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SPECIFICATION FOR STRONTIUM-90
500-WATT(e) RADIOISOTOPIC
THERMOELECTRIC GENERATOR

TES-3170

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FINAL REPORT

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FOREWORD

This document was prepared by Teledyne Energy Systems in compliance with the requirements of Exhibit A of Contract DE-AC04-83AL22028, Department of Energy, Albuquerque Operations Office.

TABLE OF CONTENTS

	<u>Page</u>
Notice	i
Foreword	ii
I Introduction	I-1
II Summary and Conclusions	II-1
III Fuel Capsule Strength Member Design Specification	III-1
1. Task I Objective	III-1
2. Heat Source Qualification - Test Requirements	III-1
3. Heat Source Design Criteria	III-3
4. Heat Source Specification.	III-6
5. Capsule Strength Member Stress Analysis	III-8
6. Conclusions and Recommendations	III-13
IV Conceptual Design	IV-1
1. Design Specification	IV-1
2. Support Equipment	IV-4
3. Design Concept	IV-6
4. Impact Protection of Shipping Package	IV-18
V Thermoelectric Analysis	V-1
1. Module Design	V-1
2. Projected Performance.	V-4
VI Thermal Analysis	VI-1
1. Heat Source	VI-1
2. Heat Rejection System.	VI-12

TABLE OF CONTENTS (Continued)

	<u>Page</u>
VII Shield Analysis	VII-1
1. Shield Design Criteria	VII-1
2. Fuel Characterization; Sources of Reduction	VII-2
3. Radiation Attenuation, Shield Thickness	VII-3
4. Adequacy of the Estimate	VII-7
5. Structural Analysis of Shield	VII-7
VIII Program Schedule	VIII-1

Attachment A Heat Source Specification 500 Watt(e) RTG

I. INTRODUCTION

The Department of Energy (DOE) By-products Utilization Program (BUP) has the goal to develop and encourage the use of nuclear by-products produced in DOE defense operations. One of the byproducts is Strontium-90 (Sr-90), a beta-emitting isotope of value as a heat source. DOE has separated Sr-90 from defense wastes and doubly encapsulated it in storage capsules at the Hanford Waste Encapsulation and Storage Facility (WESF) for several years. Currently, several hundred capsules are stored at WESF. During the next ten years, significant additional quantities of Sr-90 will be separated, encapsulated and stored at Hanford.

The coupling of encapsulated Sr-90 fueled heat sources to the hot junction of certain thermoelectric materials to induce a flow of electricity in these materials is a technology which has been developed and used in space, undersea and terrestrial applications for over twenty years. However, these radioisotopic thermoelectric generators (RTG's) have produced electric power primarily at levels at or below 100 watts.

During the next ten years, there appear to be promising applications for reliable, low-maintenance power sources such as provided by RTG's up to levels of 500 watts (electric). Potential applications could involve the MX system, the DOD Dewline Radar System and various command, control, communications, and intelligence (C³ I) devices.

The objectives of the contract were twofold: (1) to create a design specification for a capsule strength member for existing and future Sr-90 - filled standard WESF inner liner capsules that will meet or surpass all safety requirements, (2) to develop a conceptual design for a Sr-90 fueled RTG capable of producing up to 500 watts of power which could serve as a demonstration unit to encourage significant DOD utilization of future large quantities of Sr-90 produced by DOE defense programs.

II. SUMMARY AND CONCLUSIONS

A conceptual design for a demonstration 500-watt(e) radioisotopic thermoelectric generator has been created for the Department of Energy. The design effort was divided into two tasks, viz., create a design specification for a capsule strength member that utilizes a standard Strontium-90 fluoride-filled WESF inner liner, and create a conceptual design for a 500-watt(e) RTG. Both tasks have been accomplished.

The strength-member specification was designed to survive an external pressure of 24,500 psi and meet the requirements of special-form radioisotopic heat sources. Therefore the capsule can, if desired, be licensed for domestic and international transport.

The design for the RTG features a radioisotopic heat source, an array of nine capsules in a tungsten biological shield, four current technology series-connected thermoelectric-conversion modules, low-conductivity thermal insulation, and a passive finned-housing radiator for waste-heat dissipation.

The preliminary RTG specification formulated previous to contract award has been met or exceeded. The power source will generate the required power for the required service period at 28 volts dc with a conversion efficiency of 8%, provided the existing in-pool capsules at WESF meet the assumed thermal inventory requirements.

III. FUEL CAPSULE STRENGTH MEMBER DESIGN SPECIFICATION

1. Task 1 Objective

The objective of Task 1 of this study was to create the design criteria for a Sr-90 heat source for use in an RTG capable of producing 500 watts of electric power. The heat source was to utilize as much of the existing WESF storage capsule as possible.

2. Heat Source Qualification - Test Requirements

A radioisotope heat source to be used in a licensed RTG must meet certain qualification test requirements defined in a number of Federal and International Guides and Regulations. The most stringent and all encompassing heat source (capsule) test requirements are described in the International Atomic Energy Agency's (IAEA) Safety Series 33 document entitled, "Guide to the Safe Design, Construction and Use of Radioisotopic Power Generators for Certain Land and Sea Applications." The complete set of capsule test requirements, excerpted from IAEA Safety Series 33, is given in Table III-1. IAEA Safety Series 33, also specifies that for certain applications, corrosion, vibration, irradiation and creep tests may be specified for the heat source by competent authority. To date, the Nuclear Regulatory Commission (NRC) has not defined specific tests in these areas.

Preliminary tests and design calculations show that the existing WESF Sr-90 F_2 capsule hardware cannot meet the qualification test requirements. In keeping with the guideline to use as much of the WESF capsule as possible, the new heat source has been designed to use the existing WESF Hastelloy C-276 inner capsule as a fuel compatible containment barrier only with a new outer strength capsule to provide the structural integrity to meet qualification tests.

Figure III-1. Proposed Outer Strength Member WESF Capsule 500 Watt RTG

3. Heat Source Design Criteria

a. General Discussion

Design of the outer strength member is based largely on work performed at Battelle's Pacific Northwest Laboratory (PNL),⁽¹⁾ both in material selection and general sizing. The PNL report states that the American National Standards Institute (ANSI) has defined certain test requirements for large-size radioactive sources that are more stringent, or which supplement the qualification test requirements listed in Table III-1. Although these tests do not apply to RTG systems they could be adopted by the NRC in future regulations. These supplemental qualification tests are:

- (1) A 24,500 psi external hydrostatic
- (2) A 20 Kg-m percussion test
- (3) A 1 Kg-m puncture test

The increased external pressure environment has the most significant effect on the capsule design; the other two tests should cause no detrimental results in the thick walled outer capsule. Since a secondary objective of the BUP is to qualify a general purpose Sr-90 F₂ fueled heat source for future uses, the outer strength member has been designed to withstand the 24,500 psi external pressure.

b. Design Criteria

The outer strength member is designed to withstand the impact, percussion, thermal, thermal shock, and pressure tests required by IAEA Safety Series 33 and shown in Table III-1. In addition, the capsule is designed to withstand an external hydrostatic pressure of 24,500 psi. The increased external pressure capability is demonstrated analytically in item 5 of this section, but testing to requirements that do not exist at this time is not justified.

⁽¹⁾PNL-3923, "Design and Qualification Testing of Strontium-90 Fluoride Heat Source," H.T. Fullam, December 1981 Pacific Northwest Laboratory.

TABLE III-1

HEAT SOURCE QUALIFICATION TEST REQUIREMENTS

1.0 GENERAL

1.1 The tests described in paragraphs 2.1 - 2.6 inclusive shall be applied to samples or prototypes of capsules constructed as for use in a generator except that their radioactive content may be simulated by inactive material of the same or similar nature. This implies that, subsequent to satisfactory conclusion of the tests, full inspection will be carried out during the production of capsule for operational use to ensure that the standards achieved by the samples or prototypes are maintained.

In addition, every loaded capsule shall be subjected to the leakage test indicated in paragraph 2.6 prior to installation in a generator.

1.2 The capsule shall be subjected to each of the tests indicated in Section 2 below, including those for corrosion and vibration where appropriate for the particular application.

1.3 If the tests do not require to be carried out at a particular temperature, then they should be done at the operating temperature if this is practicable.

1.4 The tests shall be carried out in such a way as to ensure that the sample capsule suffers maximum damage.

1.5 After each of the tests, the capsule shall be shown to have retained its original leak-tightness within the accuracy of the chosen method.

1.6 A different sample or prototype capsule may be used for each of the tests except in the case of that indicated in paragraph 2.6.

2.0 TEST METHODS

2.1 Impact test

The capsule shall fall on to the target from a height of 9 meters. The target shall be a flat, horizontal surface of such a character that any increase in its resistance to displacement or deformation upon impact by the capsule would not significantly increase the damage to the capsule.

2.2 Percussion test

The capsule shall be placed on a sheet of lead which is supported by a smooth solid surface and struck by the flat face of a steel billet so as to produce an impact equivalent to that resulting from the free fall of 7 kilograms through 1 meter. The flat face of the billet shall be 2.5 centimeters in diameter with the edges rounded off to a radius of not less than 3 millimeters. The lead, of hardness number 3.5 to 4.5 on the Brinell scale and not more than 25 millimeters thick, shall cover an area greater than that covered by the capsule. A fresh surface of lead shall be used in each test.

2.3 Thermal test

The capsule shall be heated to a temperature of 800°C and it shall be held at that temperature for a period of 30 minutes before being allowed to cool.

2.4 Thermal shock test

The capsule shall be heated to its maximum operating temperature and then plunged in water at zero temperature where it shall be left for 10 minutes.

2.5 Pressure test

The capsule shall be shown to be able to resist an external pressure of 1000 bars, i. e. 10^8 Newtons per square meter.

2.6 Leakage test

This test relates to the requirements of paragraph 1.5. Any commonly accepted leakage test may be used, provided it is of a sensitivity comparable with the detection of leakage of 10^{-4} (STP) cm^3/sec . If this degree of leakage can be detected the test requirements will not have been met.

