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HYDROGEN ARCJET TECHNOLOGY

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ABSTRACT

During the 1960's a substantial research effort was centered on the development of arcjets for space propulsion applications. The majority of the work was at the 30 kW power level with some work at 1-2 kW. At the end of the research effort, the hydrogen arcjet had demonstrated over 700 hours of life in a continuous endurance test at 30 kW, at a specific impulse over 1000 s, and at an efficiency of 0.41. Another high power arcjet design demonstrated 500 h life with an efficiency of over 0.50 at the same specific impulse and power levels. At lower power levels, a life of 150 hours was demonstrated at 2 kW with an efficiency of 0.31 and a specific impulse of 935 s. Lack of a space power source hindered arcjet acceptance and research ceased. Over three decades after the first research effort began, renewed interest exists for hydrogen arcjets. The new approach includes concurrent development of the power processing technology with the arcjet thruster. Performance data have recently been obtained over a power range of 0.3-30 kW. The 2 kW performance has been repeated; however, the present high power performance is lower than that obtained in the 1960's at 30 kW, and lifetimes of present thrusters have not yet been demonstrated. Laboratory power processing units have been developed and operated with hydrogen arcjets for the 0.1 kW to 5 kW power range. A 10 kW power processing unit is under development and has been operated at design power into a resistive load.

INTRODUCTION

Conceptually, the operation of an arcjet is very simple. Propellant is heated directly by an electric arc and expanded through a supersonic nozzle to convert the increased thermal energy to directed kinetic energy and produce thrust. The propellant can be heated to temperatures greatly exceeding material limits and provide specific impulse levels much greater than resistojets and chemical rockets, whose propellant enthalphy levels are limited by the maximum material temperature and by energy evolved through chemical reaction, respectively. Although arcjets are simple in concept, the engineering and physics issues involved are complex. The temperature gradients due to arc heating are several thousand degrees over the space of a few millimeters. Containment of the hot gas and electrode erosion create problems in the area of high temperature materials. Losses due to dissociation, ionization, and viscosity are large and have challenged modeling efforts. Because of the complexity of the physics occuring in the device, much of the progress in arcjet technology has been achieved through parametric design and experimentation.

The first major research effort in arcjets began in the late 1950's and lasted until the the mid-1960's. A comprehensive overview of arcjet development in the early 1960's was provided by Wallner and Czika.[1] During that time period a great deal of effort was expended in evaluating various propellants for electrothermal propulsion and in using an alternating current arcjet. Discussions on those efforts are not included herein. Emphasis was on the development of a radiative/regeneratively-cooled 30 kW hydrogen engine for primary propulsion missions. Hydrogen has the ability to provide specific impulse levels exceeding 1000 s at acceptable operating temperatures. The drawback to the use of hydrogen was the lack of cryogenic storage technology.

By the mid-1960's the performance of the hydrogen arcjet at the 30 kW level had reached impressive levels. The Avco corporation demonstrated a lifetime of 723 h and a specific impulse level of 1010 s at an efficiency of 0.41.[2] Using a thruster with a fundamentally different anode/nozzle design, the Giannini Scientific Corporation (GSC) achieved a specific impulse of 1000 s at an efficiency of 0.55 with a demonstrated lifetime of 500 h.[3] Both tests were voluntarily terminated. At the 30 kW power

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level the technology appeared mature enough to enable lifetimes over 1000 h. The proposed power source for a high power hydrogen arcjet was to be the SNAP-8 nuclear reactor, the design weight of which had increased greatly over the course of the program. Once the SNAP-8 program was cancelled, the lack of a space power source hindered the application of high power arcjets.

Low power arcjets were also evaluated in the 1960's for station-keeping missions. The Plasmadyne Corporation had a development effort underway at both the 1 and 2 kW levels. Due to the small geometries in the 1 kW design, nozzle erosion was life-limiting.[4] Lifetimes were improved at the 2 kW power level. In a voluntarily terminated 150 h lifetest the average performance was 935 s specific impulse at an efficiency of 0.307.[5]

Interest has recently been renewed in high specific impulse hydrogen arcjets. Mission studies are underway to investigate the potential of a 10 kW hydrogen arcjet for an orbit transfer vehicle, and a program jointly sponsored by SDIO/IST and NASA/OAET has obtained performance measurements between 5 and 30 kW[6] on a laboratory model high power hydrogen arcjet. Presently, the program is investigating areas of potential performance enhancement and life-limiting issues. Performance of 1-4 kW arcjets has recently been reported,[7] and initial performance of very low power hydrogen arcjets for lightsat applications are reported herein. In parallel with the thruster development, a 10 kW power processing unit (PPU) is under development and has demonstrated an efficiency of 0.92 with a resistive load. At the lower power levels, 5 kW[8] and 0.4 kW[9] PPU's have been run with laboratory model arcjets as loads. This paper presents a compilation of past and present information on hydrogen arcjet and PPU designs and performance.

THRUSTER TECHNOLOGY

Experience with hydrogen arcjets has been limited to the laboratory. Over the past thirty years data have been obtained over power levels from below 0.2 kW to over 200 kW. The majority of experience was at 30 kW and at 1-2 kW. Several water-cooled thrusters were built over that time period. Because the performance of these devices were much different from radiation-cooled designs and the integration of a device which requires active cooling into a flight system adds enormous complexity, efforts on such devices are not presented in this paper.

The overall efficiency of the arcjet is defined as the thrust power divided by the input power. The input power includes the electrical power and the energy the propellant contains prior to injection into the engine. Much of the early data used only the input electrical power as the denominator for overall efficiency calculations. This results in efficiency values approximately one percent higher than if the incoming gas power were included. In order to enable direct comparisons between the performance data for different engines, all efficiency values reported herein were computed by dividing the thrust power by the input electrical power.

The performance data provided herein are taken from the original sources. The number of significant figures used in the data tables may not seem appropriate, but are consistent with the original sources. In some cases, the data are internally inconsistent. This is probably due to a lack of attention to the uncertainties in the data.

Geometric data presented in this paper do not include information on the arc gap. Several definitions exist in the literature, including the minimum electrode distance and the distance the cathode is withdrawn after making contact with the anode. The original reference should be consulted for the electrode geometry.

Excluding the nozzle geometry, all the successful designs are basically the same. The anode and nozzle are integral and are composed of pure tungsten or a tungsten alloy. All the cathodes are conically tipped and are also composed of tungsten. The electrodes are isolated from the cathode using a high temperature insulator, commonly boron nitride. All the designs employ tangential gas injection for arc stabilization. A major technology issue has been high temperature sealing techniques. These have ranged from design to design but include metal compression seals, graphite foil, electron beam welding, and high temperature brazing. In an attempt to recover energy lost to the anode, a few designs have employed regenerative heat transfer techniques.

30 kW And Above

The largest development effort involving high power arcjets was a three year program sponsored by NASA and conducted by the Research and Advanced Development Division of Avco

Corporation. The goal of the program was to develop a 30 kW arcjet with a minimum thrust level of 2.2 N and a system specific impulse range of 1000 s to 1500 s for 1400 h of continuous operation. The engine was to be capable of operating in parallel with a second engine to produce a total thrust level of 4.4 N. The research effort was to lead to application of the engine for final stage propulsion of a spacecraft initially in low Earth orbit. The performance goals of the first year effort matched the overall program goals, but the expected life was decreased to 50 h of continuous operation. The propellant specified was hydrogen or a compound containing hydrogen.

The major accomplishment of the first year effort,[10] which began in 1960, was the R-1 engine. When operated on hydrogen at the 2.2 N thrust level, the arcjet gave specific impulse values of 700 s to 1400 s and overall energy conversion efficiencies between 0.35 and 0.45 and easily met the life criterion of 50 h of continuous operation. Building on the success of the first year, the second year effort concentrated on increasing the specific impulse and lifetime.[2] The result was the fabrication and testing of three new engines designated R-2, R-3, and R-4 Mod 1. Engines R-1 through R-3 differed only by the internal geometry of the constrictor and nozzle. All of the Avco thrusters utilized a constricted arc design in which the anode attachment was in the supersonic portion of the nozzle. Figure 1 shows a typical nozzle geometry, Figure 2 provides a schematic of the R-1 thruster, and Table I presents the various geometries tested. The fourth engine, R-4 Mod 1, employed regenerative-cooling passages in the nozzle which where designed to recover some of the anode losses and to cool assembly joints subjected to high thermal flux. A schematic of the R-4 Mod 1 arcjet is presented in Figure 3. The performance of the three engines on hydrogen is summarized in Table II. Two endurance tests at specific impulse levels of 1300 s and 1500 s were performed on the R-2 engine. The 1300 s test was terminated due to failure of a braze joint of the engine after 110 h and the 1500 s test was terminated after 10 h due to a power surge resulting from a municipal power-supply fluctuation. Both failure modes resulted in severe anode degradation. The R-3 engine was operated on ammonia solely and will not be discussed herein. The R-4 Mod 1 engine successfully completed a 723 h endurance test with two restarts which was voluntarily terminated in the spring of 1963. The arcjet achieved a specific impulse of 1010 s at an efficiency of 0.407. The third year effort consisted of modification of the R-4 Mod 1 design. Two additional thrusters designed for operation at 1300 s and 1500 s were fabricated and designated R-4 Mod 2 and R-4 Mod 3, respectively. The geometries of the three engines are presented in Table I and their performances in Table II. The R-4 Mod 2 thruster was operated for 250 h with one restart at a specific impulse of 1320 s and an efficiency of 0.446. The 1500 s endurance test with the R-4 Mod 3 design encountered significant problems due to the test facility and lasted only 120 h with four restarts and had an average thruster efficiency of 0.432.

In order to design a high specific impulse radiation-cooled engine the 30 kW power limitation was lifted in the third year of the program.[11] A hydrogen arcjet designated X-1 was fabricated and operated at power levels ranging from 150 kW to 216 kW. The thruster geometric and performance data are presented in Tables III and IV, respectively. The thruster provided specific impulses between 1600 and 2210 s and efficiencies near 0.35 over that range.

