Performance and Endurance Tests of a Laboratory Model Multipropellant Resistojet

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This paper presents the results of an effort to demonstrate the technological readiness of a long-life multipropellant resistojet for space station auxiliary propulsion. A laboratory model resistojet made from grain-stabilized platinum served as a test bed to evaluate the design characteristics, fabrication methods, and operating strategies for an engineering model multipropellant resistojet developed as part of the NASA space station propulsion system Advanced Development Program. The laboratory model thruster was characterized for performance on a variety of fluids expected to be available onboard a space station, then subjected to a 2000-h, 2400-thermal-cycle endurance test using carbon dioxide propellant. Maximum thruster temperatures were approximately 1400°C. Significant observations from the laboratory model thruster performance and endurance tests are discussed as they relate to the design of the engineering model thruster.

Introduction

DURING the 1960s, there was an active technological effort to develop resistojets for the Manned Orbital Research Laboratory (MORL) using environmental control and life support system effluents. The MORL program, and the associated biowaste resistojet technology work,[1-4] was terminated in the early 1970s. Over the past seven years, high-performance hydrazine resistojets have performed north-south stationkeeping for commercial spacecraft in geosynchronous orbit, marking a renewed interest in resistojet technology. Two thruster developers have provided approximately 100 resistojet thrusters for 26 flights.[5,6]

Multipropellant resistojets have been baselined as the low-thrust option for the space station propulsion system. The resistojet can provide low levels of thrust for drag makeup while disposing of a variety of fluids expected to be present in excess quantities on board a space station. These fluids can be vented either propulsively or nonpropulsively, insuring that no condensation of high-vapor pressure compounds (i.e., steam or carbon dioxide) occurs, and that all effluents are imparted with high exit velocities to minimize contamination of the space station environment. The use of such fluids as propellant will result in significant reductions in space transportation system (STS) costs that would be associated with the launching of the necessary propellants, as well as the removal of waste fluids from the space station. Recent studies have explored these and other potential benefits of a propulsion system incorporating low-thrust resistojets.[7,8]

Recently, a resistojet technology program was reinstated by NASA to focus on material evaluation, fabrication methods, performance, plume evaluations, and life assessments of resistojet technology for space station application.[9-11] The technology goals emphasize thruster life, reliability, and multipropellant capability rather than optimum performance. The design life goal is a minimum of 10,000 h for thrusters operating on hydrogen, helium, methane, water (steam), nitrogen, air, argon, and carbon dioxide at specific impulse and thrust levels of 100–500 s and 130–450 mN, respectively.

The main objectives of this program were to evaluate thruster material/propellant compatibility and fabrication methods as well as to provide preliminary performance and lifetime data for a resistojet. A simple laboratory model resistojet was fabricated from grain-stabilized platinum and characterized on a variety of propellants at heater temperatures up to 1400°C. A duplicate of this thruster was subjected to an endurance test operating in a thermally cyclic mode using carbon dioxide propellant. These thrusters served as a test bed to provide insight into the design of a long-life engineering model resistojet for space station application.[12] The engineering model resistojet is the second-generation thruster developed under the Space Station Advanced Development Program. Valuable information was also gained regarding long-term endurance testing of space propulsion devices in ground test facilities. This paper presents the results of the performance and endurance tests conducted as part of the NASA multipropellant resistojet technology effort and discusses how the results of these tests are related to the design of the engineering model multipropellant resistojet.

Apparatus and Procedure

Laboratory Model Resistojet Description

The material used for construction of the laboratory model resistojet was grain-stabilized platinum because it exhibits long-term, high-temperature compatibility with a wide variety of oxidizing and reducing fluids.[13,14] Details of the thruster material selection process will be discussed later in this section. The platinum used employed a small quantity (less than 1%) of zirconium oxide dispersant as a grain stabilizer. The grain stabilization is desired to minimize grain growth that occurs when materials are held at high temperatures for extended periods of time. Excessive grain growth leads to distortion and weakening of components, which is of special concern for the pressure vessel/heat exchanger of a resistojet.

The laboratory model resistojet, shown in Fig. 1, was a radiatively coupled device employing a heating element located in an evacuated cavity within an annular heat exchanger body. The heat exchanger consisted of two concentric tubes sealed together to permit contained gas flow within the annu-

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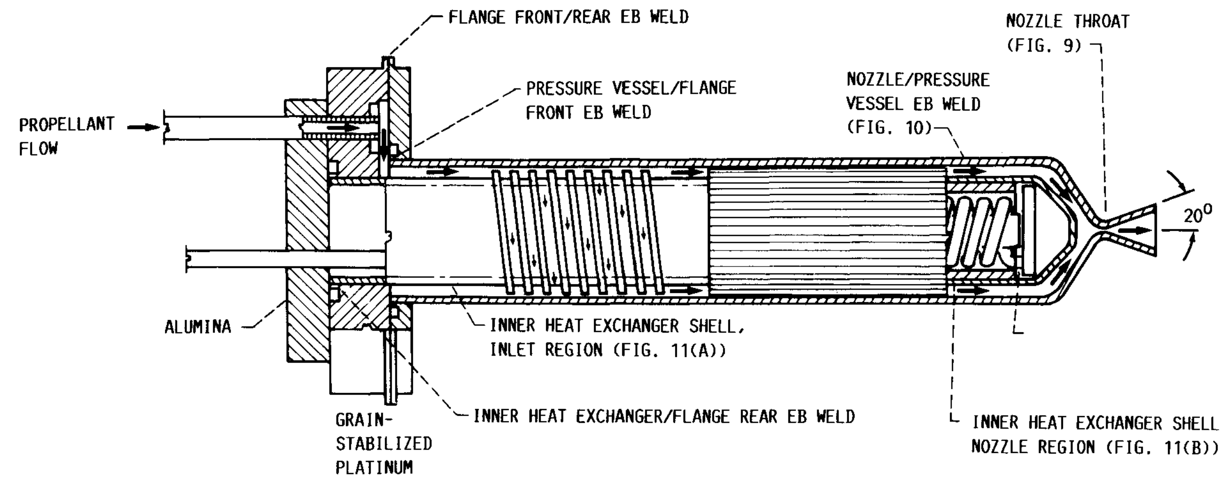
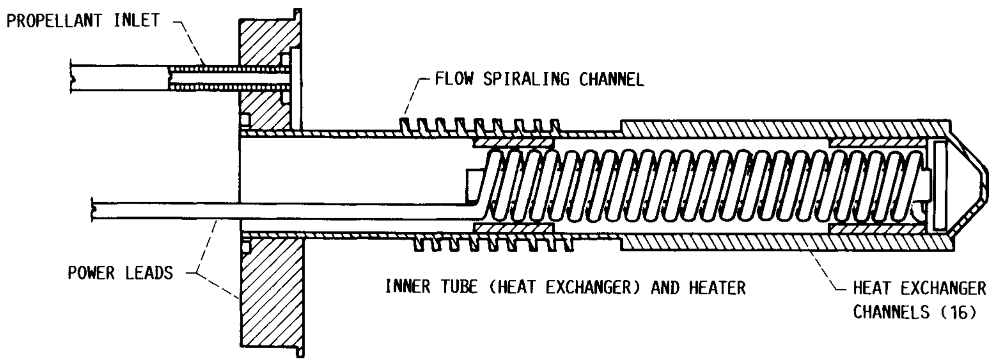
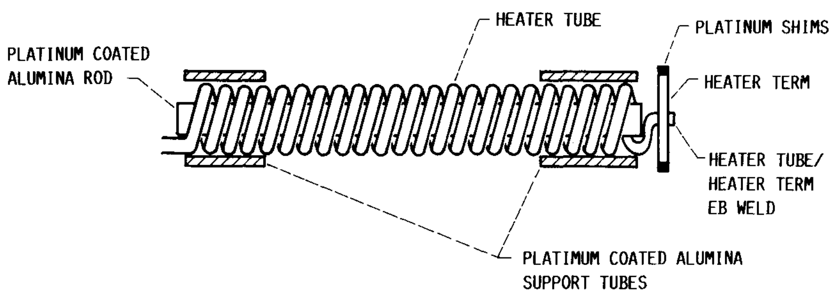


