Applied Resistojet Technology

T. KENT PUGMIRE,* ROBERT SHAW,† AND GEORGE R. ENOS‡
Avco Corporation, Lowell, Mass.

The resistojet is now an accredited flight engine. Definitions should be established for communication and comparison of individual thruster performance data. Specific engines can be modeled to provide optimum performance for 10^{-5}–10^{-1}-lb thrust applications. Ammonia data from three units modeled from the same basic design are reported. Studies have indicated possible advantages accruing to the use of biowaste resistojet thrusters for orbit maintenance and control moment gyro desaturation for future manned space stations. Use of these propellants poses new design concerns for the thruster developer. Preliminary study results are reported of the interaction of carbon dioxide, methane, and water with simple heat exchangers and representative heater materials.

Introduction

THE development of the simple electro-thermal engines, resistojets, commenced in the early 1960's. Input power levels were 1–20 kw, and efficiencies were in the range of 45–80% (a function of operating conditions and measurement techniques) with NH_3, N_2, He, or H_2 as the propellants. As it became apparent that unmanned spacecraft would be unable to supply kilowatts of electrical power for many years, resistojet development was shifted to low wattage thrusters.

The first resistojets to obtain operational status were of the thermal storage type (Fig. 1) and were used on the Vela spacecraft by TRW. The approach, though relatively simple, accomplished the objective of about doubling the specific impulse (I_{sp}) of the 1-mlb-thrust, N_2 system.[1] The next operational use of resistojets was on a Naval Research Laboratory flight program. These units, built by General Electric, were ammonia-fueled, micropound thrusters of the thermal storage type.[2] Low-power, low-thermal-inertia resistotjets (Fig. 2) were first flown as experiments on ATS-I[3] and ATS-III.[4] Thrusters of this type were then flown on the operational east-west station-keeping systems on ATS-IV and V.[5]

The thermal-storage engine (Fig. 1) in general has used a refractory, high-heat-capacity heater element. Power is continuously applied to this element and the propellant flow is pulsed. The heater and thruster insulations are designed so that a given pulse of mass flow will have the desired average I_{sp}. The advantage of this type of thruster for pulsed flow requirements is lower peak powers for high I_{sp}'s. The disadvantage is that the flow must be pulsed at a rate determined by the amount of power available, the desired thrust level (F), and I_{sp}. Efficient design requires careful attention to the moderately large volume heater element, the hot heater element power leads and connections, and the limited contact between heater element and propellant. Life of the heater and electrical connections has been a problem.

The "fast heat-up" resistojet, in contrast, has a lightweight heater element with a low thermal inertia. The simplest version is a tubular heater with a single, low-efficiency flow pass (Fig. 2). It is simple and rugged. Thermal efficiency is not particularly relevant because the thruster's applicability is generally limited to the micropound or very low millipound thrust range, and total thruster power is only a few watts. Performance of this thruster with ammonia is given in Fig. 3. The tube temperatures shown for the zero pressure condition are relevant for the low micropound thrust applications. (Note the performance of this thruster at various thrust levels with a constant input power of 5 w. The ATS-IV and V application was at 5 w, 50×10^{-6} lb_f with an I_{sp} of 135 sec.) The lack of thermal design efficiency becomes very significant at $F > 4 \times 10^{-3}$ lb_f and for $I_{sp} > 200$ sec. Though there is no inherent problem in operating the rhenium heater tube and nozzle at higher temperatures (design limit of approximately 3500°F), the lack of thermal efficiency dictates that it not be used for the higher thrust and performance applications.

An application problem associated with this type of thruster is the requirement for power conditioning. Due to the low resistance of the tubular heater element, the nominal spacecraft power must be conditioned to match with the low voltage thruster. In general, this is accomplished by use of a d.c. to a.c. converter and a power transformer. To minimize line power losses the power transformer is located near the thruster. The power loss associated with the power conditioning is 12–18%. This loss is not particularly significant at levels of 5–10 w, but is a substantial loss factor for higher performance applications as it must be considered when establishing total heater efficiency and performance. The requirement for close proximity transformer-thruster installation has created installation design problems.

A somewhat different application of a resistojet has been suggested where there is a very significant spacecraft power limitation.[6] This thruster combines the use of a resistojet thermal trigger to initiate the release of exothermic propellant chemical energy and provide sufficient thermal capacity to sustain the reaction.

Resistojet Performance Parameters and Modeling

Now that resistojets have flight credentials, propulsion suppliers are asked by spacecraft designers for performance data at various operating conditions. A meaningful parameter

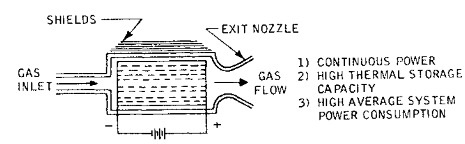

Fig. 1 Thermal storage type of low-power resistojet schematic.

