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Advanced Onboard Propulsion Benefits and Status

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ADVANCED ONBOARD PROPULSION BENEFITS AND STATUS

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SUMMARY

Future commercial space systems may include geosynchronous-orbit communication satellites; Earth-observing satellites in polar, Sun-synchronous orbits; and tended low-Earth-orbit platforms. All such space systems require onboard propulsion for a variety of functions, including stationkeeping and drag makeup, apogee motors, and delivery and return. In many cases, the onboard propulsion exerts a major influence on the overall mission performance, lifetime, and integration. NASA has established a Low Thrust Propulsion Program, which is developing chemical and electric propulsion concepts that offer potential for significant benefits for onboard propulsion for the various classes of commercial spacecraft. The onboard propulsion requirements of future commercial space systems are briefly discussed, followed by a summary of the characteristics and status of relevant elements of the NASA Low Thrust Program.

INTRODUCTION

Onboard propulsion is used for a variety of functions on many commercial class space systems. Major roles include apogee motors and north-south stationkeeping for geosynchronous (GEO) communications spacecraft (refs. 1 and 2), insertion and orbit control for Earth-observing satellites (refs. 3 and 4), and drag makeup and logistics (delivery and return) for systems in low-Earth-orbit (LEO) (refs. 5 to 7). In many cases, onboard propulsion exerts a major influence on the characteristics of the space systems and their overall mission performance.

Figures 1 and 2 show injected and on-orbit mass fractions, respectively, for several recent GEO communication satellites. Such satellites are placed in GEO directly with an apogee motor, or via a two-step process involving a perigee burn to an elliptical GEO transfer orbit (GTO) and subsequent apogee propulsion for orbit circularization. Considerations of cost and launch vehicle availability indicate that most commercial GEO systems will be placed via the latter, two-step process. Figure 1 shows that, for GEO satellites, apogee propellant now constitutes from 40 to 50 percent of the mass injected into GTO. Apogee propulsion requirements, for a given beginning-of-life (BOL) GEO mass, depend somewhat on a number of factors, including the site and characteristics of the launch vehicles. As seen in figure 1, however, it is clear that apogee propulsion represents technology of major potential mission leverage. For a number of reasons, including minimization of "gravity losses," acceleration level control, and schedule, near-term apogee propulsion will probably require chemical rockets operating at thrust levels from about 200 to 1000 N. The data of figure 2 show that GEO on-orbit propulsion for communication satellites now constitutes about 30 percent of the BOL on-orbit mass. The satellites use storable chemical and resistojet systems for stationkeeping that operate at specific impulses slightly below 300 s. The useful lifetime of communication satellites is now basically determined by availability of propellant for N-S stationkeeping. Development of higher-performance, small stationkeeping propulsion can therefore enable major increases in the revenue-producing lifetime of GEO spacecraft.

Earth-observing satellites are most often at high inclination at Sun-synchronous, middle-Earth-orbit (MEO) altitudes between about 600 to 1200 km. On-orbit propulsion is required (ref. 3) for orbit control, including maintenance of both a circular near-polar orbit and the desired ground track. These propulsive requirements derive from (1) loss of altitude due to small but non-negligible atmospheric drag and (2) lunar and solar perturbations. Some propulsion is also required for attitude control, which can be quite demanding for mission phases that require fine pointing. The SPOT spacecraft (ref. 3) is representative of this type of free-flying spacecraft, and the (hydrazine) propellant, depending on the mission, can range from about 8 to 16 percent of the initial on-orbit mass. Palaszewski and Uphoff (ref. 8) have recently presented analyses of on-orbit propulsion for several Earth-observation systems that maximize the viewing durations of selected regions on the Earth's surface. These types of systems can often require significantly greater onboard propulsion capabilities than Earth observers of the SPOT class; the reader is referred to reference 8 for details.

