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Performance of a FAKEL K10K Resistojet

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Abstract

A model K10K resistojet produced by FAKEL Enterprise was evaluated at steady-state conditions with both nitrogen and xenon propellants. Performance and operational characteristics were documented for cold gas and heater power levels up to 8 W at mass flow rates from 0.02 to 0.2 g/s. Maximum specific impulses of 84 s on nitrogen and 49 s on xenon were achieved at the highest specific power levels tested.

Introduction

As part of a continuing effort to evaluate relevant technologies for future U.S. spacecraft, a FAKEL Enterprise model K10K resistojet was obtained and evaluated under a joint NASA / Ballistic Missile Defense Organization (BMDO) program.[1]

Xenon fueled electrostatic propulsion in the form of gridded ion and Hall effect thrusters is currently of great interest to the spacecraft community. Several Russian spacecraft have used xenon fueled Hall effect thrusters including the Earth observation Meteor 2 and 3 spacecraft and the Gals and Express series of geostationary communication satellites.[2] U.S. commercial geostationary spacecraft will also soon use xenon electrostatic thrusters; the Hughes HS-702 series will use a xenon ion propulsion subsystem for North-South stationkeeping and orbit insertion.[2] The use of electrostatic thrusters for part of the orbit insertion into geostationary orbit can substantially increase satellite payload.[3,4,5] Also, NASA will use xenon gridded ion propulsion system for several interplanetary missions with the first, Deep-Space 1, being launched in 1999.[6,7]

As advanced electrostatic propulsion options are considered for use, additional system level trades are being done to consider simplifying the spacecraft and reducing propulsion system costs by going to a one propellant spacecraft. To this end, propulsion system options such as cold gas Xe thrusters or Xe resistojets are being considered for some low ΔV requirements such as momentum wheel desaturation and low ΔV attitude control. A specific example of a satellite that uses cold xenon thrusters is the STRV 1A (Space Technology Research Vehicle 1A) launched by an Araine in 1994.[2] STRV 1A was designed, built and tested by the United Kingdom's Defense Research Agency (DRA) to investigate electrostatic charge mitigation via a Xe plasma neutralizer (first space test of the hollow cathode from the UK-10 gridded ion thruster). The xenon, while primarily carried for the electrostatic discharge experiment, was also used by three cold gas thrusters: two for spinup and one as backup for precession control in case of magnetorquer failure. A second specific example of a spacecraft that was considering a one propellant Xe propulsion system was NEPSTP (Nuclear Electric Propulsion Space Test Program).[8] NEPSTP was a BMDO sponsored program that was to demonstrate and evaluate nuclear electric propulsion. This spacecraft was to have a nuclear reactor, powering a Russian Hall effect thruster and a U.S. gridded ion thruster. The spacecraft primary propulsion were these xenon electrostatic thrusters, but the spacecraft required some small ΔV attitude control when these thrusters were not firing. Cold gas Xe thrusters and Xe resistojets were the propulsion options being considered for this attitude control function because of the system level simplicity an all xenon propulsion system would have.

These types of system level trades will continue to be made for future spacecraft that employ advanced electrostatic thrusters. At this time, evaluation of relevant technologies will continue to gather credible data to use in the trades.

Apparatus

K10K Thruster

For the experiments described herein, a model K10K resistojet (Figure 1) obtained from Space Systems / Loral and the Applied Physics Laboratory was tested. This thruster was purchased from FAKEL Enterprise for evaluation for possible use on the NEPSTP spacecraft. The K10K is a derivative of the K10 hydrazine monopropellant thruster design. Over 1000 K10 monopropellant thrusters have flown on Russian spacecraft. The K10K was designed to leverage this heritage by using as many of the same components as possible. The K10K thruster, however, has a electrothermal accumulator in place of the K10 catalyst bed and a modified injector for gaseous propellants. The K10K was designed as a pulsed mode thruster to compliment the Hall effect Stationary Plasma Thruster (SPT) for low ΔV attitude control on spacecraft.[9] The configuration and materials of construction of the electrothermal accumulator were unknown to the authors, but the room temperature resistance was found to be nominally 22 Ohms. By inspection, the K10K had a throat diameter of nominally 0.66 mm and a nozzle exit diameter of nominally 6.6 mm, for a conical nozzle with an area ratio of 100:1. (Figure 2) The thruster firing valve was a solenoid type with a coil resistance of nominally 95 Ohms.

