POWER NEEDS FOR ELECTRIC PROPULSION*

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ABSTRACT

The present status and future trends of electric propulsion systems and missions are briefly reviewed. Some typical electric propulsion systems are described, these cover a thrust range from 20 micro-pounds to 65 millipounds, and are intended for space missions ranging from satellite attitude control to primary propulsion for interplanetary unmanned vehicles. Electric power needs for electric propulsion systems are summarized in terms of three general mission classes; auxiliary, intermediate and primary propulsion.

In the auxiliary-propulsion class of satellite missions, it appears that electric propulsion power needs for 2000-pound satellites will range from 2 watts to 200 watts, depending on the thrusting function and on future research and development of advanced concepts.

Intermediate-propulsion missions include the MORL and the raising of satellites to 24-hour synchronous orbits. Power for electric propulsion systems in this class of possible future missions will range from 100 watts to several kilowatts.

Possible future primary-propulsion missions include both unmanned and manned interplanetary spacecraft. Small unmanned spacecraft may require power for electric propulsion in the range from 100 watts to several kilowatts. Still farther in the future, manned interplanetary vehicles will probably require electric powerplants of several megawatts output power for the primary electric propulsion system.

Power needs are listed for those thruster systems that appear suited to each particular mission. It is intended that this survey paper will serve as a progress report to those in the field of electric power generation, and hopefully can serve as an approximate guide in the synthesis of future electric propulsion systems.

INTRODUCTION

In the past ten years research and development has brought electric propulsion systems to a flight operational status on some earth satellite spacecraft. Further, complete thruster systems are presently being developed to demonstrate the performance advantages of electric propulsion for interplanetary space flight. The present status and future trends in electric propulsion for this wide range of mission types are discussed in detail in recent articles (refs. 1-6). With electric thruster systems having reached a stage of realistic design, it is of interest to survey the electric power

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needs of the various thruster systems that may be candidates for possible future space missions.

It is the intent of the present paper to provide those working in the field of electric power generation with a comprehensive survey of the electric power needs of presently existing thruster systems, of thruster systems presently in the research and development phase, and of possible future thruster systems that fall in the realm of advanced concepts. Power needs for existing flight operational systems can be defined quite accurately, while the power needs for advanced concepts can be only approximately assessed at the present time. Because of the brief survey nature of this paper, power assessments are limited to gross power levels, and to listings of the highest voltages needed for each particular thruster system. Details of the numerous auxiliary voltages and currents for each thruster system are available from the referenced literature.

It must be noted that many of the mission applications for electric propulsion that are listed in this paper are merely possibilities for the future and should not be construed as real flight programs at this time. Furthermore, the performance characteristics of thruster systems in the research and development phase are only approximate at best and therefore should be used only as approximate guides in preliminary design studies of future vehicles. Performance parameters for the advanced concepts in electric thruster systems are even more tenuous and are included here only to indicate probable future trends in electric power needs.

GENERAL STATUS OF ELECTRIC THRUSTER SYSTEMS

Before proceeding to the assessment of power needs for electric propulsion, it is necessary to clearly define the present status and future trends of electric thruster systems. In defining this status, three general classifications are used: operational, research and development, and advanced concepts. Some thruster systems described here are in transition between these status classifications, and in such cases the judgement for classification hopefully represents the consensus of opinion of those working in the field of electric propulsion.

Operational Thruster Systems

Operational systems are those electric thruster systems that have been flown or will be flown on scheduled spacecraft missions. Some of these operational systems are prime onboard equipment to perform thrusting functions that are required for the success of the mission. Other operational systems have, or will, perform thrusting functions more in the nature of flight demonstration equipment (refs. 1 and 2).

Three examples of operational electric propulsion systems are shown in Figures 1 to 3. The resistojet thruster system shown in Figure 1 is representative of an early application of electric propulsion to operational spacecraft. This resistojet system is used for attitude control and orbit adjustment of the advanced VELA spacecraft.

The contact ion microthruster system shown in Figure 2 is presently being readied for flight on the NASA ATS-D spacecraft as a flight experiment to demonstrate attitude control and east-west station keeping functions. A notable feature of this electric propulsion system is the capability for precision thrust vectoring by means of electrostatic deflection of the ion exhaust beam with the segmented accelerating electrodes shown in the figure. Also notable in the figure is the packaging for the complete power conditioning and control system which draws power from the spacecraft solar-array bus, and provides high voltage d.c. to the thruster system.

