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HIGH RELIABILITY CATHODE HEATERS FOR ION THRUSTERS

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HIGH RELIABILITY CATHODE HEATERS FOR ION THRUSTERS

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Abstract

A number of space missions have been proposed which will utilize 30-cm mercury bombardment ion thrusters and also will require a large number of thruster restarts. A test program was carried out to determine thermal cycle life of several different cathode heater designs. Plasma/flame sprayed heaters and swaged type heaters were tested. Four of the five plasma/flame sprayed heaters tested failed in a comparatively short time. Four tantalum swaged heaters that were brazed to the tantalum cathode tube were successfully tested and met the goals that were set at the start of the test.

Introduction

A number of space missions have been proposed which will utilize 30-cm mercury bombardment ion thrusters and which require large number of thruster restarts (ref. 1). These requirements necessitate having cathode heaters that have long life and the capability of being thermal cycled several thousand times in order to ensure mission success. Long life, has been demonstrated; 15,000 hours and 20,000 hours (ref. 2 and 3 respectively). Thermal cycling had not been demonstrated. Plasma and flame sprayed cathode heaters were proposed for the 30-cm Ion Thruster (fig. 1). The SERT II thrusters (15-cm dia.) utilized this technology (ref. 4) and the cathode heaters were successful and exhibited no failure mechanisms. Due to increased emission requirements, the 30-cm cathodes are larger in diameter than those of the SERT II thruster. This fact plus the requirement for a large number (thousands) of restarts required that a test program be carried out to demonstrate heater reliability for 30-cm thrusters.

Presented in this report are the results of testing (thermal cycling) plasma/flame sprayed and swaged tantalum heaters. Also reported, are the quality assurance controls and the rigid manufacturing specifications that are necessary in the manufacturing of heaters to obtain the required high reliability.

Apparatus and Procedure

The apparatus utilized in these tests was a 0.45 meter diameter bell jar, power supplies (6 amps at 40 volts), thermocouples, controllers, timers, and cycle counters (fig. 2). The bell jar had a roughing and an oil diffusion pump using a liquid nitrogen baffle. Pressure obtained was in the low 1.3×10^{-4} N/m^2 (10^{-6} torr) range.

The control of the heating cycle of the cathode heaters was through platinum - platinum 13% rhodium (P_t-P_tRh) and chromel-alumel (C-A) thermocouples (T/C). The P_t-P_tRh T/C was spotwelded to the tip (orifice plate) of the cathode tube and the C-A T/C was spotwelded to a point 5.0mm below the last coil of the heater (fig. 3). When power was initially turned on and the heater came up to 1100°C the high contact of the P_t-P_tRh T/C controller was made and the timer started. It was set up to hold the power for ten minutes. After the ten minute on cycle, the timer opened the power circuit and the cycle was registered on the counter. The heater was then cooled to 100°C by radiation and conduction. When 100°C was reached the low limit contact of the C-A T/C controller was made which closed the power circuit and re-energized the heater.

The vacuum was maintained by an ionization gauge controller that was pre-set to 1.06×10^{-3} N/m^2 (8.0×10^{-6} torr). The contacts on the controller were in series with the heater power circuit. Whenever the pressure in the bell jar exceeded 1.06×10^{-3} N/m^2 (8.0×10^{-6} torr) the power circuit opened. Power would then have to be reset manually. This set-up resulted in an unattended operation which was checked periodically throughout the day.

Test Specimens:

The cathode heater specimens tested were the following:

Two Plasma/Flame Sprayed Units
Three Flame/Flame Sprayed Units
Four Swaged Tantalum Units
(figs. 4, 5 and 6 show typical specimens)

The plasma/flame sprayed heaters were fabricated in the following manner: A 0.63cm diameter by 7.6cm long tantalum tube was first sprayed with a 0.127mm thick coating of tungsten. This was followed by a 0.254mm thick coating of alumina (Al_2O_3) which was plasma sprayed. A helical coil of tungsten, 26% rhenium wire 0.254 mm in diameter was slipped over the alumina coat. After the heating wire was positioned in place a second flame sprayed coating of alumina was applied. This had a minimum

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thickness of 0.254mm. The three flame sprayed heaters were identical to the plasma/flame sprayed units. The only difference was that both the first and second layers of alumina were flame sprayed. Flame sprayed heater number four had a final coat of tungsten sprayed over the last coat of alumina.

The swaged tantalum heaters were constructed as follows:

A 0.508mm diameter tantalum wire was inserted into MgO (magnesium oxide) beading which in turn was assembled into a tantalum tube. After several swaging and annealing operations the final heater outside diameter (sheath) was 1.52mm and the center heating wire was swaged down to a 0.33mm diameter. This straight section heater was then coiled into a helix. After the coiling the swaged heaters were then brazed to a 0.63cm diameter by 7.6cm long tantalum cathode tube with a titanium braze, a binary braze (titanium - vanadium) or a ternary braze (titanium - tantalum - vandaium). The brazing temperature was in the 1650° - 1700°C range. Heaters numbers 1, 2, and 3 were fully brazed to the tantalum tube. Heater number 4 had only the top and bottom coils brazed to the tube.

A tantalum foil radiation heat shield (fig. 7) was installed on each heater section of the cathode tube (except the plasma/flame sprayed heater numbers 1, 2 and the number 1 swaged tantalum heater). The number of layers of foil varied from three to six (.025mm thick) (tables I & II). The end section of the last layer was lapped over the preceding layer and spotwelded. The balance of the layers were loosely coiled to keep the conductive heat transfer to a minimum. At this time, the cold resistance of the heater was measured.

Two vertical tantalum foil cylinders (3.5 and 4.5cm in diameter by 9.2cm high) and a flat tantalum plate (9.5cm diameter) served as heat shields around each cathode heater assembly tested (fig. 8). The purpose was to keep the glass bell jar as cool as possible.

Before cycling was started the heaters were baked out for 24 hours at 200°C and then at 540°C for an additional 24 hours. The purpose was to purge any moisture in the insulating material of the heater. After this bake-out procedure was accomplished the thermal cycling was started.

The first cycle was accomplished manually to condition the heater and also determine the required power (wattage) to heat the orifice plate to 1100°C. The current was brought up in 1.0 amp steps. After each increase in the current, the heater temperature and the voltage was allowed to reach steady state (the voltage would keep increasing due to the increase in the heating wire resistance as the heater came up in temperature). This voltage change continued until the temperature of the heater stablized. When the orifice plate of the cathode tube reached 1100°C and conditions were stable the current setting and voltage were then noted and recorded.