A separate development program sponsored by the Air Force sought to develop a 30 kW arcjet engine for space propulsion. The work was done by GSC, and by the end of 1963 resulted in the design and performance testing of both radiation-cooled and regeneratively-cooled 30 kW hydrogen arcjets.[3] The geometries of the two thrusters are given in Table V. The program goal was a 30 kW arcjet with a specific impulse level of 1000 s and an overall efficiency of 0.55. The GSC design was fundamentally different, and used an anode/nozzle which was chambered. A schematic of the anode is shown in Figure 4. The radiation-cooled thruster successfully completed a 100 h endurance test at a specific impulse of 1000 s and an efficiency of 0.43. The regeneratively-cooled thruster was similar to the radiation-cooled thruster but included a heat shield which was cooled by the incoming hydrogen. A schematic of the thruster is shown in Figure 5. The regenerative thruster was run for 500 h at 1000 s and gave an end-of-test efficiency of 0.551. Both thrusters were also run at high specific impulse points and the results are presented in Figures 6a and 6b. The performance of the GSC arcjet is unique and has to this date not been matched by another design at the 1000 s specific impulse performance level.

During 1965 the McDonnell Aircraft Corporation (MAC) completed performance tests of the GSC-2 thruster.[12] A total of 15 redundant thrust measurements were taken on the MAC thrust stand at a power level of 30 kW and a hydrogen flow rate of 0.334 g/s. The average thrust value was 3.15 N with an average deviation of 0.018 N. The results compared very favorably with data taken at GSC. A comparison of the MAC and GSC data is shown in Table VI.

Under the same NASA sponsored contract, MAC also tested a thruster supplied by NASA LeRC, designated NAS-1, and a thruster designed and fabricated by MAC, designated MAC-2.[12] Both thrusters were of the constricted arc design used by Avco. The geometries are given in Table VII. At the 30 kW operating point the efficiencies were around 0.22 over a specific impulse range of 740 s to 920 s for the NAS-1 thruster. The performance of the MAC-2 arcjet was even poorer. At the same power level, it had a maximum efficiency of 0.21 and the specific impulse ranged between 710 s and 850 s. Additional performance data for the two thrusters at the 30 kW power level are given in Figures 6a and 6b.

With the renewed interest in high power hydrogen arcjets for orbit raising missions a program jointly sponsored by the Innovative Science and Technology Office of the Strategic Defense Initiative Organization (SDIO/IST) and NASA/OAET was initiated. A high power hydrogen arcjet was designed and three nozzle configurations were tested in 1991.[6] The thruster design relied heavily on the work done in support of a low power hydrazine arcjet and was basically scaled up from that design. A schematic of the thruster is given in Figure 7 and the three nozzle geometries are given in Table VIII. The best performance was obtained with Nozzle B and the data are reported in Table IX. At 30 kW the efficiency decreased slightly with specific impulse but was essentially constant at 0.31 over the specific impulse range of 1158-1460 s.

Figures 6a and 6b compare the performance of the Avco R-series thrusters, the GSC radiation and regeneratively-cooled engines, the NAS-1 and MAC-2 thrusters tested at MAC, and the recent NASA LeRC data. At first glance the data seem to fall into two groups and the performance of the NAS-1 and MAC-2 thrusters appears far inferior to the others. Except for the nozzle divergence angle, the geometry of the NAS-1 thruster is very similar to the Avco R-1, and Ref. 6 has shown divergence angles shallower than 20° provide no performance advantage. Also, according to Ref. 12, the MAC-2 radiation-cooled engine gave slightly lower performance than its geometrically identical water-cooled counterpart. There is no physical reason this should occur, and it has not been reported elsewhere in the literature. The problem with the NAS-1 and MAC-2 performance data may lie in the existence of leaks occuring once the thrusters were heated. Such leaks were documented as a troublesome problem for both thrusters.[12]

Another issue of great importance is the effect of the test facility on thruster performance.[7,13] It has been documented that the ambient background pressure in the facility can adversely affect arcjet performance. The data taken at NASA LeRC do not include a pressure correction. For the high power arcjet, the facility pressures were 10-40 Pa and including a simple pressure/area correction increases the efficiency only by about one percent. The Avco R-1 data do appear to have a pressure correction, and, from Ref. 10, when the correction is removed the measured data yield an efficiency and specific impulse of 0.36 and 940 s respectively, instead of the 0.42 and 1000 s reported. It is not clear whether the data for the other R-Series engines include a pressure correction. When MAC tested the GSC regeneratively-cooled thruster, a correction factor was applied to the thrust to account for incomplete expansion of the exhaust. From Ref. 12 it appears that the performance data reported by GSC include a pressure correction; although, none are mentioned in the Giannini reports. Neglecting the pressure correction decreases the efficiency obtained by GSC by only two percent from 52.6 to 50.8 and the specific impulse from 996 s to 978 s. Because of the lower operating pressure of 29 Pa, the effects of pressure corrections on the MAC data would be smaller than those shown above. Performance of the GSC thruster was also measured at NASA LeRC during the early 1960's and the GSC results were confirmed.[14] From the independent testing it appears that the GSC thruster performance has been validated.

5 to 29 kW

The application currently proposed for hydrogen arcjets is a solar powered electric orbit transfer vehicle. The power level being considered is nominally 10 kW. Since the power level for the majority of the high power arcjet programs was set at 30 kW, very little data were reported at lower power levels. For the early arcjet work no thruster was designed for operating points below 30 kW or above 2 kW. The only performance data available were obtained by throttling down engines designed for 30 kW. No data are given for the Avco R-Series thrusters at lower power levels in the final contract reports. The Giannini thrusters were throttled down to the mid-20 kW range but data are scarce. The data which are available are given in Figure 8. MAC tested the NAS-1 and the MAC-2 thrusters down to 20 kW; however, the validity of the data are suspect for reasons mentioned earlier.

The NASA LeRC thruster has been throttled between 5 and 30 kW for the three nozzles described above. The data reported by Haag and Curran are the only data available for the power range of 5-20 kW.[6] The data for the arcjet with the Nozzle B geometry are given in Table IX, and plots of the voltage-current characteristics, efficiency versus specific impulse, and specific impulse versus specific energy are given in Figures 9a, 9b, and 9c, respectively. It is important to note that lifetimes at the stated performance points have not yet been demonstrated. Endurance tests are currently under way but early results show cathode deformation to be an issue. After only 28 h at 10 kW the thruster developed a lacy deposition of tungsten along the rim which caused severe voltage fluctuations. Initial results indicate that erosion can be decreased with increased current ripple, and tests are underway to fully understand the controlling phenomena.

The high performance of the 30 kW Giannini regenerative arcjet thruster has sparked interest in using a similar design at the 10 kW level. In a SDIO/IST sponsored program Rocket Research Company, under contract to Texas Tech University, is designing a Giannini-type hydrogen arcjet to be operated at 10 kW.

1 to 4 kW

During the early 1960's, a large effort was also expended in the development of a hydrogen arcjet at the 1 kW level for an attitude control and station-keeping system on a 250 kg synchronous communications satellite. Under NASA sponsorship a 1 kw hydrogen arcjet system was developed by the Plasmadyne Corporation for the Space Electric Rocket Test (SERT) program.[4] In 1962 the system was tested at NASA LeRC. The flight time for the SERT mission allowed for one firing of 24 minute duration. Engine efficiencies were measured between 0.1 and 0.3, and specific impulse levels were between 600 s and 1400 s; however, the reliability of the thrust measurements were poor due to thrust stand vibrations. The geometry of the thruster is given in Table X. Long lifetimes were never demonstrated and the starting technique caused nozzle damage. Because of the erosion problems associated with the small dimensions encountered in the 1 kW thruster, the power level was raised to 2 kW and the dimensions increased with the hope of increased life. During 1963 the Plasmadyne Corp. successfully completed a 150 h endurance test at 2 kW on hydrogen.[5] The thruster had an average performance over the test of 935 s specific impulse at an efficiency of 0.307. No facility pressure corrections were applied to the data. A schematic of the thruster is given in Figure 10, and the geometry of the thruster is given in Table XI.

Performance data have recently been taken by Curran, et. al.[7] for six different nozzle geometries at 1 to 4 kW on hydrogen. A schematic of the thruster is provided in Figure 11. The design is very similar to the 1-2 kW NASA LeRC hydrazine thruster. The nozzle geometries are given in Table XII. The constrictor lengths were all approximately 0.025 cm. Nozzle expansion half angles of 20°, 15°, and 10° were tested. The specific impulse ranged between 650 and 1250 s at efficiencies between 0.3 and 0.4. A degradation in performance was noted for the 10° nozzle. The performance of the NASA LeRC thruster with nozzle insert 1 was slightly better than attained with the Plasmadyne thruster in 1963. This can be partially attributed to a lower facility background pressure at which the NASA LeRC data were obtained. A comparison of the Plasmadyne and NASA LeRC 2 kW data are provided in Table XIII.

Less Than 0.5 kW

In order to satisfy propulsive requirements for small, power-limited satellites a program is under way at NASA LeRC to obtain performance data at power levels of a few hundred watts with both hydrogen and nitrogen/hydrogen mixtures (to simulate hydrazine decomposition products). Some of the hydrogen data are discussed herein. The thruster is scaled from the kilowatt-class hydrazine arcjet and is similar to the design shown in Figure 11. The nozzle geometry is presented in Table XIV and the performance data are given in Table XV. All performance data were taken at facility pressures below 0.07 Pa and at a power level of approximately 0.3 kW. Figure 12a is a plot of the voltage-current characteristics, and figures 12b and 12c present the efficiency versus specific impulse and the specific impulse versus specific energy, respectively. At 0.3 kW, efficiency was approximately 0.3 with the specific impulse ranging between 573 s to 653 s. The specific energy levels are low for hydrogen; however, this is due to stability problems encountered at low power levels. Currently, research is being conducted to increase the stability limits.

POWER PROCESSING TECHNOLOGY

The function of the power processing unit (PPU) in the hydrogen arcjet system is to modify the electrical power present on the spacecraft to the voltage and current levels necessary to operate an arcjet. In doing so, the power processor must also start the arcjet reliably in a non-destructive fashion and operate the engine stably after ignition. Design of the PPU is impossible without proper characterization of the interfaces associated with the arcjet system. This section reviews the requirements of the applicable interfaces for an arcjet system, presents a brief history of PPU development, and outlines the present state of the art and future work in laboratory and flight power processors for arcjets.

