NASA TECHNICAL NOTE

NASA TN D-3841

c. 1

NASA TN D-3841

PERFORMANCE OF TWO SUBLIMING-SOLID-PROPELLANT THRUSTOR SYSTEMS FOR ATTITUDE CONTROL OF SPACECRAFT

by Frank D. Berkopec

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1967

PERFORMANCE OF TWO SUBLIMING-SOLID-PROPELLANT THRUSTOR SYSTEMS FOR ATTITUDE CONTROL OF SPACECRAFT

By Frank D. Berkopec

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $1.00

PERFORMANCE OF TWO SUBLIMING-SOLID-PROPELLANT THRUSTOR SYSTEMS FOR ATTITUDE CONTROL OF SPACECRAFT

by Frank D. Berkopec

Lewis Research Center

SUMMARY

Two subliming-solid-propellant thrustor systems were investigated: a 10^{-2}-pound-force thrust system utilizing ammonium hydrosulfide (NH_4HS) as the propellant, and a 2×10^{-4}-pound-force thrust system utilizing ammonium carbamate ($NH_4CO_2NH_2$) as the propellant.

The 10^{-2}-pound-force thrustor system demonstrated a specific impulse of 65.0 pounds force per pound mass per second, 74 percent of isentropic, during steady-state operation. Pulsed-mode operation, with command-pulse width from 2.0 down to 0.020 second, showed the impulse bit to be repeatable and predictable. The 2×10^{-4}-pound-force thrust system demonstrated a specific impulse of 48.1 pounds force per pound mass per second, 61 percent of isentropic, during steady-state operation. The steady-state performance of both systems was comparable to that of conventional cold-gas systems.

The sensitivity of the propellant vapor pressure (and, therefore, thrust level) to temperature was approximately 5 percent per $^{\circ}R$ for both systems. This operating characteristic must be carefully controlled to facilitate the application of this type of system to attitude control.

INTRODUCTION

Cold-gas thrustor systems have been used extensively to provide attitude control and station-keeping functions for small satellites whenever the low specific impulse of the propellant did not result in excessive weight. The primary advantage of these systems is their basic simplicity. Because the propellant is stored as a gas rather than as a liquid, these systems avoid the zero-gravity propellant management problems encountered with liquid propellants. However, the disadvantage lies in the low density of the propellant which necessitates storing the gas at high pressures in order to provide the system with sufficient weight of propellant to meet the mission total impulse requirements within reasonable volume allowances. High-pressure storage increases the probability of leakage problems and contributes considerably to system weight.

A variation of the conventional cold-gas system is the subliming-solid-propellant thrustor system in which the propellant is stored as a solid and sublimes directly to the vapor phase at low pressures when subjected to a thermal input. The specific impulse obtainable, as determined from known thermodynamic properties, is comparable to that of conventionally used cold gases; for identical conditions (expansion ratio of 100, chamber temperature of 70° F, expanding to a vacuum), the specific impulses given in table I are obtained. The operating pressure is low. The propellant density is high, and the propellant is easy to handle and noncorrosive.

TABLE I. - SPECIFIC IMPULSES OF COLD GASES

Cold gas	Specific impulse, (lb force)(sec)/lb mass
Ammonium hydrosulfide (NH_4HS)	85
Ammonium carbamate ($NH_4CO_2NH_2$)	84
Nitrogen (N_2)	74
Ammonia (NH_3)	104
Carbon dioxide (CO_2)	65

This report presents the results of an experimental study of the performance and operating characteristics of two subliming-solid-propellant thrustor systems. The system that utilized NH_4HS (ammonium hydrosulfide) as its propellant had a 10^{-2}-pound-force nominal thrust. The other system, which used $NH_4CO_2NH_2$ (ammonium carbamate) as the propellant, produced a nominal thrust of 2×10^{-4} pound force. Of prime interest were two aspects of thrustor performance, the efficiency during steady-state operation and the pulsing performance in terms of impulse bit as a function of thrust duration. The pressure-time and pressure-temperature characteristics of the subliming-solid-propellant feed system were also investigated.

SYMBOLS

A area

C_f thrust coefficient, F/P_cA_t

F thrust

I_{sp} specific impulse

$\dot{m}$ mass-flow rate

P pressure

$\dot{q}$ heat flux

T temperature

α divergence half-angle

ϵ nozzle area ratio, A_e/A_t

τ first-order system time constant, sec

Subscripts:

c chamber

e exit

i isentropic (one-dimensional)

o isothermal conditions, initial value

t throat

APPARATUS AND PROCEDURE

Thrustor Systems

The two subliming-solid-propellant thrustor test systems were readily available items and were the simplest working systems obtainable. No heaters were employed, and conventional valves were used. Each system consisted of a propellant storage vessel, the thrustor valve and nozzle, and the interconnecting tubing; the 10^{-2}-pound-force system is shown in figure 1. The specifications and characteristics of both thrustor systems and their propellants are given in table II.

