| AD NUMBER: AD0823288 |
|---|
| LIMITATION CHANGES |
| TO:<br>Approved for public release; distribution is unlimited. |
| FROM:<br>This document is subjet to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory 01 Sep 1967. Other requests shall be referred to Air Force Air Force Aero Laboratory, Wright-Patterson AFB, OH. |
| AUTHORITY |
| ST-A AFAPL LTR, 12 APR 72 |

AFAPL-TR-67-80

# AREAS OF APPLICABILITY FOR ELECTRIC PROPULSION SYSTEMS

JACK W. GEIS

TECHNICAL REPORT AFAPL-TR-67-80

SEPTEMBER 1967

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, WPAFB, Ohio.

AIR FORCE AERO PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

# NOTICE

100 - November 1967 - CO455 - 13-275

# ERRATA

AFAPL-TR-67-80, Areas of Applicability for Electric Propulsion Systems
Air Force Aero Propulsion Laboratory, WPAFB, Ohio

1. Page 16 - Sentence near the middle of the page should read, "Boundaries HS and CE were established at about 300 to 500 millipounds for a single engine or for a cluster of engines, as shown in Figure 6"

2. Page 19, Table III - Under STATE OF DEVELOPMENT for a colloid engine, it should read, "Feasibility established, low to middle thrust range". Under STATE OF DEVELOPMENT for a pulsed plasma engine, it should read, "Feasibility established, low thrust range".

AFAPL-TR-67-80

# AREAS OF APPLICABILITY FOR ELECTRIC PROPULSION SYSTEMS

*JACK W. GEIS*

This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, WPAFB, Ohio.

# FOREWORD

The analysis reported herein was performed as an in-house effort by the author for the Aerospace Power Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. The work was accomplished under Task No. 314102, Project No. 3141, "Electric Propulsion Technology."

This analysis was conducted between January 1967 and May 1967. This report was submitted by the author in June 1967.

This technical report has been reviewed and is approved.

P. E. PEKO
Major, USAF
Power and Propulsion Branch
Air Force Aero Propulsion Laboratory

# ABSTRACT

An analysis was performed to define the range of specific impulse and thrust covered by most of the electric thrustors in the state-of-the-art to determine their areas of applicability. Candidate thrustors included in the study include the contact ion, bombardment ion, radioisotope ion, resistojet, radioisojet, colloid, pulsed plasma, arc, and inductive accelerator. The results of the analysis are presented in graphic form to show the areas where each of these thrustors indicated quantitative and qualitative advantages. Quantitative parameters considered in the evaluation included efficiency, thrust, specific impulse, size, and lifetime, and qualitative factors included reliability, compatibility, and complexity. A sample matrix is constructed for use in making tradeoffs in selecting the best thrustor for a specific application.

This abstract is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, WPAFB, Ohio.

## TABLE OF CONTENTS

# ILLUSTRATIONS

## TABLES

## SYMBOLS

| | |
|---|---|
| $A$ | area, in feet$^2$ |
| $C_p$ | specific heat at constant pressure |
| $F$ | thrust, in pounds |
| $g$ | gravitational constant (32.2 lbm - ft/lbf-sec$^2$) |
| Isp | specific impulse, in seconds |
| $Isp_{eff}$ | effective specific impulse, in seconds |
| $J$ | beam current density, in milliamperes/cm$^2$ |
| $m$ | mass of propellant ion |
| $P_b$ | beam power, in kilowatts |
| $P_\ell$ | power losses, in kilowatts |
| $P_t$ | total input power, in kilowatts |
| $q$ | electronic charge on propellant ion |
| $T$ | temperature |
| $t_b$ | thrust time, in seconds |
| $\dot{W}_p$ | propellant weight flow, in pounds/second |
| $W_{ps}$ | power supply weight, in pounds |
| $W_t$ | total system weight, in pounds |
| $\frac{W_{tank}}{W_p}$ | tankage/propellant weight ratio |
| $\alpha_p$ | specific weight of power supply, in pounds/kilowatt |

## SYMBOLS (CONTD)

| | |
|---|---|
| $\alpha_r$ | specific weight of radioisotope fuel capsule, in pounds/thermal kilowatt |
| $\eta$ | efficiency, percent |
| $\phi_0$ | applied ionizer voltage |
| $\|\phi_1\|$ | magnitude of applied accelerator voltage |

# SECTION I

# INTRODUCTION

For almost ten years, the Air Force and NASA have been conducting research and development, both in-house and contractual, on many types of electrical propulsion concepts. Some of these concepts have failed to prove feasible and have been dropped from consideration. Others have proved their feasibility, have been developed extensively, and are becoming competitive with other candidate engines across a broad range of thrust and specific impulse.

Each of the candidate electrical propulsion devices developed has certain advantages and disadvantages. The regions of applicability for the various electric propulsion devices within the state-of-the-art can be shown graphically on an "Areas of Applicability" chart (AOA). Such a chart can show the regions of specific impulse and thrust where each candidate thrustor operates most advantageously; it cannot show precise boundaries between the various areas, however, because precise boundaries do not exist. Many factors influence the location of boundary lines, not the least of which is a low confidence level in scaling the thrustors from one size to another and in extrapolating present engine performance to predict realistic performance for engines of the near future. Furthermore, each of the engines is in a different stage of development; some thrustors have progressed to a point where they can be considered for advanced development programs, while others have merely shown feasibility.