Presented as Paper 70-211 at the AIAA 8th Aerospace Sciences Meeting, New York, January 19–21, 1970; submitted February 18, 1970; revision received September 28, 1970. The authors extend appreciation to their fellow workers on this program: W. S. Davis, R. P. Ingemi, and R. E. Olson.

* Manager, Space Subsystems, Systems Division. Member AIAA.

† Senior Staff Scientist, Space Subsystems, Systems Division. Member AIAA.

‡ Senior Staff Scientist, Applied Physics Laboratory, Systems Division.

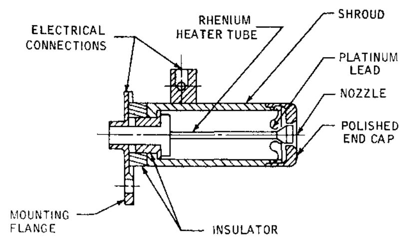

Fig. 2 Low-thermal inertia tubular resistojet.

that is readily calculated from quantities that can be measured with accuracy is the over-all thruster efficiency (η_0) defined as the thrust power of the jet divided by the electrical and chemical power supplied to the thruster. This quantity reduces to the following: $\eta_0 = 21.8\, FI_{sp}/P$, where $P = EJ + \dot{m}h$(w), F = thrust (lb_f), I_{sp} = specific impulse (sec), P = power (w), $\dot{m}$ = mass flow (lb/sec), h = enthalpy, E = voltage (v), and J = current (amp).

In other investigations, heater efficiency has been defined as the ratio of power in the jet to the sum of the chemical and electrical power. The power in the jet is defined as the chemical plus electrical minus the loss power. This definition requires the measurement or calculation of all power losses from the thruster system; all radiation and conductive losses must be integrated over the surface area of the thruster. The accuracy of this measurement-calculation process is somewhat questionable.

The heater effectiveness has also been defined in other work as the ratio of the gas temperature to the heater temperature. Inasmuch as a temperature distribution exists within the heater tube or coil, a question arises as to the temperature to be used in this efficiency. For this figure of merit to be useful, both temperatures must be well-defined and measured. If the gas temperature is deduced from equilibrium calculations, a question exists as to the chemical composition, and hence, the temperature of the gas and flow losses due to viscous effects in the nozzle throat. For the heater temperature to be meaningful, the temperature distribution of the heating element must be measured experimentally. However, it is generally not practical to utilize these methods while measuring thrust because of the nature of the thrust measuring techniques. These measurements can be very satisfactory only when made under identical operating conditions in a controlled environment when thrust is not measured.

Several adaptations of the fast heat-up thruster have been developed for the millipound thrust applications. Each of these thrusters features some regenerative cooling by the inflowing propellant. Two of these designs are quite similar with multipass flow passages, but differ as to the heater elements. One has the basic low-voltage tubular heater and requires power conditioning.[7] The other is of the coil type which is wound in a cylindrical configuration with electrical characteristics that can be made to match directly with the spacecraft power system. (This type of device is shown in Fig. 4.) The third type utilizes vortex flow propellant injection with a minimum volume heating coil and heating chamber.[8] Any of these thrusters can be designed or modified to provide an optimum efficiency over a broad thrust level. For example, by varying throat diameter, heater chamber, length and diameter, the performance (specific impulse/power input-thrust) of the multipass coil heater thruster was shifted from 10–20–40 mlb thrust. Performance data from these three units operating at 200 sec I_{sp} are shown in Fig. 5.

Each of these units at their design point (10, 20, and 40 mlb, respectively) operated at 200 sec at approximately 6–7 w/mlb thrust. (No corrections have been made to this data to adjust for the cell pressure effect.[4,9]) It is obvious from this data that for applications planning, performance modeling scaling has basis for order-of-magnitude estimates.

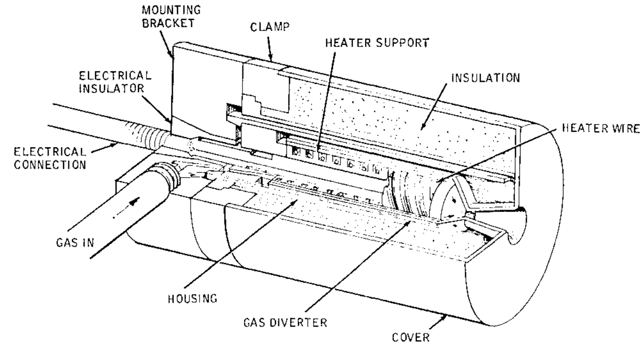

Fig. 4 Coil heater-multiflow passage heat exchanger schematic.