Delivery and return of Earth-observing satellites may be performed by transfer vehicles, such as the OMV, or by onboard propulsion. As illustrated in figure 3 (ref. 7), such maneuvers involve large velocity increments. Detailed parametric studies of on-orbit propulsion systems for delivery and return of MEO spacecraft were presented in reference 7, which evaluated onboard Earth-storable bipropellants, hydrazine, cold-gas, and stoichiometric hydrogen/oxygen (produced by an onboard electrolysis system) propulsion systems. The results of reference 7 indicate that, for the highest-performance propulsion systems, about 25 percent of the initial LEO mass was required for delivery, on-orbit functions, and return of a MEO satellite to and from 900 km. This is in good agreement with the detailed calculations[4] of delivery and return of a large radar-bearing satellite at an inclination and altitude of 99.5° and 1007 km, respectively. More recent calculations were conducted to evaluate the use of both chemical and electric propulsion for the delivery and return, after 30 months, of a 12 000-kg polar satellite between 350 and 900 km. Table I shows the results of these calculations for the baseline hydrazine, dual-mode Earth-storable bipropellant, resistojet, and arcjet systems. It is seen that significant payload benefits may be gained with advanced chemical technology and that use of electric propulsion, operated at 5 kW, can provide yet more benefits, at the expense of increased orbit transfer times.

Numerous commercial LEO systems, such as the Industrial Space Facility (ISF) (ref. 6), have been proposed. In general, the proposed LEO platforms have assumed the capacity of refurbishment ("tending") via Shuttle Orbiter and/or Space Station Freedom. The major onboard propulsion tasks are to provide for the system placement and return and to overcome drag forces when required for reasons of altitude and/or acceleration control. The capability of tending offers some unique opportunities and imposes some constraints on onboard propulsion. Resistojets, operated on waste gases have been baselined on Space Station Freedom (ref. 5). The use of waste gases eliminated requirements for (1) launch of drag makeup propellant and (2) return of the waste gases to Earth. Water resistojets were selected for the ISF (ref. 6), primarily because the benign and well-known properties of water were felt to offer major simplifications in the integration of the ISF with the Shuttle Orbiter during both launch and in-space missions phases. The issue of integration, including special considerations of safety for the crew of the tending element, will probably be of critical importance in selection of onboard propulsion for LEO tended commercial systems.

LEO orbit maneuver and drag makeup impose major propulsion requirements. Figure 4 shows a typical mission profile selected for the ISF, which resulted in reboost total impulse requirements between about 1 to 2.4×10^6 N-S/year over the time span from 1992 to 2003 (ref. 6). The impulse variations were due to changes in the atmospheric density and mission profile over the solar sunspot cycle. With a water resistojet operated at 152-s specific impulse, the propellant mass required per year ranged between 3 and 8 percent of the ISF mass (including payload). These masses did not include provisions for attitude control or special docking requirements. The fractional propellant penalty will vary with LEO system, configuration, operating altitudes of the tended and tending systems, and other issues. Propulsion is, however, a major issue for future commercial LEO systems, and the appropriate choice for specific application will probably result from detailed considerations of both performance and overall integration issues.

NASA has established the Low Thrust Propulsion Program in response to the great leverage and range of requirements for onboard propulsion. The specific elements of the Low Thrust Propulsion Program are shown on table II. The elements were selected to address the propulsion requirements of launch and orbit transfer vehicles, Earth-orbit systems, and planetary spacecraft for a broad range of civil and government missions. Some aspects of the program are, therefore, probably beyond the near-term interest of the commercial sector. It is clear, however, that onboard propulsion does and will play an important role in the characteristics and performance of future commercial space systems. The following section of the paper will briefly discuss the various relevant elements of the NASA Low Thrust Propulsion Program to provide insights into their characteristics and status regarding application to commercial systems.

LOW THRUST PROPULSION

Future commercial space applications range from GEO communications satellites, to Earth observers at MEO, to LEO platforms. The onboard propulsion requirements for these different systems are very diverse, and the NASA Low Thrust Propulsion Program contains elements with a range of characteristics to accommodate the various applications. In the following, selected elements of the NASA program will be presented and their characteristics, status, and potential use on commercial systems discussed.