Power Bus/PPU Interface

Power bus specifications and interface requirements vary with spacecraft. Important considerations include load isolation, upper and lower bus voltage limits, and electromagnetic compatibility requirements. This is by no means a complete list; however, these issues significantly impact the design of the PPU. If the individual loads must be isolated from the power bus, a topology employing an isolation transformer must be used. Applicable topologies include the parallel and full bridge converters, illustrated in Figure 13. These topologies have a history in flight and laboratory PPUs in the 0.25-5 kW power range.[8,9,15,16] The isolated topologies, though allowing flexibility in load configuration and grounding, introduce an increase in overall PPU mass and a decrease in power efficiency due to the physical characteristics and losses associated with the power transformer. In instances where isolation is not required, other topologies such as the buck converter illustrated in Figure 14, may be employed. A three-phase 30 kW buck topology was implemented for such an application in 1990.[17] Higher efficiency and lower overall mass was achieved with this design due to the lighter and more efficient magnetic circuits employed.

Electromagnetic compatibility specifications used by most spacecraft are outlined in MIL-STD-461. Conformance to these specifications generally requires the installation of an input filter to the PPU. Design of these filters is non-trivial, and the losses associated with the passive elements can reduce PPU efficiency by as much as one percent. In addition to the reduction in efficiency, these filter components add to the overall mass of the unit. Also, the impact of the filter on the transient response of the PPU must be considered, especially during the starting transient.

Arcjet/PPU Interface

The Arcjet/PPU interface is perhaps the most critical system interface and also the least understood. Characterization of this interface involves the study of starting requirements and the transitional and steady state operating modes of the arcjet itself. Interconnecting cable impedances also influence the starting and transitional modes and cannot be ignored for proper analysis. Several starting techniques have been employed in the past including electrode contact, Paschen breakdown at reduced propellant feed rates, high voltage DC, and pulse ignition.[3,4,6,18] These methods, though successful in starting the arcjet, are not all well suited for incorporation into flight systems. Additionally, some of the methods can cause severe electrode damage and can be unreliable. To properly define starting requirements for hydrogen arcjets, the method selected must be tested sufficiently to ensure that reliable non-destructive starts occur. Over 10,000 starts were demonstrated on nitrogen/hydrogen mixtures to validate the pulse ignition technique at the 1 kW power level.[18] No such test has been performed on hydrogen to date.

The transition to steady state operation from initial breakdown must also be controlled to minimize damage to the thruster electrodes. In general, the initial breakdown occurs upstream of the constrictor, in a high pressure region. This is known as low mode operation and is also characterized by a spot attachment of the arc to the anode. The arc is then blown downstream to the diverging section of the nozzle and attaches diffusely. If the arc current is not controlled during this phase a substantial current overshoot can occur, and anode damage is likely.[19] In higher power arcjets, where throttling may be necessary, the time rate change of power during the transition between power levels represents another transient which must be characterized.

The static impedance of the arcjet has a negative slope characteristic, that is, arc voltage decreases with increasing arc current. Power supply output characteristics for stable operation into these types of loads are summarized elsewhere.[15] In general, the two modes commonly used are constant current or constant power control. In either case, the PPU output characteristic is that of a high impedance current source. Regulation specifications for steady state operation for all PPUs referenced are less than one percent. Output ripple specifications are also important in that a low output ripple specification will increase the mass of the output filter. Fortunately, output ripple of 10-20% has been shown to have no measurable effect on arcjet performance.[20] In addition, higher power arcjets have exhibited accelerated electrode erosion rates with low ripple currents.[21] The relaxation of ripple specifications leads to lighter output filters, but the increased frequency content of the output current may lead to electromagnetic compatibility problems.

Spacecraft/PPU Interface

Also of great importance from an overall system standpoint are the mechanical interface requirements. These include the thermal and mass constraints on the PPU. The thermal specifications limit the amount of waste heat the spacecraft can accept from the PPU. This places a premium on PPU efficiency, and usually, the efficiency requirement for PPUs is greater than 0.9. Efficiencies for non-isolated topologies are generally higher than those of the isolated type. For example, the efficiencies of the isolated designs of Refs. 8,9, and 15 are on the order of 0.92 to 0.93, and the three phase buck regulator has demonstrated an efficiency of 0.95.[17]

The specific mass of the PPU, that is the ratio of mass to output power impacts the overall system mass and must be included during comparisons of electric and chemical propulsion systems. As previously mentioned, the non-isolated topologies are significantly lighter than isolated units due to the simpler magnetics associated with these topologies. A specific mass of 1.8 kg/kW has been demonstrated in the breadboard PPU of Ref. 17. A flight qualified unit of similar design would have a slightly higher specific mass due to the inclusion of EMI filters and the enclosure. The flight unit of Ref. 16, which is an isolated design, has a specific mass of 2.4 kg/kw. Some of the disparity between these two numbers is attributable to the difference in the power levels between the two units, but in general, the non-isolated PPUs will be less massive.

HISTORICAL BACKGROUND

In the 1960's, most of the research conducted was for primary propulsion applications at power levels exceeding 10 kW. Laboratory 60 Hz input power supplies with ballast resistors were used to power the engines. A smaller 1 kW hydrogen arcjet was developed for attitude and orbit control, and was to be incorporated on the SERT spacecraft. Its removal from the experiment occurred prior to the development of power electronics.[4] Ground testing with this thruster continued using 60 Hz input power supplies.

During the 1980's the renewed interest in low power hydrazine arcjets led to extensive research in power electronics. A lightweight, efficient 1 kW prototype PPU was developed by Gruber in 1986.[15] This unit employed the push-pull topology shown in Figure 13. A high voltage pulse of approximately 3-4 kV amplitude and 20 μs duration is used to breakdown the propellant gas into an arc. This technique is described in detail by Sarmiento and Gruber.[18] This starting technique was extensively tested and found to be reliable and non-damaging.[18,19] The open circuit output voltage of the PPU was 150 V, with an output current ripple of 15-25%. Output current was regulated to less than one percent of a setpoint, which was typically on the order of 10 A, resulting in an arc voltage of 100 to 120 V. Power conversion efficiency was 0.92.

A flight type PPU was developed based on the topology described above as part of a 1.8 kW hydrazine arcjet system for stationkeeping applications.[16] The overall dimensions of the PPU are 23.5 cm x 18.4 cm x 8.3 cm, with an overall mass of 4.3 kg and a specific mass of 2.4 kg/kW. The efficiency of this unit is reported as greater than 0.9. The PPU is currently in a flight qualification phase. Interface tests emphasizing electromagnetic compatibility have been completed with the qualification model FLTSATCOM satellite in a space simulation chamber. The test results indicated no compatibility issues between the arcjet system and the satellite in the frequency spectrum of operational avionics and communications systems.[22]

In anticipation of the increased power capacity of next-generation communication satellites, a prototype 5 kW PPU for hydrazine arcjets was demonstrated by Gruber in 1989.[8] A full bridge topology was selected as the power stage, but the output filter and starting circuit were identical to the lower power unit. This PPU was successfully integrated to a laboratory 5 kW hydrazine arcjet. It was found that the starting requirements for the 5 kW unit were not significantly different than those of the lower power thrusters. Output characteristics were similar to those of the 1 kW unit, but the arc current was typically 45 to 50 A. This basic topology was also applied to very low power (<1 kW) PPUs by Hamley in 1991 for lightsat applications.[8] The efficiency of these units was improved to 0.93 with the addition of low inductance power stage layout. All of the prototype units have also been successfully integrated with hydrogen arcjets.

In response to the need for a primary propulsion role, 30 kW power electronics were developed for ammonia arcjets by Wong et al.[17] A three-phase buck regulator topology was selected, since isolation was not required for the specific application. This unit exists in an unpackaged, prototype unit, and has demonstrated a power conversion efficiency on the order of 0.95 and a specific mass on the order of 1.8 kg/kW. Addition of necessary EMI filtering, incorporation of space qualified semiconductors, and packaging will degrade this somewhat, but the projected specific mass is still below 2 kg/kW. Arcjet starting is accomplished by shorting the output of the PPU and charging the current averaging inductor. The shorting switch is then open and a high voltage (HV) pulse is generated. The pulse is on the order of 2 kV in amplitude and 500 ns in duration. Starts have been demonstrated with ammonia; however, results with hydrogen have been inconsistent.

The future application of hydrogen arcjets will be primary propulsion for orbit raising. At this time, 10 kW power electronics are under development at NASA LeRC.[23] A full bridge topology was selected, based on past experience with this topology.[8,9] Arcjet starting will be accomplished with the pulse ignition technique described by Sarmiento.[18] The PPU has successfully operated at power levels in excess of 11 kW, and arcjet integration tests are scheduled.

CONCLUDING REMARKS

Previous hydrogen arcjet efforts were centered on the 30 kW power level, with some development work done at 1-2 kW. By the mid 1960's lifetimes of over 500 h and 700 h were demonstrated with efficiencies of over 0.5 and 0.4, respectively, at a specific impulse of 1000 s. At the lower power levels, a 2 kW arcjet completed a 150 h endurance test and had an efficiency of 0.31 and a specific impulse of 935 s. Very little work was done on power processing at that time and the lack of a high power, space power source ended the arcjet programs.

Currently hydrogen arcjets are being studied for orbit transfer vehicles with a proposed nominal power level of 10 kW. In support of that activity, performance data have been taken at power levels ranging from 1-4 kW and 5-30 kW using scaled versions of a laboratory hydrazine arcjet. Some of the performance values reported in the 1960's at high power levels have not been repeated with current technology. On the other hand, performance at low powers has been duplicated with current designs. Lifetimes for the present designs have not yet been proven, but endurance tests are underway. In support of lightsat propulsion requirements performance data have been taken at 0.3 kW. Power processors designed for use with hydrazine arcjets in the power ranges of 0.1-5 kW have been operated with hydrogen arcjets as the load. A 10 kW power processing unit is under development and has been run at design power levels into a resistive load.

