Development of a Regeneratively Cooled 30-kw Arcjet Engine

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The development of a fully regenerative-cooled 30-kw arcjet engine including a summary of the successful continuous 500-hr endurance test, is presented. This direct current arcjet engine, which uses hydrogen as the propellant, operated satisfactorily at an average measured thrust of 0.745 lb and demonstrated a total impulse of 1.34 million lb-sec during the described endurance test. Numerous analytical as well as experimental heat-transfer studies were required in order to substantiate the basic design philosophy, full regenerative-cooling using gaseous hydrogen. This electrothermal engine demonstrated a performance of 55% in over-all thruster efficiency at a specific impulse of 1000 sec, resulting in a 20% improvement in efficiency over a radiation-cooled 30-kw arcjet engine developed during 1962. The results of this development program indicated that the 30-kw arcjet engine described in this paper is one of the most advanced electrothermal propulsion devices at this power level yet reported.

Introduction

FOR an advanced space propulsion system, electrothermal engines have been the subject of numerous mission studies and many research programs. The arcjet engine described herein represents the engineering development of a particular electrothermal thruster designed for superior performance characteristics at a specific impulse of 1000 sec with a 30-kw electrical power supply (presumably the SNAP-8). A lifetime test of 500 hr demonstrated that this regeneratively-cooled arcjet engine is a reliable thrust-producing device and that this type of thruster is both practical and available for the eventual development of complete electrothermal propulsion systems.

Propellant Selection

Early electrothermal research studies[1] indicated that hydrogen was the best propellant available for the high-performance devices at the required level of specific impulse ($I_{sp} = 1000$ sec). The maximum arc chamber temperature using hydrogen at this level will be lower than for any other known propellant. This thermodynamic property, along with the fact that hydrogen does not react adversely with most high-temperature materials such as thoriated tungsten and molybdenum, made the lifetime requirement of 500 hr achievable, and an operational engine lifetime goal of 1500 hr very probable. In addition, the high heat capacity of hydrogen ($C_p = 7.00$ cal/mole °K at 600 °K)[2] made it particularly attractive for this regeneratively-cooled engine design.

Thruster Design

The performance of an arcjet engine is directly affected by the mechanisms of energy transfer from the arc discharge to the propellant exhausted. In order to obtain the maximum over-all efficiency of any electrothermal thruster, all energy losses must be reduced to a minimum. During the research and development program on this 30-kw arcjet, particular emphasis was placed on eliminating the known thermal losses from the anode nozzle by applying the regenerative-cooled approach in its design.[3]

The term "regenerative cooling" in rocket engine design is used when a propellant is circulated through cooling passages around the thrust chamber prior to its injection into the chamber. It is a cooling technique using the mechanism of forced convection heat transfer. The term "regenerative" may not be altogether applicable in the case of an arcjet engine; however, it does convey the fact that thermal energy absorbed by the coolant (propellant) is not wasted by external radiation, but increases the enthalpy of the propellant before it is introduced into the arc chamber. Because of the high heat capacity of the hydrogen propellant, this regenerative process resulted in a significant increase in specific impulse and thruster efficiency for this arcjet engine.

A cutaway drawing of this regeneratively-cooled arcjet engine is shown in Fig. 1. In direct current (d.c.) arcjet engines of the conventional design, the thruster assembly includes a propellant injector, a negative electrode (cathode), a positive electrode (anode), an exhaust nozzle, and an arc chamber or constrictor between the propellant injection area and the exhaust nozzle. All these parts must be contained in a suitable housing with propellant lines and electrical power connectors. At least one high-temperature electrical insulator is required between the cathode and anode and is usually made of boron nitride. The cathode is a rod of thoriated tungsten with a conical tip. The anode is also made of thoriated tungsten and may have one of several geometric configurations. In most designs the arc chamber and nozzle

