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A 10,000-hr Life Test of an Engineering Model Resistojet

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SUMMARY

One of the major issues associated with using resistojet thrusters on Space Station Freedom is the long life required. An engineering model resistojet was life-tested to determine if it was capable of meeting that requirement. This thruster, which was designed for 10 000 hr of operation at 2552.4 °F (1400 °C) or less under cyclical thermal conditions, successfully operated for 10 036 hr at 1836 °F (1002 °C) while undergoing 141 thermal cycles.

INTRODUCTION

A 10 000-hr life test of an engineering model resistojet (serial number 002, fig. 1) was conducted to determine if this thruster could meet a design requirement of 10 000 hr of operation at 2552.4 °F (1400 °C) or less while undergoing cyclical thermal stress (ref. 1). In addition to testing the design's ability to withstand the conditions cited, this test addressed the design's mechanical aspects. It did not address the so-called "multipropellant" aspects of the design; that is, the ability of the thruster to withstand these conditions while alternately using oxidizing and reducing gases as propellants. The only fluids used as propellants during this test were carbon dioxide and nitrogen.

Resistojets have been proposed as a way to eliminate the waste gases that will be generated continuously on S.S. Freedom while it is in operation (ref. 2). These waste gases will come primarily from the Environmental Control and Life Support System (ECLSS) and the various experiments on board. Projections indicated that any resistojet used on S.S. Freedom would need to last at least 10 000 hr (ref. 3). Such a life had not been demonstrated in an existing resistojet, so this test was needed to determine if the thruster design, in its present form, was a viable candidate for use on S.S. Freedom.

This report describes the thruster, the equipment used to test it, the test procedure and how it was determined, and the results of the test. Included in the results are periodic throat diameter and specific impulse measurements, along with a statistical analysis of the achieved cycle parameters. In addition, a new and more accurate resistance-temperature curve (fig. 2) was obtained; it should replace the curve in reference 1.

APPARATUS

The test chamber, shown in figure 3, consisted of a 24-in.-diam (61-cm) by 36-in.-long (91-cm) bell jar attached to a 730-ft^3 (180-m^3) per minute rotary piston vacuum pump. When pumped down and under no-flow conditions, this facility was capable of maintaining a 0.00126-psi (0.065-torr) vacuum. During testing with carbon dioxide (CO_2) and nitrogen (N_2) flowing through the thruster, these values were 0.0058 and 0.0097 psi (0.3 and 0.5 torr), respectively. In figure 4, the open test chamber shows the thruster mounted in its test position.

A variety of problems - from nozzle erosion due to particles, to mechanical property degradation due to unknown gases - can result from impurities in the fluid propellants. To minimize these effects, only highly pure fluids were used as propellants. The carbon dioxide was instrument grade with a minimum purity of 99.99 percent, that is, less than 100 ppm noncondensibles and less than 220 ppm oxygen; the nitrogen was liquid nitrogen boil-off that was routed throughout the building containing the test chamber.

At the beginning of this test an amperage-controlled direct current power supply provided power to the thruster. In cycle 4 a problem developed that made necessary a switch to an alternating current power supply As a result, the thruster was powered by a 60-cycle, voltage-controlled alternating current. This problem is discussed in detail in the RESULTS AND DISCUSSION section.

HEATER TEMPERATURE-RESISTANCE CURVES

At the beginning of this life test, the best information available on heater resistance as a function of temperature was a graph from the contractor (see ref. 1). Investigation revealed that this curve was calculated by using material properties. So that the temperature results of this report could be more confidently reported, a new curve was generated by using a virtually identical thruster (serial number 001) that was manufactured under the same contract.

This thruster (serial number 001) had been previously modified by cutting three windows in it to provide access to the heater sheath. One thermocouple per window was welded to this sheath, as shown in figure 2 (thermocouples 1 to 3), and a fourth thermocouple was welded to the lead end of the thruster. Thermocouple 4 monitored the heater temperature at the lead connection so that melting of the braze material connecting the heater to the leads could be prevented.

To minimize the effects of radiation losses on this test, the windows that had been cut in the thruster were completely covered by a nickel-based superalloy sheet, which was wrapped around the thruster and fastened. To minimize conduction losses, the test was conducted in a high-vacuum facility capable of pressures in the range of 1.0×10^{-6} torr.

The result of this test, which was run using a direct current power supply, is presented in figure 2. Great care was taken to ensure that the thruster was at thermal equilibrium when the measurements were made; however, no corrections were made for radiation or conduction effects. Note that for a given heater resistance, the actual temperature appears (at least at about 2192 °F, i.e., 1200 °C) to be approximately 300 °F (167 °C) less than the original curve would indicate. Such a difference would signify that the maximum heater temperature actually achieved by this thruster during thermal cycling was 1836 °F (1002 °C). Consequently, any further testing of this thruster should use the curve generated for this report, not the curve in reference 1.

TEST SPECIMEN

The engineering model resistojet shown in the cutaway view in figure 5, consists of a hollow, cylindrical, platinum heat exchanger around which a platinum resistance heater element is wrapped. In figure 6, the heater and heat exchanger sections have been removed from the body of the thruster to better illustrate this configuration. Located around the outside of the heater element are a series of heat shields designed to reduce the radiation losses of the thruster. The nozzle through which the working fluid is accelerated and exhausted is attached to the end of the heat exchanger. Figure 7, a cross section of the thruster, better shows the passages through which the propellant fluid flows while being heated.

The engineering model resistojet is operated by applying electrical power to the resistance heater, which causes the heater's temperature to rise. This energy is then conducted and radiated to the encased heat exchanger through which the gas propellant is flowing. The heated gas is then accelerated and expanded through a nozzle, thereby providing thrust.