At the lower thrust levels, the differences in the quantitative parameters for the different engines are not significant. At these levels, therefore, the qualitative parameters assume more importance in selecting a specific device for a specific purpose. Qualitative parameters can be subject to much discussion, and the relative importance of each will be influenced by current and near future satellite demands, as well as by personal views of the electric propulsion industry as to what function a certain device should perform.

In spite of these problems in establishing detailed parameters for electric thrustor performance, general parameters can be established in an AOA chart that will be useful in describing electric thrustors. In addition to listing the quantitative and qualitative parameters to be considered, the AOA chart will assist the industry in evaluating the relative merits, advantages, and requirements for specific electric engine concepts. As more definitive data becomes available, the chart can be revised to reflect mission constraints and the capabilities of specific electric thrustors, as well as to indicate which concepts do not contribute to advancing the state-of-the-art in electric propulsion and should be discontinued.

# SECTION II

# THE SPECIFIC IMPULSE PARAMETER

Specific impulse plays an important role in determining the applicability of any electric thrustor. Let us, therefore, define this term first, and then show how it affects engine characteristics.

Specific impulse is defined as the length of time in seconds an engine can operate at a certain thrust level on a given amount of fuel. The higher the specific impulse value for a given thrustor, the more economical that thrustor is in using its propellant. Specific impulse can be expressed as

$$\mathrm{Isp} = F/\dot{W}_p \qquad (1)$$

where

Isp = specific impulse, in seconds

F = thrust, in pounds

$\dot{W}_p$ = propellant weight flow, in lbs/sec.

An electric engine requires electrical power to produce thrust. This electrical power is given by

$$P_t = F \ \mathrm{Isp} \ (10^2/45.9\eta) \qquad (2)$$

where

$P_t$ = total input power to thrustor, in kilowatts

F = thrust, in pounds

$\eta$ = efficiency, in percent.

If mission constraints dictate minimum power consumption, then the electric thrustor must operate at a low Isp. Figure 1 shows the amount of power required by three different types of electric thrustors operating at three different values of specific impulse but providing the same amount of thrust (10 millipounds). Of these three thrustors, the resistojet, operating at an Isp of 250 seconds, would use the least input power.

Specific impulse affects total system weight, and in many missions, total system weight is a most important factor. Total system weight can be calculated from