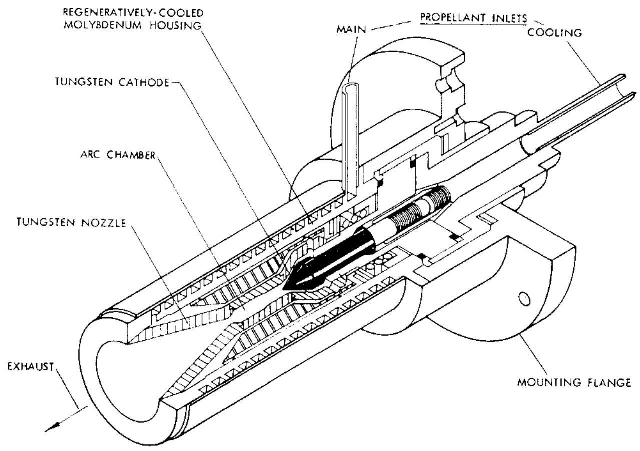

Fig. 1 Cutaway view, 30-kw regeneratively-cooled arcjet engine.

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Table 1 Dimensions of a typical regeneratively-cooled direct current hydrogen arcjet engine

Arc chamber diameter (inlet)	0.250 in.
Arc chamber diameter (maximum)	0.312 in.
Arc chamber length (nominal)	1.125 in.
Nozzle throat diameter	0.187 in.
Nozzle cone half-angle	15°
Nozzle area ratio	60:1
Cathode-anode gap (minimum)	0.060 in.
Cathode tip angle (total)	60°

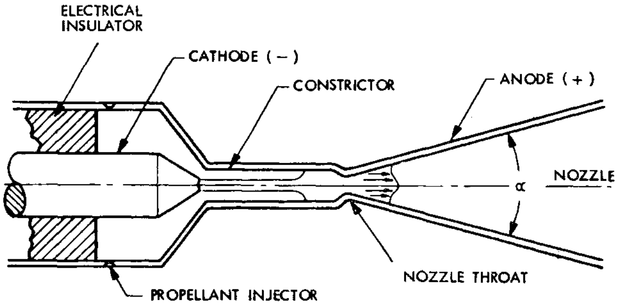

Fig. 2 Schematic drawing, 30-kw d.c. arcjet thruster.

together become the anode. The design considered for this development was such that the arc chamber was the area in which the arc terminated, and the divergent channel functioned only as a supersonic nozzle (Fig. 2).

The upstream part of the thruster is the propellant injection area. A propellant vortex is induced by injecting the gas tangentially in the annular space surrounding the cathode. The propellant then flows over the cathode to cool it before being introduced into the chamber. In the arc chamber (or constrictor) the arc "burns" in the propellant stream and heats the propellant to a very high temperature. At the downstream end of the arc chamber this high-temperature gas (plasma) enters the convergent-divergent nozzle and is expanded to a very high velocity.

The low pressure in the core of the propellant vortex provides a preferred path for the arc and serves to stabilize the arc column in the center of the arc chamber (or constrictor) in order to minimize erosion. The vortex also tends to keep the anode arc attachment point moving to affect lower erosion rates and at the same time promotes mixing within the adjacent propellant flow streams.

Because of the very high energy release rates and high temperatures involved in the operation of arcjet engines, some form of cooling for the thruster body must be provided. Early arcjet engines and other electrothermal research devices were water-cooled in order to avoid materials problems. Water-cooled arcjets have generally demonstrated lower thruster efficiencies at a given value of specific impulse as a consequence of operating at low wall temperatures. Furthermore, water does not appear to be a suitable coolant for space operation because the relatively low cooling-cycle temperature would require large and heavy space radiators.

The details of the arcjet engine configuration shown in the sketches (Fig. 1 and 2) are given in Table 1. These values are representative of the final thruster design that resulted from this development program.

Thruster Development

It became apparent during a preceding arcjet thruster research program that a fully regeneratively cooled design approach was needed at the required specific impulse value of 1000 sec to further improve the over-all efficiency.[4] A design review of the radiation-cooled 30-kw arcjet thruster was conducted. Aerodynamically defined contours for the nozzle throat and arc chamber entrance areas were included in the first redesign of this thruster, which became the test vehicle for obtaining the heat-transfer and energy loss data.

The initial regeneratively-cooled heat shield (regenerator) was designed so as to mount directly on the radiation-cooled thruster in the thrust stand. The coolant used during the preliminary radiation energy-loss tests was water. The results of this energy balance showing the percentage of input power radiated from the anode-nozzle as a function of thruster input power are given in Fig. 3. The amount of radiated energy from the anode-nozzle (~11% at 30 kw) checked closely with the values calculated from the measured values of outer wall temperatures of this thruster.

