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Design Development and Testing of 60-Watt Capsules

Joseph D. Ruhkamp

September 27, 1995

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Abstract

To satisfy the safety requirements of a terrestrial 60-watt radioisotope heat source, it was necessary to determine whether the internal pressure buildup from the helium generated from Pu-238 decay would pose problems in a fire environment. Nine strength members (capsules), three of the end-cap weld design and six of the girth weld design, were pressure-burst tested. The end-cap weld design was not successful, with failure times of less than three minutes. The girth weld design gave favorable results, with life times ranging from 8 to 240 hours. All of the girth weld capsules failed in the center of the weld. The Oak Ridge National Laboratory stress rupture model equation for determining test life does not predict the test hours to failure for the girth weld design.

Introduction

The object of these tests was to determine the creep rupture properties of the 60-watt strength member and to confirm the Teledyne Brown model of rupture time as a function of stress and temperature for T-111 alloy. The test capsules were pressurized with helium at room temperature and heated to test temperature in a vacuum furnace. Time, temperature, capsule pressure, furnace vacuum, and helium partial pressure were the parameters monitored until capsule failure.

There were two strength member designs, end-cap weld and girth weld. The first three tests, which were unsuccessful, were of capsules with the end-cap weld design. The remaining six tests, which gave favorable results, were of the girth weld design.

During the first tests it was determined that the ideal gas law was not appropriate for use in this pressure system. Since the gas in this system is not at constant temperature, an equation for a polytropic process was used to determine the starting pressure for each test. A discussion in Appendix A covers this approach.

Weld Design Development Testing

End Cap Design

The first design tested was of the end cap configuration, shown in Figure 1. The results of the first three tests are given in Table 1.

Figure 1 - End cap weld design.

Both of the gas tungsten arc (GTA) welds PB1 and PB2 failed in a similar manner. The weld overlap area had a crack that was intergranular in nature. Figure 2 shows a cross section of the weld joint and crack for PB1. Figure 3 is an external view of the cap showing a circumferential crack.

The GTA welds of PB1 and PB2 had large grains in the welded areas. The third capsule was electron beam welded to reduce the grain size. The failure mode for the PB3 test was complete separation of capsule body from the cap. The failure of PB3 appeared intergranular in nature. The grain size in the electron beam (EB) welded area appears smaller than the grain size in the GTA welds. There was a small area without complete weld penetration, probably a result of not optimizing the joint for EB welding.

A calculation of the tangential stresses at the intersection of cap and cylinder wall are presented in Table 2 (see Appendix B for equations). By interpolation of the data in Table 13 from NASA report CR-72859, *Investigation of High*

Figure 2 - Cross section shows cracked weld joint of end cap design (5X).

Figure 3 - Circumferential crack in weld joint of end cap design (4X).

Temperature Fracture of T-111 and ASTAR-811C, it can be stated that at 1171°C the ultimate tensile strength for T-111 is 40,500 psi and the yield strength is 24,900 psi. These values predict that the end cap design should fail.

Table 1 - TEST RESULTS FOR END CAP WELD				
Capsule Number	Type of Weld	Temperature (°C)	Pressure psig	Failure Time Minutes
PB1	GTA	1171	4585	2
PB2	GTA	1171	4575	3
PB3	EB	1171	4395	2

Table 2 - TANGENTIAL STRESSES				
Temperature °C	Pressure psig	Stress (psi)		
		Cylinder	Plate	Total
500	2700	18600	6290	24890
600	3100	21400	7220	28620
1171	4500	31000	10480	41480

Girth Weld Design

A stress reduction of 25%, not accounting for stress concentration, can be obtained by eliminating the tangential stress caused by the cap. This was accomplished by moving the weld joint to the capsule cylindrical wall, thereby eliminating the tangential stress and reducing the stress concentration (Figure 4).

Figure 4 - Girth weld design.