Test Facilities

An impulse balance (fig. 2) was used to measure the impulse bit per pulse and the steady-state thrust of the 10^{-2}-pound-force system. The balance consists of a swinging gate mounted on a nonvertical hinge, as shown in figure 2. The gate swings like a seismic pendulum, and its displacement is proportional, within limits, to the impulse bit or the steady-state thrust. This displacement is sensed and permanently recorded for subsequent analysis. The system is calibrated remotely in both the steady-state and the

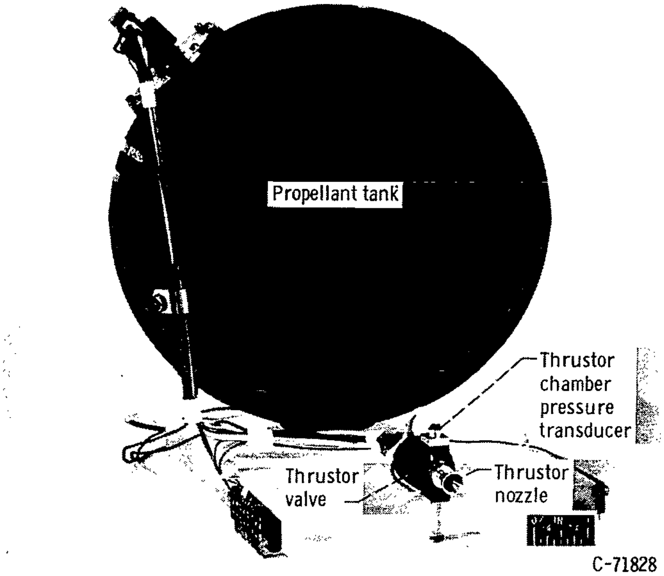

Figure 1. - Test model of 10^{-2}-pound-force subliming-solid-propellant thrustor system.

TABLE II. - TEST SYSTEMS

[Propellant density, 0.02 to 0.04 lb mass/in.^{3}; propellant tank volume, 380 in.^{3}; initial mass of propellant, 10 lb mass.]

	10^{-2}-lb-force thrust system at 65° F	2×10^{-4}-lb-force thrust system at 80° F
Propellant		
Solid phase	Ammonium hydrosulfide	Ammonium carbamate
Gas phase, molal mixture	1 Ammonia plus 1 hydrogen sulfide	2 Ammonia plus 1 carbon dioxide
Heat of sublimation at 65° F, Btu/lb mass	782	877
Molecular weight of gas phase, lb mass/mole	25.6	26.0
Ratio of specific heats at 70° F	1.315	1.317
Vapor pressure, psia	6.25	1.93
Theoretical specific impulse,[a] I_{sp}, (lb)(sec)/lb mass	85	84
Nozzle (conical)		
Area ratio, ϵ	100	9
Divergence half-angle, α, deg	15	20
Throat diameter, in.	0.040	0.012
Chamber volume, in.^{3}	2.3×10^{-2}	9.3×10^{-3}
Valve orifice area, in.^{2}	1.74×10^{-3}	4.9×10^{-4}

[a]For area ratio of 100, chamber temperature of 70° F, and vacuum.

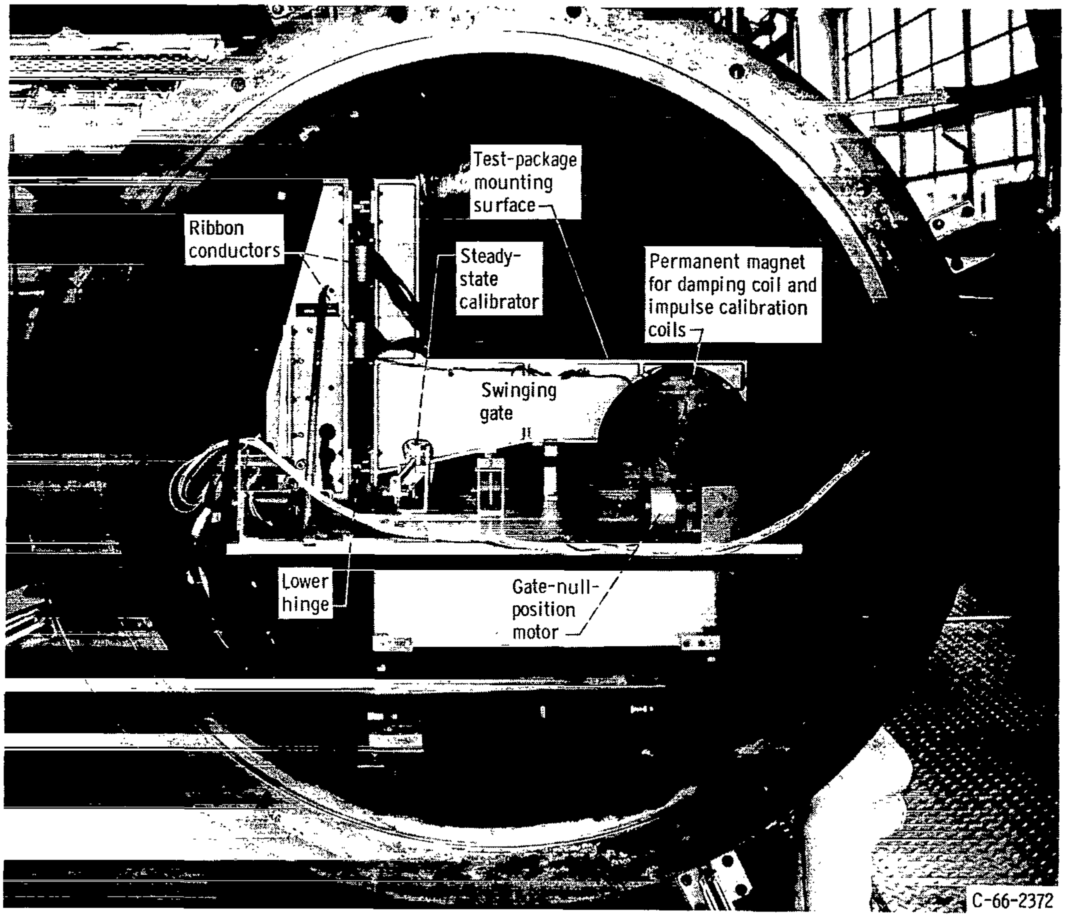

Figure 2. - Impulse balance in vacuum test facility.

dynamic modes at any time the thrustor is not operating. The steady-state calibration is the primary standard and is traceable to the National Bureau of Standards. Power and instrumentation are carried to and from the test package by way of the permanent, flexible ribbon leads. The capabilities of the impulse balance are summarized in table III.

