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PERFORMANCE TESTS OF A 1/2-MILLIPOUND (2.2 mN) AMMONIA RESISTOJET THRUSTOR SYSTEM

by Harold Ferguson and James S. Sovey

Lewis Research Center
Cleveland, Ohio

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November 1967

Page 8: The second equation should read

$$\eta = \frac{g^2}{2} \frac{\dot{m}\left(I^2 - I_{cold}^2\right)}{P_{in}}$$

Page 8: Below the second equation insert the following definition in the list of symbols:

g acceleration due to gravity

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SUMMARY

Performance data were obtained and evaluated for a nominal 1/2-millipound- (2.2 mN) thrust resistojet system, with ammonia as the propellant. The system is defined to include the thrustors, the propellant storage and feed components, and the power and signal conditioning module. For a nominal system input power of 8 watts, the valves and power conditioning required 3 watts. The power delivered to the thrustor was 5 watts, of which approximately 1 watt represented augmented thrust power. For these conditions, a specific impulse of 140 seconds was obtained. The system was capable of maintaining specified thrust tolerances for either liquid or vapor propellant extraction and thus should be able to operate in a zero-gravity environment.

INTRODUCTION

In recent years considerable interest has been shown in small thrustors for use in control maneuvers of various spacecraft. One form of small thrustor that has extensive application employs cold gas, such as nitrogen, as a mass expellant. Although this thrustor system has the advantages of simplicity, the weight of the system is high because of the low specific impulse and the high storage pressure of the gas. Thus, for systems with long mission times or intricate control maneuvers that require substantial total impulse, the propellant and system weight often become prohibitively large.

Extensive studies of the "resistojet" system, in which system the propellant is heated electrically as it passes through the thrustor, have been made in order to increase the specific impulse of the cold-gas system while retaining the advantages of its simplicity. The use of propellants which could be stored as a liquid to further reduce the weight have been included in these studies. As part of these studies Lewis has developed under contract (refs. 1 and 2) a resistojet thrustor system capable of rapid turn-on and suitable for use in a control system of a typical spacecraft. The system produces a thrust of 1/2 millipound (2.2 mN) for a system input power of less than 10 watts and uses ammonia, stored as a liquid, as a propellant.

This report presents the results of tests conducted to obtain the performance parameters of typical components and to demonstrate at least 50 hours of successful operation of the complete system. The investigation was divided into three steps to meet these objectives. First, the thrustor performance was obtained for a range of input power and supply pressure; second, the electrical, mechanical, and thermodynamic operations of the storage and feed system were investigated; and third, the integrated system was operated for a period in excess of 50 hours. Since no control logic is incorporated in the system as defined, it is sufficient to demonstrate the ability to provide the required performance on command.

APPARATUS

Resistojet System

The complete resistojet system is shown photographically (fig. 1) and in mechanical and electrical diagrams (fig. 2). The system consists of a stainless-steel propellant storage and feed module of approximately 1-pound (0.45-kg) capacity, two thrustors, and the power and signal conditioning. The thrustors together with their respective power conditioning and valves are identified in connection with their use in an attitude control system as clockwise and counterclockwise modes.

The thrustor (fig. 3) consists of a rhenium heater tube surrounded by a stainless-steel shield. The inner diameter of the heater tube is 19 mils (0.483 mm), and the wall thickness is approximately 7 mils (0.177 mm). Reference 2 gives a complete description of the thrustor fabrication techniques. The tube is heated by passing a current through the tube, and the propellant is heated by contact with the inner walls.

The propellant is stored as a liquid in equilibrium with its vapor. A second chamber (the plenum) is provided in which the propellant is in the vapor state. The plenum and the liquid storage tank are separated by a small volume, the preplenum. The functions of the preplenum are to assure a gaseous propellant feed and to reduce the pressure excursions in the plenum. Thus, a more constant pressure is provided immediately upstream of the heater-tube inlet. The preplenum and plenum are separated by a small subsonic orifice. As propellant is withdrawn, the pressure in the preplenum decreases until the pressure switch closes at a preset lower limit and opens the control valve located between the storage tank and the preplenum. Propellant flows into the preplenum and causes the pressure to increase to the desired upper limit, at which time the pres-