Storable Chemical Rockets

For several years, efforts have been under way to develop storable chemical rockets that can operate at very high temperatures with Earth- and, ultimately, space-storable bipropellants. An AerojetTechSystems and Ultramet team conducted a program to identify material combinations that could withstand the oxidizing environments associated with storable bipropellants and then fabricate and demonstrate 22- and 445-N thrust rockets. After an extensive test program, rhenium coated with iridium was selected for the rocket chamber. Small, Earth-storable bipropellant rockets now use columbium coated with silicides for resistance to oxidation. The state of the art of these rockets is shown on figure 5 as a time to failure versus chamber operating temperature. The AerojetTechSystems/Ultramet program was extremely successful as increases in rocket chamber temperatures of about 800 K were demonstrated for significant periods of time (fig. 5). This capability allowed elimination of the film cooling usually used to maintain the silicides at acceptable temperatures and thereby resulted in increases in specific impulse of between 20 and 30 s at a fixed thrust level. The increased performance offers significant reductions in propellant masses for functions such as apogee insertion of GEO spacecraft and delivery and return of MEO space systems. From figure 5, it is also clear that the rhenium/iridium concept can offer great increases in on-orbit propulsion system lifetimes. This feature may also be of leverage for commercial space systems where on-orbit lifetimes are directly related to overall system value.

Resistojets

Resistojets are under development for several applications. All resistojets basically add enthalpy to the propellant from a heater element and accelerate the gas by expansion through a nozzle. Multipropellant resistojets were baselined for Space Station Freedom, and a Rocketdyne/Technion team designed and fabricated a concept that operates at about 0.5 kW. This device has been successfully tested on H_2, H_e, CH_4, N_2, A_r, CO_2, and water (steam) and has demonstrated 10 000 h of operation in a life test with CO_2. The multipropellant resistojet was designed to accept gaseous propellants. The interest in water resistojets for the ISF (ref. 6) led to development of a resistojet concept that could accept liquid as well as gaseous propellants (ref. 9). Figure 6 shows the selected "cyclone boiler" approach, in which the liquid vaporization (if required) and propellant heating are provided by a single heater. To date, the water resistojet has been demonstrated at thrust, power, and specific impulse levels up to about 0.35 N, 1 kW, and 190 s, respectively. As discussed previously, the concept of a "water economy" may offer some significant benefits to the integration of propulsion systems during launch and in-space mission phases. The water resistojet may be of use in those situations where integration issues are paramount and/or may exert major resource leverage on a particular space application.

Arcjets

NASA is developing 1-kW-class arcjets for stationkeeping applications (ref. 10). In arcjets, the propellant is heated by an electrical arc (fig. 7) struck between a cathode and an anode. The anode is usually the nozzle through which the propellant is expanded. The propellant temperature, hence values of specific impulse, achievable via arc heating are significantly above those possible with chemical rockets or resistojets. For example, with hydrazine fuel, the upper limits of specific impulse of monopropellant chemical, bipropellant chemical (with NTO as the oxidizer), and resistojets are about 235, 350, and 325 s, respectively. One-kilowatt hydrazine arcjets have been operated at specific impulses over 700 s which, where power is available and low thrust levels are acceptable and/or preferred, enables major mission benefits. The Rocket Research Company, under NASA sponsorship, is developing a flight-type, 1-kW, hydrazine arcjet system. The arcjet has been fabricated, structurally qualified, and has met design thermal interface and performance goals. Similar arcjets have demonstrated 1000 h/500 cycles, which is adequate for over 15-years on-orbit lifetime on a typical GEO communication satellite. Major arcjet system efforts are now concentrated on demonstrations of an efficient and flightweight power processor and long-life catalyst beds to vaporize the hydrazine. Efforts are also under way (ref. 11) to evaluate fully arcjet particle and field effluents to assure that they pose no problems to spacecraft subsystems and functions.

The arcjet represents a first step toward propulsion systems with performance levels beyond those dictated by material limits. Use of the arcjet for N-S stationkeeping on a 1600-kg (BOL) GEO satellite has been estimated to result in life extensions of over 5 years. Additionally, as seen on table I, use of modestly powered arcjets may result in very great propellant savings for MEO system delivery and/or return if the substantial increases in associated transit times are acceptable.