2.7 Other tests

For certain applications, corrosion, vibration, irradiation and creep tests may be specified by the competent authority.

c. Material Selection

Based largely on work done at PNL over the past 6 years and the recommendations of PNL Report⁽¹⁾, Hastelloy 'S' was selected as the outer strength member material.

Hastelloy alloy 'S', produced by the High Technology Division of Cabot Corp., is a nickel-base, high temperature alloy with a unique combination of properties. It has excellent thermal stability, low thermal expansion and outstanding oxidation resistance to 2000°F. In addition, the alloy has good high temperature and thermal fatigue strength. Alloy 'S' retains its strength and ductility after aging at temperatures of 800 to 1600°F.

The outer strength member housing and end caps are to be machined from solution heat treated bar stock certified to AMS-5711 specification.

d. Outer Strength Member Configuration

The outer strength member assembly and components are shown in Figure III-1. The assembly consists of a housing and two similar threaded end caps. The end caps are designed to bottom on a shoulder machined in the housing. When 'seated' the maximum gap at the weld joint is 0.004 inch. A circumferential weld was employed to be compatible with the existing WESF welding fixtures. The end cap/housing interface, although designed for TIG weld would also be suitable for either plasma arc or electron beam welding. The weld joint, as presently configured, assumes that the weld penetration can be obtained without the use of filler wire. The end cap seating area is capable of withstanding the external pressure loads and the threads provide a degree of 'fixity' needed to minimize the weld penetration requirements. One end cap is designed with a tapped hole into which an eyebolt or similar handling device can be screwed to facilitate capsule handling and RTG loading. The other end cap is designed with a small tapered opening to accept a mating tapered pin. This opening is provided so that the gap between the inner capsule and outer strength member can be filled with helium. The main purpose

of the helium gas fill in this gap is to reduce the temperature gradient between the inner and outer capsules. Of course, the helium also facilitates subsequent leak testing of the final outer capsule weld joints. The tapered pin is centrally located in the end cap so that the existing welder can effectively seal this final joint with a single weld "sting."

The outer strength member is designed to accept the inner WESF capsule with a nominal diametrical clearance of 0.120 inch and a nominal axial clearance of 0.140 inch. The outer strength member design is similar to the configuration tested by PNL except the end cap design has been modified to simplify fabrication.

The configuration of the weld test specimens, used exclusively in a weld development program, is shown in Figure III-2. Sub-sized weld specimens, without threads, but with the weld joint configuration are intended for initial weld parameter evaluation. The units are undersized only to take advantage of available material to expedite the development work. Plain slabs are provided, from which tensile and bend test specimens can be machined. Finally, the full size weld test specimens are exact duplicates of the actual heat source joint configurations, but are shorter than the actual heat source housing in overall length.

4. Heat Source Specification

A comprehensive heat source specification was created which defines all of the requirements and quality assurance provisions that each production heat source must meet. In addition, the specification defines the heat source outer strength member qualification test requirements. This specification, TES-3164, "Heat Source Specification - 500 Watt(e) RTG" is attached as Attachment 1.

After meeting with DOE, RHO and PNL personnel, the only unresolved items within the specification concern the required RTG thermal inventory range and the

Figure III-2. Capsule Weld Test Specimens

accuracy to which heat source calorimetry can be measured. These items are not of immediate significance, since existing WESF capsules and inherent calorimetry will be selected for the demonstration RTG.

5. Capsule Strength Member Stress Analysis

The fuel capsule proposed for the 500 Watt RTG concept has been evaluated for an external pressure of 24,500 psi. The capsule will be fabricated from Hastelloy S with the following room temperature structural properties:

Yield strength	$= \sigma_y = 52,900 \text{ psi}$
Ultimate tensile strength	$= \sigma_u = 125,300 \text{ psi}$
Elastic modulus	$= E = 29.8 \times 10^6 \text{ psi}$
Elongation	$= \epsilon = 54\%$

Plastic deformation of both the cylindrical shell and the end closures will occur because of the very high external pressure. However, the plastic deformation is relatively low when compared to the ultimate capability. The design is not marginal.

As the pressure increases on the thick-walled shell the maximum stresses occur in the circumferential direction at the inner surface until it reaches the material's yield point. A "plastic front" is formed which moves radially outward as a function of the increase in applied pressure.

Assuming a rigid-perfectly plastic material model, it can be shown that the pressure associated with the initiation of this front can be obtained from the equation,

$$p^* = \frac{\sigma_y}{2} \left(1 - \frac{a^2}{b^2} \right)$$

where

a = inside radius = 1.188

b = outer radius = 1.688

$$\therefore p^* = \frac{52900}{2} \left[1 - \frac{(1.188)^2}{(1.688)^2} \right] = 13349 \text{ psi}$$

For the case of full plasticity, the pressure is,

$$\begin{aligned} p^{**} &= \frac{b-a}{b} \sigma_y \\ &= \left(\frac{1.688 - 1.188}{1.688} \right) 52900 = 15669 \text{ psi} \end{aligned}$$

However, this approach is very conservative because Hastelloy S has extensive strain hardening capability. For this reason, a finite element representation was developed and the material model was elastic-linear strain hardening. The ANSYS general purpose finite element program was utilized.

The ANSYS formulation includes the Prandtl-Reuss flow equations and yielding is based on the von Mises criterion.

Figure III-3 presents the relatively simple finite element model which represents the thick-walled cylindrical shell. Only a unit length cylinder model is required when applying radial displacement compliance at node pairs (i. e., 1 and 11, 2 and 12, etc.).

The elastic-plastic solution indicated a maximum equivalent stress at the inner surface ($R = 1.188$) of 54,300 psi. The equivalent strain was found to be 1.2%. The ultimate tensile strength and elongation of 125,300 psi and 54%, respectively, suggest a large structural margin.

Figure III-4 presents the finite element model of the closure for the elastic-plastic analysis utilizing ANSYS. The material model for Hastelloy S is the elastic-linear strain hardening stress-strain representation previously defined.

Based upon typical machining tolerances, the threaded closure prior to welding can have an axial gap at either the weld interface or at the lower cylinder-closure interface (nodes 40, 53, 66, 79, and 91). The former is much preferred because the direct lower interface provides a more optimum foundation for the closure rather than forcing the threads to take nearly all of the axial loading. Although the R/t of the closure is relatively small, the vertical shear capability of the thread coupled with the foundation extremity at node 40 provides a significant rotational constraint at the plate periphery. This reduces center deflection and stress magnitude.

For the applied pressure of 24,500 psi, the center deflection is .0024 inch and the top and bottom fiber stresses are -40,400 psi and 23,300 psi, respectively. The maximum equivalent stress is a local discontinuity of 70,540 psi at node 117. However, the major contribution is compressive and the material's capability is well above this stress level.

Additional analyses will be performed in the future for any design modifications, i. e. relocation of the weld, variation of gaps due to fabrication tolerances, etc. The

Figure III-3. Finite Element Model for the Cylindrical Shell

EXTERNAL PRESSURE 24,500 PSI

Figure III-4. Capsule Closure

results will be similar. Plastic strains will exist, but will be of relatively low magnitude.

6. Conclusions and Recommendations

Based on design calculations and test results achieved by PNL on similar hardware, the outer strength member designed for the 500 watt(e) RTG will meet all of the qualification test requirements specified in Table III-1. Furthermore, should NRC adopt the supplemental tests presently defined in ANSI-N 542 sometime in the future, the capsule could be re-qualified without any design modifications.

It is recommended, that following successful qualification testing of the prototype capsules that DOE apply for registry of the sealed Sr-90 F_2 heat source. Registration/certification of the heat source will simplify licensing of RTG's or power generating devices by potential users, because no additional heat source qualification tests would be required. DOE would have, in effect, a qualified, general purpose, sealed Sr-90 F_2 heat source.

IV. CONCEPTUAL DESIGN

The basic groundrule for Task II of this study was to create a conceptual design of a 500 watt(e) RTG using existing WESF inner capsules re-encapsulated in new outer strength members. The RTG was to serve as a demonstration model with a five year mission life, fully shielded and licenseable for transport. .

1. Design Specification

a. Electrical Requirements

The RTG shall provide a minimum output power of 500 watts(e) at the end of a five year performance period. The RTG will employ a shunt type voltage limiter to control the output voltage from the generator at a nominal value of 28 volts d.c. The limiter will be adjustable between the values of 24 volts and 32 volts. Voltage regulation will be less than 1% from no load to full generator capacity.

The output power of the generator will be routed through a hermetically sealed MS type connector(s) and will mate externally with a threaded straight plug(s). External connections to the voltage limiter will be made at a terminal board. Connectors shall be located on the cylindrical housing of the RTG in an area not subject to damage.

Insulation resistance between the RTG output power circuit and the housing of the generator shall be at least one megohm.

The RTG system shall have as a design goal, an efficiency of 8%.

b. Material Requirements

Materials used in the RTG external shell; housing fins, end covers, electrical receptacles, seals and attaching hardware; shall be physically, chemically and thermally compatible with every other material with which it will be in contact.

Anodic coatings or a suitable paint system shall be applied to all RTG external surfaces to inhibit corrosion for the design life of the unit.

c. Fuel Capsule Requirements

DOE is to make available for the demonstration RTG, the nine selected WESF capsules shown in Table IV-1.

The average capsule thermal inventory is to be 800 watts as determined by calorimetry to the best accuracy feasible with existing measurement equipment. An estimate of calorimetry measurement accuracies should be made by RHO. It must be noted that reduced thermal inventory will result in a reduction of RTG power output and other performance features.

d. Environmental Conditions for Shipping and Storage

The RTG, when installed in a qualified shipping container and on short-circuit, shall be capable of withstanding the following environmental conditions:

- (1) Ambient air temperatures from -40°F to 120°F .
- (2) Shocks and vibrations incident to normal shipping by vessel, cargo-only aircraft and motor vehicle.
- (3) Relative humidity in a salt air atmosphere from 0% to 100%.

e. Environmental Conditions for Operation

The RTG, when operated in its normal attitude (fins vertical), shall be able to provide the specified power under the following conditions:

- (1) Ambient air temperatures from -40°F to 100°F .
- (2) Relative humidity in a salt air atmosphere from 0% to 100%.
- (3) Time period up to five years from time of fueling.
- (4) Following normal shipping and storage environments specified in d above.