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Table I. Geometry of AVCO RAD R-series 30 kW hydrogen arcjets [2,10,11]

	R-1	R-2	R-4 Mod 1	R-4 Mod 2	R-4 Mod 3
Constrictor length (cm)	0.762	0.762	0.889	0.804	0.610
Constrictor diameter (cm)	0.381	0.318	0.444	0.356	0.305
Length to diameter ratio	2	2.4	2	2.26	2
Nozzle exit diameter (cm)	1.22	1.0	1.15	1.075	1.065
Nozzle area ratio	10	10	6.7	9.2	12.2
Nozzle half angle (deg)	7	7	7	7	7

Table II. Performance of Avco RAD R-Series 30 kW hydrogen arcjets [2,10,11]

	R-1	R-2 Test A	R-2 Test B	R-4 Mod 1	R-4 Mod 2	R-4 Mod 3
Test length, h	50	110	10	723	250	120
Thrust, N	2.45	1.79	1.48	2.47	2.07	1.77
Mass flow rate, g/s	0.25	0.14	0.10	0.25	0.16	0.12
Specific impulse, s	1000	1300	1510	1010	1320	1500
Efficiency	0.42	0.377	0.367	0.407	0.446	0.432
Voltage, V	180	170	131	200	198	170
Current, A	170	175	229	150	151	177
Power, kW	30	30	30	30	30	30
Specific energy, MJ/kg	120	214	300	120	188	250

Table III Geometry of Avco RAD X-1 hydrogen arcjet [11]

Constrictor length, cm	1.27
Constrictor diameter, cm	0.602
Length to diameter ratio	2.11
Nozzle exit diameter, cm	2.61
Nozzle area ratio	19
Nozzle half angle, deg	10

Table IV. Performance of Avco RAD X-1 hydrogen arcjet [11]

Voltage	Current	Power	Mass flow rate	Thrust	Specific Impulse	Efficiency	Specific energy
V	A	kW	g/s	N	s		MJ/kg
162	928	150	0.143	6.47	1600	0.337	1050
163	928	151	0.396	6.38	1640	0.339	381
163	928	151	0.376	6.28	1702	0.346	402
162	948	153	0.347	6.23	1830	0.364	441
159	964	153	0.327	6.18	1925	0.381	468
160	1080	173	0.327	6.47	2080	0.370	529
161	1232	198	0.327	6.80	2120	0.356	606
160	1350	216	0.327	7.10	2210	0.356	661

Table V. Geometry of GSC regeneratively-cooled
30 kW hydrogen arcjet [14]

Arc chamber diameter (inlet), cm	0.635
Arc chamber diameter (max), cm	0.793
Arc chamber length (nominal),cm	2.86
Nozzle throat diameter, cm	0.475
Nozzle area ratio	60
Nozzle half angle, deg	15

Table VI. Comparison of McDonnell and Giannini performance data on
GSC-2 hydrogen arcjet [12]

Tested by	Power input kW	Flow rate g/s	Tank Pressure Pa	Pressure correction N	Measured thrust N	Corrected thrust N	Specific impulse s	Efficiency
MAC	0	0.334	28	0.022	0.881	0.903		
MAC	30.0	0.334	28	0.022	3.15	3.17	970	0.503
GSC	0	0.331	120	0.089	0.801	0.890		
GSC	30.0	0.331	87	0.058	3.18	3.24	996	0.526

Table VII. Geometries of NAS-1 and MAC-2 arcjets [12]

	NAS-1	MAC-2
Constrictor length, cm	0.762	1.27
Constrictor diameter, cm	0.381	0.635
Length to diameter ratio	2	2
Nozzle exit diameter, cm	3.81	3.81
Nozzle area ratio	100	36
Nozzle half angle, deg	15	15

Table VIII. NASA LeRC high power hydrogen arcjet nozzle geometries [6]

	Nozzle A	Nozzle B	Nozzle C
Constrictor length, cm	0.508	0.356	0.071
Constrictor diameter, cm	0.254	0.178	0.254
Length to diameter ratio	2.0	2.0	0.28
Nozzle exit diameter, cm	2.43	2.90	2.43
Nozzle area ratio	91.5	265	91.5
Nozzle half angle, deg	20	20	10

Table IX. Performance at 30 kW of NASA LeRC arcjet with Nozzle B [6]

Voltage	Current	Power	Mass flow rate	Thrust	Specific Impulse	Efficiency	Specific energy
V	A	kW	g/s	N	s		MJ/kg
0	0	0	0.0915	0.255	250		0
120.4	38.0	4.58	0.0309	0.286	944	0.290	148
135.6	49.7	6.74	0.0452	0.450	1015	0.332	149
134.1	67.3	9.02	0.0452	0.496	1118	0.301	200
121.1	93.2	11.30	0.0452	0.533	1203	0.279	250
145.3	62.5	9.08	0.0609	0.613	1027	0.340	149
144.9	84.0	12.20	0.0609	0.689	1154	0.320	200
141.9	107.4	15.24	0.0609	0.754	1264	0.307	250
142.4	107.3	15.30	0.0609	0.748	1253	0.301	251
139.9	130.4	18.24	0.0609	0.804	1347	0.292	300
152.0	75.6	11.50	0.0762	0.770	1030	0.338	151
150.9	101.0	15.20	0.0762	0.883	1181	0.336	200
150.4	126.5	19.03	0.0762	0.965	1291	0.321	250
150.5	126.9	19.10	0.0762	0.967	1294	0.321	251
149.0	153.6	22.90	0.0762	1.025	1371	0.301	300
147.8	175.4	25.92	0.0762	1.081	1446	0.296	340
160.4	85.3	13.68	0.0915	0.938	1045	0.352	149
159.7	114.8	18.30	0.0915	1.064	1185	0.338	200
158.7	144.1	22.90	0.0915	1.170	1303	0.326	250
153.5	149.0	22.87	0.0915	1.152	1283	0.317	250
155.0	177.4	27.50	0.0915	1.252	1395	0.312	300
154.5	177.9	27.49	0.0915	1.250	1392	0.310	300
155.0	200.9	31.14	0.0915	1.310	1460	0.301	340
172.2	107.1	18.44	0.1228	1.238	1028	0.339	150
170.8	144.2	24.60	0.1228	1.405	1166	0.327	200
168.7	182.2	30.70	0.1228	1.545	1282	0.316	250
161.0	260.5	41.94	0.1228	1.761	1461	0.301	341
181.4	121.1	22.11	0.1474	1.478	1022	0.335	150
179.8	166.2	29.90	0.1480	1.682	1158	0.319	202

Table X. Geometry of Plasmadyne 1 kW arcjet [4]

Constrictor length, cm	0.025
Constrictor diameter, cm	0.023
Length to diameter ratio	1.1
Nozzle exit diameter, cm	0.127
Nozzle area ratio	31
Nozzle half angle, deg	30

Table XI. Geometry of Plasmadyne 2 kW hydrogen arcjet [5]

Constrictor length, cm	0.089
Constrictor diameter, cm	0.089
Length to diameter ratio	1
Nozzle exit diameter, cm	0.63
Nozzle area ratio	50
Nozzle half angle, deg	20

Table XII. Geometry of NASA LeRC 1-4 kW arcjet nozzles [7]

	Nozzle					
	1	2	3	4	5	6
Constrictor diameter (cm)	0.061	0.053	0.053	0.076	0.076	0.076
Nozzle area ratio	240	310	310	150	150	150
Nozzle half angle (deg)	20	15	10	20	15	10

Table XIII. Performance comparisons between NASA LeRC and Plasmadyne 2 kW hydrogen arcjets [5,7]

	LeRC Nozzle 1	LeRC Nozzle 1	Plasmadyne
Power, kW	1.91	2.00	2.00
Mass flow rate, g/s	0.0112	0.0161	0.0145
Thrust, N	0.111	0.154	0.134
Specific impulse, s	1010	973	935
Efficiency	0.287	0.367	0.307
Specific energy, MJ/kg	171	124	138

Table XIV. Geometry of the NASA LeRC very low power arcjet

Constrictor length, cm	0.005
Constrictor diameter, cm	0.030
Length to diameter ratio	0.17
Nozzle exit diameter, cm	0.907
Nozzle area ratio	915
Nozzle half angle, deg	20

Table XV. Performance of NASA LeRC very low power arcjet

Voltage	Current	Power	Mass flow rate	Thrust	Specific Impulse	Efficiency	Specific energy
V	A	kW	g/s	N	s		MJ/kg
96.0	3.5	0.336	0.00495	0.0317	653	0.302	67.9
97.5	3.5	0.341	0.00495	0.0317	653	0.298	69.0
100.7	3.25	0.327	0.00495	0.0314	647	0.305	66.1
100.4	3.25	0.326	0.00495	0.0313	645	0.304	65.9
103.1	3.0	0.309	0.00495	0.0305	629	0.305	62.5
125.1	2.0	0.250	0.00495	0.0291	599	0.342	50.6
104.0	3.25	0.338	0.00596	0.0366	626	0.332	56.7
105.9	3.0	0.318	0.00596	0.0360	616	0.342	53.3
110.5	2.75	0.304	0.00596	0.0356	610	0.351	51.0
116.0	2.5	0.290	0.00596	0.0350	600	0.356	48.7
92.5	3.0	0.278	0.00394	0.0222	573	0.224	70.4
96.2	3.0	0.289	0.00394	0.0232	599	0.235	73.2

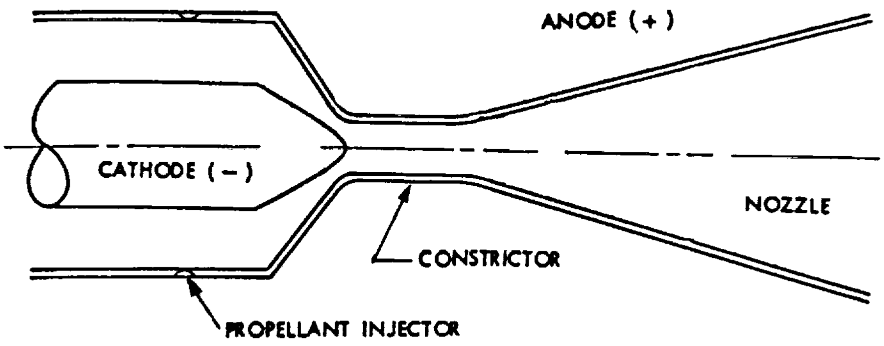

Figure 1. Avco electrode geometry [2]