Prior to the beginning of the test, three thermocouples were attached to the outside of the thruster, as shown in figure 5. These thermocouples were used to monitor the shell temperatures during testing and to provide information on the radiation losses of the thruster.

TEST PLAN

Thermal Cycle Determination

In determining the test procedure, several assumptions were made about how the thruster would be operated on S.S. Freedom. These assumptions, which formed the basis for an attempt to duplicate the anticipated operating conditions there, are explained in this section.

<u>(1) User contamination</u>. - On the basis of user contamination limits for S.S. Freedom, the resistojet thrusters were assumed to operate once every 14 days during a nonquiescent period. (A nonquiescent period occurs when contamination limits are suspended and operations such as venting and thruster operation are permitted.) During this period, all waste gases generated (ref. 2) since the last period of operation must be exhausted.

<u>(2) System configuration</u>. - A resistojet system consisting of four thrusters operating simultaneously was assumed (ref. 3).

<u>(3) System operating conditions</u>. - A resistojet heater temperature of 2192 °F (1200 °C) and a constant power-variable flow control method was assumed (ref. 3). The constant power input to the thruster was chosen as 500 W, with the flow being varied to maintain the chosen heater temperature. This control method would provide the maximum flexibility for mission planning, while also

allowing operation with the greatest propulsive efficiency (thrust per unit of fuel or specific impulse I_{sp}) which is defined as

$$I_{sp} = \frac{\text{thrust}}{\text{propellant mass flow rate}}$$

For any given heater temperature, a simple adjustment of the chamber pressure for any gas or gas mixture will permit operation at the maximum I_{sp}.

On the basis of the preceding assumptions and the anticipated waste fluid inventory for 1995, as generated by the Bosch ECLSS (ref. 2), a continuous run time of approximately 3 days was determined. A cool-down period of at least 4 hr to ambient conditions followed.

Health Monitoring

To keep track of how the thruster was holding up, the throat diameter, the specific impulse I_{sp}, and the leak rate of the thruster were periodically monitored. The throat diameter and I_{sp} measurements are presented in the RESULTS AND DISCUSSION section. An initial attempt at performing a helium leak check of the thruster proved futile. There appeared to be no good way of sealing the thruster nozzle. Consequently, an attempt to check for leaks was abandoned at the outset. This check was not considered crucial since a significant leak would have been indicated by a decrease in I_{sp}.

Gravity Effects

To reduce the effects of gravity on the thruster during testing and to attempt to simulate zero g, the thruster was inverted on its test stand after every 1500 hr of operation at temperature. There was some concern that the tag end of the heater, which was unsupported, could sag under its own weight and precipitate a failure. However, since such a failure would not occur in a true space environment, it could not be considered a deficiency in the design.

TEST PROCEDURE

A thermal cycle began with the thruster under a 0.00126-psi (0.065-torr) vacuum and at ambient temperature, as shown in the three thermocouples attached to the outside shell of the thruster (fig. 4). Alternating current power was applied manually by a voltage-controlled power supply. A rheostat was slowly turned to increase voltage while keeping the amperage below an arbitrarily defined 30 A. When the thruster was receiving 500 W of input power, the fluid flow was started and allowed to stabilize. Initially, the flow was adjusted to maintain 500 W of input power and a heater resistance corresponding to a temperature of 2192 °F (1200 °C). The resistance-temperature curve used was obtained from reference 1. The thruster was allowed to run for approximately 3 days . At the completion of the run, the power and flow were turned off, and the thruster was allowed to return to ambient temperature, thus completing the cycle.

RESULTS AND DISCUSSION

The tested thruster successfully met its design goals and completed 10 036 hr of operation at 1836 °F (1002 °C) and 141 thermal cycles with no noticeable degradation. For the individual cycle parameters, refer to the summarized data in the appendix. Currently, testing has stopped while a decision is being made about whether to continue the test or to dissect the thruster to obtain information on such things as grain growth, erosion rates, and so on.

One anomaly was noted at the beginning of the test when a direct current power supply was being used. During the fourth cycle the voltage began dropping, and the power input to the thruster could not be maintained. Testing was stopped, and a meeting was held with the manufacturer of the heater. At this meeting ion-migration was identified as a likely candidate for the cause of the observed behavior; switching to an alternating current power supply was the suggested solution. After this was done, no further problems were encountered during the remainder of the test.

Note that the data in this report are presented in direct current units throughout to maintain consistency. This was possible because the measured phase angle between the voltage and current vectors for alternating current power was 1°, thereby giving a power factor approximately equal to 1.0.

Throat Diameter Measurements

An optical comparator was used to take throat diameter measurements at approximately 1500-hr increments; the results are plotted in figure 8. If the data points taken at 1500 hr, which are obviously in error, are ignored, the endpoints indicate a nozzle deposition rate of about 0.001246 in. (0.03164 mm) diam per 10 000 hr of operation. Considering that over 17 400 lb of propellant flowed through this thruster during this life test, we can speculate that the decrease in nozzle diameter was due to contaminants in the fluid plating out on the throat.

Specific Impulse (I_{sp}) Measurements

Periodically, the thruster was removed from the test chamber and placed on a calibrated test stand to measure the thrust and flow rate and to determine if they were changing. The specific impulses calculated from these data are presented in figure 9, which shows that there was basically no change since the beginning of the test.

Statistical Analysis of Results

The statistical thermal cycle parameters are shown in table I, and the gas-dependent parameters, in table II. These data were statistically calculated from the summarized data in the appendix.

