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Space Propulsion Applications of Helium Arcjets

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With currently available space electric power systems, the optimum specific impulse for electrically propelled satellite transfers from low Earth orbit to geosynchronous Earth orbit appears to be in the 1000 to 1200 second range. Arcjets operating with helium as a propellant may be the most efficient electric thruster capable of operating in this specific impulse range. This work reports on a recent set of experiments which examined the effects of arcjet configuration, and propellant composition and flow rates, on arcjet performance. In these tests, it was found that increasing the cathode-anode gap over that normally used with hydrogen or ammonia propellants increased arc stability and significantly improved specific impulse and electrical efficiency. Hydrogen seeding was found to improve arc stability, particularly at smaller cathode gaps, but it had a very small effect on overall performance of the arcjet. The primary variable which affected arcjet performance was found to be propellant flow rate. The efficiency of the helium arcjet was found to increase with increasing propellant flow rate up to the maximum flows available for the current set of experiments.

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Space Propulsion Applications of Helium Arcjets

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Abstract

With currently available space electric power systems, the optimum specific impulse for electrically propelled satellite transfers from low Earth orbit to geosynchronous Earth orbit appears to be in the 1000 to 1200 second range. Arcjets operating with helium as a propellant may be the most efficient electric thruster capable of operating in this specific impulse range. This work reports on a recent set of experiments which examined the effects of arcjet configuration, and propellant composition and flow rates, on arcjet performance. In these tests, it was found that increasing the cathode-anode gap over that normally used with hydrogen or ammonia propellants increased arc stability and significantly improved specific impulse and electrical efficiency. Hydrogen seeding was found to improve arc stability, particularly at smaller cathode gaps, but it had a very small effect on overall performance of the arcjet. The primary variable which affected arcjet performance was found to be propellant flow rate. The efficiency of the helium arcjet was found to increase with increasing propellant flow rate up to the maximum flows available for the current set of experiments.

Introduction and Background

Continuing developments in electric propulsion are making it increasingly attractive for satellite operations. Beyond the launch of satellites from the Earth's surface to low Earth orbit, there are two main space propulsion applications; controlling satellite attitude and position, and transferring satellites from one orbit to another.[1] Attitude and position control, or station keeping, is characterized by very low thrust levels and intermittent operation for periods of several years. The total velocity change depends on the lifetime of the satellite. Orbital transfer applications are characterized by one-time velocity changes whose magnitude depends on the orbital parameters of the initial and final orbits. The most common orbital transfer is the transfer from low Earth orbit to geosynchronous Earth orbit, the LEO-to-GEO transfer. Station keeping is an application ideally suited to electric propulsion systems, and a significant increase in the use of EP for this application has been seen over the past five years.[2,3] On the other hand, although there is a significant potential for cost savings using EP for orbit transfer, operational use of EP for this application is still several years in the future. With the development of effective electric propulsion systems, and with the trend toward increasing power demands of the payloads,[1,3] satellites destined for geosynchronous Earth orbit will face additional deployment options. Electric propulsion engines available for use within approximately the next decade include the arcjet, resistojet, ion engine, and stationary plasma thruster or SPT. The primary solar electric propulsion option calls for a conventional launch to LEO, followed by a slow spiral transfer to GEO.

The motivating factor behind the selection of electric propulsion (or any other option) for geosynchronous deployment will be to minimize the dollar cost of that deployment. The largest portion of the deployment cost is usually the cost of the launch to LEO. The primary advantage of electric propulsion is that, for a given GEO mass, it offers the potential to reduce the mass required in LEO below a certain minimum inherent in chemically propelled LEO-to-GEO transfers.

Electric propulsion options include several different classes of engines, as well as various propellants. In considering electric propulsion systems, the electrical efficiency of the engines and storability of the propellants are parameters equally as important as the specific impulse. Ion engines typically operate with specific impulses in the 3000 to 10000 second range, well above the optimum specific impulse for the LEO to GEO

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transfer. The Stationary Plasma Thruster (SPT), can operate in the 1500 to 2000 second I_{SP} range, but the efficiency is typically about 50%.[4] Another disadvantage of the SPT is that the beam is highly divergent, which leads to concerns about spacecraft contamination.[5] Arcjets operate by heating a gas with an electric arc, and expanding the heated gas through a converging-diverging nozzle to produce thrust. Arcjets typically operate at specific impulses between 500 and 1200 seconds, with electrical efficiencies of about 50%.

These experiments were conducted using a laboratory model 1 kW arcjet as designed at NASA-Lewis.[6] This design is cylindrically symmetric, with a central cathode, and an anode in the shape of a nozzle. A gas flows through the region between the cathode and anode, exhausting through the converging/diverging nozzle to provide thrust. An electric arc is struck between the electrodes, with the anode arc attachment normally downstream of the constriction in the nozzle. The gas is heated either by passing through, or mixing with gas which has passed through, the arc. Arcjets can operate on a variety of propellants. For the LEO-to-GEO transfer, likely propellants include hydrogen and ammonia.[7,8,9] Helium has also been considered as a propellant for this application because of the potential for much higher efficiency with arcjets operating on helium.

Propellant Selection

Selection of propellant for arcjets requires consideration of several issues. The two most important are propellant related effects on engine performance, and space storability of the propellant. Minor issues include safety and contamination concerns. Performance in electric propulsion systems is measured in terms of two parameters, the specific impulse and the electrical efficiency.[10]

Specific impulse has historically been defined as the ratio between the thrust F of an engine, measured in pounds, and the propellant mass flow rate $\dot{m}$, measured in pounds per second, giving specific impulse units of seconds. Since seconds are the same in all systems of units, this customary usage has persisted, even in organizations using mks units. In fact, however, the value of g, the Earth surface gravitational acceleration, is implicitly contained in the units, as the concept of a pound of mass depends on the value of g. In the mks system, it is necessary to think of specific impulse in terms of the ratio between thrust and mass flow rate where the mass flow is properly defined independently of the value of g, thus:

$$I_{sp} = \frac{F}{\dot{m}g}. \tag{1}$$

But thrust is the product of mass flow rate and the exhaust speed u_e, giving

$$I_{sp} = \frac{\dot{m}u_e}{\dot{m}g} = \frac{u_e}{g}. \tag{2}$$

Since the specific impulse is directly proportional to the exhaust speed, it is very useful to think in terms of exhaust speed as an important performance parameter.

To increase exhaust speed, and therefore I_{SP}, electric propulsion engines such as the ion engine or SPT take advantage of electric fields to accelerate the propellants. Arcjets, on the other hand, are often referred to, along with resistojets, as electrothermal thrusters. These two engine types use electric power to heat a propellant, but then depend on a thermal expansion through a converging-diverging nozzle to accelerate the propellant. The exhaust speed of an ideal thermal expansion through a supersonic nozzle is proportional to $\sqrt{T/M}$ where T is the plenum temperature of the gas, and M is the molecular weight. This proportionality is strictly true only for ideal gases. As the temperature increases, the effects of chemistry, electronic excitation, or ionization will influence the energy available for propulsion. In any case, higher specific impulses are clearly obtained by increasing the temperature and decreasing the molecular weight of the gas. The practical upper limits on temperature are determined by the characteristics of the heat transfer from the gas to the thruster body, and by the properties of the thruster body materials. The practical lower limit on the molecular weight is 1 AMU with atomic hydrogen; this is the reason hydrogen is often the preferred propellant for arcjets.