a) Heat exchanger-nozzle cross section



b) Heater—heat exchanger



c) Heater and support structure cross section

Fig. 1 Schematics of the multipropellant resistojet.

Table 1 Multipropellant resistojet design characteristics

Shell/nozzle	
Material	Grain-stabilized platinum
Nozzle throat diameter, mm	0.84
Nozzle area ratio	82
Nozzle half-angle, deg	20
Body length, cm	13.0
Body diameter, cm	1.92
Heat exchanger	
Material	Grain-stabilized platinum
Number of channels	16
Heater element	
Material	Grain-stabilized platinum
Tubing o.d., mm	2.03
Tubing i.d., mm	1.52
Coil length, mm	5.82
Coil pitch	0.10
Coil diameter, cm	1.04
Maximum operating temperature, °C	1400
Design life, h	10,000

lar region between them. A spiral channel near the rear (inlet end) of the heat exchanger directed the flow of the cold incoming gas circumferentially to reduce heat loss from the rear of the thruster. The flow was then directed axially by 16 small channels in the forward (hottest) section of the heat exchanger, after which the gases were expanded through the nozzle. The heating element was made from a coiled tube comprised of 22 turns over a length of 5.8 cm. The platinum thruster components were joined by electron beam welds. To minimize radiative heat losses from the outer surface of the heat exchanger, the thruster was wrapped with radiation shielding consisting of two layers of 0.03-mm platinum foil followed by 13 layers of 0.13-mm stainless steel foil. The layers of shielding were separated by small-diameter wires. Basic dimensions of the laboratory model resistojet are summarized in Table 1.

Two separate thrusters were used to carry out this series of tests: one for generation of a complete performance map, and a second for endurance testing. These two thrusters differed only in the configuration of the heater support structure, which was required to prevent heater coil sag induced by operation in standard gravitational acceleration. In the thruster used for endurance testing, this support structure consisted of 6.4-mm-diam by 6.0-cm-long alumina rod located in the center of the platinum coil and one length of 1.2-cm-o.d, 1.0-cm-i.d. alumina tubing surrounding each end of the heater coil (see Fig. 1c). The heater support structure in the thruster used for performance mapping did not include the two sections of alumina tubing. While interactions between alumina and grain-stabilized platinum at high temperatures have been observed to cause degradation of the platinum structure,[15] preliminary tests suggested that applying a thin coating (nominally 200 Å) of platinum to the alumina surface retards this interaction.

Material Compatibility Testing

The requirement that the space station resistojet be capable of operation for extended periods of time on a variety of propellants is extremely stringent, since the range of fluids of interest includes both oxidizing and reducing gases. The material chosen for this application was grain-stabilized platinum. This platinum-based material was believed to have an adequate combination of high-temperature strength and corrosion resistance in both oxidizing and reducing atmospheres. The grain stabilization is desired to minimize grain growth that occurs when materials are held at high temperatures for extended periods of time. Unfortunately, published information on the long-term compatibility of grain-stabilized platinum with the propellants of interest at 1400°C was not available. Therefore, a study was conducted to evaluate the effects of long-term exposure of high-temperature grain-stabilized platinum tubes to environments of carbon dioxide, methane, hydrogen, ammonia, and steam. The apparatus and procedures used to conduct this investigation are described in detail elsewhere,[13,14] but the pertinent results will be reviewed later in this paper.

Table 2 Vacuum tank 5 pumping capability using hydrogen and nitrogen with two pumping configurations

	Hydrogen		Nitrogen	
Pumping configuration	Flow rate, g/s	Pressure,[a] Torr	Flow rate, g/s	Pressure,[a] Torr
20 oil diffusion pumps	0.02	7×10^{-4}	0.1	5×10^{-4}
Four lobe blowers and four oil sealed rotary	0.02	6×10^{-2}	0.1	4×10^{-2}

[a]Pressure measured with cold cathode ionization gage, with readings corrected for gas type.

Performance Testing

Performance mapping of both laboratory model resistojets was conducted in a vacuum chamber measuring 4.6 m in diameter and 19 m long,[16] equipped with a pumping train consisting of 20 0.8-m-diam oil diffusion pumps backed by four lobe-type rotary blowers and four oil-sealed rotary piston pumps. This system can achieve pressures of approximately 4×10^{-7} Torr with no flow and maintain a tank pressure of 6×10^{-4} Torr with a gas load of 10 standard liters per minute of hydrogen. Data relating some flow rates and the corresponding tank pressures for hydrogen and nitrogen are summarized in Table 2.

The resistojets were characterized using a thrust stand, which relates the horizontal displacement of a mounting plate as an indication of applied thrust.[6] Figure 2 illustrates this thrust stand schematically. The mounting plate is made from a machinable ceramic material to reduce heat transfer from the thruster to the rest of the thrust stand and is supported by four flexures made from stainless steel shim stock. Displacement of the mounting plate is monitored by a linear variable differential transformer (LVDT). The output of the LVDT was calibrated against thrust using small weights (approximately 148 mN each) hung from a length of cord. A low-friction pulley transfers the vertical force exerted on the weights by gravity into a horizontal (thrust) force. The magnitude of the calibration thrust was changed by varying the number of calibration weights supported by the cord. This was accomplished by using a movable weight pan.

