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High- and Low-Thrust Propulsion Systems for the Space Station

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HIGH- AND LOW-THRUST PROPULSION SYSTEMS FOR THE SPACE STATION

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Abstract

The purpose of the Advanced Development Program was to investigate propulsion options for the Space Station. Two options were investigated in detail: a high-thrust system consisting of 25 to 50 lbf gaseous oxygen/hydrogen rockets, and a low-thrust system of 0.1 lbf multipropellant resistojets. An effort is also being conducted to determine the life capability of hydrazine-fueled thrusters. During the course of this program, studies clearly identified the benefits of utilizing waste water and other fluids as propellant sources. The results of the H/O thruster test programs are presented and the plan to determine the life of hydrazine thrusters is discussed. The background required to establish a long-life resistojet is presented and the first design model is shown in detail.

Introduction

The purpose of this paper is to present the results of the Advanced Development Program that were specifically concerned with the propulsion systems for the Space Station. Through a process of evaluation a selection would be made, during the phase B Space Station effort, of the propulsion system to be employed on the IOC Space Station. This paper will briefly discuss the program content and the results that have been obtained.

Previous papers have discussed the content of the Advanced Development Program and its purposes in considerable detail.[1,2] The planned thruster programs investigated both a high- and low-thrust propulsion system for the IOC Space Station. The choice of two propulsion systems with differing thrust and operational capabilities provides the Space Station propulsion options that have the capability for a wide variety of propulsion or thrusting capabilities. The propulsion systems selected for study were 25 to 50 lbf gaseous oxygen-hydrogen fueled rockets and the 0.1 lbf multipropellant resistojet. The combination of these two systems provides the Space Station with more possible ways of "flying" than are possible with a single thrust level system. The advantages of the dual-mode propulsion system are obvious ones. While sufficient force is available for all large motions of the Space Station, including contingencies for collision avoidance, delicate maneuvers are continuously possible at a thrust level that will not interfere with scientific research and observations.

One additional benefit of these choices for Space Station propulsion is the synergism obtained by the integration of the propulsion system with other station systems. Sources of propellants are available from the life support system and from the scientific and materials laboratories. Utilization of these fluids alleviates two fundamental problems; resupply of propellants is minimized and the quantity of waste fluids that must be returned to Earth is lessened. The first results in a direct cost saving by reducing the mass to be carried into orbit. The second helps to solve a serious problem of storing and carrying down wastes and thus improves the Shuttles' payload capability in returning to Earth.

This paper will present information on the potential on-station propellant availability, and the results that have been obtained with the both high-thrust and low-propulsion system programs.

Propulsion Requirements

The Space Station propulsion system must be able to provide thrust for altitude maintenance, collision avoidance, attitude control, and momentum management. As the studies have continued during Phase B, the propulsion requirements have gradually risen. Initial requirements and choice of operating mode and altitude have all been rethought during this study phase. Initially, an altitude of 250 nmi was assumed for the Station and altitude reboost would be conducted after each Shuttle docking. Presently the operating mode proposed for the Station is at a lower altitude and in a mode corresponding to an average acceleration of 0.3 micro-g. As the atmospheric density varies over an 11 yr cycle, the altitude required will also vary.

Table 1 compares the total-impulse requirements for a growing and evolving Space Station over an 11-yr cycle for the initial 250 nmi altitude with the present micro-g requirement. These values have been computed by assuming a 1995 IOC station of 500 000 lb mass that grows to 1 000 000 lb in 10 yr. Assumptions as to the frontal area and ballistic coefficient are also used to compute the impulse requirements. The values computed also assume a nominal atmosphere. Note that the altitude has been lowered by up to 70 nmi which certainly eases the problems of the Shuttle getting to the Station. Most significant, however, is the six-fold increase in propulsion requirements. As missions in space go, the Space Station was never considered a mission where specific impulse of the propulsion system was paramount. However, as can be seen by the increased levels of total-impulse; propulsion system specific impulse is becoming more important and improved levels of specific impulse will be sought.

Propellant Source

To augment the thruster research efforts, several studies were conducted that investigated the propellant source and resupply and their impact on thruster system design.[3-5] Initially, those studies assumed that the hydrogen and oxygen would be supplied from supercritical storage tanks similar to the PRSA (Propellant Reactant and Supply Assembly) tanks utilized on the Shuttle. As the studies progressed alternative sources of propellant appeared more attractive. It became apparent from studies of the Environmental Control and Life Life Support Systems (ECLSS) that the Station could have a significant water disposal problem. These studies clearly identified the potential of electrolyzing this water to provide the required oxygen and hydrogen and the concomitant savings possible by minimizing resupply. Additional sources of water were also found. Significant quantities of water are to be found on board the Shuttle and can be transferred to the Station. Such sources include water from fuel cells and waste water. The actual availability of water is still subject to decisions as to the choice of the environment control system - Bosch or Sabatier - and the extent of water stored and withdrawn from the Shuttle. Table 2 shows the yearly levels of water available for each environmental system and assumes Shuttle visits at 45 or 90-day intervals and that Shuttle water is transferred to the station. The total levels of water availability are close to that required and can be substantially more depending on solar year, altitude and whether resistojets are also utilized. As indicated previously, the propulsion requirements for the Space Station have already increased, and may do so again. Assuming a specific impulse for the O/H thrusters of 380 sec at a mixture ratio of 8:1, 10 000 lb of water would be required to meet the total-impulse requirement for the year 1995. As indicated in Table 2 sufficient water could be available to fulfill this propulsion requirement.

Water, however, is not the only potential propellant source. The selection of the multipropellant resistojet adds significantly to the overall propulsion capability of the Station. Continuing studies indicate that there are large quantities of waste gases that could be made available for propulsion. If these gases are not utilized for propulsion, then they must be stored and disposed of by a suitable means. That could mean that these excess or waste fluids would be returned to earth. Table 3 lists the levels of fluids available from the Bosch and Sabatier environmental systems. Table 4 lists other fluids that are believed to be available from the Materials Technology Laboratory (MTL). Rather than vent or return these gases to Earth we propose to use them as propellants for the resistojet. The total availability of all fluids from all sources is given in Table 5, assuming that the Sabatier System is chosen for ECLSS. This level of propellant supply when coupled with that available from the electrolysis of water clearly goes a long way toward supplying the Station propulsion requirements.

High Thrust Propulsion

The high thrust propulsion system was selected to be gaseous oxygen-hydrogen fueled rockets. The presumed thrust level was chosen to lie within the 25 to 50 lbf range. While no absolute thrust size could be predetermined, this size seemed the correct one to identify any technology issues. This program specified that the O/F mixture should be 4:1 for these rockets as this would provide maximum values of specific impulse. Later, the potential use of propellants from water required that tests be conducted at a mixture ratio of 8:1. The program goal was primarily life oriented. Performance (specific impulse) would be sacrificed to achieve long operation life. This effort to investigate life capability of small rockets is just beginning and will continue with more emphasis on 8:1 mixture ratios.