Vacuum Facility

The experiments were conducted in a medium size space simulation facility (VF8) at NASA Lewis Research Center (Figure 3). The facility is a 1.5 m diameter by 5 m long vacuum vessel equipped with four 1 m diameter oil diffusion pumps, using silicon-based oil, with a pumping capacity of 140,000 l/s at 3×10^{-4} torr (air) backed by a rotary blower and two mechanical roughing pumps. The background pressure during most of the experiments was maintained below 5×10^{-4} torr. The only tests conditions where the vacuum facility pressure exceeded this was at the high nitrogen flowrates (>0.07 g/s). Under these conditions only the rotary blower and mechanical roughing pumps were used and the background pressure was maintained below 0.15 torr. No facility effects at these relatively high pressures were encountered.

Experimental Procedure

Heater current and voltage, propellant mass flow rate, and thrust were monitored periodically during the test.

All data were recorded manually. Heater current and voltage were monitored with commercially available digital multimeters. The heater current meter was connected in series with the power supply and the heater voltage meter in parallel. As these were initial tests and the heater materials and configuration were unknown, heater preheating associated with pulsed operation was deemed too risky, initial testing was only performed at steady-state. Testing at steady-state made it possible to regulate propellant mass flow rate by commercially available precision mass flow controllers. One of two controllers (full scale readings of 2 SLM and 10 SLM) were used depending on the mass flow rates desired. Both mass flow controllers were calibrated on nitrogen and xenon. A precision flexure thrust stand was used to measure thrust. The deflection was recorded via a strip chart recorder and calibrated in-situ with precision weights.

To initiate flow to the resistojet, the firing valve was energized by applying 10 V across the valve coil. This power level (1 W) was chosen as it was the minimum power level that would reliably unseat the valve, hold it open, and minimize heating of the propellant by the valve coil. Propellant mass flow rates were then set by the precision mass flow controller.

Initial cold gas performance was recorded over the maximum range of mass flow rates the test setup could accommodate. They ranged from the maximum the facility could pump and maintain a good vacuum to the lowest the flow controllers could deliver accurately. The cold gas performance was recorded to isolate the unheated nozzle effects. Once at the highest flow rate, the heater was turned on at the lowest power level (2 W). Mass flow rate was then decreased while heater power was maintained constant. Once a sweep of flow rate from high to low was made, the heater power was increased to 4.6 W and another mass flow rate sweep was made. Finally, the heater power was increased to 8 W and another mass flow rate sweep was made. Data at each point in a mass flow rate sweep was taken at 4 minutes after initial setting of the point. Four minutes was sufficient to reach steady-state from looking at the steadiness of the thrust profiles. Data were taken with both nitrogen and xenon as the propellants. Figures 4 and 5 show the test matrix (heater power and mass flow rate) performed with each propellant.

Results & Discussion

Summaries of all the data taken are provided in Tables I and II. Descriptions of the thruster characteristics important to the spacecraft user, specific impulse versus thrust, specific impulse versus specific power (heater input power/mass flow rate), thruster efficiency versus thrust are provided in the following sections.

Nitrogen

Testing on nitrogen was performed over the mass flow rate range 0.020 to 0.158 g/s with cold gas and heater input powers up to 8 W. Plots of specific impulse versus thrust, specific impulse versus specific power, and thruster efficiency versus thrust were made and are provided as figures 6, 7, and 8, respectively. Figure 6 indicates a cold gas performance of 74 s at 100 mN thrust. With 8 W of heater power, a specific impulse of 80 s is achievable at 100 mN of thrust. However, as the mass flow rate, hence thrust, is decreased below 50 mN the nozzle effects begin to dominate the cold gas performance. This can be seen by the drop off in specific impulse to 65 s at 20 mN of thrust. As heater power was increased, the nozzle effects dominated at progressively lower mass flow rates. This is illustrated in the specific impulse versus specific power plot (Figure 7). This plot shows the specific power of the gas at a given heater power where the nozzle effects begin to dominate. It can be seen that for a given power the K10K has an optimal specific power that is dictated by the nozzle effects. Figure 8 shows thruster efficiency versus thrust characteristic. Here it can be seen that thruster efficiency with cold gas was 85% at 100 mN and 73.6% at 20 mN . At a heater power of 8 W the thruster efficiency was 82.2% at 107.7 mN and 49.3% at 17.27 mN.