TABLE IV-1

CAPSULES SELECTED FOR 500-WATT RTG

<u>Capsule Number</u>	<u>Calorimeter Date</u>	<u>Calorimeter Reading watts (t)</u>	<u>Inventory as of 3/31/84 watts(t)</u>
S-458	3/16/77	1045.0	882.1
S-77	11/21/75	970.2	793.2
S-83	12/3/75	932.8	763.2
S-93	12/6/75	1000.7	849.2
S-79	12/6/75	923.4	755.7
S-86	12/10/75	967.8	792.3
S-112	2/2/76	989.8	813.3
S-122	3/2/76	1008.5	838.3
S-427	1/7/77	894.1	751.3
Total			7200.5
Average			800.1

f. Radiation Dose Level Requirements

The RTG shall be designed such that the following radiation dose levels are not exceeded:

- (1) 200 mr/hr at the RTG/shipping container accessible surface.
- (2) 10 mr/hr at a distance of three feet from the accessible surface.

g. Physical Characteristics

The RTG, exclusive of shipping container shall not exceed 54 inches in diameter or 48 inches in height.

The RTG shall not exceed a weight of 7200 pounds without shipping container.

The RTG shall be designed to be handled by either/both forklift truck and handling sling.

2. Support Equipment

This section includes the design requirements for related support equipment to be used in the testing, storing, shipping, handling and operating the RTG.

a. Electrically Heated Thermoelectric Generator (ETG)

The RTG will initially be fabricated and tested as an electrically heated generator. Resistance type cartridge heaters inserted in stainless steel bars, dimensionally equivalent to the fuel capsule, will be used to simulate the radioisotope fuel thermal inventory. One of the biological shield plugs will be replaced with a stainless steel plug through which the heater wiring can be routed. The heaters, connected in a series-parallel array, will be connected to an individual power input hermetically sealed receptacle. All other generator components will be the actual RTG components. The ETG will be used to verify RTG performance at beginning of life, end of life and at other thermal inventories. The ETG shall be capable of providing any thermal inventory up to 8000 watts.

b. ETG Power Supply

Power to the ETG will be controlled by a Variac adjustable a.c. power supply. The power supply will be capable of providing over 8000 watts from a 240 volt a.c. source. A fine adjustment Variac will be provided to improve the resolution of the power setting. Wattmeter connection points will be provided along with connections to the ETG power input leads.

c. RTG/ETG Load Box

A variable load will be provided for testing the generator either/both fueled and electrically heated. The load will be capable of dissipating the full generator output and will be variable over a range from about 1/3 to 3 times the RTG matched load.

A knife switch will be provided to allow measurement of the generator open circuit voltage and a shunt will be included to facilitate measurement of generator load currents.

d. Voltage Limiter

The output voltage from the RTG/ETG will be controlled at a nominal 28 volts dc by a shunt type voltage limiter. The voltage limiter will be adjustable between the values of 24 volts and 32 volts (minimum). Voltage regulation will be better than 1% from no load to full generator capacity.

e. Shorting Plug

A threaded plug(s) designed to mate with the RTG/ETG power output receptacle will be provided as a "shorting plug." When installed, the plug will furnish a direct short circuit across the generator power output terminals. The shorting plug is to be used at times while the RTG is in shipment or in storage.

f. Shipping Container

A suitable shipping container will be provided to serve as the RTG "package,"

as specified in 10 CFR Part 71, and 49 CFR Parts 170-190. The shipping container with generator installed shall be designed to be handled by either/both forklift truck and handling sling. The shipping container will be of minimum size consistent with meeting the NRC license requirements. If feasible, the shipping container shall be designed such that the RTG can perform as specified while installed in the shipping configuration.

g. Handling Sling(s)

Handling sling(s) necessary to lift the RTG/shipping container will be designed to OSHA requirements and proof tested to 1 1/2 times the design loads.

3. Design Concept

The basic 500 watt(e) RTG concept is shown in Figure IV-1. The major components comprising the RTG assembly are:

- The heat source or modified WESF capsules.
- The biological shield assembly.
- The thermoelectric conversion assemblies.
- Thermal insulation.
- The external containment shell which includes a finned housing, end covers interface seals and electrical receptacles.

a. Heat Source

The design criteria and heat source specification governing the heat sources to be used in the 500 watt(e) RTG have been completed under a separate task of this study contract. The heat source design criteria are discussed in detail in Section III. Briefly, the heat source(s) for the demonstration RTG unit utilizes fueled WESF inner capsules re-encapsulated in a new outer strength member designed to provide the structural integrity necessary to meet "special form" test requirements.

Figure IV-1. 500 Watt(e) RTG Concept

b. Biological Shield Assembly

The biological shield assembly, shown in Figure IV-2 consists of a shield body and two shield plugs attached to the body with high strength alloy steel bolts. The shield is designed to accept nine (9) modified WESF capsules based on an average thermal inventory of 800 watts. The capsule holes in the shield body are through-holes to facilitate fabrication and the end plugs are designed with an internal lip for ease of assembly alignment.

The biological shield assembly is designed so that the RTG will meet the radiation dose requirements of 49 CFR Part 173.393. This single component represents about 60% of the total RTG weight and will be the largest shield ever used in an RTG.

Two basic materials were considered for use in the biological shield, depleted uranium alloyed with 8-10% molybdenum, and tungsten. The uranium alloy shield due to its higher density and attenuation factor would result in a somewhat lighter shield than the tungsten. However, even with the addition of molybdenum, oxidation of the shield would occur when operated continuously at temperatures near 1100°F. To preclude oxidation, uranium shields are generally "canned" in a sealed stainless steel container. The "canning" operation not only adds back in most of the weight advantage but would increase fabrication costs significantly. We have been unable to locate a vendor willing to fabricate a depleted uranium shield.

Teledyne Energy Systems has employed tungsten alloy shields in all of their commercial RTG's over the past 13 years. The tungsten alloy has good density and better thermal stability and oxidation resistance than does uranium. The tungsten alloy to be used in the 500 watt(e) RTG is basically 95% tungsten with small additions of nickel, copper, iron, and binding agents. The material density is at least 16.9 g/cc. The proposed shield will be fabricated as a number of interlocking rings brazed together with a

Figure IV-2. Biological Shield Assembly - 500 Watt RTG

copper braze. The interlocking ring joints are designed to prevent radiation streaming.

The configuration of the shield body is that of a right circular cylinder with flat sections designed to interface with the thermoelectric conversion assemblies. Several nine-capsule configurations were evaluated with an irregular hexagonal shape and others with cylindrical shape but with material removed within the circle of capsules to reduce weight. After evaluations considering shielding properties, central heat source temperatures and fabricability, the present design concept was selected.

c. Thermoelectric Conversion Assemblies

The 500 watt(e) RTG will employ approximately 360 thermoelectric couples. These couples will be made of Teledyne's TAGS/lead telluride thermoelements bonded with current thermoelectric technology. A typical thermoelectric couple is shown in Figure IV-3 and consists of a hot shoe, 'P' and 'N' type thermoelectric elements and cold caps to facilitate subsequent interconnections. Each of the four thermoelectric conversion assemblies used in the RTG, reference Figure IV-4, contain 90 thermoelectric couples. A typical conversion assembly is fabricated by inserting the couples through pre-machined holes in a block of insulation such that the cold caps are minimally exposed. Interconnecting copper straps are soldered in place with the use of a bonding fixture which coordinates the location of couples and connecting straps. The resulting assembly is a monolithic series-connected circuit block. Over five million generator hours, with an average of about 36 series connected couples, have been logged without failure.

When installed in the RTG, a dielectric strip of mica or alumina is used between the couple hot shoes and the shield. A heat sink/module bar, with individual spring loaded pistons over each thermoelement, makes contact with the finned housing.

Figure IV-3. Thermoelectric Couple 500 Watt RTG

Figure IV-4. 500 Watt(e) RTG Assembly

The heat flow then is from the shield through the thermoelectric couples, through the pistons and heat sink bar into the finned housing. The spring pressure at each element maintains thermal contact of both the hot shoes and heat sink. The pistons and module bars are both fabricated from an aluminum alloy and hardcoated to provide electrical isolation from the power circuit. Hardcoating is an anodic finish which forms a dielectric coating on the surface of aluminum parts. The pistons and piston hole bores in the module bar are designed for very close sliding fits to maximize thermal transfer from the couple cold side to the housing. The spring loaded pistons have the further advantage of automatically compensating for thermal expansions in the converter assembly.

The thermoelectric conversion assemblies along with their associated pistons, springs and heat sink bar are generally referred to as thermoelectric modules and are assembled into the housing by the use of specialized tooling which compress all of the springs and locate the units within the housing.

d. Thermal Insulation

The thermal insulation to be used in the 500 watt(e) RTG is a combination of Min-K TE1400 and Min-K TE 1800, both produced by the Johns-Manville Corporation. Min-K TE 1400 and 1800 are insulations developed for use in contact with lead-telluride thermoelectric elements. The products consist primarily of submicron silica particles, an opacifier and fibrous reinforcement. The material has a density of 20 lbs per cubic foot which represents a reasonable tradeoff of physical and thermal properties. TE 1400, with a hot face limit of 1400°F, has a fairly even balance of coarse and fine fibers which makes it stronger and suitable for load bearing applications. TE 1800 with a temperature limit of 1800°F has somewhat better thermal properties than 1400 but was designed as non-load bearing. Outgassing of the thermal insulation will be accomplished both as an ETG and again after fueling the RTG to get rid of absorbed moisture.

e. External Containment Shell

The finned RTG housing and end covers will be fabricated from 6061-T6 aluminum alloy. This material has a high strength to weight ratio, is easily machined and readily weldable by a number of techniques. The housing will be machined from an aluminum tubular billet and the full length heat dissipating fins welded from one side around the circumference of the housing. Four of the fins will be designed as structural members for use as lifting points and tie-down or shipping container attachment points.