The electrical efficiency of an arcjet is the ratio between thrust power and electrical input power:

$$\eta = \frac{P_T}{P_e}. \tag{3}$$

The thrust power is defined as

$$P_T = \frac{\dot{m}u_e^2}{2} = \frac{F^2}{2\dot{m}} \tag{4}$$

where u_e is the exhaust speed of a uniform propellant stream which would provide the thrust F. Thus, the efficiency is given by

$$\eta = \frac{F^2}{2P_e\dot{m}}. \tag{5}$$

Inefficiencies in arcjet thrusters include any path by which power is lost from the arcjet other than the thrust. Principal paths include heat transfer to the arcjet body which is not recovered by regenerative cooling, nozzle inefficiencies which result in non-directed kinetic energy in the exhaust plume, and frozen flow losses due to atomic or molecular excitation and ionization, and unrecovered dissociation energy. The relative importance of these loss mechanisms depends on the properties of the propellant and on the operating conditions of the arcjet.

Frozen flow losses include electronic, vibrational, and rotational excitation of the exhaust species, as well as any energy which may be required for dissociation. These losses occur because of the failure of atoms, electrons, and ions to recombine and relax during their residence time in the nozzle. The associated energies are not recoverable and are "frozen" into the flow. Under the conditions typical of arcjets, freezing takes place at the throat.[11] The significance of this loss mechanism depends on the properties of the propellant gas. For a diatomic gas like hydrogen, vibrational and rotational states are excited at relatively low temperatures; as the temperature increases, electronic excitation, dissociation, and ionization will increase. For a monatomic gas such as helium, there are no rotational or vibrational modes, as well as no dissociation. Additionally, with helium, electronic excitation and ionization take place at much higher temperatures than in any other gas, including hydrogen. Figure 1 shows the theoretical frozen flow efficiency for selected arcjet propellants operating at a stagnation pressure of 1 atmosphere.[12] Operating at a specific impulse of 1200 seconds, we see that a hydrogen arcjet should have a frozen flow efficiency near 0.4, and this will be the dominant loss mechanism. A combination of experimental and numerical work by Hoskins et. al.[13] showed frozen flow losses in a 10 kW class hydrogen arcjet to be between 30 and 40 % of the input power. At the same specific impulse, a helium arcjet should have a frozen flow efficiency above 0.9.

Propellant storage for helium arcjets also presents a problem. Early work on helium arcjets in the 1960's was abandoned when it was realized that helium would require a very large tankage mass fraction for realistic missions. Since then, however, the technology for long term storage of cryogens in space has improved, and tankage fractions less than 10% now appear possible for helium propelled LEO-to-GEO transfers.[14]

Previous Helium Arcjet Work

After a small initial effort on helium arcjets in the early 60's, very little additional work was done to evaluate their potential application. Preliminary work in this laboratory[15] indicated that high efficiency operation might be possible, but several issues remained to be resolved. The first experiments in this laboratory showed that, in contrast to hydrogen or ammonia, helium arcjets are unstable on time scales ranging from fractions of a second to tens of minutes. Specifically, using a constant mass flow, and a constant current power supply, the measured voltage, power, and thrust of the arcjet fluctuated by up to 40% over periods of seconds to minutes. The cause of the observed instability in helium operation is unknown. On the other hand, hydrogen operation has been observed to be stable within 1% for hours at a time.[15] The most obvious difference in operation, other than the instability, is the difference in voltage drop across the arc. In hydrogen operation, the arc voltage is typically 100 to 135 volts, where helium operation will give a voltage drop of 25 to 60, depending on conditions. The voltage drop across the helium arcjet is a function of the gas flow rate; at very high flow rates, the voltage drop increases.

It was also noted during those helium arcjet experiments that addition of a small amount ($\sim$1%) of hydrogen to the flow had a significant effect on plume appearance. While no measurements were made at the time, it appeared likely that hydrogen seeding would have some effect on arc stability as well as arcjet efficiency.

With this background in mind, a set of experiments has been planned to evaluate the utility of helium arcjets for the LEO-to-GEO transfer. This paper reports on a series of experiments in which the effects of arcjet configuration, mass flow rate, and propellant composition were evaluated through measurements of arcjet performance.

Experiment Description

These experiments were conducted using an Aerospace manufactured derivative of the NASA-Lewis 1 kW laboratory model arcjet. Its modular design allows for easy interchange of nozzles with varying constrictor diameters, and for easy adjustment of the cathode-anode gap as shown in Figure 2. In the current set of experiments, the constrictor diameter was held constant at 0.030 inches, while the cathode gap was changed over the range 0.025 to 0.075 inches. In addition to the changes in cathode gap, the arcjet was run on a variety of propellants, consisting of either pure hydrogen, pure helium, or helium seeded with a small fraction (typically less than 1% by mass) of hydrogen. Power to the arcjet was supplied by a regulated dc source and a nominal 1 kW arc power conditioner supplied by NASA-Lewis. This unit was capable of supplying up to 15 amps to the arc. In this set of experiments, arc current was varied from 9 to 15 amps.

Arcjet specific impulse and overall electrical efficiency are determined by simultaneously measuring arcjet power, propellant mass flow rate, and thrust. Of these, the thrust measurement is the most problematic because of the low thrust and low thrust-to-weight ratio of the engine. In this set of experiments, thrust was measured using the thrust balance illustrated in Figure 3, which operates on the principle of displacement against a spring force. This system was originally developed at NASA-Lewis[6] for measuring the thrust on a 1-kW arcjet. It was duplicated at the Aerospace Corporation for the current application and other similar applications.[15] The thrust balance is a hinged parallelogram platform in an inverted pendulum configuration with steel shim stock for the hinges. The bottom plate is stationary, while the upper plate moves in response to a force, but remains parallel to the bottom plate. Engine thrust is balanced by a restoring spring connecting the two plates. On the original design, a feedback controlled electromagnetic damping coil was used to minimize oscillations. Because of the possibility of thermal effects and electrical noise from the arcjet, the thrust balance is enclosed in a grounded, water-cooled copper box, and there is additional water cooling at the base of the arcjet mount. Water cooling for the arcjet mount, and propellant for the arcjet are supplied through coiled tubes. Power for the arcjet is supplied through flexible, unstrained wires suspended from the roof of the vacuum tank, rather than through the thrust balance, to avoid resistive heating within the water-cooled case. Displacement of the upper plate is measured with a linear displacement-transducer. The output of the transducer is periodically read by computer at a selectable data rate up to 100 Hz. Provided the displacement of the upper plate is within the elastic deformation limit of the restoring spring, the displacement will be linearly proportional to the thrust. The spring constant is measured in vacuum using an externally controlled stepper motor to suspend a series of weights over a pulley. The gravitational force on the weights is thereby converted to a horizontal force acting on the thrust balance.