Girth Weld Testing

Six tests were conducted using the procedures from Mound Technical Manual MD-22139, *60 Watt Pressure Burst Test Procedures*. The Oak Ridge National Laboratory (ORNL) regression model for stress rupture life, Equation 1, was used to predict failure time.

$$\ln(t) = a + b \cdot \ln(\text{sig}) + c \cdot T \quad (1)$$

where:

- t = predicted life (hours)
- sig = maximum stress (7.3*pressure) (psi)
- T = temperature (°R)
- a = 84.34
- b = -5.272
- c = -1.006×10^{-2}

Table 3 gives the test parameters, the life (failure time) from Teledyne Brown, and the ORNL equation. Table 4 gives the results of the development pressure burst tests.

Table 3 - TEST MATRIX FROM TELEDYNE BROWN				
Temperature °C	Pressure psia	Life hours	Capsule Number	ORNL Equation
1000	6300	107	PB8	107
1000	6900	62	PB9	66
1171	3800	*	PB4	69
1171	2750	17.5	PB5	382
1260	2740	78	PB6	78
1260	3560	20	PB7	20

* Life predicted from weld data is 1.7 hours and 66 hours from parent material data.

Table 4 - TEST MATRIX OF PRESSURE BURST RESULTS			
Temperature °C	Pressure psia	Life hours	Capsule Number
1000	6409	131.7	PB8
1000	6952	152.1	PB9
1171	3910	27.5	PB4
1171	2912*	239.1	PB5
1260	2589	40.2	PB6
1260	3541**	8.6	PB7

* Average pressure of two tests.

** Pressure prorated for test time.

Test of Capsule PB5

The first test of a girth weld capsule was made on PB5, a capsule with a tantalum fill tube. The test was conducted at 1171°C and reached a maximum pressure of 2907 psig. The capsule was at temperature for 104.5 hours. During this time the capsule pressure dropped to 2820 psig. The test was stopped when a large increase in helium partial pressure caused the ion pump to shut off.

When the capsule was removed from the furnace, it appeared that the fill tube had failed and not the capsule. The tantalum tube had swelled (Figure 5) just above the capsule. The tube was cut off and a new tube was EB welded in place. This new tube was an alloy of tantalum with 10% tungsten.

After capsule PB4 was tested, PB5 was installed in the furnace and retested. The test was stopped after less than 10

Figure 5 - View of capsule PB5 and failed tantalum fill tube (2X).

The tube was replaced with a tantalum plus 10% tungsten alloy tube, and the capsule was placed in the furnace for retesting. The capsule could not be high-pressure leak-checked because excessive amounts of helium kept turning off the ion pump. The capsule was removed from the furnace and leak-checked

This was the second girth weld test at 1171°C. The pressure ranged from 3897 to 3371 psig. The test was stopped after 27.5 hours, when an increase in furnace pressure turned off the ion gauge. It appeared that the fill tube had failed in the same manner as on capsule PB5.

Test of Capsule PB4

Figure 6 - View of weld area showing approximate location of crack as indicated by the two lines (8X).

minutes at temperature because of a leak. The capsule was removed from the furnace and the tube intersection was rewelded (EB) at a 45° angle. The capsule was retested for 135.5 hours before failure. The pressure range during the test was 2890 to 2699 psig. The capsule was removed from the furnace, submerged in alcohol, and pressurized to 40 psig in a protected container using argon. Figures 6 and 7 show the area of the leak. Graphs of the data for this and the other tests are in Appendix A.

using the same method used for PB5. The leak was in the center of weld, in the same general location as the leak in PB5.

Figure 7 - Same area as in Figure 6, showing the crack (25X).

Test of Capsules PB6, PB7, PB8, and PB9

The next four capsules to be tested were the same size and used the tantalum plus 10% tungsten alloy fill tube. The failure mode was the same as in the previous two tests (PB4 and PB5). The location of the leak was in the center of the weld. Table 5 gives the approximate location of the defect in relation to the end of the weld. Figures 8 and 9 show the capsule, fill tube, and the end of the weld of capsule PB7. By definition the crack is counter clockwise (CCW) from the end of the weld.

Table 5 - DEFECT LOCATION FROM END OF WELD		
Capsule Number	Direction	Location Degrees
PB4	CCW	20-30
PB5	CCW	20-30
PB6	CCW	20-30
PB7	CCW	0-5
PB8	CCW	20-30
PB9	CW	90-100

Figure 8 - View of capsule showing relation from end of weld to approximate location of crack (1X).