Three small rockets, provided by three different manufacturers were included in this program. Aerojet TechSystems provided a 25-lb thruster and Bell Aerospace provided a 50-lbf thruster; both under contract to NASA Lewis. Rocketdyne provided a 25-lbf thruster, constructed as part of their IRAD program, to Marshall Space Flight Center where the performance and life tests were conducted.[8] The results of these test efforts have been extensively reported elsewhere.[6-9] Table 6 compares the basic design parameters of the Aerojet, Bell, and Rocketdyne thrusters. Figure 1 shows the Aerojet thruster mounted on a thrust stand. Figures 2 and 3 are photographs of the Bell and Rocketdyne thrusters respectively. These thrusters all operate at modestly low chamber pressure and have similar overall dimensions. They do, however, differ markedly in the design approach taken, method of fuel injection, nozzle area ratio, and extent of regenerative cooling employed.

When the decision was made to test these thrusters at a mixture ratio of 8:1, it was clear that some thruster design modification was in order. Time did not permit a redesign of each thruster, so compromises were made. For example, the Aerojet thruster with regenerative cooling of the 100:1 area ratio nozzle should have been redesigned to a smaller area ratio. As this was not possible, the effect was simulated by cooling the hydrogen to a level such that fuel injection temperature would be that value estimated for less regenerative cooling. In a similar manner the Bell thruster material was changed to Hastelloy X from 347 stainless steel and the hydrogen cooling flow was held constant. This resulted in a higher thrust and chamber pressure at a mixture ratio of 8:1. The Rocketdyne thruster had the regenerative cooling flow rerouted, utilizing down-pass cooling instead of up-pass cooling. At no time were any operational difficulties encountered and the test program proceeded as planned. Table 7 lists the total number of seconds of testing for each thruster at mixture ratios from 2:1 to 8:1. Note that large times were obtained at mixture ratios of 7:1 and 8:1. Table 7 also shows the total impulse demonstrated by each thruster over the same range of mixture ratios. The life goal 2×10^6 lbf/sec was achieved by the Rocketdyne thruster. Time and funding limited the test programs with Aerojet and Bell but large values of total-impulse were obtained at high mixture ratios.

These results clearly illustrate that the program goal for life was obtainable. Indeed, an examination of the physical state of the thrusters leads one to conclude that the actual obtainable life is substantially greater. It is important that the life of such thrusters be determined for two reasons. First, just to know and have a reasonable expectation of what life might be planned for, and secondly, to determine the failure modes that lead to life limitation. Future tests are planned to address these issues, as well as to strive for increased levels of specific impulse. It is also important to recognize that these life results were obtained with three different design concepts, provided by three separate contractors.

Figure 4 compares the specific impulse performance obtained with the Aerojet and Bell thrusters over the mixture ratio range from 2:1 to 8:1. Both thrusters suffered significant decreases in specific impulse as mixture ratio increased. The data obtained with the Bell thruster were taken with a fixed configuration and a fixed hydrogen flow rate in order to assure adequate cooling of the throat. Thus chamber pressure and thrust level were increasing as mixture ratio increased from 4:1. The Aerojet data were obtained with varying splits of hydrogen used for film cooling; up to 92 percent being used for film cooling at a mixture ratio of 8:1. These losses in performance for both designs were greater than anticipated and reflect nonoptimized designs. Performance improvements can be obtained by redesigning these thrusters and recognizing that operation will be required over a wide range of mixture ratios, but with primary operation near a mixture ratio of 8:1. The impact of such design changes on total life of the thrusters will have to be determined.

Hydrazine Thruster Life Test

The requirement that any propulsion system for the Space Station exhibit long life has led to an investigation of the life capability of hydrazine-fueled thrusters. Generally, the actual operating lifetime of such thrusters is poorly known. The life requirement of the Space Station makes the determination of component life and the evaluation of life improvement concepts of critical importance. At the Lewis Research Center we have undertaken an effort to determine the actual useable life of a small, 5-lbf, hydrazine thruster. The thruster is provided to the program by Rocket Research under the aegis of a cooperative agreement with NASA. The thruster will be instrumented and installed on a thrust stand in the Rocket Engine Test facility (R.E.T.F.). Figure 5 is a photograph of the thruster provided for test by Rocket Research. This thruster incorporates their latest technology to obtain long life from the catalyst bed. A spring mechanism surrounding the catalyst bed will continually apply compression to the catalyst bed to prevent the formation of and/or collapse any void channels. It is the presence of large voids or channels within the catalyst bed that cause rough operation (chamber pressure fluctuations) leading to reduced operational life.

The Rocket Research thruster will be tested over an operational cycle of steady-state and pulse firing that simulates the Space Station duty cycle. The program will attempt to obtain 2 million lb/sec of total impulse from the present thruster and performance and chamber pressure will be continually monitored. Figure 6 shows a small thruster mounted on the test stand in RETF. The thruster will exhaust into the diffuser shown at the left to assist in maintaining a low pressure within the test capsule. A low pressure is obtained primarily by the use of air ejectors which are capable of providing continous low pressure for these tests. Future tests are planned where the life capability of the Aerojet and Bell H/O thrusters will be determined.

Low Thrust Propulsion System

The application of the resistojet as a Space Station propulsion system imposes new operational considerations on the design of such thrusters. Use of resistojets in a wide variety of spacecraft applications is well known and documented.[10,11] Resistojets for these applications may be characterized as having a requirement for maximum specific impulse, short operating lives, and use with a single propellant. As has been indicated previously, the primary criteria for a Space Station resistojet are long life and operation with a wide variety of potential propellants.[2,3]

Since the Space Station resistojet has different criteria from high performance resistojets, it is critical that the design chosen be based on a solid foundation. First and foremost, it was obvious that material-propellant compatibility had to be addressed in order to select a resistojet material that could be expected to provide the useful life required. The wide variety of possible propellants from ECLSS, MTL, attached, payloads or other sources all had to be studied. A resistojet material had to be selected that would have minimum interaction with such propellants. For our studies we examined two forms of grain stabilized platinum. Platinum had been a previous choice for a biowaste resistojet considered in the 1970's because of its excellent resistance to corrosion and oxidation. Resistance to grain growth, a time at high temperature phenomenon, was required to minimize the likelihood of stress-rupture. The program studied both yttria and zirconia grain stabilized platinum materials.