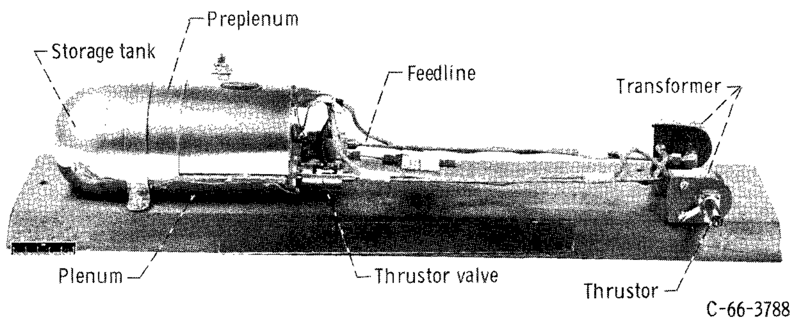
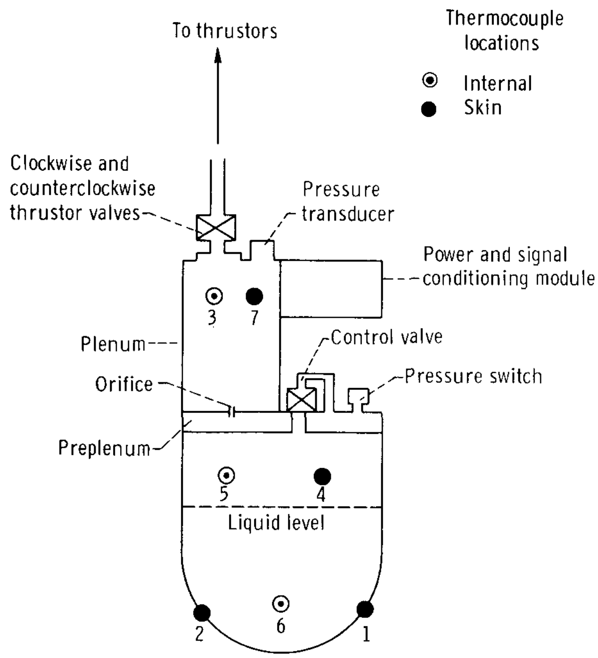
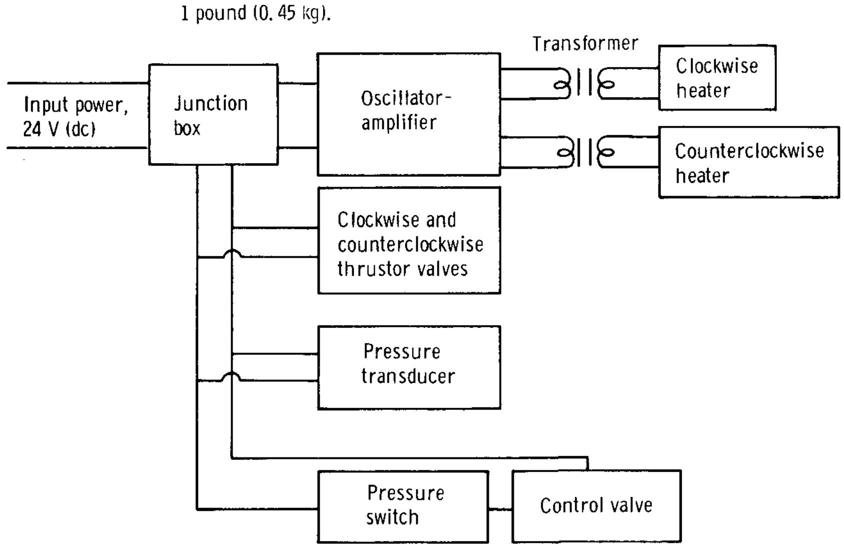


Figure 1. - Ammonia resistojet system.



(a) Mechanical diagram. Propellant storage capacity, approximately 1 pound (0.45 kg).



(b) Electrical diagram.

Figure 2. - Schematic diagrams of resistojet system.

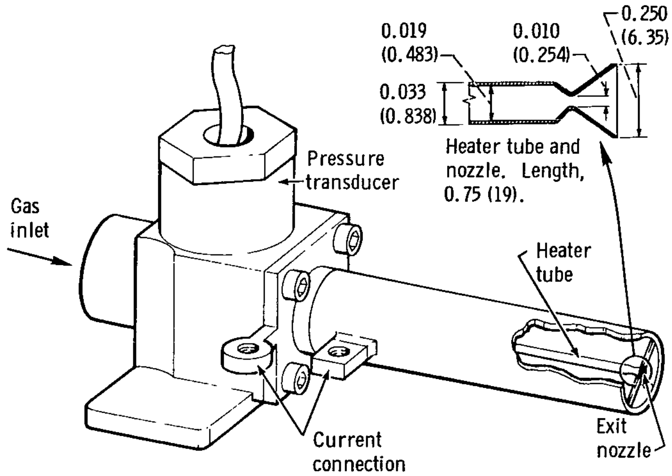


Figure 3. - Thrustor assembly. (Dimensions in inches (and mm).)

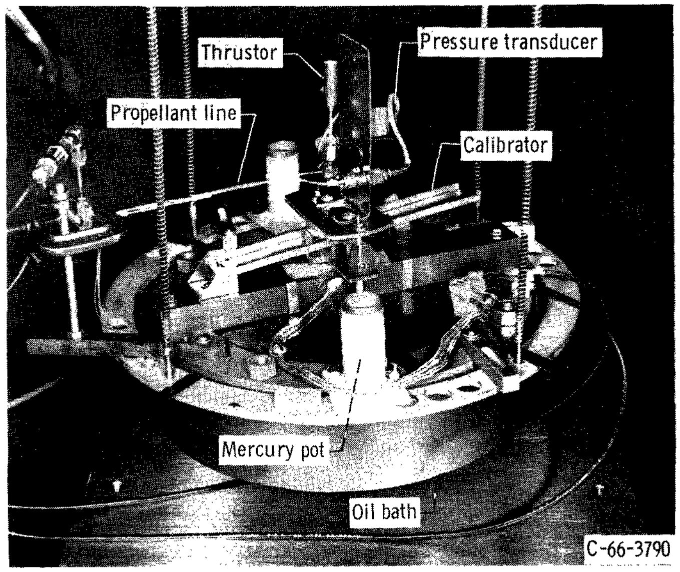
sure switch opens and closes the control valve. This procedure is repeated continually as the system operates. No heat is intentionally added to the liquid in the storage tank to provide for the heat of vaporization of the propellant. The pressure at the inlet to the thrustor heater tube is the pressure of the gas in the plenum chamber.