The cesium bombardment thruster system shown in Figure 3 is representative of systems intended for north-south station keeping functions on synchronous satellites.

Systems in Research and Development

There are a number of electric thruster systems in various stages of research and development. Each of these systems are expected to have improved performance or operational advantages over the present operational systems. The systems that are classified here in the R & D category have a complete compliment of all components that would be required in a flight version of the system. In addition, all have been operated in laboratory vacuum facilities under test conditions and durations adequate to establish their operational feasibility.

A resistojet system has been proposed as a possible propulsion system for manned orbiting research laboratories to provide thrust for drag cancellation and for attitude control. This proposal is illustrated in Figure 4, and would consist of a total of twenty-four resistojet thrusters located in four modules around the periphery of the MORL. A significant feature of this proposed system is the utilization of carbon dioxide biowaste as propellant for the resistojets. Resistojet systems have been operated with carbon dioxide at specific impulse values high enough to provide the required daily total impulse without exceeding the daily production rate of carbon dioxide biowaste.

Another example of an electric thruster system in the research and development stage is shown in Figure 5. This four-thruster array of mercury bombardment thrusters is typical of the system size and complexity that would be required for primary propulsion of interplanetary unmanned spacecraft. This thruster array is presently under development at JPL for purposes of demonstrating the feasibility of solar electric propulsion systems (refs. 3 and 4).

Advanced Thruster Concepts

A number of advanced concepts have been proposed that have marked potential improvements in performance or operational characteristics. Some of these advanced concepts are discussed in the recent literature (refs. 2 and 6). All of these advanced concepts are based on demonstrated performance of individual components, but none have been operated as complete thruster systems. These advanced concepts are included in the present survey for the purposes of indicating approximate future trends.

POSSIBLE MISSIONS FOR ELECTRIC PROPULSION

Missions for electric propulsion can be roughly divided into three categories: auxiliary, intermediate, and primary propulsion missions. Auxiliary propulsion is generally defined to include thrusting functions of a relatively low magnitude in which the spacecraft velocity is not appreciably affected. The control of satellite attitude is certainly an auxiliary propulsion function, and the station keeping of synchronous satellites may also be included in this category. Intermediate electric propulsion can be defined to include thrusting functions such as drag cancellation for low-level satellites, and significant orbit transfers such as raising a satellite from a low parking orbit to the twenty-four-hour synchronous orbit. Primary electric propulsion missions are those where the electric propulsion system is an upper stage in the overall mission profile.

Propulsion requirements for auxiliary propulsion missions can be defined in terms of an effective vehicle velocity increment, ΔV per year, and for a given spacecraft mass a total impulse per year can be determined (refs. 6 and 7). Propellant weight W_{pr} is simply the ratio of total impulse to specific impulse, I:

$$W_{pr} = (\text{total-impulse/yr})/I \quad , \quad \text{lb/yr} \tag{1}$$

where W_{pr} is the propellant consumption per year, total-impulse/yr is the mission requirement, and specific impulse I is an electric thruster performance parameter. From inspection of equation (1) it is evident that very long missions will require high specific impulse in order to avoid excessive propellant weights.

In general, higher specific impulse in electric thrusters is attained by increasing the electric power input to the thruster. This is illustrated by the following expression:

$$P = 1/2 \; g_c \; FI/\eta_{th} \tag{2}$$

where P is power input to the electric thruster system in watts, g_c is the gravitational conversion factor 9.81 meters/sec^2, F is the thruster system thrust in newtons, I is specific impulse, and η_{th} is thruster system efficiency. By considering equations (1) and (2) simultaneously it is evident that there will be an optimum value of the specific impulse for each particular set of mission parameters and propulsion system parameters.

Mission and trajectory analysis for electric propulsion spacecraft is not a simple matter as the preceding discussion may imply. However the general features of the influence of specific impulse on propellant weight and powerplant weight are as expressed by equations (1) and (2). This trade-off between propellant weight and propulsion system weight should be kept in mind in considering the text of the next section.