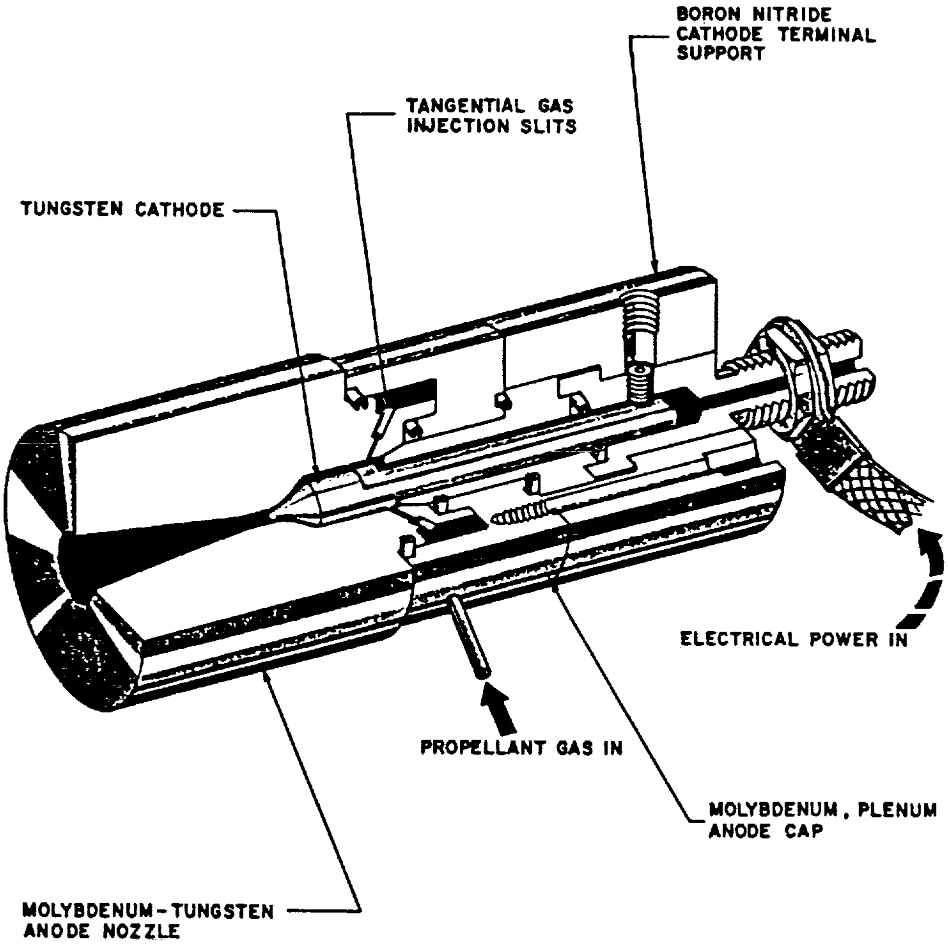

Figure 2. Avco R-1 30 kW hydrogen arcjet [10]

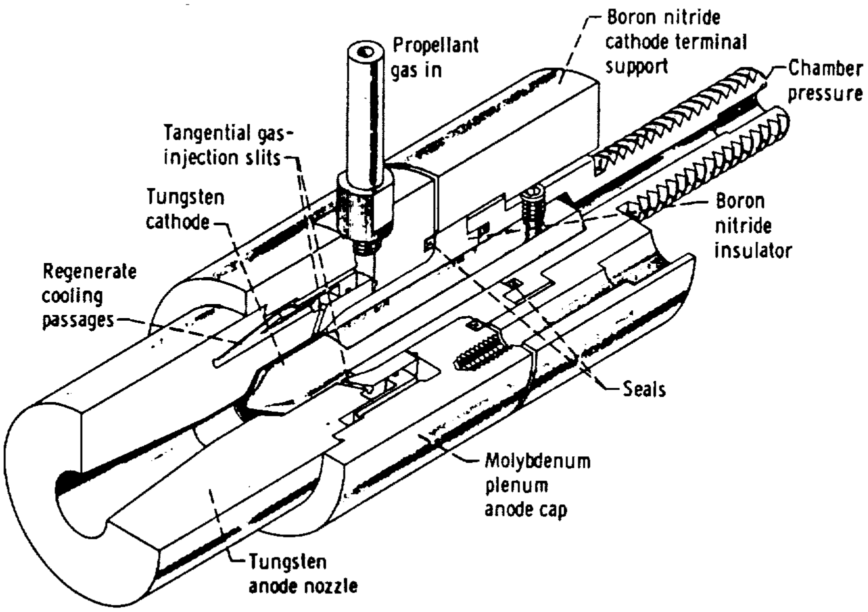

Figure 3. Avco R-4 30 kW hydrogen arcjet [2]

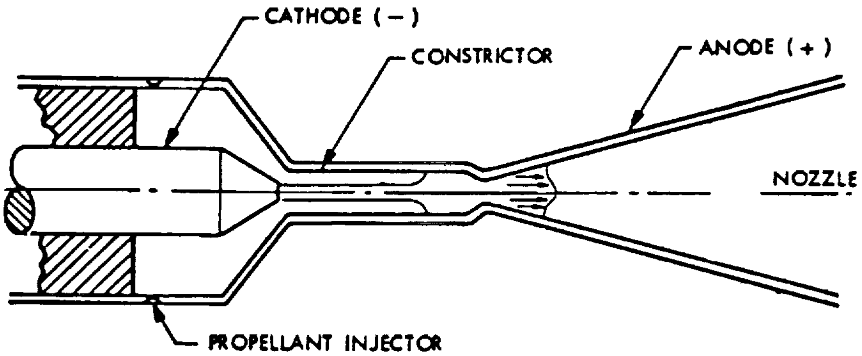

Figure 4. Giannini Scientific Corp. 30 kW arcjet electrode geometry [14]

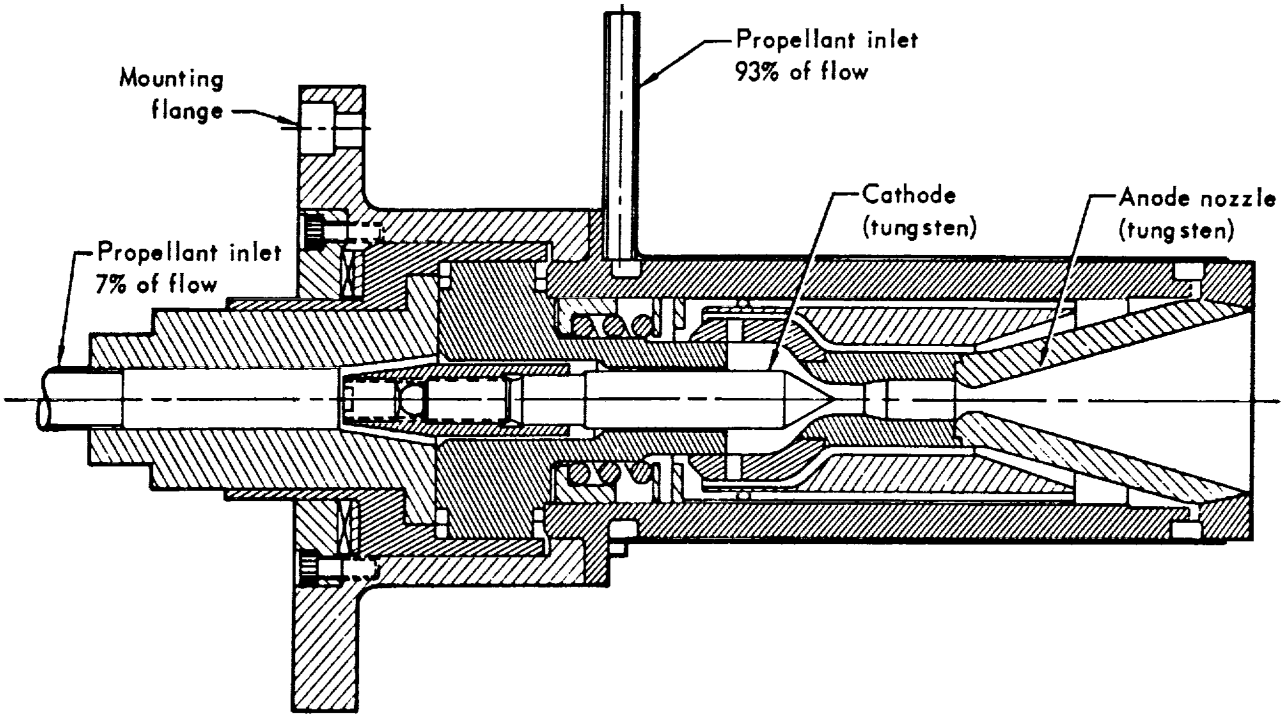

Figure 5. Schematic of GSC 30 kW regeneratively-cooled hydrogen arcjet [12]

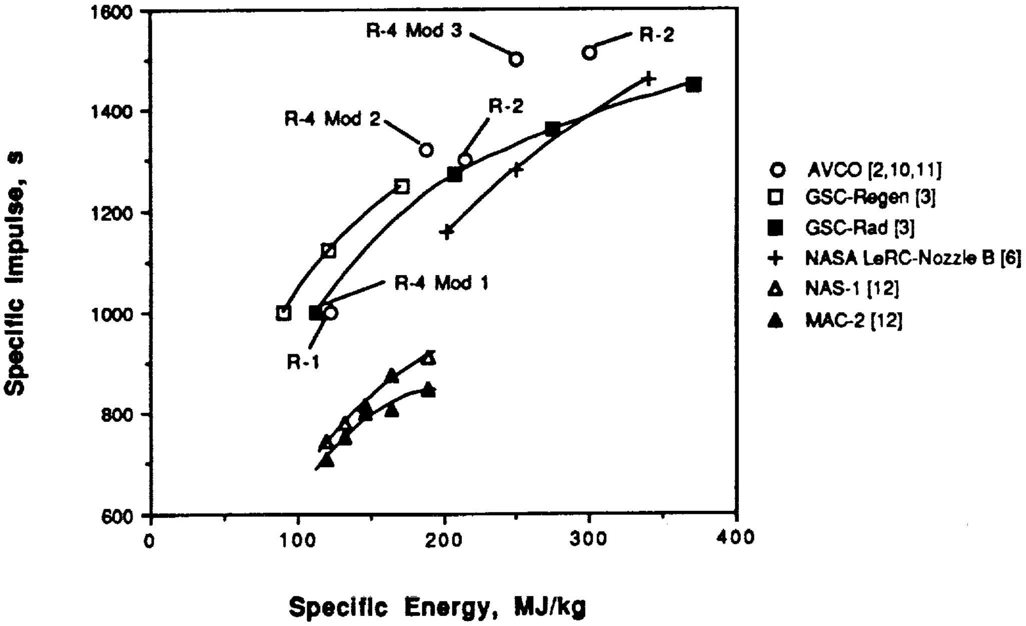

Figure 6a. Specific impulse versus specific energy for 30 kW hydrogen arcjets

Figure 6. cont.