Figure 9 - View of capsule PB7 showing crack at end of weld overlap (15X).

Evaluation Of ORNL Regression Model

To evaluate the ORNL regression model, the percent error from calculated life to actual life was determined for each test. The average error was 57.6% with a standard deviation of 91.6. This equation does not predict failure life satisfactorily. Table 6 gives a summary of this evaluation.

Table 6 - ORNL PREDICTED LIFE COMPARED TO ACTUAL TEST LIFE					
Test Temperature °C	Test Pressure psig	Stress psi	Predicted ORNL Time hours	Actual Test Time hours	Change percent
1000	6490	46786	97.5	131.7	-26.0
1000	6952	50750	63.5	152.1	-58.2
1171	3910	28543	59.7	27.5	+117.1
1171	2912	21258	282.4	239.1	+18.1
1260	2589	18900	104.8	40.2	+160.7
1260	3541	25849	20.1	8.6	+133.7

Conclusions

The end cap weld design was unacceptable, with failure in three minutes or less. The results of the girth weld design tests were favorable. All of the girth weld capsules failed in the center of the weld and five of the six in the same area from the end of the weld.

The ORNL regression model does not predict failure life for welded T-111.

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PB4

START TO 1171 DEG. C

PB4

1171 DEG. C TO FAILURE

PB5

START TO 1171 DEG. C

PB5

1171 DEG. C TO FAILURE (TUBE)

PB5

START TO 1171 DEG. C

PB5

1171 DEG. C TO FAILURE (TUBE)

SECOND RETEST OF PB5

START TO 1171 DEG. C

SECOND RETEST OF PB5

1171 DEG. C TO FAILURE

SECOND RETEST OF PB5

SECOND RETEST OF PB5

PB6

START TO 1260 DEG. C

PB6

1260 DEG. C TO FAILURE

PB6

1260 DEG. C TO FAILURE

PB6

START TO 1260 DEG. C

PB7

START TO 1260 DEG. C

PB7

1260 DEG. C TO FAILURE

RETEST OF PB7

START TO FAILURE

RETEST OF PB7

1260 DEG. C TO FAILURE

RETEST OF PB7

START TO FAILURE

RETEST OF PB7

START TO 1260 DEG. C

PB8

START TO 1000 DEG. C

PB8

FROM 40 HOURS TO FAILURE

PB8

START TO 1000 DEG. C

PB8

FROM 40 HOURS TO FAILURE

PB9

START TO 1000 DEG. C

PB9

1000 DEG. C TO FAILURE

Appendix B

Determination of Starting Gas Pressure

The milliwatt capsule starting pressure was determined by the ideal gas equation ($PV = mRT$). The steps and assumptions are:

Starting conditions: $P_1V_1 = mRT_1$

Maximum conditions : $P_2V_2 = mRT_2$

Without leakage in the capsule the mass "m" is constant.

Rearranging the equations gives: $P_1V_1/T_1 = P_2V_2/T_2$

Assumption: $V_1 = V_2$ for small thermal expansion

Solving for pressure: $P_1 = P_2T_1/T_2$ or $P_2 = P_1T_2/T_1$

The 60-watt capsule test system is not the same as the milliwatt system. The milliwatt capsule/stem is sealed and placed in the hot zone of the furnace. This system does not allow measurement of the pressure, P_2 , at test temperature. The 60-watt system has the capsule attached to a tube that exits the furnace. The pressure, P_2 , is measured in the tube outside the furnace. The temperature of the gas whose pressure is being measured is not constant, but varies from test temperature to room temperature. The 60-watt test conditions do not satisfy the ideal gas requirements.