Inasmuch as the energy balance test was successful with water as the coolant, gaseous hydrogen was used as the next coolant. The preheated hydrogen from the regenerator was introduced normally into the radiation-cooled arcjet thruster. This hybrid unit was operated without incident and yielded the necessary performance data for the design of an arcjet engine having an integral regenerator.

The initial tests of the regeneratively cooled 30-kw thruster demonstrated a substantial improvement in over-all thruster efficiency at a specific impulse of 1000 sec. A comparison of the typical performance data obtained from both the radiation-cooled and regeneratively cooled thrusters is shown in Fig. 4. Although the first tests of this new thruster design were considered very successful, a mechanical problem was observed with regard to sealing the stainless-steel regenerator to the thoriated tungsten anode nozzle. For the initial design a seal of Inconel-X was welded to the stainless-steel housing and mated with a lip of tungsten on the nozzle. This approach to the seal design was obviously not satisfactory for the lifetime required, so the substitution of thoriated (TD) nickel for Inconel-X was made. This interim solution to the seal problem was satisfactory for tests of 100 hr duration or less; however, it still was not the ultimate solution. A welded joint was ruled out at the beginning since this would make the replacement of parts very difficult during such a development program. The final solution, which appeared simple after being proved, was to use a tapered, lapped surface between the molybdenum regenerator housing and the thoriated tungsten anode-nozzle which was sealed together with spring and gas pressure forces.

A characteristic arc voltage fluctuation has been observed during the operation of hydrogen arcjet thrusters.[5] The phenomenon of increased voltage fluctuation frequency during the warm-up period of the thruster, however, is apparently a function of the change in propellant temperature (and related thermodynamic properties) entering the arc chamber. As previously noted, the basic design approach was to maintain the internal geometry of the preceding radiation-cooled thruster

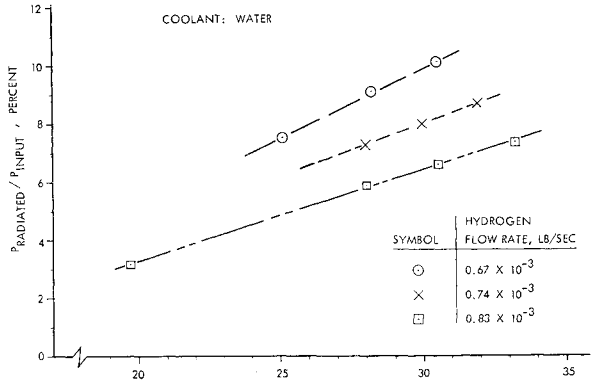

Fig. 3 Measurement of thruster radiated power.

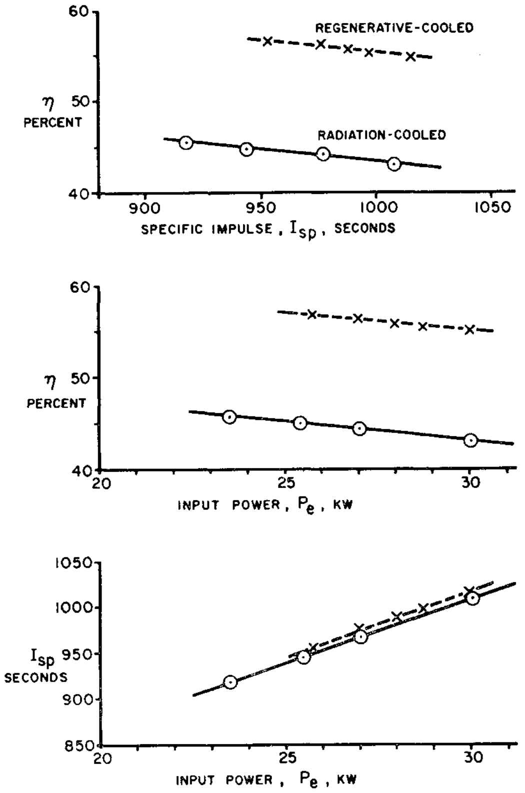

Fig. 4 Performance comparison, regenerative vs radiation cooled 30-kw arcjet engine.

while attempting to improve the factors affecting the performance and lifetime of the engine. The addition of an integral regenerator to the propellant flow path improved the over-all performance by utilizing the radiated (lost) energy to increase the enthalpy of the propellant prior to its introduction to the arc chamber. A small part of the total propellant gas flow (~7%) was used to cool the cathode subassembly before being introduced into the arc chamber. This was deemed necessary from lifetime and reliability considerations of the cathode insulating materials.