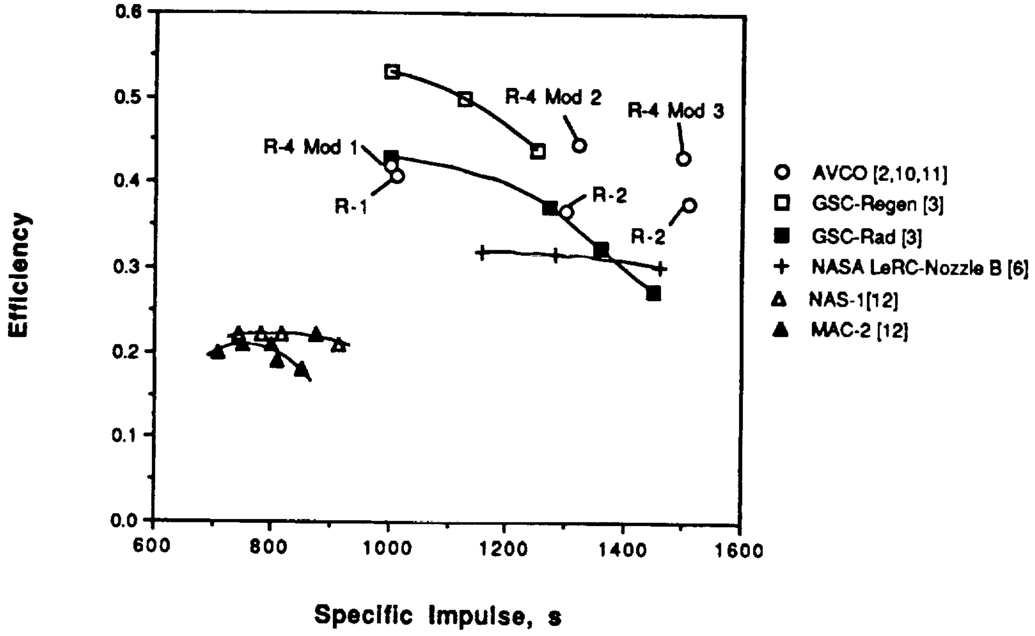

Figure 6b. Efficiency versus specific impulse for 30 kW hydrogen arcjets

Figure 6. Performance comparisions of 30 kW hydrogen arcjets

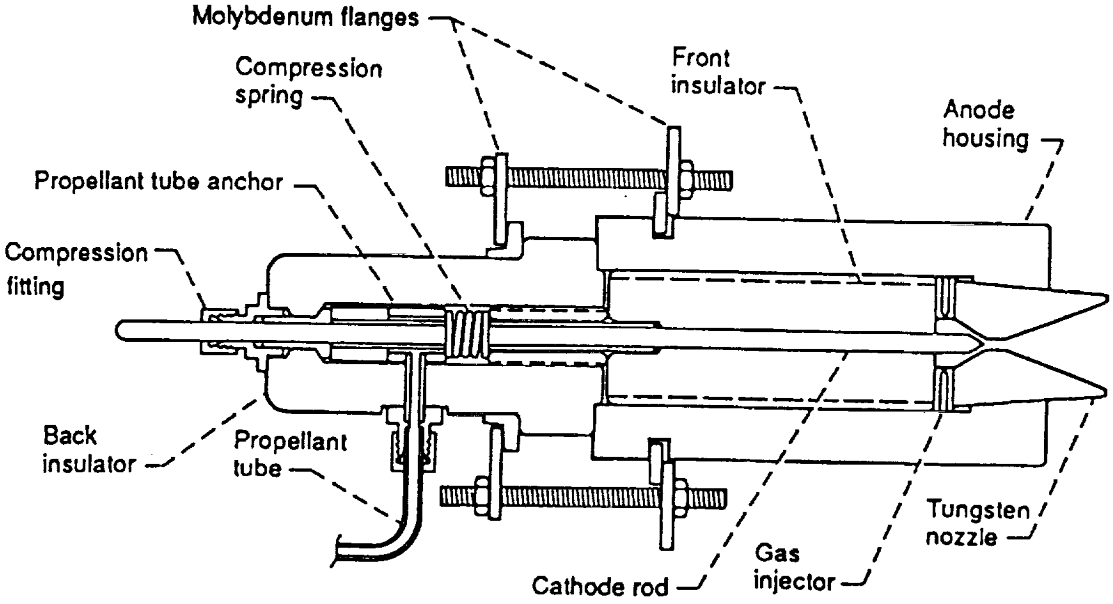

Figure 7. Schematic of NASA LeRC high power hydrogen arcjet [6]

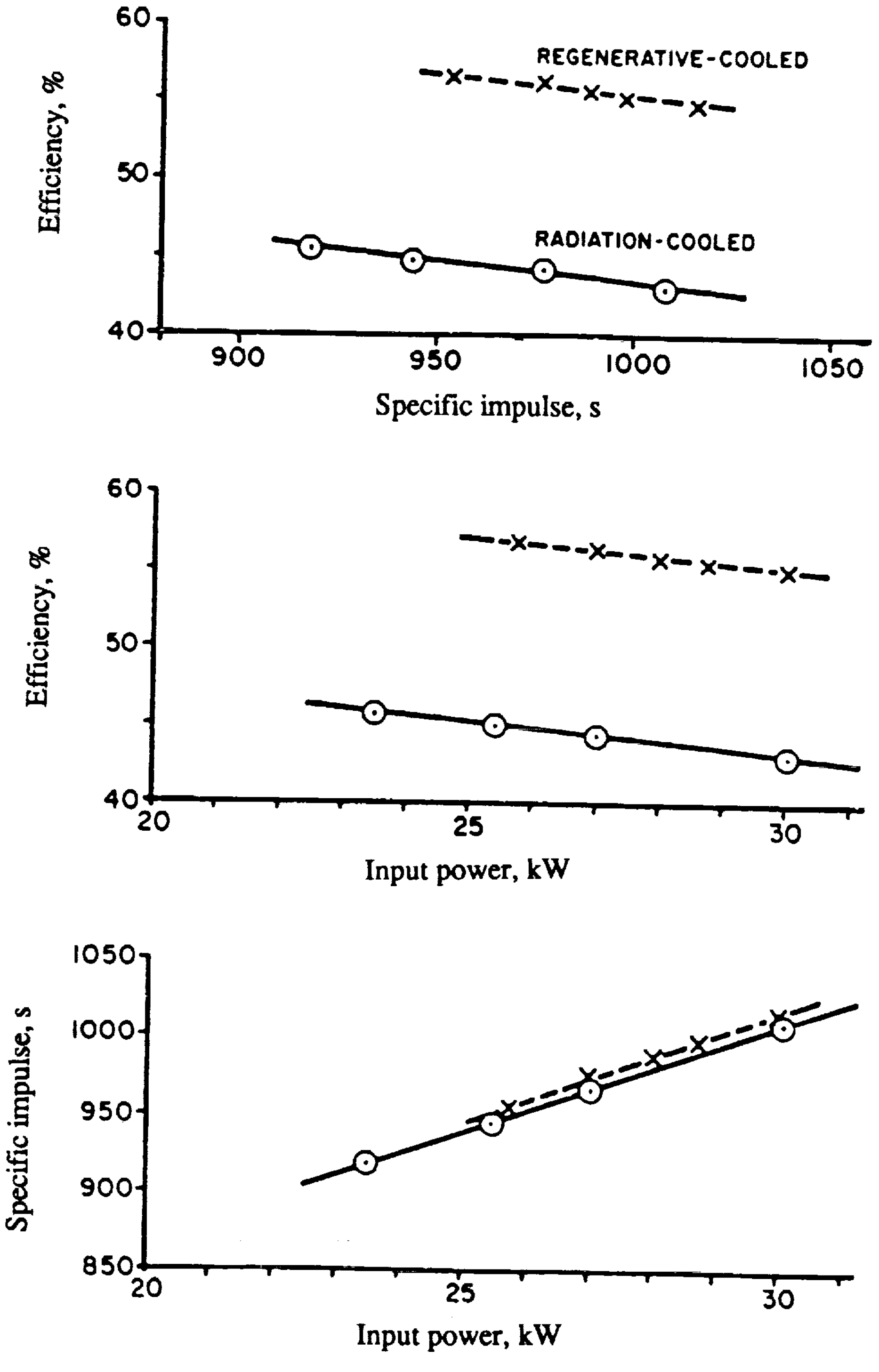

Figure 8. Performance of GSC radiation and regeneratively-cooled hydrogen arcjets [3]