The compression and expansion of a gas obey the equation $PV^n = C$ fairly well, provided that the proper value is selected for the exponent n. The exponent n may have many values ($-\infty$ to $+\infty$). Any process obeying this law is called a polytropic process. The general relations are: $P_1V_1^n = P_2V_2^n$

By substituting the ideal gas equation into the polytropic equation, a relationship between temperature and pressure can be obtained. The following shows these steps:

$$P_1 V_1 = mRT_1 \quad \text{and} \quad P_2 V_2 = mRT_2$$

$$V_1 = mRT_1/P_1 \quad \text{and} \quad V_2 = mRT_2/P_2$$

Then substitute into: $P_1 V_1^n = P_2 V_2^n$

$$P_1 (mRT_1/P_1)^n = P_2 (mRT_2/P_2)^n$$

$$P_1 T_1^n P_1^{-n} = P_2 T_2^n P_2^{-n}$$

$$(P_1/P_2)^x = T_2/T_1 \quad \text{where } x = (1-n)/n$$

The girth weld pressure burst test conditions were used in the comparison of the ideal gas equation and the polytropic equation. The starting pressure (P1) and the temperatures (T1 and T2) were used to calculate the maximum pressure (P2) and the percent error from the actual maximum pressure. Table B-1 shows the ideal gas equation results and Table B-2 shows the polytropic equation results.

The ideal gas equation gave an average error of 46% in predicting P2, and this is not satisfactory. The polytropic equation has an average error of less than 3% for P2. In Table B-2 the second value for each temperature has less error than prior test. This is a result of using the information from the first test to calculate the exponent for the second test at that temperature.

The test data from the girth weld capsules were used in a regression analysis to determine the exponent for the polytropic equation given the capsule volume ($V \text{ cm}^3$), test temperature ($T_2 \text{ }^\circ\text{K}$), and test pressure ($P_2 \text{ psia}$). The equation for the exponent is:

$$n = -6.0495\text{E-}02 \times V - 2.4681\text{E-}04 \times T_2 - 5.5824\text{E-}05 \times P_2$$

Table B-3 shows the results using the exponent calculated from the regression analysis.

Table B-1 - PREDICTION OF P2 USING IDEAL GAS EQUATION					
STARTING CONDITIONS			TEST	IDEAL GAS EQUATION	
T1 °C	T2 °C	P1 PSIG	P2 PSIG	P2 PSIG	ERROR PERCENT
20.2	1171	833	2907	4161	43.2
18.9	1171	1083	3897	5417	39.0
21.0	1260	750	2575	3974	54.3
20.0	1260	1029	3555	5447	53.2
20.0	1000	2104	6394	9191	43.8
22.7	1000	2298	6937	9943	43.3

Table B-2 - PREDICTION OF P2 USING POLYTROPIC EQUATION					
STARTING CONDITIONS			TEST	POLYTROPIC EQUATION	
T1 °C	T2 °C	P1 PSIG	P2 PSIG	P2 PSIG	ERROR PERCENT
20.2	1171	833	2907	2760	-5.0
18.9	1171	1083	3897	3780	-3.0
21.0	1260	750	2575	2732	6.1
20.0	1260	1029	3555	3538	-0.5
20.0	1000	2104	6394	6297	-1.5
22.7	1000	2298	6937	6933	-0.1

Table B-3 - PREDICTION OF P2 USING REGRESSION EXPONENT				
TEST	EXPONENT n REGRESSION	TEST P2	REGRESSION P2	EXPONENT ERROR
-2.9012	-3.311	2922 psia	2885 psia	-1.25%
-3.4578	-3.954	3912 psia	3934 psia	+0.56%
-3.4269	-2.884	2590 psia	2601 psia	+0.41
-2.8476	-2.939	3570 psia	3589 psia	+0.53
-2.8918	-3.033	6409 psia	6396 psia	-0.20
-3.0562	-3.063	6952 psia	6953 psia	+0.01

Stress Equations for End Cap Weld Design

The tangential stresses at the intersection of the cylinder wall and the end cap are the sum of the following:

1. Hoop stress in a thin wall cylinder

$$SC = (P*r)/t$$

where P = internal pressure (psi)

r = inside radius

t = wall thickness

2. Tangential stress in a flat plate fixed at edge

$$SP = [(3*W)/(8*3.1416*m*t)]*[(m+3)(r^2/a^2) - (m+1)]$$

where W = total force on cap

m = inverse of Poisson's ratio

a = inside radius

r = distance from center (for this case r = a)

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