At this time the power was cut and the heater was allowed to cool to 100°C. The controllers were then energized and the power came back on (at the fixed current and voltage determined in the first cycle) and the automatic and unattended cycling started.

The heater would come up to temperature (1100°C) in 2-3 minutes after the application of power. The timer would keep the power on for a ten minute period. A cooling period of 18-20 minutes was required to reach 100°C.

Results and Discussions

Plasma/Flame Sprayed Heaters

Table III shows the resistance, input power, the temperature and the number of thermal cycles achieved for the five plasma/flame sprayed heaters tested.

Heater number one achieved 15 cycles. On the 16th cycle - it shorted (fig. 9). Arcing took place in the heating wire and blew out through the outer alumina insulating layer. The alumina insulation cracked in several areas.

Heater number two could not be heated to 1100°C with over 6.0 amps applied. After removal from the bell jar the cold resistance was 0.22 ohms (originally it was 1.10 ohms). This heater also had a crack in the insulation (fig. 10).

Heater number three was cycled 57 times before it failed. The resistance dropped to 0.81 ohms (originally it was 1.12 ohms). It also had cracks.

Heater number four (fig. 5) was cycled 834 times before it failed. It also had a drop in resistance; it measured 0.72 ohms after removal from the bell jar (originally it was 1.10 ohms). The increased life of this heater over the first three could be attributed to the final coating of tungsten that was flame sprayed over the outer alumina layer. It may have strengthened the outer alumina layer.

Heater number five was cycled 627 times. It did not fail during this testing. It was removed from the bell jar in order to be used in a subsystem test. At the time of removal there was no change in the resistance (it measured 1.10 ohms).

Evidently when a plasma or flame sprayed heater is cycled, the heat transfer by conduction (from the tungsten wire to the outer alumina layer) is not rapid enough when the power is applied. Thus a large temperature difference must exist between the two materials. This temperature difference creates thermal stresses in the interface region of the tungsten heating wire and the alumina insulating layer and these stresses cause the bonded surfaces to separate. After a few thermal cycles, cracks develop (both in the axial and circumferential directions) because the heating wire is increasing in temperature at a faster rate than the alumina, (even though the coefficients of expansion are similar). The resulting expansion of the wire cracks the insulation. Also, hot spots are created in the heating wire at these cracked areas. These hot spots cause local high thermal stresses and can result in rupturing of the wire causing a short or an open condition. Other failures are partial shorting in the assembly causing a drop in resistance.

These failures occurred without any precursor indication. This behavior precludes, or makes very difficult, selecting out (from a batch) heaters which would meet the multiple start requirement. Also there was no apparent way to make any changes in the manufacturing of the sprayed heaters to correct the problem. Therefore, this type of heater was not considered for any further testing.

Swaged Tantalum Heaters

As noted in Table IV none of the four swaged tantalum heaters failed. The goals set for the swaged tantalum heaters were met in all four heaters tested. Heaters number one, two and three achieved 2007, 2137, and 2112 thermal cycles respectively (goal was 2000 cycles) and heater number four that had a 3000 cycle goal reached 3044. Tests were terminated when the goals were met. Heater number one required the maximum amount of power since it had no radiation shields. At the end of the test (after 2007 cycles) the cathode tube of heater number one had deformed slightly (fig. 11) since it had no orifice tip plate welded-in which would have reinforced it. The thermal strains produced by the brazed heater rippled the inside surface of the thin (0.254mm wall) tube and also curved it slightly. Heaters two (fig. 12), three (fig. 13) and four (fig. 14) had the orifice tip plate welded-in and the distortion was minimal. Also, heaters two and four had a heavier wall tube (0.381mm) and the rippling on the inside of the tube was very minimal.

Short term tests that were accomplished comparing heaters that were brazed to the cathode tube (0.254mm thick) (fig. 15a) and non-brazed heaters (fig. 15b) (they were slipped over the tube with a slight press fit) showed only a 5 to 10 watt additional power requirement (for the non-brazed heaters). The reason being is that radiation is the primary mode of heat transfer and conduction is secondary. The slipped-on heater did not distort the tube since it was not rigidly bonded to the tube. It could flex freely as it heated up. If brazing was a requirement, then the cathode tube wall would have to be increased to 0.508mm or 0.635mm so that no distortion would take place on the inside wall. Also, 5 to 10 more watts of power would be required to maintain the same temperature. In addition, there may be a change in the heat characteristics of the cathode with a thicker wall. These trade-offs would have to be considered if a brazed heater would be desirable. A non-brazed heater would have to be mechanically fastened to the cathode tube in order to sustain the launch vibration environment.

Swaged tantalum heaters have been used in thrusters with varying degrees of success. Heaters have failed by shorting, partial shorting (drop in resistance) or by opening. These were heaters that were manufactured to "standard commercial practices." This means, spot inspections (visual) of materials, processing temperatures not necessarily optimum for the end operating temperature of the heater and minimal inspections and tests after each manufacturing operation.

An analysis of the manufacturing processes required to produce swaged heaters revealed the fact that heaters could be fabricated that would have excellent thermal cycling life by applying rigid reliability and quality controls and optimum manufacturing specifications.

The swaged heaters tested did not have all the quality controls applied during their manufacture as is discussed in the following section, but some of the controls and specifications were implemented and used.

Quality Controls and Manufacturing Specifications Required to Produce High Reliability Heaters

The reliability of a swaged heater is determined at the time of the original design and when the specifications are formulated. In the initial design, the heating capacity (wattage), current and voltage requirements must be determined. These factors determine the heating wire size, insulation thickness and sheath diameter. Thermal stress levels must be low (or reasonable) in order to have long thermal cycling life.

After the design is fixed, the next consideration is the selection of materials and manufacturing processes. Since tantalum has high temperature and above average fatigue strength it is an excellent candidate for a heater that will operate in a vacuum environment. All phases of the manufacturing process must be considered. Material utilized must be certified and meet minimum tensile strength requirements. One hundred percent visual inspection (under 30X magnification)

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of the heating element wire must be performed. No defects that can result in "stress raisers" can be tolerated. Typical ones that can cause stress problems are shown in figure 10. Material with these defects must not be used. The insulation used must be high purity material (99% plus). Also it must be air fired at the operating temperature of the heater to eliminate all impurities. The inspection of the insulation beads must also be performed. Any chipping of the ends of the beads (tubes) that can cause voids in the insulation of the finished heater cannot be tolerated. The sheath material (tubing) must also be visually inspection (under 10 - 30X magnification) for defects. Cracks, abrasions, nicks, etc. cannot be accepted.