POWER NEEDS FOR TYPICAL MISSIONS

Power needs for a number of typical electric propulsion missions are shown in Table I to III. Each of these missions could be flown with any one of several thruster systems. In general, the power needs of the various thruster systems are widely different, depending on the thruster efficiency, and other factors. For this reason there are quite a few thruster systems listed for each of the missions in Tables I to III.

The missions considered in this paper are merely intended to be representative, particularly with respect to the space-craft weights that have been assumed. For example, in Table I, it has been assumed that the final satellite in 24-hour synchronous orbit will have a mass corresponding to a ground weight of 2000 lbs. Synchronous satellites of much greater mass are certainly within the realm of possibility, even with existing booster rocket capabilities. The 20-micropound and 490-micropound thrust levels have been determined for 2000-lb satellites with continuous thrusting modes of operation (ref. 7). The 700-micropound thrust level for north-south station keeping has been suggested (ref. 8) as a system redundancy feature where one of a pair of opposing thrusters could do the north-south station keeping in case the other thruster failed. Thrust levels would be higher for more massive satellites.

In Table II, the MORL mission is based on a recent study (ref. 9). Important mission parameters in this study are a 36,000-pound vehicle in a 164 nautical mile circular orbit, requiring a total impulse of 1900 lb-sec/day. Any changes in these mission parameters could be reflected in changes of power levels. The satellite orbit maneuvers mission shown in Table II is based on an estimate of thrust levels that might be required for substantial changes in satellite orbit or position (ref. 8). With one exception, the power levels shown in Table II for the synchronous satellite raising mission were determined from basic trajectory information (ref. 10). These calculations are based on a 300 nautical mile parking orbit, with raising by electric propulsion to the 24-hour synchronous circular orbit, with the constraint that the electric propulsion system including the solar cell array (or other powerplant) is included in the final 2000-pound spacecraft. It was also assumed that the electric propulsion is done only 1/2 time in each orbit about earth (because of Earth-shadowing of the solar arrays), and no allowance is made for the plane change from the 300 nautical mile parking orbit to the final equatorial synchronous orbit. Trajectory and mission parameters for the 180-day synchronous satellite mission with the mercury bombardment thruster system are reported elsewhere (ref. 11).

Mission parameters for the 600-pound unmanned spacecraft interplanetary mission shown in Table III represent a minimal approach to unmanned spacecraft (ref. 12). The 2300-pound unmanned spacecraft mission shown in Table III is representative of scientific probe missions to the major planets (refs. 3, 4, 13, 14). The 600,000-pound manned interplanetary round-trip mission listed in Table III is representative of possible future applications of electric propulsion (ref. 15).

Electric power needs for the various thruster systems and missions listed in Tables I to III were calculated from the information and references summarized in the Appendix. The detailed information in the Appendix is provided primarily for the benefit of those having particular interest in electric thrusters per se, and secondarily as supporting documentation for the power levels shown in Tables I to III.

Operational thruster systems for auxiliary propulsion missions have relatively high electric power needs, particularly at the higher values of specific impulse that will be required for long duration missions. The two thruster systems listed in Table I in the research and development category will not offer much reduction in power requirements at high specific impulse. However, there are several advanced thruster concepts that have promise of significantly lower power needs at high specific impulse. Whether these possible future reductions in electric power are especially advantageous will depend on the size of the spacecraft powerplant. If the spacecraft is a communications satellite in a 24-hour synchronous orbit, it is possible that the spacecraft powerplant will be in the kilowatt class, and if this is the case then the power savings indicated in Table I may not be sufficiently advantageous to justify the development of the advanced concepts for that particular mission.

There is another important feature of the thruster systems for auxiliary propulsion missions that are listed in Table I in the R & D and the advanced concept categories. This feature is the ability of some of the thruster systems to operate at relatively low voltage levels in comparison with the high voltages required by the operational systems at high specific impulse. For example, the mercury bombardment thruster system presently in the R & D phase has a maximum of 400 volts d.c. in the overall system, which is a voltage level that seems attainable directly from the solar cell array without any intervening power conditioning required (ref. 2). Virtual elimination of the high voltage power conditioning equipment would be an advantage both in cost and in improved reliability. In the advanced concept category the lithium isotope/ resistojet offers the possibility of operating directly from the spacecraft bus at practically any voltage, but this thruster system has a relatively low specific impulse, and therefore would have a high propellant weight for long duration missions. In this same category the potassium hollow-cathode ion expansion concept would have a significantly lower voltage than the mercury bombardment thruster in the R & D category, and in addition would have a higher specific impulse. The ultimate in auxiliary electric propulsion systems is represented by the isotope/liquid-spray thruster concept which has a high specific impulse and a very low electric power need, e.g., just enough for the telemetry. This advanced concept would have its own electric power source completely independent from the spacecraft powerplant.