$$W_t = P_t \ \alpha_p + \dot{W}_p \ t_b \qquad (3)$$

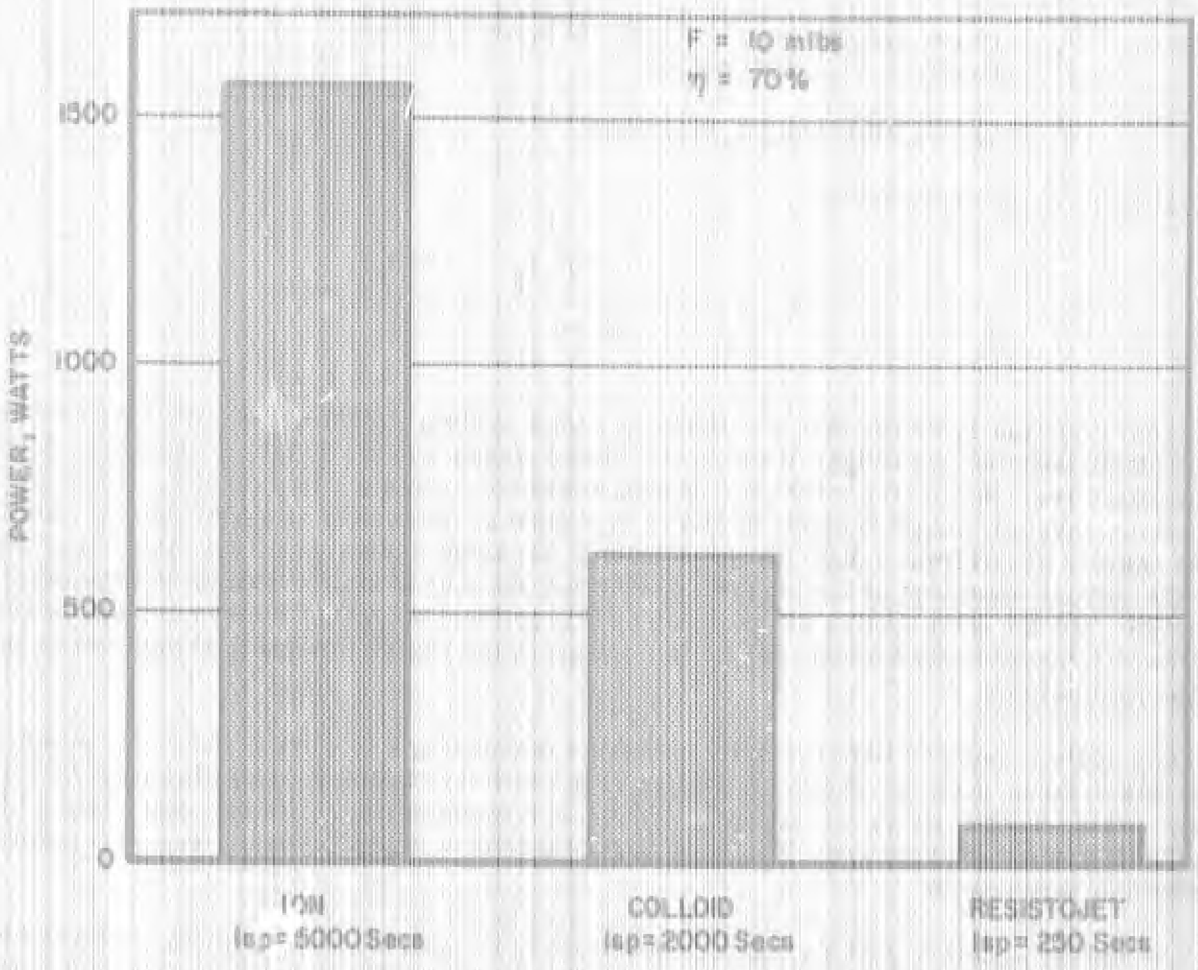


Figure 1. Power Comparisons for Electric Thrustors

where

$P_t$ = total input power, as given by Equation 2

$\dot{W}_p$ = propellant flow rate, as given by Equation 1

$t_b$ = thrust time, in seconds

$\alpha_p$ = power supply specific weight, in pounds of power supply per kilowatt output

$W_t$ = total system weight, in pounds.

Equation 3 can be expanded to

$$W_t = \frac{F \ \mathrm{Isp} \times 10^{3} \ \alpha_p}{45.9\eta} + \frac{F \ t_b}{\mathrm{Isp}} \tag{4}$$

From Equation 4, we can see that the lowest total system weight will be achieved by making a tradeoff between the weight of the initial power supply and the weight of the total amount of propellant required for the mission. The total amount of propellant is a function of thrust time. A typical system weight tradeoff is shown in Figure 2, which depicts three electric thrustors that operate at different values of Isp but provide the same amount of thrust. The initial weight of the device operating at the highest Isp (the ion system) is higher than that of the other two systems, but the total system weight (including propellant weight) of the two devices operating at lower Isp eventually exceeds the system weight of the engine operating at high Isp as thrust time accumulates.

Duty cycle is another parameter that affects system weight. Figure 3 shows the weights for the same three systems shown in Figure 2 but with the thrustors operating on a 20 percent duty cycle. In this case, the tradeoffs occur at a mission time 5 times longer than with the engine operating continuously. The time axis, therefore, must be based on mission duration instead of thrust time.

The entire specific impulse range, therefore, is of interest to the systems designer using electric propulsion because of the tradeoffs that he can make in achieving optimum system power and weight. These tradeoffs involve the parameters of thrust level, specific impulse, power supply weight, mission duration, and thrust duty cycle.