Table 2 Averaged values of arcjet engine performance data 500-hr endurance test

d.c. electric power	30.3 kw
Arc voltage	261 v
Arc current	116 amp
Total thrust	0.745 lb
Specific impulse (vacuum)	1013 sec
Over-all thruster efficiency	55%
Arc chamber inlet pressure	1105 mm Hga
Test chamber pressure	0.8 mm Hga

One of the most significant design improvements in terms of time and cost (no measured difference in performance) was the segmented (three piece) thoriated tungsten anode nozzle. This design feature greatly reduced the number of microcracks in those areas where there has previously been a relatively heavy tungsten section. Also, having the center (arc chamber) cylindrical segment separate from the inlet (vortex generator) and exhaust (supersonic nozzle) segments allowed parametric design changes with a minimum of effort. Small changes in the arc chamber did not affect the performance as much as arc stability. The optimum configuration was then included in the final engine assembly for the endurance test.

500-hr test

The 500-hr lifetime test of this arcjet engine was required to demonstrate the integrity of the mechanical design. At the start of this test the thruster met all the concurrent performance requirements, $\eta \geq 55\%$ at an $I_{sp} \geq 1000$ sec for 30-kw power input to the thruster. The electrical input power to the thruster was monitored to keep it at or above 30 kw for the duration of the endurance test.

The voltage/current ratio at constant input power indicated an increasing trend with time, as can be deduced from the in-