The unit built at Aerospace was recently modified for use with a 10-cm ion engine.[16] For this application, the sensitivity and resolution were increased to allow measurements in the 10-40 mN range with a resolution of 0.3 mN. This was accomplished by replacing the spring with one having a lower spring constant, replacing the calibration weights with ones appropriate to the new thrust range, and aggressively searching out sources of noise and calibration uncertainty. As modified, the unit is still able to measure thrust levels up to the 150 mN necessary for arcjet applications. Two problems have made it difficult to maintain the 0.3 mN resolution in arcjet operation. One of the steps used for noise reduction in ion engine operation was to remove the feedback-controlled electromagnetic damping circuit. This was done because this circuit tended to introduce a non-reproducible calibration uncertainty of up to 1 mN. The circuit was unnecessary in ion engine operations because ion engines are smoother in operation than arcjets. Even with this modification, however, the shot noise of the system was maintained below $\pm$ 0.3 mN in arcjet operations through techniques which were developed for filtering out oscillations during the data analysis. The second difficulty was that of long term zero drift, due primarily to thermal loads.[16] In arcjet operation, the drifts tended to be smaller than $\pm$ 0.5 mN.

In addition to thrust measurement, calculation of specific impulse and efficiency requires measurement of arc current and voltage, and propellant mass flow rate. The computer which acquires the thrust data also simultaneously reads the voltage and current in the arcjet, and the flow rates for the gases. All data are acquired by an eight channel A-to-D converter operating in the -10 to +10 volt range. The linear-displacement transducer controller for the thrust stand has an analog output which is fed directly to the A-to-D converter, and the whole system is calibrated simultaneously. The current is measured using the output of a hall effect current meter calibrated using a standard current source. The voltage is measured using a voltage divider circuit calibrated using volt meters capable of handling the full voltage range of the arcjet. There is also a circuit in place to filter out the arcjet start pulses to protect the A-to-D converter and the computer.

Propellant feed to the arcjet is controlled by flow meters manufactured by MKS which operate by monitoring the thermal effects of the flowing gases. In our configuration, the flow is metered upstream of the flow controller, so that the flow meter operates at regulator supply pressure (typically 50 pounds per square inch), independent of arcjet feed pressure. The flow meter controller has analog outputs which are linearly proportional to the flow rates. These outputs are input directly to the A-to-D converter and read simultaneously with the thrust, voltage, and current of the arcjet. The flow meters are each calibrated for their respective gases by flowing the gas through either a 100 ml or a 1.5 liter bubble meter, depending on flow rate, downstream of the flow meters and flow controllers.

These experiments were conducted in the space simulation facility at Aerospace Corporation. The system was pumped with a roots blower and maintained a chamber pressure of 200 to 400 mtorr during arcjet operation.

Experimental Results

In the earlier work in this laboratory with hydrogen-seeded helium arcjets[15] it was noted that the hydrogen addition, even in amounts as small as 1%, resulted in significant changes in the appearance of the plume. It was thought that the changes in plume appearance indicated changes in the distribution of internal energies in the plume which would affect frozen flow losses. As such, it was anticipated that hydrogen seeding would affect helium arcjet performance. However, careful performance measurements were not made at that time.

In the current set of experiments, particular attention was paid to the effect of hydrogen seeding. The hydrogen seeding resulted in changes in plume appearance similar to those noted earlier; a significant reduction in the overall optical emission from the plume, and a change of color from yellow toward red. In addition, at small cathode separations, the hydrogen seeding was essential to stabilize the arc. For example, with a cathode gap of 0.050 inches (double that normally used in hydrogen or ammonia operation), the arc was stable when operating at 12 amps with helium flow rates between 15 and 30 mg/s along with 0.15 mg/s of hydrogen. When the hydrogen flow was turned off, the arc became immediately unstable, and tended to go out within a few seconds if the hydrogen was not restored.

At the higher cathode gaps used in this series of tests, the arc was close to stable in the absence of hydrogen seeding, but the operating conditions tended to oscillate. Other than arc stability, however, the effect of hydrogen seeding on performance was generally too small to be measured. Specific impulse changes were smaller than 10 seconds, and efficiency variations were smaller than 1%. Figure 5 shows the results of a series in which the hydrogen seeding rate was varied from 0.075 to 0.645 mg/s. This series was run with a cathode gap of 0.062 inches, 24 mg/s helium propellant flow, and 14.9 amps arc current. At the lowest hydrogen flow, the specific impulse showed fluctuations of about 25 seconds, while the efficiency varied by about 1%. With seeding rates at 0.015 mg/s and above, the specific impulse showed a very slight tendency to rise, while the efficiency showed a very slight decline. These two results are consistent with a slight decrease in average molecular weight and increase in internal energy modes with additional hydrogen concentration.

Rather than hydrogen seeding, the primary factors which affected arcjet performance were the cathode gap and the propellant mass flow rate. The NASA-Lewis arcjet was nominally designed for use with hydrogen, ammonia, and simulated hydrazine (made by mixing hydrogen and nitrogen in appropriate ratios). With these gases, the arcjet operates well with a cathode gap of 0.025 inches. In the current series of tests, the arcjet was run with cathode gaps ranging from 0.025 to 0.075 inches. The larger cathode gaps contributed to increased stability of the helium arcjet both with and without hydrogen seeding. At low cathode gaps, hydrogen seeding was required for stable operation, and even then, it was not always completely stable. Figure 4 shows a typical arc instability which was often observed at low cathode gaps. In this figure, the arc voltage is shown as a function of time for 3000 seconds of a test run with a cathode gap of 0.040 inches, an arc current of 15.0 amps, and helium and hydrogen flow rates of 22 mg/s and 0.16 mg/s respectively. The voltage fluctuates by about 5 volts on a random time scale. Other operating parameters of the engine, such as specific impulse and efficiency, fluctuate in a similar manner. At larger cathode gaps, these fluctuations are greatly reduced. More importantly however, the larger gaps lead to an increase in arc voltage which improves the energy deposition process. Figure 6 shows the arc voltage and thruster efficiency as a function of cathode gap for an arcjet operating on 25 mg/s helium at 14.9 amps. Since adjustments to the cathode gap require removing the arcjet from the vacuum chamber, the data was compiled from several runs over a period of weeks. Although the data is quite noisy as a result, the trend is clear. Similar trends are seen in data taken at other operating conditions.

By far the largest changes in performance in the helium arcjet were observed as a function of changes in the helium mass flow rate. Increased mass flow resulted in increased arc stability, increased arc voltage, slightly increased specific impulse, and significantly increased arcjet efficiency.

The trend in arc voltage is very clear as seen in Figure 7, where the arc voltage is plotted as a function of time for operation with an arc current of 15 amps and a cathode gap of 0.075 inches. During this run, the helium flow rate was increased in a step-wise fashion, as indicated by the labels in the figure. Although the increase in arc voltage resulted in a net increase in the total power into the arc, the increase in flow rate was sufficiently larger to result in a net decrease in energy density in the propellant.