Electric power needs for the intermediate propulsion missions shown in Table II will vary widely, depending on the particular mission and the particular thruster system. In the MORL class mission where biowaste is used as the propellant, it appears that considerable power savings might be achieved by the advanced thruster concept where an isotope heater is coupled with the electric heater in the resistojet thruster system. This reduction in electric power needs would be achieved in principle by thermally heating the propellant to a fairly high temperature, then raising the propellant to its final high temperature with electric power. The ammonia resistojet and the lithium isotope/ resistojet might also be used in the MORL class missions, especially where propellant resupply would not be a significant disadvantage.

The ultimate choice of thruster system for the satellite orbit maneuvers missions will depend primarily on the total impulse requirement of the orbit maneuvers, and on whether or not a considerable amount of electric power is onboard the satellite for other purposes. For instance, direct-broadcast synchronous satellites may eventually have onboard power in the kilowatt range, and if this power were available for orbit maneuvers then the mercury bombardment or the hollow-cathode ion expansion thrusters shown in Table II might be preferable to the resistojets.

Availability of onboard power for electric propulsion may be a very important consideration in possible synchronous satellite raising missions. For instance, if the satellite had somewhat more than 1000 watts of electric power for broadcast functions after positioning, then this power might be used for the lithium isotope/resistojet advanced thruster concept in raising the satellite from a low parking orbit to the 24-hour synchronous orbit. With a specific impulse of 400 seconds, and effectively "free" power this advanced concept should have performance superior to all-chemical delivery systems. Even if additional power were used to reduce the raising time to 40 days, the lithium isotope/resistojet concept appears to offer payload advantage over conventional chemical rockets in this mission. These remarks are not intended to promote electric propulsion for this particular mission, but rather to indicate the great importance of power level assessment in the field of electric propulsion.

Electric power level is of major importance in the primary electric propulsion missions shown in Table III. Because of the high total-impulse requirements of interplanetary unmanned and manned missions, optimum specific impulse is in the 2000 to 3000 second range for propulsion systems having power-plant specific mass of 50 to 100 lb/kwe. The mercury bombardment and the cesium bombardment thruster systems shown in the R & D category in Table III are not very efficient in this range of specific impulse, thereby increasing the electric power requirement. In addition, their voltage requirements are 1000 volts d.c., which may dictate the use of power conditioning in solar electric systems. The hollow-cathode ion expansion thruster system in the advanced concepts category has promise of higher efficiency and lower voltage in the specific impulse range of interest for solar electric unmanned interplanetary spacecraft. This same observation may be made for possible future manned interplanetary spacecraft with nuclear electric powerplants. Although the hollow-cathode ion expansion advanced concept could in principle have a thrust density sufficiently high for reasonable packaging in the payload shroud of very large chemical booster rockets, the MPD arc advanced concept has much promise for a very high thrust density, which may be a definite advantage for the megawatt power levels that would ultimately be required for manned interplanetary electric spacecraft.

CONCLUSIONS

From this survey of electric power needs for electric propulsion, it can be concluded that power levels may range from several watts to several megawatts depending on the mission and the propulsion function. Missions with high total impulse will require specific impulse of the thruster system in the range above 2000 seconds in order to avoid excessive propellant requirements. Operation at these high values of specific impulse will require commensurately high electric power needs. In such systems with very high power levels, electric thruster system efficiency will become of crucial importance in order to minimize powerplant size and mass. There are a number of advanced concepts that offer significant improvements in thruster efficiency.

The need for higher specific impulse in intermediate and in auxiliary propulsion missions will become more acute as mission durations are increased to 5 or 10 year periods. The concomitant increase in power needs for the electric thruster system might be conveniently absorbed in satellites that have high power levels onboard for other functions. However, in the interest of cost reductions, ease in packaging in the booster vehicles, and elimination of sun-orienting mechanisms, there will certainly be many satellites where electric power will be at a premium. In these cases, reduction of power needs by a matter of a few watts will still serve as a strong impetus to the further work on advanced concepts in auxiliary electric propulsion systems.