Xenon

Testing on xenon was performed over the mass flow rate range of 0.022 to 0.221 g/s with cold gas and heater input powers up to 8.9 W. Plots of specific impulse versus thrust, specific impulse versus specific power and thruster efficiency versus thrust were made and are provided as figures 9, 10, and 11, respectively. Figure 9 indicates a cold gas specific impulse of 33 s over the entire range of thrust. As heater power was increased to 7.9 W a maximum specific impulse of 49.4 s was achieved at 10.79 mN of thrust. In contrast to the aforementioned nitrogen data no knee in the curve indicating nozzle effects was seen in this plot. This is confirmed by the specific impulse versus specific power plot (Figure 10) in which no discernible knee is evident. The thruster efficiency curve (Figure 11) lends some insight by showing a very low thruster efficiency of 32% for all conditions tested with xenon as the propellant. It appears that nozzle and/or compressibility effects dominated over the entire xenon test matrix.

Summary

FAKEL Enterprise's model K10K resistojet was tested at steady-state conditions to give insight to its applicability to future U.S. spacecraft. The thruster was tested on nitrogen and xenon with cold gas and heater powers up to 8 W. A maximum specific impulse of nominally 84 s on nitrogen and 49 s on xenon was achieved at a heater power of 8 W and mass flow rate of 0.02 g/s. A thruster efficiency of 82% was achieved with nitrogen at a heater power of 8 W. When xenon was used as the propellant, a thruster efficiency of 32% for all conditions tested was achieved, including the cold gas cases.

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Table I - FAKEL K10K Thruster Operating on Nitrogen

Data Point Number	Heater Voltage (V)	Heater Current (A)	Heater Power (W)	Mass Flow Rate (g/s)	Propellant Feed Pressure (kPa)	Thrust (mN)	Specific Impulse (s)	Thruster Total Efficiency (%)
1	0.0	0.00	0.0	0.158	238.9	115.0	74.2	85.1
2	0.0	0.00	0.0	0.138	210.4	100.7	74.2	85.1
3	0.0	0.00	0.0	0.119	182.7	86.6	74.2	85.1
4	0.0	0.00	0.0	0.099	151.8	71.7	73.9	84.5
5	0.0	0.00	0.0	0.090	139.6	64.9	73.8	84.2
6	0.0	0.00	0.0	0.079	124.7	57.5	73.7	84.0
7	0.0	0.00	0.0	0.070	110.1	50.2	73.3	83.1
8	0.0	0.00	0.0	0.060	95.3	42.8	72.4	81.1
9	0.0	0.00	0.0	0.060	95.3	43.3	73.4	83.3
10	0.0	0.00	0.0	0.052	82.1	36.2	71.1	78.2
11	0.0	0.00	0.0	0.041	66.3	28.4	71.2	78.4
12	0.0	0.00	0.0	0.040	64.7	27.4	69.9	75.6
13	0.0	0.00	0.0	0.030	51.0	20.4	69.0	73.6
14	0.0	0.00	0.0	0.021	38.6	13.8	67.5	70.5
15	0.0	0.00	0.0	0.020	37.0	13.2	66.1	67.6
16	0.0	0.00	0.0	0.020	37.2	13.2	66.1	67.6
17	6.5	0.30	2.0	0.158	240.6	116.3	75.0	83.7
18	6.6	0.30	2.0	0.060	98.1	45.2	76.9	82.6
19	6.7	0.31	2.1	0.138	212.6	102.2	75.3	83.7
20	6.7	0.31	2.1	0.119	184.7	88.0	75.4	83.2
21	6.8	0.31	2.1	0.099	155.6	73.6	75.6	82.7
22	6.8	0.32	2.2	0.080	127.4	59.3	75.9	82.0
23	6.8	0.32	2.2	0.060	97.6	44.6	75.7	79.4
24	6.9	0.32	2.2	0.041	68.3	29.6	74.6	73.5
25	6.9	0.32	2.2	0.021	40.2	14.7	72.0	60.0
26	7.1	0.33	2.3	0.021	39.4	14.3	69.8	55.7
27	7.2	0.33	2.4	0.040	68.3	30.1	76.1	75.2
28	9.9	0.46	4.5	0.158	244.8	119.5	77.1	84.2
29	10.0	0.46	4.6	0.060	100.9	47.1	80.0	79.5
30	10.0	0.46	4.6	0.080	130.9	62.2	79.6	82.7
31	10.0	0.46	4.6	0.040	71.2	31.9	80.7	73.5
32	10.0	0.46	4.6	0.021	41.2	15.4	75.3	51.5
33	10.0	0.46	4.6	0.119	188.2	91.4	78.5	84.7
34	10.0	0.46	4.6	0.099	159.4	76.5	78.6	83.1
35	10.0	0.46	4.6	0.138	216.6	105.5	77.6	84.1
36	10.1	0.46	4.6	0.060	99.6	46.6	79.2	77.7
37	10.1	0.46	4.7	0.041	71.2	32.2	80.4	73.3
38	10.1	0.46	4.7	0.020	41.0	15.6	77.9	53.5
39	13.1	0.60	7.9	0.158	247.7	121.7	78.5	82.1
40	13.1	0.60	7.9	0.138	219.5	107.7	79.3	82.2
41	13.1	0.60	7.9	0.099	162.5	78.8	80.8	80.4
42	13.1	0.60	7.9	0.119	187.5	93.2	80.0	81.6
43	13.2	0.60	7.9	0.060	103.5	48.9	83.0	74.8
44	13.2	0.60	7.9	0.080	133.8	64.1	81.7	78.3
45	13.2	0.60	8.0	0.041	73.5	33.6	84.3	67.7
46	13.2	0.60	8.0	0.021	43.7	17.3	84.1	49.3