Assembly of the heater components is the next step in the manufacturing process that must be considered. Special precautions must be taken to ensure the insulation beads are butted together (without gaps) as they are slipped over the center heating wire and slipped into the sheath. Any spacing (gaps) in the beads can cause voids in the heater after swaging. Voids in the insulation material causes over-heating (hot spots) in the heating element wire due to the lack of thermal conduction. The overheated wire means high thermal stresses in these areas and minimum cycle life. This condition can lead to an open, a partial or complete short.

After the swaging operations the speed through the annealing furnace is important in order to have complete annealing take place. If too fast, the heater is not completely annealed which can cause fractures (due to brittleness) in a following cold work process. Also the optimum annealing temperature must be used in order to maximize the ductility. Tests were conducted at 1100°C, 1200°C and 1300°C to determine maximum elongation and tensile strength on sample tantalum wire. Tests confirmed that 1200°C should be the annealing temperature for the tantalum wire and tubing that was used for the heaters.

After all the swaging and annealing operations are performed the straight (uncoiled) heater must be radiographed (2 views - 90° apart) at this time to determine if the heating element wire is centered in the sheath and no voids exist in the insulation. Also after the final swaging operation has been performed and before the tip is welded a small piece of the swaged section is cut-off from the heater and a compaction (density) test is made on the insulation. If the density of the insulation does not meet the specification that heater is rejected. This density test determines the heat transfer capability of the heater and is one of the measurements which determines the reliability or life of the heater. Also the tip weld should be microscopically inspected for defects and then dye penetrant inspected. Any units that exhibit cracks, off-centered welds and other defects should be rejected.

Following the above procedures the accepted units can then be coiled (into a helix) per the specifications. After the coiling, one more visual microscopic inspection is required. If the outer sheath is not ductile enough (due to improper annealing) cracks can develop during the coiling operation. Heaters with these defects can cause an overheating failure by losing the insulation compactness (in the fractured area) that is required for good heat transfer.

The accepted units after this final manufacturing process and inspection are then ready for the electrical resistance measurement. Accepted heaters at this point normally meet the resistance specification. One final control would be to thermal cycle the accepted heaters 50 to 100 times before assembling them to the cathodes. This would qualify them to be used on a space flight thruster. If a swaged heater is defective in any way it will usually fail early in its life.

If all the above required quality inspections are performed during the manufacturing stages and non-defective tooling, proper procedures, optimum annealing temperatures are used, tantalum swaged heaters for thruster cathodes can be manufactured that will give thousands of thermal cycles and long life (endurance) that is necessary for successful operation of space thrusters.

Concluding Remarks

The thermal cycling tests revealed the following:

Plasma/flame sprayed cathode heaters do not appear to have the integrity required for the thousands of thermal cycles a space thruster may have to sustain.

Swaged tantalum cathode heaters do have the capability to satisfy the stringent mission requirements of thousands of thermal cycles if rigid quality controls are applied in the manufacturing process.

Brazing the heater to the cathode tube is not required from a heat transfer standpoint. A non-brazed heater does require 5 to 10 more watts than a brazed unit. However, since the brazed unit requires a thicker tube wall to preclude distortion and the added material increases the power by 5 to 10 watts, the earlier power advantage is cancelled-out. Since the heater must be fixed to the tube to withstand the launch vibration environment a non-brazed unit would have to be fastened mechanically to the tube.

Thermal cycling of heaters (that have met all the quality control requirements) 50 to 100 times is recommended to qualify them for a space flight thruster.

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2. Mirtich, M. J., Kerslake, W. R., "Long Lifetime Hollow Cathode for 30-cm Mercury Ion Thrusters," AIAA Paper 76-985, Key Biscayne, FL, 1976.

3. Wintucky, E. G., "A 20,000 Hour Endurance Test of a Structurally and Thermally Integrated 5-cm Diameter Ion Thruster Main Cathode," AIAA Paper 75-368, New Orleans, LA, March 1975.

4. Zavesky, R. J., Hurst, E. B., "Mechanical Design of SERT II Thruster System," NASA TM X-2518, March 1972.

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TABLE I

DESCRIPTION OF PLASMA/FLAME SPRAYED HEATERS

HEATER NO.	CATHODE TYPE	TYPE (SPRAYED)	CATHODE TUBE THICKNESS, mm	NO. OF COILS	RADIATION SHIELDS
1	MAIN	PLASMA/FLAME	0.254	6	NONE
2	MAIN	PLASMA/FLAME	.254	6	NONE
3	MAIN	FLAME/FLAME	.254	6	3
4	NEUTRALIZER	FLAME/FLAME	.254	6	6
5	NEUTRALIZER	FLAME/FLAME	.254	6	6

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TABLE II

DESCRIPTION OF SWAGED TANTALUM CATHODE HEATERS

HEATER NO.	CATHODE TYPE	CATHODE TUBE THICKNESS, mm	BRAZE TYPE	NO. OF COILS	RADIATION SHIELDS
1	NEUTRALIZER	0.254	TITANIUM	6	NONE
2	NEUTRALIZER	.381	TITANIUM TANTALUM VANADIUM	8	6
3	NEUTRALIZER	.254	TITANIUM VANADIUM	8	6
4	NEUTRALIZER	.381	TITANIUM TANTALUM VANADIUM	8	6

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2	MAIN	PLASMA/FLAME	.254	6	NONE
3	MAIN	FLAME/FLAME	.254	6	3
4	NEUTRALIZER	FLAME/FLAME	.254	6	6
5	NEUTRALIZER	FLAME/FLAME	.254	6	6

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4	NEUTRALIZER	.381	TITANIUM TANTALUM VANADIUM	8	6

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TABLE III
CATHODE HEATER THERMAL CYCLING
PLASMA/FLAME SPRAYED HEATERS

HEATER NO.	RESISTANCE, Ω	CURRENT, A, AVG	VOLTAGE, V, AVG	POWER, W, AVG	TEST TEMP, °C	GOAL, CYCLES	CYCLES ACHIEVED
1	0.94	5.8	16.4	95.1	1100-1150	2000	15
2	1.10	6.6	10.11	66.7	886 (MAX)	2000	0
3	1.12	4.4	14.0	61.6	1100	2000	57
4	1.14	4.1	12.0	49.2	1100-1120	2000	834
5	1.10	4.1	12.9	52.8	1100-1130	2000	[a]627

[a]TEST TERMINATED AT THIS TIME - HEATER WAS NEEDED FOR THRUSTER SUBSYSTEM TEST.