Testing with the impulse balance was conducted in a 4-foot-diameter by 6-foot-long vacuum chamber. The pumping capacity was sufficient to maintain the pressure at less than 10^{-3} torr during all testing. Although the facility was subjected to a wide variety of vibrational disturbances, these environmental effects were sufficiently reduced by conventional isolation techniques to obtain accurate thrust measurements at the 10^{-2}-pound-force level.

At a 2×10^{-4}-pound-force thrust, however, vibrational levels were of sufficient magnitude to invalidate the data obtained with the impulse balance, so a spherical gas bearing was used for thrust measurements. The bearing provides a low friction load support for the testing of spacecraft of up to 500 pounds, within a vacuum environment. It can rotate

TABLE III. - IMPULSE-BALANCE CAPABILITIES

Duration, sec	
Low range	0.1 to 10
High range	0.02 to 1
Thrust, lb force	
Low range	10^{-4} to 10^{-1}
High range	10^{-1} to 5
Thrust threshold, lb force	10^{-5}
Impulse threshold, (lb force)(sec)	10^{-7}
Error of output signal, percent of measured value	±3
Test package	
Size, in.	12 by 10 by 10
Weight, lb force	2 to 25

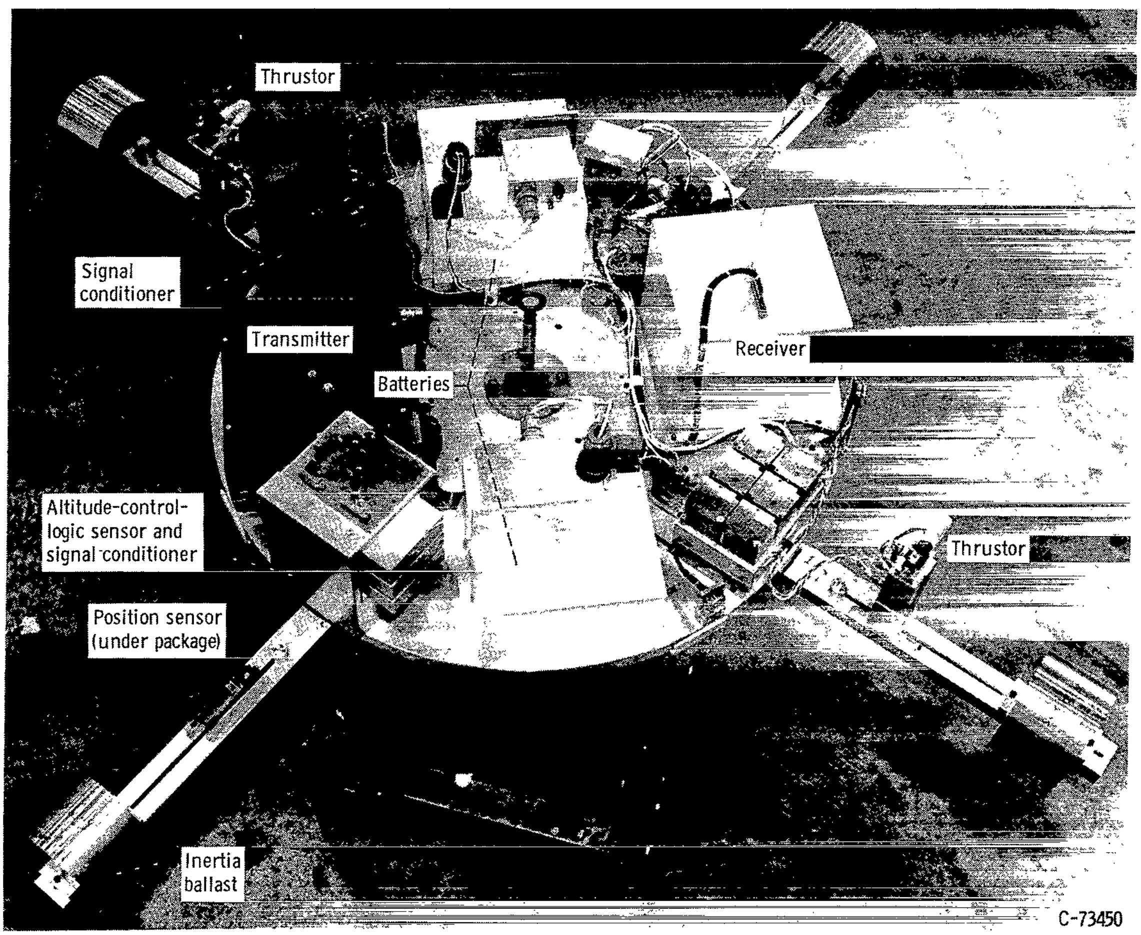

Figure 3. - Test package to be mounted to gas bearing.

freely around the vertical axis, and can tilt as much as 6^{o} from vertical. The test package suspended from the bearing was completely self-contained (see fig. 3), and all intelligence was transmitted by way of FM-FM telemetry. The rotational position of the test package was detected by a photosensor mounted on the test package and a light source mounted on the vacuum chamber. Angular rate data were graphically obtained from the angular position data, and the thrust was calculated as the product of test-package inertia and change in angular rate divided by the thrustor moment arm and the thrusting duration over which the change in rate occurred. A more complete description of the gas bearing facility is given in reference 1.