The end covers will be machined from 6061-T651 aluminum alloy plate and fastened to a flange machined on both ends of the housing with 2024 aluminum bolts. Threaded stainless steel "heli-coil" inserts will be used in the aluminum housing flanges to provide the required "pull-out" strength. The end cover/housing interfaces will be sealed with a Viton 'O'-ring. Viton is a fluoroelastomer with good mechanical properties and chemical resistance that remains usefully elastic indefinitely at temperatures up to 400°F.

The electrical receptacles will have aluminum shells with threaded couplings meeting all requirements of MIL-C-26500. The connectors will be supplied with a black anodized finish.

The exposed RTG outer surfaces will be finished with two coats of epoxy primer and two finish coats of "Insigna-White" epoxy enamel.

f. Shipping Container

With the major emphasis of this study devoted to the finalized heat source design and to the 500 watt(e) RTG concept, little effort was expended for a suitable RTG shipping container concept.

Originally, the conceptual design goal was to design all of the shipping safety features into the RTG such that no shipping container would be required. However, when the mass of the biological shield was determined, it became apparent that an external

"package" would indeed be needed. The governing design regulation which appears in 10 CFR, Part 71, Appendix B is the requirement that following a 30 foot drop (hypothetical accident condition) the radiation dose level at accessible surfaces must not exceed 1,000 mr/hr. This essentially dictates that the shield must remain intact. The enormous energy associated with the drop of an object of over 4700 pounds through a distance of 30 feet must be absorbed to protect the relatively fragile shield.

Two approaches have been considered for further evaluation in the detailed design contract phase. One approach, shown in concept only in Figure IV-5 would employ the use of foam filled "cushions" at the top and bottom of the RTG and extending well beyond the fin diameter. The use of a low density polyurethane foam as an energy absorbing device is not new to Teledyne. Such structures are used in Teledyne's Protective Packaging of low level radioisotopic waste systems. The foam releases considerable thermal energy when being formed and therefore must be contained in steel containers. It is estimated that such a system would add about 1600 lbs. to the overall RTG system. A further drawback of the foam system for this particular application, is that it prevents the natural air circulation up through the fins and would increase the generator temperatures. A two-piece upper structure could be fabricated, as shown to permit air flow but sufficient work has not been completed to assure that either the required foam volume is available or that RTG operation can be achieved without removal of this energy absorber. The foam filled structures, however, are a good energy limiting technique and will be further analyzed.

A second design approach is to suspend the RTG on a series of heavy duty helical shock mounts from a structural steel shipping pallet and framework. The framework could then be "screened" in and the RTG need never to be removed from its "package" for proper operation. This concept is shown in Figure IV-6. This approach has not even been analyzed in a cursory manner, but appears to be feasible and has advantages

Figure IV-5. RTG in Shipping Configuration

Figure IV-6. Shipping Configuration - Shock Mount Concept

over the foam "cushion" concept. One obvious advantage is that the entire shipping container is "open" such that air circulation is not impeded in any manner. A second advantage is that the voltage limiter for the RTG could be permanently mounted on a base plate and interconnecting wires attached to the structure along its route. One further asset, if the RTG is to remain permanently within the package, is that the screening outside the shipping container framework now would be defined as the "accessible" surface; this would possibly allow a small reduction in shield thickness and a reduction in shield weight.

4. Impact Protection of Shipping Package

A structural analysis of the shipping configuration shown in Figure IV-5 has been performed.

In order to protect the RTG from extensive damage and maintain fuel containment following a transportation or handling accident, a crush-up material can be utilized to absorb the available energy. One effective material for this approach is a polyurethane foam. It is a pour-in-place plastic that is formed by the reaction of two liquids, a polyol and a polyisocyanate in the presence of a gas producing agent such as freon. The compression or crushing stress-strain representation is shown here. Assuming a foam density of about 6.5 lbs/ft³, the yield strength at approximately 7% compression is about 165 psi. This magnitude is essentially constant until 60% displacement is obtained.

The following analysis addresses the 30 foot fall to a nonyielding surface. For an RTG weighing about 7000 lbs. the available energy is,

$$E_a = 7000 (30) (12) = 2.52 \times 10^6 \text{ in-lbs.}$$

Impact orientations examined herein include the top, side and a corner. For an impact on the top, the crushing or strain energy is,

$$E_s = \pi (R_1^2 - R_2^2 + R_3^2) t_e \sigma$$

where: $\sigma = 165 \text{ psi}$

$t_e = \text{effective crush thickness} = .6 t$

$R_1 = 41.75$

$R_2 = 22.25$

$R_3 = 11$

$$\therefore E_s = 4.26 \times 10^5 t$$

Equating the two energies, the minimum required thickness of foam is,

$$t_{\min} = \frac{2.52 \times 10^6}{4.26 \times 10^5} = 5.9 \text{ inches}$$

This value is somewhat unconservative since a portion of the foam is radially beyond the fins and therefore a rigid foundation is limited. However, a minimum thickness of 12 inches was incorporated.

For a side impact, the volume is,

$$V = \frac{R_1}{2} (\theta - \sin \theta) L$$

where $L = 2 (21) = 42$

$R = R_{\text{fin}} + t$

$R_{\text{fin}} = 26.25$

$$\frac{\theta}{2} = \cos^{-1} \frac{R_f + .4t}{R_f + t}$$

The available energy is $V\sigma$. Solving simply for the minimum foam thickness,
 $t = 16$ inches.

An impact on a corner is depicted in the sketch below.

The crush volume can be approximated by an ungula of a right circular cylinder where the volume is given by,

$$V = r^3 \tan \alpha \left[\frac{2}{3} \sin^3 \frac{\theta}{2} - \frac{1}{2} \cos \frac{\theta}{2} (\theta - \sin \theta) \right]$$

Multiplying this equation by the crushing stress, 165 psi, and equating to the potential energy, the effective volume can be iteratively obtained as a function of θ .

The results indicated $h' = 18.26$ inches where $h' = r \left(1 - \cos \frac{\theta}{2}\right) \sin \alpha$.

A deceleration can also be derived. The velocity at the time of impact, $v_i = \sqrt{2 g h_o}$ where h_o is the height of the drop. Also $v_i = \sqrt{2 a h'}$ with respect to the crush displacement. Therefore,

$$a = \frac{h_o}{h'} \quad (\text{in g's})$$

For the corner drop, as an example,

$$a = \frac{30 (12)}{18.26} = 19.7 \text{ g's.}$$

The following represent some additional design considerations:

- a. A denser polyurethane foam may be found more optimum.
- b. Foam coupon testing may be required at the strain rates of interest (associated with the actual velocity at impact).
- c. The shells containing the foam must be structurally evaluated with respect to the force associated with crush-up of foam.
- d. A shock isolator support system will be evaluated.

V. THERMOELECTRIC ANALYSIS

1. Module Design

Design of the thermoelectric module involved the selection of a number of ground-rules for the thermoelectric (T/E) couple. These were:

- a. N-leg TE 1004 PbTe material.
- b. P-leg TAGS with a SnTe segment on the hot side.
- c. SnTe thickness - 0.075"
- d. Total leg length - 0.7"
- e. Cup on P-leg (.004" thick iron cup $\sim$.075" long from hot junction to SnTe-TAGS interface).
- f. Maximum hot junction temperature (T_{HJ}) = 925 °F.
- g. Cold junction temperature (T_{CJ}) = 200 °F at fueling
- h. 28 volts load voltage for the RTG.
- i. Copper connecting straps both hot side and cold side.

This selection was based largely on experience. The 200 °F cold junction temperature represents a value which yields the power/efficiency goal with reasonable heat rejection system weight (see Section VI.2). The thermoelectric module is comprised of a single series circuit of thermoelectric couples which gives good reliability with a minimum number of parts.

To maximize end-of-mission (EOM) power, the thermoelectric module was designed for peak efficiency at EOM. This was done, using a Teledyne Energy Systems' computer code (VT). Our computer code employs basic thermoelectric property data to predict couple and generator performance. A VT computer run was made, using EOM thermoelectric properties, to predict the optimum shape factor (D_N/D_P) and gross load voltage per couple at EOM conditions, see Figure V-1. "Gross" load voltage here means load

Figure V-1. Thermoelectric Performance at 66 Months
Sn Te-TAGS TE1004

voltage across the couple with no adjustment made for the couple interconnecting hardware or hot/cold straps. Note that $T_{\text{hot junction}} (T_{\text{HJ}})$ and $T_{\text{cold junction}} (T_{\text{CJ}})$ are 865°F and 185°F, respectively. These are best estimates of degraded values that were 925°F and 200°F, respectively at fueling.

At this point, the specific RTG design was evaluated for insulation heat loss at EOM. The current concept utilizes nine capsules with a total thermal inventory of 7200 watts. From the insulation heat losses calculated at EOM, the heat available to the thermoelectric module at EOM is:

$$\begin{aligned} Q_{\text{T/E}} &= Q_{\text{Total}} - Q_{\text{Losses}} \\ &= 6308 - 397 \\ &= 5911 \text{ watts} \end{aligned}$$

$$\begin{aligned} \text{where: } Q_{\text{T/E}} &= \text{heat to the T/E} \\ Q_{\text{Total}} &= \text{fuel inventory} \\ Q_{\text{Losses}} &= \text{insulation heat losses} \end{aligned}$$

The fuel inventory (Q_{Total}) is the initial 7200 watt value degraded over 5.5 years, using a Sr-90 half life of 28.8 years. With the optimum $Q_{\text{T/E}}/\text{NA}$ from Figure V-1 of 30.42 watts/in² and the total available $Q_{\text{T/E}}$ of 5911 watts, the required NA or total thermoelectric area is 194.3 square inches. (N is the number of T/E couples and A is the area per couple.) From the desired operating load voltage of 28 volts (net) and the fact that the hot and cold shoe IR loss dictates a gross load voltage of approximately 29 volts, it is evident from Figure V-1 that 360 thermoelectric couples are required to generate the optimum voltage per couple of 0.0805 volts (gross)/couple. Finally, from Figure V-1, since $(D_N/D_P)_{\text{OPT}} = 1.0396$

$$\text{NA} = 194.3 = 360 \left(\frac{\pi}{4} \right) (D_N^2 + D_P^2), \text{ in}^2$$

$$194.3 = 360 \left(\frac{\pi}{4} \right) (1.0396)^2 + 1 D_P^2, \text{ in}^2$$

$$D_P = 0.575 \text{ in.}$$

$$D_N = 0.597 \text{ in.}$$

During the next contractual phase, the thermoelectric module may undergo re-design because of:

- The acquisition of refined thermoelectric properties
- New heat source capsule calorimetry.