TABLE IV
CATHODE HEATER THERMAL CYCLING
SWAGED TANTALUM CATHODE HEATERS

HEATER NO.	RESISTANCE, Ω	CURRENT, A, AVG	VOLTAGE, V, AVG	POWER, W, AVG	TEST TEMP, °C	GOAL, CYCLES	CYCLES ACHIEVED*
1	0.375	6.7	10.8	72.36	1100-1120	2000	2007
2	.499	5.4	9.7	52.38	1100-1120	2000	2137
3	.45	5.0	9.0	45.0	1100-1105	2000	2112
4	.44	5.1	9.3	47.43	1100-1105	3000	3044

*TESTS TERMINATED - NO FAILURES.

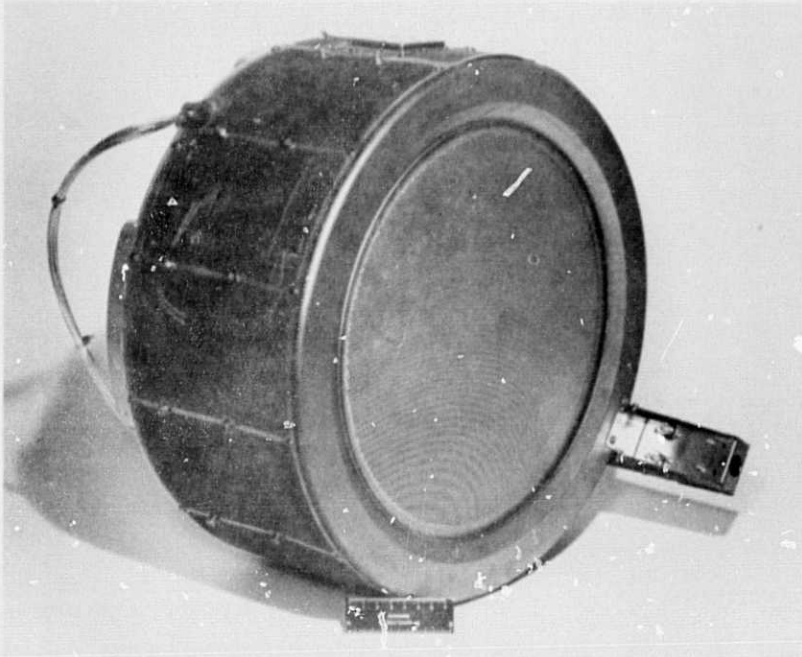

Figure 1. - 30 cm Diameter ion thruster.

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Figure 2. - Bell jar and test set-up.

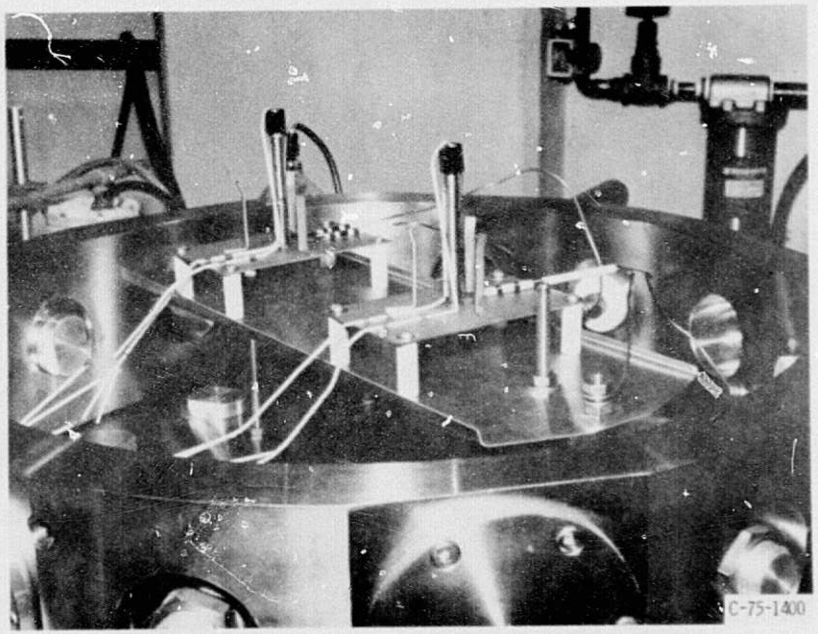

Figure 3. - Heaters with thermocouples attached.

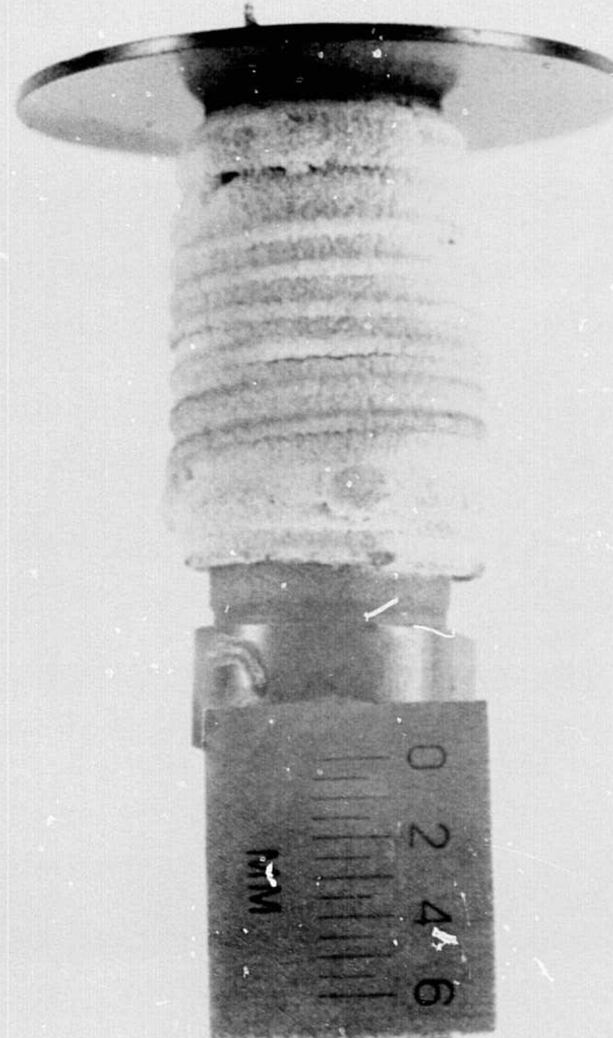

Figure 4. - Plasma/flame sprayed heater before cycling.

