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SPACE STATION PROPULSION

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ABSTRACT

Two propulsion systems have been selected for the space station: gaseous H/O rockets for high thrust applications and the multipropellant resistojets for low thrust needs. These two thruster systems integrate very well with the fluid systems on the space station, utilizing waste fluids as their source of propellant. The H/O rocket will be fueled by electrolyzed water and the resistojets will use waste gases collected from the environmental control system and the various laboratories. This paper presents the results of experimental efforts with H/O and resistojet thrusters to determine their performance and life capability, as well as results of studies to determine the availability of water and waste gases.

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INTRODUCTION

An integral part of the plan to develop the space station is the Advanced Development Program. This program has the objective to "provide technology alternatives for the initial and the evolutionary space station which optimize the system's functional characteristics in terms of performance, cost, and utilization.[1] A reference configuration was established for the space station,[2] and a high thrust (222 N) propulsion system using hydrazine as the propellant was initially selected as the baseline system. The Advanced Development Program has as its charter the investigation, evaluation, and development of viable propulsion options for initial or future use on the space station. This paper will present the program conducted to study propulsion options for the space station and the results that have been obtained.

Based upon previous studies of manned space stations, two propulsion systems were investigated.[3-8] A high-thrust system, 111 to 222 N (25 to 50 lbf), consisted of hydrogen/oxygen chemical rockets. The hydrogen and oxygen propellants would be stored either as supercritical fluids in specially designed tanks or as high pressure gases. The low thrust system consisted of the 0.45 N (0.1 lbf) multipropellant resistojet. The propellants for the resistojet would be hydrogen or other gases that might be available from the Environmental Control and Life Support System (ECLSS) or from the various laboratories, materials processing facilities, and attached payloads. These gases might be mixtures of CO_2 and/or CH_4 and possibly water. The ability of the resistojet to utilize a variety of propellants makes its use on space station especially attractive.

The choice of two propulsion systems with differing thrust and operational capabilities provides the space station with a wide variety of propulsion options. The combination of these two systems provides more possible ways of "flying" than are possible with a single thrust level system. While sufficient force is available for all large motions, including contingencies for collision avoidance with the high thrust chemical rockets, delicate maneuvers are possible using resistojets at a thrust level that will not interfere with scientific research and observations.

An additional benefit of these propulsion choices is the synergism obtained by the integration of the propulsion system with other space station systems. Propellants are obtained as by-products from the life support system and the waste gases from the scientific and materials laboratories. Utilization of these fluids results in two fundamental advantages: 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 the wastes and improves the shuttle's payload capability by not returning these wastes to Earth.

Experimental programs were started to examine the technology readiness and life capability of the H/O thrusters and to establish the technical base for the multipropellant resistojet. Studies were undertaken to ascertain levels of propellants available by integration of the propulsion system with space station fluid systems. The programs conducted on each propulsion system are discussed and the results obtained are presented.

PROPULSION REQUIREMENTS

The space station propulsion system must be able to provide thrust for altitude maintenance, collision avoidance, attitude control, and momentum management. As studies have continued during Phase B of the Space Station Definition effort, the propulsion requirements have gradually increased. Initial requirements and choice of operating mode and altitude have all been rethought during this study phase. Initially, an altitude of 463 km (250 nmi) was assumed for the station and altitude reboost would be conducted after each shuttle docking. Over a period of 90 to 120 days, the station would slowly descend, eventually returning to its initial altitude in time for another shuttle rendezvous. 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 μg. In this mode, the station maintains a near-constant altitude to operate in a constant-drag mode. As the atmospheric density varies over an 11 year cycle, the altitude required will also vary slightly.

Table I compares the total-impulse requirements for a growing and evolving space station over an 11-year cycle for the initial 463 km altitude operating mode with the present lower operating altitude and 0.3 μg operation. These values of total-impulse have been computed by assuming a 1995 Initial Operating Capability (IOC) station of 227 000 kg (500 000 lb) mass that grows to 454 000 kg (1 000 000 lb) in 10 years. The values computed also assume a nominal atmosphere. Note that the altitude has been lowered by up to 130 km (70 nmi) which eases the problems of the shuttle getting to the station. Most significant, however, is the four-fold increase in propulsion requirements. The space station has never been 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 Propellant Reactant and Supply Assembly (PRSA) 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 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 waste and fuel cell water are to be found on board the shuttle and might be transferred to the station. The actual availability of water depends on whether the Bosch or Sabatier concept is selected for the environment control system, and the extent of water stored and withdrawn from the shuttle. Table II 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.

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.[9] If these gases are not utilized for propulsion, then they must be stored and disposed of by suitable means. That means that these excess or waste gases would have to be returned to earth or vented, nonpropulsively, in a manner that would not contaminate the station or interfere with observations or experiments. Sources of waste gases identified to date include the shuttle scavenging, ECLSS, the Materials Technology Laboratory (MTL), the Japanese and Columbus module laboratories, and attached payloads.[9]

The MTL, with up to 14 experimental facilities operational at the IOC, and the international modules will produce varying amounts of excess fluids. Amounts of waste fluids generated by these modules are dependent on the complement of experiments being performed and on the amount of space station crew time spent performing the experiments. Contaminants and associated concentration levels contained in the produced fluids are unavailable at this time. It is assumed that the waste fluids will be cleaned sufficiently to allow for safe, long-term storage and also for use in the resistojet propulsion system.

Attached payload waste gases result from both purging of the experiments and cryogenic boiloff. To avoid venting, and its associated external contamination impacts, these gases must be collected and stored. These relatively clean gases may then be used to meet other station requirements (e.g., MTL or propulsion) or be recycled for reuse by the attached payloads where feasible. Attached payload waste gases vary greatly as a function of time both in their types and amounts due to relatively short run times at the station (typically 1 to 4 yr). The attached payload complement scheduled for operation at or near IOC which require and generate gases is: the Cosmic Ray Nuclei Experiment, the Solar Terrestrial Observatory, the Long Term Cryogenic Storage, and the Active Optic Technology.

Table III summarizes the overall space station waste gas inventory for IOC and growth.[9] The growth predictions are based on the station growing from 227 000 kg at IOC to 454 000 kg after 10 years and 2 crew members added every 2 years from 8 crew members at IOC to 18 at IOC +10 years. Japanese and Columbus Labs waste gas output is assumed constant for the 10 year period. Attached payload growth predictions are based on station mass growth starting with the above four waste fluid-generating payloads. The amounts of excess water (if any) are not included since many options that affect the water balance have not been defined, e.g., the ECLSS process or water available from shuttle scavenging.