Also, if it should become apparent that the demonstration unit will be a unique RTG and future RTG's will be of lesser power, then the thermoelectric module will be redesigned.

2. Projected Performance

Several VT computer code runs were made to predict performance. In these runs several T_{HJ} values were considered at three points in time, viz., fueling (100 hours), 7000 hrs and EOM (5.5 years after fueling), Figures V-2, V-3 and V-4. A computer program was written in BASIC for a Teledyne Energy Systems TEKTRONIX mini-computer which uses these results along with specific design information to:

- Calculate insulation heat losses.
- Determine T_{HJ} , $Q_{T/E}$ and power output.
- Calculate efficiencies: thermal, thermoelectric, strap, system.

This code was used for all performance calculations presented here; it was also used to perform the thermoelectric sizing presented in Section V.1. Basically, the code solves the heat balance equations given in Section V.1.

$$Q_{T/E} = Q_{Total} - Q_{Losses} \quad (V-1)$$

to determine the hot junction temperature. At a discrete time point of 100 hours, 7000

Figure V-2. Sn Te/TAGS-TE 1004 Performance
at 100 Hours

Figure V-3. Sn Te/TAGS-TE 1004 Performance
at 7000 Hours

Figure V-4. Sn Te/TAGS-TE 1004 Performance at 66 Months

hours or 5.5 years, the code determines Q_{Total} from Sr-90 fuel decay, then calculates Q_{Losses} using the insulation thermal conductivity data shown in Figure V-5. Integrated average thermal conductivities are used with one-dimensional heat flow equations to determine insulation heat losses for various regions of the RTG. Table V-1 summarizes these insulation heat losses at fueling and at 5.5 years. Once $Q_{\text{T/E}}$ is determined from equation V-1, then the value of T_{HJ} shown in Figure V-2, V-3 or V-4 that yields the calculated $Q_{\text{T/E}}$ is determined by interpolation. Since Q_{Losses} in equation V-1 are a function of T_{HJ} , the BASIC code iterates until $Q_{\text{T/E}}$ from equation V-1 agrees with the $Q_{\text{T/E}}$ obtained from Figure V-2, V-3 or V-4. Once T_{HJ} is determined, gross power output is obtained from the P/NA data shown in Figures V-2 thru V-4. Net power output is found by subtracting the thermoelectric hot and cold strap I^2R losses. Table V-2 summarizes these results and Figure V-6 is a plot of performance versus time. Note that the fueling T_{HJ} is 921 °F, close to the desired goal of 925 °F. Of most interest is the power output of 503 watts at 5.5 years with a system efficiency of 8.0%. (At two (2) years, these values become 550 watts and 8.2%.) From Table V-2 there is a 108 watt power loss over 5.5 years. Nearly all of this, 100 watts (e), is due to Sr-90 fuel decay; the rest is due to thermoelectric degradation.

Figure V-7 is a VT computer code where the fuel inventory was held constant for either the fueling or 5.5 years case and power output and T_{HJ} were allowed to vary as load voltage was varied. These results are useful in showing:

- (1) The system performance if the user desires to operate at a load voltage other than 28 volts.
- (2) System performance for comparison with voltage parametric test results.
- (3) That T_{HJ} drops 115 °F from 28 volts load to short circuit (< 1 volt operation).

Figure V-5. Thermal Conductivity of Min-K in Argon
(TES Measurements)

TABLE V-1
RTG HEAT FLOW SUMMARY (WATTS)

	<u>Fueling</u>	<u>5.5 Years</u>
Thermoelectric material	6766	5910
Thermoelectric module insulation (Min-K 1800, low k direction)	95	88
Other side insulation (Min-K 1800 low k and high k directions)	258	236
Corner insulation (Min-K 1800 high k direction)	36	33
End insulation (Min-K 1400 low k direction)	45	41
Total	<hr/> 7200	<hr/> 6308

TABLE V-2
RTG PERFORMANCE SUMMARY

	<u>Fueling</u>	<u>5.5 Years</u>
Fuel inventory (watts)	7200	6308
Power output (watts)	611	503
Hot junction temperature (°F)	921	865
Cold junction temperature (°F)	200	185
Fin root temperature (°F)	150	143
Thermoelectric efficiency (%)	9.44	8.82
Thermal efficiency (%)	94.0	93.7
System efficiency (%)	8.49	7.98
Strap efficiency $P_{\text{Net}}/P_{\text{Gross}}$ (%)	95.7	96.6

V = 28 volts

N = 360 thermoelectric couples

$D_N = 0.597$ in., $D_P = 0.575$ in., $L_{T/E} = 0.7$ in.

Gas = 1 ATM Argon

Sink temperature = 80 °F

Figure V-6. Beneficial Uses RTG Performance

Figure V-7. Beneficial Uses RTG Performance

This last effect is useful for storage or transportation under high ambient temperature conditions. In these cases, the generator may be operated on short circuit for indefinite periods of time to reduce T_{HJ} , thus reduce thermoelectric degradation.

VI. THERMAL ANALYSIS

1. Heat Source

Thermal analysis has been performed on the nine-capsule RTG heat source to predict component temperatures for the steady state condition. Finite element analysis was used with the ANSYS computer code. Boundary conditions and major assumptions were as follows:

Heat shield outer surface temperature	1050 °F
Fuel inventory	
Outer eight capsules	800 watts, each
Central capsule	880 watts
Gap, heat shield to capsule strength member	0.020 inch
Gap, capsule strength member to liner	0.055 inch
Gas, heat shield to capsule strength member	Argon
Gas, capsule strength member to liner	Helium or Argon
Surface emissivity on heat shield, strength member, liner	0.2, each

A finite-element portrayal of the two-dimensional model is shown in Figures VI-1, VI-2 and VI-3, with numbered nodal points and $r-\theta$ coordinates indicated. Figure VI-1 is an overall model of the heat source. The view is that obtained by passing a transverse mid-plane through the heat source; only 1/16th of the heat source is needed in the circumferential direction from symmetry considerations. Figure VI-2 is a detailed close-up of the central capsule and Figure VI-3 is a detailed section of an outboard capsule. Materials and their thermal conductivities are summarized in Table VI-1. The model treats both radiation and gas conduction at all gaps.

A computer generated element plot is shown in Figure VI-4. Temperature results are shown in Figures VI-5 through VI-9 as follows:

Figure VI-1. Heat Source Model

Figure VI-2. Central Capsule Model

SCALE 3/1

Figure VI-3. Outboard Capsule Model

3/24/83 7.492 E1

ZU=1

BENEFICIAL USES RTG HEAT SOURCE (1-INCH DEPTH) EPLTANSYS 3

Figure VI-4. ANSYS Element Plot

LINER O.D. GAP: Helium

Figure VI-5. Heat Source Temperatures, °F (°C)

Liner O.D. Gap: Helium

SCALE 5/1

Figure VI-6. Central Capsule Temperatures, °F (°C)

Liner O.D. Gap : Helium

SCALE 3/1

Figure VI-7. Outboard Capsule Temperatures, °F (°C)

Liner O.D. Gap: Argon

SCALE 5/1

Figure VI-8. Central Capsule Temperatures, °F (°C)

Liner O.D. Gap: Argon

SCALE 3/1

Figure VI-9. Outboard Capsule Temperatures, °F (°C)

TABLE VI-1
MATERIALS AND THERMAL CONDUCTIVITIES USED IN ANSYS

<u>Item</u>	<u>Material</u>	<u>Thermal Conductivity (BTU/Ft-Hr °F)</u>				
		<u>400 °F</u>	<u>800 °F</u>	<u>1200 °F</u>	<u>1600 °F</u>	<u>2000 °F</u>
Heat shield	Tungsten alloy	39.6	39.6	39.6	39.6	39.6
Strength member or liner	Hastelloy-C276	7.4	9.4	11.4	13.4	15.4
Gas	Helium	0.118	0.161	0.197	0.232	0.266
Gas	Argon	0.014	0.019	0.024	0.264	0.030
Fuel	Sr-90 F ₂	2.06	1.36	1.00	0.78	0.67

Figure VI-5	Heat Shield
	Argon between heat shield and strength member Helium or Argon between strength member and liner
Figure VI-6	Central Capsule
	Argon between heat shield and strength member Helium between strength member and liner
Figure VI-7	Outboard Capsule
	Argon between heat shield and strength member Helium between strength member and liner
Figure VI-8	Central Capsule
	Argon between heat shield and strength member Argon between strength member and liner
Figure VI-9	Outboard Capsule
	Argon between heat shield and strength member Argon between strength member and liner

Table VI-2 presents a summary of maximum temperatures on each part for each of the two gas fills considered. Present plans call for a final gas fill of greater than 80% helium in the strength member-to-liner gap. Thus, the maximum strength member temperature is judged to be slightly under 800 °C at beginning of life, steady state - an acceptable result.

The analysis, as presented here, is judged to be conservative because it neglects the conductive contribution of the heat shield plugs and it neglects any conduction due to contact of parts at the "gas gaps."