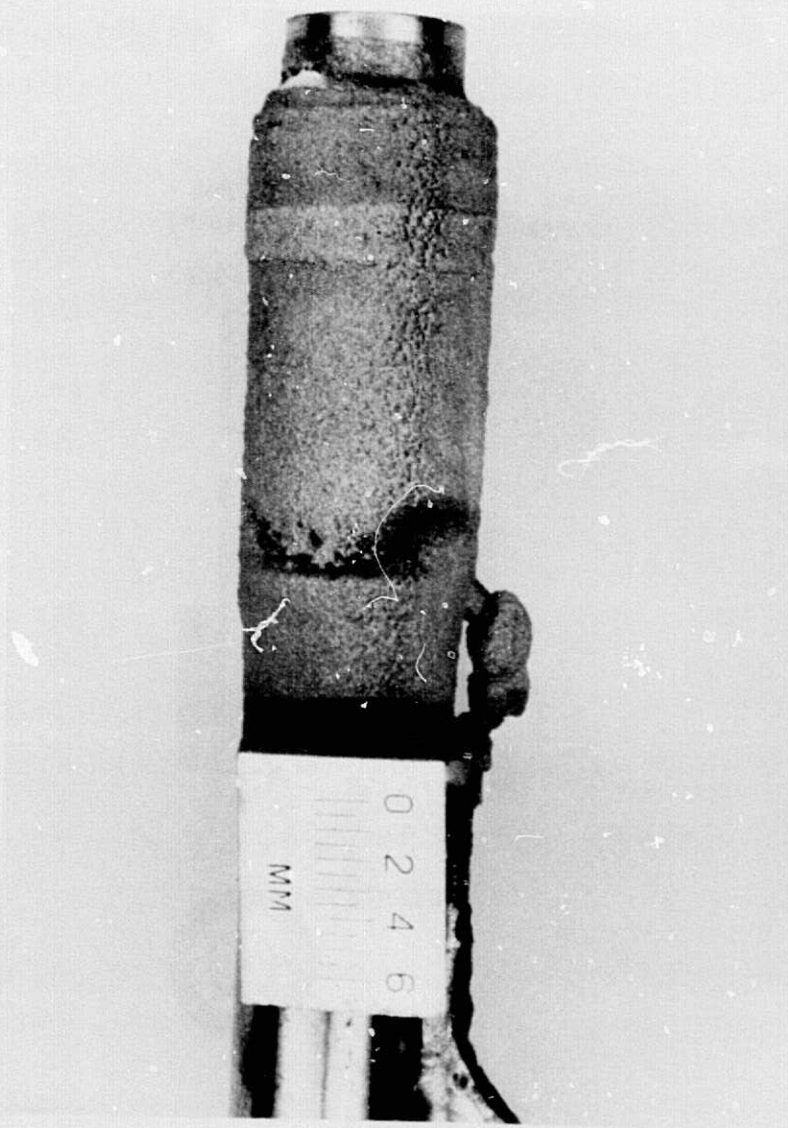

Figure 5. - Flame/flame sprayed heater with layer of tungsten sprayed over aiumina layer.

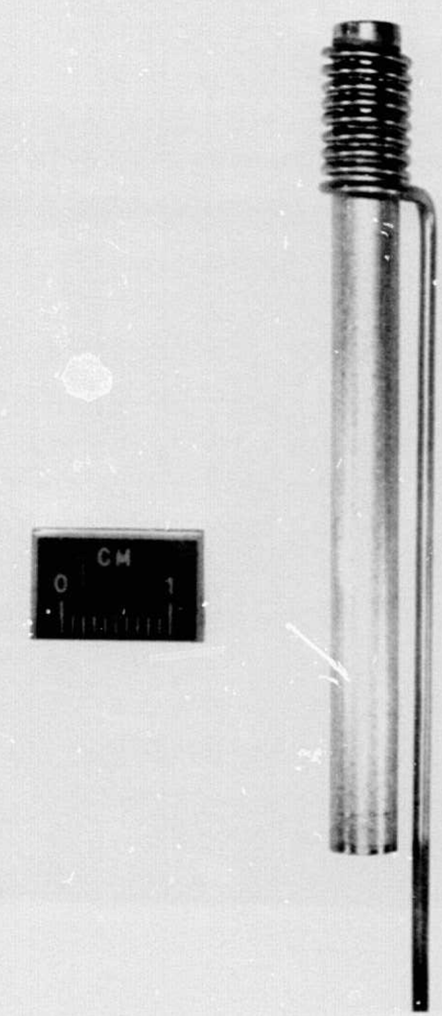

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Figure 6. - Swaged tantalum heater (brazed to tube).

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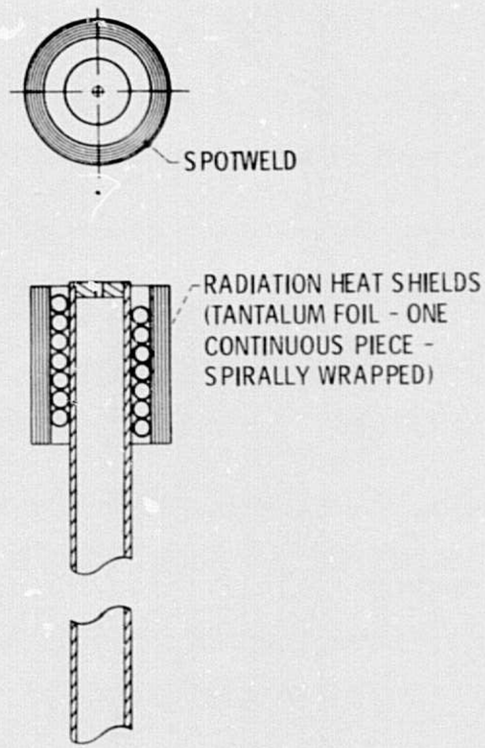

Figure 7. - Cathode heater with radiation heat shields.