The selection of the lower operating altitude as shown in Table I has raised the propulsion requirements significantly and it is not clear whether waste fluids would be available in sufficient quantity to fulfill the entire propulsion requirements. An estimate of the propellant availability is obtained by summing the amounts of water from Table II with waste gases from Table III. Assume a "worst-year" scenario of the year 2000 and a specific impulse of 360 sec for the H/O rockets and 220 sec for the mixed gases for the resistojet. The total-impulse available using both propulsion systems just exceeds the total-impulse requirement regardless of which ECLSS is chosen. Best case situations result in excess propellant which can either be vented, nonpropulsively, or provided to co-orbiting or free-flying, station based spacecraft. Studies of waste water and gas utilization as propellants will continue as the space station evolves. However, the economies inherent by the utilization of wastes will not be diminished, even if these propellants are not available in sufficient quantity to meet all the propulsion needs in a given year.

HIGH THRUST PROPULSION SYSTEM

As mentioned previously, H/O rockets were selected for the high thrust system using gaseous state propellants. The thrust size was picked based upon estimates of the station structural load limitations, the time required for reboost and allowable structural deflections.[10] For a four-thruster pad array, it has been estimated that the total thrust level must be greater than 178 N (40 lbf) and less than 356 N (80 lbf). A thrust level of 111 to 222 N (25 to 50 lbf) was selected for the Advanced Development Program thruster efforts. This thrust level is sufficient to meet the station requirements for Reaction Control System (RCS) stability and control authority and is also in the size range where any technology problems for operation on gaseous H/O would become evident.

Contracts were awarded to Aerojet TechSystems and Bell Aerospace. Rocketdyne also participated by supplying a thruster supported by their IRAD program. Initial designs for these thrusters assumed an operating mixture ratio range from 3:1 to 5:1. Table IV presents the basic design parameters for these three engines. These engines were subjected to a series of tests to determine their performance and life capability. The results of these tests have been extensively reported elsewhere.[11-14,18]

Figure 1 shows the Aerojet thruster mounted on a thrust stand. Figures 2 and 3 are photographs 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.

During the initial phases of the investigation, the three thrusters were operated over a range of mixture ratios from 3 to 5. At this time some minor changes were incorporated in each design. A series of tests, design changes and retests were done on the Bell thruster to improve the mixing of fuel and oxygen in the combustion chamber. Initial tests gave wall temperatures too high for the stainless steel chamber and a non-uniform distribution as well. Adjustments to the oxygen injector cup resulted in uniform and lower wall temperatures. The injector design was changed on the Rocketdyne thruster from the initial doublet design to a co-axial injection system. In addition, the head plate was changed from a porous stainless steel material to a solid copper disk with a few injection points for hydrogen to film cool the walls. This change resulted in improved cooling of the headplate and higher thruster performance. The Aerojet thruster underwent no hardware changes and the early tests were used to establish the proper level of film cooling to insure thruster life.

When the decision was made to test these thrusters at a mixture ratio of 8:1, it was clear that some further thruster design modifications were in order. The time available for testing was not sufficient for a redesign of each thruster, so compromises were made. For example, the Aerojet thruster, with regenerative cooling of the 113:1 area ratio nozzle, should have been redesigned to a smaller area ratio to accommodate the higher heat load. As this was not possible, the effect was simulated by cooling the hydrogen to a level such that the chamber 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 of about 378 N (85 lbf) and a higher chamber pressure at a mixture ratio of 8:1. The Rocketdyne thruster had the regenerative cooling flow rerouted, utilizing parallel-flow cooling instead of counter-flow cooling to provide for the added heat load. At no time were any operational difficulties encountered and the test programs proceeded as planned. Table V lists the total number of seconds of testing for each thruster at mixture ratios from 2:1 to 8:1. Note that large times, up to over 10 hr, were obtained at mixture ratios of 7 and 8:1. Table V also shows the total impulse demonstrated by each thruster over the same range of mixture ratios. The life goal 8.9×10^6 N-sec (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. The life of such thrusters should be determined to establish a life and reliability data base and 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, and in no case was any life-limiting problem uncovered.

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 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 perforance for both designs were greater than anticipated and reflect non-optimized designs. 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. 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.

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.[15-16] Resistojets for these applications are characterized as having a requirement for maximum specific impulse, an operating lifetime of only a few hundred hours, and use with a single propellant. As indicated, previously, the primary criteria for space station resistojets are very long life and operation with a wide variety of potential propellants.[9,17-18]

Material-propellant compatibility had to be addressed in order to select a resistojet material that could provide the useful life required with the wide variety of possible propellants from ECLSS, MTL, Attached Payloads, or other sources. In the material compatibility studies two forms of grain-stabilized platinum were used. Platinum had been a previous choice for a biowaste resistojet considered in the 1970's because of it's excellent resistance to corrosion and oxidation.[6-8] 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.

Tests were conducted with CO_2, CH_4, H_2, NH_3, and steam in a flowing gas environment at a pressure of about 141 kPa. 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 which could lead to carbon deposition and buildup within the resistojet. These tests were conducted for as long as 2000 hr and have been reported in detail.[19] Test results are summarized in Table VI 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. 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 due to the porous nature of the platinum. When the heater temperature was reduced to below 1000 °C surface attack by ammonia virtually disappeared, and operation at that temperature should be possible.

These tests have been expanded to include decomposed hydrazine as a potential resistojet propellant. Tests of up to 1000 hr have been conducted with yttria-stabilized platinum at temperatures of 1000 and 1400 °C. Results similar to those obtained with ammonia have been obtained in that surface attack occurred at 1400 °C, but none was evident at temperatures of 1000 °C or less.[20] This was expected because decomposed hydrazine is essentially N_2, H_2, and NH_3.

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. The results of the 2000-hr test are reported in reference 21.

ENGINEERING MODEL RESISTOJET

Figure 5 is a photograph of the space station resistojet and Fig. 6 is a cross-sectional sketch with the major features identified. The resistojet design is the result of a Rocketdyne/Technion effort, on contract to NASA Lewis. The detailed discussion of the design choices, features, and construction details can be found in reference 22. The features of this resistojet design that lead to long operational life are:

(1) A sheathed heater element is wrapped around the outside of the heat exchanger body. This eliminates the potential for shorting of the heater by surrounding the current-carrying resistance element with a layer of compressed magnesia insulation, which is covered with a metal sheath. The sheathed heater is secured in position by a series of semi-circular grooves machined into the outer surface of the forward half of the heat exchanger. This feature eliminates the possibility of movement of the heater, which would result in changes in the thermal characteristics of the thruster, and provides a large contact area between the heater and heat exchanger. The temperature difference between the heater and heat exchanger in this design is inherently low, and preliminary thermal tests on the first engineering model indicate that its temperature drop is less than 200 °C for a nominal heater temperature of 1200 °C.

(2) Large-surface-area diffusion bonds are used to join the platinum parts. The diffusion bonds are backed by EB welds located in relatively cool regions of the engineering model thruster to ensure gas-tight integrity. This joining technique eliminates potential failures due to adverse effects on the grain stabilization of the platinum by the EB welding process.