Ion Thrusters

NASA has conducted and sponsored technology programs on ion propulsion for many years. In ion thrusters (fig. 8), a propellant is ionized by electron impact, and ions are then accelerated by pure electrostatic forces applied by perforated ion optics systems. The use of electrostatic forces enables propellant velocities not attainable by any chemical, resistojet, or arcjet system. For a number of reasons, ion thrusters operate most efficiently at values of specific impulse above about 2500 s. The ratio of thruster power to thrust level for any electric propulsion device is roughly proportional to the value of specific impulse. Therefore, ion thrusters require more than about 8 and 2.5 times the power, for a given thrust, than resistojets and arcjets, respectively. Additionally, ion thrusters of present design use inert gas propellants, which implies a propellant management system different from that routinely used on commercial spacecraft. Regardless of the requirements for power and new propellant systems, the ion thruster does offer unprecedented performance. This quality, as well as the substantial ground and space test development history in the United States and several other countries, has led to recommendation (ref. 12) of ion propulsion for stationkeeping applications and planned space tests on a GEO, Japanese (ref. 13) and a MEO, West German (ref. 14) space system in the near future.

SUMMARY OF RESULTS

Future commercial space systems will include GEO communication spacecraft, and may include MEO Earth observers, and LEO tended platforms. Onboard propulsion is required for all such space systems and can exert major leverage on their performance and resource expectations and constraints. At present, apogee propulsion represents between 40 and 50 percent of the mass injected into geosynchronous transfer orbit, and the useful on-orbit lifetime of GEO communication satellites is now determined by the performance of the N-S stationkeeping propulsion systems. Earth-observing satellites are usually in polar

Sun-synchronous orbits and require propulsion for orbit and attitude control and may also demand delivery/return functions. The on-orbit propulsion for this class of satellite can represent over 10 percent of the BOL on-orbit mass, and studies indicate that the propellant for placement and return is of the order of 25 percent of the initial mass in LEO. Drag makeup and logistics for LEO platforms is also demanding, and evaluation of the proposed Industrial Space Facility, taken as a representative LEO commercial system, indicated requirements for propellant masses between 3 and 8 percent of ISF mass/year. Onboard propulsion is therefore a very major leverage issue for the various classes of potential commercial space systems. NASA has established a Low Thrust Propulsion Program, which includes a variety of chemical and electric propulsion concepts that offer major benefits for onboard propulsion. In particular, advanced Earth and space-storable rockets, resistojet, arcjets, and ion thrusters appear to have promise of near-term application for commercial space systems.

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TABLE I. - PROPULSION REQUIREMENTS FOR BOOST, ON-ORBIT, AND DEBOOST OF A 12 500-kg (BOL) SATELLITE

[Initial and operational altitudes, 350 and 900 km; 5 kW of power assumed for resistojets and arcjets.]

System	Orbit transfer/ on orbit		Propellant mass, kg	Mass of propellant and tanks, kg	Mass G N_2H_4 propellant and tanks, percent	Orbit transfer time, days	Thrust-to-weight ratio
	Thrust, N	Specific impulse, s					
N_2H_4 monoprop	220/220	220/220	3510	3945	---	0.2	2×10^{-3}
NTO/N_2H_4 on-orbit N_2H_4	220/22	310/220	2610	2950	-25	.2	2×10^{-3}
N_2H_4 resistojet	3.2	350	2210	2500	-37	13	3×10^{-5}
N_2H_4 arcjet	1.0	500	1540	1760	-55	40	8×10^{-6}

TABLE 2. - ELEMENTS OF THE NASA LOW THRUST PROPULSION PROGRAM

Low thrust propulsion	
Chemical	Electric
Storables	Resistojets
Integrated H/O	Arcjets Ion MPD