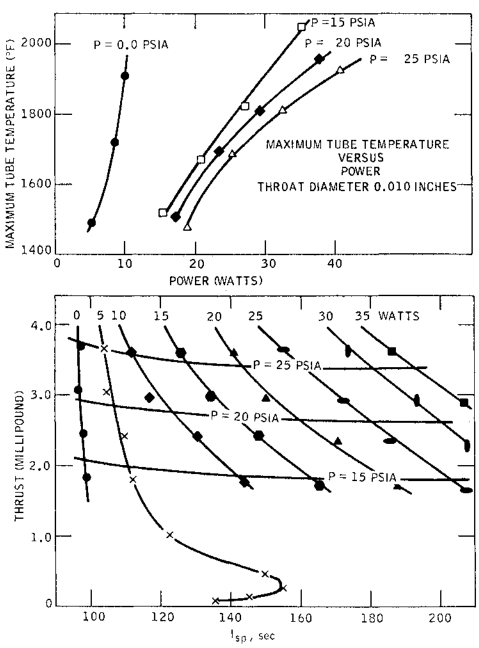

Fig. 3 Performance of low thermal inertia tubular resistojet with ammonia.

Biowaste Propellants

There is little question as to the presence of potential biowaste propellants, carbon dioxide, methane, and water on space stations or space bases.[10–12] The extent of their use rests on questions of quantities (total and rate availability),

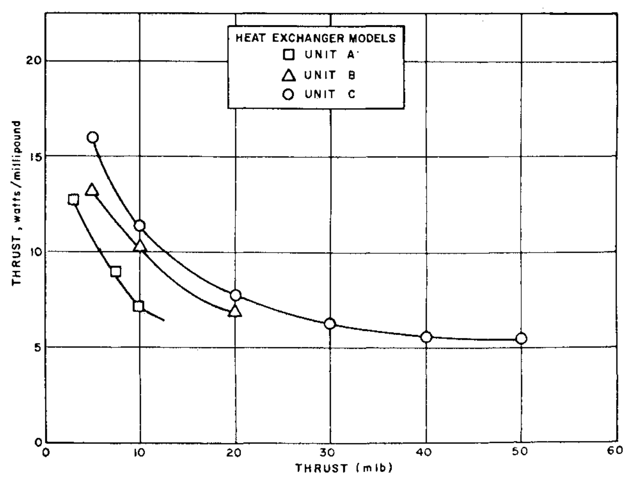

Fig. 5 200 sec I_{sp} performance of modeled heat exchangers with ammonia.

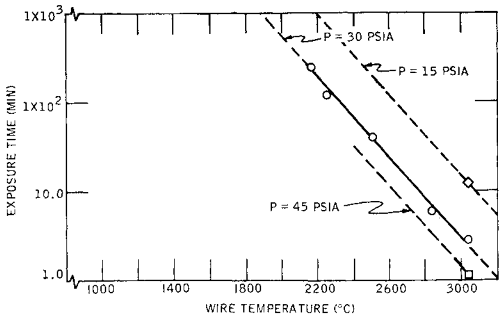

Fig. 6 Time required to deposit 1 mil of carbon on a 90% Pt-10% Rh heater vs wire temperature.

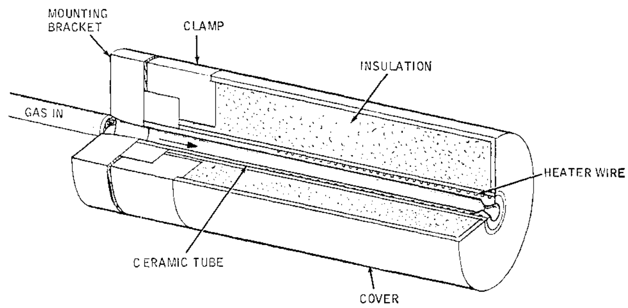

Fig. 8 Ceramic heat exchanger schematic.

impulse, weight, volume, reliability requirements, which must be answered by the station planners. The types and quantities of biowaste propellants will be a function of the additional processing storage equipment required (power required, weight, volume, reliability, adaptability), vs the use of nonfunctional removal processes with the propulsion function being provided by other means which also entails the consideration of the factors of propellant weight (resupplied), power, volume, etc.

Station planners will also establish the feasibility, location and number of thrusters and the supporting equipment and services of telemetry, command logic control and power. These planners will determine and specify operational parameters, based on propulsion needs and engine performance data, thrust level, specific impulse, duty cycle, and electrical and mechanical interfaces. The operating conditions are likely within the following range: thrust—0.01–0.2 lb; power—0–2500 w; propellants—carbon dioxide, methane and water.[10–12] Though a firm specification of actual requirements may not exist for some time, several technology problems of biowaste resistojets have been defined. Three of these are: 1) establishment of boundary conditions related to production of undesirable or prohibitive jet exhaust materials; 2) reliability of thruster materials with typical biowaste propellants; 3) potential and limitations of use of a single heat exchanger (thruster) for different propellant combinations.