2. Heat Rejection System

The heat rejection system of an RTG must be designed thermally to reject a certain quantity of heat at a desired temperature level. This goal requires a knowledge (or assumption) of certain boundary conditions. In this specific case, for the demonstration unit, the following major assumptions have been made:

TABLE VI-2

MAXIMUM COMPONENT TEMPERATURES (°F/°C)

	<u>Helium*</u>	<u>Argon*</u>
Heat Shield	1189/643	1189/643
Strength member		
Outboard capsule	1258/681	1260/682
Central capsule	1314/712	1315/713
Liner		
Outboard capsule	1309/709	1544/840
Central capsule	1375/746	1627/886
Fuel		
Outboard capsule	1513/823	1771/966
Central capsule	1622/883	1885/1029

*Gas fill between strength member and liner.

- a. Reject heat is 7000 watts.
- b. Heat transfer mode is natural convection to an air environment with no surrounding obstructions.
- c. Ambient air temperature is 80°F
- d. Desired fin root temperature (i. e. housing temperature) is 150°F.
- e. Heat rejection system is made of 6061-T6 aluminum. Vertical rectangular profile fins, 36" high are chosen.
- f. It is desired to limit the diametral envelope by restraining fin width (root-to-tip distance) to twelve inches.

A few remarks will be made on these assumptions. First, the reject heat is the initial fuel inventory less the output power since the fin sizing design point is with the RTG on electrical load; that is, the output power is not part of the heat rejection load. The value of 7000 watts was a best estimate at the time this analysis was done. Subsequent heat source definition has resulted in a heat rejection value of about 6600 watts for the mini-capsule design and so the calculation is slightly conservative.

Natural convection heat transfer is the dominant mode for a finned RTG at this temperature level. A small amount of heat is rejected by radiation but has been neglected. Note that RTG's are commonly used in water environments, soil burial environments, and even with heat pipe assists. For this demonstration unit, the expected environment of air exposure was assumed with air temperature at 80°F.

Fin root temperature selection is usually a tradeoff between system efficiency and fin weight/size. The 150°F value is a reasonable compromise that should yield about an 8% efficient system with less than 1000 pounds of fin weight. The 150°F fin temperature corresponds to a thermoelectric cold junction temperature of about 200°F.

The key remaining fin design variables are number of fins and fin thickness, one of

which can be independently selected. It turns out that 120 fins is a reasonable choice, based on the criteria of moderate fin spacing and low total fin weight. This choice results in a fin thickness of 0.16 inch and a fin efficiency of 78%, both reasonable.

These results are based upon solution of the following equations:

$$h = 0.281 \left(\frac{T_R - \theta}{H} \right)^{1/4} C$$

$$q = 2 h H N b \eta_{fin} (T_R - \theta)$$

$$\eta_{fin} = \frac{\tanh m b}{m b}$$

$$m \equiv \sqrt{\frac{h P}{k A}} \approx \sqrt{\frac{2 h}{k t}}$$

where:

h	=	natural convection heat transfer coefficient in laminar regime
T_R	=	fin root temperature = 150 °F
θ	=	air temperature = 80 °F
H	=	fin height = 3 feet
C	=	correction factor for boundary layer interaction between adjacent fins = 0.98
N	=	number of fins = 120
η_{fin}	=	fin efficiency
b	=	fin width (root-to-tip) = 1 foot
q	=	reject heat = 7000 watts = 23891 BTU/hr
P	=	fin perimeter $\approx 2H$
A	=	fin cross-sectional area $\approx Ht$
k	=	thermal conductivity of 6061-T6 aluminum = 97 BTU/ft-hr-°F
t	=	fin thickness

Solution of these equations yields:

$$h = 0.61 \text{ BTU/ft}^2\text{-hr-}^\circ\text{F}$$

$$\eta_{\text{fin}} = .78$$

$$t = 0.164 \text{ inch}$$

Fin weight totals 850 pounds for the 120 fins.

VII. SHIELD ANALYSIS

Radiation shielding for the RTG is provided by a shield constructed of "tungsten compress" material. Shield component pieces are formed by pressing and sintering a tungsten powder alloy which is greater than 95% pure tungsten and machining the parts to specified dimensions. This technology has been employed for more than a decade for the many Teledyne Energy Systems' SENTINEL RTG's which use strontium fuel forms. Physically, this unit differs from SENTINEL units in that: (1) a number of fuel capsules are used as opposed to a single fuel capsule for SENTINEL RTG's and (2) the larger fuel loading and resultant larger size of the shield necessitates fabrication of the shield body and lid from a number of piece parts as opposed to single pressed units for the SENTINEL body and lid. The basic analysis techniques employed for shield sizing are the same as those applied for SENTINEL units. Additional analysis (discussed below) was performed to assess the effects of multiple capsule units.

1. Shield Design Criteria

RTG shielding is such that the unit is in compliance with DOT and NRC shipping regulations for ground shipment of Type B quantity radioactive material on an open-bed truck. That is, dose rates at the accessible surface of the unit shall not exceed 200 mrem/hr and dose rates at three feet from the accessible surface shall not exceed 10 mrem/hr. For this unit, the accessible surfaces are the external surfaces of the housing above and below the unit and the fin tips to the side of the unit. For design purposes, the external housing surface was assumed to be six inches above or below the shield surface (top and bottom) and the fin extremities were assumed to be fifteen (15) inches from the shield surface (side). (Actual dimensions are somewhat greater.)

Typically, for this size unit, the dose rate which controls shield thickness is the three (3) foot from the surface value. Shield design, is based on a nominal 8 mrem/hr maximum at three feet from the surface.

Transportation regulations also require that, given a series of hypothetical accident conditions (Appendix B, 10 CFR, Part 71), dose rates at three feet from the resultant configuration shall not exceed one rem/hr. Given an intact shield after the accident sequence, the resultant dose rates will be well below the one rem/hr level.

2. Fuel Characterization; Sources of Reduction

Physical properties assumed for the Sr-90 F₂ fuel form are consistent with those quoted for the material as loaded in the WESF capsules currently available.⁽²⁾ The fuel form is 95% Sr-90 F₂ (5% other materials). At the time of loading, the Sr-90 content of the strontium was 55%. As loaded, the fuel was compacted to a density of 3.0 g/cm³ (70% theoretical density) and the nominal loading per capsule was 960 watts corresponding to a power density of 1.04 watts/cm³ or 0.345 watts/g. The half life of Sr-90 is 28.8 years.

Strontium-90 decays by β^- emission to short lived Y-90 which, in turn decays by β^- emission to stable Zr-90. Strontium-90 is a pure beta emitter; Y-90 is effectively a pure beta emitter. Essentially, all of the emitted betas are absorbed within the fuel form. External radiation is in the form of Bremsstrahlung produced during slowing down of the betas in the fuel form. The Bremsstrahlung source spectrum assumed for radiation attenuation calculations is that calculated by Spamer⁽³⁾ for a SrTiO₃ fuel form and scaled to account for additional Bremsstrahlung created in the Sr-90 F₂ form. The adequacy of the spectral prediction was demonstrated by comparison of calculated and measured dose rates from a SrTiO₃ source beyond varying thicknesses of lead shielding. A scale factor of 1.16 was applied to the SrTiO₃ spectrum to account for additional Bremsstrahlung production in Sr-90 F₂.

⁽²⁾BNWL 2284, "Strontium Fluoride Data Sheets," H.T. Fullam, Oct. 1977, Battelle, Pacific Northwest Lab., Richland, Washington, 99352.

⁽³⁾MND-P-2529, "Shielding Kilocurie Amounts of Strontium-90," A.M. Spamer, March 1961, The Martin Co., Baltimore, Maryland.

Attenuation calculations assume a per capsule loading of 800 watts with a fuel density of 3.0 grams/cm³. This corresponds to a loading of 1.19×10^5 curies per capsule

3. Radiation Attenuation, Shield Thickness

Shield calculations account for radiation attenuation within the source material, encapsulating material (Hastelloy-C liner and capsule) and the tungsten compress shield material. The basic calculation uses an energy dependent point-kernel technique to integrate over the source geometry of a single fuel capsule and determine the dose rates at selected points beyond the shield material. Ten energy groups ranging from 0.11 to 2.09 Mev span the Bremsstrahlung energy range. Energy dependent gamma absorption coefficients used are derived from basic NBS elemental data.⁽⁴⁾ Energy dependent infinite medium buildup factors (point isotopic, dose) for tungsten are included in the kernel to account for the effects of scattered radiation. Single capsule-shield geometry is essentially exact. Dose rates from a single capsule at the selected distances beyond the shield surface as a function of shield thickness are as shown in Figures VII-1 and VII-2.

Above or below the shield, the cumulative dose rate from multiple capsules will be nearly equal to the product of the dose rate from a single capsule and the number of capsules employed. Hence, the required shield thickness to achieve the 8 mrem/hr dose rate at three feet from the exterior surface (42 inches above or below the shield surface) is found by applying a factor of 9 to the data of Figure VII-1. The required shield thickness of 3.66 inches is then read directly from the resultant curve.

To the side of the unit, actual dose rates are significantly less than that which would be produced by nine individually shielded capsules. A series of additional point kernel type integrators were employed to estimate the contribution to the dose rate from

⁽⁴⁾NSRDS-NBS 29, "Photron Cross Section, Attenuation Coefficients and Energy Absorption Coefficients from 10 keV to 100 GeV," J.H. Hubball, Aug. 1969, National Bureau of Standards.

FIGURE VII-1. TOP OR BOTTOM DOSE RATES AS A FUNCTION OF SHIELD THICKNESS

FIGURE VII-2. SIDE (RADIAL) DOSE RATES AS A FUNCTION OF SHIELD THICKNESS

capsules other than those closest to the dose point. These calculations accounted for additional shield material and intertwining source material resultant from the actual source/shield geometry. The calculations indicated that the actual maximum dose rate to the side of the nine capsule unit would be no more than 2.1 times the dose rate from a single capsule. Applying the factor to the single capsule dose rate of Figure IV-2 yields the required shield thickness of 3.84 inches. As defined herein, the radial shield thickness is the minimum tungsten thickness required between any of the eight periphial capsule holes and the external surface of the shield. The estimate assumes the geometry of Figure IV-2 for the nine capsules.