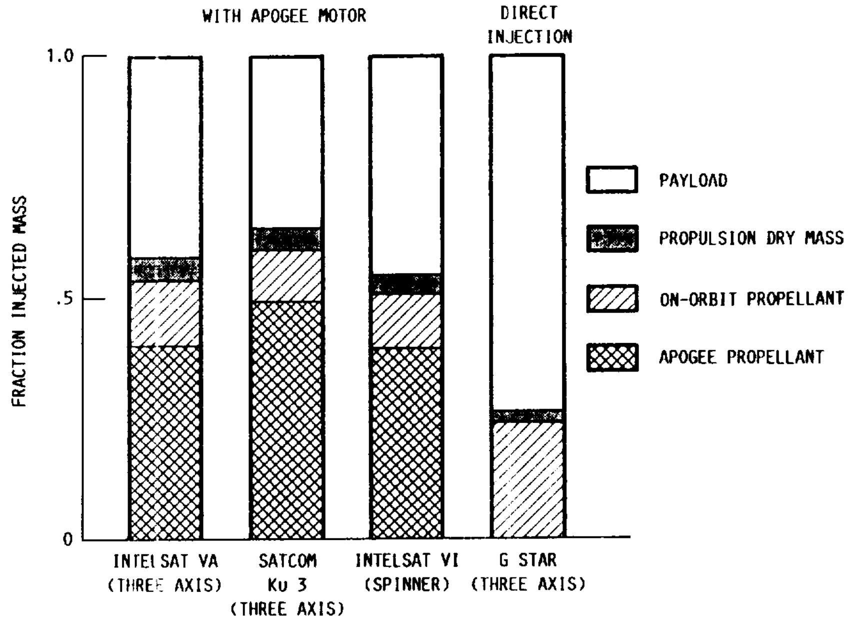

FIG. 1 INJECTED PROPULSION AND PAYLOAD MASS FRACTIONS FOR GEOSYNCHRONOUS SATELLITES.

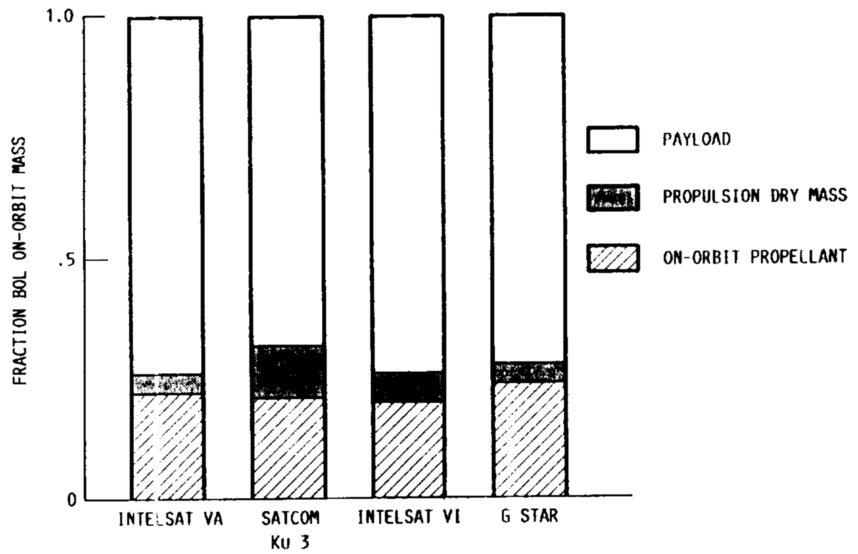

FIG. 2 BEGINNING OF LIVE (BOL) ON-ORBIT PROPULSION AND PAYLOAD MASS FRACTIONS FOR GEOSYNCHRONOUS SATELLITES.