Methane

Methane can be considered as a good propellant. As a cold gas, specific impulses of 100 sec may be obtained. Used with an oxidizer, specific impulses of 240 sec are developed. Heated in resistojets, specific impulses of over 200 sec have been achieved. The principal problem associated with methane is its tendency to dissociate at elevated temperatures so as to produce solid carbon which can be deposited in the heat exchanger, nozzle, or in the efflux. Though this time dependent dissociative process is a function of temperature and pressure, it is also a strong function of the chemical related environment. The presence of oxygen tends to quantitatively reduce the magnitude of the problem; however, there are practical limits to this solution in that the quantity of oxygen added must be at least equal to the amount of carbon in the methane for temperatures above 1800°R and for equilibrium conditions. (This homogeneous oxidation, if accomplished in a steam or carbon dioxide environment is somewhat undesirable as it is also endothermic.[13])

One of the most promising approaches to inhibit homogeneous decomposition is to limit the exposure or "stay time" in the thruster. However, heterogeneous decomposition rates are faster than homogeneous kinetics by orders of magnitude, and it may be quite difficult to rely on short stay times in practical heat exchanger designs, particularly in the presence of many metals.

In an attempt to obtain some definition of the methane decomposition problem, wires of different materials were placed in flow tubes of methane. The temperature of the wires was varied at several pressure levels. Measurements were made of the time required to deposit one mil of carbon on the wire. Typical of the results are the data shown in Fig. 6 for a platinum-rhodium wire. Tests using the wires as exposed heating elements produced large changes in the electrical characteristics of the heaters. Obviously, any similar buildup of these deposits would produce unacceptable results in an actual engine.

Dissociate absorption of methane has been observed at temperatures as low as 1100°R.[14] Though there is a variation in the heterogeneous decomposition rates of methane in the presence of moderate to high-temperature metals, the spread is small in comparison to the difference between the homogeneous rate and the heterogeneous rates in general. The fastest heterogeneous rate is associated with platinum and the slower ones are with the refractories. Nickel, which is used in many commercial applications with methane, is near the middle.[15] The carbon deposition wire tests with tungsten-rhenium at the lower temperatures <2500° when compared to that of platinum, showed the relative heterogeneous rate difference cited in the literature[15]; however, at 3000°R, no rate difference was experimentally distinguishable.

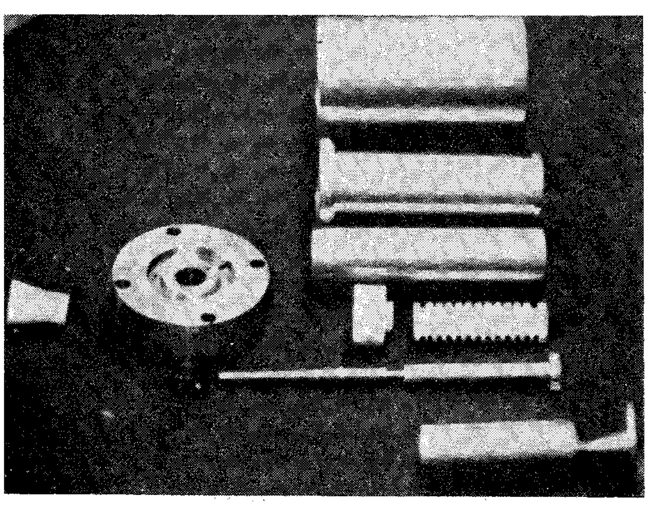

Fig. 7 Inconel heat exchanger parts.

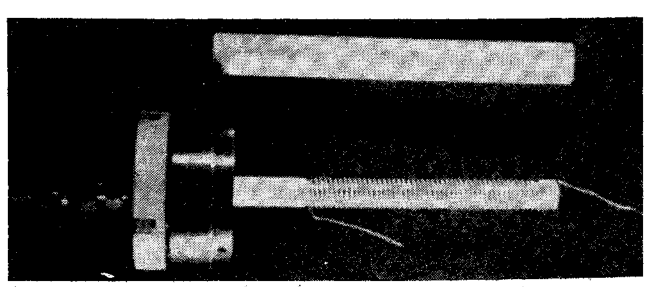

Fig. 9 Ceramic heat exchanger parts.

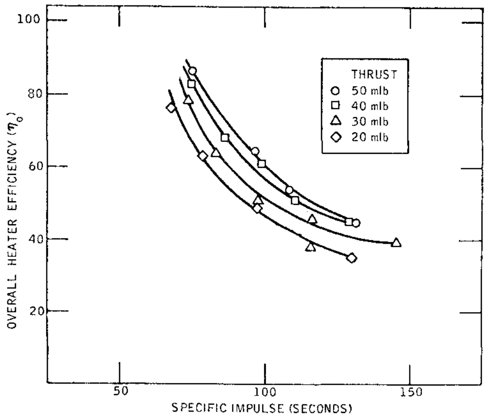

Fig. 10 Carbon dioxide performance with inconel heat exchanger.