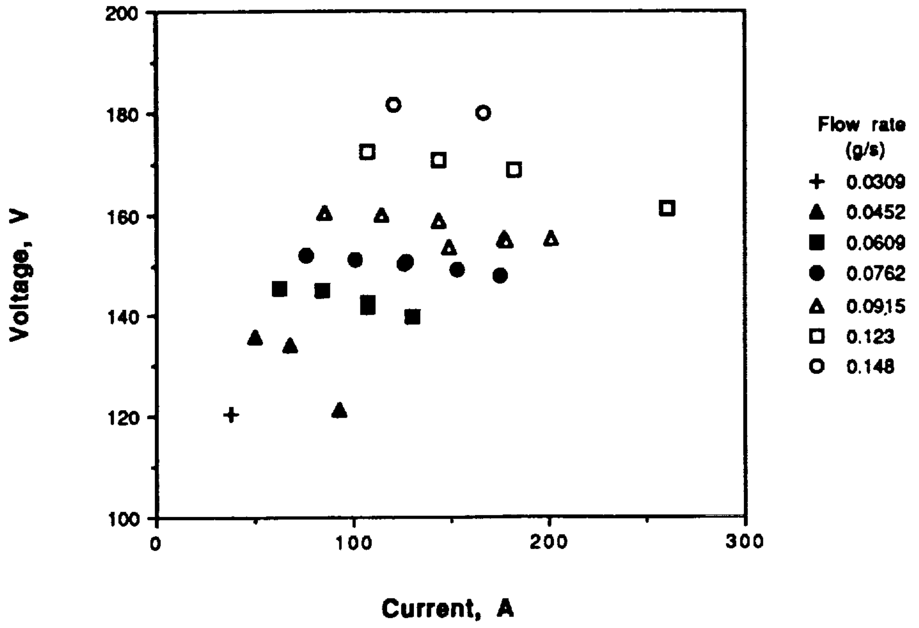

Figure 9a. Voltage-current characteristics

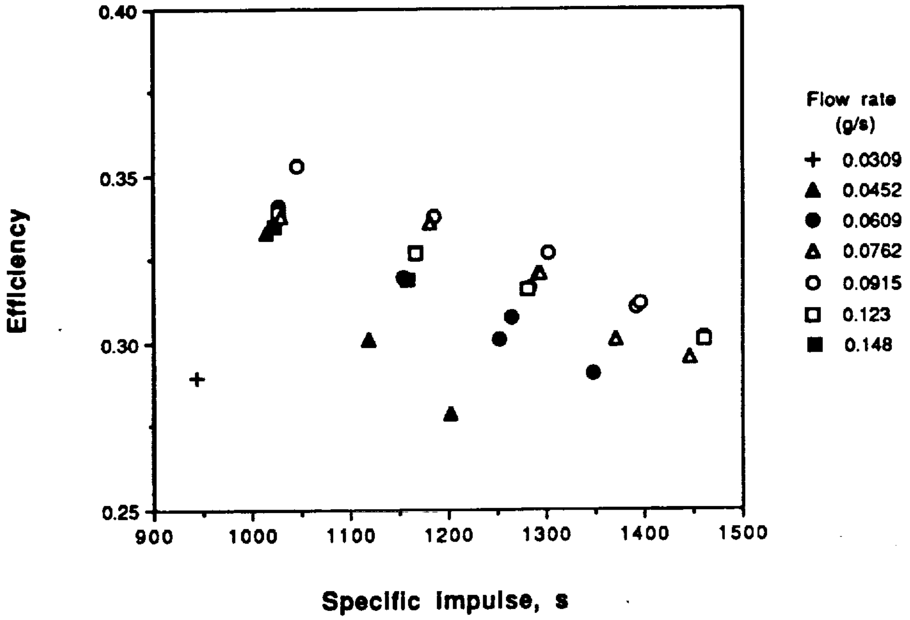

Figure 9b. Efficiency versus specific impulse

Figure 9. cont.

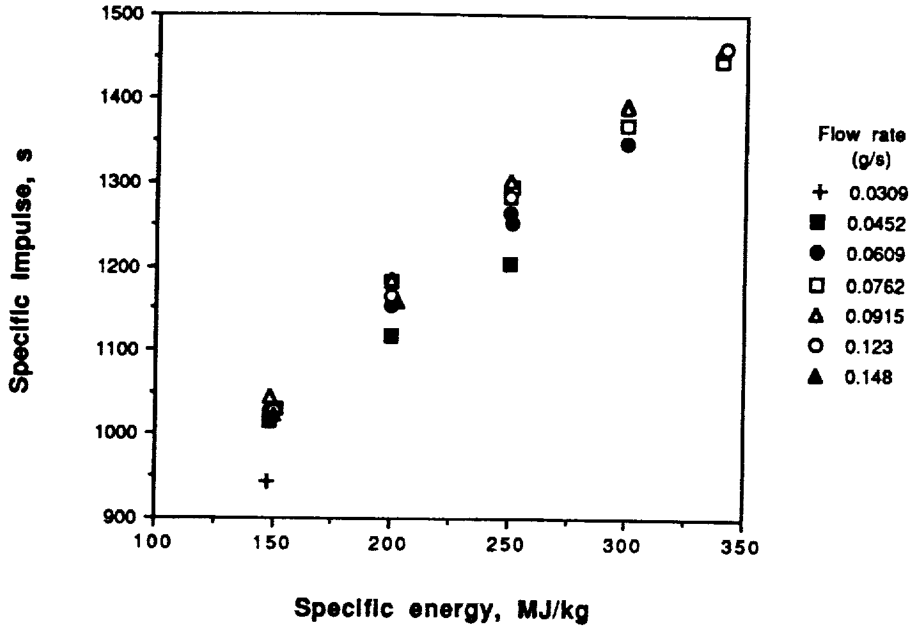

Figure 9c. Specific impulse versus specific energy

Figure 9. Performance of NASA LeRC high power hydrogen arcjet with nozzle insert B

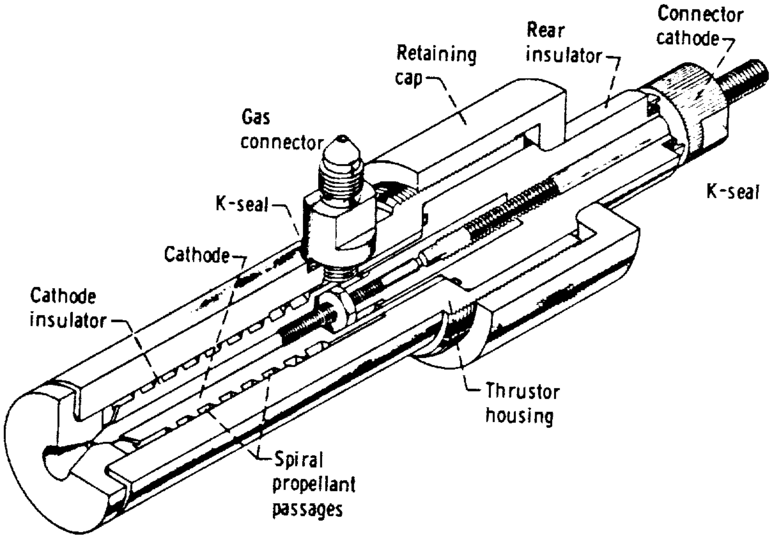

Figure 10. Schematic of Plasmadyne 2 kW hydrogen arcjet [5]

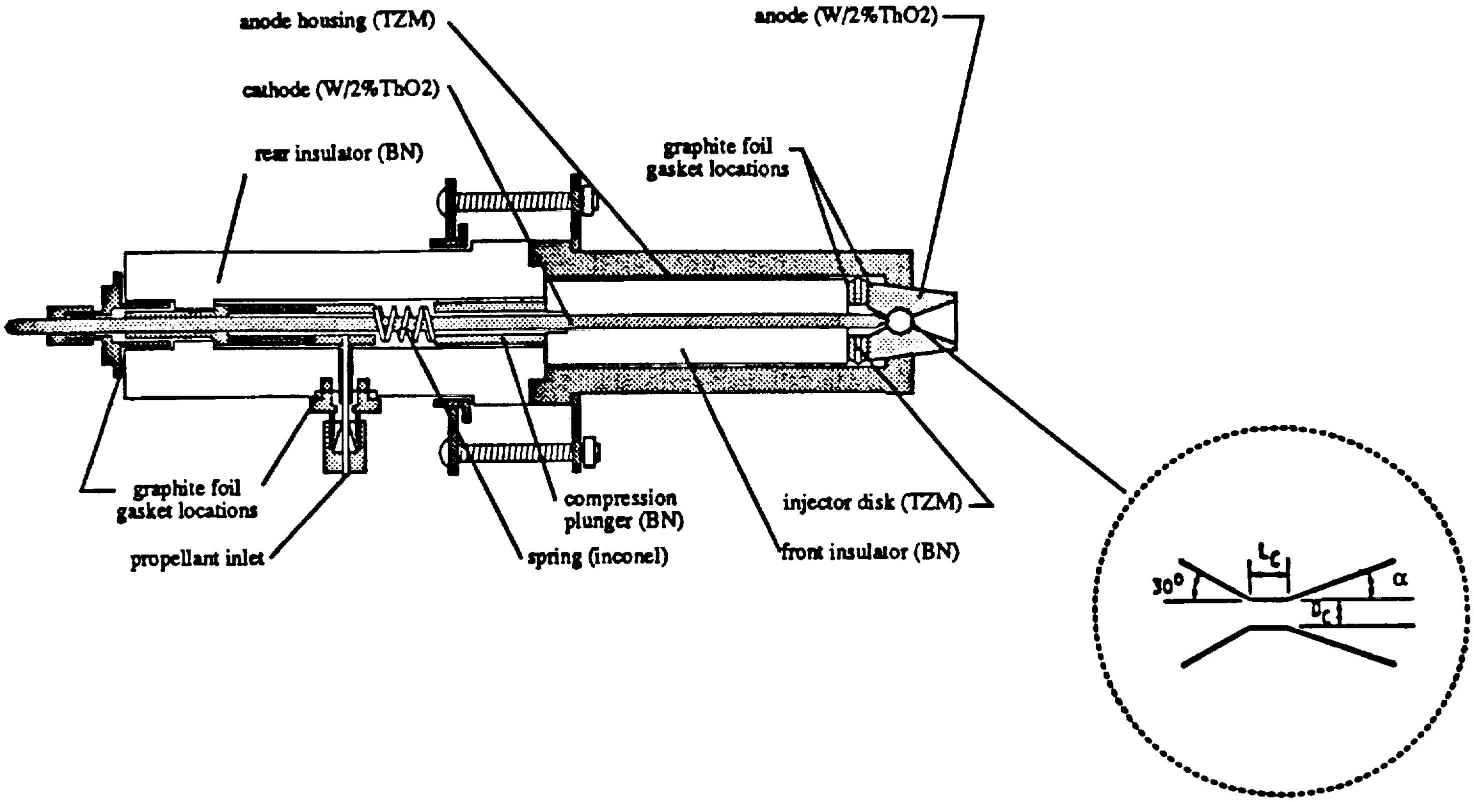

Figure 11. Schematic of NASA LeRC 1-4 kW hydrogen arcjet [7]