The gas bearing was mounted from an overhead support in a vacuum chamber 15 feet in diameter and 63 feet in length. The vacuum pumping capacity was sufficient to maintain the ambient pressure below 3×10^{-4} torr during all testing.

Test Procedure

For simplicity, radiation from the surrounding environment was utilized as the propellant heat source. The propellant tank was insulated from its surroundings to reduce conduction to the smallest practical level. Thrustor chamber pressure and temperature and the propellant storage and feed system temperatures were measured during all testing. The nozzles of both thrustor systems operated fully expanded for all tests. Average mass flows were determined from pretest and posttest system weights. When these values are used, the specific impulse, discharge coefficients, and velocity coefficients are necessarily average values. Accurate steady-state thrust measurements on the impulse balance required thrust durations of 50 seconds or longer to allow the long natural-period oscillations to damp out. Data were obtained for thrust durations ranging from 50 to 300 seconds.

Pulsed-mode operation of the 10^{-2}-pound-force system was investigated by systematically reducing the duration of the applied thrustor-valve actuation voltage (the command-pulse width) from 2.0 to 0.020 second. The valve voltage and current characteristics were recorded, and the time during which the valve orifice was open was determined. The pulse durations were related to the impulse bit, as measured on the impulse balance.

Data were obtained on the gas bearing by alternating thrusting the opposing thrustors so that the desired test package dynamics were obtained. This resulted in thrusting durations ranging from 30 to 80 seconds.

The error of the output signal of the impulse balance, after all known systematic errors were accounted for, was estimated to be ±3 percent of the measured value, and that of the gas bearing test system was estimated to be ±7 percent of the measured value.

RESULTS AND DISCUSSION

Feed System Characteristics

The variation of the equilibrium vapor pressure with the temperature for the subliming solid propellants, ammonium hydrosulfide (NH_4HS) and ammonium carbamate ($NH_4CO_2NH_2$), is shown in figure 4. This variation is exponential in form. In the temperature range of interest, 60° to 80° F, the vapor pressure sensitivity with temperature change is approximately 5 percent per $^\circ$R.

The calculated degradation of the chamber pressure with thrusting duration is presented in figure 5. This degradation is given for various conditions of energy input to the propellant mass, which range from no heat transfer (adiabatic) to isothermal. When propellant is not being used, equilibrium temperature and vapor pressure are established. As thrust is required and mass is expelled, the thermal input rate and the heat capacity of the system govern the change in chamber pressure with time until a new equilibrium temperature, vapor pressure, and flow rate are reached.

Experimental results showing the degradation of thrustor chamber pressure with time for duty cycles of 9 and 51 percent (duration of 1.20 seconds on) are presented in figure 6. For comparison are presented the calculated results for the same duty cycles with no thermal input. The 9 percent duty cycle represents what is apparently an upper limit for contemporary and anticipated control techniques. The degradation of chamber pressure to 55.4 percent of the initial value in 8 hours is indicative of the degradation of thrust and the impulse bit that would be encountered. This is further demonstrated by the data for the 51-percent duty cycle, also shown in figure 6. Such a duty cycle might result from conditions in which disturbance torques (e.g., from gravity gradients) are encountered.

Also indicated in figure 6 for the subliming-solid-propellant thrustor system is the thermal sensitivity, which is expressed graphically by figures 4 and 5. The average thermal input during testing, as determined from figure 5, was 30 watts. The necessity of a controlled thermal input to maintain a desirable thrust tolerance, as will be required in the majority of anticipated applications, is clearly shown. The means of obtaining the necessary thermal energy can be any combination of the variety of available techniques. One source of energy is the waste heat of spacecraft components.

Steady-State Performance

Steady-state performance for both systems is presented in figures 7 to 11. The curves through the data in figures 7 to 10 are least-squares regression lines calculated

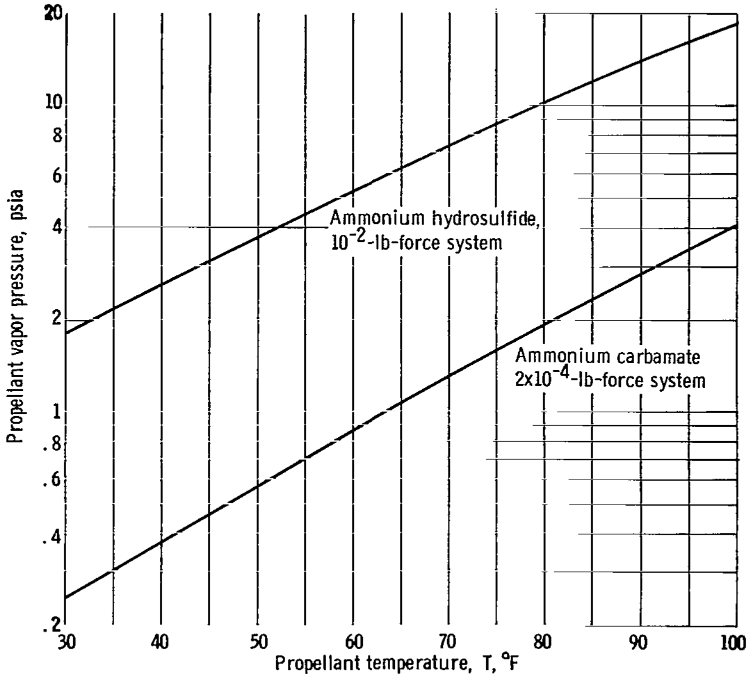

Figure 4. - Propellant vapor pressure as a function of propellant temperature (data taken from ref. 6).