A final observation can be made with regard to voltage levels required for electric thruster systems. Specific impulse in the range of 2000 to 3000 seconds is of particular interest for solar electric interplanetary spacecraft. In this range of specific impulse, the ion thrusters have accelerating voltages in the range from 100 to 1000 volts d.c. These factors have led to an interest in research and development leading to solar cell arrays having such output voltages. Virtual elimination of power conditioning equipment is a strong motivation in this regard. This trend towards lower voltages may be of direct benefit to future nuclear electric power generation systems for electric propulsion. For example, alternator output voltage in turboelectric systems might be matched directly to the power needs of the primary electric thruster system.

APPENDIX - THRUSTER SYSTEM CHARACTERISTICS

Information, data, and assumptions that have been used in assessing the power needs for electric propulsion are summarized in this appendix.

AUXILIARY - PROPULSION

Operational Thruster Systems

NH_3 resistojet. I = 150 sec. Valves, 2 w; telemetry, 2 w. (Ref. 1)

NH_3 resistojet. I = 200 sec. Valves, 2 w; telemetry, 2 w. (Ref. 16)

liquid-spray. I = 900 sec. Telemetry, 2 w; neutralizer, 5 w; vaporizer, 5 w. For F = 490 micropounds, P = 2+(14+5+5)/.7 = 36 watt, where 14 w thruster power includes a thruster efficiency of 70%, and where power-conditioning efficiency is 70%. (Ref. 17)

pulsed-plasma. I = 1000 sec. Telemetry not included. $\eta_c = .8$. (Ref. 18)

Cs-bombardment. I = 5000. Power conditioning efficiency, 70%. (Ref. 19)

Cs-contact. I = 6700 sec. (Ref. 1)

Thruster Systems in Research and Development

magnetic-expansion MPD. I = 420 sec. at F = 490 micropounds, I = 570 sec. at F = 700 micropounds. Xenon propellant, all permanent magnets. Power conditioning assumed to be not needed. (Refs. 20 and 21)

Hg-bombardment. I = 1700 sec. Power/thrust = 220 watt/mlb. Power conditioning efficiency assumed to be $\eta_c = 0.7$. $P = (P/F)(F)/(\eta_c) = 220 \times .49/.7 = 154$ watts. (Ref. 11)

Advanced Concepts

Li isotope/resistojet. I = 400 sec. Power/thrust = 5 watt/mlb. (Ref. 2)

liquid spray. I = 1200 sec. Assumes improved charge/mass. Power conditioning efficiency, 0.7. P = 2 + (18+5+5)/.7 = 42 watts. (Ref. 22)

K hollow-cathode ion expansion. I = 2600 sec. Potassium propellant. Beam current, 300 milliamp. Thruster system ev/ion, 97. Net accelerating voltage, 110 v. Power conditioning assumed to be not needed. Neutralizer power, 5 watt. Vaporizer power, 5 watt. Total power P = .3(110+97) + 10 = 72 watts. (Refs. 2, 23, and 24)

isotope/liquid-spray. I = 4000 sec. Telemetry, 2 watts. Power from radio-isotope electrogenerator integral with thruster system. (Refs. 2 and 25)

INTERMEDIATE PROPULSION

Thruster Systems in Research Development

CO_2 biowaste resistojet. I = 180 sec. Thruster power/thrust, P/F = 4.5 watt/mlb. Power for CO_2 collection, 110 watt for 24 millipounds thrust level. (Ref. 9)

NH_3 resistojet. I = 300 sec. Thruster power/thrust, P/F = 15.7 watt/mlb. (Ref. 26)

Hg bombardment. I = 1900 sec. Thruster system power/thrust, P/F = 86 watt/mlb. Power conditioning efficiency, η_c = 0.88. (Ref. 11)

Advanced Concepts

CO_2 biowaste isotope/resistojet. I = 180 sec. Thruster power/thrust, P/F = 1.5 watt/mlb. Power for CO_2 collection, 110 watt for 24 millipound thrust level. (Ref. 2)