(3) A thick-walled pressure vessel/heat exchanger improves the stress-rupture characteristics of the engineering model resistojet. However, the question of whether grain growth occurs within the walls of the engineering model heat exchanger persists, since the thruster heat exchanger is planned to operate at a maximum temperature of 1200 to 1400 °C.

Figure 7 shows the range of specific impulse obtained at various power levels for operation at a constant propellant inlet pressure of 0.14 MPa.[23] The nominal thrust levels measured are shown, as are the corresponding cold gas specific impulse values. As expected, the specific impulse decreases with increasing molecular weight. Although the absolute value of specific impulse for the lighter fluids (hydrogen, helium) is rather low, it should be noted that the power levels tested were highly conservative relative to the design power level of 500 W. Operation on all of the tested fluids at a fixed power level of 500 W would have shown greater specific impulse values for the fluids with higher specific heats. Subsequent tests at power levels as high as 740 W using carbon dioxide propellant produced maximum thruster temperatures of about 1200 °C.[23]

Four resistojets of the type shown in Fig. 6 have been obtained. These have been used in continuing studies of resistojet performance, life tests, and plume dispersion. In addition, a fifth model has been obtained which incorporates a few minor design changes to simplify the manufacture of the thruster. The radiation shield pack has been redesigned, the electron beam weld procedure modified and some minor changes have been made to the material specifications.[23]

SPACE STATION PROPULSION MODULES

The space station reboost module is presently planned to be mounted on an extendable structure, between several of the habitat modules. Figure 8 shows the location of this module after the second assembly flight with the truss structure unextended. Mounted on the truss are two H/O modules and one resistojet module.

The location of the reboost module is through the geometric center of the station which should be nearly through the center of gravity. This is important when considering the torques imposed upon the station, even those as small as the ones created by the resistojets. Potential impingement of the plume upon the modules or the Japanese experiments porch is not a problem using an extendable boom as shown.

A fully completed station is shown in Fig. 9 with the propulsion module truss fully extended. This figure shows that there are two modules of H/O thrusters, with triple redundancy in each of two axes. There are also two resistojet modules, each consisting of four resistojets. Figure 10 shows the resistojet module layout and identifies most of the components. Note that a water vaporizer has been included. While it is envisioned that all water will be electrolyzed for use in the H/O rockets, provisions are available to utilize any excess water as a resistojet propellant.

CONCLUDING REMARKS

The experimental efforts discussed in this paper have produced results that clearly indicate that H/O rockets and the multipropellant resistojet can meet both the performance and life required of the space station propulsion system. Recognition of this has resulted in these propulsion systems being selected as the propulsion baseline for the space station. Since these propulsion systems utilize wastes as propellants, propellant resupply is minimized and waste disposal problems are greatly simplified.

Lifetimes in excess of 10×10^6 N-sec are to be expected from H/O thruster based on presented life test data. Measured specific impulse values were low, 330 sec at a mixture ratio of 8:1, and future programs will seek performance levels of 360 sec. Performance of the resistojet has been as expected. Life estimates based on material-propellant compatibility tests far exceed the expected life of the heater element. However, 10 000 hr of operation appears to be easily achievable, though tests of this duration have yet to be performed. Actual life determination and the identification of life limiting effects still need to be addressed for all those future applications where thrusters, utilizing any combination of propellants, will be refueled to meet the propulsion demands of long duration spaceflight.

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

[Nominal atmosphere assumed.]

Year	Variable altitude average, 0.3 μg		Nominal 463 km altitude
	Altitude, km	Impulse, n-s	Impulse, N-s
1995	350	9.225×10^6	2.926×10^6
1996	341	8.878	1.596
1997	333	9.652	1.394
1998	333	12.25	1.239
1999	333	26.24	1.365
2000	355	20.70	2.328
2001	374	23.09	4.572
2002	394	27.35	8.475
2003	409	27.54	11.769
2004	389	20.85	9.617
2005	380	20.37	7.644
TOTAL		195.9×10^6	52.93×10^6

TABLE II. - WATER AVIALABLE FOR PROPULSION kg/yr

Options	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	Total
45 day visits Bosch ECLSS	8235	8458	8390	8612	8542	8764	8696	8919	8848	9071	86 537
90 Day visits Bosch ECLSS	4420	4624	4554	4776	4708	4930	4862	5083	5014	5235	48 206
45 Day visits Sabatier ECLSS	7076	7003	6937	6869	6801	6733	6662	6594	6524	6456	67 655
90 Day visits Sabatier ECLSS	3257	3171	3101	3033	2965	2897	2828	2758	2690	2620	29 319

TABLE III. - ANNUAL WASTE GAS PRODUCTION FROM ALL SOURCES

[Assumed Bosch ECLSS, changes with Sabatier ECLSS in Parenthesis (kg/yr).]

Gas/year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Argon	575	575	575	575	613	613	613	466	466	504
CO_2	92	92	92	205	339	229	118	118	118	118
CO_2/CH_4	0	0	0	0	0	0	0	0	0	0
	(1700)	(1700)	(1700)	(1700)	(2550)	(2550)	(2550)	(2550)	(2550)	(3400)
Freon	3	3	3	3	4	4	4	4	4	4
Helium	16	16	56	407	370	370	370	370	370	371
Hydrogen	83	83	146	146	319	179	115	115	115	148
	(19)	(19)	(83)	(83)	(224)	(84)	(20)	(20)	(20)	(20)
Nitrogen	764	764	764	834	1203	1133	1063	958	958	1257
Oxygen	110	110	110	110	152	152	152	152	152	194
Kryton	36	36	36	36	36	36	36	36	36	36
Xenon	40	40	40	40	50	50	50	50	50	60
Totals	1720	1720	1825	2357	3085	2765	2520	2270	2270	2716
Sabatier	3440	3440	3608	4140	5859	5399	4975	4724	4724	5989

TABLE IV. - H/O THRUSTER INITIAL DESIGN PARAMETERS

	Rocketdyne	Aerojet	Bell
Thrust, N	111	111	222
Specific impulse, sec	415	440	410
Nozzle area ratio	30	113	40
Chamber pressure, MPa	0.688	0.515	0.515
Throat diameter, cm	1.07	1.27	1.75
Exit diameter, CM	5.84	12.7	11.15
Type	Regen cooled	Regen cooled	Film cooled

TABLE V. - H/O THRUSTER TEST SUMMARY

Mixture ratio,	Aerojet		Bell		Rocketdyne	
	Total duration, sec	Total impulse, N-S	Total duration, sec	Total impulse, N-S	Total duration, sec	Total impulse, N-S
2	60	5 791	-----	--------	------	----------
3	180	22 716	275	59 914	32 148	3 574 857
4	4 039	398 211	1 619	354 225	12 697	1 411 906
5	224	24 802	124	27 235	408	45 369
6	221	21 030	83	19 424	478	53 153
7	17 560	1 908 178	65	15 341	440	48 928
8	118	14 327	3 116	1 003 499	40 237	4 474 354
	22 402	2 395 055	5 282	1 479 638	85 968	9 608 557

TABLE VI. - 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.