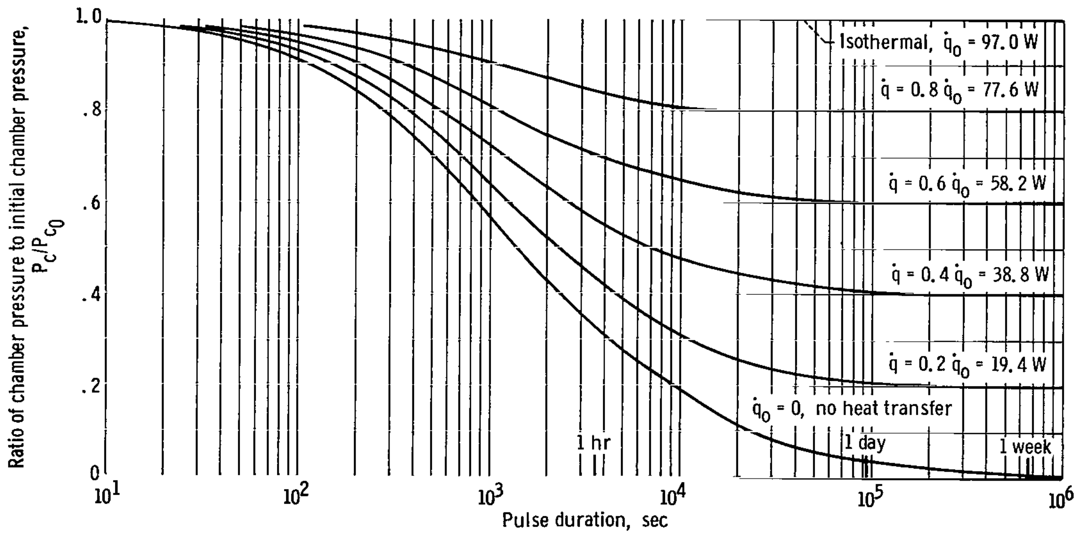

Figure 5. - Chamber-pressure degradation with time for various conditions of heat transfer to propellant mass. System, 10^{-2} pound-force; initial temperature, 70° F; initial mass, 10 pounds mass; initial flow rate, $1.18x10^{-4}$ pounds mass per second. Heat flux, q; isothermal heat flux, q_0.

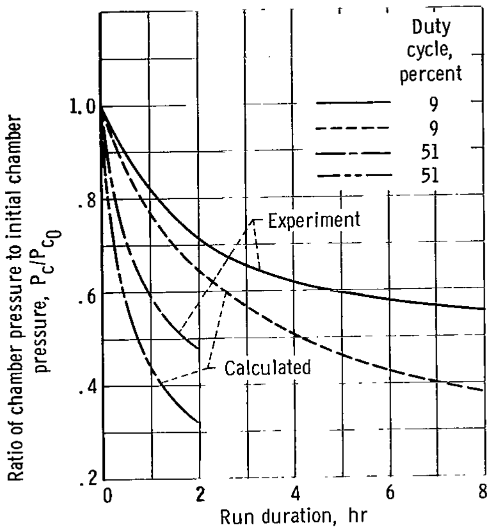

Figure 6. - Degradation of chamber pressure with time for various duty cycles. System, 10^{-2} pound-force; initial temperature, 70° F; initial mass, 10.0 pounds mass; 1.20 seconds on-time.

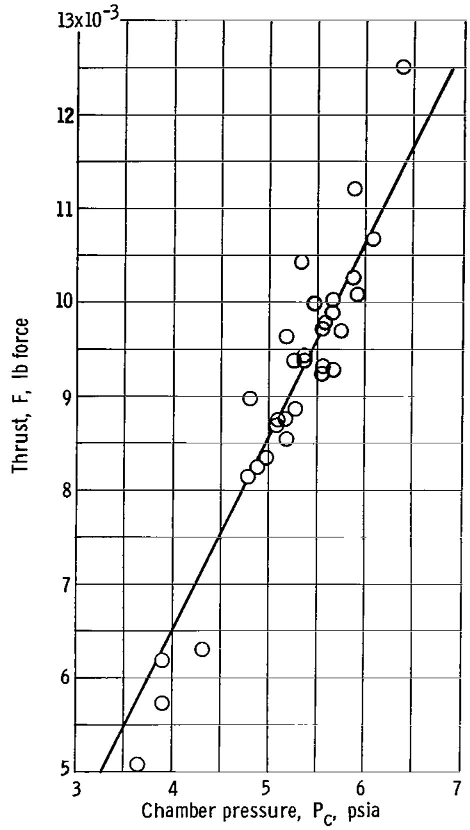

Figure 7. - Steady-state thrust as a function of chamber pressure for 10^{-2}-pound-force system.