Electrical power was supplied to the thruster by two 0.32-cm-diam copper rods. Propellant was fed to the thruster

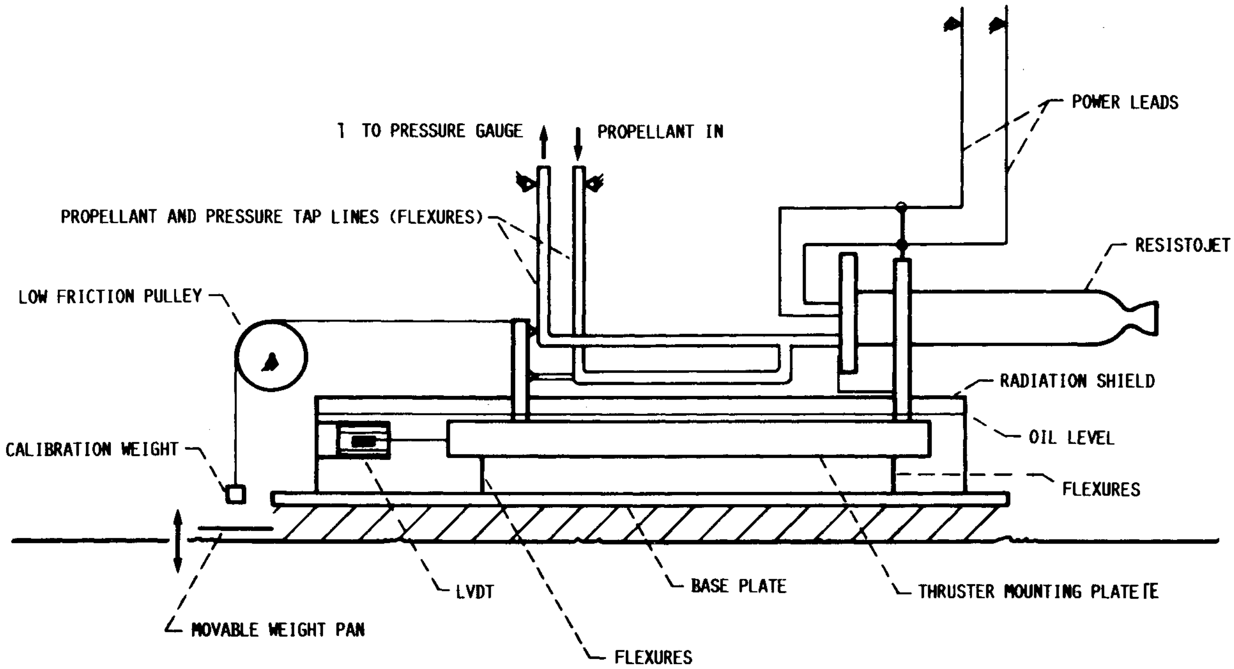


Fig. 2 Thrust stand schematic.

through a length of 0.32-cm-o.d. thin-walled stainless steel tubing. A second tube (identical to the feed line) connected the thruster inlet to a pressure gauge. The propellant feed and presure tap tubes were shaped in a sine-wave configuration to minimize their lateral stiffness, thus increasing the sensitivity of the thrust stand.

The thruster mounting plate and LVDT were submerged in an oil bath to minimize thermal expansion of the base plate and the associated thermal drift in the LVDT output. This thrust system yielded a standard deviation in indicated thrust of approximately 1 mN during calibration. Thermal drift during operation at the power levels required by the laboratory model thruster was minimal. This drift was negated by allowing the thruster to establish equilibrium at each operating point, then turning off propellant flow to cancel thrust, allowing a new thrust standard zero reading to be obtained. The thruster was assumed to be at equilibrium when the inlet pressure and heater voltage stabilized while the propellant mass flow rate and heater current were held constant.

Heater power was provided by a dc power supply with an output capacity of 50 V at 50 A. This unit was operable in both current- and voltage-limited modes. The dc power supply was used in conjunction with a dc resistance controller, which allowed constant heater resistance operation of the thruster.

Propellant flow rates were measured using transducers that were thermally sensitive to gas mass flow rate and heat capacity. These flow meters were calibrated for output reading vs actual mass flow rate for each of the propellants used in the multipropellant resistojet. The calibration curves were linear over the range of flow rates tested. The uncertainty in the measured values of the propellant flow rates was estimated to be less than 3% for all but the lowest flow rates measured.

Performance of the multipropellant resistojet was measured for each of seven propellants over a range of thrust levels at constant heater temperature. The heater temperature tested was 1400°C and was determined during the thruster operation based on a temperature-resistance calibration of the heater performed prior to assembly of the thruster using a two-color optical pyrometer to measure heater temperature.

Endurance Testing

The endurance testing of the laboratory model resistojet began with a pretest analysis. The thruster was then placed in the test chamber where operation time was accumulated, after which a posttest analysis was performed. The purpose of the pretest analysis was to describe the condition of the test thruster thoroughly prior to initiation of the endurance test. This characterization consisted of an electrical calibration of the heater element, a brief performance test, and documentation of critical thruster dimensions. The electrical calibration of the heater element provided the relationship between the heater temperature and electrical resistance. This allowed the resistance to be used as an indication of heater integrity during the course of the endurance test. During this calibration, the heater temperature was measured with a two-color optical pyrometer, and resistances were measured for temperatures from 900–1400°C. The purpose of the pretest performance test was not to probe the limits of the capabilities of the test article, but to provide a benchmark against which any changes in thruster behavior could be gaged and to aid in the selection of operating conditions during the endurance test. The pretest performance test was conducted by measuring cold-flow performance at two thrust levels and warm-flow performance at three thrust levels with heater temperatures of approximately 1400°C.

The endurance test was carried out in a test chamber measuring 0.6 m in diameter × 1.0 m long, equipped with a rotary piston vacuum pump. The thruster was operated for a total of 2400 1-h thermal cycles with a heater duty cycle of 83% and propellant mass flow rate held approximately constant at 0.1 g/s. The propellant used was high-purity carbon dioxide and was chosen because it could be stored in liquid form, was inert (important for facility safety considerations), and was a likely candidate for use as a propellant onboard a space station. Heater voltage and current, propellant mass flow rate, thruster inlet pressure, and temperatures at three locations on the outer layer of the radiation shielding were all monitored continuously during the test. The heater was operated at 29.0 A in a current-limited mode. This current level was chosen to produce an equilibrium heater temperature of 1400°C at the beginning of the test. The choice of heater temperature was based on the expectation that the flight model resistojet would also be operated at up to 1400°C, a temperature at which the glass fabrication industry has extensive experience with operation of grain-stabilized platinum heaters. Test facility pressure during the test remained approximately constant at 40 Pa (0.3 Torr).

The endurance test was voluntarily terminated at the completion of 2400 thermal cycles and 2000 h under power. The resistojet was removed from the test chamber and subjected to a series of posttest inspections intended to document its condition thoroughly. The critical thruster dimensions were recorded, cold and hot performance was documented, and the electrical characteristics of the heater element were evaluated. The posttest analyses also included a complete sectioning of the heater and heat exchanger to allow examination of the platinum microstructures at various places throughout the thruster. This provided information regarding the effects of extended high-temperature operation and electron beam weld joining on the grain stabilization properties of the platinum.