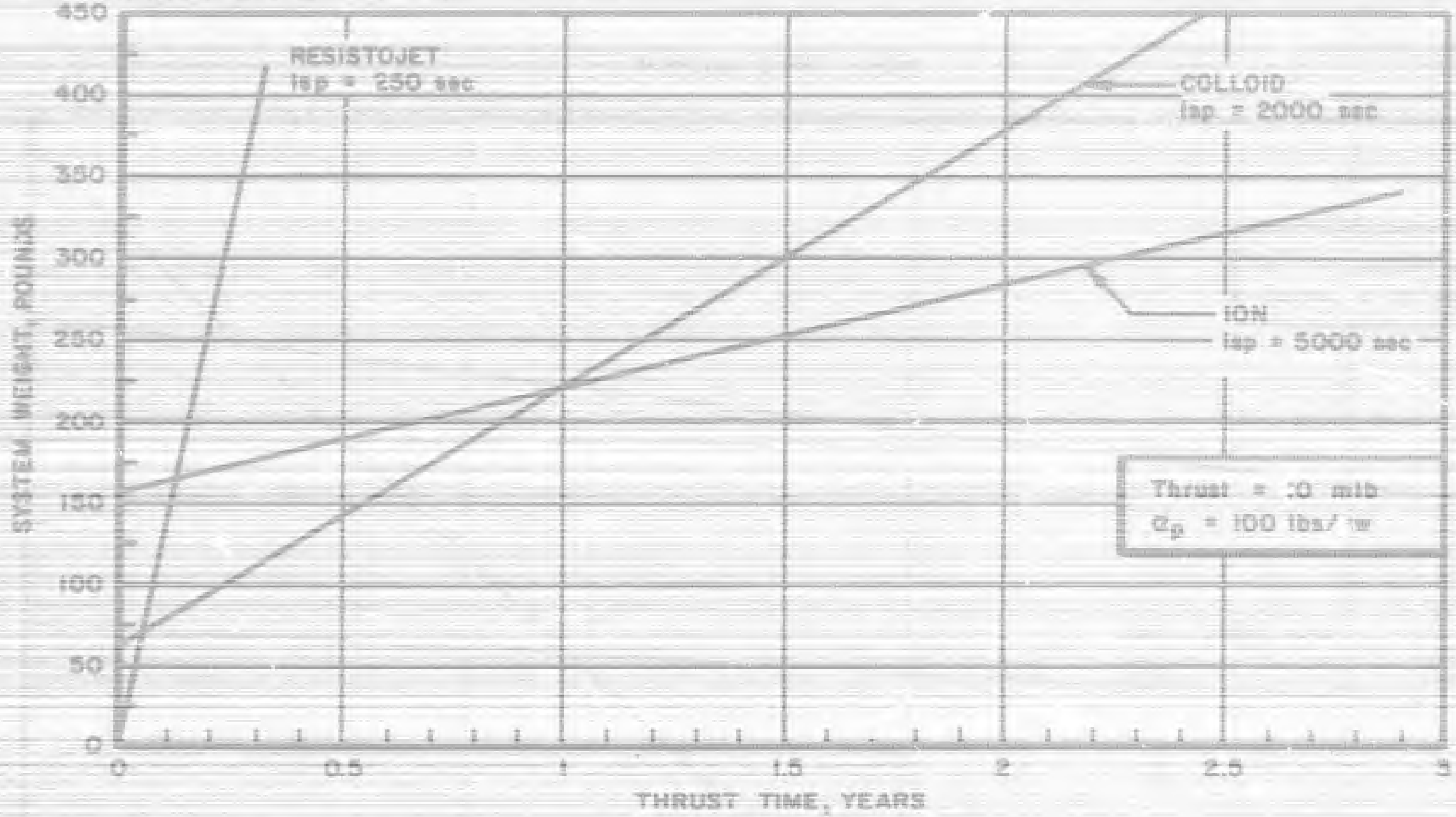


Figure 2. System Weight Comparisons for Electric Thrusters, Continuous Thrust

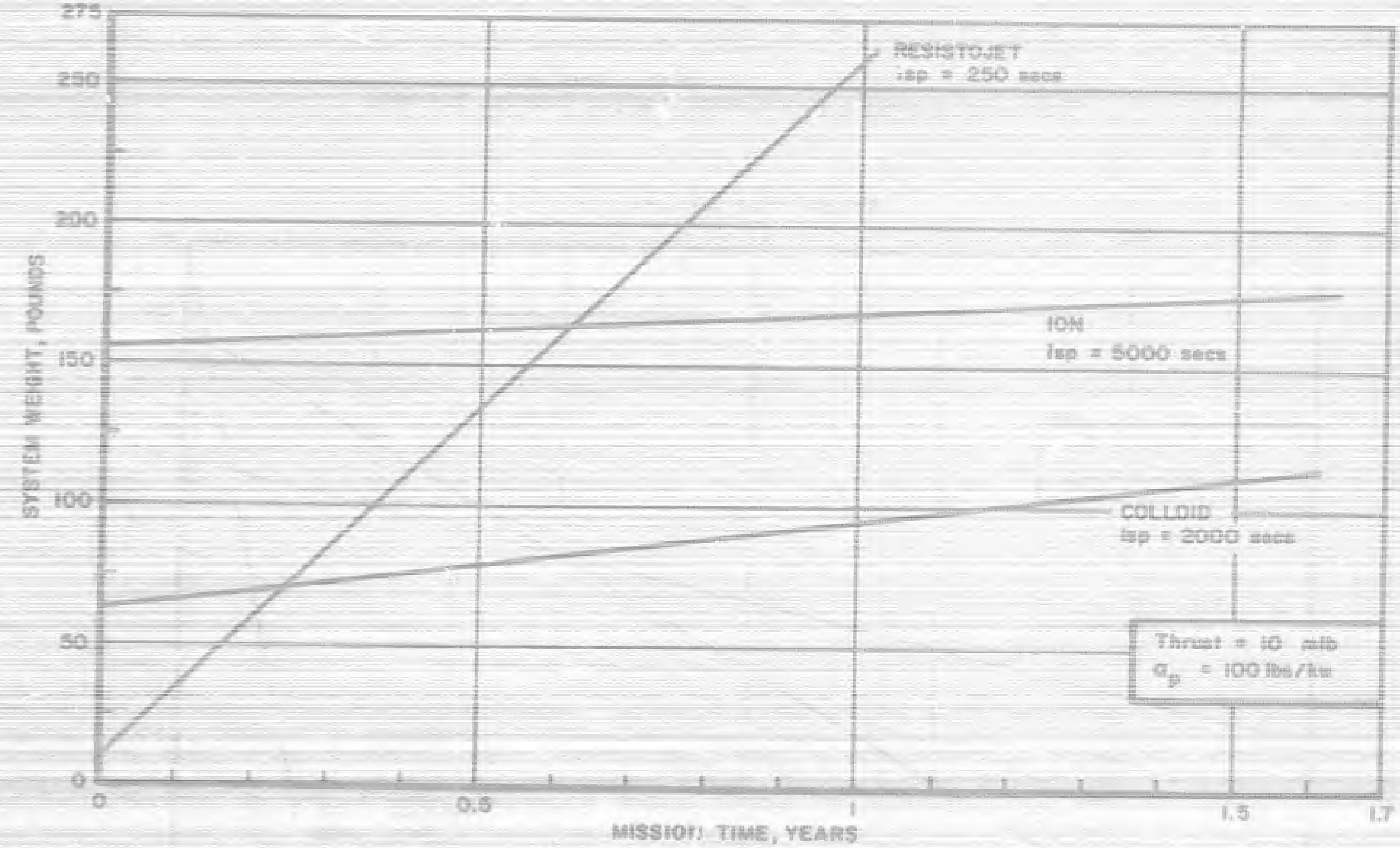


Figure 3. System Weight Comparisons for Electric Thrustors, 20 Percent Duty Cycle

# SECTION III

# DETERMINING THE AREAS OF APPLICABILITY

An Areas of Applicability chart is presented in Figure 4. This semilog chart is broken down into six regions, labelled A through F, which are based on requirements for specific impulse and thrust. The tables indicate the types of electric thrustors and how each meets the requirements for the areas. Specific electric thrustors will then be selected for operation in each of these areas.

## 1. AREAS A, B, AND C

Based on specific impulse capability, the contact ion, radioisotope ion, bombardment ion, arc, and inductive accelerator engines are all competitive for operation in Area A. On the basis of thrust, however, only the first three (contact, radioisotope, and bombardment ion) can operate effectively in Area A, as shown in Table I.