Figure 7 shows the test chamber used to evaluate the Platinum alloy heaters in contact with potential propellants. These tests were conducted with H_2, CH_4, CO_2, NH_3, N_2 and steam in a flowing gas environment at a pressure of about 1.4 atm. All tests except those containing CH_4, either alone or in mixtures, were conducted at a heater temperature of 1300 to 1400 °C. Gases containing CH_4 were tested at a temperature of 500 °C to avoid thermal decomposition of CH_4. These tests were conducted for as long as 2000 hr and have been reported in detail in Refs. 12 and 13. Test results are summarized in Table 8 and indicate that from a material, or mass loss, standpoint, a 10 000 hr operational life should be easily obtained with all propellant-material combinations studied. Figure 8 shows a micrograph cross-section of the heater tube both before, and after a 2000-hr test at 1300 °C with CO_2. No significant grain growth has occurred and surface attack by CO_2 has been minimal. Surface attack was significant with ammonia at 1400 °C, and though no mass loss was observed, a life of 10 000 hr would probably not be obtained. When the heater temperature was reduced below 1000 °C surface attack virtually disappeared.

These tests have recently been expanded to include hydrazine as a potential resistojet propellant. Tests of up to 1000 hr have been conducted with yttria-stabilized platinum at temperature of 1000 and 1400 °C. Similar results to those obtained with ammonia have been obtained.[14] That is, surface attack at 1400 °C, but no noticeable effect when the temperature was lowered to 1000 °C.

These tests served several valuable purposes. The compatibility of the platinum material was confirmed with many potential propellants, useful lifetime data were obtained and where material-propellant attack occurred, a useful operational temperature range has been determined.

A further evaluation of the resistojet as a structure was obtained by conducting a 2000-hr life test using CO_2 as the propellant. The purpose of this test was to determine the impact of cyclic thermal and mechanical stresses on the platinum material as well as the welded joints. At the conclusion of the tests the thruster shown in Fig. 9 was sectioned to examine the interior surfaces for attack. As expected, there was no effect of this test on the structure that could lead to a life limiting problem. These tests help to establish the basic design and operating parameters for the resistojet for Space Station application. Table 9 lists these parameters for a variety of possible propellants. The fundamentals of the design are; a maximum heater temperature of 1400 °C, a power level of 500 W, and a design operating life of 10 000 hr. Also shown in the table are expected values of specific impulse and thrust with the various propellants. The laboratory model resistojet shown in Fig. 9 was operated with these propellants and the performance values obtained are shown in Fig. 10.

Figure 11 is a photograph of the resistojet constructed for use on the Space Station. Figure 12 is a cross-sectional sketch of this resistojet with the major-features identified. This design is a result of a Rocketdyne/Technion effort, on contract to NASA Lewis. The design choices, features, and construction details are to be found in Ref. 15. Four resistojets of this type are to be constructed and used in performance characterization and life tests. Based on the information obtained from these extensive tests, the resistojet will be redesigned to correct any life and/or performance deficiencies. The redesign also has a goal to reduce the amount of platinum required and to simplify the construction and assembly, where possible.

Concluding Remarks

The Advanced Development Program explored propulsion options in detail and produced results that have indicated major economies for the Space Station by their use and their ability to utilize waste fluids as propellants. The Space Station baseline propulsion system has been changed to the high-thrust oxygen-hydrogen and low-thrust multipropellant resistojet propulsion systems. The advantages to the station by the use of this dual-mode approach will continue to grow if the demands for increased propulsion capability escalate with time. Program efforts will continue as the issues of life determination and failure modes are very important and require a long-term dedicated effort.

Acknowledment

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TABLE 1. - TOTAL-IMPULSE REQUIRED FOR REBOOST/ALTITUDE MAINTENANCE

[Nominal atmosphere assumed.]

Year	Variable altitude average, 0.3 micro-g		Nominal 250 nmi altitude
	Altitude, nmi	Impulse, lbf/sec	Impulse, lbf/sec
1995	189	3 840 854	657 840
1996	184	4 500 470	358 910
1997	180	5 054 046	313 331
1998	180	4 855 411	278 491
1999	180	5 356 076	306 930
2000	192	4 753 118	523 467
2001	202	5 274 946	1 027 970
2002	213	5 967 411	1 905 387
2003	221	6 480 000	2 646 000
2004	210	7 478 224	2 162 223
2005	205	7 621 082	1 718 600
Total		61 181 635	11 899 149

TABLE 2. - WATER AVIALABLE FOR PROPULSION lbm/yr

Options	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
45 Day visits Bosch ECLSS	18 140	18 630	18 480	18 970	18 815	19 305	19 155	19 645	19 490	19 980	190 610
90 Day visits Bosch ECLSS	9 735	10 185	10 030	10 520	10 370	10 860	10 710	11 195	11 045	11 530	106 180
45 Day visits Sabatier ECLSS	15 585	15 425	15 280	15 130	14 980	14 830	14 675	14 525	14 370	14 220	149 020
90 Day visits Sabatier ECLSS	7 175	6 985	6 830	6 680	6 530	6 380	6 230	6 075	5 925	5 770	64 580

TABLE 3. - SUMMARY OF FLUIDS AVAILABLE FOR PROPULSION FROM ECLSS lbm/yr

Fluid	Year									
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
(Bosch) Hydrogen	41.4	51.8	51.8	62.1	62.1	72.5	72.5	82.8	82.8	93.2
(Sabatier) CO2	564	705	705	846	846	987	987	1128	1128	1269
Methane	371	464	464	557	557	649	649	742	742	835
Total CO_2/CH_4	935	1169	1169	1403	1403	1636	1636	1870	1870	2104

TABLE 4. - ESTIMATE OF FLUIDS AVAILABLE FOR PROPULSION FROM MTL lbm/yr

Fluid	Year									
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Argon	56	63	70	77	84	90	97	104	111	118
CO_2	21.3	24	27	29	32	34	37	40	42	45
Helium	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5
Nitrogen	314	353	391	430	468	507	545	584	622	661
Hydrogen	.3	.3	.4	.4	.4	.5	.5	.5	.6	0.6
Totals	395.6	444.8	493.4	541.9	590.4	638	686.5	736	783.6	833.1

TABLE 5. - TOTAL OF FLUIDS AVAILABLE FROM ALL SOURCES WITH SABATIER ECLSS lbm/yr

Fluid	Year									
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Argon	403.2	415.5	427.8	440.2	452.2	463.6	475.9	488.2	500.4	512.7
CO_2	149.9	167.6	185.1	202.6	220.6	237.6	255.6	273.6	290.6	308.6
Helium	78.8	87.4	96	104.6	113.2	121.9	130.5	139.1	147.8	156.3
Hydrogen	35.7	40	44.5	48.8	53.1	57.6	61.9	66.2	70.7	75
CO_2/Methane	935	1169	1169	1403	1403	1636	1636	1870	1870	2104
Nitrogen	458	514.7	570.3	627	682.7	739.3	795	851.7	907.3	964
Krypton	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
Totals	2080.4	2414	2512.5	2846	2944.6	3275.8	3374.7	3708.6	3806.6	4140.4