Table 3 Summary of grain-stabilized platinum experiments

Propellant	Coiled heater temperature, °C	Heater initial mass, g	Coiled heater mass loss, g[a]	Extrapolated life,[b] h
		Platinum-yttria		
CO_2	1400	9.0194	0.0030	300,000
CH_4	500	12.6384	0.0008	1,500,000
H_2	1400	12.6589	0.0062	200,000
NH_3	1400	12.5982	0.0055	200,000
H_2	1400	13.0695	0.0116	113,000
		Platinum-zirconia		
CO_2	1400	13.1955	0.0016	800,000
CH_4	500	11.6969	0.0000[c]	1,000,000
H_2	1400	13.2093	0.0031	400,000
NH_3	1400	13.0632	0.0066	200,000
H_2O	1400	11.5133	0.0245	45,000

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

Results and Discussion

Material Compatibility Testing

The results of the material compatibility investigation, summarized in Table 3, indicate that grain-stabilized platinum tubes are compatible with hydrogen, methane, steam, and carbon dioxide under the test conditions. The extrapolated lifetimes of the test specimens in these environments, based on 10% mass loss as end-of-life, are well in excess of the 10,000-h design life goal in all cases. Sections of the test specimens were polished and inspected under high magnification. The grain structures of samples exposed to hydrogen, methane, steam, and carbon dioxide showed no significant increase in grain dimensions when compared to polished sections of annealed samples prior to exposure to propellant gases. Evidence of chemical attack on these samples was minimal. However, the sample exposed to ammonia showed pitting that extended well into the material. This suggested a possible interaction between grain-stabilized platinum and hydrazine decomposition products, which contain up to 20% ammonia. Reduction of the operating temperature to about 900°C in ammonia-containing atmospheres resulted in a significant reduction in such pitting.

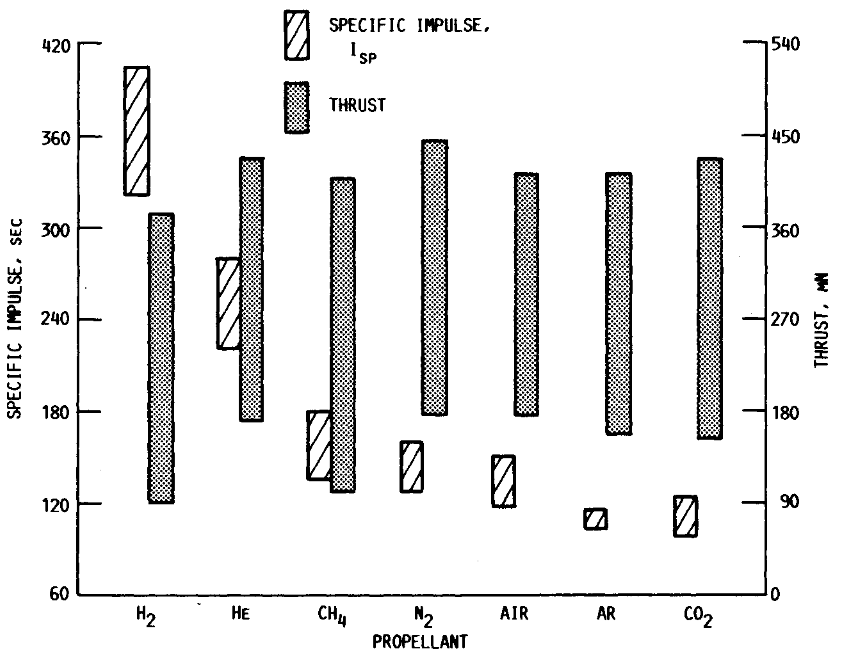


Fig. 3 Specific impulse and thrust ranges for multipropellant resistojet operated on various propellants at heater temperatures of 1400°C.

Performance Characterization Results

Thruster performance evaluation was conducted at a power level of about 200 W for thrust levels ranging from 90-420 mN. Specific impulse, thrust, and input power levels are reported for each of the seven propellants tested. The data were also reduced to examine the values of overall efficiencies and some estimates of gas stagnation temperatures.

With this simple, radiatively coupled thruster design, large temperature drops between the thruster heater and heat exchanger were expected. Estimates of the temperature difference between the heater and heat exchanger wall range from 200°C for low-thrust operation on argon propellant to 1100°C for operation on hydrogen at high thrust levels. These estimates were based on the assumption that the wall temperatures were approximately 150-200°C higher than the estimated gas temperature at the nozzle inlet. The gas temperature was estimated by first calculating the gas stagnation enthalpy, then using tables of standard gas properties[17] that listed enthalpy as a function of temperature. The gas stagnation enthalpy h_f was estimated by dividing the measured thrust power by the square of the nozzle efficiency and the propellant mass flow rate:

$$h_f = \frac{T^* I_{sp}\, g_e}{2^* \dot{m}^* (\eta_{noz})^2} \tag{1}$$

where T and I_{sp} are measured values of thrust and specific impulse, respectively, η_{noz} is an estimate of the nozzle specific impulse (I_{sp}) efficiency, and $\dot{m}$ is the mass flow rate. The nozzle I_{sp} efficiency is defined as the ratio of the actual specific impulse to that predicted by one-dimensional isentropic flow theory for a nozzle with the same stagnation temperature as the nozzle being investigated. The nozzle I_{sp} efficiencies used were approximated by the square root of the overall power efficiency of the resistojet while operating on the various gases with no electrical power input (cold flow):

$$\eta_{noz} = \sqrt{\eta_o} = \sqrt{\frac{T^* I_{sp}\, g_e}{2^* \dot{m}^* h_o}} \tag{2}$$

where h_o is the gas enthalpy at 300 K. Since it is well known that the nozzle I_{sp} efficiency decreases for low Reynolds number flow, the use of the cold-gas values for warm-gas flow may

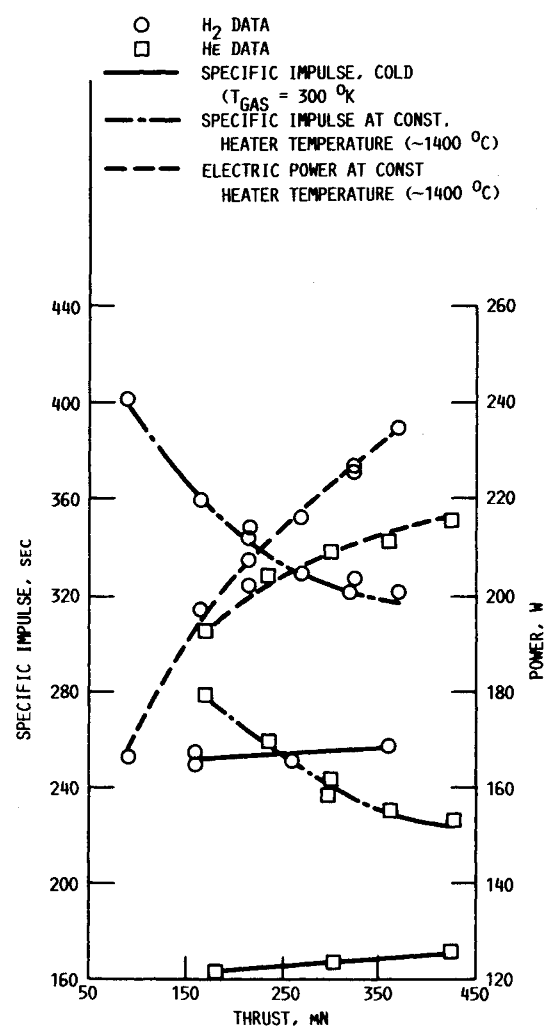


Fig. 4 Specific impulse and input power vs thrust for multipropellant resistojet using H_2 and He.

seem an unlikely choice. However, recent studies [18] indicate that the nozzle I_{sp} efficiency is relatively constant for throat Reynolds numbers above 4×10^3. Most of the performance data obtained for the laboratory model resistojet were at throat Reynolds numbers well above this value, so the nozzle efficiency estimates employed were unlikely to introduce significant error into the estimates of the gas stagnation temperature.