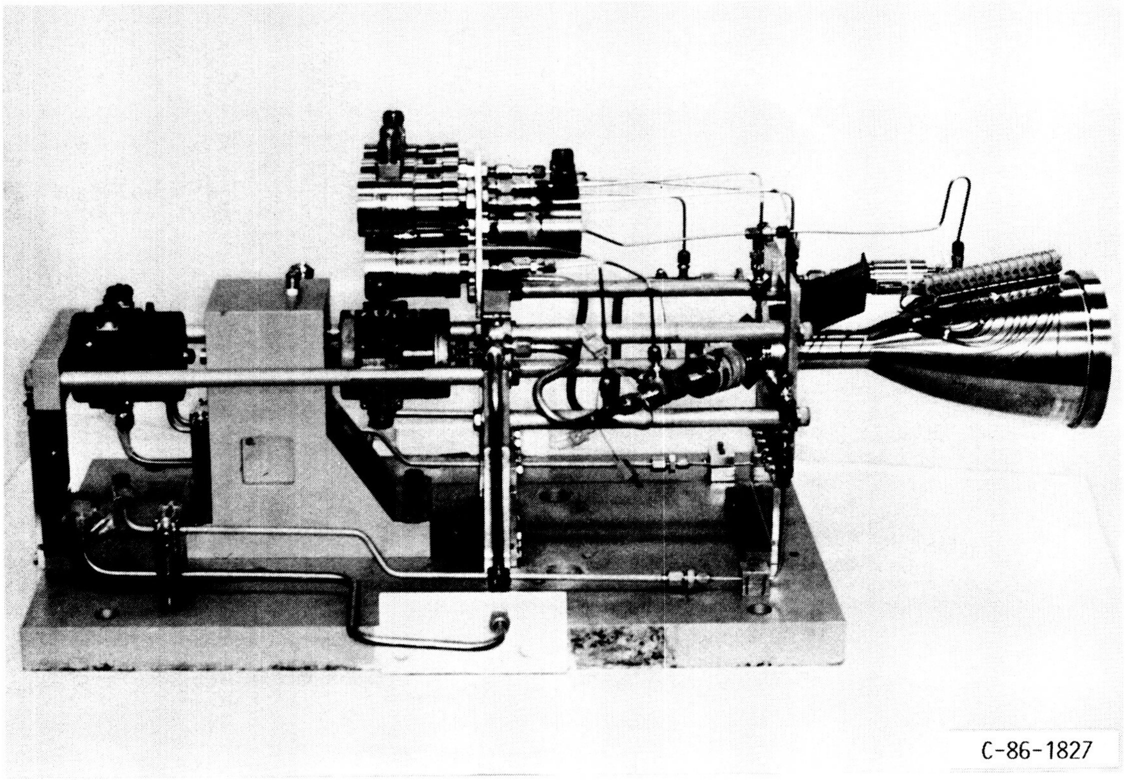
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FIGURE 1. - AEROJET 111N ROCKET ENGINE ON THRUST STAND.

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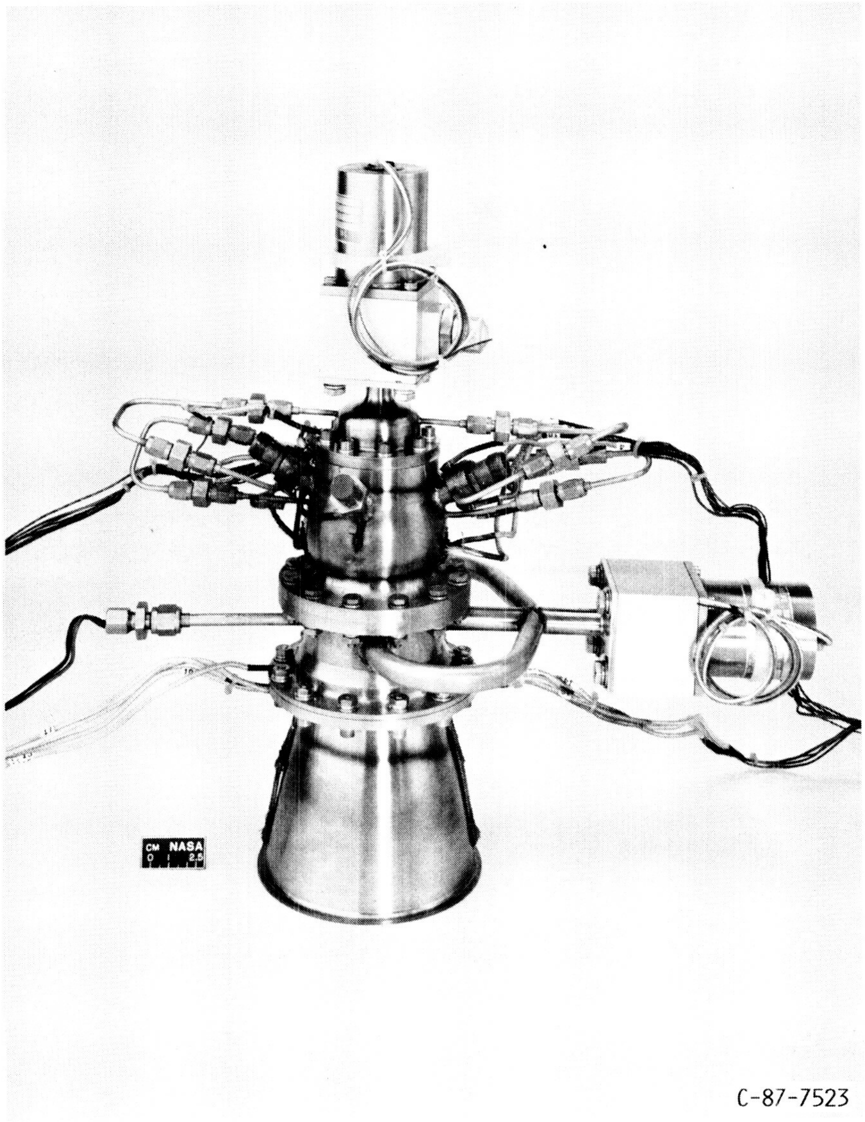

FIGURE 2. - BELL AEROSPACE 222N H/O ROCKET ENGINE.