CONCLUDING REMARKS

The throat diameter measurements presented herein lead to the conclusion that nozzle deposition rates are so low that they can be ignored. It is important to note, however, that the gases used as propellants during this test were either instrument grade carbon dioxide or liquid nitrogen boil-off. This implies low levels of contaminants. If further examination of this thruster shows that the deposition in the throat was indeed caused by impurities in the propellant, careful attention will need to be paid to the quality of the propellant supplied to this thruster during operation.

The curves of specific impulse as a function of time (fig. 9) lead to the conclusion that no significant leaks developed in this thruster during the test. If any leaks had developed, their effect would have shown up as a decrease in the specific impulse. Figure 9 illustrates that the specific impulses for this thruster remained essentially constant throughout the duration of the test.

By surviving the life test, this thruster demonstrated both ruggedness and reliability. It appears to be a perfect candidate for use on S.S. Freedom, which will have long life requirements but minimal extra-vehicular activity available for maintenance.

One problem remains that should be addressed as soon as practical. If there are plans to operate this thruster on direct current power, the problems encountered in cycle four, and discussed in the RESULTS AND DISCUSSION section of this report, should be investigated. In fact, unless the problem is identified and corrected, operating on direct current power for any length of time presents an unnecessary risk and should not be contemplated.

ACKNOWLEDGMENTS

The following people contributed data to the appendix of this report: Robert R. Tacina, Dean W. Harter, and Edward P. Braunscheidel of the NASA Lewis Research Center.

APPENDIX - SUMMARIZED DATA

RUN NO.	LENGTH (HRS)	HEATER VOLTAGE (VOLTS)	HEATER AMPERAGE (AMPS)	*HEATER POWER (WATTS)	*HEATER RES. (OHMS)	*HEATER TEMP. (DEG. F)	MASS FLOW (LBM/HR)	THERMOC. #1 (DEG. F)	THERMOC. #2 (DEG. F)	THERMOC. #3 (DEG. F)	CHAMBER PRESSURE (PSIA)	GAS TYPE
1	63.00	21.4	23.5	503	0.911	1930	1.37					CO2
2	68.00	21.4	23.5	503	0.911	1930	1.53					CO2
3	24.00	21.3	23.5	501	0.906	1912	1.58	791	682	850	27.5	CO2
4	72.00	21.0	23.5	494	0.894	1866	1.49	789	680	814	26.6	CO2
5	46.00	21.4	23.5	503	0.911	1930	1.58	790	684	864	28.0	CO2
6	55.00	21.2	23.5	498	0.902	1896	1.68	774	669	865	29.2	CO2
7	72.00	21.2	23.5	498	0.902	1896	1.77	749	660	880	36.3	N2
8	118.00	21.2	23.5	498	0.902	1896	1.76	774	673	881	35.3	N2
9	28.00	21.2	23.5	498	0.902	1896	1.85	759	699	795	37.5	N2
10	63.00	18.6	23.5	437	0.791	1477	1.93	700	605	725	37.9	N2
11	27.50	20.8	23.6	491	0.881	1817	1.85	764	662	842	37.2	N2
12	25.00	20.9	23.5	491	0.889	1847	1.77	787	673	819	36.0	N2
13	237.00	21.4	23.6	505	0.907	1915	1.80	782	675	870	36.3	N2
14	102.00	21.3	23.5	501	0.906	1912	1.61	703	620	740	27.0	CO2
15	90.00		22.1				1.58	716	624	827	26.8	CO2
16	86.00	18.9	22.3	421	0.848	1692	1.61	712	621	811	26.8	CO2
17	46.00	19.1	22.5	430	0.849	1696	1.65	714	626	834	27.7	CO2
18	88.50	19.1	22.4	428	0.853	1711	1.61	728	635	833	27.3	CO2
19	28.50	19.3	22.5	435	0.858	1730	1.60	729	635	772	27.3	CO2
20	89.00	18.9	22.5	425	0.840	1662	1.77	699	605	787	34.8	N2
21	88.00	19.2	22.6	434	0.850	1700	1.73	671	604	745	34.3	N2
22	75.00	19.2	22.5	432	0.853	1711	1.62	655	594	718	35.3	N2
23	71.00	19.1	22.5	430	0.849	1696	1.76	667	601	711	35.2	N2
24	75.00	19.2	22.6	434	0.850	1700	1.77	663	599	796	35.2	N2
25	71.50	19.2	22.7	436	0.846	1685	1.79	661	595	716	35.2	N2
26	90.50	19.1	22.6	432	0.845	1681	1.79	664	601	736	35.5	N2
27	66.50	19.3	22.7	438	0.850	1700	1.79	666	599	726	34.7	N2
28	89.50	19.0	22.6	429	0.841	1666	1.79	656	596	729	34.8	N2
29	80.00	19.8	22.9	453	0.865	1757	1.76	697	632	754	34.8	N2
30	70.00						1.76					N2
31	67.50	20.7	23.6	489	0.877	1802	1.76	715	654	785	35.5	N2
32	97.50	21.2	23.9	507	0.887	1840	1.79	729	662	788	36.5	N2
33	48.00	21.1	23.8	502	0.887	1840	1.79	725	659	782	36.3	N2
34	72.00	20.2	23.2	469	0.871	1779	1.79	691	629	767	35.8	N2
35	43.50	20.3	23.2	471	0.875	1794	1.76	708	639	777	35.2	N2
36	114.50	20.8	23.7	493	0.878	1806	1.79	720	653	787	36.0	N2
37	68.00	21.0	23.8	500	0.882	1821	1.77	732	661	844	36.3	N2
38	62.00	20.2	23.2	469	0.871	1779	1.77	699	636	808	35.7	N2
39	66.00	20.2	23.0	465	0.878	1806	1.63	717	654	817	27.8	CO2
40	90.50	20.7	23.5	486	0.881	1817	1.63	727	664	823	28.2	CO2
41	75.00	20.6	23.4	482	0.880	1813	1.65	716	656	816	28.7	CO2
42	89.00	20.7	23.6	489	0.877	1802	1.65	719	662	775	28.7	CO2
43	31.00	20.5	23.4	480	0.876	1798	1.63	777	665	821	25.5	CO2
44	66.50	20.6	23.4	482	0.880	1813	1.63	782	667	804	25.5	CO2
45	90.50	21.3	23.7	505	0.899	1885	1.68	808	681	814	31.2	N2
46	65.00	21.6	24.2	523	0.893	1862	1.79	797	678	836	33.2	N2
47	76.50	21.1	23.7	500	0.890	1851	1.65	798	686	840	26.0	CO2
48	73.00	20.7	23.5	486	0.881	1817	1.74	778	658	827	32.0	N2
49	87.00	19.6	22.9	449	0.856	1723	1.70	747	644	830	27.3	CO2
50	87.50	19.0	22.5	428	0.844	1677	1.63	723	621	728	25.2	CO2
51	66.50	20.1	23.0	462	0.874	1791	1.71	750	634	739	30.8	N2
52	65.00	20.7	23.6	489	0.877	1802	1.80	772	652	843	32.8	N2
53	162.00	20.7	23.5	486	0.881	1817	1.77	774	654	829	31.8	N2
54	69.00	19.3	22.6	436	0.854	1715	1.74	736	619	841	31.5	N2
55	70.50	19.8	23.1	457	0.857	1726	1.82	739	626	756	32.3	N2
56	75.50	20.8	23.6	491	0.881	1817	1.74	780	663	787	32.0	N2
57	95.00	20.8	23.6	491	0.881	1817	1.65	765	663	764	27.8	CO2
58	20.00	20.8	23.5	489	0.885	1832	1.65	786	676	812	25.7	CO2
59	39.50	20.8	23.5	489	0.885	1832	1.65	792	678	823	25.7	CO2
60	91.50	20.7	23.5	486	0.881	1817	1.71	770	659	758	32.2	N2
61	64.00	20.6	23.4	482	0.880	1813	1.74	763	651	757	32.2	N2
62	63.50	20.7	23.5	486	0.881	1817	1.77	779	657	849	32.8	N2
63	63.00	20.5	23.4	480	0.876	1798	1.79	768	650	797	32.5	N2
64	93.00	20.3	23.1	469	0.879	1810	1.73	770	650	794	31.8	N2
65	17.50	20.2	23.1	467	0.874	1791	1.76	745	641	772	32.0	N2
66	92.00	20.6	23.5	484	0.877	1802	1.79	706	641	772	35.7	N2
67	64.00	20.9	23.5	491	0.889	1847	1.74	718	652	768	35.7	N2
68	65.00	21.0	23.5	494	0.894	1866	1.70	723	661	747	35.2	N2
69	88.50	21.0	23.4	491	0.897	1878	1.68	734	670	788	34.3	N2
70	89.50	20.3	23.0	467	0.883	1825	1.74	704	638	751	35.5	N2
71	65.00	20.8	23.4	487	0.889	1847	1.68	723	659	759	35.0	N2
72	115.50	20.6	23.3	480	0.884	1828	1.74	728	662	759	36.3	N2
73	19.00	21.0	23.5	494	0.894	1866	1.76	725	657	814	36.0	N2
74	88.00	21.5	23.6	507	0.911	1930	1.77	742	672	825	36.2	N2
75	88.00	21.2	23.7	502	0.895	1870	1.74	734	666	799	36.3	N2