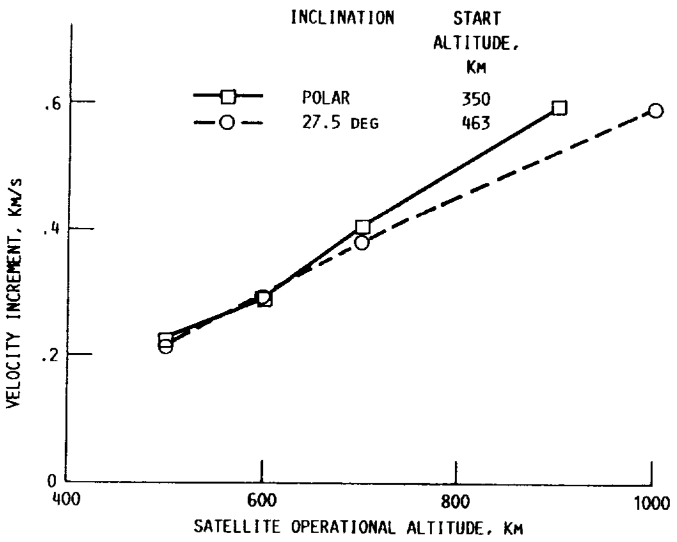

FIG. 3 ROUND TRIP VELOCITY INCREMENTS FOR MEO SATELLITES.

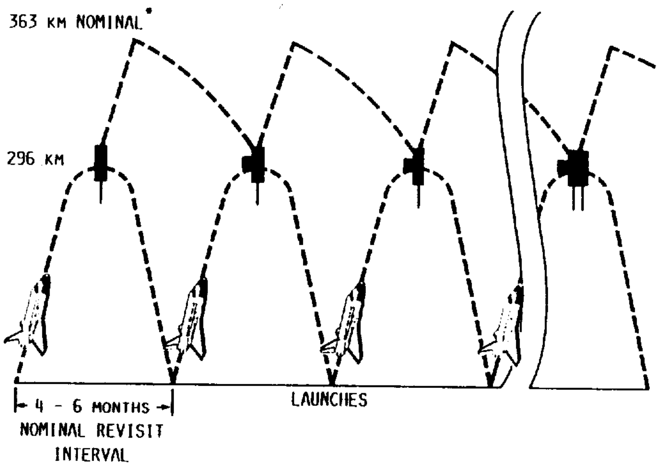

FIG. 4 NOMINAL MISSION PROFILE FOR THE ISF.

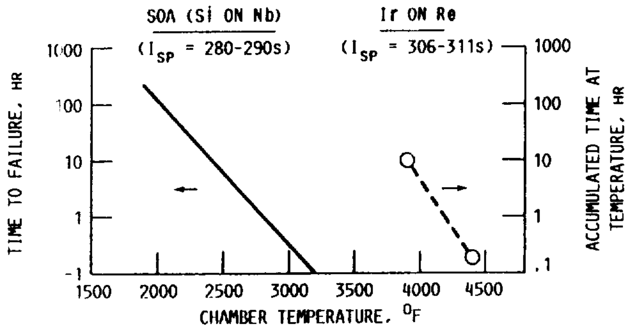

FIG. 5 LIFETIMES OF STATE-OF-ART AND ADVANCED 22N ROCKETS ON EARTH-STORABLE BIPROPELLANT.

