stainless steel plate on each end of a special bellows. The sealed chamber is formed by bolting one end of the bellows assembly to the top of the shield using two tubular metal O-rings to seal the interface and by bolting the other end to a machined step in the housing using two Viton-O-rings to seal that interface. This allows the RTG's upper end cover, preload components, insulation and shield plug to be removed for fueling without disturbing the seals at either end of the bellows.

Housing and Heat Rejection System

The housing is machined from a forged 6061-T6 aluminum billet. It's wall thickness, except at the ends, is 2.0 inches, sized to minimize temperature gradients both along the length of the housing and around its circumference. The heat rejection system, designed to dissipate over 6500 watts, consists of 132 cooling fins, 0.080 inch thick x 12.7 inches wide and 40.6 inches long. It would be extremely difficult to weld these fins to the thick housing without burning away the fins. To overcome this difficulty, 0.080 inch thick fin stubs are machined on the housing. In addition to the cooling fins, four structural fins are attached to the housing. They are used as lifting points for the RTG as well as points to attach the RTG to its shipping container. The 6061-T6 aluminum alloy was selected for the housing, fins and end covers because of its high strength to weight ratio, plus it is easily machined and readily weldable by a number of techniques. The outer surfaces of the RTG will be finished with a chromate conversion coating which provides exceptional resistance to corrosion.

Shipping Container

The BUP-500 in its shipping container is shown in Fig. 6. Although the container was designed for transporting the generator, it is also intended to serve as an operating stand. In other words, once the RTG is fueled and installed in the container, it need never be removed. The shipping container is 6060-T6 aluminum alloy tubular framework covered with expanded metal to allow natural air circulation. The RTG is attached to eight shock isolators which are mounted on the container. These isolators reduce the forces that are transmitted to the RTG during transportation and handling. The container has a lug at each upper corner which is used both for lifting and tie-down and an additional tie-down lug near the mid-point of each vertical corner member. It rests on two structural channels which are designed so the unit can be handled by fork-lift truck.

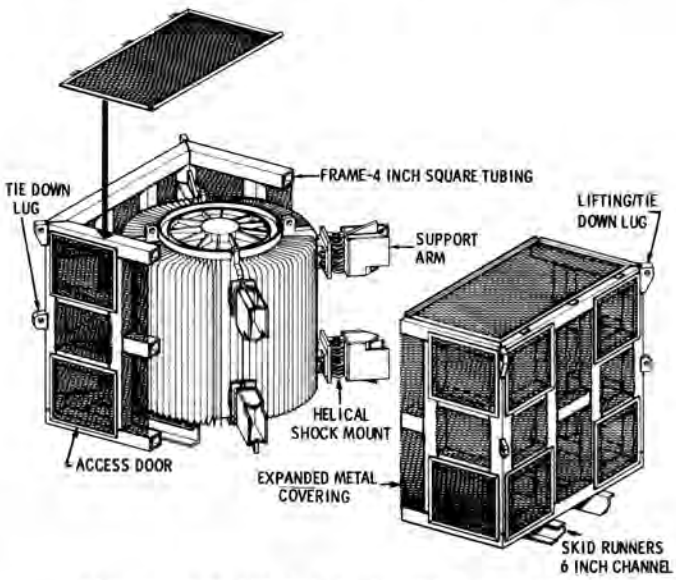

Fig. 6. BUP-500 RTG in Shipping Container

Performance

The BUP-500's performance at beginning-of-life and end-of-mission are summarized in Table I.

TABLE I

BUP-500 Performance Summary

	BOL	EOM
Thermal inventory, watts(t)	7504	6640
Hot junction temperature, °F	961	900
Cold junction temperature, °F	198	186
Fin root temperature (avg), °F	150	143
Ambient temperature, °F	75	75
Parasitic heat losses, watts(t)	512	468
Heat to thermoelectrics, watts(t)	6992	6172
Power output, watts(e)	610	508
Thermal efficiency, %	93.2	93.0
Thermoelectric efficiency, %	9.16	8.55
Strap efficiency, %	95.2	96.2
System efficiency, %	8.12	7.65

NOTES:
1. Load voltage - 28 volts
2. 336 couples in series
3. D_N = 0.610", D_P = 0.602", L = 0.7"
4. RTG gas fill: argon at 1 atm.
5. BOL: Beginning of Life
6. EOM: End of Mission

REFERENCES

1. "Guide to the Safe Design, Construction and Use of Radioisotopic Power Generators for Certain Land and Sea Applications," Safety Series No. 33, International Atomic Energy Agency (1970).

2 Title 10, Code of Federal Regulations, Part 71.

3. Title 49, Code of Federal Redulations, Para. 173.401-173.478.

4. "Regulations for the Safe Transport of Radioactive Materials, 1973 Revised Edition," Safety Series No. 6, International Atomic Energy Agency (1973).

5. H. T. FULLAM, "Compatibility of Strontium-90 Fluoride with Containment Materials at Elevated Temperatures," PNL-3833, Pacific Northwest Laboratory (1981).

6. H. T. FULLAM, "Design and Qualification Testing of a Strontium-90 Fluoride Heat Source," PNL-3923, Pacific Northwest Laboratory (1981).