TABLE 6. - H/O THRUSTER INITIAL DESIGN GOALS

	Rocketdyne	Aerojet	Bell
Thrust, lbf	25	25	50
Specific impulse, sec	415	440	410
Nozzle area ratio	30	100	40
Chamber pressure, psia	100	75	75
Throat diameter, in.	0.42	0.5	0.69
Exit diameter, in.	2.3	5.0	4.39
Type	Regen cooled	Regen cooled	Film cooled

TABLE 7. - O_2/H_2 THRUSTER TEST SUMMARY

Mixture ratio, °F	Aerojet		Bell		Rocketdyne	
	Total duration, sec	Total impulse, lbf/sec	Total duration, sec	Total impulse, lbf/sec	Total duration, sec	Total impulse, lbf/sec
2	60	1 302	-----	-------	------	---------
3	180	5 107	275	13 470	32 148	803 700
4	4 039	89 526	1 619	79 637	12 697	317 425
5	224	5 576	124	6 123	408	10 200
6	221	4 728	83	4 367	478	11 950
7	17 560	428 997	65	3 449	440	11 000
8	118	3 221	3 116	225 607	40 237	1 005 925
	22 402	538 457	5 282	332 653	85 968	2 149 200

TABLE 8. - SUMMARY OF GRAIN STABILIZED PLATINUM EXPERIMENTS

Propellant	Coiled heater temperature, °C	Heater initial mass, g	Coiled heater mass loss g[a]	Extrapolated life,[b] hr
Platinum - Yttria				
CO_2	1400	9.0194	0.0030	300 000
CH_4	500	12.6384	.0008	1 500 000
H_2	1400	12.6589	.0062	200 000
NH_3	1400	12.5982	.0055	200 000
H_2O	1400	13.0695	.0116	113 000
Platinum - Zirconia				
CO_2	1400	13.1955	0.0016	800 000
CH_4	500	11.6969	.0000[c]	1 000 000
H_2	1400	13.2093	.0031	400 000
NH_3	1400	13.0632	.0066	200 000
H_2O	1400	11.5133	.0245	45 000

[a]After 1000 hr operation.
[b]Time to 10 percent mass loss.
[c]0.0001 g, accuracy of balance.

TABLE 9. - SPACE STATION MULTIPROPELLANT RESISTOJET PERFORMANCE GOALS

Propellant	CO_2	H_2O (Steam)	CO_2/CH_4	N_2H_4 decomp. prod.	H_2
Thrust, mlbf	110	90	85	90	30
Specific impulse, s	130	200	160	250	500
Power, w	500	500	500	500	500
Design life, hr	10 000	10 000	10 000	10 000	10 000
Total impulse per thruster, lbf-s	$4x10^6$	$3x10^6$	$3x10^6$	$3x10^6$	$1x10^6$
Yearly resupply impulse for reboost, ref. ss config. lbf-s	$2x10^6$	$2x10^6$	$2x10^6$	$2x10^6$	$2x10^6$
Mass throughput at design life, lbm	30 500	16 200	19 100	13 000	2 200

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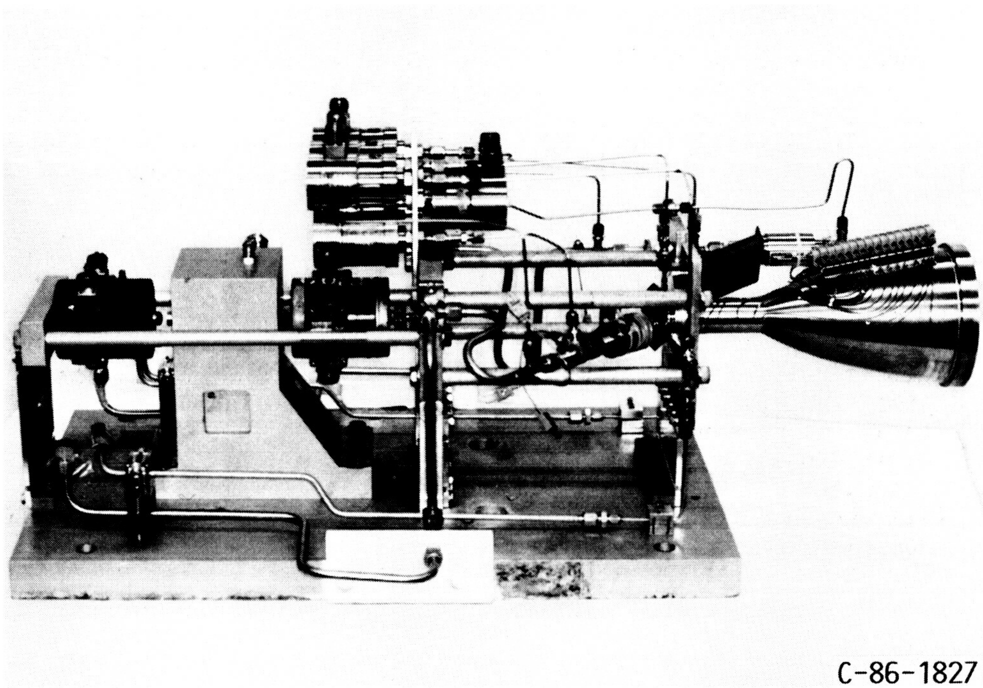

FIGURE 1. - AEROJET 25-lbf ROCKET ENGINE ON THRUST STAND.

