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**Design, Testing and Fabrication
of Heat Sources for
Underwater Application**

D. F. Luthy and C. G. Anderson

November 5, 1975

Research and Development Report

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Design, Testing and Fabrication of Heat Sources for Underwater Application

D. F. Luthy and C. G. Anderson

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SUMMARY

The sequence of events in the design, testing and fabrication of a radioisotopic heat source using available plutonium-238 dioxide fuel that would be amenable to a Navy 0.5-W (electrical) Radioisotopic Thermoelectric Generator for undersea application is discussed. Various designs were considered as a function of heat leak in order to adopt the most desirable capsule for a volume-constrained application. Testing considerations are discussed for capsule compliance with IAEA/ENEA Safety Series 6 and 33 and 10CFR71.

INTRODUCTION

In early 1973 Mound Laboratory initiated a study for the U. S. Navy to determine which of the presently available plutonium-238 fuel forms, and which method of encapsulating that fuel form, could be used most economically in a volume-constrained, undersea application.¹ In April the U. S. Navy asked Mound Laboratory to perform a parametric study for the design of a radioisotopic heat source amenable to a Navy 0.5-W (electrical) Radioisotopic Thermoelectric Generator (RTG), with the fuel form, capsule design philosophy, and materials of construction to be consistent with the original study initiated in 1973.

This paper discusses the sequence of events, requirement considerations, and major assumptions made in the design, fabrication, and testing of a heat source to meet the requirements of that request.

CAPSULE DESIGN CONSIDERATIONS

Several capsule designs were considered to meet the specifications (Table 1), with the most serious consideration given to those shown in Figure 1. Data were computed for internal length/diameter (L/D) ratios from 1 to 7.59 and total thermal output from 12 to 32 W. Data were plotted (see Figure 2) for heat leak versus L/D ratio (outside) for the different capsule designs at a thermal output of 16 W. The design having both ends flat (FF) and the one having both ends hemispherical (RR) were eliminated because of their greater heat leak. Furthermore, from this plot (Figure 2) the optimum L/D ratio for minimum heat leak was determined to be between 1.75 and 2.0.

In Figure 3 the FR capsule design is considered for heat leak at several thermal output levels as a function of L/D ratio. This plot shows that the selection of a constant clad outside diameter of 0.980 in. (2.49 cm) and a constant strength member wall thickness of 0.032 in. (0.081 cm) for optimum heat leak from 12 to 20-W levels would be a definite and desirable possibility. Because the final thermal output required was unknown and

FIGURE 1 - Capsule types.

Table 1

HEAT SOURCE DESIGN SPECIFICATIONS

Thermal Output:	Varies from 12 to 24 W (thermal), depending on requirements of RTG contractors.
RTG Dimensions:	Maximum external diameter of 1.60 in., maximum length of 6.0 in.
Operational Temperature:	400°C
Operational Life:	15 yr
Fuel:	Substoichiometric plutonium dioxide ($^{238}\text{PuO}_{2-x}$)
Capsule Requirements:	<p>Withstand test conditions specified in 10CFR71 and International Atomic Energy Agency (IAEA) Safety Series No. 6 and No. 33.</p> <p>Containment of fuel within for approximately ten half-lives.</p> <p>Fueled capsule to withstand an 800°C fire test for 0.5 hr after imposing conditions equal to a 20-yr-life capsule pressure at an operating temperature of 300°C.</p> <p>Capability to withstand fuel degradation, ten half-lives of interaction with seawater, and ten half-lives of interaction with fuel.</p> <p>Capability to withstand atmospheric degradation for ten half-lives when fueled.</p>

could vary according to the contractor design, an approach was made employing the use of a constant outside diameter and the selection of various lengths to accommodate the required contractor thermal output. This permitted early initiation of hardware fabrication. This standardization was a necessary choice considering the time period of scarcely 10 mo from design to required delivery of demonstration units to several RTG contractors.

Using these constant dimensions, feasible heat source parameters were calculated as shown in Table 2. Compilation of the pressure-stress-creep rupture data by computer analysis for a 0.032-in. (0.081-cm) strength member wall resulted in the increase of the wall thickness to 0.037 in. (0.094 cm) for increased safety margin.

Calculation of the fire test safety factor for the 18-W capsule after a 15-yr life supports the selection of the 0.037-in. (0.094-cm) wall thickness (see Table 3).