Figure 3 shows the ranges of thrust levels and specific impulse values observed for the various propellants for heater temperatures of approximately 1400°C. This heater temperature was chosen due to heater material limitations. Because of the configuration of the heater element, this temperature limitation caused maximum power dissipation by the heater to be in the vicinity of 200 W. Flow rates for all propellants ranged from 0.08 to 1.6 kg/h at stagnation temperatures from approximately 110°C for hydrogen at high flow rates to about 1040°C for argon a low flow rates.

Figures 4–6 illustrate the variations of specific impulse and input electrical power with thrust for all fluids tested at heater temperatures of 1400°C. Thrust levels were varied by changing the propellant mass flow rate. Power consumption varied approximately as the square root of thrust. The maximum specific impulse levels obtained ranged from a high of 402 s for hydrogen to a low of 133 s for argon. The high values of specific impulse for the remaining fluids were 278, 180, 154, and 122 s for helium, methane, nitrogen, air, and carbon dioxide, respectively. Specific impulse values at gas stagnation temperatures of about 300 K are also shown in Figs. 4–6.

Figure 7 shows the ranges of overall efficiency calculated for the multipropellant resistojet for heater temperatures of 1400°C for the seven propellants tested. The overall efficiency is defined as the ratio of thrust power to total input power, including both incoming gas and electrical sources:

$$\eta_o = \frac{T^* I_{sp} g_e}{2^*(\dot{m}^* h_o + P_e)} \tag{3}$$

where h_o and P_e are the gas enthalpy at 300 K and the input electrical power, respectively. The specific impulse values for which the maximum and minimum efficiencies were calculated are also shown. The maximum efficiencies generally correspond to the minimum specific impulse values. Similar resistojet performance characterizations at higher heater temperatures using hydrogen, ammonia, and nitrogen propellants have been reported.[19,20]

Endurance Test Results

Figure 8 shows the variation in heater voltage during the course of the test, indicating a drop in heater resistance during

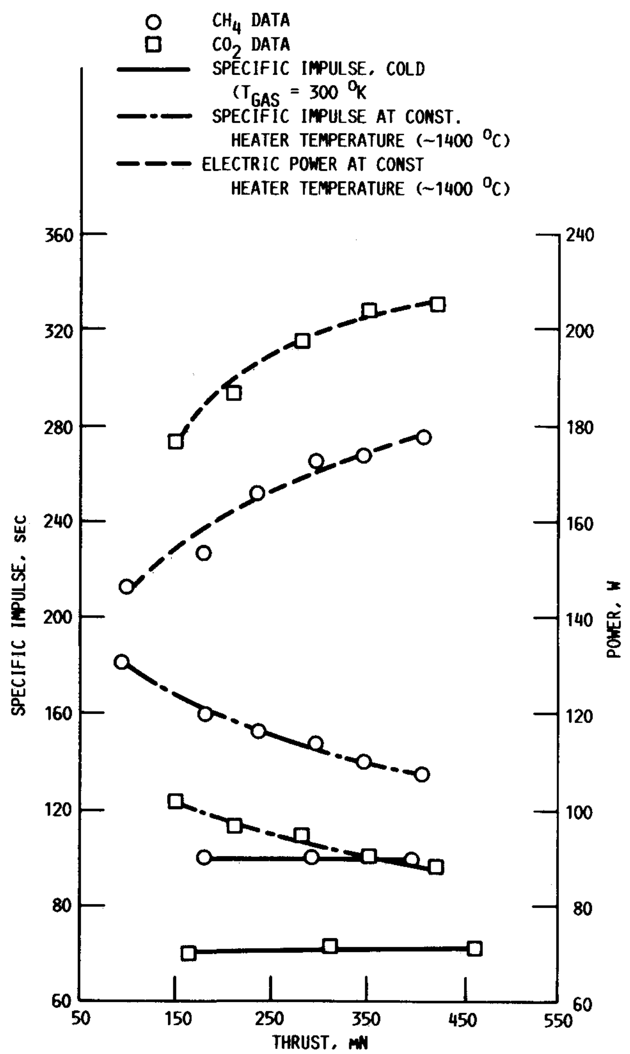


Fig. 5 Specific impulse and input power vs thrust for multipropellant resistojet using CH_4 and CO_2.

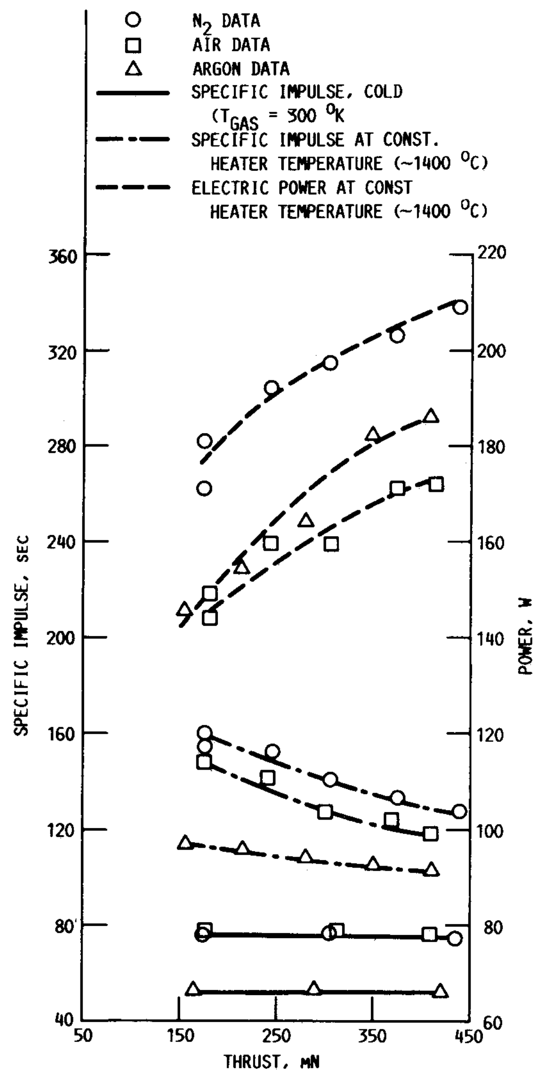


Fig. 6 Specific impulse and input power vs thrust for multipropellant resistojet using N_2, air, and Ar.