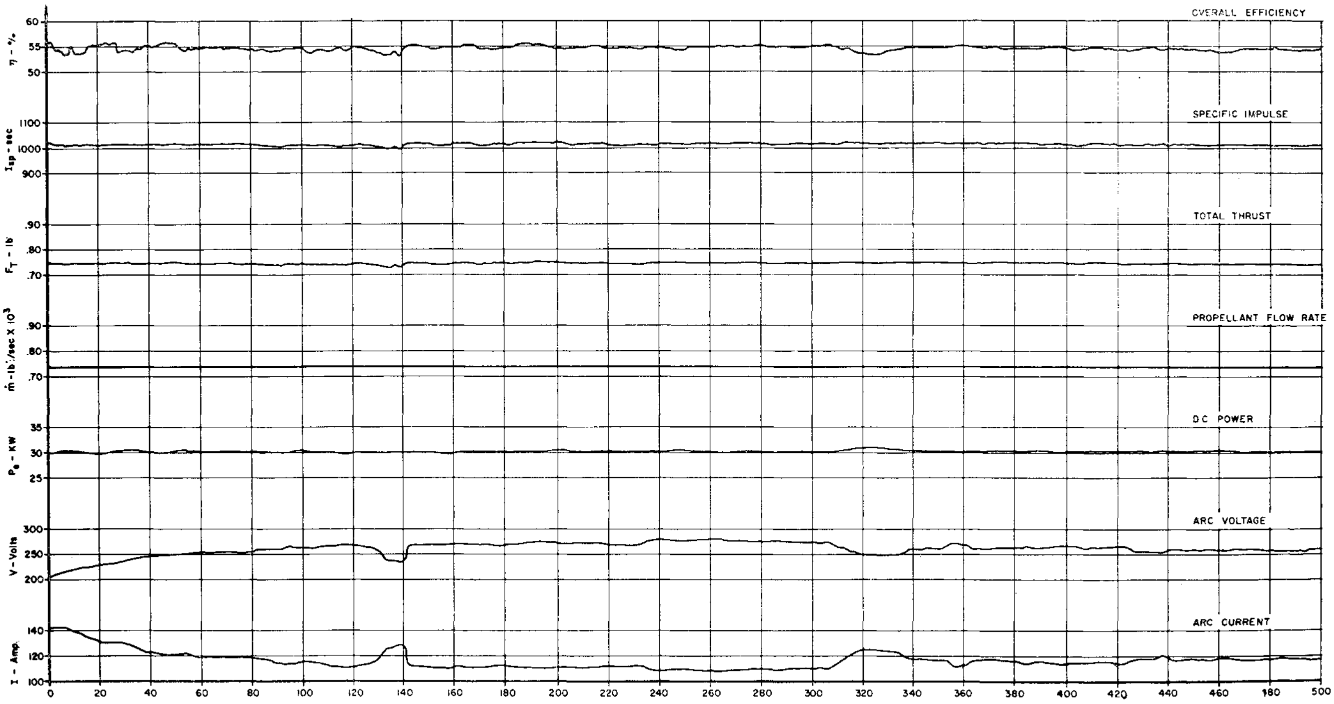

Fig. 5 Performance summary of continuous 500-hr endurance test. Thruster: model 141-400A; test dates: December 6–27, 1963: propellant: hydrogen; and total time: 501.45 hr (30,087 min).

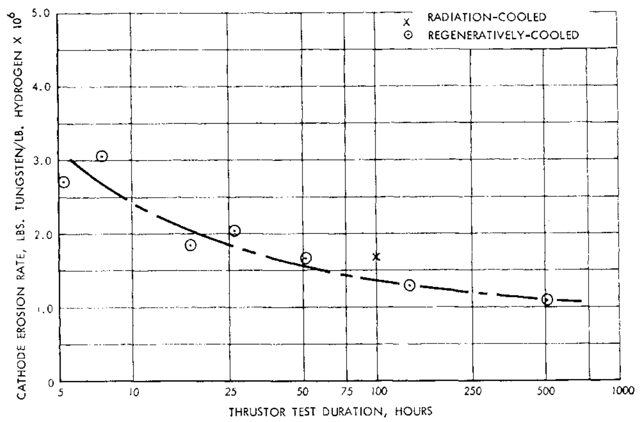

Fig. 6. Cathode erosion rate characteristic, 30-kw arcjet engine.

creasing arc voltage and decreasing arc current characteristics shown in Fig. 5. Although this change in voltage/current ratio (over-all resistance characteristic) with time presented no problem for ground operation using manual power controls, it could cause a compatibility problem for the space power control and/or power conditioning equipment. Also, two significant changes in the electrical characteristics took place during the test after 140 and 330 hr from the start. Although there is no definite explanation for these discrete changes in the electrical characteristic of the thruster, it has been theorized that the emitting surface of the cathode may have been transferred from a point within the tip "crater" to multiple (random) points on the sharp edges of the cathode tip area. It is also possible that some molten cathode material was being expelled during this period of operation. This phenomenon was not observed during shorter test runs, but is being noted here for future reference.

The lifetime test was voluntarily terminated after operating continuously for 501.45 hr (30,187 min). In terms of over-all propulsion performance, this regeneratively cooled 30-kw arcjet engine produced an average thrust of 0.745 lb and a total impulse of 1.34 million lb-sec. The erosion rate of the cathode (Fig. 6), which is considered the critical eroding part during the operation of this arc device, was only 1.07×10^{-6} lb tungsten/lb hydrogen propellant used, or less than 0.4% of the initial cathode weight.

Performance calibration data taken after the completion of 500 hr of continuous operation indicated negligible performance degradation. Over-all efficiency after the test was 55.1% at an I_{sp} of 1000 sec compared with 55.3% for the same value of specific impulse at the start of the endurance test. These calibration data were considered more accurate than the individual readings taken every 30 min throughout the entire test. An arithmetic average of the periodic data readings which are representative of the various performance parameters during the lifetime test is presented in Table 2.

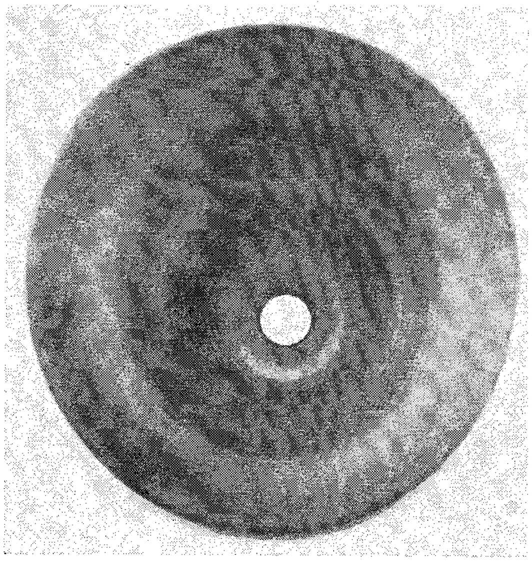

Fig. 7. 2X view of nozzle throat taken from nozzle exit after 500-hr endurance test.