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TABLE I. - MEAN THERMAL CYCLE PARAMETERS

[See appendix for standard deviations, maximums, and minimums.]

Run length, hr	71.12
Heater	
Potential, V	20.7
Amperage, A	23.4
Power,[a] W	485
Resistance,[a] Ω	0.886
Temperature, °F	1836
Thermocouple, °F	
1	740
2	653
3	789

[a]Calculated quantity.

TABLE II. - CO_2- AND N_2-DEPENDENT CYCLE PARAMETERS

Parameter	Chamber pressure, psia		Mass flow, lbm/hr	
	CO_2	N_2	CO_2	N_2
Mean	27.1	34.1	1.61	1.76
Standard deviation	1.14	1.87	.07	.04
Maximum value	29.2	37.9	1.70	1.93
Minimum value	25.2	30.8	1.37	1.62

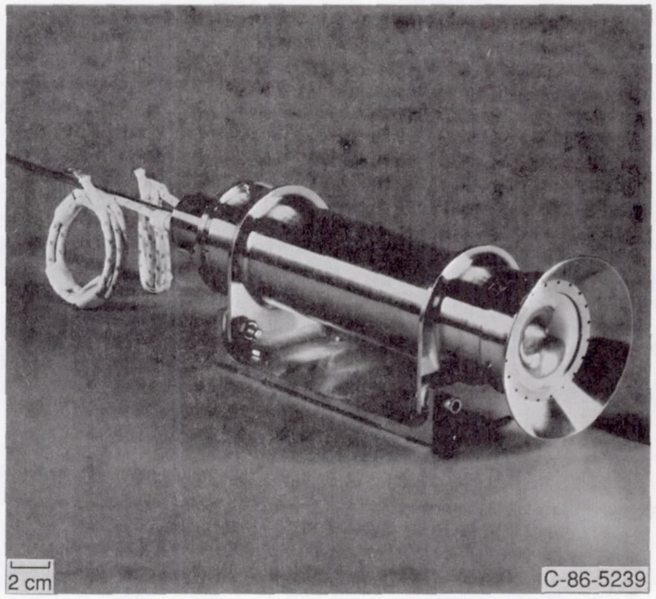

Figure 1.—Engineering model resistojet.