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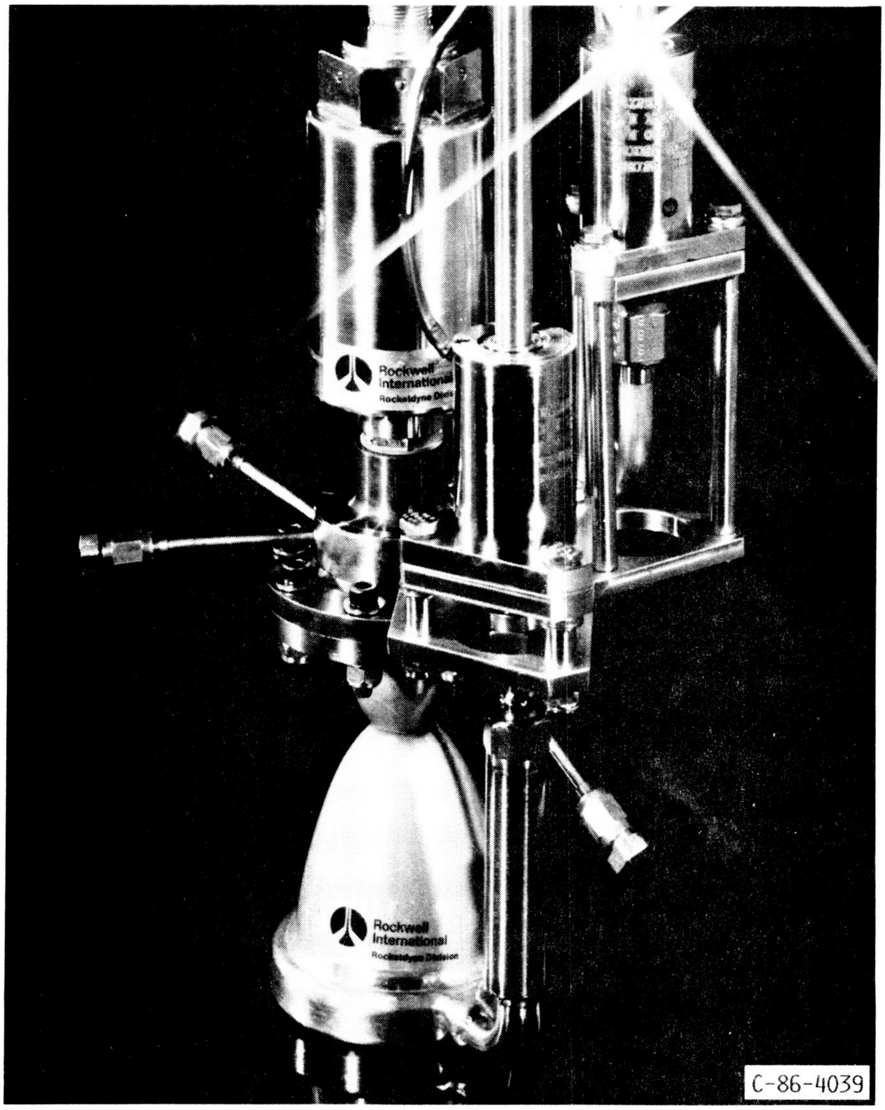

FIGURE 3. - ROCKETDYNE 111N (25-LBF) THRUST HYDROGEN/OXYGEN ROCKET.

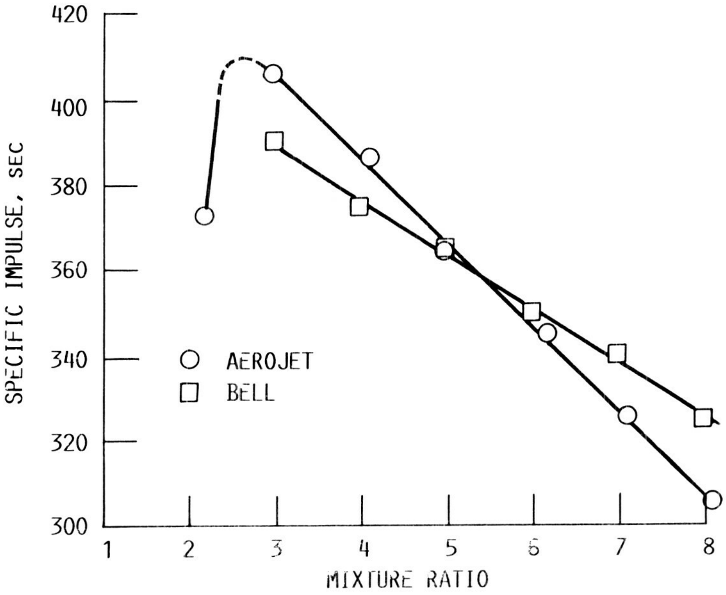

FIGURE 4. - PERFORMANCE OF H/O THRUSTERS OVER A RANGE OF MIXTURE RATIOS.