Figure 8 shows the trends in specific impulse as a function of mass flow rate observed in a large number of runs at a variety of cathode gaps, arc currents, and hydrogen seeding levels. The chart shows two groups of data. The group lower and to the right (at specific impulses less than about 550 seconds) is the helium data, while the upper left group is a reference set of data showing operation on pure hydrogen. The broad difference between the two gases is due to the difference in molecular weight, and the higher energy density possible at the higher arc voltages obtained with hydrogen operation. The specific impulse under helium operation shows a slight increase over the range from 10 to 20 mg/s mass flow rate, with a leveling off at flow rates above 20 mg/s. The leveling of the specific impulse beyond 20 mg/s is probably due to the reduction in energy density in the helium as a result of reaching the maximum power capability of the currently available arc power supply.

Since specific impulse increases with increasing propellant temperature in a thermal expansion engine, it is expected that specific impulse will increase with increasing energy density in the propellant. Indeed, this is what is seen in the current series of tests, as shown in Figure 9. The data in this figure comprises the same operating points seen in Figure 8. In this case, the hydrogen-only operating points appear well to the right because of their higher energy density. The large grouping of data points between 20 and 40 kJ/g are the helium operating points. Figure 10 shows the helium data from Figure 9, expanded, and grouped according to helium mass flow rate. Two trends are clear in this figure. First, as expected, the specific impulse increases with increasing energy density for a given mass flow rate. Additionally, the specific impulse increases with increasing mass flow rate. When the trends for each of the mass flow rates are examined in Figure 10, it is seen that, at any given energy density, there is an increase of about 50 seconds in the specific impulse resulting from an increase in mass flow from 22 to 31 mg/s.

The trend in arcjet efficiency with changing mass flow rate is more significant, as seen in Figure 11. This chart includes all the operating points seen in Figure 8. Although the clear trend toward an increase in efficiency with increasing mass flow shows no sign of leveling off at the maximum flow rates and powers available with the current equipment, the efficiency cannot exceed 100 %. It is expected that the trend will level somewhere near 70 %.

Summary and Conclusions

Several conclusions regarding the optimization of arcjets for operation on helium can be drawn from the results obtained to date. The two primary changes relative to hydrogen or ammonia operation are that both the propellant flow rate and the cathode gap need to be significantly increased. In this work, the cathode gap ranged from 0.025 inches up to 0.075 inches. Even at this highest value, the trends were still toward increasing arc stability and arcjet efficiency. Propellant flow rates in these experiments ranged from 15 to 35 mg/s, with the upper limit being set by the maximum power capacity of the available supply. Again, at the highest flow rates, the trend was toward increasing arc stability, and strongly toward increasing arcjet efficiency, and without any corresponding loss in specific impulse.

When considering the effect of higher flow rates on the internal operation of the arcjet, the most probable significant effect is the increase in pressure in the region upstream of the nozzle constrictor. This would imply that designs incorporating a smaller constrictor diameter than the 0.030 inches used in the present experiment would allow higher pressure operation at lower flow rates, which would be more appropriate for the available 1 kW power supply.

Hydrogen seeding cannot yet be completely discounted as a method of improving the utility of helium arcjets. In this work, there was no significant increase in arcjet performance, in the form of efficiency or specific impulse, as a result of hydrogen addition. Hydrogen seeding at about 1% by mass did contribute to arc stability even at the highest cathode gaps and flow rates included in this study. On the other hand, the trends were toward a smaller effect, and hydrogen seeding may be unnecessary with the configurations, power levels, and flow rates appropriate for space propulsion applications.

The work to date indicates the directions which must be taken to optimize space propulsion arcjets for operation with helium as a propellant. In addition the trends are still indicating that high efficiency operation may be possible in the 1000 to 1200 second specific impulse range of interest for the LEO to GEO transfer.

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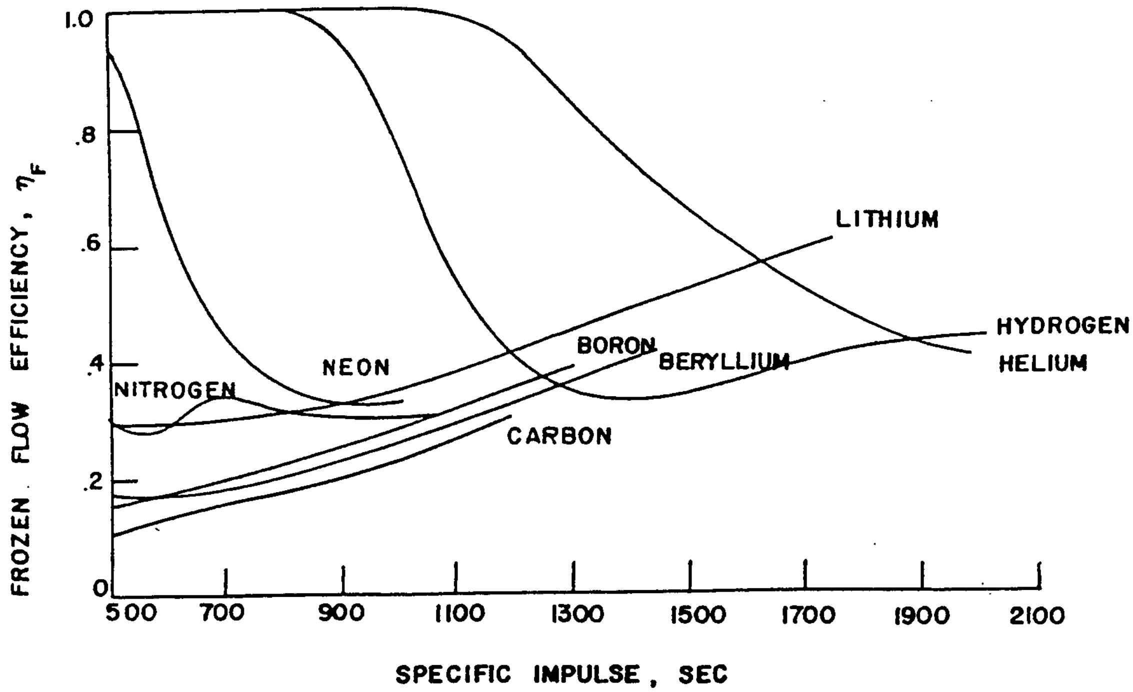


Figure 1. Theoretical frozen flow efficiency for selected arcjet propellants operating at a stagnation pressure of one atmosphere. From Reference 12.

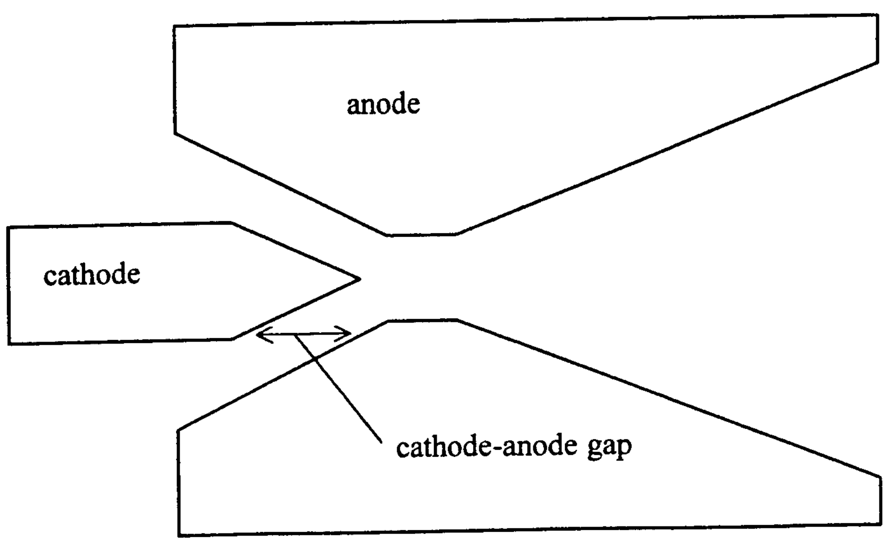


Figure 2. Magnified diagram of the constrictor region of the arcjet, showing how the cathode-anode gap is measured.