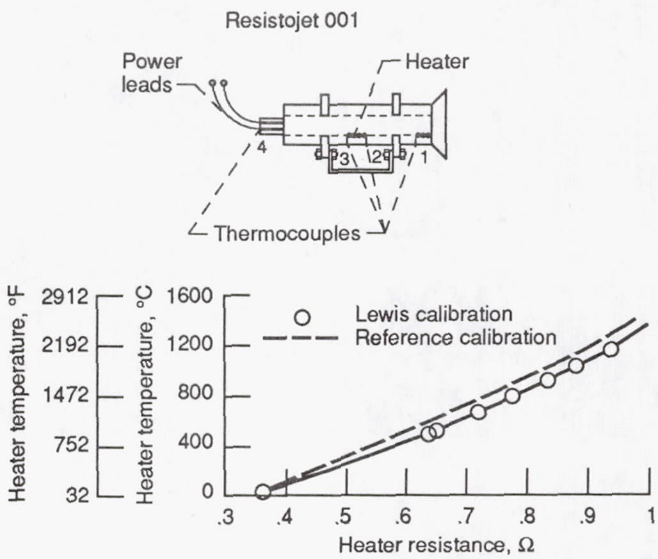

Figure 2.—Heater calibration curve for resistojet thruster 001.

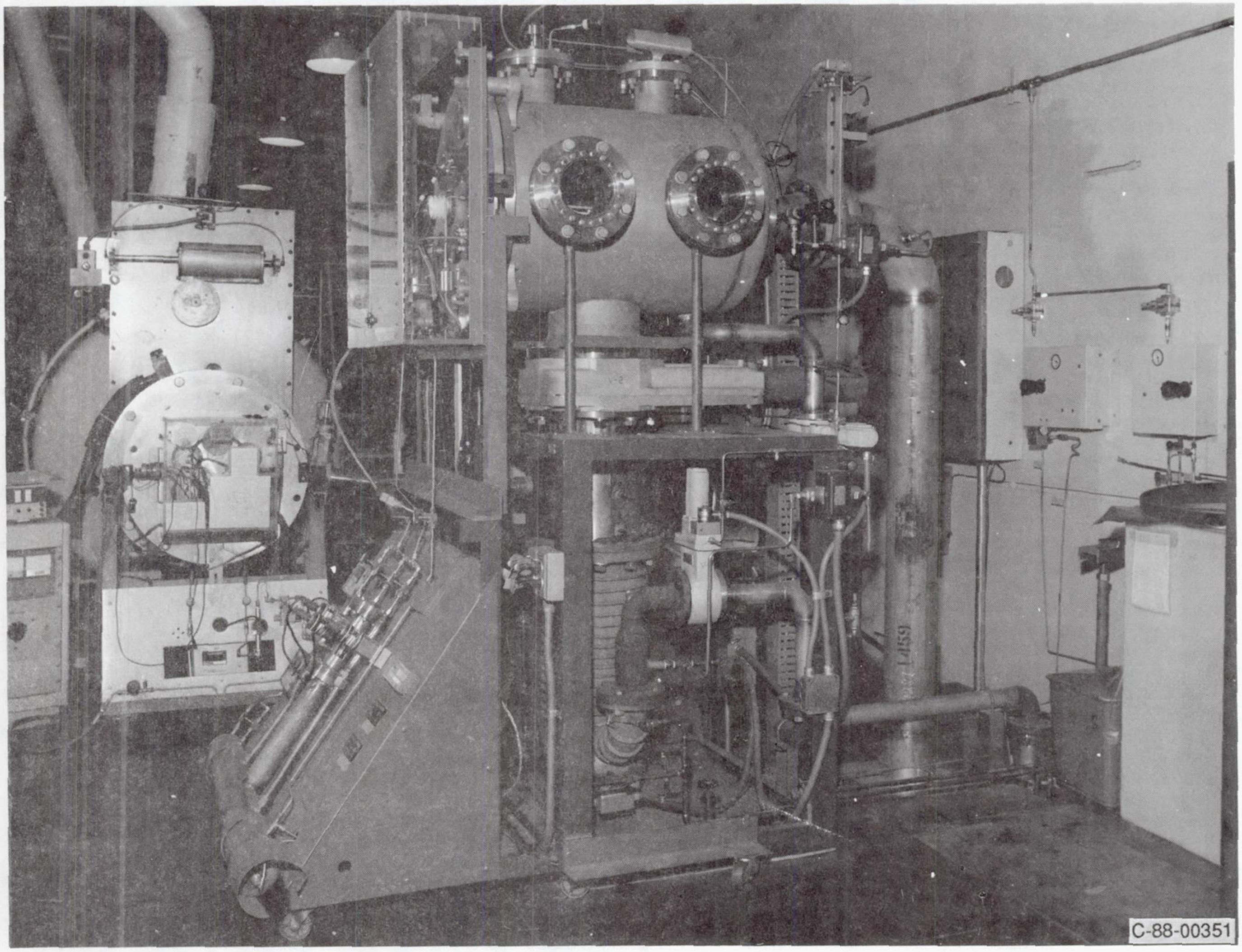

Figure 3.—Test chamber.