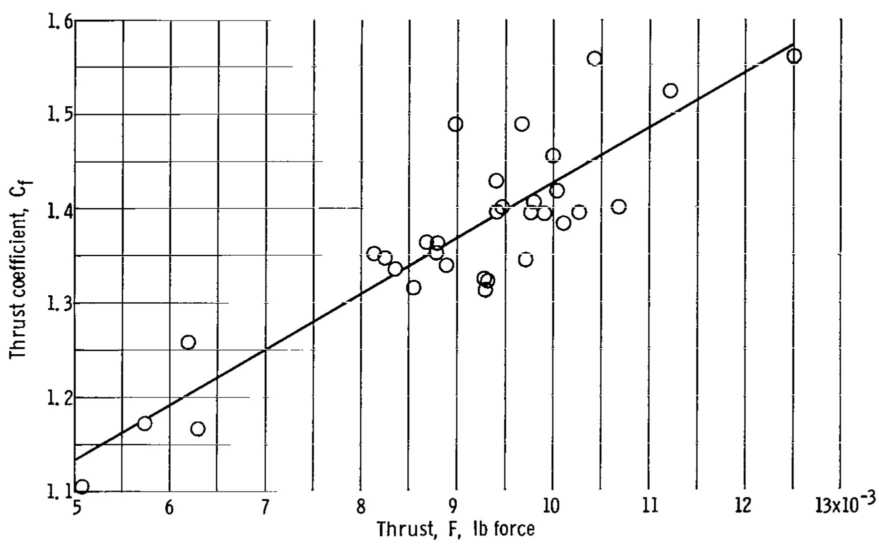

Figure 8. - Thrust coefficient as a function of thrust for 10^{-2}-pound-force system.

from the data. The scatter in the data for 10^{-2}-pound-force system, obtained on the impulse balance, is ±6 percent; and the scatter for the 2×10^{-4}-4-pound-force system, obtained on the gas bearing, is ±10 percent.

The steady-state thrust as a function of the chamber pressure for the 10^{-2}-pound-force system is presented in figure 7. A wide variation in system operation is evident: an increase in chamber pressure from 3.3 to 6.9 pounds per square inch absolute results in an increase in thrust from 5.0×10^{-3} to 12.5×10^{-3} pound force. Such an increase in chamber pressure results from a 21° F increase in propellant temperature. The variation in performance over this range is indicated in figure 8. For the aforementioned increase in thrust, the thrust coefficient increases from 1.13 to 1.57. At the test average thrust of 9.09×10^{-3} pound force, the thrust coefficient is 1.37, 74 percent of the one-dimensional isentropic value, calculated from thermodynamic properties. The average specific impulse is 65.0 pounds force per pound mass per second, 74 percent of the isentropic value. The average discharge and velocity coefficients are 0.96 and 0.75, respectively.

The operating characteristics observed for the 2×10^{-4}-pound-force system are similar to those of the 10^{-2}-pound-force system. These characteristics are presented in figures 9 and 10. An increase in chamber pressure from 1.70 to 2.10 pounds per square inch absolute results in an increase in thrust from 2.1×10^{-4} to 2.5×10^{-4} pound force; the chamber-pressure increase results from a 6° F increase in propellant temperature. At the test average thrust of 2.2×10^{-4} pound thrust, the thrust coefficient is 1.06 or 64 percent of the isentropic value. The specific impulse is 48.1 pounds force per pound mass per second, 61 percent of the isentropic value. The average discharge and velocity coefficients are 1.05 and 0.64, respectively.

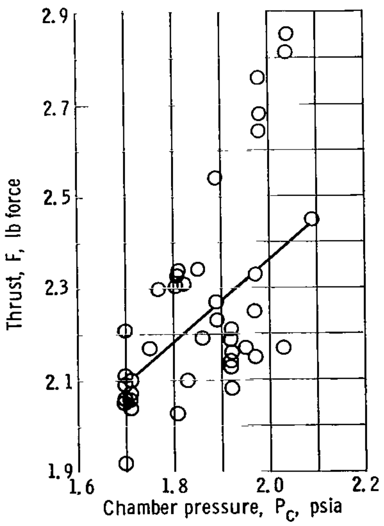

Figure 9. - Thrust as a function of chamber pressure for 2×10^{-4}-pound-force system.

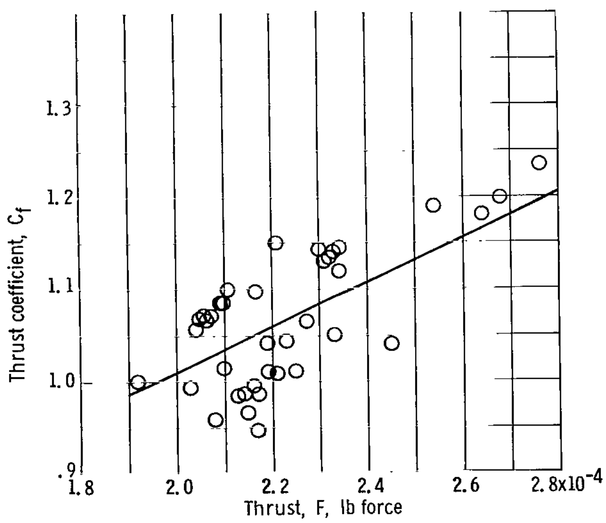

Figure 10. - Thrust coefficient as a function of thrust for 2×10^{-4}-pound-force system.

Nozzle efficiencies $C_f/C_{f,i}$ of 75 and 64 percent, for the 10^{-2}- and 2×10^{-4}-pound-force systems, respectively, indicate the inherently poor nozzle performance frequently encountered with small nozzles (ref. 2). In small nozzles, the boundary layer approaches an appreciable fraction of the nozzle diameter. Studies have indicated that, for nozzles producing thrusts of less than 0.1 pound force with Reynolds numbers (based on nozzle throat diameter) between approximately 100 and 1000, the nozzle efficiency $C_f/C_{f,i}$ is limited to approximately 0.75. The Reynolds numbers for the 10^{-2}- and 2×10^{-4}-pound-force systems are approximately 6500 and 660, respectively.