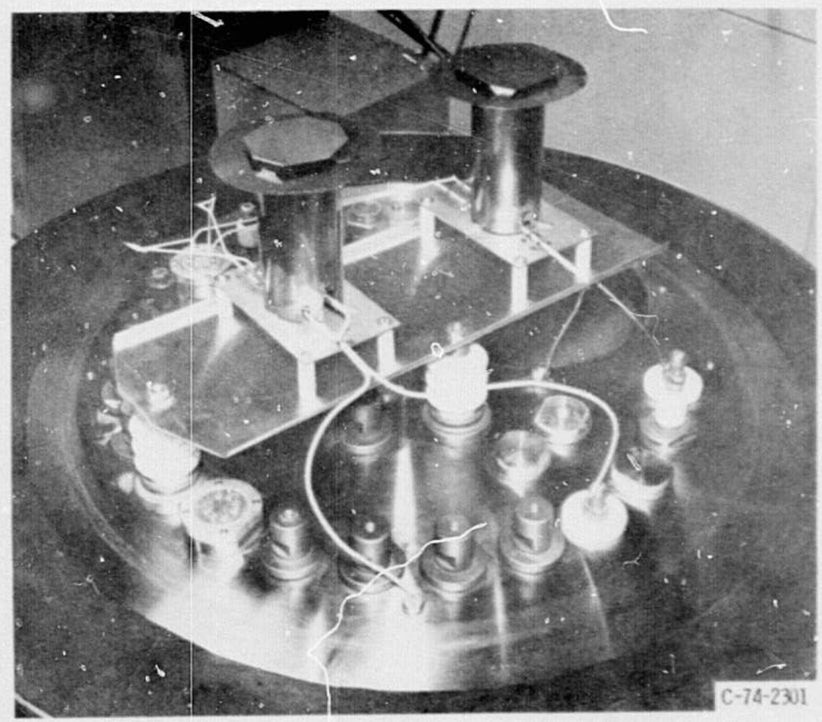

Figure 8. - Tantalum heat shields surrounding test specimens.

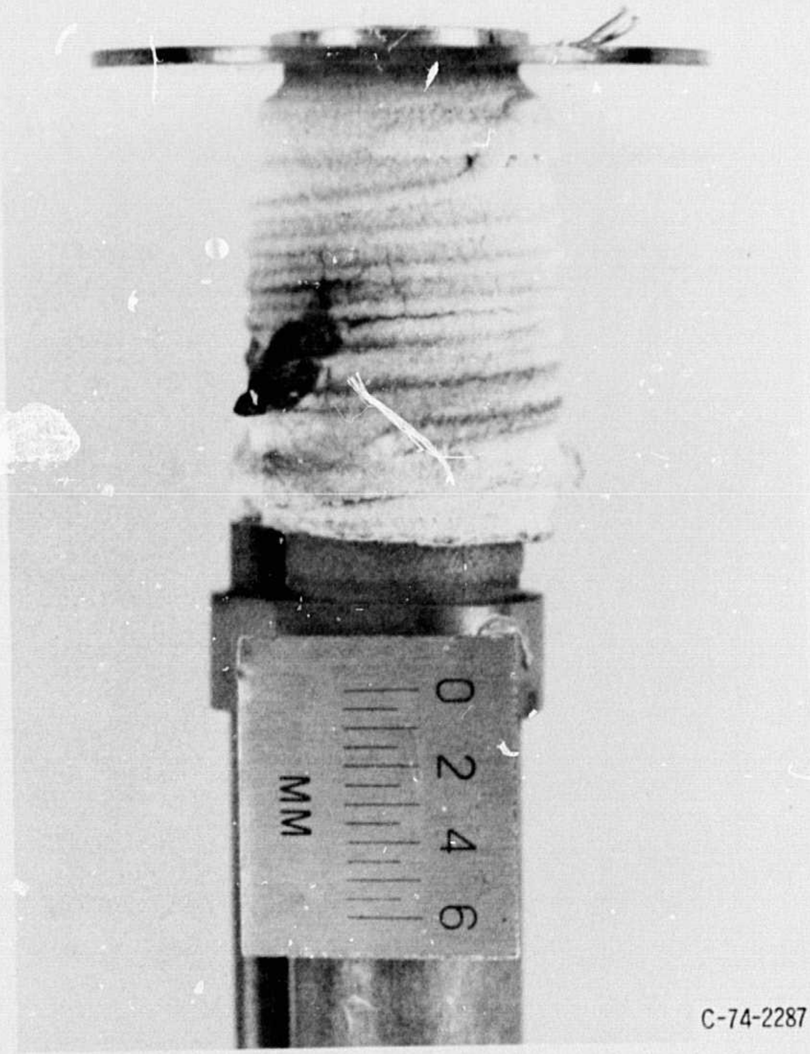

Figure 9. - Plasma/flame sprayed heater no. 1 after failure.

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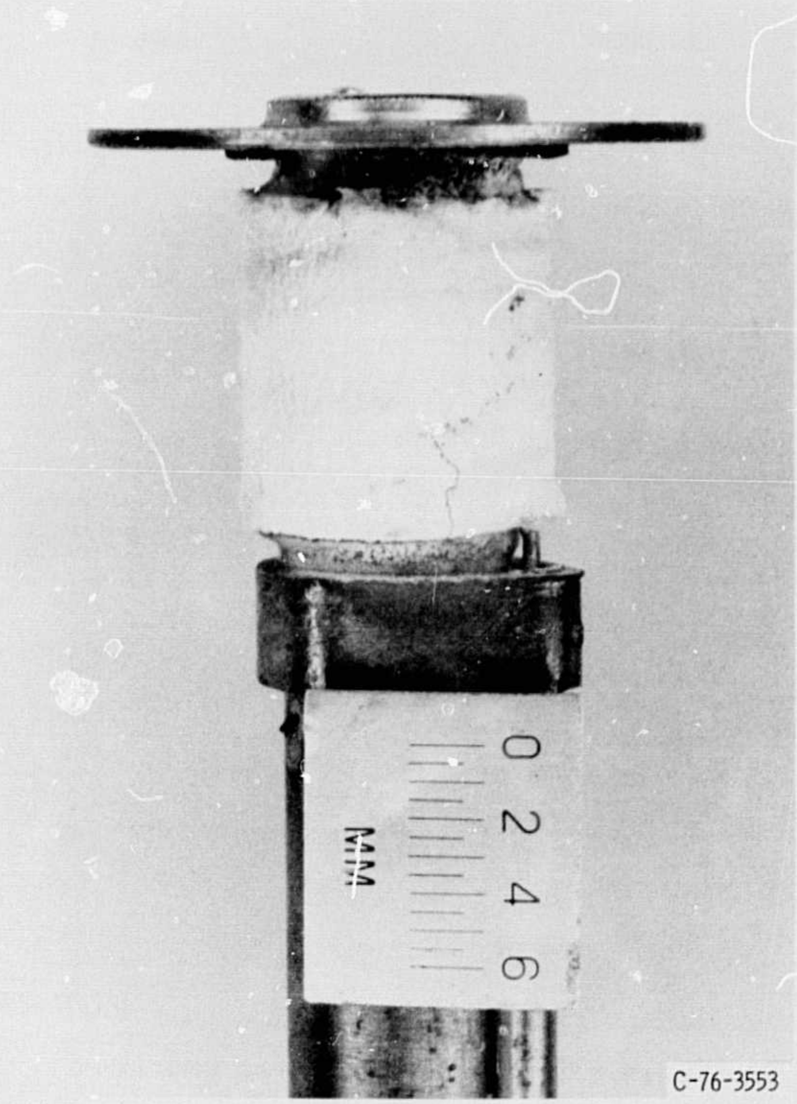

Figure 10. - Plasma/flame sprayed heater no. 2 after failure.