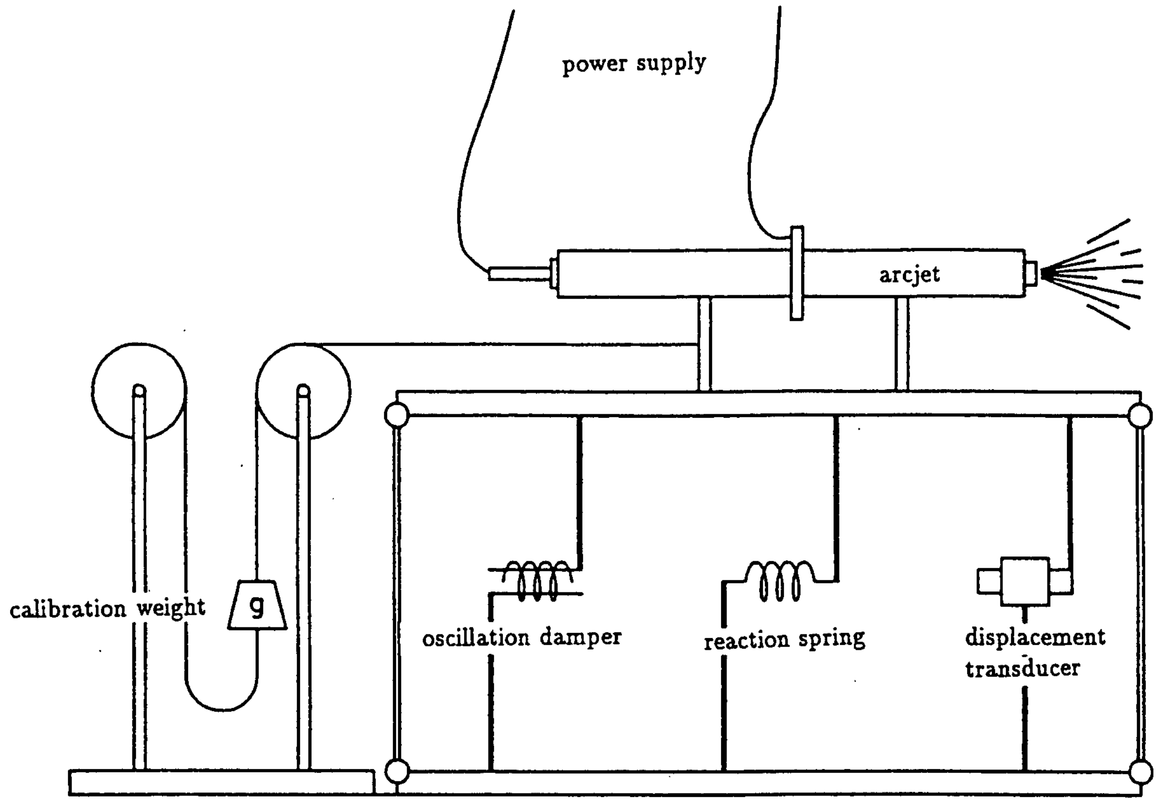


Figure 3. Diagram of the thrust balance.

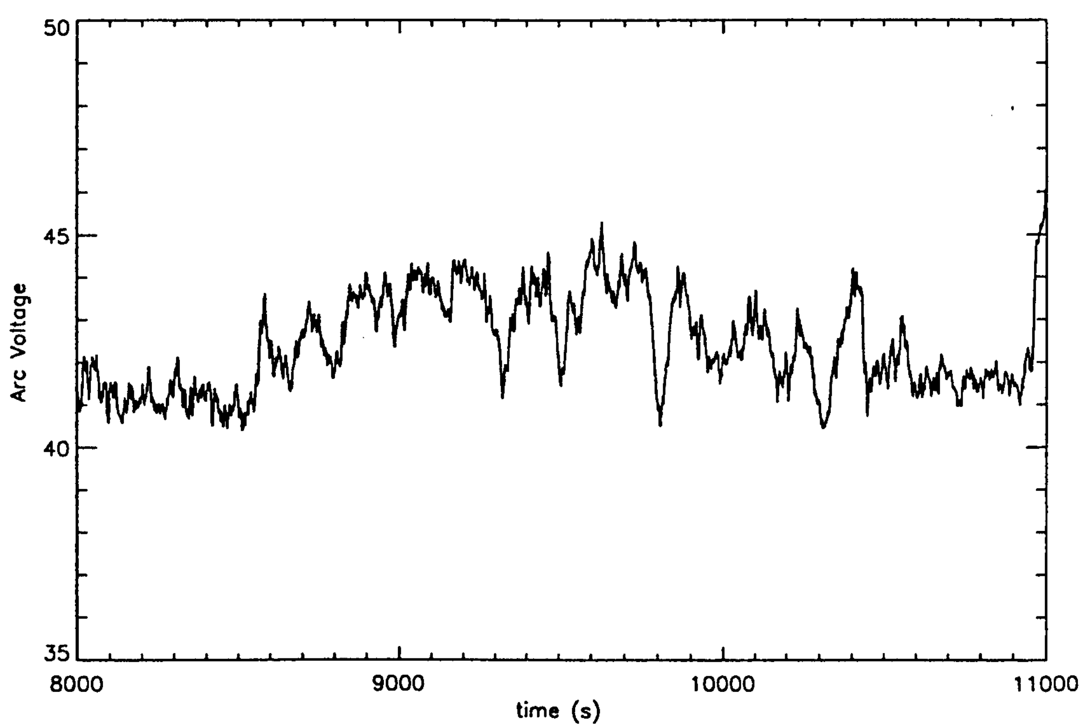


Figure 4. Time fluctuation of arc voltage for an arcjet operating at 15 amps with 22 mg/s helium, 0.16 mg/s hydrogen, and a cathode gap of 0.040 inches.