For Areas B and C, the same five candidate thrustors are competitive on the basis of specific impulse. On the basis of thrust, however, the arc engine and the inductive accelerator can meet requirements only at the upper thrust range. (The arc engine and the inductive accelerator are inherently high-power devices.)

Three electric thrustors, therefore, can operate satisfactorily in Areas A, B, and C -- the contact ion, the radioisotope ion, and the bombardment ion. Let us now select one of these engines for each area by generally defining the boundaries. Precise boundaries cannot be located for any area, however, because many factors must be considered in selecting an engine for any specific mission.

## 2. BOUNDARIES AB AND AC

The contact ion engine has been selected for Area A because the technology for cesium contact ion engines to operate at thrust levels up to about 100 to 200 micropounds is well established (Reference 1). Complete engine systems, including thrustor, feed system, and power conditioning and control system, have been developed past the prototype stage into the qualification and flight system stages. Current plans call for using 20 micropound thrustor systems on near-future satellites. A photograph of a flightworthy, micropound-thrust, cesium contact ion engine system is shown in Figure 5. The cylindrical containers covering the thrustor and the electronics package are shown superimposed on the photograph. Systems such as these are being planned for advanced development to prove out the long-term reliability and compatibility of the total system.

The contact ion engine has proved it is versatile in performing thrust vectoring and thrust throttling functions, which are required of engines of this size. Radioisotope ion engines and bombardment ion engines can also operate effectively in this region, but the advantages they would provide at this low thrust level are not sufficient to warrant advanced development. At thrust levels above several hundred micropounds, however, performance of the bombardment ion engine has proved to be superior to that of the conventional contact ion engine, both in efficient operation at moderate values of Isp and in long-term reliability. At the higher values of Isp ( > 7000 seconds), the efficiency of the contact ion engine is slightly greater than that of the bombardment engine, but this advantage is insignificant in the micropound thrust region.

## 3. BOUNDARY BC

For the BC boundary, the weight of the system is the important factor and the boundary is based upon a comparison of the performance of the bombardment engine with that of the