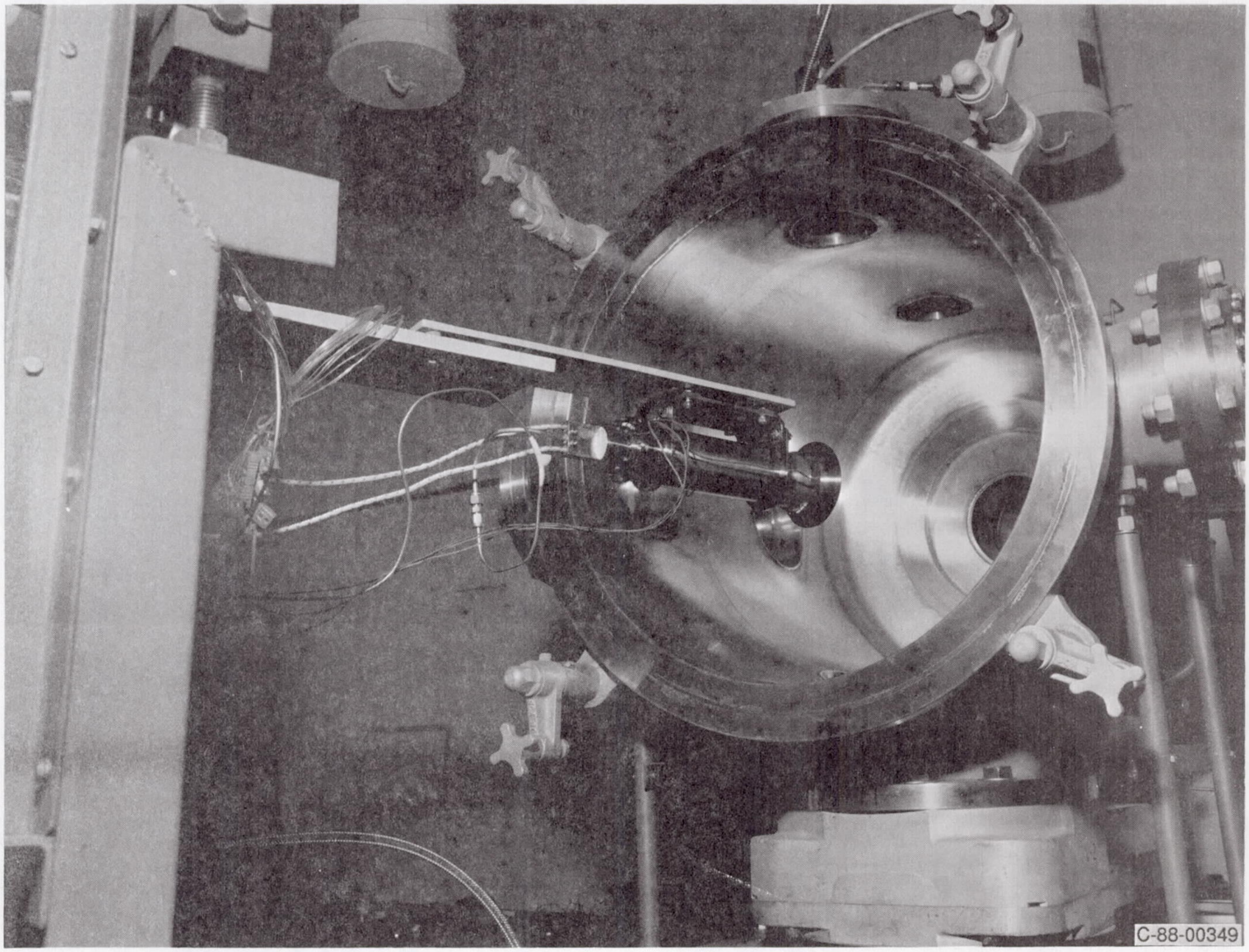

Figure 4.—Thruster mounted in test chamber.