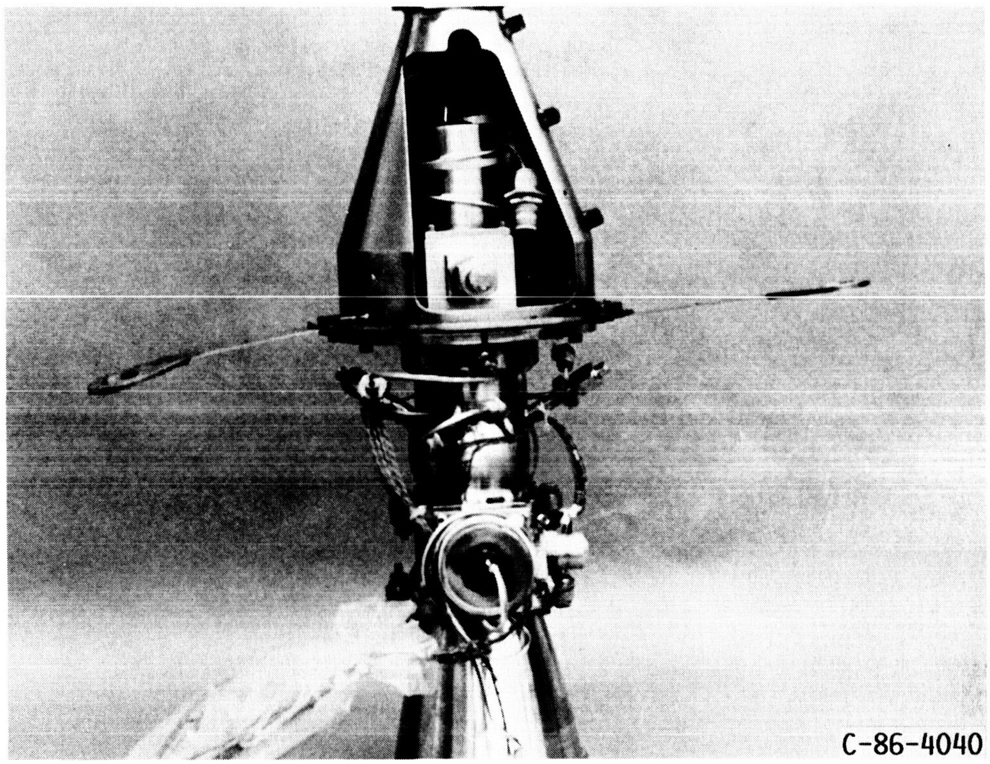

FIGURE 2. - BELL AEROSPACE 50-lbf THRUST HYDROGEN/OXYGEN ROCKET.

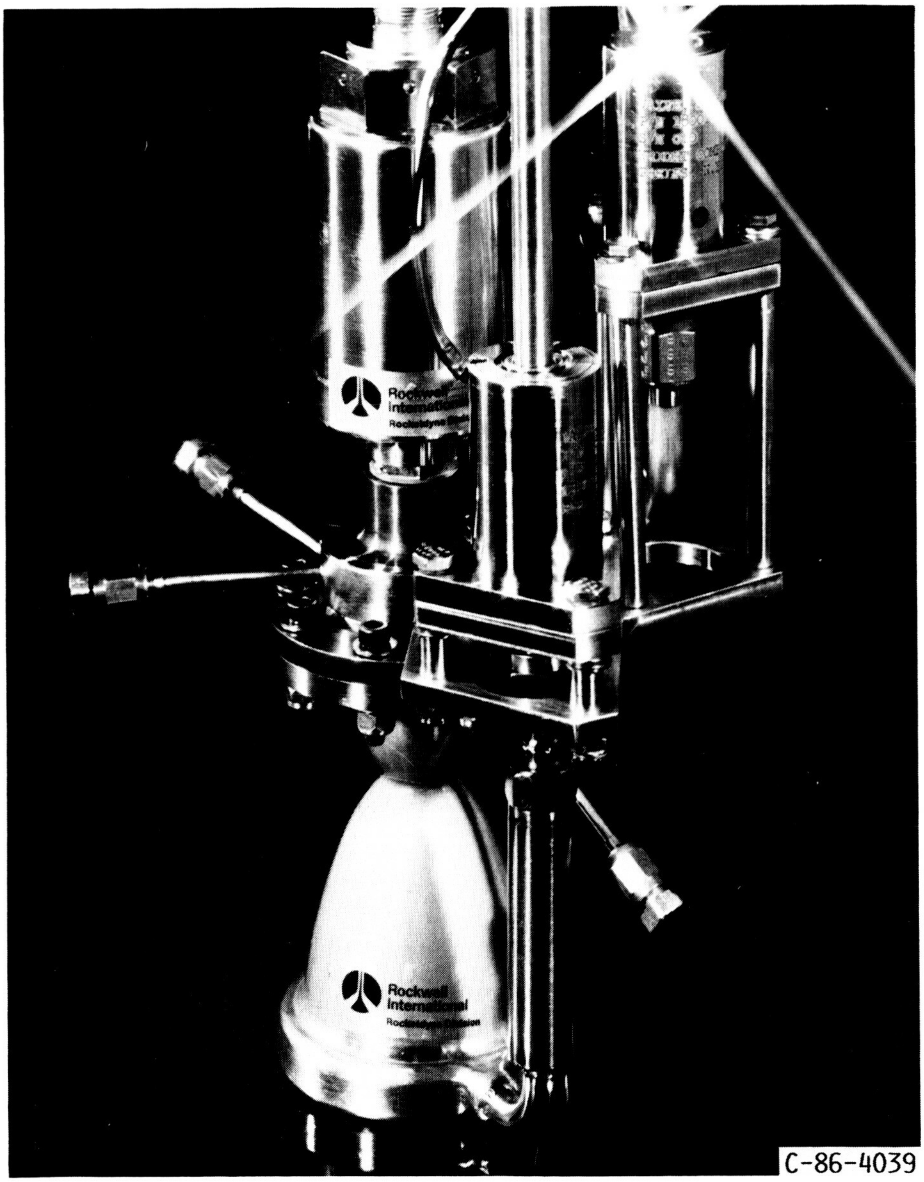

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FIGURE 3. - ROCKETDYNE 25-lbf THRUST HYDROGEN/OXYGEN ROCKET.

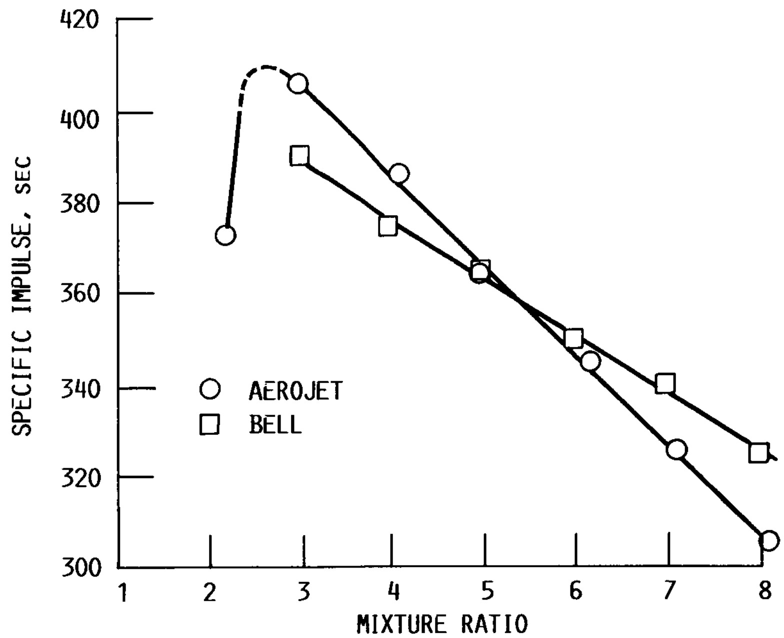

FIGURE 4.- PERFORMANCE OF H/O THRUSTERS OVER A RANGE OF MIXTURE RATIOS.