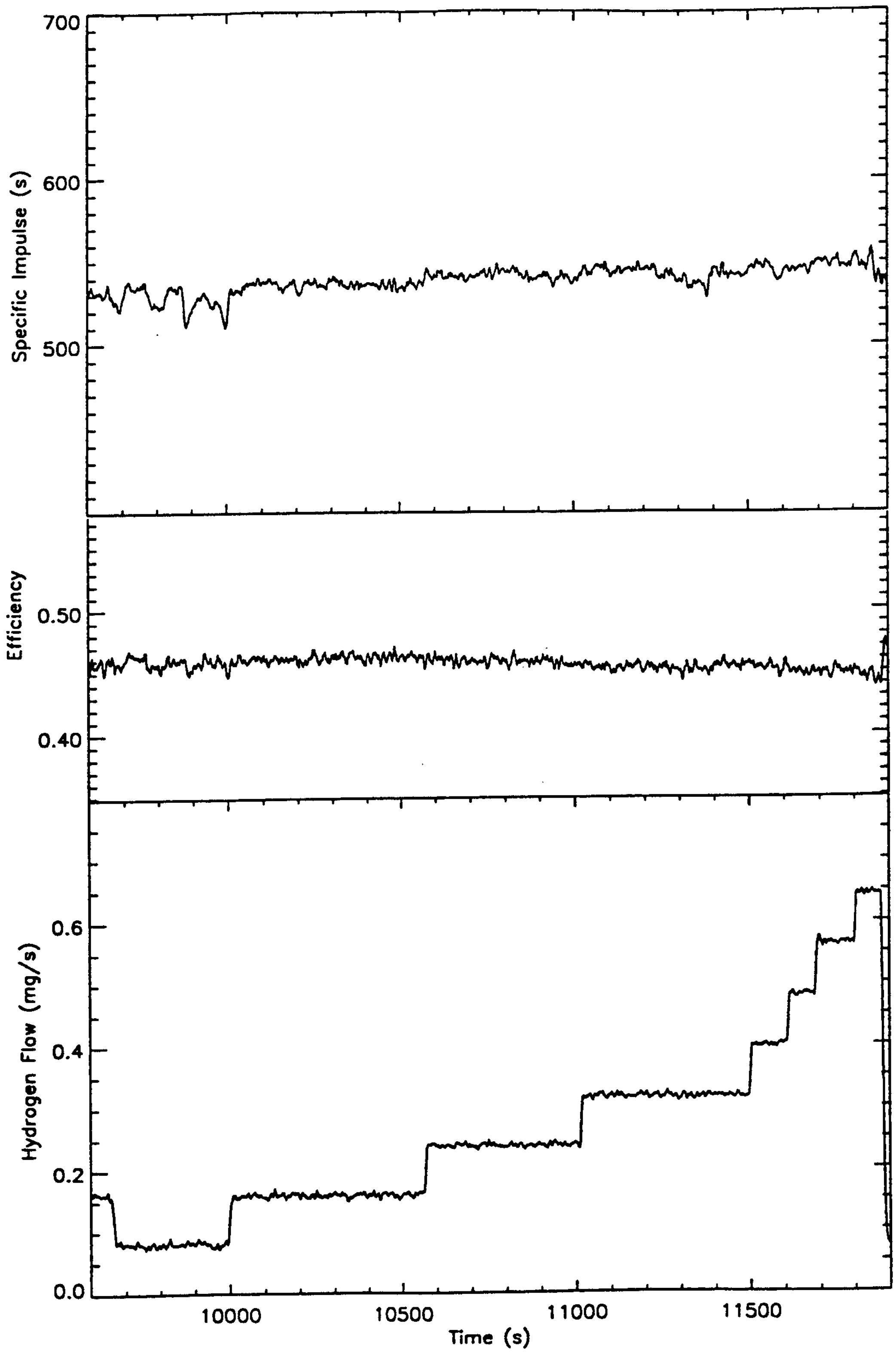
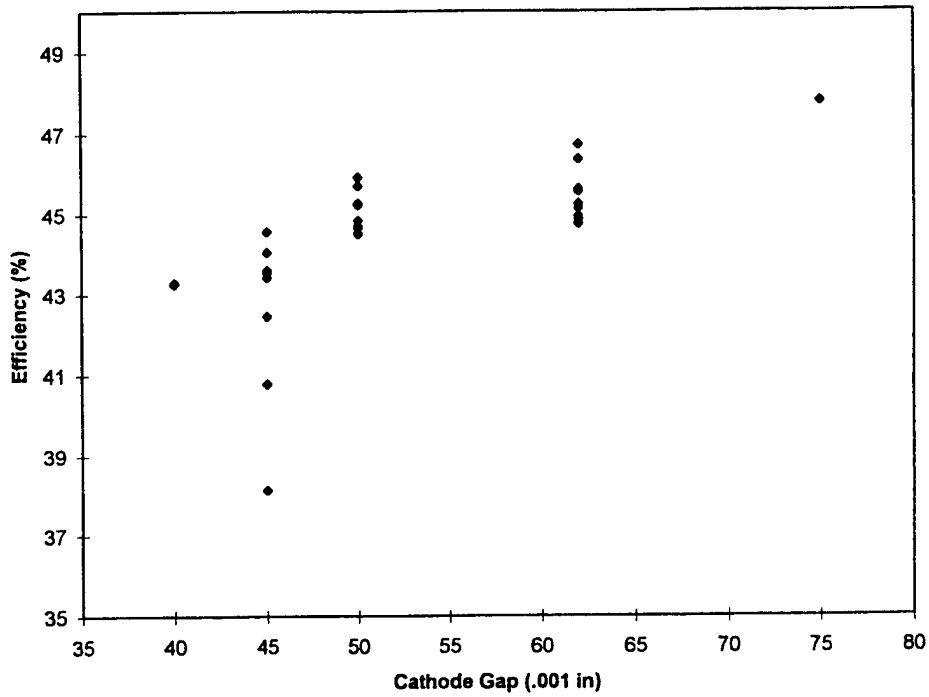


Figure 5. The effect of changes in the hydrogen seeding level on arcjet efficiency and specific impulse for an arcjet operating at 15 amps with 25 mg/s helium and a cathode gap of 0.062 inches.



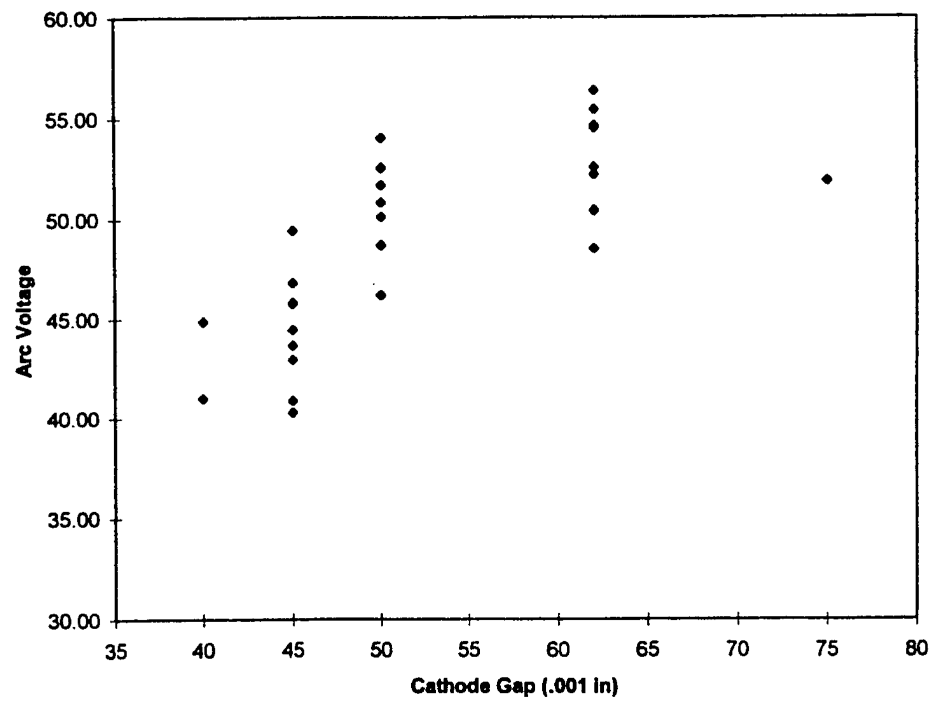


Figure 6. Arc voltage and arcjet efficiency as a function of cathode gap for a series of arcjet runs at 14.9 amps with 25 mg/s helium, and hydrogen seeding levels between 0.0 and 0.66 mg/s.