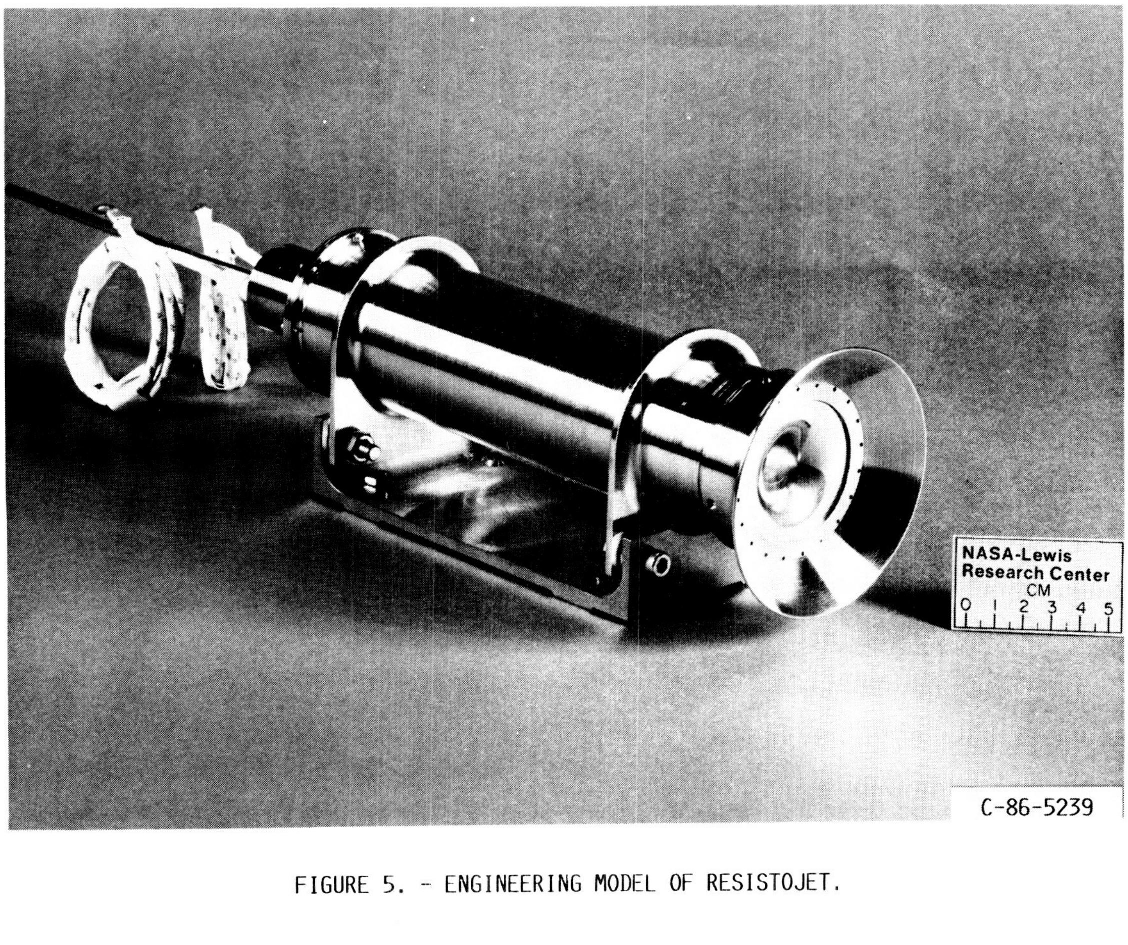

FIGURE 5. - ENGINEERING MODEL OF RESISTOJET.

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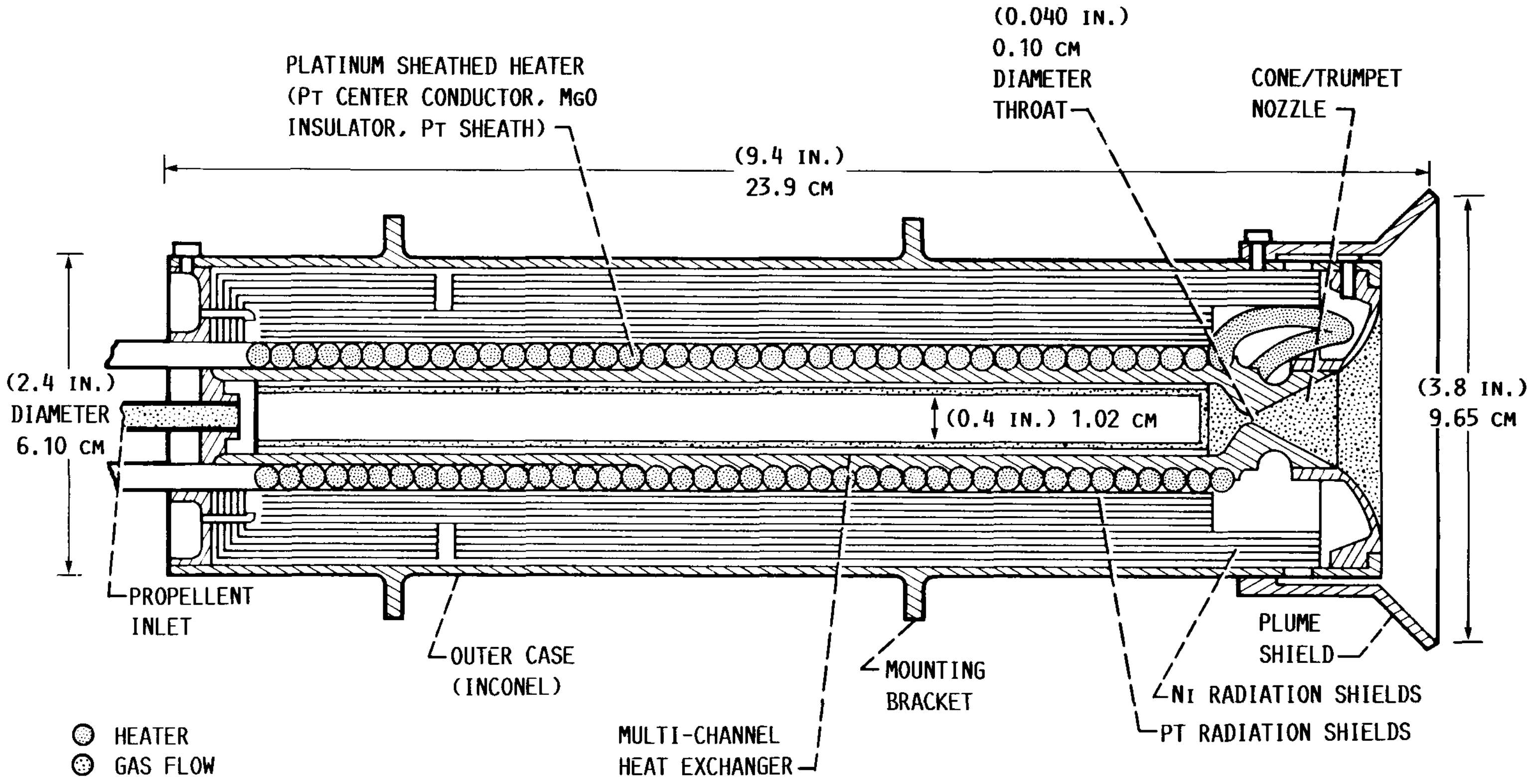

FIGURE 6. - ADVANCED DEVELOPMENT ENGINEERING MODEL RESISTOJET.