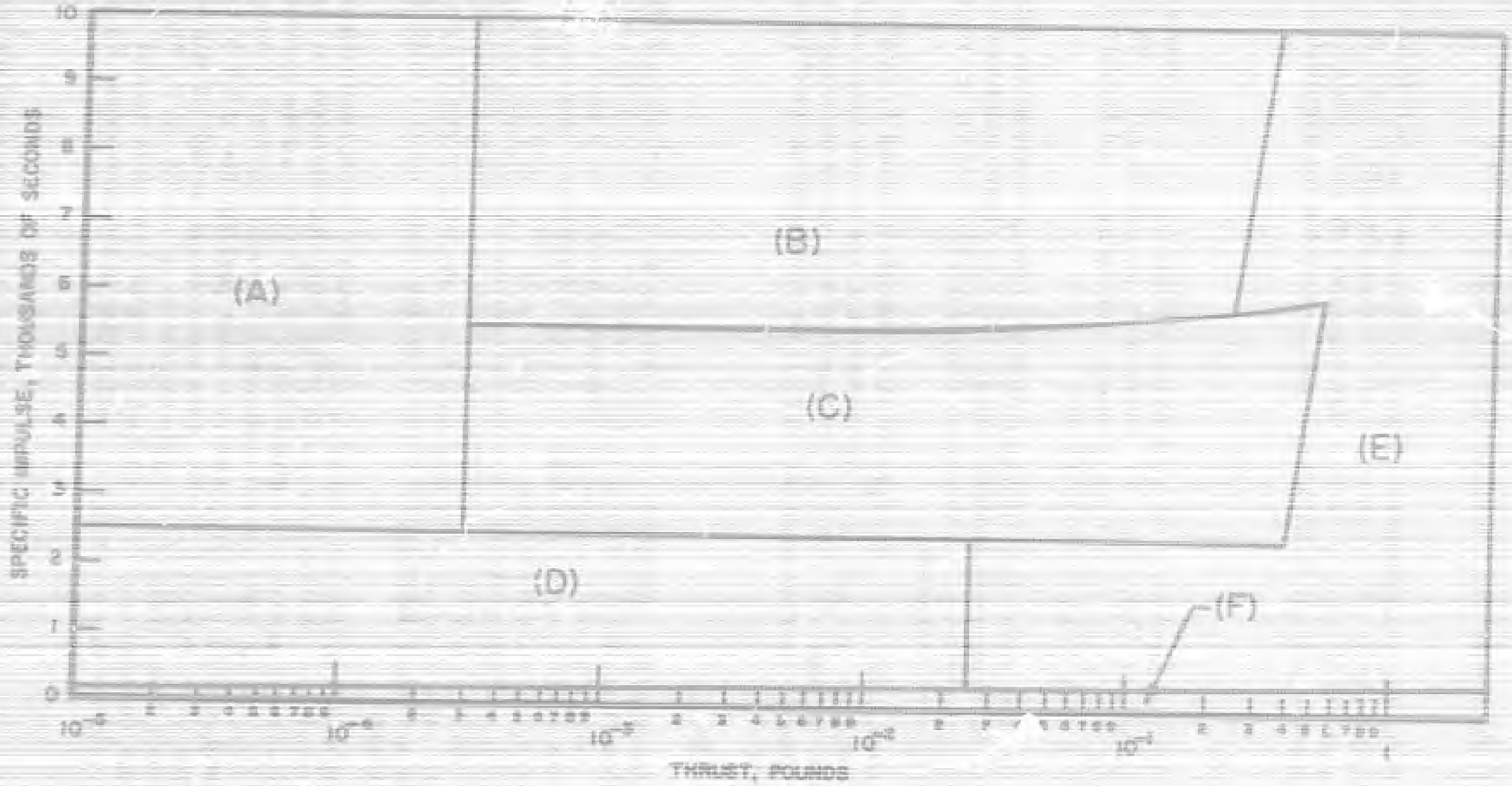


Figure 4. Areas of Applicability for Electric Thrustors

## TABLE I

## CANDIDATE THRUSTORS FOR AREA A

| ENGINE | SPECIFIC IMPULSE REQUIREMENT | THRUST REQUIREMENT | STATE OF DEVELOPMENT |
|---|---|---|---|
| Contact Ion | Yes | Yes | Engineering capability established; systems developed in 20 micropound range |
| Bombardment Ion | Yes | Yes | Engineering capability established; systems developed in 20 micropound range |
| Radioisotope Ion | Yes | Yes | Feasibility established for 100 micropound isotope capsule |
| Resistojet | No | – | – |
| Colloid | No | – | – |
| Pulsed Plasma | No | – | – |
| Arc | Yes | No | – |
| Inductive Accelerator | Yes | No | – |
| Radioisojet | No | – | – |

TABLE II
CANDIDATE THRUSTORS FOR AREAS B AND C

| ENGINE | SPECIFIC IMPULSE REQUIREMENT | THRUST REQUIREMENT | STATE OF DEVELOPMENT |
|---|---|---|---|
| Contact Ion | Yes | Yes | Engineering capability established; clustering and fabrication studies required at upper thrust range |
| Bombardment Ion | Yes | Yes | Engineering capability established; clustering and fabrication studies required at upper thrust range |
| Radioisotope Ion | Yes | Yes | Engineering capability established; clustering and fabrication studies required at upper thrust range. Isotope capsule development required. |
| Resistojet | No | - | - |
| Colloid | No | - | - |
| Pulsed Plasma | No | - | - |
| Arc | Yes | Upper range, only | Feasibility established, upper range |
| Inductive Accelerator | Yes | Upper range, only | Feasibility established, upper range |
| Radioisojet | No | - | - |

Figure 5. Contact Ion Microthrustor System

radioisotope-heated contact ion engine in the millipound size. The use of a radioisotope fuel capsule to heat the contact ionizer eliminates the radiated losses from the hot ionizer, which is the major source of power loss in millipound size engines of this type (Reference 2). In this comparison, total system weight must include the weight of the electrical power supply required to accelerate the ion beam as well as that of the radioisotope capsule.

The weight of the electrical power supply for a conventional contact ion or bombardment ion engine can be computed by:

$$W_{ps} = P_t \alpha_p = P_b \alpha_p + P_\ell \alpha_p \tag{5}$$

where

$W_{ps}$ = power supply weight, in lbs

$P_b$ = beam power, in kilowatts

$P_\ell$ = power losses, in kilowatts

The power-to-thrust ratio, in kilowatts per pound, is

$$W_{ps} / F\alpha_p ) = (P_b + P_\ell ) / F = P_t / F \tag{6}$$

For a thrustor in which part of the power is supplied by a radioisotope capsule, Equation 5 becomes

$$W_{ps} = P_b \alpha_p + P_\ell \alpha_r \tag{7}$$

where

$\alpha_r$ = radioisotope capsule specific weight, in pounds of capsule weight per thermal kilowatt output.

The effective or normalized power-to-thrust ratio is given by

$$\frac{W_{ps}}{F\alpha_p} = \frac{P_b}{F} + \left(\frac{P_\ell}{F}\right)\left(\frac{\alpha_r}{\alpha_p}\right) = \frac{1}{F}\left[P_b + P_\ell\left(\frac{\alpha_r}{\alpha_p}\right)\right] \tag{8}$$

The percent performance gain provided by reducing power supply weight, or the effective power-to-thrust ratio of the radioisotope ion engine over that of the bombardment ion engine (Reference 2), is shown in Figure 6. The efficiency of ion engines decreases with a decrease in specific impulse; however, a greater relative performance gain can be made with a radioisotope ion engine in the lower Isp range. The lines representing constant percent performance gain are not strictly horizontal at the lower thrust levels because the thrustor beam power is a smaller fraction of the total power, and all power losses change little with changes in thrust.

The boundary line BC divides an area covered by the cesium bombardment ion engine at the higher range of Isp from the area covered by the radioisotope ion engine at the lower range. The line indicates a difference in performance between the two thrustors of approximately 20 percent. At higher values of specific impulse (at least at the lower millipound thrust levels), a reduction in power supply weight does not indicate a definite advantage for the radioisotope ion engine.