A correlation of specific impulse with mass flow was first suggested in reference 3. This was found to be a consistent specific impulse correlation. The results obtained during testing of the subliming-solid-propellant thrustor systems are presented in fig-

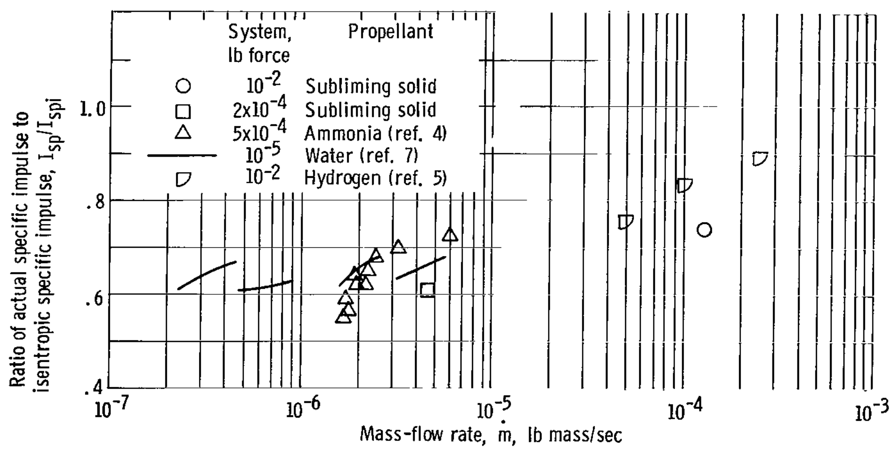

Figure 11. - Correlation of specific impulse with mass-flow rate.

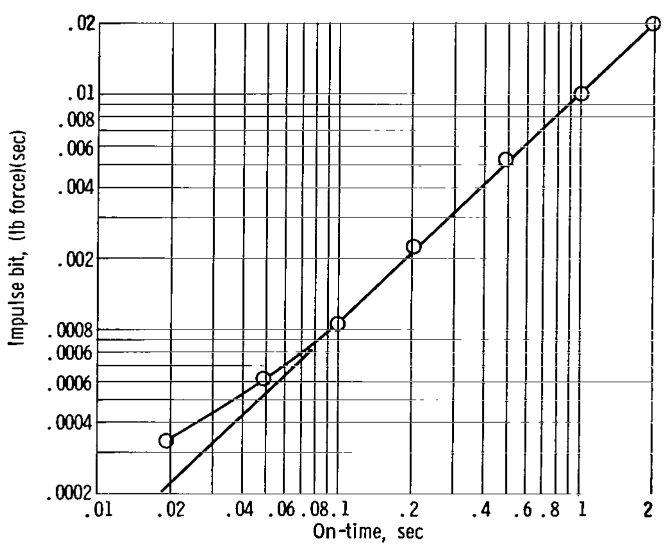

Figure 12. - Impulse bit as a function of thrustor-valve voltage on-time (command-pulse width), nominal thrust, 10^{-2} pound force.

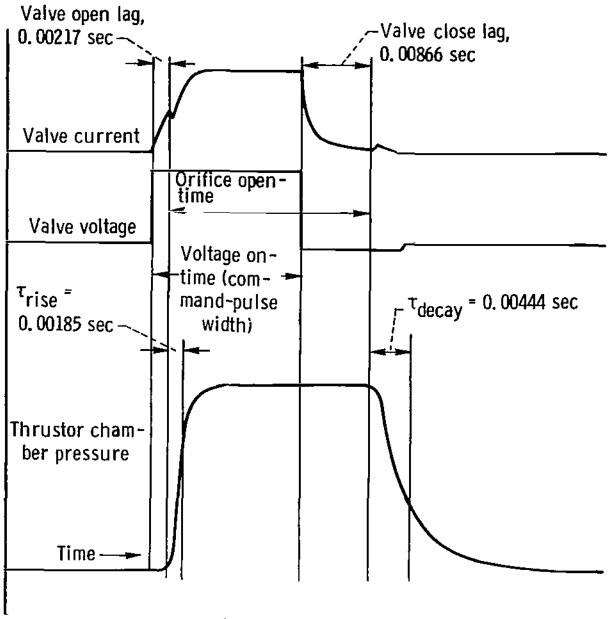

Figure 13. - Valve characteristics.

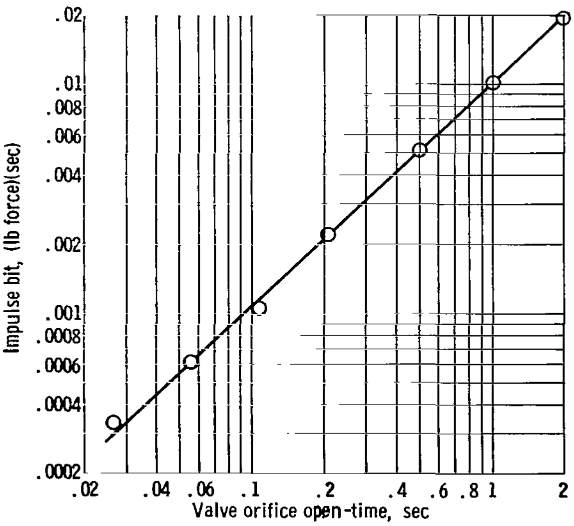

Figure 14. - Impulse bit as a function of thrustor-valve orifice open-time.