The input to the system (fig. 2(b)) is 24 volts (dc), which is applied to the valves, the pressure transducer, and the power conditioning unit. Thrustor heater power is supplied by an amplifier-oscillator and a transformer which changes the current to alternating current and reduces the voltage to the lower value required at the thrustor terminals.

Thrust Stand

The thrustor performance was obtained by using a linear-displacement-type thrust stand, where the restoring force is provided by wires in tension. The thrust stand was developed for low-thrust fast-response measurements; a detailed description is given in reference 2. In the present investigation, the measurements were essentially steady state, and therefore permitted certain alterations to the basic stand to minimize thermal instability. The modified thrust stand is shown in figure 4.

The temperature sensitivity of the fine wires used as deflecting members of the thrust stand resulted in severe excursions in the transducer output voltage and some consequent problems in steady-state thrust measurements. As operation of the thrustor affected the ambient conditions in the vacuum chamber, the thrust-stand members responded to changes in temperature which tended to alter the zero of the output signal. Some smaller parts were made more massive and wires of lower thermal expansion



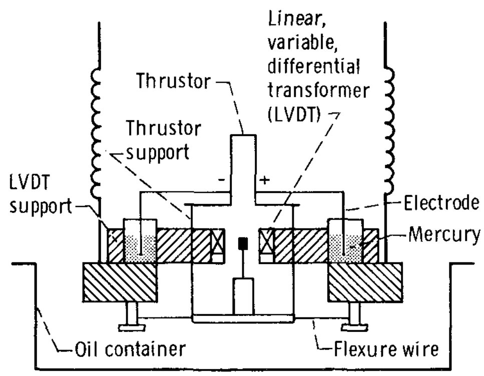


Figure 4. - Thrust stand.

coefficient were provided to reduce temperature response in order to alleviate this problem. In addition, the wires were submerged in oil for further isolation and to provide some damping.

Propellant was introduced through a 77-mil- (1.96-mm-) diameter stainless-steel tube rigidly attached to the outer ring of the thrust stand at one end. The other end of the tube was attached to the thrustor at its centerline and underwent the same deflection as the thrustor. Although the tube increased the force to the deflection ratio of the suspension, its contribution was reversibly elastic; and this arrangement proved to be stable.

Electric power was supplied to the thrustor through two mercury pots with submerged rods rigidly attached to the thrustor. For the thrustor calibration tests, the voltmeter leads were attached to the thrustor terminals to eliminate losses. Direct-current power was supplied to the thrustor for calibrations, in contrast to actual system operation when alternating-current power is used.

Calibration of the thrust stand was accomplished with three small weights. The weights were alternately placed on the deflecting ring by a carrier which was pivoted at one end and raised and lowered at the other end by a motor-driven camlike arrangement. This arrangement permitted a remote-controlled thrust calibration.

For the thrustor calibration tests, a volumetric displacement system was devised to measure flow rates over a range of pressures below 1 atmosphere (10.1 N/cm^2). This system is described in the appendix. Mass-flow data were obtained for a range of heater input power to 12 watts and for heater-tube inlet absolute pressures of 6.1 and 5.2 psi (4.2 and 3.6 N/cm^2).

Measurement of System Characteristics

Systems instrumentation was provided to monitor the valve and heater input voltage signals for each thrustor and the output of the plenum-chamber pressure transducer. Signal conditioning consists of providing a 0- to 5-volt signal for possible telemetry encoding.

The direct-current input voltage to the system and the pressure transducer output were measured with a permanent-magnet, moving-coil voltmeter accurate to ±0.5 percent. Transformer secondary output voltage was measured with a vacuum-tube voltmeter accurate to ±3.0 percent for alternating-current rms voltage.