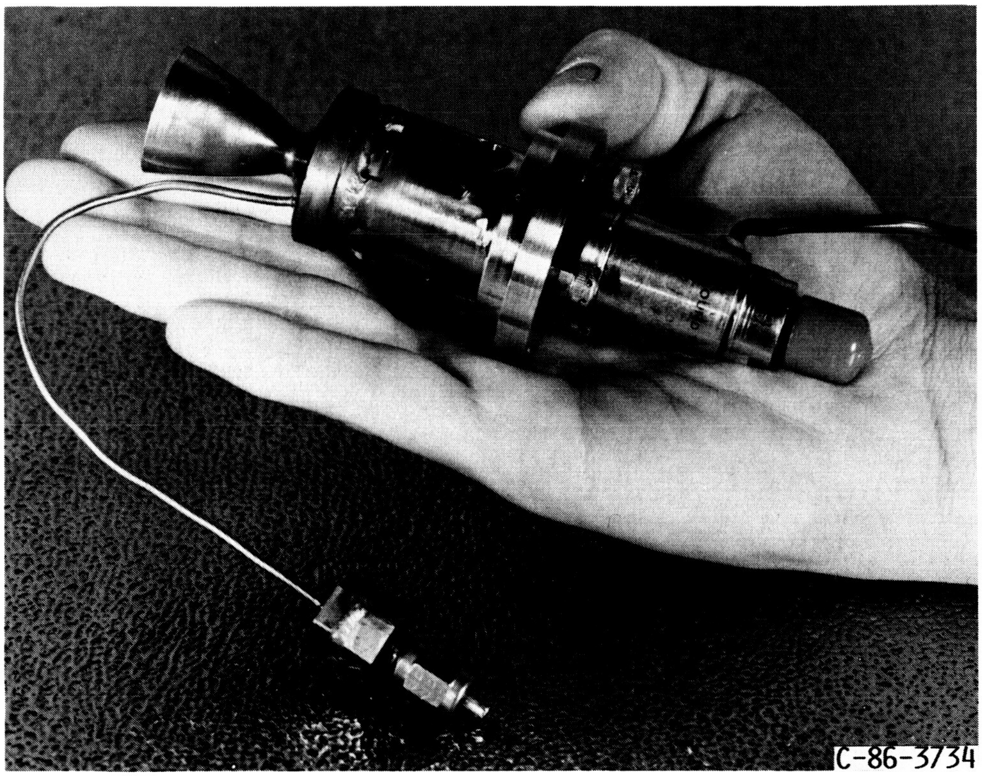

FIGURE 5. - SMALL HYDRAZINE THRUSTER FOR LIFE TESTS.

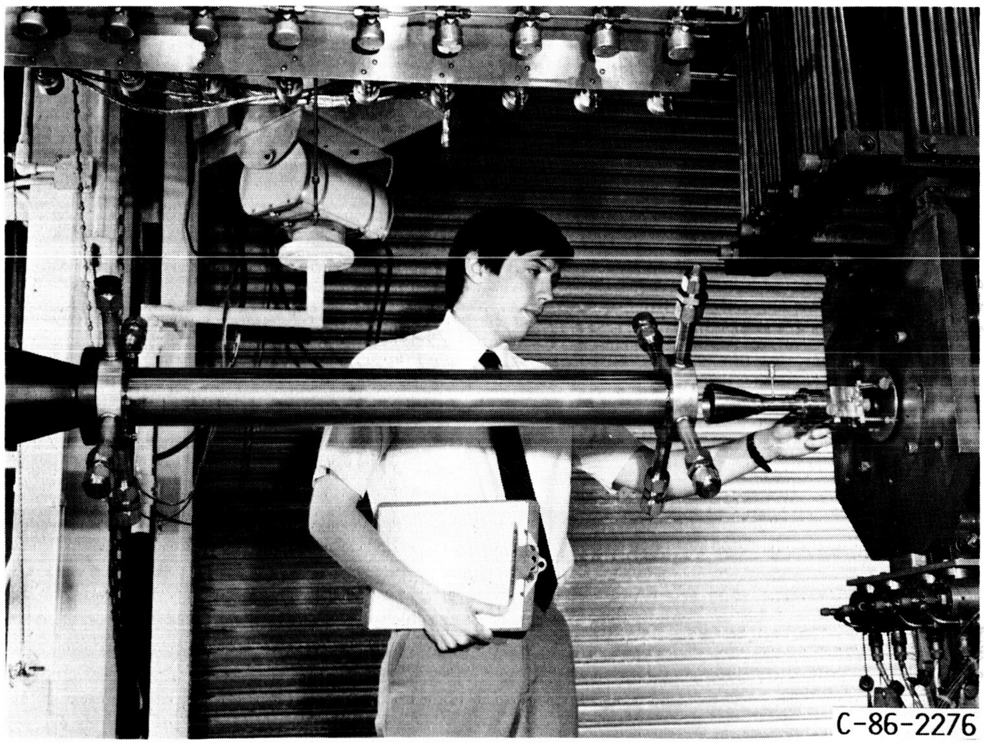

FIGURE 6. - HYDRAZINE THRUSTER AND DIFFUSER AT THE ROCKET ENGINE TEST FACILITY.

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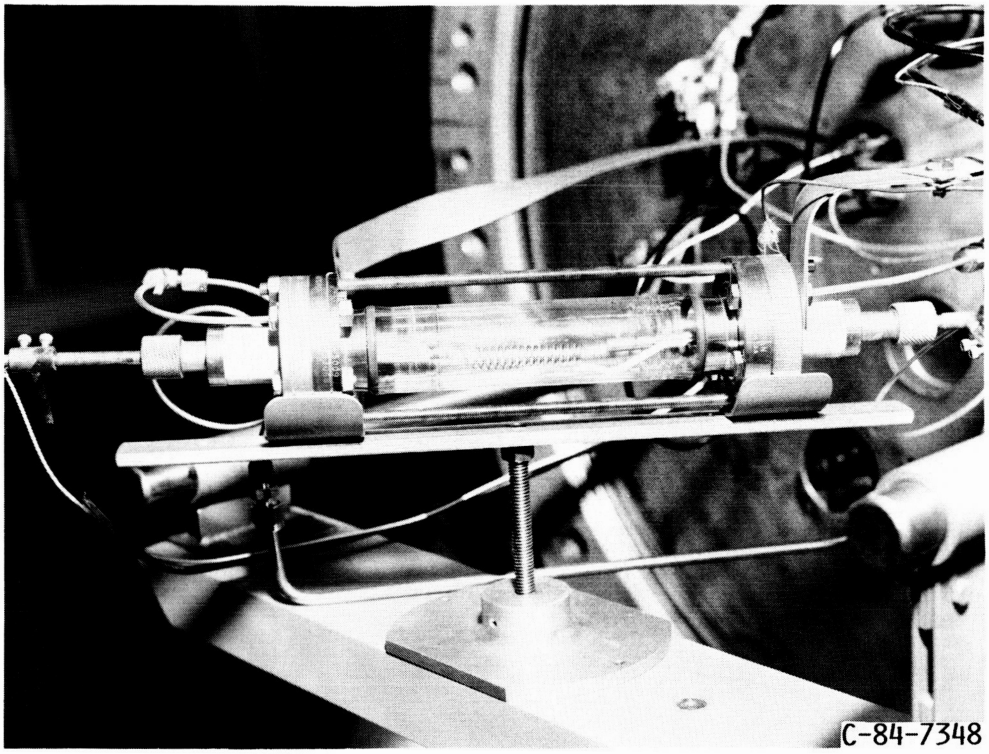