Carbon Dioxide

Carbon dioxide is not an ideal resistojet propellant due to its relatively large molecular weight, its poor heat-transfer characteristics and its oxidizing properties. The optimum high-temperature heat exchanger requires relatively long stay times and/or moderately high pressures and oxidization resistant materials. Wire-flow tube tests, similar to those described earlier for methane, were also performed with carbon dioxide. The test results were in agreement with data in the literature regarding oxidation susceptibility. Five mil rhenium wire, in one atmosphere of flowing carbon dioxide, showed visible oxidization on the wire after ten minutes at 1500°R. At 2300°R, the wire would become destructively oxidized in two to three minutes. No decomposition problems for carbon dioxide, similar to that of methane, were observed.

Water

Water as a propellant (without a prevaporizer upstream of the thruster) is considerably different from use of a gas as powerless operation is not possible under vacuum conditions. A problem with a thruster that provides both the heat of vaporization and super heat is fluid control, particularly if the heat exchanger is operated in a current-limiting mode. An irregular injection of mass flow potentially could cause a localized cooling of the heater coil with a resulting local resistance and power dissipation drop. If the perturbation is sufficiently large there could be incomplete vaporization and the possibility of icing.

Performance Results

To explore the problems associated with operation of resistojets with these biowaste propellants, several laboratory type heat exchangers were fabricated. No particular attempt was made to optimize the thermal efficiency; rather, attention was directed to exploratory units which could be easily diagnosed, disassembled, inspected, and modified. To this end, the heat exchangers shown in Figs. 4, 7–9 were developed.

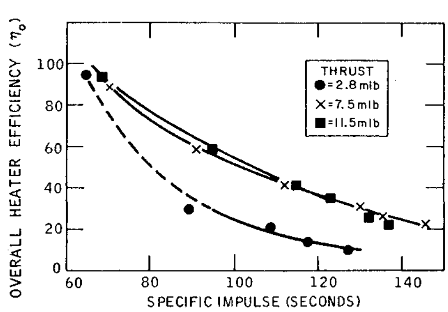

Fig. 11 Carbon dioxide performance with rhenium heat exchanger.

Table 1 W/mlb thrust for carbon dioxide

Specific impulse, sec	Inconel, w/mlb	Rhenium, w/mlb	Ceramic, w/mlb
100	2.6	3.1	3.9
125	5.2	8.9	11.5
150	8.1	...	16.5

Several materials were considered for these laboratory heat exchangers to test the relative effects of carbon dioxide, methane, and water at elevated temperatures. Metals capable of operating at high temperatures were either catalytic (noble metals—Pt, Rh, etc.) to methane or would oxidize (refractory metals—W, Mo, etc.) in the presence of carbon dioxide and water. The decision was made to fabricate a unit of rhenium for short residence time operation <0.02 sec, an oxidation resistant metal heat exchanger for >0.02 sec operation, and a noncatalytic, high-temperature ceramic heat exchanger.

As another investigator was studying the potential of the oxidization resistant platinum alloy, our attention was directed to one of the much used oxidation resistant engineering materials such as Hastelloy, Inconel, etc. This limited the operating temperature of this heat exchanger to <3000°R. Hastelloy-X has been widely used for similar temperature and oxidation applications. However, Inconel-601 provided the higher oxidation resistance and higher melting point and was therefore selected.[16]

Any one of several materials would have met our requirements for the simple ceramic heat exchanger. What was desired was a material that would be noncatalytic, oxidation resistant, and a relatively good nonconductor for temperatures up to 2600°R. As boron nitride met these requirements and was easily machinable, it was selected.

The Inconel and rhenium heat exchangers are shown schematically in Fig. 4, and a photograph of the disassembled component parts of the Inconel unit in Fig. 7. These units feature a multipass flow passage, a moderate voltage heater coil, and some insulation. During these tests the units were mounted to a water cooled support base. Approximate gas stay time in the Inconel heat exchanger is 0.05 sec, for the rhenium unit about 0.015 sec.

The ceramic heat exchanger (boron nitride), Figs. 8 and 9, features a simple single-pass tubular heater with the gas isolated from the electrical heater by a ceramic tube. The base of this heater was also supported by a water cooled mount. The average stay time in this unit for the reported tests was 0.02 sec.