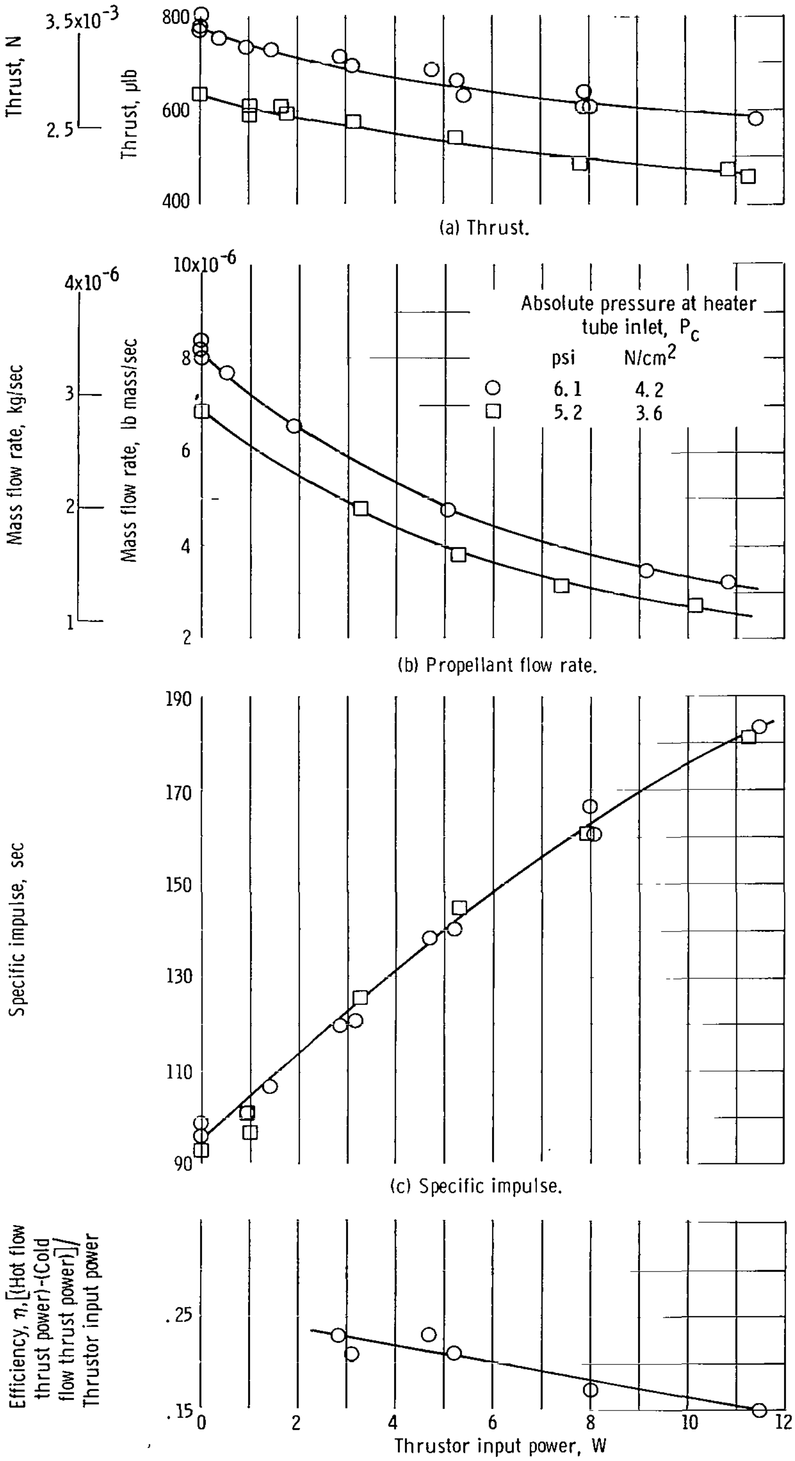
The pressure and temperature transients of the system were obtained for two orientations: the upright orientation, for which the propellant adjacent to the control valve was gaseous; and the inverted orientation, for which the propellant adjacent to the control valve was liquid. Temperature data were obtained for the propellant supply module at the locations shown in figure 2(a). Internal and skin temperatures were measured at the plenum chamber and at the liquid tank both above and below the liquid level. For these transient tests, the storage and feed unit was placed in a stainless-steel cylinder which had been lined with aluminum-foil radiation shielding to minimize any external thermal input.

RESULTS AND DISCUSSION

Thrustor Performance

The thrustor performance data in terms of thrust, propellant flow rate, specific impulse, and efficiency are shown in figure 5. These data were obtained by fixing the heater-tube inlet pressure and varying the input power.

Figure 5(a) shows the variation of thrust with input power for heater-tube inlet absolute pressures of 6.1 and 5.2 psi (4.2 and 3.6 N/cm^2) and input power to 12 watts. As the input power and the wall temperature increase, the friction and the momentum pres-



(d) Efficiency. Specific impulse at 74° F (296° K), 96 seconds.

Figure 5. - Thrustor performance. Inlet temperature, 74° F (296° K). Vacuum tank pressure, less than 0.2 micron of mercury (0.027 N/m²).

sure drop in the tube increase and result in a lowering of the pressure at the nozzle inlet and hence a decrease in thrust. For example, at an absolute inlet pressure of 6.1 psi (4.2 N/cm^2) and cold flow (input power = 0), the thrust is approximately 780 micropounds (3.47×10^{-3} N) and decreases to 590 micropounds (2.62×10^{-3} N) at 12 watts, a decrease of approximately 25 percent.

The propellant flow rate corresponding to figure 5(a) is shown in figure 5(b). As input power (or temperature) increases, the propellant flow rate decreases reflecting a change in density and pressure at the nozzle inlet. For cold flow and an absolute inlet pressure of 6.1 psi (4.2 N/cm^2), the propellant flow rate is approximately 8.2×10^{-6} pounds per second (3.72×10^{-6} kg/sec) and decreases by over a factor of two as power is increased to 12 watts.

The effect of input power on specific impulse is shown in figure 5(c). The specific impulse increases markedly with increasing thrustor input power. The specific impulse for cold flow (296° K) is approximately 95 seconds compared with a theoretical isentropic expansion value of 115 seconds. At an input power of 12 watts, the specific impulse increased to about 185 seconds. The thrustor inlet pressure does not exhibit any material effect on specific impulse for the small pressure range investigated. This phenomenon is indicative of the nature of heat transfer in the heater tube.