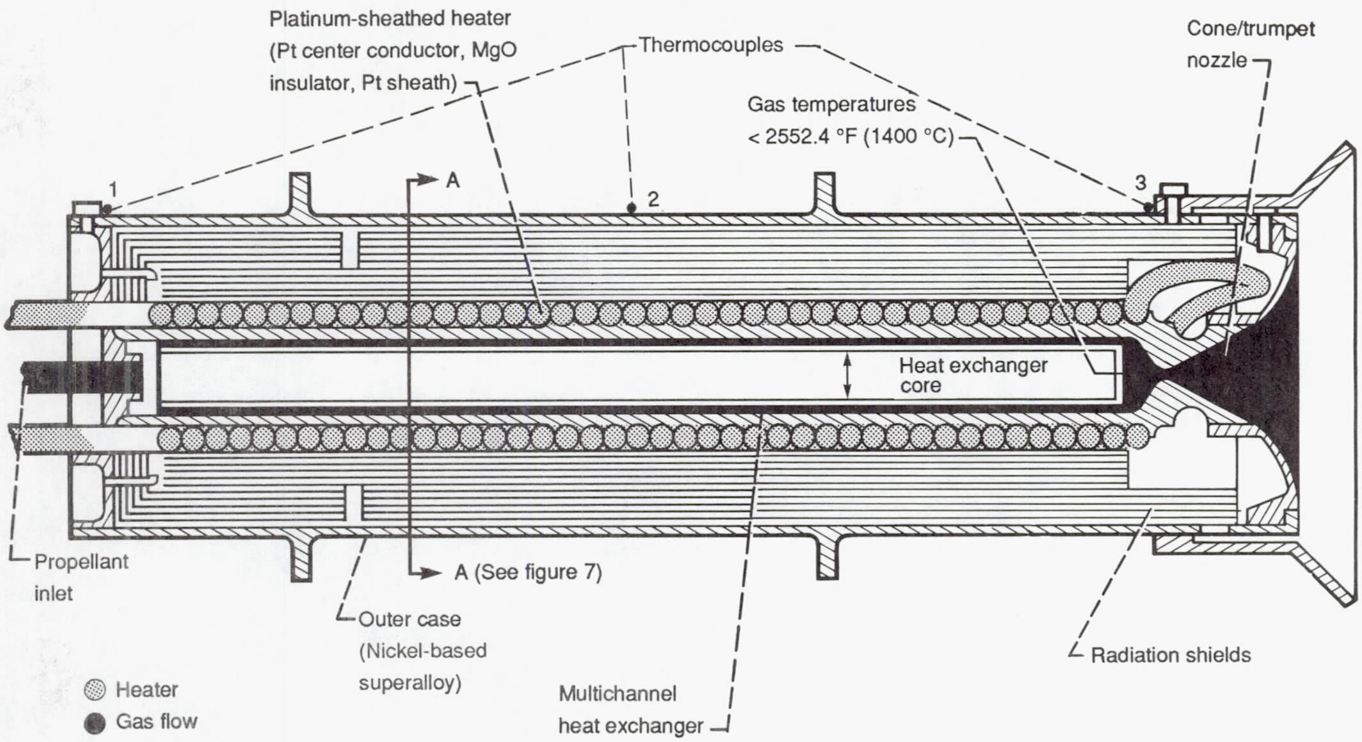

Figure 5.— Engineering model resistojet test specimen.

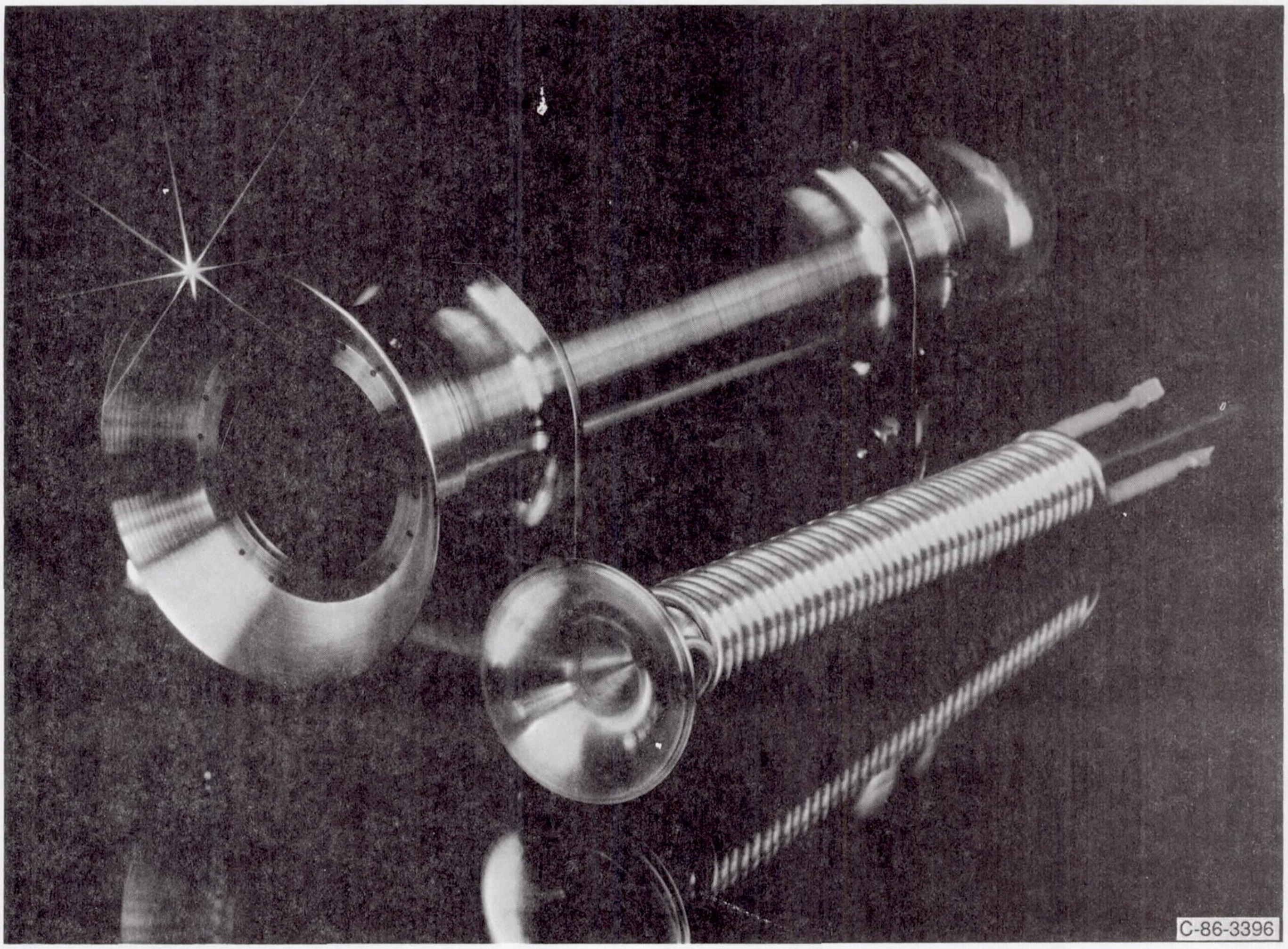

Figure 6.—Heater and heat exchanger assembly removed from thruster.