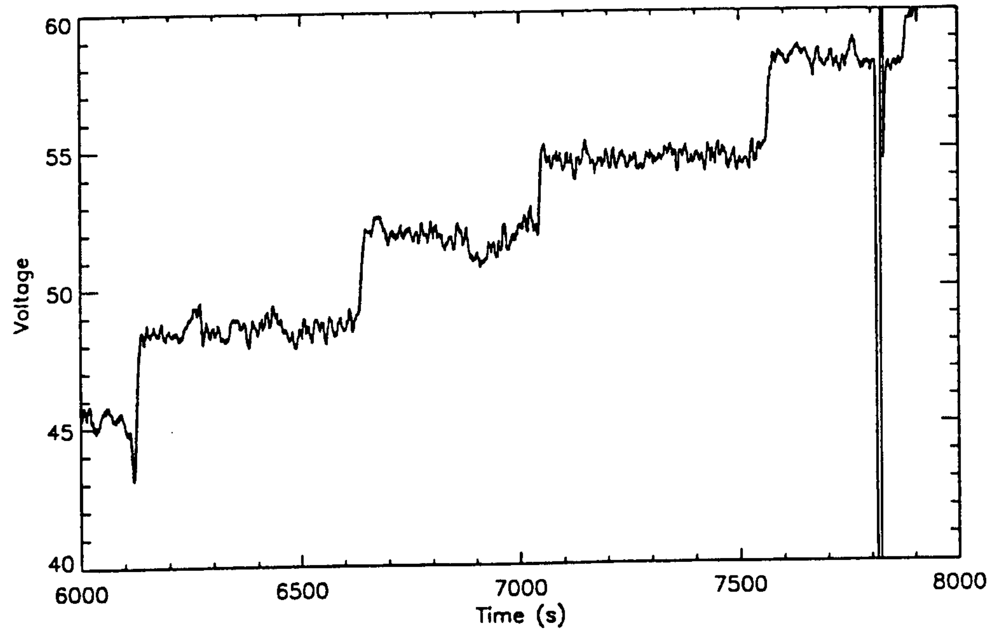


Figure 7. Variation in arc voltage as the helium flow rate is increased in a stepwise fashion from an initial 19 mg/s to 22, 25, 28, and 31 mg/s successively. The arcjet was operating with a cathode gap of 0.075 inches, a hydrogen seeding rate of 0.16 mg/s, and a constant arc current of 15 amps.

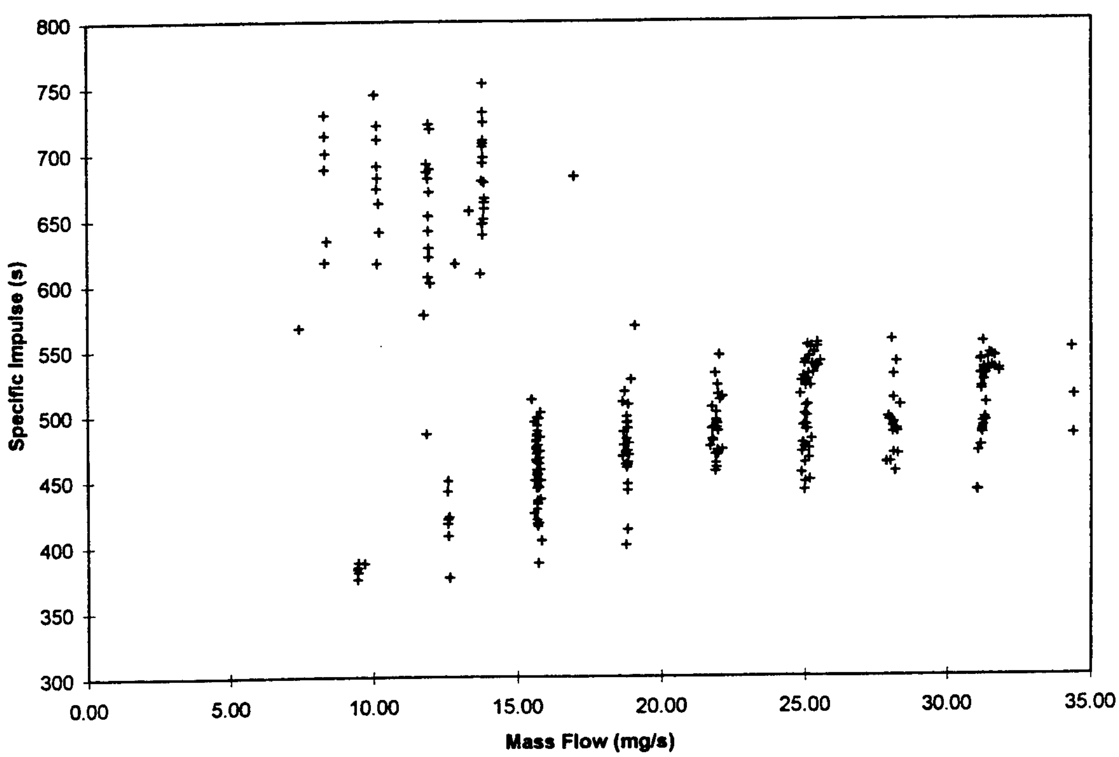


Figure 8. Variation in arcjet specific impulse as a function of propellant mass flow. The upper left data group (at specific impulses above 550 seconds) includes only pure hydrogen propellant, while the lower data group includes pure helium and hydrogen-seeded helium operation.