If the specific impulse is considered to be insensitive to pressure, the relative amount of input power converted to thrust may be approximated as follows:

$$\eta = \frac{\text{Hot-flow thrust power - Cold-flow thrust power}}{\text{Electrical input power}}$$

or

$$\eta = \frac{g^2}{2} \frac{\dot{m}(I^2 - I^2_{cold})}{P_{in}}$$

where

η efficiency

$\dot{m}$ mass flow rate

I specific impulse

P_{in} input power

g acceleration due to gravity

This efficiency is shown in figure 5(d) as a function of input power for constant propellant flow rate. In the preceding equation, η represents an explicit expression of the manner in which the thrustor uses electric power to increase specific impulse. The data indicate that for a given input power, the wall temperature is substantially determined by the radiation characteristics of the material, while the power absorbed by the propellant is small in comparison with the total input power. In addition, for these low propellant flow rates, the data indicate that the heater-tube length is sufficient to allow the gas to reach the maximum temperature.

System Power Requirements

The operation of the system has been explained in the section APPARATUS. Briefly, the system was designed to deliver thrust on command and to require no power in the no-thrust mode.

The electrical characteristics of the system are shown in figure 6. Here the voltage impressed on the heater tube and the output voltage of the transformer secondary are shown as a function of current. The voltage shown for the transformer secondary (ac rms) was obtained in a dummy load test, while for the thrustor the direct-current voltage from the thrustor calibration tests is shown. The combined system with thrustor would be expected to operate at the intersection of these two curves. For the present tests, the op-

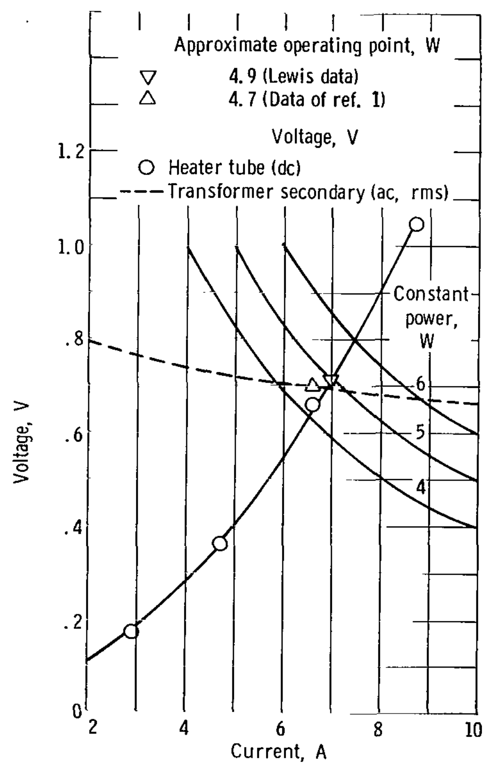


Figure 6. - Component electrical characteristics.

erating point corresponds to a thrustor input power of 4.9 watts. For these conditions, the total input power to the system is approximately 7.9 watts, and thus about 3.0 watts are required for the valves and associated electronics which includes power and signal conditioning. The operating point for tests of a similar system (ref. 1) is shown for comparison.

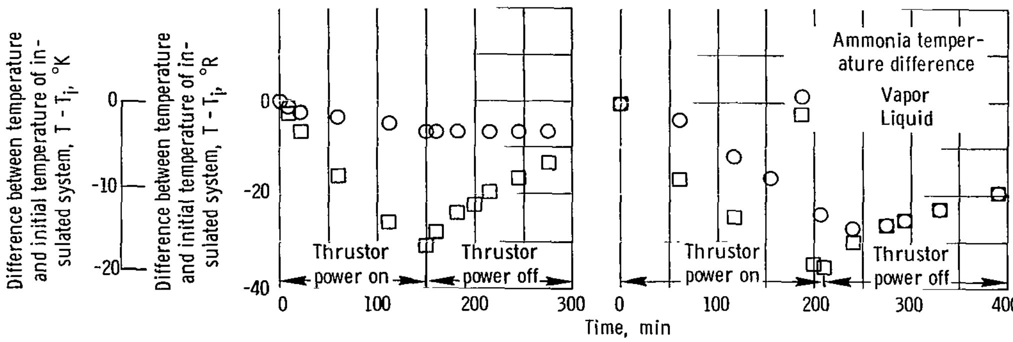
The input power can be used to obtain the thrustor performance parameters from figure 5. For example, at a nominal thrustor input power of 5 watts, the specific impulse was 140 seconds (fig. 5(c)). The thrust was 650 and 540 micropounds (2.89×10^{-3} and 2.40×10^{-3} N) at heater inlet absolute pressures of 6.1 and 5.2 psi (4.2 and 3.6 N/cm^2), respectively (fig. 5(a)).

Feed-System Performance

Flow regulation. - The ability of the system to maintain thrust within the specified tolerance (±10 percent) is uniquely determined by the operation of the pressure switch - control valve combination which controls the thrustor inlet pressure. For an average plenum absolute pressure of 5.7 psi (3.94 N/cm^2), the change in pressure on opening the control valve was approximately 0.3 psi (0.207 N/cm^2) for liquid extraction. For vapor extraction, the change in pressure was less but somewhat erratic, varying from about 0.05 to 0.14 psi (0.035 to 0.097 N/cm^2). The thrust change corresponding to the 0.3-psi (0.207-N/cm^2) maximum pressure variation is approximately 40 micropounds (0.18×10^{-3} N). Thus, the system maintains the thrust limits for vapor or liquid extraction and indicates the ability to perform in a zero-gravity environment.