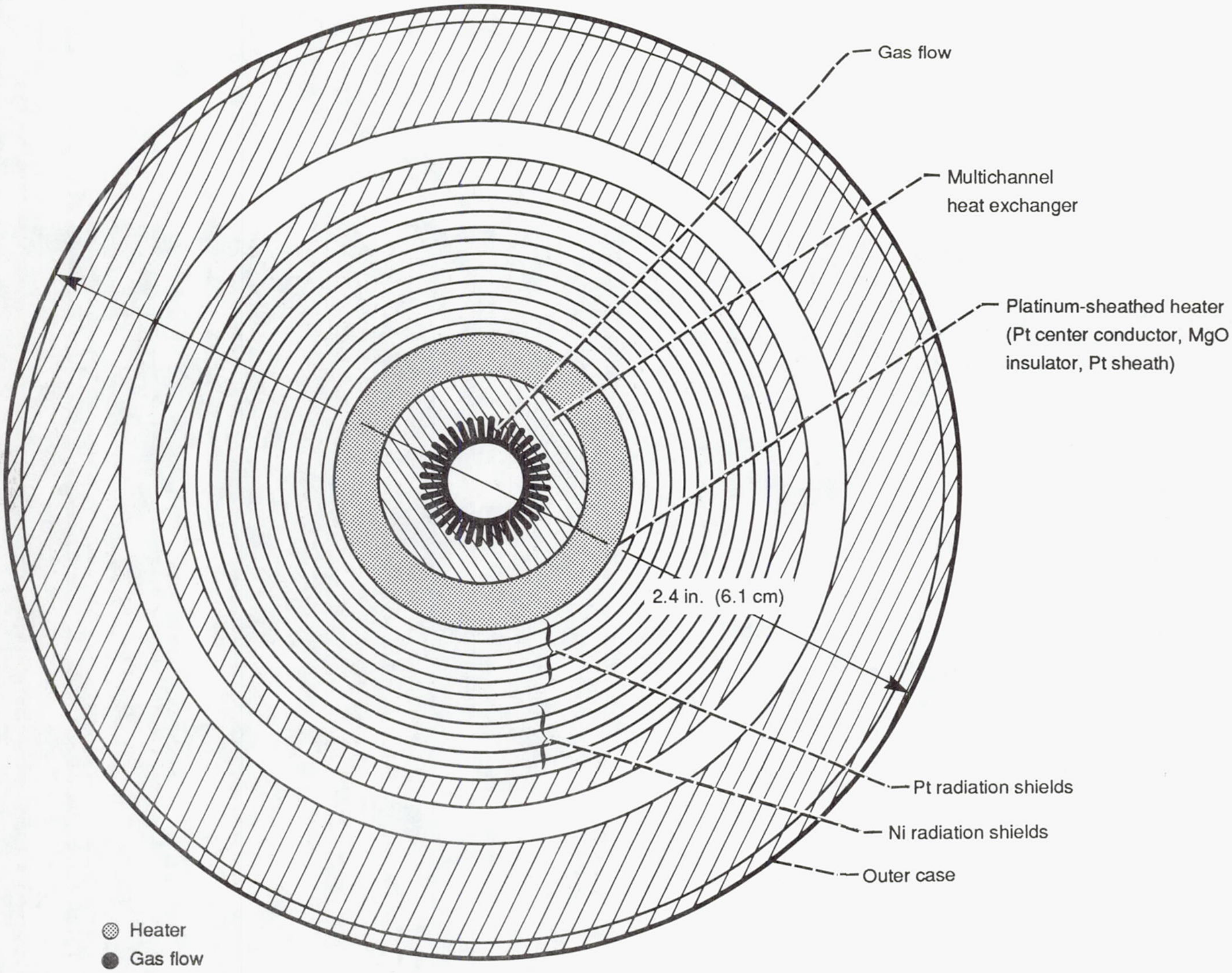

Figure 7.—Section A-A of test specimen.

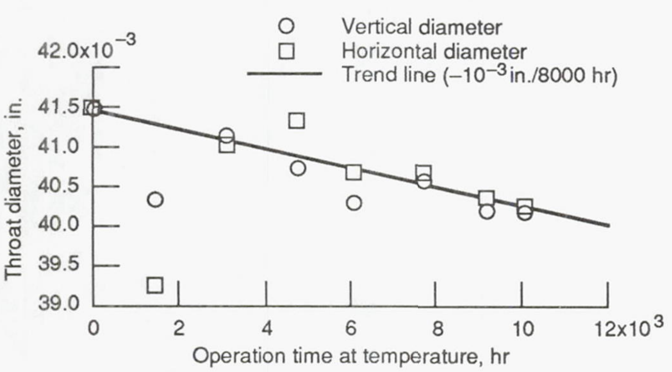

Figure 8.—Change in diameter of thruster throat for engineering model 002.

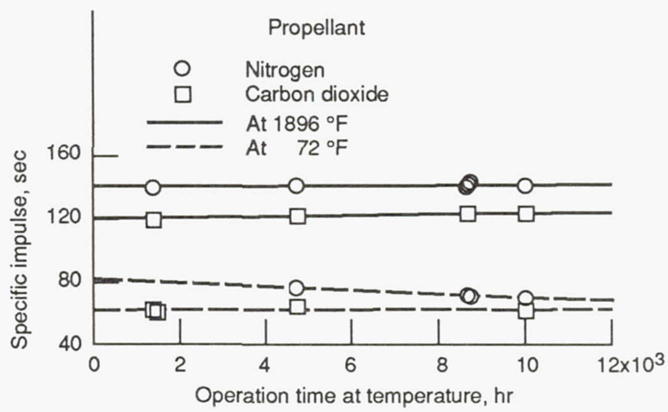

Figure 9.—Specific impulse variation for engineering model 002.

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Report Documentation Page

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16. Abstract

One of the major issues associated with using resistojet thrusters on Space Station Freedom is the long life required. An engineering model resistojet was life-tested to determine if it was capable of meeting that requirement. This thruster, which was designed for 10 000 hr of operation at 2552.4 °F (1400 °C) or less under cyclical thermal conditions, successfully operated for 10 036 hr at 1836 °F (1002 °C) while undergoing 141 thermal cycles.

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