Table II - FAKEL K10K Thruster Operating on Xenon

Data Point Number	Heater Voltage (V)	Heater Current (A)	Heater Power (W)	Mass Flow Rate (g/s)	Propellant Feed Pressure (kPa)	Thrust (mN)	Specific Impulse (s)	Thruster Total Efficiency (%)
1	0.0	0.00	0.0	0.220	149.8	71.6	33.2	31.6
2	0.0	0.00	0.0	0.169	117.6	55.1	33.3	31.8
3	0.0	0.00	0.0	0.118	82.5	37.8	32.7	30.6
4	0.0	0.00	0.0	0.058	40.5	18.0	31.7	28.8
5	0.0	0.00	0.0	0.046	33.7	14.6	32.4	30.1
6	0.0	0.00	0.0	0.034	26.8	11.3	33.5	32.1
7	0.0	0.00	0.0	0.022	18.8	7.5	34.0	33.1
8	6.5	0.30	2.0	0.119	92.8	43.9	37.7	37.1
9	6.6	0.30	2.0	0.169	126.7	60.5	36.6	35.9
10	6.6	0.30	2.0	0.169	125.4	59.6	36.0	34.7
11	6.7	0.31	2.1	0.022	20.3	8.7	40.1	29.5
12	6.7	0.31	2.1	0.034	29.6	13.4	40.3	34.1
13	6.8	0.31	2.1	0.058	46.1	22.1	38.8	35.5
14	6.8	0.31	2.1	0.046	38.0	17.8	39.3	34.8
15	10.1	0.46	4.6	0.169	134.8	65.9	39.8	39.0
16	10.1	0.46	4.6	0.058	48.0	23.0	40.4	31.7
17	10.1	0.46	4.7	0.058	49.1	23.8	41.9	34.0
18	10.1	0.46	4.7	0.118	99.2	48.6	42.1	41.1
19	10.1	0.46	4.7	0.046	41.3	19.8	43.8	34.3
20	10.1	0.46	4.7	0.022	23.3	10.1	46.3	27.2
21	10.1	0.46	4.7	0.034	32.7	15.1	45.0	31.9
22	10.1	0.46	4.7	0.221	166.0	81.5	37.6	36.0
23	13.2	0.60	7.9	0.022	25.3	10.8	49.4	22.2
24	13.3	0.60	8.0	0.034	35.5	16.2	48.3	27.9
25	13.3	0.60	8.0	0.046	45.0	21.4	47.3	31.5
26	13.3	0.60	8.0	0.058	53.9	26.3	46.3	33.8
27	13.9	0.63	8.7	0.221	169.3	81.7	37.7	33.0
28	13.9	0.63	8.8	0.120	101.3	49.3	42.0	35.2
29	14.0	0.63	8.9	0.120	104.1	51.7	44.1	38.6