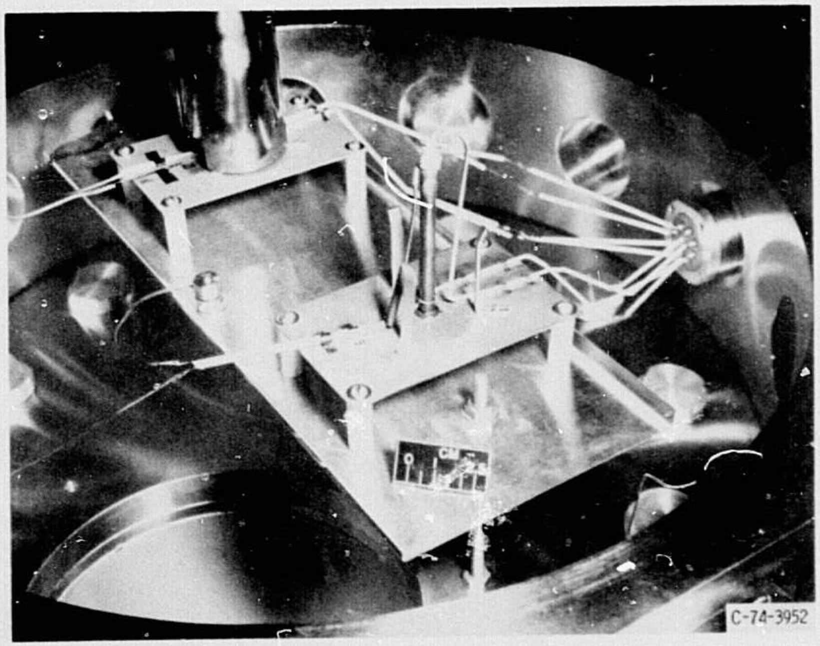

Figure 11. - Swaged tantalum heater no. 1 after 2007 thermal cycles.

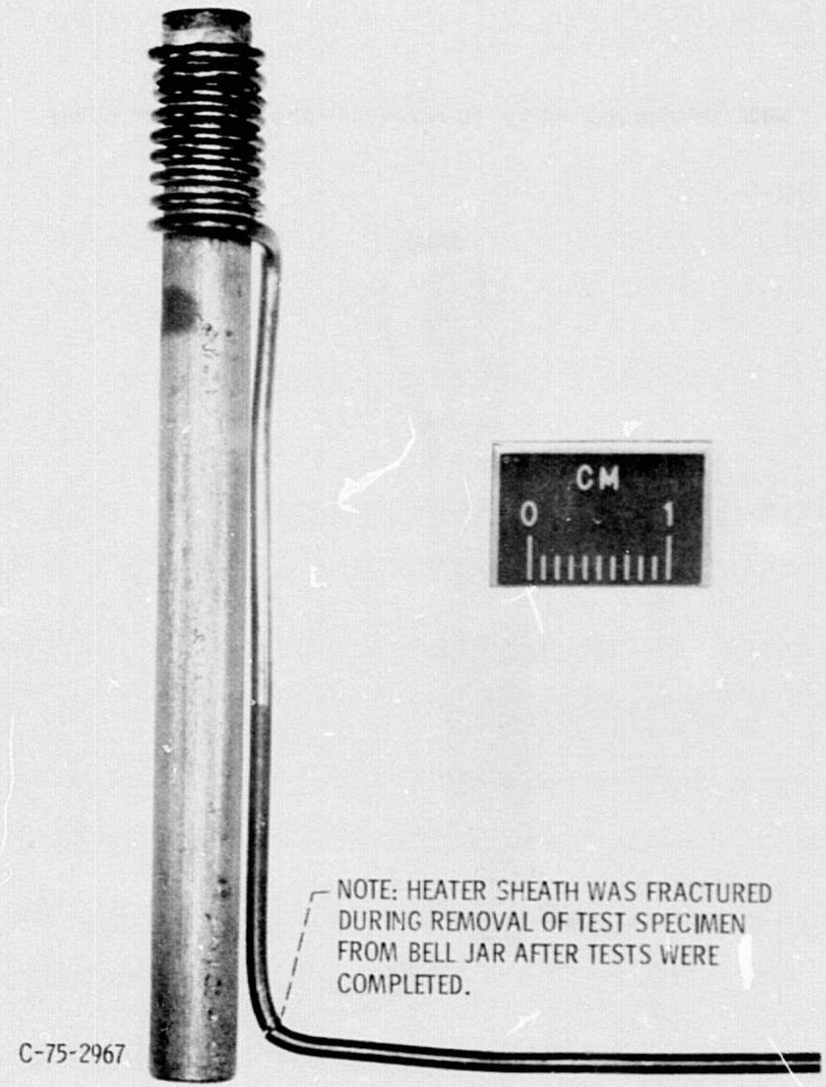

Figure 12. - Swaged tantalum heater no. 2 after 2137 thermal cycles.

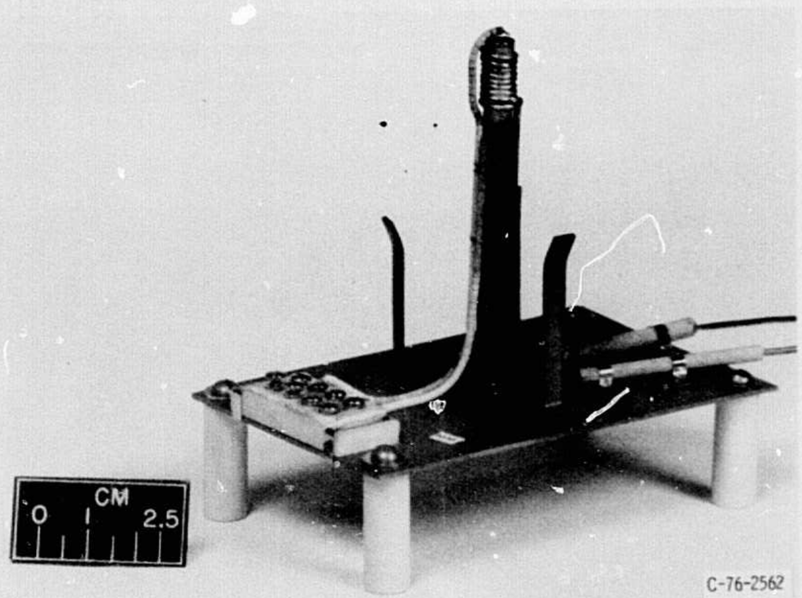

Figure 13. - Swaged tantalum heater no. 3 after 2112 thermal cycles.