FIGURE 7. - TEST APPARATUS USED TO EVALUATE PROPELLANT-MATERIAL COMPATABILITY FOR LONG-LIFE RESISTOJETS.

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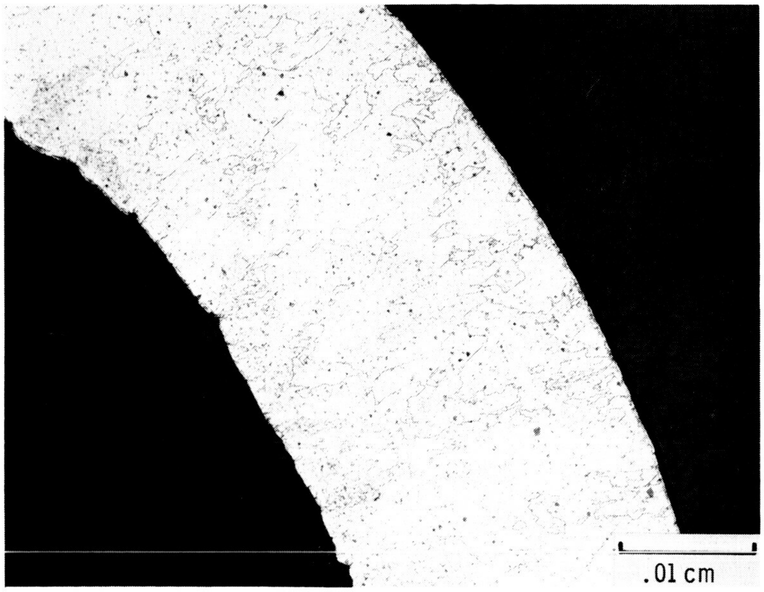
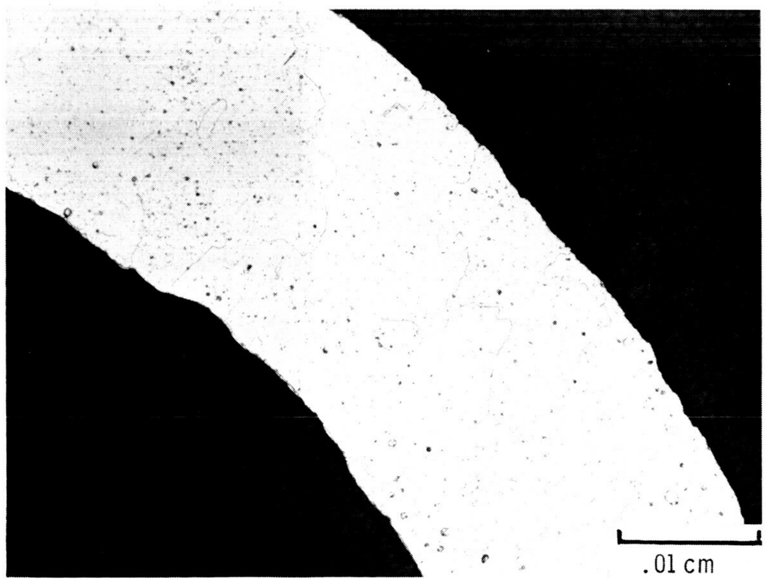


BEFORE



AFTER

FIGURE 8. - CROSS SECTION OF Pt/Y_2O_3 TUBE BEFORE AND AFTER TESTING FOR 2000 HR AT 1300 °C IN CO_2.

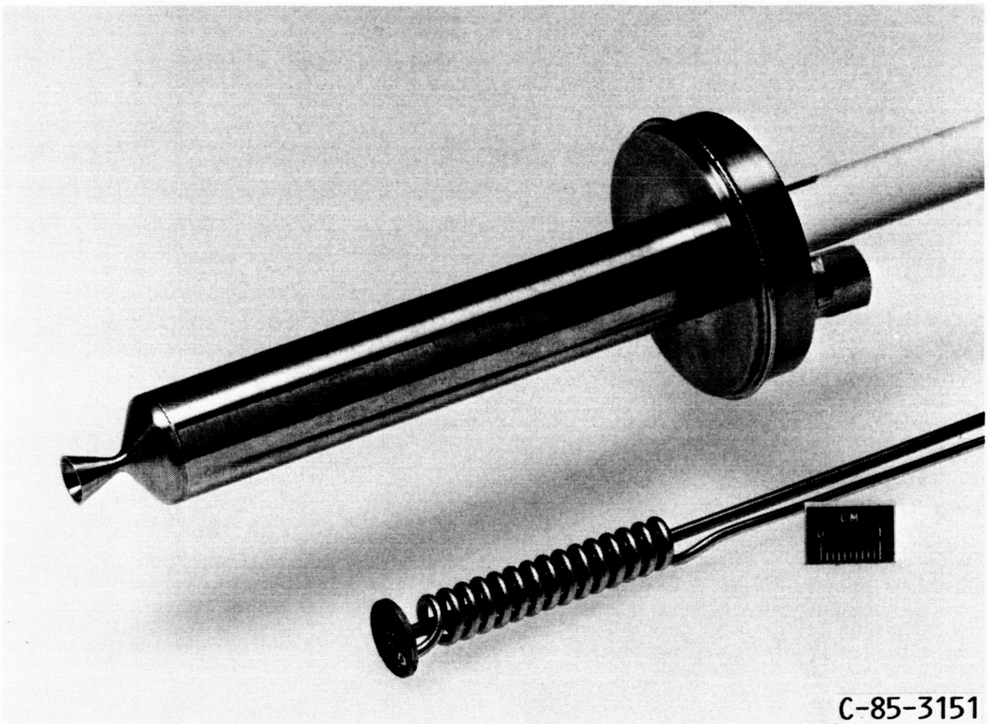


FIGURE 9. - LABORATORY MODEL OF RESISTOJET AND COILED TUBE HEATER.