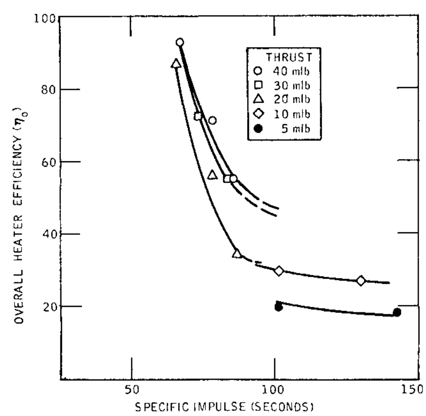

Fig. 12 Carbon dioxide performance with ceramic heat exchanger.

Table 2 Equilibrium composition of methane (CH_4)

		Number of moles/mole of CH_4 initially[a]						
P, atm	T, °K	CH_4	CH_3	C_2H_2	C_2H_4	H_2	H	C_{solid}
0.1	500	0.9698				0.0605		0.0302
	1000	0.0188	0.989×10^{-8}	0.272×10^{-8}	0.131×10^{-6}	1.962	0.141×10^{-7}	0.9812
	1500	0.509×10^{-3}	0.152×10^{-5}	0.210×10^{-4}	0.609×10^{-6}	1.999	0.111×10^{-3}	0.9994
	2000	0.795×10^{-4}	0.180×10^{-4}	0.176×10^{-2}	0.125×10^{-5}	1.993	0.0103	0.9964
1	500	0.9904				0.0191		0.00957
	1000	0.1508	0.261×10^{-7}	0.236×10^{-8}	0.105×10^{-5}	1.698	0.400×10^{-8}	0.849
	1500	0.506×10^{-2}	0.478×10^{-5}	0.209×10^{-4}	0.605×10^{-5}	1.990	0.349×10^{-4}	0.9949
	2000	0.780×10^{-3}	0.571×10^{-4}	0.176×10^{-2}	0.126×10^{-4}	1.995	0.324×10^{-2}	0.9956
10	500	0.9970				0.00605		0.00303
	1000	0.5466	0.363×10^{-7}	0.126×10^{-8}	0.380×10^{-5}	0.907	0.820×10^{-9}	0.4533
	1500	0.0474	0.143×10^{-4}	0.200×10^{-4}	0.567×10^{-4}	1.905	0.107×10^{-4}	0.953
	2000	0.790×10^{-3}	0.179×10^{-3}	0.175×10^{-2}	0.124×10^{-3}	1.981	0.102×10^{-2}	0.9882

[a] The following other species and their respective minimum concentrations were considered: $C_{vapor} < 10^{-9}$; CH $< 10^{-8}$; $CH_2 < 10^{-5}$.

Carbon Dioxide Data

Performance summaries for carbon dioxide operation in the Inconel heater is given in Fig. 10, the rhenium heater Fig. 11, and the ceramic unit Fig. 12. As can be seen from the over-all efficiency plots, the energy conversion process becomes increasingly inefficient as the thrust (chamber pressure) is reduced. A comparison of these units in terms of w/mlb thrust for several specific impulses for selected thrust levels is given in Table 1. No significant damage occurred to any of the heaters used in these tests though some surface changes were noted with the rhenium unit.

Methane Data

Each of the three types of heat exchangers was operated with methane. In the exploratory tests with the Inconel unit, methane was injected at a flow rate of approximately 0.06 lb/sec and the heater was operated with 200 w (Inconel temperature over 2000°R). In less than one hour of operation, the heater voltage dropped by 50% because of carbon layering on the heater wire and flow passages were nearly blocked. (Stay time ~0.050 sec.) It was nearly impossible to obtain meaningful data from this test except at very low temperatures.

Conversely, no major operating problem was encountered with methane in the short stay time rhenium unit (~0.015 sec), though a residue was observed in the heat exchanger following the tests. (Equilibrium calculations indicate that nearly all of the methane should have been decomposed to hydrogen and solid carbon at the operating temperatures, Table 2.)

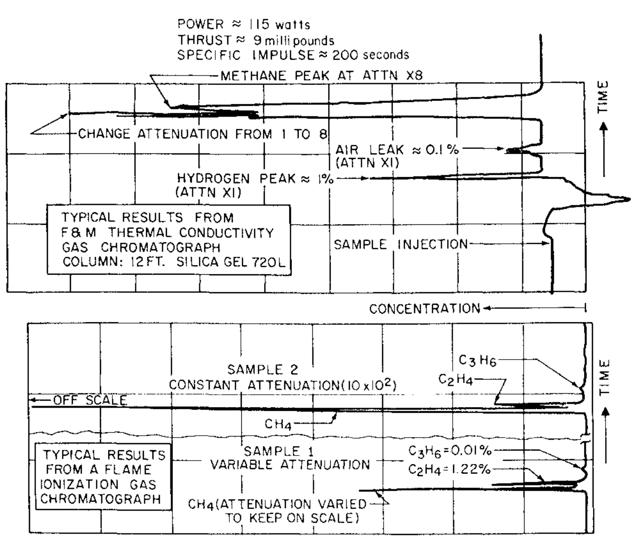

Fig. 13 Gas analysis of exhaust products with methane.