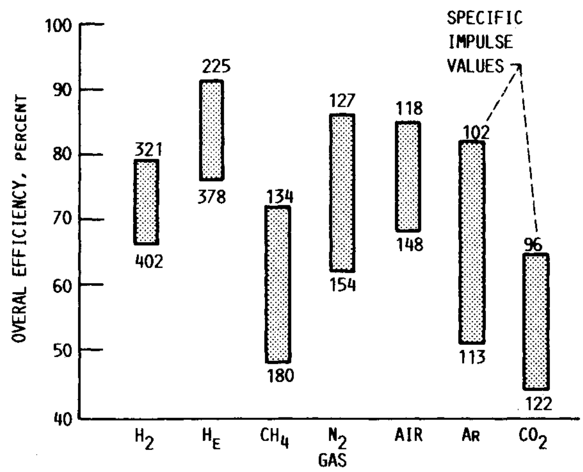


Fig. 7 Overall efficiency ranges and corresponding specific impulse values for multipropellant resistojet using various propellants at heater temperatures of 1400°C.

the test. After the thruster had been disassembled, it was learned that five of the 22 turns of the heater coil were shorted. This shorting occurred when coils moved axially along the alumina support rod during the cyclic expansion and contraction of the heater. Nonuniformities in this motion caused bunching at various locations along the heater length and resulted in the observed shorting.

The heater and heat exchanger designs employed in the engineering model resistojet[12] were chosen to eliminate heater shorting due to movement as observed in the laboratory model truster. The engineering model design is based on a sheathed heater, which consists of a rugged platinum/rhodium heater wire surrounded by a layer of magnesium oxide insulation, all of which is contained in a grain-stabilized platinum sheath. This assembly is processed by swaging the outer sheath, compacting the magnesia between the sheath and the center conductor, and insuring proper centering of the conductor within the sheath. The heater is wound around a central heat exchanger that incorporates a series of semicircular grooves in the forward section designed to hold the heater in place while providing a large surface area for heat conduction.

The purposes of the pretest performance characterization were to provide a basis for selection of the thruster operating conditions during the life test as well as to allow for exposure of any gross degradation of thruster condition, such as gas leaks. It was desirable that the test thruster operate at a mass flow rate and maximum temperature of approximately 0.12 g/s and 1400°C, respectively, since these were the nominal operating conditions anticipated for the engineering model resistojet. The data gathered during the pretest characterization indicated that a current level of 29.0 A at the specified mass flow rate would produce the desired conditions. However, some difficulty in keeping the heater coil centered in the heat exchanger was experienced at the initiation of the endurance test. Therefore, two sections of platinum-coated alumina tubing were installed around the heater coil to keep it centered. The addition of these tubes caused a change in the thermal environment around the last three turns on each end of the heater coil, resulting in a reduction in temperature in these regions for a given heater current. This caused the average resistance of the heater to decrease for a given operating condition. The temperature in the center of the heater coil is believed to have remained at 1400°C for a current of 29.0 A, although the average temperature indicated by the resistance measurement at the initiation of the test was about 1300°C. Comparison of the beginning-of-test performance data to the end-of-test performance data (see Table 4) indicated a significant reduction in warm-gas performance during the test. The heater shorting caused by axial movement of the coils was the

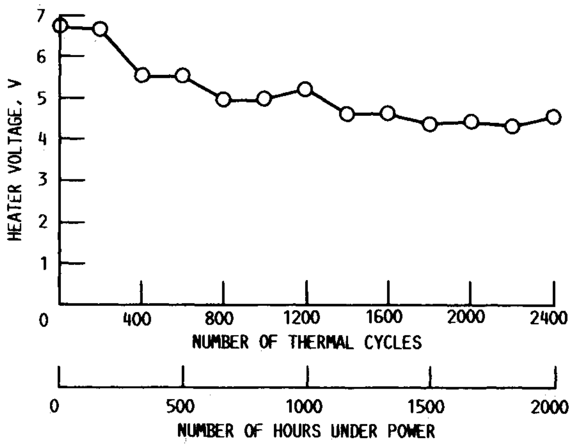


Fig. 8 History of heater voltage during endurance text.

Table 4 Summary of endurance test operating conditions

	Beginning of test	End of test
Measured parameters		
Inlet pressure, MPa	0.18	0.16
Mass flow rate, kg/s	1.23×10^4	1.24×10^4
Voltage, V	6.70	4.40
Current, A	29.0	29.0
Calculated parameters		
Thrust, mN	147	125
Specific impulse, s	122	103
Resistance, Ω	0.231	0.152
Power, W	194	128
Heater temperature, °C	1400	900
Heat exchanger temperature (estimated), °C	800	600

apparent cause of this reduced performance, since the lower heater resistance reduced the maximum power that could be dissipated. No degradation in cold-gas performance was observed, so no gas leaks were indicated.

The effects of prolonged high-temperature, cyclic operation in a ground test facility and the joining of thruster components using electron-beam welds on the grain stabilization of platinum were of major interest, since the engineering model thruster is fabricated from this material. Whereas some data on the stress-rupture and creep properties of grain-stabilized platinum are available in the literature,[21] no data for test times in excess of 1000 h were available. To evaluate the posttest condition of the platinum microstructure, several cross sections of the laboratory model thruster were polished and photographed at magnifications up to 200X.

Figure 9 shows an axial section of the nozzle throat. The grains in the immediate vicinity of the nozzle throat are significantly smaller than the grains in the surrounding material. This observation was not expected, since the throat was one of the hottest regions in the heat exchanger and should have exhibited increased grain growth over cooler areas. However, the machining processes employed during fabrication of this part included the drilling of the nozzle hole as well as additional working to produce a smooth transition from the throat into the nozzle cone. This level of cold working could account for the relatively small grains in this region. Comparison of the posttest condition of this part to the pretest condition of an identically processed part would be desirable, but no additional unused parts were available for sectioning.

The joining of grain-stabilized components using welds has been observed to destroy the oxide dispersion, causing enhanced grain growth within the weld region. Figure 10 shows a section of the tube-to-nozzle weld (weld number 1 in Fig. 1). The broken white lines indicate the interface between the components prior to welding. Note that the weld did not fully penetrate the intended weld region, leaving a void through approximately one-third of the pressure vessel wall. This condition was present through approximately 50% of the tube-to-nozzle weld circumference, indicating the need for further experimentation to determine the optimum EB weld energy density for such joints. Table 5 shows the energy densities (total weld energy/weld length) used to perform some of the welds used to join the thruster components. An interesting feature of the weld in Fig. 10 is that the grains in the weld region are generally no larger than those in the regions surrounding the weld. In fact, some of the grains within the welds appear to be smaller than those in the surrounding material. It is possible that these relatively small grains were caused by

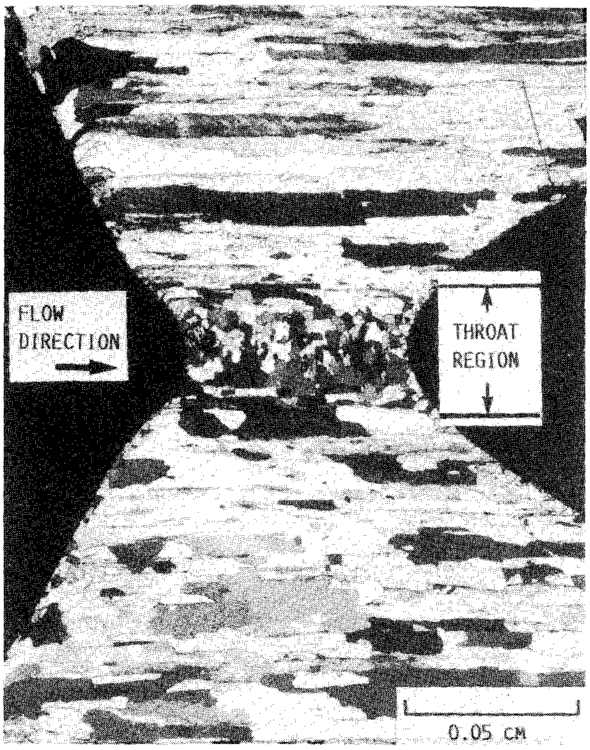


Fig. 9 Grain structure at nozzle throat.