Shield thicknesses and resultant maximum dose rates are as summarized below:

	Tungsten- compress Required Shield Thickness (inches)	Dose Rate (mrem/hr)	
		<u>Surface</u>	<u>3 Ft from Surface</u>
Top or bottom	3.66	115	8.0
Side	3.84	47	8.0

U-8 moly (uranium, 8% molybdenum by weight) was also considered as a shield material. This alloy is more efficient for attenuation of the Bremsstrahlung radiation. Required shield thicknesses, as defined above, and resultant maximum dose rates are as follows:

	Required Shield Thickness (inches)	U-8 Moly (17.5 g/cm ³) Dose Rate (mrem/hr)	
		<u>Surface</u>	<u>3 Ft From Surface</u>
Top or Bottom	3.08	122	8.0
Side	3.23	48	8.0

Here again, capsule/shield geometry is as in Figure IV-2.

4. Adequacy of the Estimate

Generally, as applied to single capsule SENTINEL units, the shield design technique tends to be conservative. Measured maximum radial dose rates at three feet from the surface of these units range from near the design value to about one-half of the design value. Measured dose rates directly above the SENTINEL units tend to be significantly lower than the design value because of additional attenuation from the thermoelectric module which for the SENTINEL is mounted above the shield. This RTG has side mounted thermoelectric modules which partially cover the shield and may tend to further reduce the actual dose rates to the side of the unit. Actual dose rates above or below the unit are expected to be nearer the nominal computed value.

To assure compliance with the transportation regulations, final shield design should be based on actual fuel density and the upper limit to the fuel loading per capsule. Additionally, the upper limit of other gamma emitting radioisotopes in the fuel form should be determined and specified since their presence may influence shield requirements.

5. Structural Analysis of Shield

As stated previously, the shield body and lids will be fabricated as piece parts and brazed together with a copper braze material. Because of our inability to locate structural data for copper-brazed cold pressed and sintered 95W - 5 Fe Ni alloy, we were unable to perform stress analysis on the shield. The vendor for the shield has agreed to fabricate several brazed test specimens and determine their mechanical properties. Shield stress analysis must await these data.

VIII. PROGRAM SCHEDULE

Figure VIII-1 shows the program schedule. The detailed design, fabrication, fueling, and testing of the RTG will be concluded in a twelve-month period with a thirteenth month scheduled for the final report that will include a reduction of the RTG test data that will have just been concluded.

Figure VIII-1

TES-3170

ATTACHMENT A

HEAT SOURCE SPECIFICATION

500 WATT(e) RTG

TES-3164

REVISION B

April 1983

1.0 SCOPE

1.1 General

This specification establishes the requirements for the radioisotope fuel and its encapsulation for application in a 500 Watt(e) thermoelectric generator.

1.2 Description

The completed heat source assembly consists of the fuel in the form of sintered agglomerates of irregular granule size, or cylindrical pellets fabricated by hot pressing techniques, or cast in-place billets, sealed in the Waste Encapsulation and Storage Facility (WESF) inner capsule or liner, which, in turn is inserted and sealed in an outer strength member. The inner capsule, or liner, serves only as a compatible containment barrier for the fuel and facilitates contamination control for the subsequent assembly. The outer strength member provides the structural integrity and oxidation and corrosion resistance to prevent release of the isotope in specified accident situations.

2.0 APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form a part of this specification to the extent specified herein. In the event of conflict between this specification and the documents referenced herein, the requirements of this specification shall govern.

2.1 Specifications and Standards - of the issue in effect on the date of this specification.

ASTM E-493, "Test Method for Leaks Using the Mass Spectrometer Leak Detector in the Inside-out Mode."

ASME Boiler and Pressure Vessel, Code V, "Non-destructive Examination."

American National Standard N542; "Sealed Radioactive Sources, Classification."

2.2 Drawings - (Teledyne Energy Systems) of the latest issue in effect at time of fuel encapsulation:

 BUP-01-0003 Proposed outer strength member WESF capsule - 500
 Watt RTG.

3.0 REQUIREMENTS

Each heat source assembly and its components shall meet the requirements of this section.

3.1 Fuel

The basic fuel, for purposes of this specification, shall be the radioisotope strontium-90.

3.1.1 Chemical Form

The fuel shall be in the sintered fluoride form ($^{90}\text{SrF}_2$).

3.1.2 Fuel Composition

The fuel composition, for purposes of this specification, shall be $^{90}\text{SrF}_2$ as synthesized and stored at the WESF at Richland, Washington. The WESF $^{90}\text{SrF}_2$ is precipitated and further processed from a feed solution whose composition is given in Appendix A.

3.1.3 Fuel Quantity

(B) The total quantity of strontium-90 per RTG loading shall be TBD watts $\pm$ TBD watts. This quantity is to be achieved by selecting individual heat sources with previously measured thermal inventories that total to the desired range. Heat source thermal inventory is to be determined by source calorimetry. The absolute thermal inventory is to be measured to within TBD %.

Note - This requirement does not apply to the demonstration RTG unit.

3.2 Heat Source Components

3.2.1 Fuel Liner Assembly and Components

The liner or inner capsule assembly and components are those currently being utilized in the existing WESF storage capsule. The inner capsule is fabricated from 'Hastelloy C-276' alloy to the dimensions shown in Figure 3-1. The new heat source assembly covered by this specification uses the existing WESF inner capsule without modification.

Quality Control measures and acceptance criteria governing the WESF inner liner are not part of this specification and are assumed to be as specified by the appropriate WESF Facility personnel.

Dimensions of the WESF $^{90}\text{SrF}_2$ Hastelloy C-276
Inner Capsule

3.2.2 Strength Member Assembly and Components

The strength member assembly or outer capsule consists of a housing and two end caps. One end cap is tapped to accept a capsule "Handling Knob" used to lower the capsules into an RTG shield. The other end cap is machined to accept a tapered pin, which is to be welded in place after backfilling the void between inner and outer capsules with helium. The helium serves both to aid in the heat transfer and to facilitate leak testing. Component dimensions are depicted on TES Dwg. BUP-01-0003.

3.2.2.1 Materials

The strength member housing, end caps and taper pins are to be fabricated from "Hastelloy" Alloy 'S' procured in the solution heat treated condition and certified to AMS-5711. Hastelloy Alloy S is a nickel-base, high-temperature alloy with the desired combination of properties produced by Cabot Corporation, Kokomo, Indiana.

3.2.2.2 Qualification Testing

Prior to use in an RTG, the new outer strength member must be subjected to "Special Form" testing as a minimum requirement for licensing. The recommended strength member qualification test requirements are specified separately in Appendix B. The tests described in Appendix B shall be applied to samples or prototype capsules to qualify the capsule design. Subsequent to satisfactory conclusion of the tests, quality control measures must be carried out during production of capsules for operational use to ensure that the standards achieved by the test specimens are maintained.

3.3 Heat Source Assembly

The complete heat source assembly, for purposes of this specification, consists of the $^{90}\text{SrF}_2$ fuel with a nominal thermal inventory of TBD watts, sealed within a Hastelloy C-276 inner capsule or liner, which, in turn is inserted into and sealed within a Hastelloy S outer strength member. This heat source utilizes the existing WESF inner capsule design and specifications

governing the fabrication and testing of the inner capsule are not included as part of this specification. Prior to inserting the inner capsule into the strength member, one end cap of the strength member must be welded in place, as a sub-assembly. This initial weld need not be a remote weld but should be accomplished and tested in accordance with Section 3.4 prior to insertion into the final heat source weld facility. The inner capsule is to be inserted in a clean outer strength member and some degree of thermal equilibrium, as established by development testing, achieved prior to welding in the second end cap. Welding of the end cap is to be in accord with Section 3.4 herein. Following completion of the end cap weld, the capsule should be evacuated and backfilled with helium, through the small tapered hole provided in one end cap. The helium fill, as demonstrated in weld development tests shall be 80% minimum. The close fitting tapered pin is then to be inserted and seal welded in place. Minimum weld penetration of the end cap weld is to be as specified on TES Dwg. BUP-01-0003.

3.3.1

Identification

Each outer capsule body and both end caps of the completed heat source are to be identified by a serial number, unique to each heat source, applied in a permanent manner (electro-chemical etch, metal stamp or vibro-etch).

3.3.2

Heat Source Surface Contamination

Removable radioactive contamination of the exterior surfaces of the completed heat source assembly shall not exceed 10,000 DPM per 100 square centimeters as determined by a wipe test in accordance with para. 4.3.1.

3.4

Welding

The method of welding the heat source assembly (TIG, plasma arc or electron beam) shall be at the discretion of the encapsulating facility provided sufficient penetration (see TES Dwg. BUP-01-0003) and the additional requirements of this section are satisfied.

3.4.1 Welder and Welding Operator Qualification

To insure that production heat sources meet the requirements of this specification, a Quality Assurance Plan is to be prepared by the fueling facility. The Quality Assurance Plan should include current specifications and engineering drawings, written operating and test procedures, and the training of competent personnel. The Quality Assurance Plan shall, in general, comply with the intent of ANSI-N542 - Appendix B.

(A)

3.4.2 Weld Testing

All outer strength member weld joints shall be welded using processes, welders and/or welding operators qualified under Section 3.4.1. All weld joints shall be subjected to the following tests:

A. Helium Leak Test -

The completed heat source assembly is to be leak tested in accordance with ASTM E-493 "Test Methods for Leaks using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode" "American National Standard N542; Sealed Radioactive Sources, Classification" - Paragraph A.2.25 "helium sealing test or an equivalent, acceptable helium leak test method.

(A)

B. Ultrasonic Tests

All welds except the tapered pin weld shall be tested to determine the depth of weld penetration and weld integrity. The weld joints are to be tested in accordance with ASME Boiler and Pressure Vessel Code, Section V "Nondestructive Examination," Appendix 12 "Ultrasonic Examination of Welds or an Equivalent Ultrasonic Pulse-Echo Examination.

(A)

3.4.3 Weld Acceptance Criteria

All welds, when tested in accordance with para. 3.4.2 herein, shall meet the following criteria:

- A. Leakage - The leak rate on tested heat source assemblies shall not exceed 1×10^{-7} STD cc/sec helium.