The large pressure fluctuation for the situation in which liquid is adjacent to the fill valve is a consequence of the valve open time. For a given valve open time, a given volume of material is passed; and if this material is liquid, the greater density of the liquid results in more mass flowing into the plenum chamber and, consequently, in greater pressure fluctuations. If closer tolerance is required, the fill valve must have an extremely fast response in order to reduce the valve open time, or a method must be found to assure that the propellant immediately upstream of the fill valve is in the vapor phase. In a zero-gravity environment, the phase of the extracted propellant could be controlled by the use of suitable baffles (ref. 3).

Thermodynamic transients. - Temperature data were obtained for the liquid and vapor in the storage tank and for the vapor in the plenum (fig. 7). The system was operated in both the upright and inverted attitudes. The significance of these orientations is the relative position of the liquid and vapor in the storage tank with respect to the fill valve. For upright operation, the propellant adjacent to the valve was vapor, while in the inverted attitude, the liquid and vapor are reversed. The data are indicative of the



(a) Upright system; vapor extraction. Mass flow rate, 8.0×10^{-6} pound mass per second (3.63×10^{-6} kg/sec).

(b) Inverted system; liquid extraction. Mass flow rate, 10.04×10^{-6} pound mass per second (4.55×10^{-6} kg/sec).

Figure 7. - Storage tank temperature.

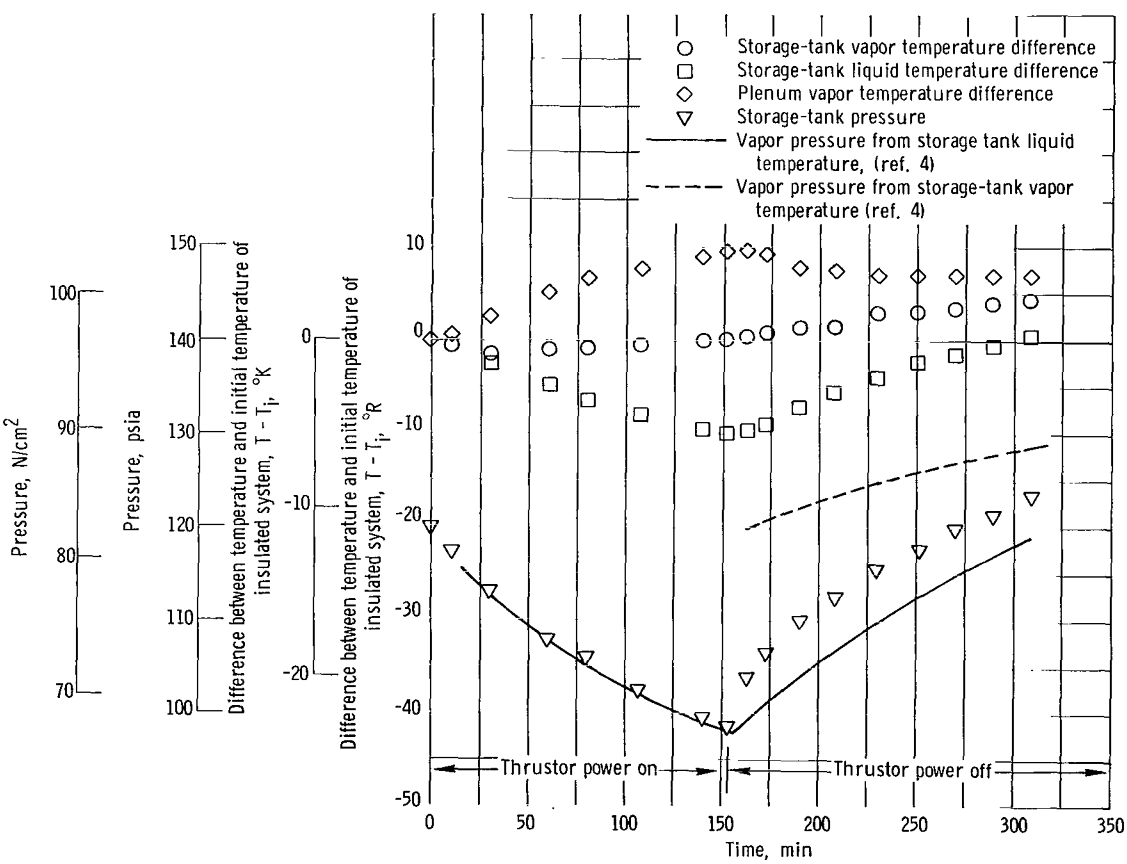


Figure 8. - System pressure and temperature as function of time for vapor extraction. Ammonia flow rate, 4.56×10^{-6} pound mass per second (2.07×10^{-6} kg/sec).

temperature trends which may be expected in the evaporative extraction of a two-phase propellant.