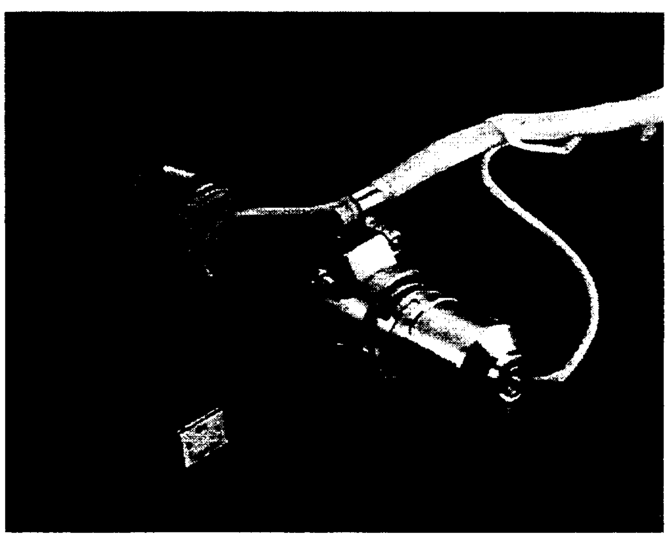

Figure 1 - FAKEL K10K Resistojet

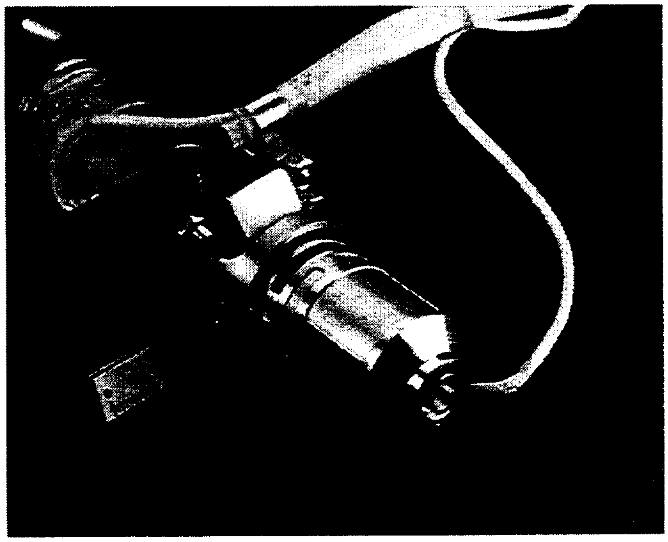

Figure 2 - Close-up of Nozzle Region of FAKEL K10K

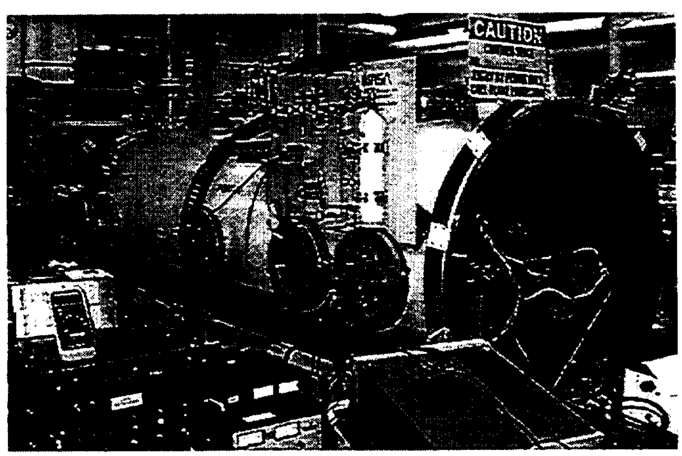

Figure 3 - NASA Lewis Research Center Vacuum Facility 8

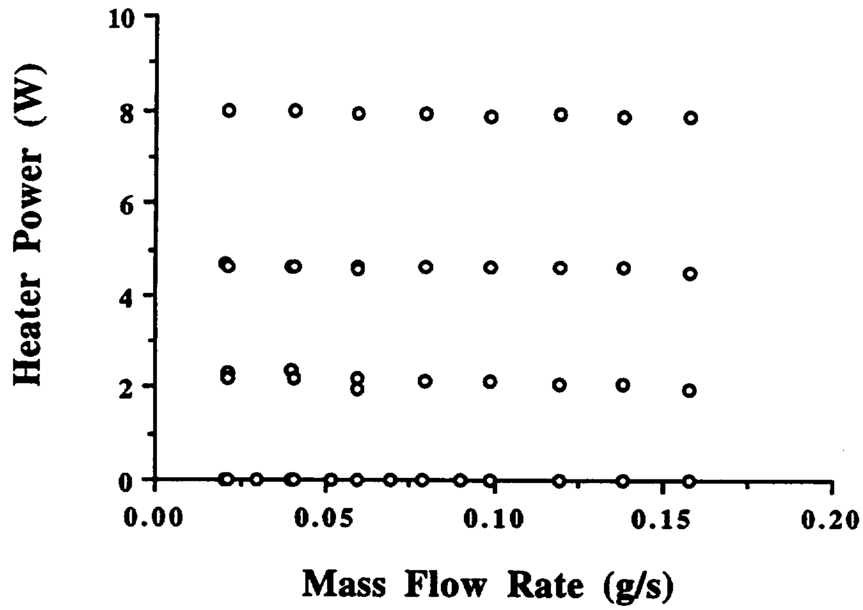