ure 11. Presented also are results from references 4, 5, and 7 for different propellants at a variety of conditions; actual reported values were normalized to the uncorrected isentropic values. At the present, in the region of interest (shown in fig. 11), parameters based upon gas dynamics have not yielded a useful, general correlation. The ratio of actual specific impulse to the one-dimensional isentropic specific impulse was 0.74 at an average mass flow rate of 1.30×10^{-4} pound mass per second (average thrust of 9.09×10^{-3} lb-force) and was 0.61 at 4.65×10^{-6} pound mass per second (average thrust of 2.22×10^{-4} lb-force) for the 10^{-2} - and 2×10^{-4}-pound-force systems, respectively. The results presented in figure 11 indicate the expected performance of low-thrust thrustors. The data for the subliming-solid-propellant thrustor systems agree with those for comparable systems. The data indicate a probable practical maximum performance level of approximately 70 percent of the isentropic specific impulse below mass flows of 10^{-5} pound mass per second.

Pulsing-Mode Performance

Pulsing-mode performance is necessarily the transient performance of the entire thrustor system. The thrustor chamber volume, valve orifice size, valve voltage and time characteristics, and propellant line volume all affect the transient behavior. Thus, the reported pulsing-mode performance is restricted to systems totally identical to the test system.

A variable that is a convenient basis for comparison of pulsing-mode performance is the valve-voltage on-time (or the command-pulse width), defined as the duration of valve actuation voltage from signal-on to signal-off. Pulsing-mode performance of the 10^{-2}-pound-force system is presented in figure 12 as the variation of impulse bit with thrustor-valve-voltage on-time. Each data point represents 25 to 45 test points; scatter was ±4 percent at 2×10^{-2} pound force-second, increasing to ±6 percent at 10^{-3} pound force-second, and up to ±18 percent at 3.3×10^{-4} pound force-second (near the practical limit of the impulse balance in its present environment).

The characteristics of the valve used in the test system are shown in figure 13. From the chamber-pressure signal and the valve current and voltage signals, it can be observed that the valve response lags the applied voltage. Thus, the valve orifice open-duration is the command-pulse width plus the difference between the valve closing and opening lag times. These lag times are constant for a given actuation voltage (24 V, d. c.) and the range of pressures of interest. The system pressure rise and decay transients were constant (for a given valve voltage) over the range of pressures of interest.

The impulse bit as a function of orifice open-time is shown in figure 14. The impulse bit ranged from 2.0×10^{-2} pound force-second at 2.0 seconds to 3.3×10^{-4} pound force-second at 0.030 second orifice open-time. Figure 14 indicates that the deviations from linearity with the pulse time noted in figure 12 are entirely due to valve and volume characteristics, at least to the times studied.

SUMMARY OF RESULTS

Two subliming-solid-propellant thrustor systems were tested to determine their operating characteristics for attitude control.

A 10^{-2}-pound-force thrust system using ammonium hydrosulfide as the propellant was investigated in order to establish the characteristics of the feed system and the thrustor performance for both steady state and pulsed-mode operation. The feed system characteristics showed a chamber-pressure variation with both time and temperature. The system attained a steady-state specific impulse of 65.0 pounds force per pound mass per second, 74 percent of the one-dimensional isentropic value. General steady-state operation was normal and predictable. The pulsing-mode performance down to command-pulse widths of 0.020 second was repeatable and predictable.

A 2×10^{-4}-pound-force system using ammonium carbamate as the propellant was tested for steady-state performance only. Steady-state operation was normal and predictable. The attained specific impulse of 48.1 pounds force per pound mass per second was 61 percent of the theoretical value.

The performance obtained with both systems is comparable to that of conventional cold-gas systems. Such results at these low thrust levels were expected, and they correlated with data presented in the literature.

Neither test system utilized thermal control of the propellant feed system; however, the thermal sensitivity of the propellant of both systems tested (approximately a 5-percent-per-$^{\circ}$R increase in vapor pressure and, therefore, thrust) indicated that this operating characteristic must be carefully controlled to obtain satisfactory performance in the majority of anticipated applications. Once such control is achieved, this type of system can be used for attitude control.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 8, 1966,
128-31-02-50-22.

REFERENCES

1. John, Richard R.: Resistojet Research and Development, Phase II. Rep. No. AVCO-RAD-TR-65-13 (NASA CR-54330), AVCO Corporation, June 10, 1965.

2. Wilner, B.; Hays, L.; and Buhler, R.: Research and Development Studies to Determine Feasibility of a Solar LH_2 Rocket Propulsion System. Rep. No. EOS-C3140-Final (RTD-TDR-63-1085, DDC No. AD-345094), System. Electro-Optical Systems, Inc., Sept. 1963.

3. Tinling, Bruce E.: Measured Steady-State Performance of Water Vapor Jets for Use in Space Vehicle Attitude Control Systems. NASA TN D-1302, 1962.

4. Bennett, S.; Huss, W.; John, R. R.; and Tuchman, A.: Experimental Propulsion Performance of a Low Power Pulsed Resistojet. Paper No. 65-97, AIAA, Jan. 1965.

5. Spisz, Ernie W.; Brinich, Paul F.; and Jack, John R.: Thrust Coefficients of Low-Thrust Nozzles. NASA TN D-3056, 1965.

6. Hodgman, Charles D., ed.: Handbook of Chemistry and Physics. 42nd. ed., The Chemical Rubber Pub. Co., 1960.

7. Kanning, Gerd: Measured Performance of Water Vapor Jets for Space Vehicle Attitude Control Systems. NASA TN D-3561, 1966.

NASA-Langley, 1967 E-3530

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546