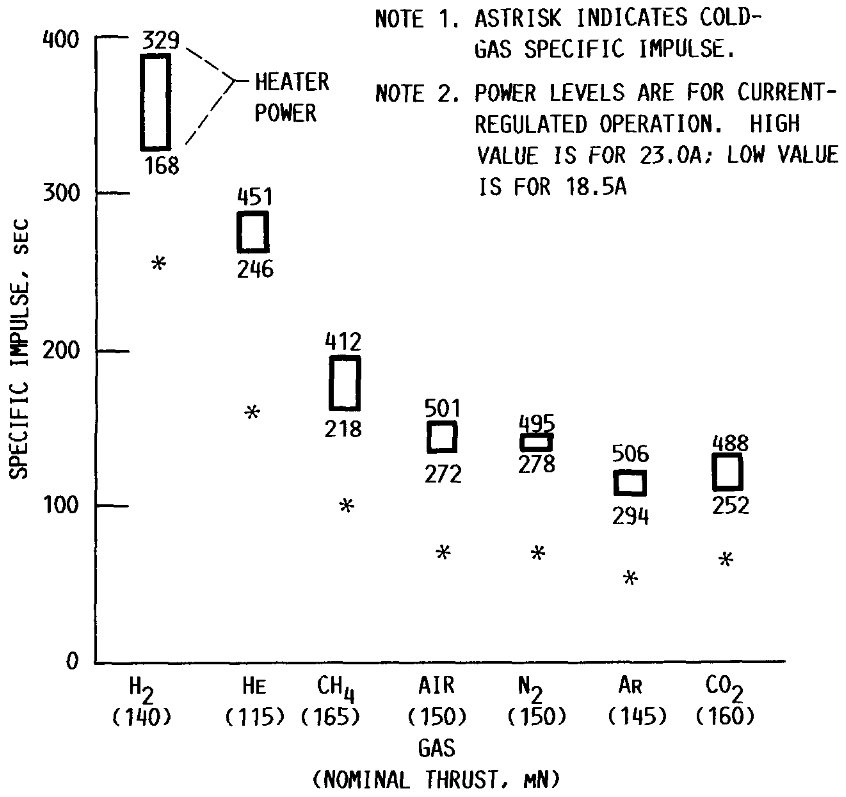

FIGURE 7. - SPECIFIC IMPULSE AND POWER RANGES FOR ENGINEERING MODEL RESISTOJET FOR INLET PRESSURE OF 0.14 MPA.

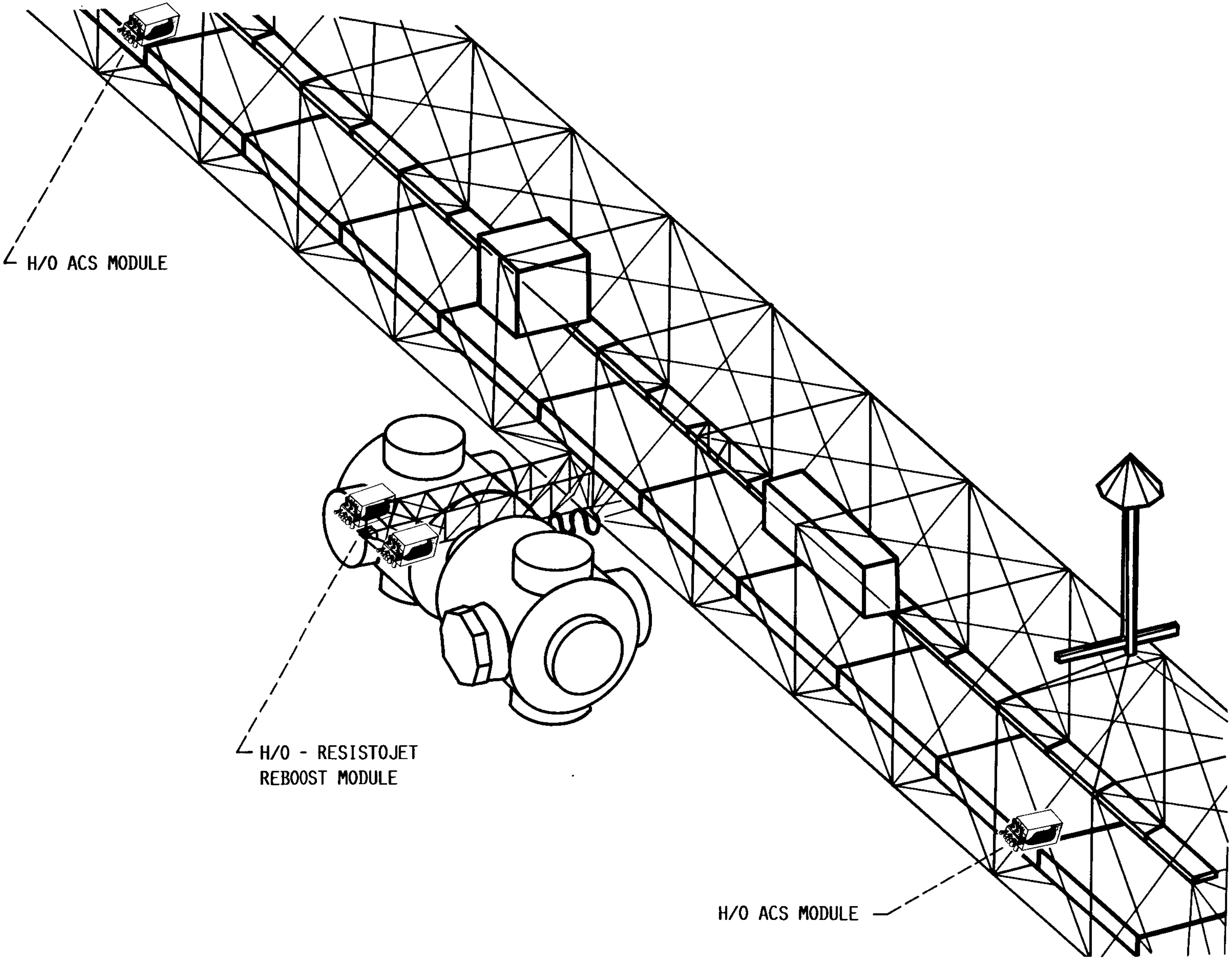

FIGURE 8. - ASSEMBLY FLIGHT NUMBER 2.