As shown in figure 7(a), the liquid temperature decreases as propellant is extracted from the tank. Vapor temperature is somewhat higher, indicating some possible difference in heat transfer to the liquid and vapor. In figure 7(b), the same measurements are presented for the inverted orientation. The vapor temperature now shows a trend toward lower values, as the liquid apparently absorbs some of the heat conducted toward the storage tank from the system internal heat sources. Of the two possible sources of heat transfer (the surroundings and the electronics), the predominant mode appears to be heat transfer from the electronics.

The vapor pressures corresponding to these data for vapor extraction are shown in figure 8. The pressures corresponding to measured liquid and vapor temperatures (ref. 4) are shown for comparison. In the operating mode, the pressure is predicted by the liquid temperature. After shutoff, however, the pressure assumes a value intermediate to that predicted by the liquid and vapor temperature but shows the same trend as the liquid temperature curve. Thus, the pressure of the vapor cannot always be inferred from the temperature.

Endurance Test

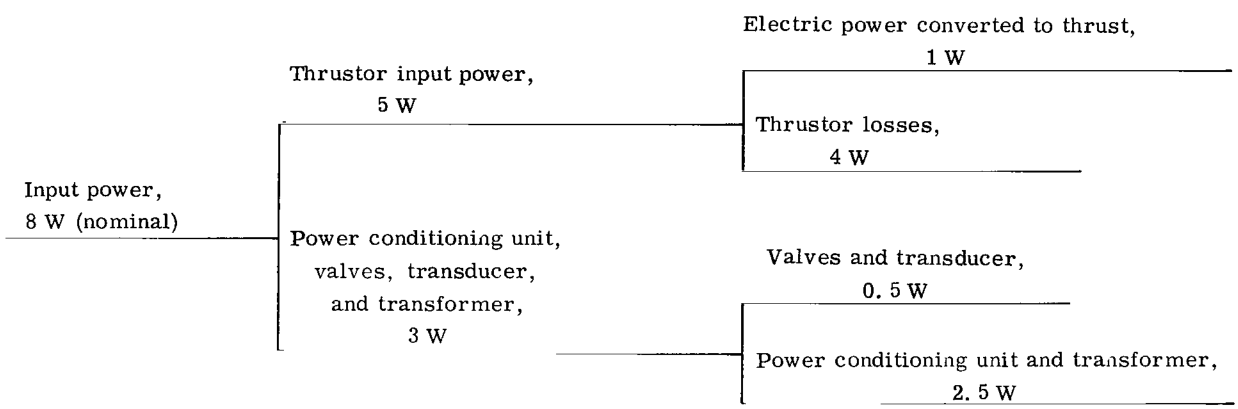
An endurance test was conducted in which the clockwise and counterclockwise modes were operated intermittently to establish the long-term operational capability of the system. For this test, the clockwise mode was operated with vapor propellant extraction. The counterclockwise mode was operated with both vapor and liquid extraction. The data for these tests together with the operating time for each mode are shown in the following table. (The total accumulated operating time was in excess of 55 hr.)

Mode	Input power, W	Absolute plenum pressure		Thrust[a]		Propellant flow rate[b]		Specific impulse,[c] sec	Thrustor power,[d] W	Accumulated time, hr
		psi	N/cm^2	lb force	N	lb mass/sec	kg/sec			
Clockwise[e]	7.9	5.7	3.94	607×10^{-6}	2.70×10^{-3}	4.45×10^{-6}	2.02×10^{-6}	136	4.9	25.0
Counterclockwise[f]	8.4	5.8	4.01	610	2.71	4.33	1.96	141	5.4	15.0
Counterclockwise[e]	8.4	5.7	3.94	597	2.65	4.09	1.86	146	5.4	6.7
Counterclockwise[e]	8.4	5.7	3.94	597	2.65	4.37	1.98	137	5.4	8.5

[a]Interpolated from fig. 7.
[b]By direct weight.
[c]$I_{sp} = \dfrac{\text{Thrust}}{\text{Propellant flow rate}}$
[d]Power balance.
[e]Vapor extraction.
[f]Liquid extraction.

The same thrustor was used for both the clockwise and counterclockwise modes. The thrustor power for these modes differs by 0.5 watt because of slight differences in power conditioning. This difference would not occur in a two-thrustor system because the heater resistance would be matched to the power conditioning on assembly. However, the thrust and system input power for the data shown fall well within the specified tolerance of thrust and power with only a slight decrease in thrust occurring as the input power is increased. Thrustor power was determined approximately from the difference in system input power with and without the attached thrustor. A typical distribution of power is shown in the following sketch. Mass flow data were obtained by direct weight before and after operation, while the other performance parameters were estimated from the thrustor and systems calibration tests.

At the end of the endurance test, the system was disassembled, and the thrustor was recalibrated for mass flow. No significant changes were detected. The system electrical characteristics were checked by measuring the total input power while varying the resistance across the transformer secondary terminals. No significant change in the characteristics was noted.



SUMMARY OF RESULTS

Performance data obtained for the components of a low-thrust ammonia resistojet system and testing of the integrated system in vacuum for a period in excess of 55 hours yielded the following results:

Thrustor Performance

1. The thrust decreased with increasing input power because of flow losses in the

thrustor heater tube. For cold flow and a heater-tube inlet absolute pressure of 6.1 psi (4.2 N/cm^2), the thrust was approximately 780 micropounds (3.47×10^{-3} N), and decreased to approximately 590 micropounds (2.62×10^{-3} N) at an input power of 12 watts, a decrease of approximately 25 percent.