Figure 4 - Test Matrix for K10K Operating on N2

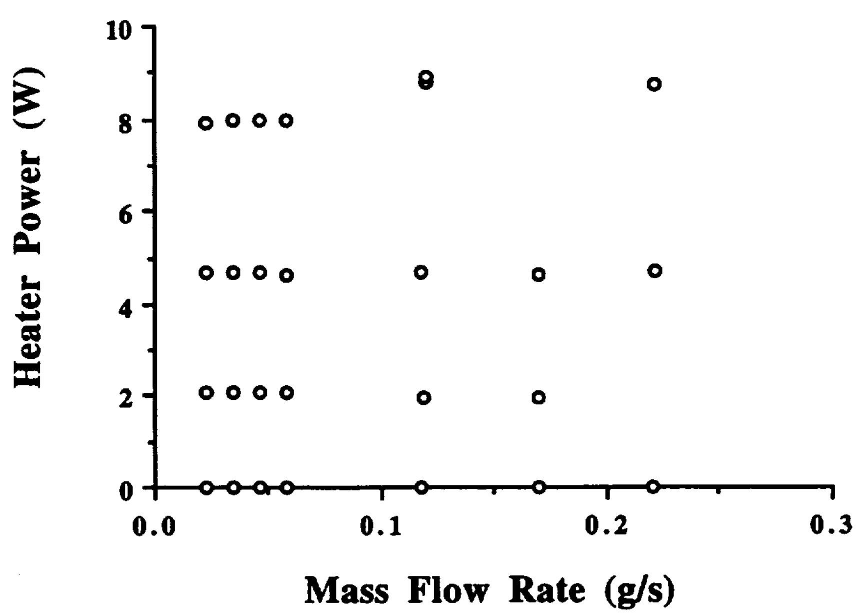

Figure 5 - Test Matrix for K10K Operating on Xe

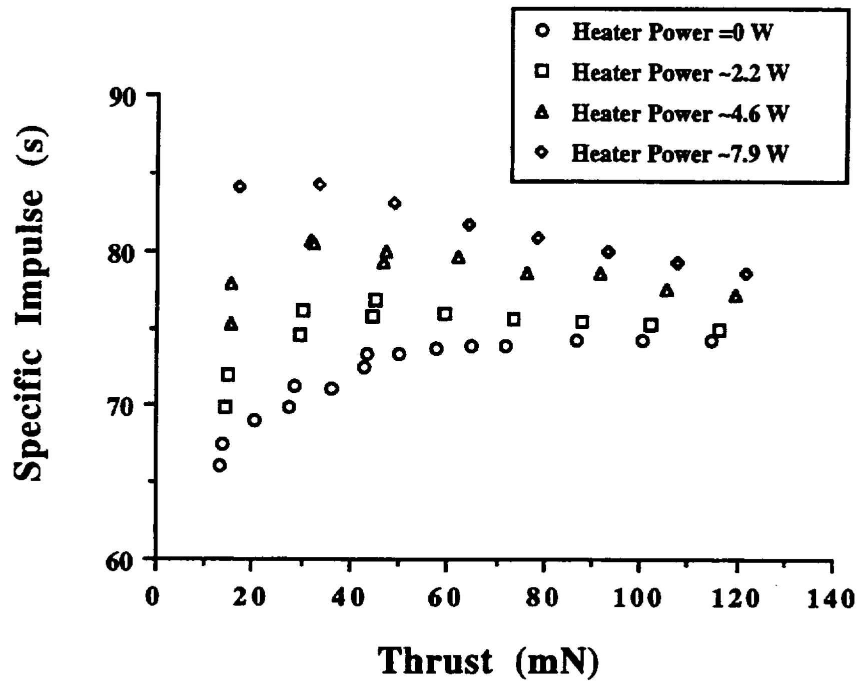

Figure 6 - Specific Impulse Versus Thrust for K10K Operating on N2 at Various Power Levels