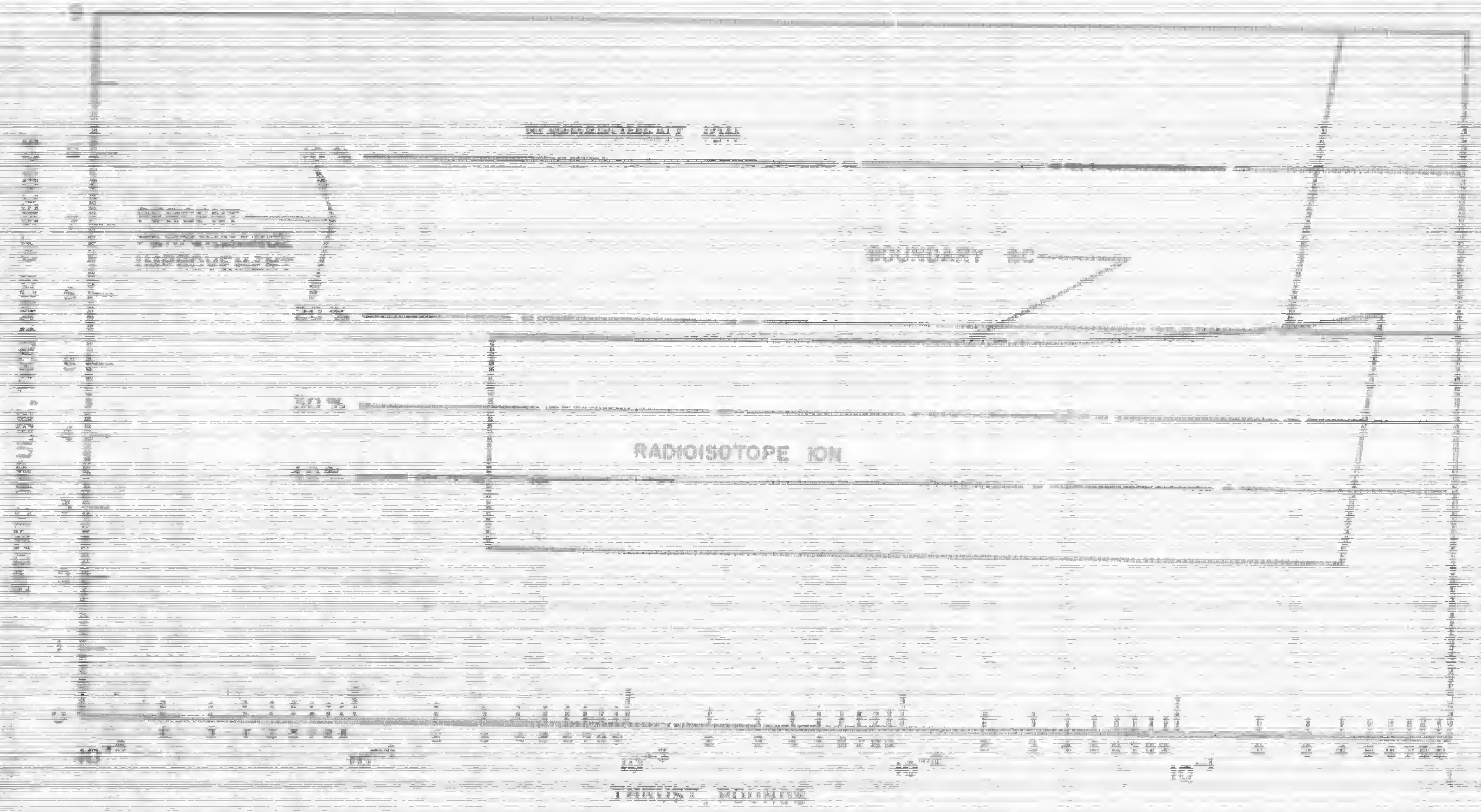


Figure 5. Relative Performance Gain (Power-To-Thrust Ratio) of Radioisotope Ion Over Bombardment Ion

## 4. BOUNDARIES AD, CD, AND CE

For these boundaries, the factors involved are beam current density, accelerator/decelerator ratio, neutral fraction, electrode material, and electrode spacing as they affect the lifetime of the accelerator electrode of an ion engine. The accelerator/decelerator ratio can be determined by

$$\text{accel-decel ratio} = \left(\frac{\phi_0 + |\phi_1|}{\phi_0}\right) \tag{9}$$

where

$\phi_0$ = applied ionizer voltage

$\phi_1$ = magnitude of applied accelerator voltage.

In order to maintain good efficiency in the conventional contact ion engine, to minimize size and weight of the radioisotope capsule in the radioisotope ion engine, and to minimize thrustor size in the bombardment ion engine, the ion beam current must be kept fairly constant as specific impulse is decreased (Reference 3). A fairly constant ion beam current will ensure that the thrust delivered from the engines will not decrease providing the accelerating voltage, $\phi_0 + |\phi_1|$, is maintained at least at space-charge-limited conditions. As specific impulse is decreased, however, the ionizer voltage decreases by

$$\phi_0 = \frac{m}{2q}\ \text{Isp}^2\ g^2 \tag{10}$$

where

m = mass of propellant ion

q = electronic charge on propellant ion

g = gravitational constant.

To keep $\phi_0 + |\phi_1|$ at some limiting value determined by space-charge-limiting conditions, the voltage on the accelerator, $|\phi_1|$, must be increased. Increasing the voltage on the accelerator increases the accel-decel ratio, as shown by Equation 9. Both in-house and contractual studies (Reference 4) have shown that accelerator current drain rises rapidly with an increase in accel-decel ratio. It is theorized that this is due to the ion beam spreading as the accel-decel ratio increases, which provides a greater probability of the ions striking the accelerator electrode and causing it to erode.

Figure 7 shows the relative effect of decreasing the specific impulse on the lifetime of accelerator electrodes for ion engines. The horizontal lines indicate the lifetimes determined for a contact ion engine, based on the observed rise in accelerator drain with decrease in specific impulse (for a constant beam current operation).

All of the factors mentioned, such as beam current density and the electrode materials, influence the way in which lowering the specific impulse affects the lifetime of the electrodes. Thus, the minimum specific impulse limits for ion engines are imposed by the reduction in electrical efficiency and electrode lifetime.