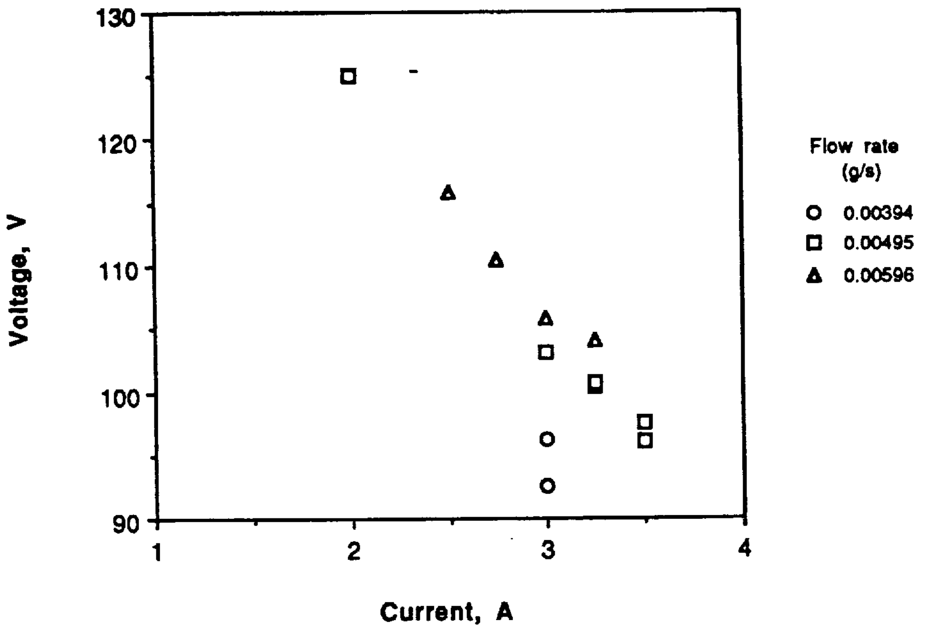

Figure 12a. Voltage-current characteristics

Figure 12. cont.

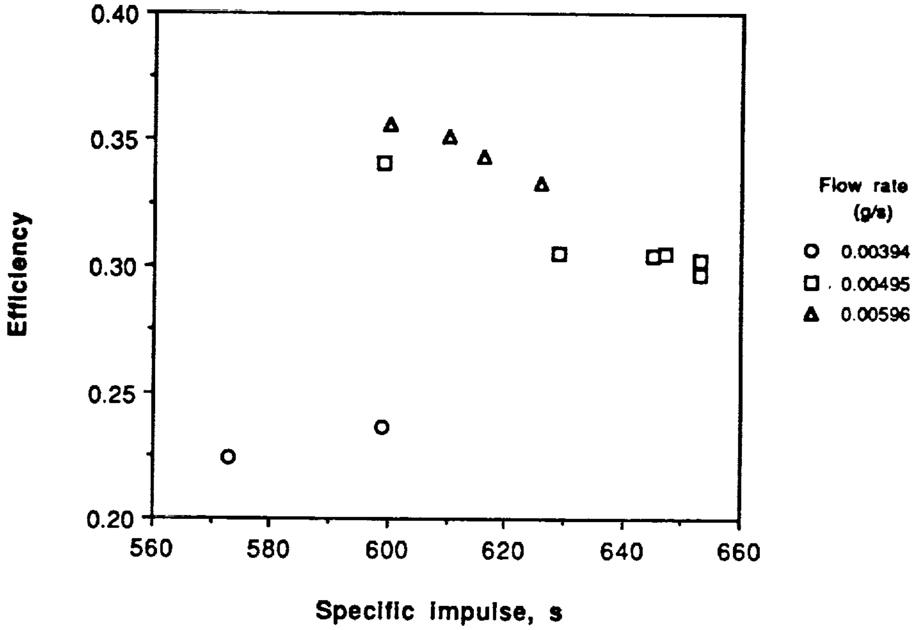

Figure 12b. Efficiency versus specific impulse

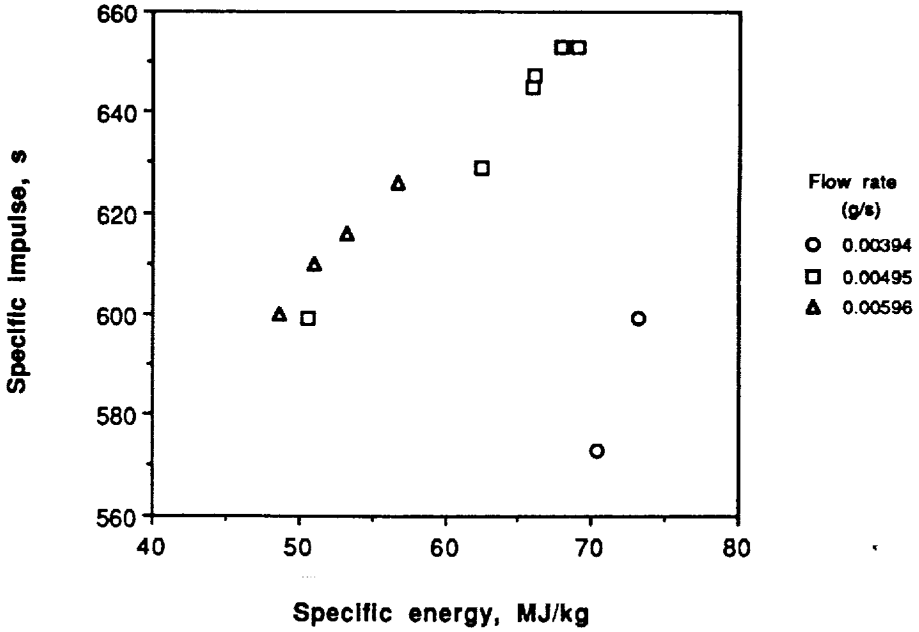

Figure 12c. Specific impulse versus specific energy

Figure 12. Performance of NASA LeRC very low power hydrogen arcjet

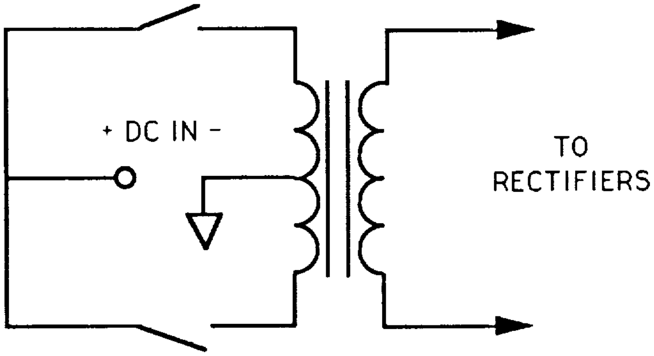

Figure 13a. Push-pull topology

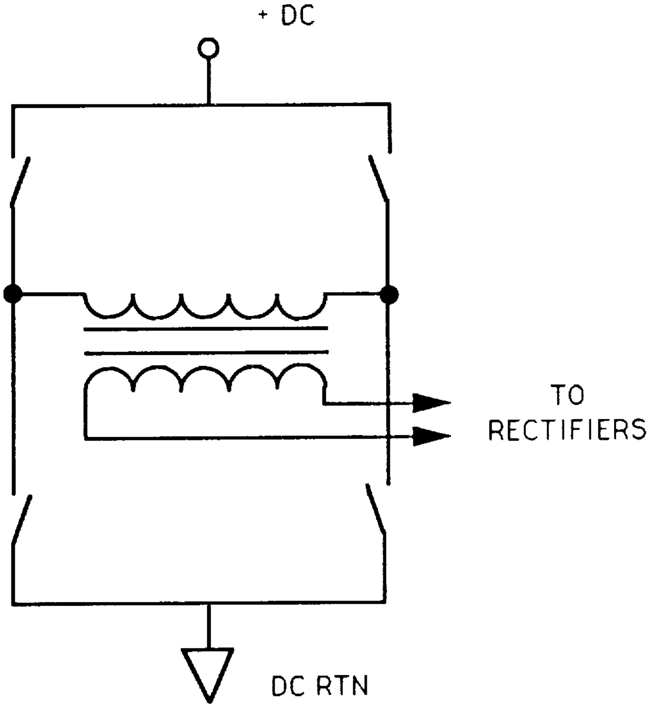

Figure 13b. Bridge topology

Figure 13. Power processor input topologies

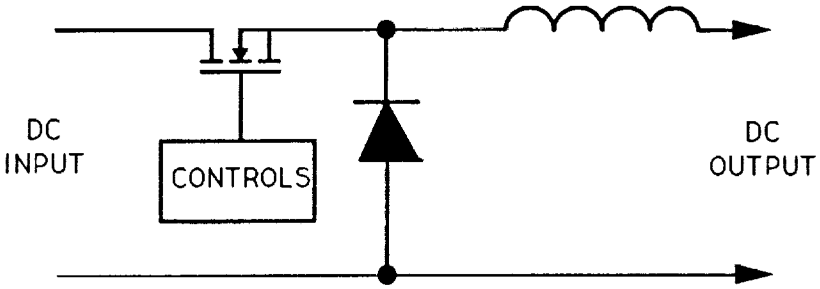

Figure 14. Buck converter topology

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13. ABSTRACT ***(Maximum 200 words)***

During the 1960's a substantial research effort was centered on the development of arcjets for space propulsion applications. The majority of the work was at the 30 kW power level with some work at 1-2 kW. At the end of the research effort, the hydrogen arcjet had demonstrated over 700 hours of life in a continuous endurance test at 30 kW, at a specific impulse over 1000 s, and at an efficiency of 0.41. Another high power arcjet design demonstrated 500 h life with an efficiency of over 0.50 at the same specific impulse and power levels. At lower power levels, a life of 150 hours was demonstrated at 2 kW with an efficiency of 0.31 and a specific impulse of 935 s. Lack of a space power source hindered arcjet acceptance and research ceased. Over three decades after the first research effort began, renewed interest exists for hydrogen arcjets. The new approach includes concurrent development of the power processing technology with the arcjet thruster. Performance data have recently been obtained over a power range of 0.3-30 kW. The 2 kW performance has been repeated; however, the present high power performance is lower than that obtained in the 1960's at 30 kW, and lifetimes of present thrusters have not yet been demonstrated. Laboratory power processing units have been developed and operated with hydrogen arcjets for the 0.1 kW to 5 kW power range. A 10 kW power processing unit is under development and has been operated at design power into a resistive load.

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