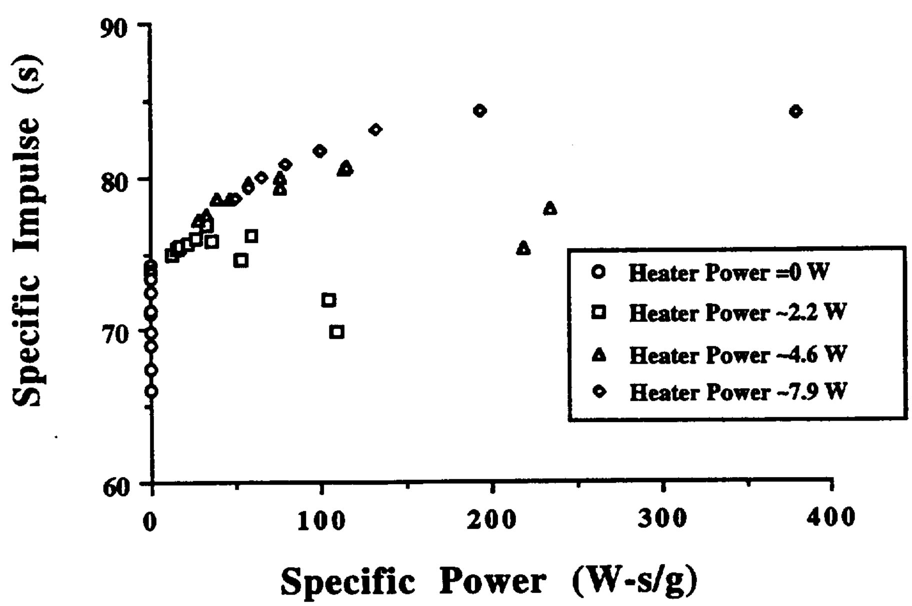

Figure 7 - Specific Impulse Versus Specific Power for K10K Operating on N2 at Various Power Levels

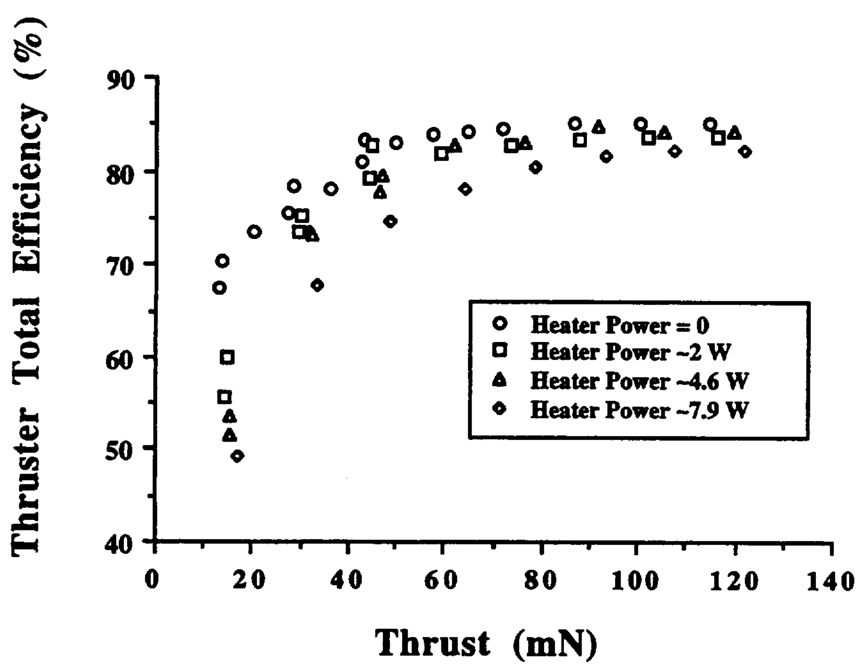

Figure 8 - Thruster Efficiency Versus Thrust for K10K Operating on N2 at Various Power Levels