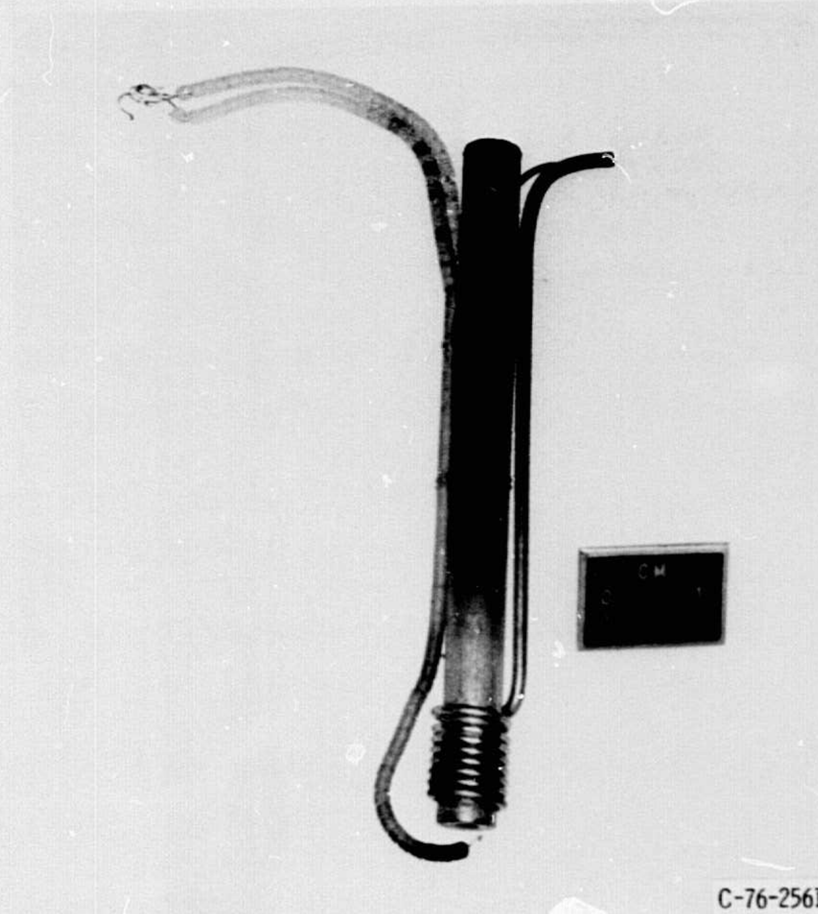

Figure 14. - Swaged tantalum heater no. 4 after 3044 thermal cycles.

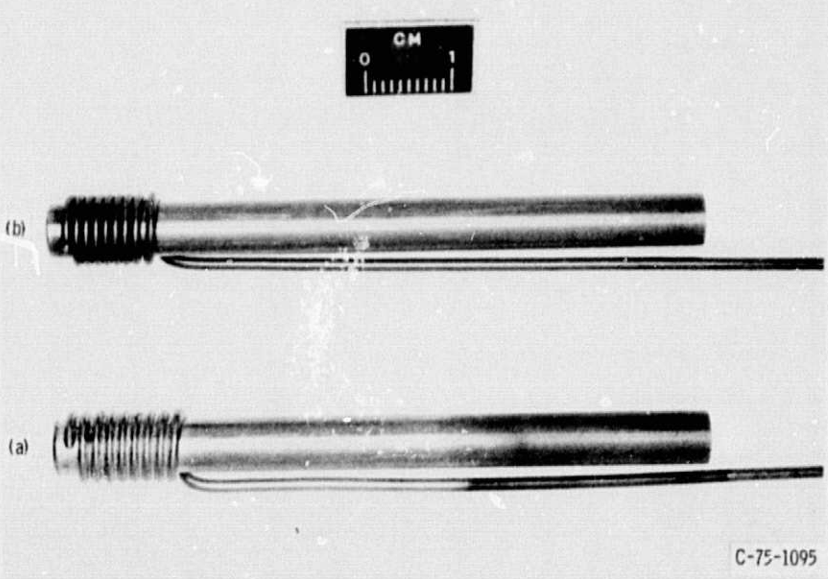

Figure 15. - Swaged tantalum heaters - brazed (a) and non-brazed (b) before thermal cycling.

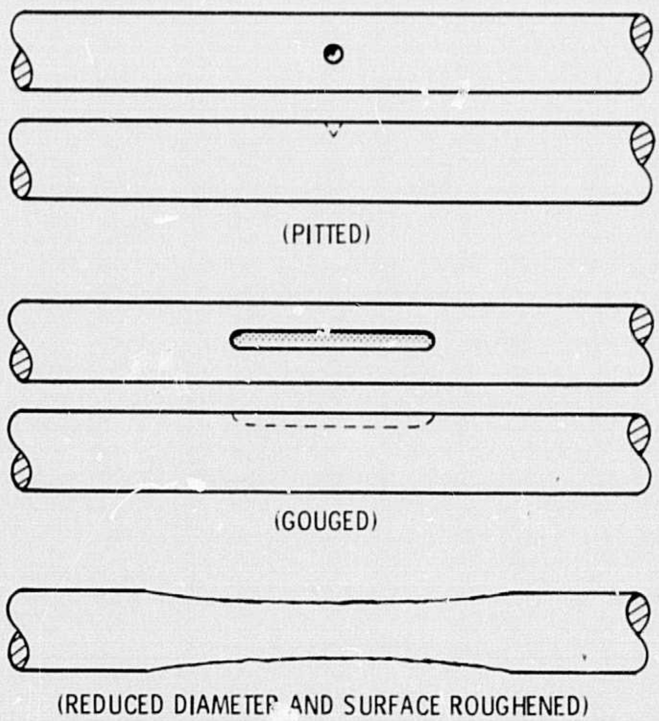

Figure 16. - Typical defects found in tantalum wire (0.508 mm diameter).