Li isotope/resistojet. I = 400 sec. Thruster power/thrust, P/F = 5 watt/mlb. (Ref. 2)

hollow-cathode ion expansion. I = 1000 sec. Thruster power/thrust, P/F = 60 watt/mlb. Power conditioning assumed to be not needed. (Refs. 2, 23, and 24)

PRIMARY PROPULSION

Thruster Systems in Research and Development

H_2 resistojet. I = 740 sec. Plenum temperature, 2200°K. Thruster power/thrust, P/F = 24 watt/mlb. (Ref. 26)

Hg bombardment. I = 2670 sec. Thruster efficiency, η_{th} = 0.7. Power conditioning efficiency, η_c = 0.88. Power/thrust, P/F = (4.45x26.700)/(2x.7x.88) = 96.5 kw/lb. (Ref. 11)

Cs bombardment. I = 3360 sec. Thruster efficiency, η_{th} = 0.59. Power conditioning efficiency, η_c = 0.88. Power/thrust, P/F = (4.45x33,600)/(2x.59x.88) = 144 kw/lb. (Ref. 19)

Advanced Concepts

Li isotope/resistojet. I = 400 sec. Power/thrust, P/F = 5 watt/mlb. (Ref. 2)

hollow-cathode ion expansion. I = 2400 sec. Cesium propellant. Discharge power, 85 ev/ion. Other powers (neutralizers, vaporizers, etc.), 25 ev/ion. Propellant utilization efficiency, η_U = 0.99. Net accelerating voltage, 400 v. Thruster efficiency, η_{th} = .99/(1 + 110/400) = 0.77. Power/thrust, P/F = $4.45v_j/(2\eta_{th})$ = 4.45x24,000/(2x.77) = 69 kw/lb. (Refs. 2, 23, and 24)

MPD arc. This thruster concept has promise of high performance in the megawatt power range. It is assumed here that this concept may be developed to a performance level equal to that of the ion expansion advanced concept listed above. The arc voltage is approximately $60/\eta_{th}$ = 60/.77 = 78 volts. (Ref. 27)

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TABLE I - POWER FOR TYPICAL AUXILIARY-PROPULSION MISSIONS
24-HOUR SYNCHRONOUS SATELLITE
(ELECTRIC BUS POWER, WATTS)

	THRUSTER SYSTEM	SPECIFIC IMPULSE, SEC	HIGHEST VOLTAGE IN THRUSTER SYSTEM	E-W STATION KEEPING AND ATTITUDE	NORTH-SOUTH STATION KEEPING	
			SPACECRAFT, LB	2000	2000	2000
			THRUST, MICROPOUNDS	20*	490	700†
OPERATIONAL	NH_3 RESISTOJET	150	24	12	-	-
OPERATIONAL	NH_3 RESISTOJET	200	24	-	20	22
OPERATIONAL	LIQUID-SPRAY	900	6000 D.C.	5	36	45
OPERATIONAL	PULSED-PLASMA	1000	1400 D.C.	7	-	-
OPERATIONAL	Cs - BOMBARDMENT	5000	2000 D.C.	-	159	226
OPERATIONAL	Cs - CONTACT	6700	3000 D.C.	35	175	249
R & D	MAGNETIC-EXPANSION MPD	420	60 D.C.	-	70	100††
R & D	Hg - BOMBARDMENT	1700	400 D.C	-	154	220
ADVANCED	Li ISOTOPE/RESISTOJET	400	S/C BUS	-	8	11
ADVANCED	LIQUID SPRAY	1200	6000 D.C.	6	42	55
ADVANCED	K HOLLOW-CATHODE ION EXPANSION	2600	110 D.C.	-	-	72
ADVANCED	ISOTOPE/LIQUID-SPRAY	4000	S/C BUS	2	2	2

* INCLUDES PRECISION THRUST-VECTORING CAPABILITY

† FOR SYSTEM REDUNDANCY WHERE ONE FIXED THRUSTER CAN DO N-S STATION-KEEPING IF OTHER THRUSTER FAILS

†† SPECIFIC IMPULSE, 570 SEC.