Several experimental techniques were used to evaluate the exhaust products of the methane tests to determine the amount or pressure of carbon solids. One of the methods used with the rhenium heat exchanger involved collecting the efflux and making chromatographic measurements. The results of this investigation for methane in the rhenium heat exchanger operating at approximately 200 sec I_{sp} are presented in Fig. 13. The thermal conductivity cell measurements indicate the purity of the sample, (less than 0.1% air leak) and the presence of 1% H. The measurements from the flame ionization cell indicated 1.2% C_2H_4 and <0.1% C_3H_6. The concentration of hydrocarbons with H/C = 4 is balanced by the amount of hydrogen formed. The problem with these measurements is the amount of carbon solid produced must be deduced indirectly from these composition measurements. Though the apparent chemical balance from the measurements and physical examination of the collection sample container did not show carbon, it was felt to be inconclusive because of the presence of a small carbon residue found in the rhenium heater following the test.

For tests with methane in Inconel and ceramic heat exchangers, a white target (boron nitride) was placed ~1 in. downstream of the heat exchanger nozzle. The heat exchanger temperature was then increased until evidence of carbon deposition has occurred on the target or in the heat exchanger.

The Inconel unit produced deposits for temperatures as low as 1800°R. The ceramic heat exchanger was operated at a temperature of 2600°R for a period of two hours and no evidence of carbon deposition was found on the target or in the heater. Addition of an Inconel wire to the inner chamber of the ceramic unit caused carbon to appear on the target after operation at a temperature of 2000°R for only 5 min. Carbon deposits observed in these tests were of the amorphous type. In the wire-flow tube tests this was also the case for temperatures below 2600°R. For temperatures above 2600°R, pyrolytic deposition of the carbon was observed. This will likely

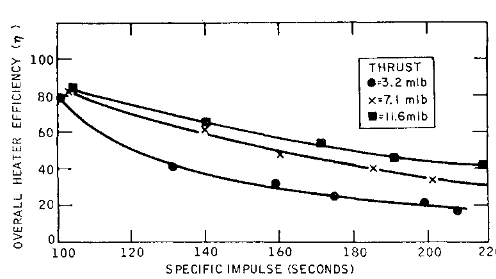

Fig. 14 Methane performance with rhenium heat exchanger.

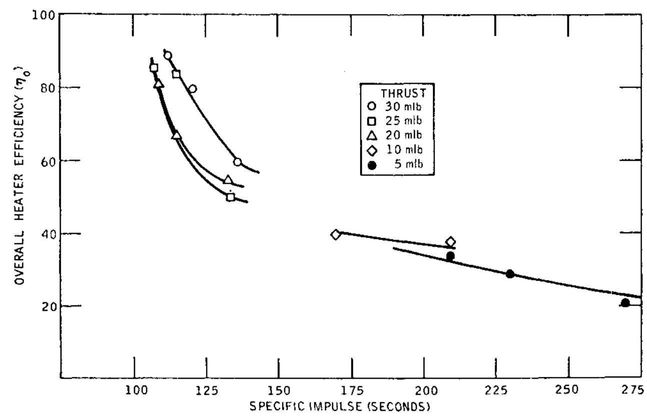

Fig. 15 Methane performance with ceramic heat exchanger.

be a limiting thermal-chemical mechanism for even a noncatalytic, short stay time heater.

Methane performance data from the rhenium and ceramic heat exchanger are presented in Figs. 14 and 15, respectively. Though the data obtained thus far are incomplete, it is clear that very high, well in excess of 200 sec, I_{sp} can be obtained in a ceramic thruster with minimum risk of solid carbon formation. Obiously, this will be obtained at better efficiencies with a thruster designed for minimizing the thermal losses.

Water Performance Data

As indicated previously, these preliminary tests with water coupled the processes of water vaporization and super heating in the same unit. The principal emphasis of the tests were to investigate the feasibility of this concept and to define design and operational parameters of this type of heater. All of these tests were done in a rhenium unit of the type shown in Fig. 4. The performance data are given in Fig. 16. The input power data includes that needed for the heat vaporization. The theoretical curve for specific power vs I_{sp} assumes that the heat of vaporization is a frozen-flow loss and will not be recovered in the nozzle flow. At thrust levels of 8.9 to 11.1 mlb, the specific impulse ranged from 180 to 220 sec at specific powers of 11 to 14.9 w/mlb. The power inputs for these data points ranged from 90 to 135 w. With only a small amount of optimization of the boiling region within the heat exchanger, 10 mlb thrust can be delivered at 200 sec at a power expenditure of 120 w. On the same curve, data is presented at lower thrust values and reduced power. If the thrust is reduced to the 1.3 to 3.2 mlb range, the specific power is increased to approximately 17.5 w/mlb. The efficiency at lower thrust and pressure was also seen in the mean coil temperature.