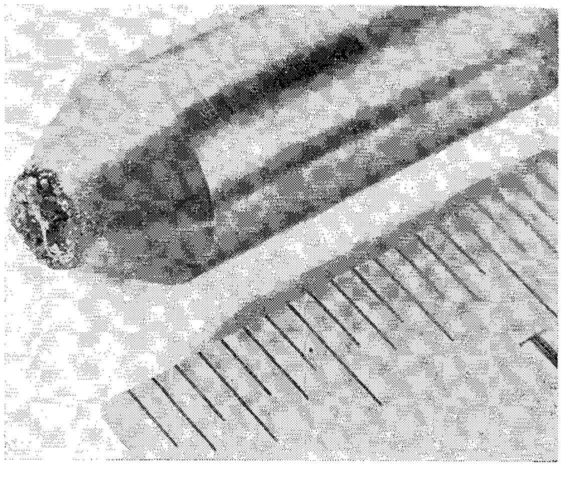

Fig. 8 4X view of cathode after 501.45 hr of continuous operation at an average power level of 30.3 kw.

Following the successful completion of the endurance test, the arcjet engine was disassembled, inspected, and documented with photographs. Figures 7 and 8 are magnified pictures of the anode nozzle (2*x*) and the cathode (4*x*) and indicate the excellent condition of these critical parts. It should be noted that many of the "cold end" parts were also used in other engine assemblies prior to this long test. Several parts had accumulated a total operating time of 712+ hr and were still in good condition.

Miscellaneous

As a final substantiation of the performance characteristics for this arcjet engine design, a unit was tested at the NASA Lewis Research Center. The performance data obtained while testing in tank no. 5 (15-ft diam by 60 ft long) at the Electric Propulsion Laboratory confirmed those data taken at our test facility.

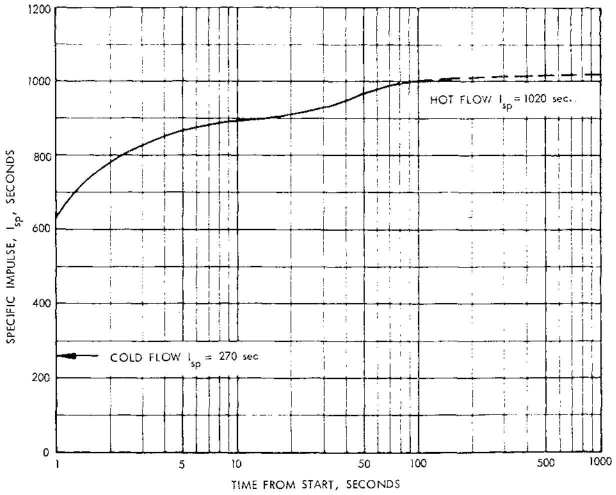

Fig. 9 Typical start-up characteristic of regeneratively-cooled 30-kw arcjet engine.