TABLE II - POWER FOR TYPICAL INTERMEDIATE-PROPULSION MISSIONS
(ELECTRIC BUS POWER, WATTS)

	THRUSTER SYSTEM	SPECIFIC IMPULSE, SEC	HIGHEST VOLTAGE IN THRUSTER SYSTEM	MORL*	SATELLITE ORBIT MANUEVERS	SYN. SAT. RAISING** 40 DAYS	SYN. SAT. RAISING** 180 DAYS
			SPACECRAFT, LB	36,000	2,000	2,000	2,000
			THRUST, MILLIPOUNDS	24	50	1,000	300
R & D	CO_2 BIOWASTE RESISTOJET	180	6	240†	-	-	-
R & D	NH_3 RESISTOJET	300	6	380	790	17,400	4,000
R & D	Hg BOMBARDMENT	1900	500 D.C.	-	4,300	-	25,000††
ADVANCED	CO_2 BIOWASTE ISOTOPE/RESISTOJET	180	S/C BUS	146†	-	-	-
ADVANCED	Li ISOTOPE/RESISTOJET	400	S/C BUS	120	200	5,000	1,200
ADVANCED	Cs HOLLOW CATHODE ION EXPANSION	1000	100	-	3,000	-	-

* TOTAL IMPULSE, 1900 LB-SEC/DAY

† INCLUDING 110 WATT FOR CO_2 COLLECTION

** FROM 300 N.M. TO SYNCHRONOUS ALTITUDE, ASSUMING ONE-HALF TIME IN EARTH SHADOW, SOLAR-ARRAY INCLUDED IN FINAL 2000 LB.

†† FROM 1000 N.M., FINAL VEHICLE MASS = 7100 LB., INCLUDING 25 KW SOLAR ARRAY, BUT NOT INCLUDING ELECTRIC THRUSTERS, TANKAGE, AND SOME POWER CONDITIONING.

TABLE III - POWER FOR TYPICAL PRIMARY PROPULSION MISSIONS
(ELECTRIC BUS POWER, WATTS)

	THRUSTER SYSTEM	SPECIFIC IMPULSE, SEC	HIGHEST VOLTAGE IN THRUSTER SYSTEM	UNMANNED		MANNED
	SPACECRAFT, LB			600	2300	600,000
	THRUST, POUNDS			.018	.065	20
R & D	H_2 RESISTOJET	740	6	430	1,560	-
	Hg BOMBARDMENT	2670	1000 D.C.	1,730	6,300	1.94 Mw
	Cs BOMBARDMENT	3360	1000 D.C.	2,600	9,350	2.9 Mw
ADVANCED	Li ISOTOPE/RESISTOJET	400	S/C BUS	90	325	-
	Cs HOLLOW-CATHODE ION EXPANSION	2400	400 D.C.	1,200	4,500	1.4 Mw
	MPD ARC	2400	78	-	-	1.4 Mw

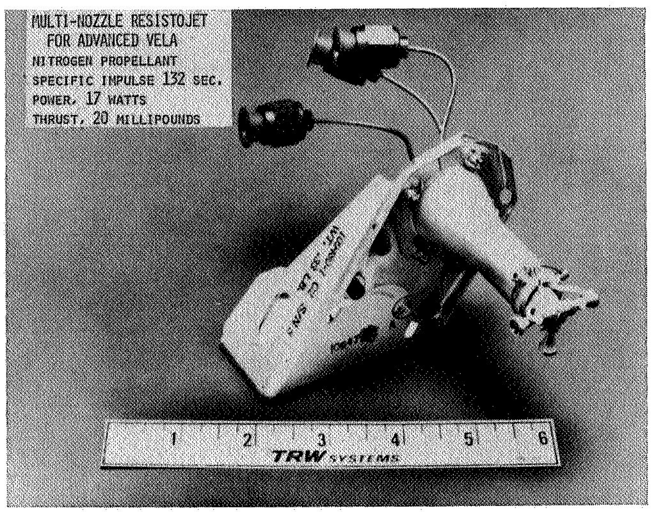

FIG. 1 - TRW three-nozzle resistojet for VELA advanced spacecraft.