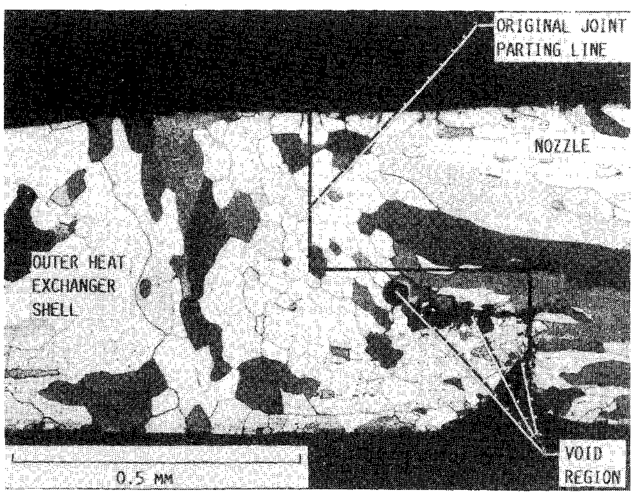


Fig. 10 Nozzle/pressure vessel EB weld.

migration of the stabilization dopant, zirconia, to the grain boundaries where it was still able to retard growth of the grains. This situation may still tend to weaken the weld region. Therefore, the load-bearing joints in the engineering model resistojet employ diffusion bonding over relatively large surface areas with backup EB welds to insure gas-tight integrity.

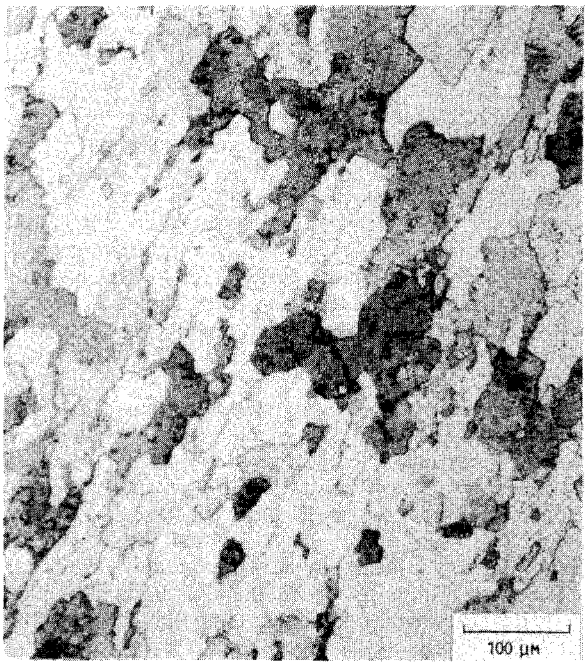
Figures 11a and 11b show sections of the inner heat exchanger shell in the gas inlet region and near the nozzle, respectively. It is apparent that the grains in the inlet (cooler) region are smaller than those in the higher temperature nozzle region. Typical grain dimensions in Fig. 11b are about 0.8 mm, or 10% of the heat exchanger wall thickness. This region was estimated to have operated at about 600°C during the majority of the endurance test, although this temperature was probably closer to 800°C during the first 300 thermal cycles. These estimates are based on an assumed temperature difference between the gas and heat exchanger wall, where the gas temperature was estimated as discussed earlier. The value of the nozzle I_{sp} efficiency was assumed to be 0.92 based on the measured value of the overall cold-gas efficiency of the test thruster.

The heater was expected to show the greatest sensitivity to time and temperature effects on the grain structure. During the test, the heater tube operated at temperatures estimated to be 90–1400°C, the lower temperatures being associated with the areas where coils had shorted together. Microstructures of the heater tubing showed that the grains exhibited an elongated shape with typical grain lengths several times the typical grain width. Many grains spanned the entire thickness of the tubing wall (about 0.25 mm). Since the engineering model thruster pressure vessel walls are 2.5 mm thick, grains of this size would be approximately 10% of this wall thickness, a condition that was present in the pressure vessel of the laboratory model thruster and caused no apparent problems during 2000 h of operation.

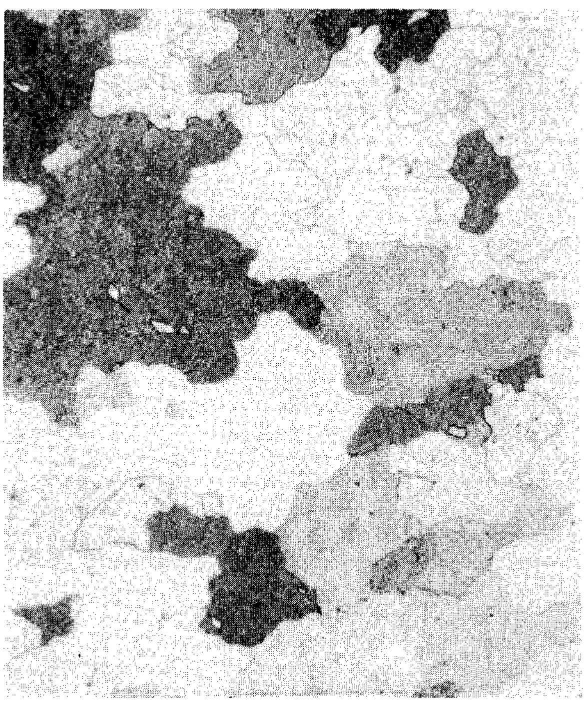
Grain dimensions are known to approach a maximum value asymptotically with time at a given temperature.[22] Reference 14 data show that significant growth can occur during annealing at 1000°C, although the potential for further grain growth cannot be ascertained due to limitations on grain size imposed by the sample dimensions. Likewise, the point on the growth curve represented by the heater tubing microstructures could not be identified (i.e., the grain dimensions could have been limited by the tubing dimension or by operating temperature). Thus, the grains in the pressure vessel walls of the engineering model thruster could grow larger than those observed in the laboratory model heater since the engineering model section provides more room to grow. There are then two questions that must be answered: 1) How large would the grains in a grain-stabilized platinum sample of large cross section be after several thousand hours at temperatures of importance to the design of the engineering model thruster, and 2) How large can the grains within the pressure vessel walls of the engineering model thruster be before the structural integrity is unacceptably compromised. An investigation to determine the relationships between time at temperature and grain size in grain-stabilized platinum samples representative of the engineering model pressure vessel would be valuable.