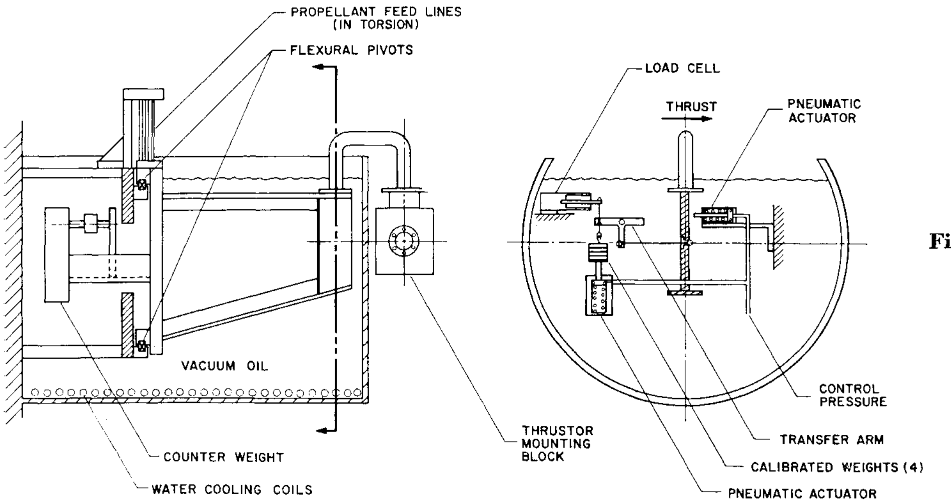

Fig. 10 Schematic, liquid-cooled thrust measuring system.

Because of the inherent steady-state performance advantages of a regeneratively cooled design, the thermal lag in the heat exchanger system will affect its transient characteristics. A typical start-up in the characteristic for this 30-kw arcjet engine is shown in Fig. 9 and indicates that the transient performance of this model is not significantly slower than the radiation-cooled model. This figure also points to the interesting advantage of the good specific impulse ($I_{sp} \approx 270$ sec) with a "cold" flow of hydrogen for the case where an interruption of a space power supply might otherwise prove to be catastrophic for a particular propulsion application.

Description of Arcjet Test Facility

The test facility used for the development of this regeneratively cooled arcjet engine included a space simulation (vacuum) test chamber, associated instrumentation, and a control console. The test chamber is a double-walled, water-cooled vacuum vessel 3 ft in diameter and 5 ft long. The chamber is connected by the appropriate valves and pipes to a 5000 ft^3/min (air) pumping system. The hydrogen exhaust from the engine enters a calorimeter (water-cooled heat exchanger) located inside the vacuum pipe, and the gas temperature is thereby reduced to less than 150°F within a distance of 10 ft.

The liquid-cooled thrust measuring system is a balanced rotating beam with the pivot points located in the vertical plane. Rotation of the beam is limited to 1° at 1 lb of force by the characteristics of the piezo-resistive strain gage load cell used to measure thrust. Bendix flexural pivots were used at the hinge points to approach zero friction. The entire beam, with load cell, is submerged in a constant temperature vacuum-oil bath to prevent thermal drift. A unique calibration system for the thrust measuring system (Fig. 10) was one reason the endurance test could be made without stopping for thrust calibrations. A true zero reading and four incremental load readings can be made while the thruster is in operation. In addition, the normal static load and no load calibrations are made following the completion of a thruster test as a normal procedure.

The propellant (hydrogen) flow rate was measured using two different types of instruments. A calibrated laminar flowmeter (low Δp) was upstream and in series with a critical orifice flowmeter. A temperature-controlled heat exchanger was located upstream of these flowmeters. During the endurance test the hydrogen flow rate was kept at a constant orifice upstream pressure, which resulted in a constant flow rate. For long duration tests, gaseous hydrogen trailers, each having a capacity of approximately 28,000 ft^3, were connected to the gas cylinder manifold through a check-valve to supply an uninterrupted source of propellant.

In order to obtain sufficient, reliable d.c. power for endurance, as well as performance testing, two 40 kw triple-voltage selenium rectifier units were used. These units were connected to supply 720 v, open circuit. A Variac control was used with the rectifier to control the d.c. power input to the test chamber. During the endurance test the parameter that had to be monitored most often was the input power. Twice each day significant changes in municipal power voltage levels were detected and had to be compensated for in the rectifiers in order to maintain the correct (30 kw minimum) electrical power to the arcjet engine.

Summary and Conclusions

1) A regeneratively cooled 30-kw arcjet engine has been operated at a specific impulse of 1000 sec and an over-all thruster efficiency of 55% for over 500 hr without failure.

2) Further performance improvement might be available if a technique for propellant recombination can be developed.

3) A diagnostic study of the exhaust jet from this engine should be performed in order to separate the dissociation and ionization losses from the nozzle momentum losses. A complete physical understanding of this area of arcjet technology is still lacking.

4) The application of this type of engine to manned space vehicles appears advantageous, but pulsed-mode performance characteristics have not yet been measured.

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