Table 2
NAVY CAPSULE PARAMETERS (FR TYPE)

Thermal Power (W)	Power Density ^a (W/cm ³)	Length/Diameter (Outside)	Clad Diameter Outside (in.)	Liner Diameter Inside (in.)	Clad Length Outside (in.)	Liner Length Inside (in.)	Strength Member Wall (in.)	Q ^b Heat Leak (W)
12	1.85	1.409	0.980	0.728	1.381	1.081	0.032	4.27
16	1.85	1.735	0.980	0.728	1.701	1.401	0.032	5.15
20	1.85	2.062	0.980	0.728	2.021	1.721	0.032	6.04
24	1.85	2.80	0.980	0.728	2.341	2.041	0.032	6.93

P = constant = NRT/V_v = 4680 psi at 20 yr and 800°C

S_u (1/2 hr @ 800°C) = 85,000 psi; SF = 1.21 @ 20 yr (S.M. only)
1.56 @ 15 yr (S.M. only)

S_a = 70,000 psi, design stress (S.M. only)

^aIncludes void volume.

^bUsing $\Delta T = 250^\circ\text{C}$; $K = 0.00085 \text{ W-in./in.}^2\text{-}^\circ\text{C}$; insulation o.d. = 1.6 in.

Table 3

FIRE TEST SAFETY FACTOR FOR AN 18-W CAPSULE

This safety factor is calculated at 800°C for 0.5 hr after a 15-yr operational life. The strength member has a 0.037-in. (0.094-cm) wall thickness and a 0.782-in. (1.98-cm) internal diameter.

Fuel Loading

Power density for ^{238}Pu = 0.576 W/g

$$\frac{18}{0.576} = 31.25 \text{ g of } ^{238}\text{Pu}$$

Moles of ^{238}Pu

$$N_0 = \frac{^{238}\text{Pu Weight}}{\text{Atomic Weight}} = \frac{31.25}{238} = 0.1313 \text{ mole of } ^{238}\text{Pu}$$

Moles of Helium Produced in 15 yr

$$\begin{aligned} N &= N_0 (1 - e^{-\lambda t / t_{1/2}}) \\ &= 0.1313 [1 - \exp(-0.693 \times 15 / 87.4)] \\ &= 0.0147 \text{ mole of helium after 15 yr} \end{aligned}$$

N = Moles of helium
 N_0 = Moles of ^{238}Pu
 λ = 0.693
 t = Time in years
 $t_{1/2}$ = Half-life of ^{238}Pu
 $\quad$ = 87.4 yr

Pressure in Capsule after 15 yr

$$\begin{aligned} P &= NRT/V_V \\ &= 0.0147(82)(1073)/5.378 \\ &= 240.5 \text{ atm} = 3535 \text{ psi} \end{aligned}$$

V_T = Total volume in capsule
 $\quad$ = 9.81 cm³
 V_V = Void volume in capsule
 $\quad$ = 5.378 cm³
 R = Gas constant = 82
 T = Temperature = 800°C = 1073 K

Actual Stress

$$\begin{aligned} S_a &= K_C \times \frac{D_{sm}}{2t_{sm}} \times P \\ &= 1.42 \times \frac{0.782}{2(0.037)} \times 3535 \\ &= 53,060 \text{ psi} \end{aligned}$$

P = Internal pressure
 D_{sm} = Strength member diameter
 t_{sm} = Wall thickness
 K_C = 1.42 corner stress concentration factor*

Ultimate Stress

$$S_u = 97,000 \text{ psi}$$

Safety Factor

$$SF = S_u / S_a = 97,000 / 53,060 = 1.83$$

* K_C = empirically determined and experimentally verified as dependent upon the ratio of cap thickness to wall thickness.

FIGURE 2 - Heat leak as a function of L/D ratio for several types of capsule design (16 W total), with a design stress (S_a) value of 70,000 psi and insulation external radius value (C) of 0.80 in.

SAFETY TESTING

For the purpose of assuring the validity of the heat source design, four thorium-fueled heat sources fabricated to final design specifications were subjected to tests as outlined in Table 4.

After each test, the capsules satisfactorily passed a 10^{-4} cm³/sec helium leak test. After the testing series was completed each capsule underwent a post-mortem examination which substantiated that all capsule components were intact and there had been no breach in any member.

Five strength members were pressurized in excess of the 20-yr-life capsule pressure at an operating temperature of 300°C and given a simulated fire test at 800°C in excess of 0.5 hr. All five strength members satisfactorily passed this test.