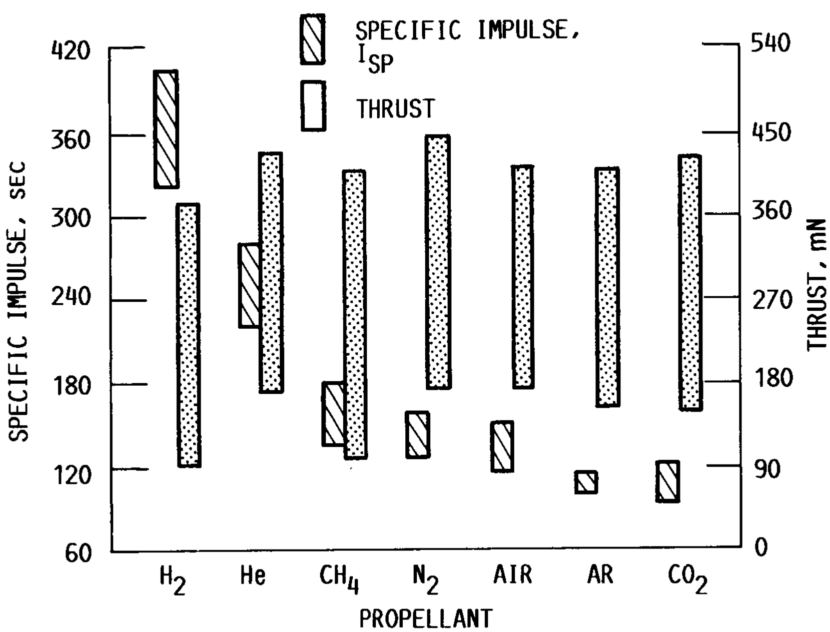


FIGURE 10.- SPECIFIC IMPULSE AND THRUST RANGES FOR A MULTIPROPELLANT RESISTOJET OPERATED ON VARIOUS PROPELLANTS AT A HEATER TEMPERATURE OF 1400 ^{o}C.

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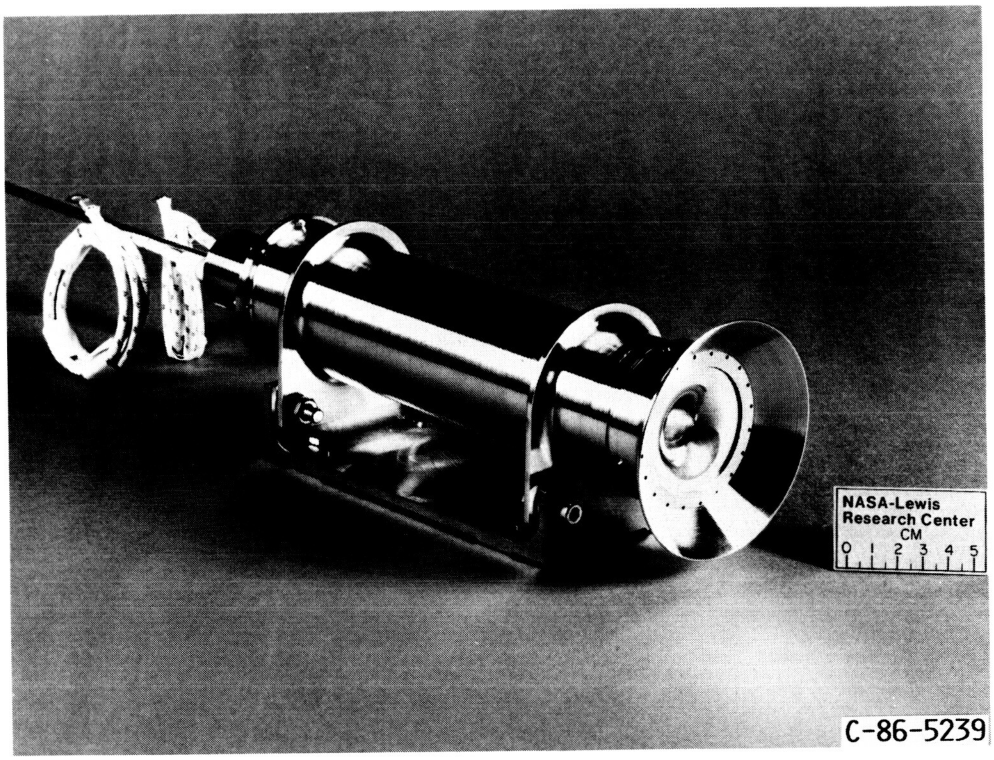

FIGURE 11. - ENGINEERING MODEL OF RESISTOJET.

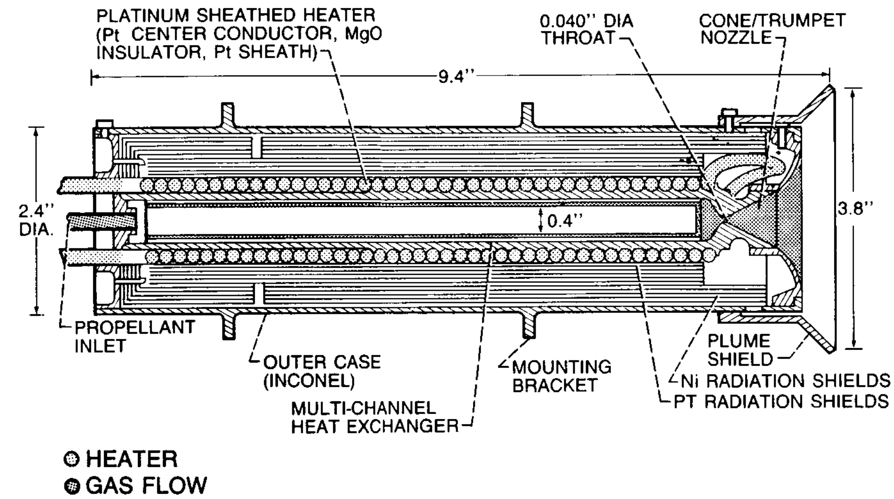

FIGURE 12.- CROSS-SECTIONAL SKETCH OF ENGINEERING MODEL OF RESISTOJET.

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15. Supplementary Notes

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16. Abstract

The purpose of the Advanced Development Program was to investigate propulsion options for the Space Station. Two options were investigated in detail: a high-thrust system consisting of 25 to 50 lbf gaseous oxygen/hydrogen rockets, and a low-thrust system of 0.1 lbf multipropellant resistojets. An effort is also being conducted to determine the life capability of hydrazine-fueled thrusters. During the course of this program, studies clearly identified the benefits of utilizing waste water and other fluids as propellant sources. The results of the H/O thruster test programs are presented and the plan to determine the life of hydrazine thrusters is discussed. The background required to establish a long-life resistojet is presented and the first design model is shown in detail.

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