- B. Penetration - The weld penetration shall not be less than that specified by TES Dwg. BUP-01-0003.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 Inspection System Requirements

The Fueling Facility shall establish and maintain a system of Quality Control Inspection and Documentation to verify compliance with the requirements of of this specification and the appropriate Teledyne Energy Systems drawings.

4.2 Certification

The Fueling Facility shall certify, in writing, the following items:

- a. Fuel Chemistry - The fuel contained in the completed fuel capsules has been processed from feed solution that complies with the composition shown in Appendix A.
- b. Fuel Quantity - The quantity of fuel in thermal watts as measured by source calorimetry and the possible error tolerance.
- c. Outer Capsule Weld Quality - Outer capsule welds shall comply with the requirements of para. 3.4.3 as established by testing in accordance with para. 3.4.2.
- d. Surface Contamination - The completed fuel capsule shall comply with the requirements of para. 3.3.2 established by testing in accordance with para. 4.3.1.

4.3 Testing

Tests performed by the Fueling Facility to verify conformance with the requirements specified herein shall be as follows:

4.3.1

Wipe Test - Removable contamination on the exterior surface of the completed capsule shall be evaluated using the wipe technique as follows:

- a. Wipe an absorbent paper/asbestos Health Physics wipe with moderate pressure over an area of approximately 100 square centimeters. Wipes should cover the weld and surface, the body area and the capsule bottom.
- b. Evaluate the wipes in a calibrated, shielded detector scaler assembly. Results shall be reported as DPM per 100 cm².

4.3.2

Leak Test

Testing of all completed heat source assemblies shall be performed in accordance with ASTM E-493 "Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the inside-out Testing Mode," "American National Standard N 54-2; Sealed Radioactive Sources, Classification" paragraph A.2.25 helium sealing test or and equivalent, acceptable helium leak test method.

(A)

4.3.3

Ultrasonic Examination

Heat Source Weld Joints (except tapered pin weld) are to be examined in accordance with a procedure prepared by the Fueling Facility to encompass the intent of ASME Boiler and Pressure Vessel Code, Section V, "Non-Destructive Examination" - Appendix 12 "Ultrasonic Examination of Welds or an Equivalent Ultrasonic Pulse-Echo Examination.

(A)

4.3.4

Heat Source Calorimetry

The thermal inventory of each completed heat source shall be determined in accordance with a procedure prepared or developed by the Fueling Facility.

4.4

Non-Compliance Items

Any item which does not comply with the requirements or Quality Assurance provisions of this document or the appropriate Teledyne Energy Systems drawing shall be properly documented and submitted to a Review Board. This Review Board is to be established to review these discrepant items to determine the cause of event, to propose corrective action to prevent recurrence, and to determine the disposition of affected hardware. The operation of this Review Board is to be defined by the Fueling Facility.

4.5

Deliverable Data

The following data items shall be delivered by the Fueling Facility to Teledyne Energy Systems covering all heat sources used in the 500 watt RTG:

- a. Fuel chemistry certification (4.2a)
- b. Fuel quantity certification (4.2b)
- c. Leak rates as measured (4.3.2) on applicable capsules
- d. Verification of compliance to Sections 3.4.3 and 3.3.2
- e. Verification of process controls on welding and leak testing.

APPENDIX A

Rockwell
International

Atomica International Division
Rockwell Hanford Operations
P.O. Box 800
Richland, WA 99352

DEC 1 1977

Mr. W. A. McDonald
Teledyne Energy Systems
110 West Timonium Road
Timonium, Maryland 21093

Reference: Letter, October 18, 1977, J. H. Roecker to
W. A. McDonald, same subject

Dear Mr. McDonald:

Strontium Fluoride

We understand you need to have information over and above that which was provided in the attachment to reference letter. This is provided below.

Composition of Feed to Strontium Encapsulation

<u>Ions</u>	<u>Ion/Sr Ratio*</u>
Total Trivalent Cations (Fe, Cr, RE, Al)	$\leq 7 \times 10^{-3}$
Total of Mg, Ba, Ca Cations	≤ 0.10
Pb	$\leq 3 \times 10^{-4}$
Cd	$\leq 3 \times 10^{-4}$
Mn	$\leq 3 \times 10^{-4}$
SO ₄ ⁼	$\leq 7 \times 10^{-2}$
⁸⁹ Sr + ⁹⁰ Sr	≤ 0.66
⁹⁰ Sr Range 45-51 percent	

*All analytical data reported as a "less than" value will be considered zero.

Very truly yours,

J. H. Roecker
Program Manager
Waste Management

JHR/LIB/mm

cc:

W. C. Johnson, Jr. - DOE-RL
H. T. Fullam - BNW

APPENDIX B

RECOMMENDED OUTER STRENGTH

MEMBER QUALIFICATION TESTING

1.0

INTRODUCTION

A Radioisotope-Fueled Thermoelectric Generator (RTG) is a device in which heat given-off by the decay of a radioactive fuel is transmitted through a number of thermoelectric couples where a portion of the heat is converted to electrical energy. In order to obtain proper Nuclear Regulatory Commission (NRC) Licensing for approval to transport an RTG, the heat source or fuel capsule must meet certain environmental, test and hypothetical accident conditions as specified in a number of national and international guides and regulations. The 500 watt RTG is designed to utilize the existing Waste Encapsulation and Storage Facility (WESF) $^{90}\text{SrF}_2$ inner capsule, but with a new outer strength member designed to meet all applicable licensing requirements. Much use was made of the work performed at Battelle's Pacific Northwest Laboratory (PNL) (Ref. 1), both in material selection and general sizing of the outer strength member.

2.0

DESIGN PARAMETERS

The major design constraint imposed on the outer strength member was that it accept the existing WESF inner capsule as is. An added constraint is that the outer capsule meet the qualification test requirements without support from the inner capsule.

The outer strength member is designed to withstand an external hydrostatic pressure of 24,500 psi and this requirement has a profound effect on capsule design. This capability has been demonstrated analytically in Ref. 2. The design criteria such as impact, percussion, puncture, heating, and thermal shock requirements are readily verified by testing, but verification without testing requires complex analytical treatment.

2.1

DESIGN CONFIGURATION

The outer strength member assembly and components are shown on TES Dwg. BUP-01-0003. The assembly consists of a housing and two similar

threaded end caps. The end caps are designed to "bottom" on a shoulder machined in the housing and to be flush with the housing top or bottom surface. The end cap/housing interface is a joint suitable for TIG, plasma arc, or electron beam welding. The joint, as presently configured, assumes that the weld penetration can be obtained without the use of filler wire. The shoulder area is capable of withstanding the external pressure and the threads provide the degree of "fixity" needed to minimize the weld penetration required. This type of end cap closure has been used successfully on capsules tested to 15,000 psi external hydrostatic pressure. The selected end cap design is much simpler to fabricate than the one designed in Ref. 1 and the threads reduce shear stresses in the weld joint to acceptable limits.

All strength member components are to be fabricated from Hastelloy Alloy S bar stock procured in the solution heat treated condition. Because of the length of the housing and the required tolerances on the ID, the double end cap design has a fabricability advantage when compared to a single end cap design.

3.0

QUALIFICATION TESTS RECOMMENDED FOR OUTER STRENGTH MEMBER

The following tests are recommended for qualifying the outer strength member.

- A. Pressure Test - The outer strength member shall be shown to resist an external pressure of 14,500 psi (1000 Bar).
- B. Impact Test - The capsule shall be shown to resist a free drop through a distance of 9 meters (approximately 30 ft) on to a flat essentially unyielding horizontal surface, striking the surface in an orientation as to suffer maximum damage. This test should be performed with an inner capsule or simulated inner capsule in place since such may add to possible damage to the strength member.
- C. Percussion Test - The outer strength member shall resist the impact of the flat face of a steel billet 2.5 centimeters (1 inch) in diameter with the edges rounded off to a radius of not less than 3 millimeters dropped through a distance to produce an impact equivalent to that resulting from the free fall of 7 kilograms through 1 meter. The outer

strength member shall be placed on a sheet of lead, of hardness number 3.5 to 4.5 on the Vickers scale, and not more than 25 millimeters (approximately 1 inch) thick, supported by a smooth essentially unyielding surface.

- D. Thermal Test - The outer strength member shall retain its integrity after being heated to a temperature of 800°C (1472°F) and held at that temperature for a period of 30 minutes before being allowed to cool.
- E. Thermal Shock Test - The outer strength member shall retain its integrity after being heated to 800°C (1472°F) or the maximum operating temperature and then plunged into a 50% by volume water-ethylene glycol solution at 0°C (32°F) where it shall be left for 10 minutes.

A different sample may be used for each of the tests defined.

3.1

Acceptable Criteria

Following each of the tests shown in Para. 3.0, the capsule must show a helium leak rate of less than 1×10^{-7} STD cc/sec helium when tested in accord with any commonly accepted leakage test.

The tests outlined in Para. 3.0 are those defined by current Federal and International Regulations pertaining to a "Package" license for transport.

The PNL report (Ref. 1) states that the American National Standards Institute (ANSI) has defined certain qualification test requirements for sealed radioactive sources which could be adapted in the future as Federal Standards. The pertinent requirements are:

- A. A 20 kg-m percussion test
- B. A 24,500 psi external hydrostatic pressure test
- C. A 1 kg-m puncture test

The proposed outer strength member has been designed to meet requirement B, that requirement deemed to affect the design in the most significant manner.

Indeed it could possibly pass the remaining requirements as well. However, testing to requirements which do not exist would not be justified at this time.

Following the successful completion of the tests herein, the 500 watt RTG license applicant can claim that the $^{90}\text{SrF}_2$ material meets "Special Form Requirements" without additional heat source testing.

REFERENCES

1. PNL-3923, " Design and Qualification Testing of a Strontium-90 Fluoride Heat Source," H. T. Fullam, August 1981.
2. TES-Memorandum-BU-FAS-004, " Structural Analysis of the Fuel Capsule; 500 W Sentinel RTG," F. Schumann, 21 January 1983.