2. The specific impulse increased markedly with increasing input power. For cold flow, the specific impulse was approximately 95 seconds and increased to 185 seconds at an input power of about 12 watts. The specific impulse did not vary appreciably with pressure for the range investigated.

System Performance

1. The system maintained acceptable thrust limits for both liquid and vapor propellant extraction and thus should be capable of operating in a zero-gravity environment.

2. For a nominal system input power of 8 watts, the valves and power conditioning required 3 watts. The power delivered to the thrustor was 5 watts, of which approximately 1 watt represented augmented thrust power.

3. The pressure change in the storage tank was observed to correlate with the liquid rather than the vapor temperature. During periods of propellant extraction, the vapor pressure was predicted by the liquid temperature. After shutoff, the vapor pressure was predicted by a temperature intermediate to both liquid and vapor temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 6, 1967,
128-31-02-50-22.

APPENDIX - MEASUREMENT OF PROPELLANT FLOW RATE

One of the most important parameters for the determination of thrustor performance is the propellant flow rate. The difficulty in measuring the extremely small flow rates encountered in control thrustors is more pronounced if these measurements must be made below atmospheric pressure. A secondary device, which is calibrated with some error, is usually necessary; and then flow rates are approximated from such calibration data. Ordinarily, one of the most effective methods of measurement is the use of the critical orifice, with upstream pressure and temperature as the governing parameters. However, in cases where the downstream orifice pressure must be maintained at a given level, several difficulties may arise which can preclude the simple determination of flow rates.

A simple system which provided an accurate method of measurement was used to avoid these difficulties. The system (fig. 9) consists of a volumetric calibrator which has been modified for use below atmospheric pressure by including a source tank for establishing the required pressure and appropriate valves. The procedure consists of trapping a volume of propellant between the piston and the thrustor at the desired pressure and measuring the time rate of change in displacement of the piston. After the system is purged of foreign gases and evacuated to a very low pressure, propellant is introduced into the system, raising the pressure to slightly above the desired operating level. During this fill operation, valve V_4 and the thrustor valve V_1 are closed while valves V_5,

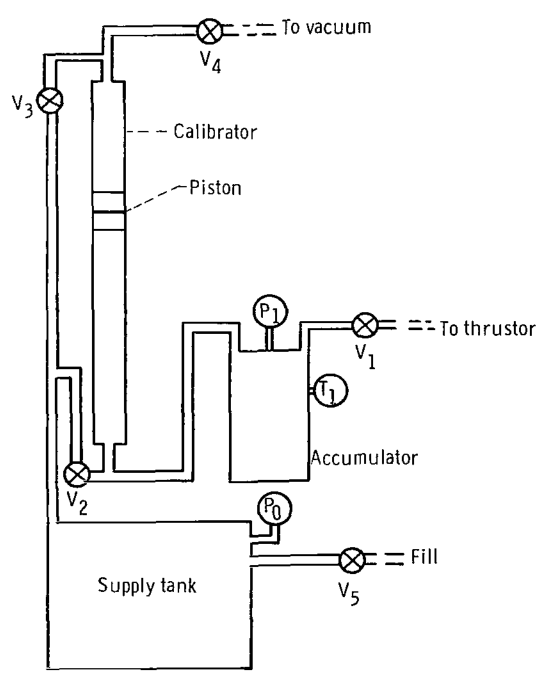


Figure 9. - Mass-flow calibration apparatus.

V_2, and V_3 are open. Valve V_3 is then closed, and V_4 is opened slightly to vacuum, allowing the piston to rise to the top of the calibrator tube. Valves V_4 and V_2 are closed, and V_3 is then opened so that calibration may proceed. The thrustor valve is then opened, and pressure P_1, temperature T_1, displacement of the piston, and time are recorded. This procedure is repeated several times, and the average of the readings is determined.

The flow rate may be calculated as follows:

$$\dot{m} = \rho_1 \frac{V_d}{\Delta t} = \frac{P_1 V_d}{R T_1 \Delta t}$$

where

ρ_1 gas density downstream of piston

V_d volume displacement of piston

Δt time lapse for displacement

P_1 pressure downstream of piston

R gas constant

T_1 temperature downstream of piston

The change in system pressure during calibration is one possible source of error. The system volume has been determined so that the decrease in pressure over one calibration cycle is minimized. The percentage change in pressure may be approximated as follows:

$$\frac{\Delta P}{P_0} = \frac{V_d}{V_0 + V_d}$$

where

ΔP change in pressure for calibration interval

P_0 initial pressure

V_0 initial system volume upstream of piston

The volume displacement of the piston per calibration was 150 cubic centimeters, while the total system volume was approximately 33 000 cubic centimeters; alternatively, the relative change in pressure was approximately 0.5 percent.

The pressure and temperature of the propellant at the calibrator must be used in calculating the actual mass extracted. The thrustor calibration data, however, must make use of the parameters as measured at the thrustor inlet.

The value of the present system lies in its ability to measure extremely low flow rates regardless of the required pressure, while other methods may be pressure limited. Another advantage is the ability to measure flow rates directly as other performance parameters are being determined.

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