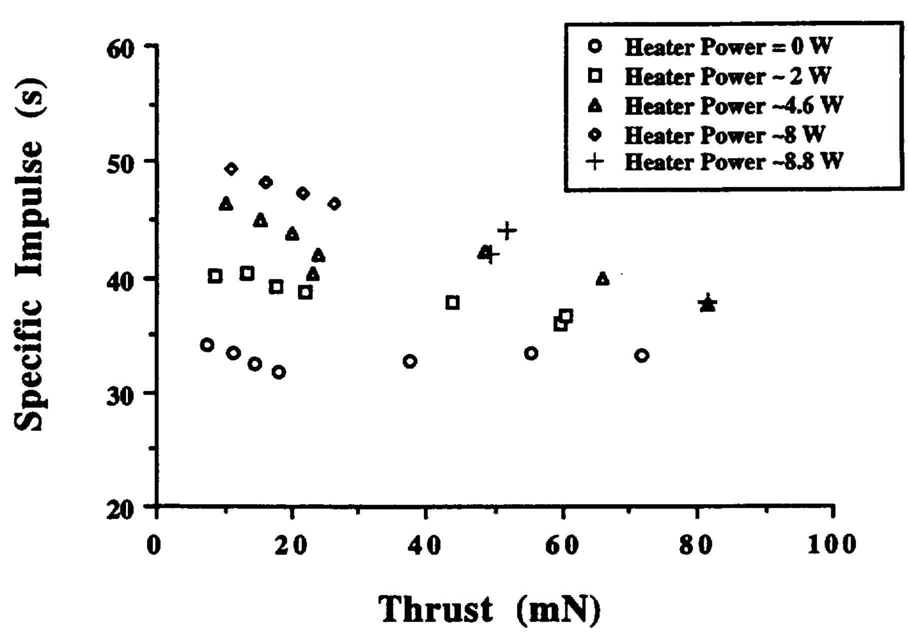

Figure 9 - Specific Impulse Versus Thrust for K10K Operating on Xe at Various Power Levels

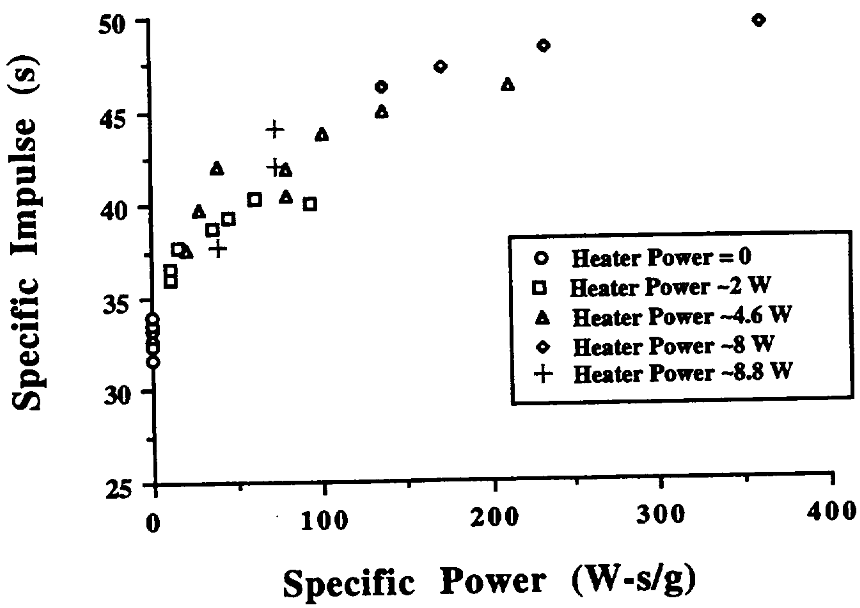

Figure 10 - Specific Impulse Versus Specific Power for K10K Operating on Xe at Various Power Levels

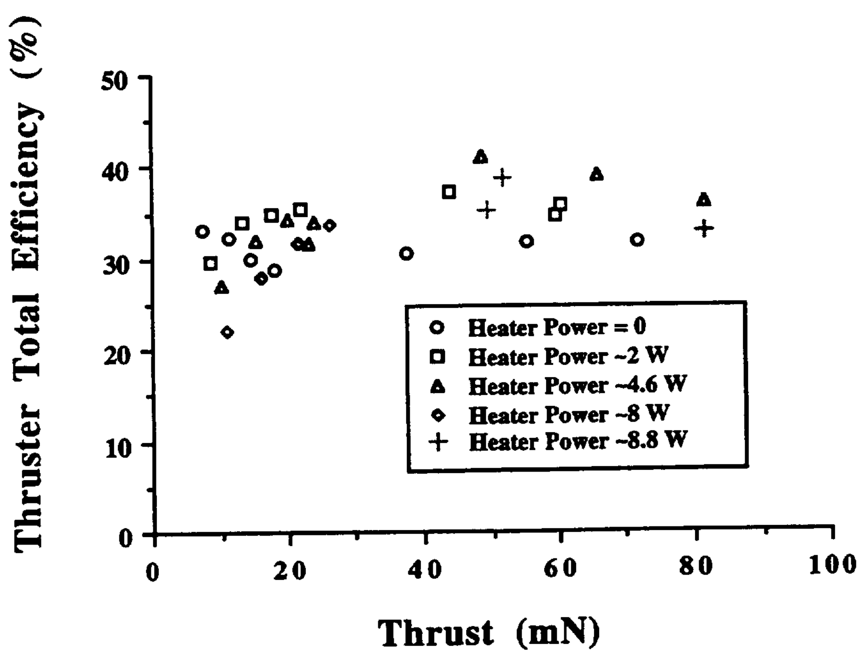

Figure 11 - Thruster Efficiency Versus Thrust for K10K Operating on Xe at Various Power Levels

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