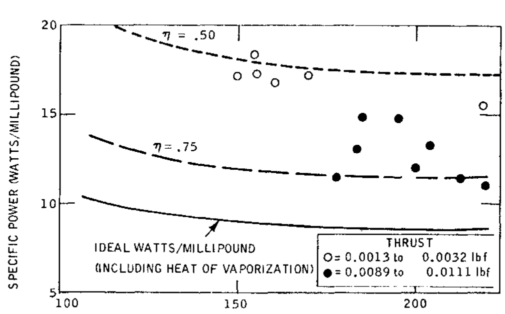

Fig. 16 Water performance with rhenium heat exchanger.

In general, the lower thrust (and I_{sp}) required a higher mean tube temperature when compared to the ideal exit temperature.

The use of water as a fuel requires a boiling process and thus, great variation in the heat-transfer coefficient. The extreme values of this parameter cause a large temperature distribution to exist within the heater coil. Thus, at the heat exchanger exit a considerably higher temperature than the mean exists which provides the thermal potential to superheat the stream. The existence of large temperature distributions within the heater coil require that care be used in the design of the heater region to tailor the power dissipated per unit length to the demands of the fluid. The wide range in specific impulse for small changes in power can be seen from the nominal 10 mlb thrust data.

Conclusion

Although the data reported are incomplete and are only partially definitive of the operational characteristics of resistojets, it is clear that these simple devices can be tailored to meet a broad range of applications including a great variety of propellants. However, optimum performance and thruster life will be a function of how well the interacting chemical, material, and thermodynamic functions are understood and applied.

References

[1] Jackson, F. A. et al., "An Operational Electrothermal Propulsion System for Spacecraft Reaction Control," AIAA Paper 66-213, San Diego, Calif., March 1966.

[2] "NRL Ammonia Vapor Microthruster System-Final Technical Report," Contract N100041-66-C0129, Sept. 1966, General Electric Co.,

[3] White, A. F., "Electrothermal Microthrust Systems," AIAA Paper 67-424, Washington, D.C., July 1967.

[4] Pugmire, T. K., Davis, W. S., and Lund, W., "ATS-III Resistojet Thruster System Performance," *Journal of Spacecraft and Rockets*, Vol. 6, No. 7, July 1969, pp. 790–794.

[5] Shaw, R., Pugmire, T. K., and Callens, R. A., "Ammonia Resistojet Station Keeping Subsystem Aboard Applications Satellite (ATS-)IV," AIAA Paper 69-296, Williamsburg, Va., March 1969.

[6] Schreib, R. R., Pugmire, T. K., and Chapin, S. G., "The Hybrid (Hydrazine) Resistojet," AIAA Paper 69-496, U.S.A.F. Academy, Colo., June 1969.

[7] Halbach, C. R. and Yoshida, R. Y., "Development of a Biowaste Resistojet," AIAA Paper 70-1133, Stanford, Calif., Sept. 1970.

[8] Murch, C. K. and Krieve, W. F., "Electrothermal Thruster Performance with Biowaste Propellants," AIAA Paper 70-1161, Stanford, Calif., Sept. 1970.

[9] Yoshida, R. Y., Halbach, C. R., and Hill, L. S., "Life Test Summary and High Vacuum Tests of 10 MLB Resistojets," AIAA Paper 70-1136, Stanford, Calif., Sept. 1970.

[10] Bliss, J. R., Greco, R. V., and Nelson, W. G., "Biowaste Resistojet System Definition for the NASA Space Station," AIAA Paper 70-1132, Stanford, Calif., Sept. 1970.

[11] Duncan, L. F. and Laubach, G. E., "Resistojet Waste Methane Utilization in Manned Space Application," AIAA Paper 70-1131, Stanford, Calif., Sept. 1970.

[12] VanLandingham, E. E. and Willis, S. P., "Integrated Environmental Control/Life Support-Resistojet Systems," AIAA Paper 70-1130, Stanford, Calif., Sept. 1970.

[13] Storch, H. H., *The Chemistry of Petroleum Hydrocarbons*, Vol. 2, Reinhold Publishing Corp., New York, 1955, Chap. 35.

[14] Morikawa, M., Benedict, W. S., and Taylor, H. S., *Journal of American Chemical Society*, Vol. 58, 1936.

[15] Bond, G. C., *Catalysis by Metals*, Academic Press, New York, 1962.

[16] *Materials Engineering*, Vol. 71, Reinhold Publishing Corp., New York, 1970.