FIGURE 3 - Optimum heat leak levels for type FR capsules as a function of L/D ratio using a design stress (S_d) value of 70,000 psi and insulation external radius (C) value of 0.80 in.

HEAT SOURCE FABRICATION

Fabrication of the components was initiated after finalization of the heat source design.

Fuel Preparation

The plutonium-238 dioxide fuel was precipitated as a hydroxide and was allowed to convert to a hydrous oxide by self-heating. The hydrous oxide was then crushed and sized to the desired 53-500 μm particle size. The fuel was then weighed into the required fuel charges and calorimetered for verification.

Table 4

CAPSULE SAFETY TESTS

Item	Test	Test Description	Test Requirement Source
1	Impact Test ^a	A 9-m (29.53-ft) drop of the capsule at room temperature, then at operating temperature on an unyielding surface.	IAEA/ENEA Safety Series 33 Appendix I, 2.1
2	Percussion Test ^a	A 7-kg (15.44-lb) drop of a steel bar 2.5 cm (0.98 in.) in diameter from a height of 1 m (39.4 in.) with its flat end hitting the capsule at room temperature, then at operating temperature, while the capsule is resting on lead sheet on an unyielding surface.	IAEA/ENEA Safety Series 33 Appendix I, 2.2
3	Thermal Test	A hot soak of capsule at 800°C for 30 min.	IAEA/ENEA Safety Series 33 Appendix I, 2.3
4	Thermal Shock	Heat capsule to operating temperature and plunge it into 0°C water and cool for 10 min.	IAEA/ENEA Safety Series 33 Appendix I, 2.4
5	Immersion Test	Immerse capsule in water at a pressure equivalent of 15 m (21.5 psig) for 24 hr.	IAEA/ENEA Safety Series 6 Section VII, 721 & 10CFR71
6	Pressure Test	Apply external pressure of 1000 bars (14,700 psig) to the capsule.	IAEA/ENEA Safety Series 33 Appendix I, 2.5
7	Leakage Test	A helium leakage test shall show no more than 10^{-4} cm ³ /sec (STP) after the testing equipment has been calibrated with a 10^{-8} cm ³ /sec (STP) range standard leak. This test will be made after each of the above tests.	IAEA/ENEA Safety Series 33 Appendix I, 2.6 Reg. Guide 6.3, Section C
8	Fire Simulation Creep Rupture Test	A minimum of five strength members will be internally pressurized to the 20-yr-life capsule pressure at an operating temperature of 300°C and given a simulated fire test at 800°C for 0.5 hr.	IAEA/ENEA Safety Series 33, Design Conformation

^aRoom temperature for these tests is defined as 18 to 29°C, and operating temperature as 400°C.

Hardware Fabrication

The liner and strength member bodies were fabricated from T-111 sheet stock by a three-step deep draw operation with a cleaning and annealing step between each draw. The parts were turned on a lathe for uniformity, inspected, cleaned, and outgassed.

The clad bodies were fabricated from Hastelloy C-276 by a three-step deep draw operation with a cleaning and solution annealing step between each draw. The parts were turned on a lathe for uniformity, inspected, cleaned, and outgassed.

The liner shims were blanked from T-111 sheet stock. The liner and strength member caps were also blanked from T-111 sheet stock and steps were machined into them. The clad cap was turned from Hastelloy C-276 sheet stock. In addition to machining of the step in the lid, the clad lids were faced off to control flatness which was required for final assembly. All caps were inspected, mated to bodies, cleaned, and outgassed accordingly.

Encapsulation

The plutonium-238 dioxide fuel charges are loaded into the liner body and blended with yttrium in the ratio 0.136 g of yttrium per watt of $^{238}\text{PuO}_2$ (reference 2). After welding and leak checking of the liner and strength member subassemblies, the heat sources are pretreated for 1 hr at 1350°C in a vacuum before being welded into the Hastelloy C-276 clad. The pretreatment of the fuel in the presence of an oxygen getter (yttrium) produces an improved substoichiometric plutonium dioxide ($^{238}\text{PuO}_{1.75-1.80}$). Therefore, the fuel becomes less oxidizing to the refractory metal liner and minimizes embrittlement.

The entire assembly and encapsulation procedure is performed in a helium-controlled atmosphere, with gas-tungsten arc weld (GTAW) used for all welds.

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R. P. Ratay, Editor