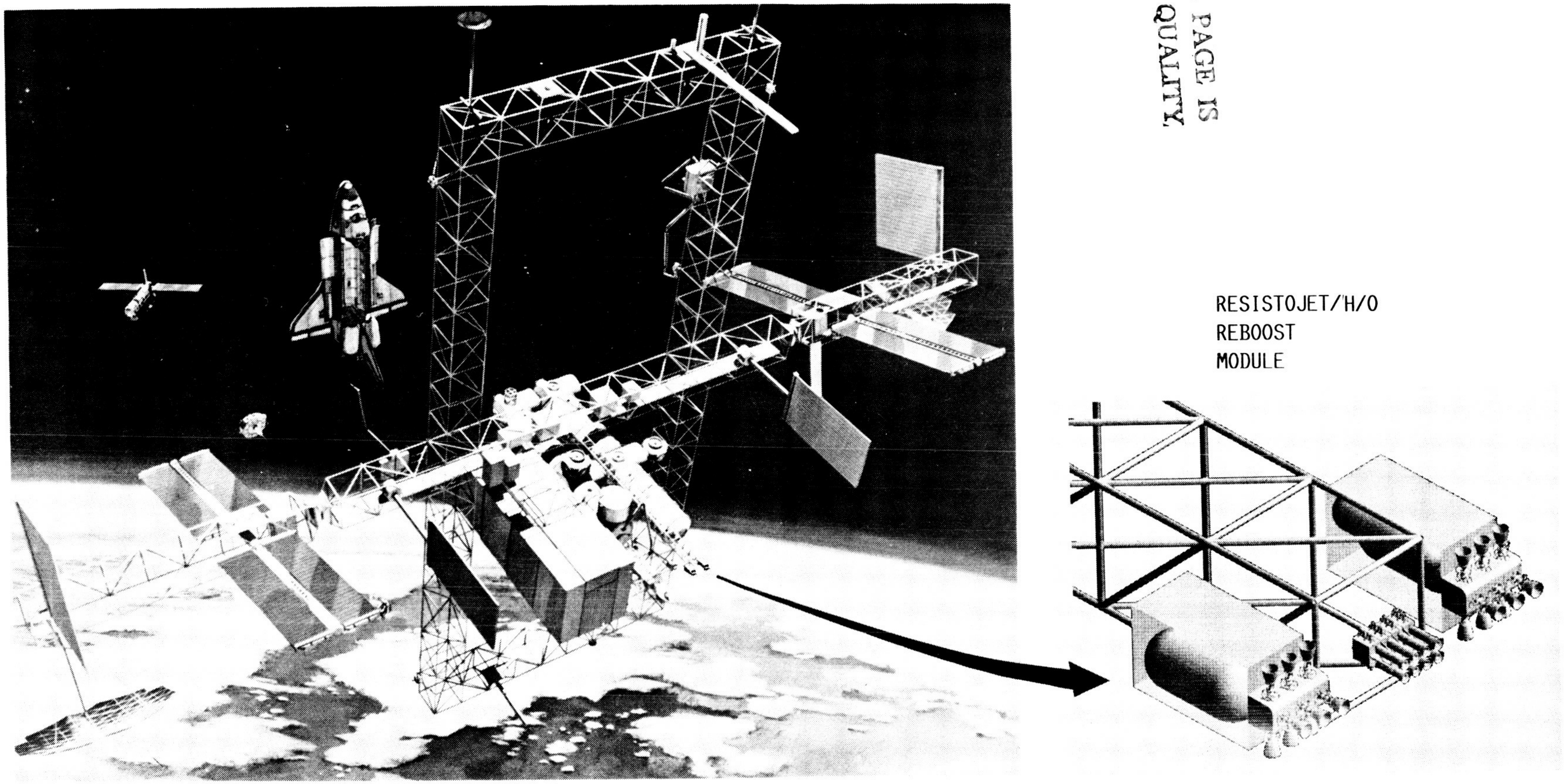

FIGURE 9. - INITIAL OPERATING CONFIGURATION.

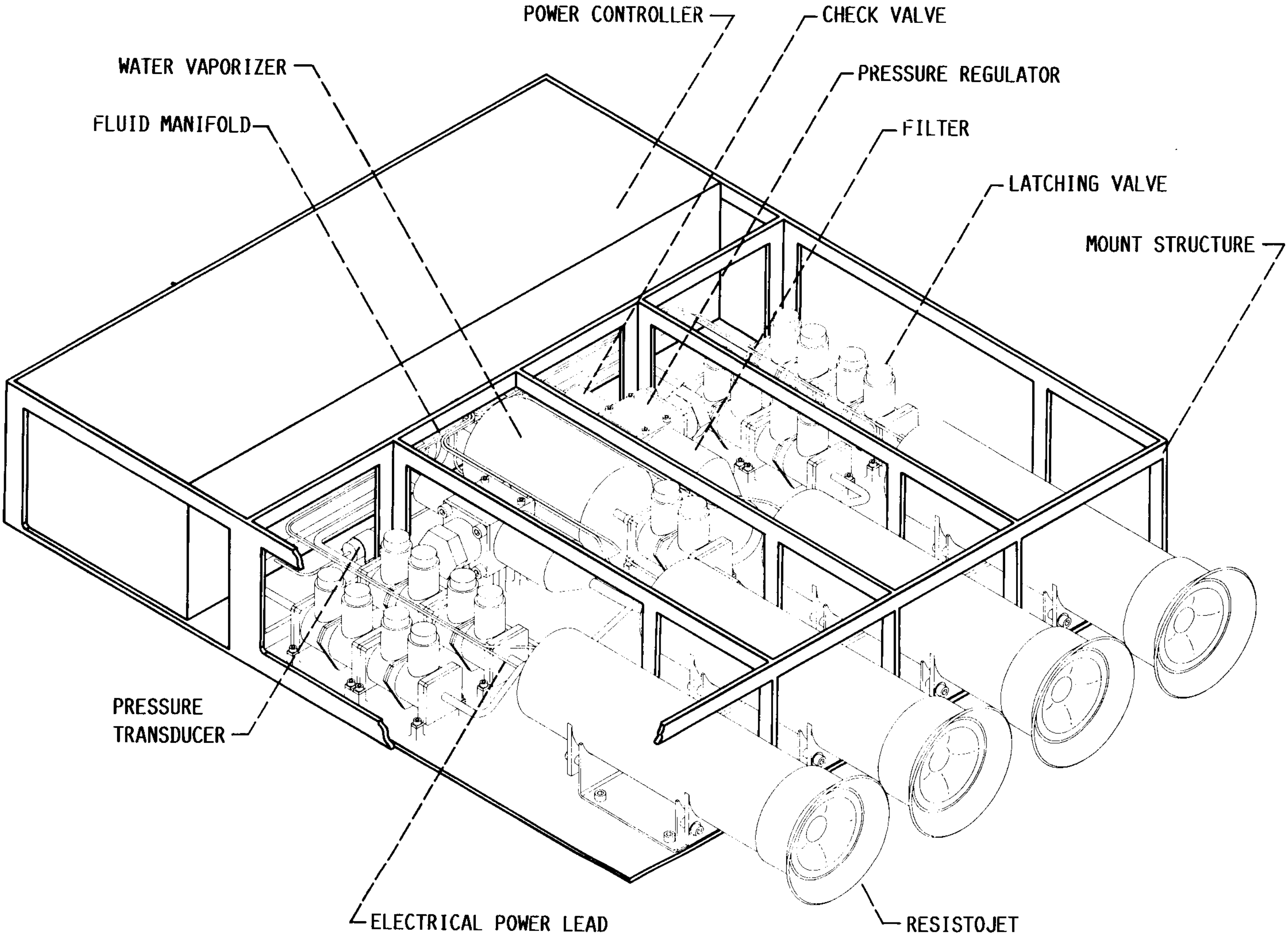

FIGURE 10. - MODULE LAYOUT.

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16. Abstract

Two propulsion systems have been selected for the Space Station: gaseous H/O rockets for high thrust applications and the multipropellant resistojets for low thrust needs. These two thruster systems integrate very well with the fluid systems on the space station, utilizing waste fluids as their source of propellant. The H/O rocket will be fueled by electrolyzed water and the resistojets will use waste gases collected from the environmental control system and the various laboratories. This paper presents the results of experimental efforts with H/O and resistojet thrusters to determine their performance and life capability, as well as results of studies to determine the availability of water and waste gases.

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