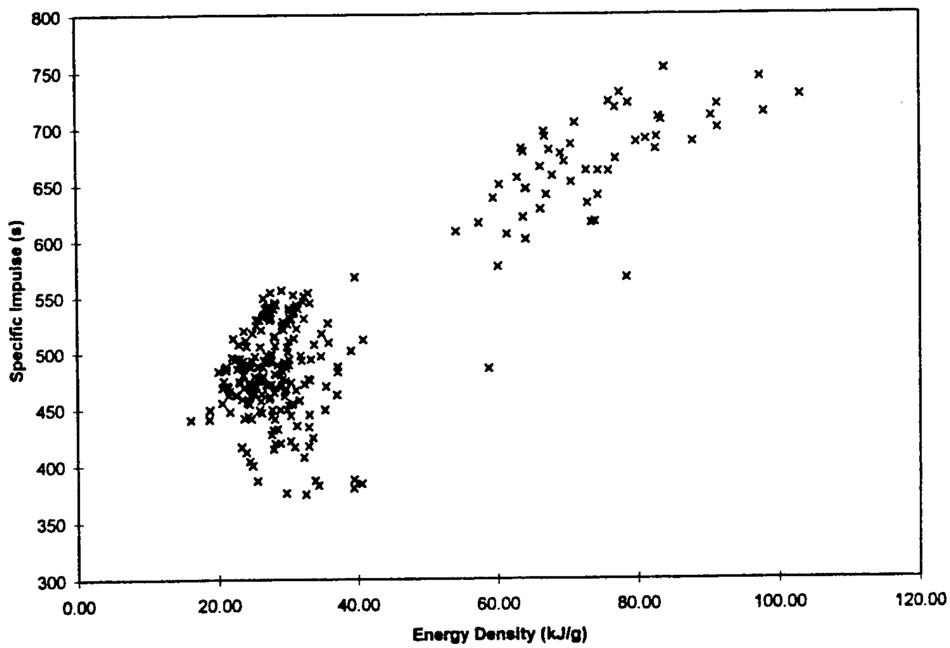


Figure 9. Variation in arcjet specific impulse as a function of propellant energy density. The upper right data group (at energy densities above 50 kJ/g) includes only pure hydrogen propellant, while the lower left data group includes pure helium and hydrogen-seeded helium operation.

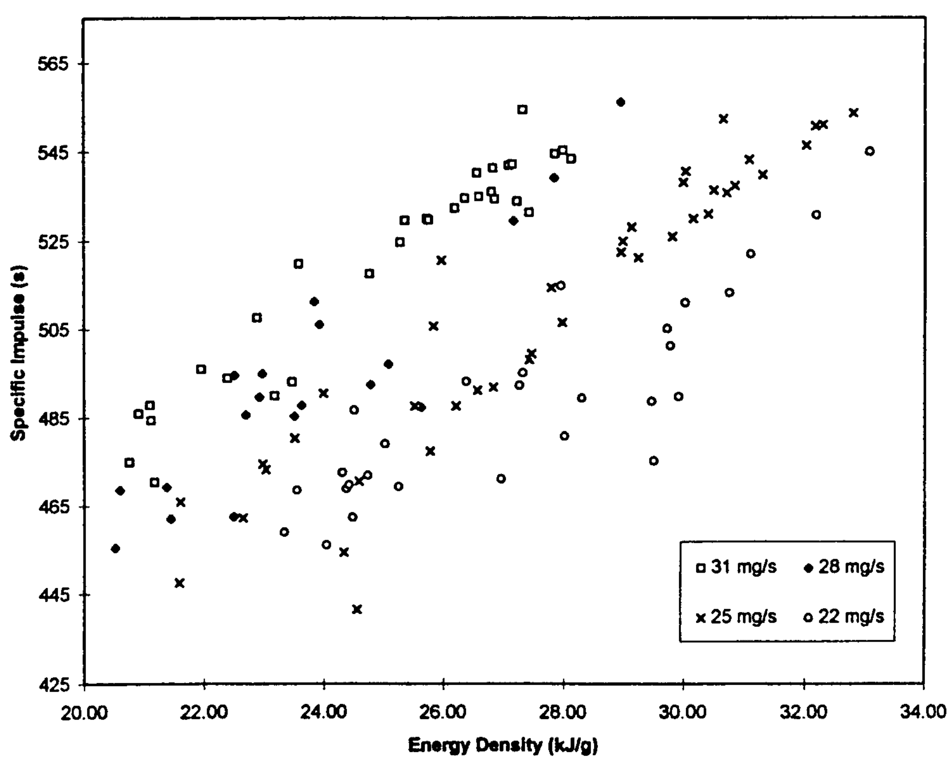


Figure 10. Variation in arcjet specific impulse as a function of propellant energy density. This figure shows the helium data of figure 9, expanded, and sorted according to helium mass flow rate.

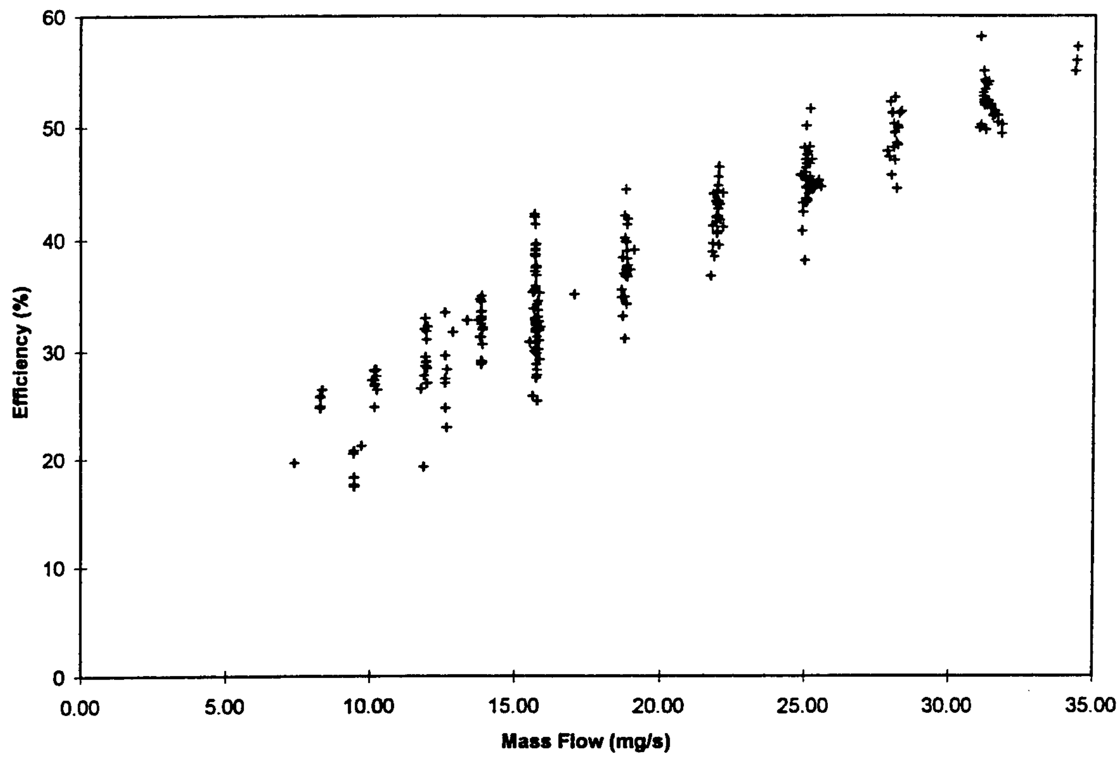


Figure 11. Arcjet efficiency as a function of propellant mass flow.

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Center for Microtechnology: Microelectromechanical systems (MEMS) for space applications; assessment of microtechnology space applications; laser micromachining; laser-surface physical and chemical interactions; micropropulsion; micro- and nanosatellite mission analysis; intelligent microinstruments for monitoring space and launch system environments.

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