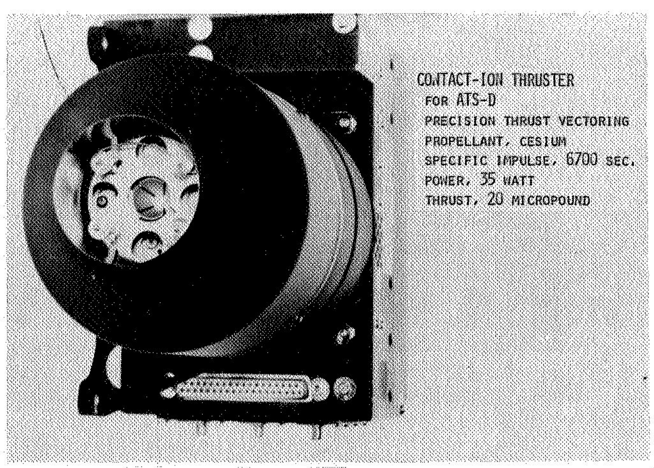

FIG. 2 - EOS cesium contact ion thruster for NASA ATS D spacecraft.

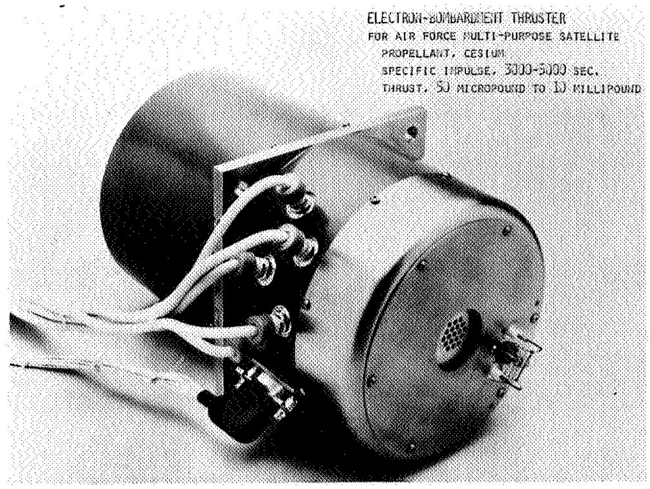

FIG. 3 - EOS cesium bombardment thruster for air force multi-purpose satellite program.

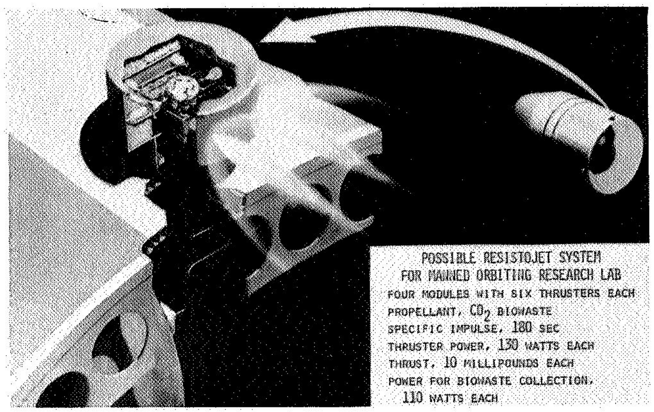

FIG. 4 - Possible resistojet system for MORL.

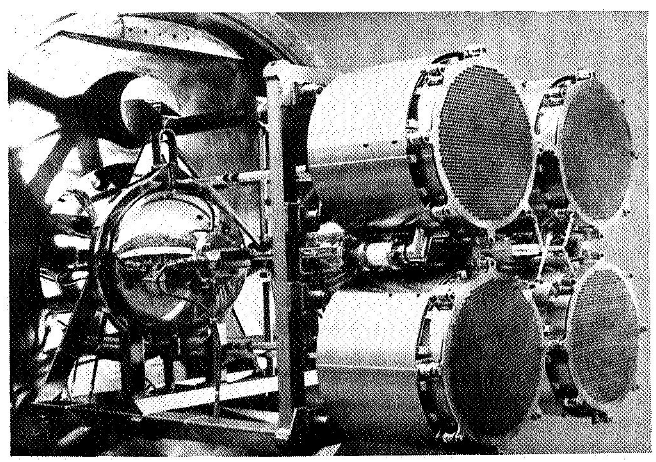

FIG. 5 - Electric thruster system under development at Jet Propulsion Laboratory for possible solar-electric interplanetary spacecraft. Thrust, 65 millipounds. Specific impulse, 2700 sec. Thruster system power, 10 kilowatts.