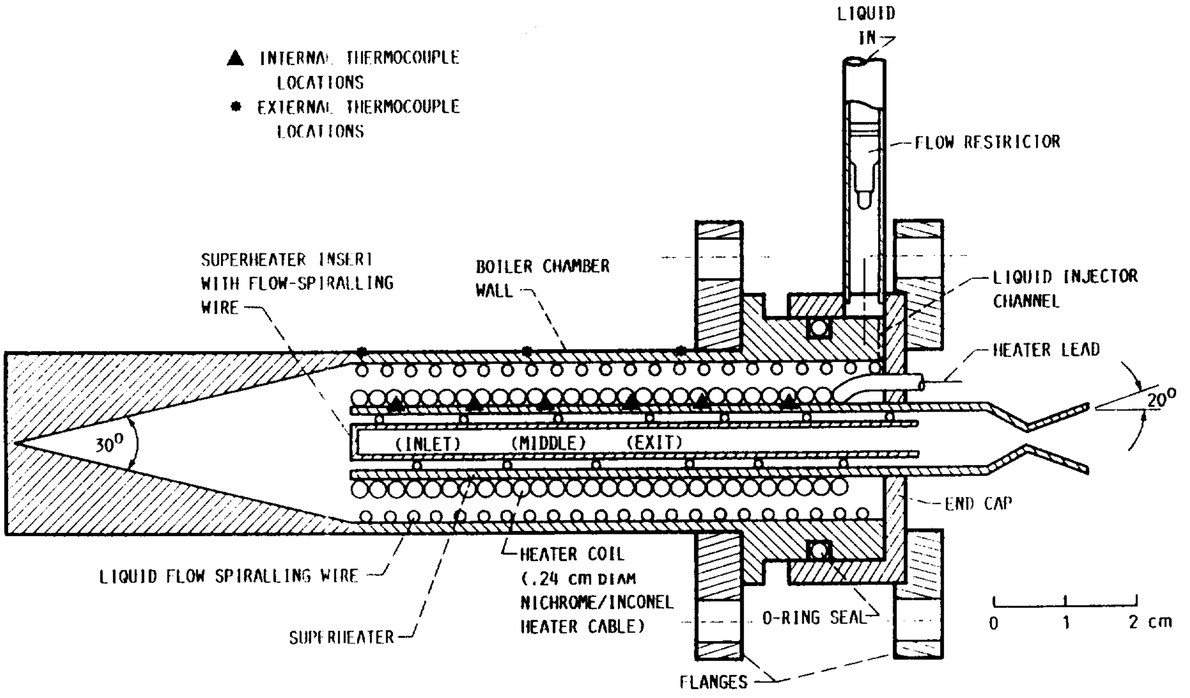

FIG. 6 CYCLONE BOILER WATER RESISTOJET CONCEPT.

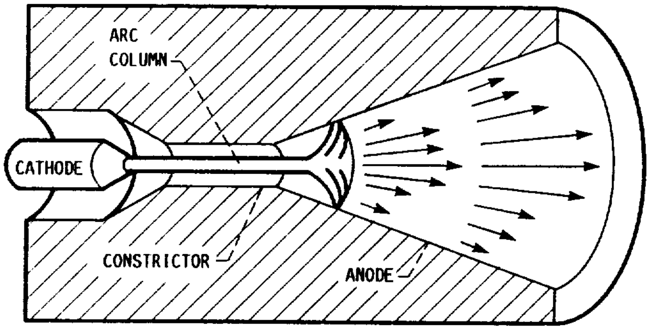

FIG. 7 ARCJET SCHEMATIC.

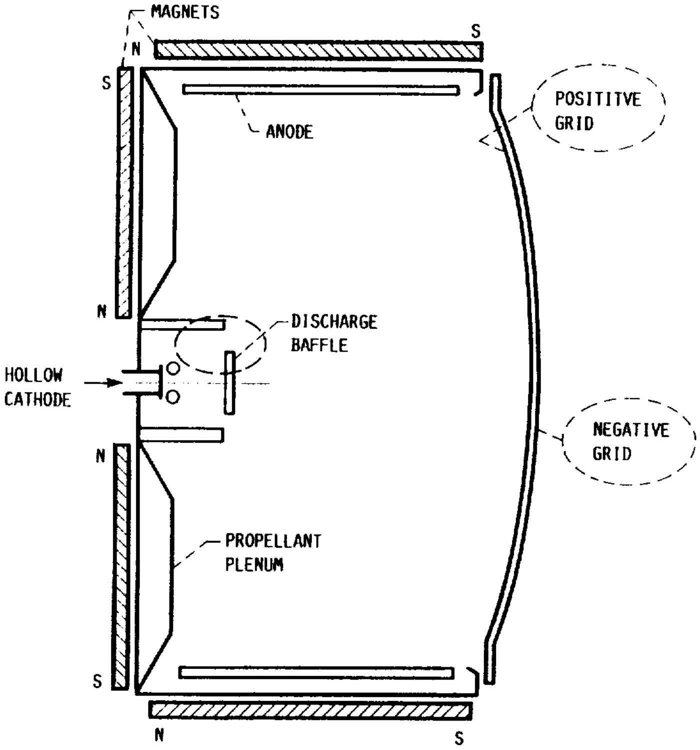

FIG. 8 ION THRUSTER SCHEMATIC.

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16. Abstract

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