Table 5 Electron-beam weld energy densities for laboratory model resistojet

Joint description	Energy density, kJ/cm	Fig. 1 reference number
Nozzle/pressure vessel	0.95	1
Pressure vessel/flange front	1.2	2
Inner heat exchange tube/flange rear	0.92	3
Flange front/flange rear	0.90	4
Heater tube/heater terminal disk	$\frac{2}{M}$	5



a) Inlet region



b) Nozzle region

Fig. 11 Grain structure of inner heat exchanger shell.

The environment in the test chamber during the endurance test caused no apparent contamination of the grain-stabilized platinum thruster material. This observation indicates that future endurance tests on platinum thrusters can be conducted in similar test environments without fear of facility effects introducing error into the test results.

Engineering Model Resistojet Design

The objectives of these tests were to serve as test beds for material compatibility, hardware fabrication processes, operating conditions, and strategies for ground testing multipropellant resistojets with long-life characteristics. The information gained from this test has yielded valuable insight into the design of the engineering model resistojet, which will serve as a preprototype space station thruster. The engineering model resistojet incorporates significant design improvements over the laboratory model thruster, which will give it reliable long-life characteristics.[12] Figure 12 shows a cross-sectional drawing of the internal layout of the engineering model resistojet. Among the most significant differences between the laboratory model and engineering model resistojets are the following:

1) The coiled tube heater is replaced by a coiled sheathed heater. 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 wound around a rugged central heat exchanger and is secured in position by a series of semicircular 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 replace the stress-bearing EB welds used in the laboratory model thruster. The diffusion bonds are backed by EB welds located in relatively cool regions of the engineering model thruster to insure 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 replaces the thin-walled pressure vessel employed by the laboratory model thruster. This change improves the stress-rupture characteristics of the engineering model resistojet. However, the question of grain growth within the walls of the engineering model heat exchanger persists, since the thruster heat exchanger is planned to operate at a maximum temperature of 1200–1400°C.

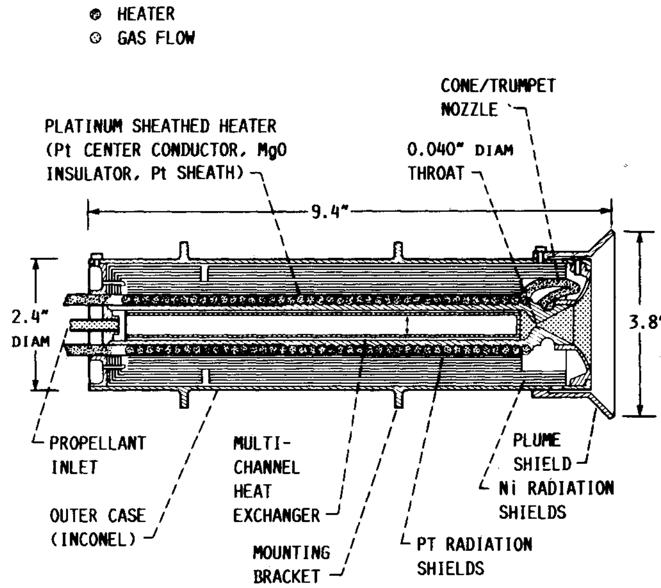


Fig. 12 Engineering model resistojet schematic.

Conclusions

Resistojet thrusters capable of operating for extended periods of time on a variety of propellant fluids have been baselined at the low-thrust option for space station propulsion. Their benefits include simplicity, low cost, and the ability to provide drag makeup while disposing of fluids that would otherwise have to be removed from the space station via shuttle.

Experiments were performed to evaluate the compatibility of grain-stabilized platinum with various propellant gases at temperatures up to 1400°C. All samples tested showed extrapolated lifetimes in excess of 10,000 h based on 10% mass loss as end of life. However, samples tested in ammonia at 1400°C showed severe pitting. Further tests showed that reducing the metal temperature to about 900°C (± 100°C) significantly reduced this material interaction.

A laboratory model thruster fabricated from grain-stabilized platinum was subjected to a series of performance tests as well as a 2000-h, 2400-thermal-cycle endurance test. The performance tests were conducted using seven propellants expected to be available in excess quantities onboard a space station. These included hydrogen, helium, methane, nitrogen, air, argon, and carbon dioxide. Thrust levels observed varied from 90 to 420 mN at input power levels ranging from 140 to 240 W. Heater temperatures for all hot-gas performance tests were approximately 1400°C. Cold-gas performance data were also obtained. The endurance test was carried out using carbon dioxide propellant. The propellant inlet pressure ranged from 0.10 to 0.17 MPa during the endurance test, exerting a maximum hoop stress of 3.2 MPa on the outer wall of the heat exchanger, which is estimated to have operated at a maximum temperature of 600°C during most of the test. No degradation in the integrity of the heat exchanger/pressure vessel was observed. Evidence of mechanical distortion occurred in the heater element, causing shorting and reduction in power level.

The microstructure of the grain-stabilized platinum pressure vessel components generally exhibited an elongated, cylindrical shape, except at the electron-beam-welded joints and in the vicinity of the nozzle throat. The grains in these regions were more nearly spherical. The microstructures of the heater coil tubing, which operated at temperatures of 900–1400°C during the test, showed grain dimensions of the same order as the walls of the heater tubing. It is possible that the grain size was limited by the tubing dimension rather than the operating conditions or the duration of the test. The grain dimensions in the hottest section of the heat exchanger were on the order of 0.05 mm, or about 10% of the pressure vessel wall thickness. These sections are estimated to have operated at 600°C for most of the test. Grains in the heat exchanger walls are believed to have reached their maximum size, since the rate of grain growth generally decreases with increasing time at temperature.

The results obtained from the endurance test performed on the laboratory model resistojet yielded valuable insight into the design of an engineering model resistojet. The design of the engineering model thruster incorporates significant improvements over the laboratory model. Specifically, the problem of heater shorting due to distortion has been eliminated by using a rugged coiled sheathed heater wrapped around a thick-walled heat exchanger incorporating a series of semicircular retaining grooves in the forward section. The use of stress-bearing diffusion bonds backed by electron-beam welds in the engineering model resistojet provides an excellent gas-tight load-bearing joint. The use of a thicker wall section and a smaller inside diameter in the engineering model pressure vessel than in the laboratory model resulted in an 87% reduction in hoop stress and an 80% reduction in the ratio of grain dimension to wall thickness. If the engineering model is operated with a maximum pressure vessel temperature of 600°C, a significant margin of safety will exist with respect to stress level and grain growth. Thus, a safe operating temperature limit has been established for the engineering model thruster.

At the onset of this program, the maximum operating temperature for the engineering model resistojet was chosen to be 1400°C. This limit was chosen because of extensive glass fabrication industry experience in the operation of grain-stabilized platinum at 1400°C for periods in excess of 10^4 h. However, microstructures of the laboratory model heater tubing, which operated at 900–1400°C, suggested that excessive grain growth might become a problem if the engineering model thruster were operated at 1400°C. An evaluation of the dependence of grain growth on time and temperature would yield important insight into the maximum safe operating temperature for the engineering model resistojet.

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