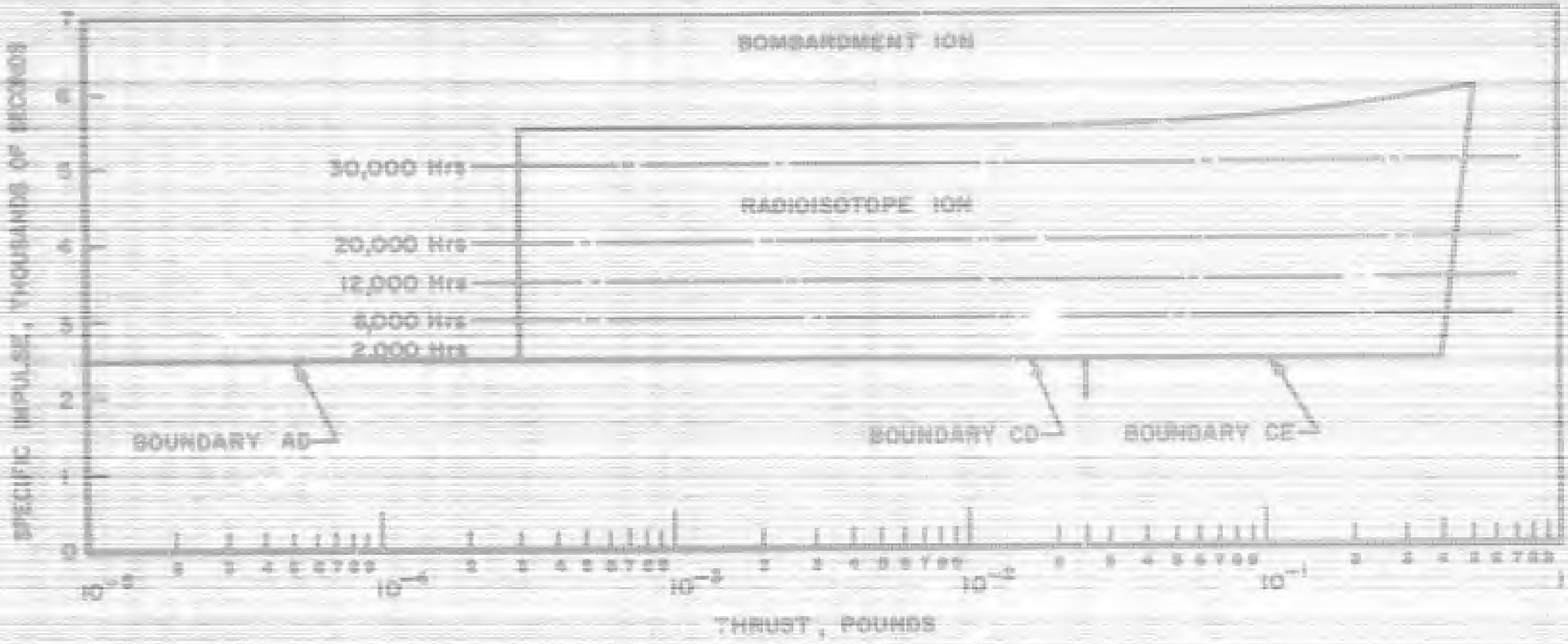


Figure 7. Estimated Ion Engine Accelerator Electrode Lifetimes

## 5. BOUNDARIES BE AND CE

Volume and size of the thrustor as functions of thrust and Isp determine these boundaries. The frontal area (accelerator area) of an ion engine is shown in Figure 8 as a function of thrust and Isp. The frontal area (accelerator area) can be determined for space-charge-limited conditions by

$$A = F \Big/ \left(11.82 \times 10^{-3}\; J \sqrt{\phi_0}\right) \qquad (11)$$

where

$A$ = area in cm$^2$

$F$ = thrust, in millipounds

$J$ = beam current density, in ma/cm$^2$

$\phi_0$ = net accelerating potential, in kilovolts.

Therefore, thrustor size is influenced not only by beam current density, but also, although to a smaller extent, by specific impulse (which is a function of $\phi_0$ as shown by Equation 10).

Boundaries BE and CE were established at about 30 to 60 millipounds for a single engine, as shown in Figure 8. Whether or not the ion engines would be used at very high thrust levels might well depend upon the size and volume constraints imposed by the particular satellite.

## 6. AREA D AND BOUNDARIES AD AND CD

Candidate thrustors for Area D are listed in Table III. For this area, the ion and resistojet engines no longer meet requirements for specific impulse. Here the colloid and pulsed plasma engines are competetive, and the arc and inductive accelerators begin to become competitive at the higher thrust levels.

One of the parameters involved in the use of the colloid engine is the voltage that must be applied. The required extraction voltage as a function of specific impulse, based on a predicted charge-to-mass ratio (q/m) of 10,000 coulombs/kg, is shown in Figure 9. These values were calculated from Equation 10. This figure shows that accelerating voltages become unrealistic at higher values of specific impulse.

In pulsed plasma devices, stored energy is discharged from a capacitor into a solid propellant and the propellant is vaporized. The vaporized propellant is then accelerated to high velocities by some means such as fluid dynamic expansion or Hall or Lorenz acceleration techniques. Pulsed plasma devices have been shown to be capable of operating at specific impulse values greater than 10,000 seconds, but current Air Force programs emphasize devices in the 500 to 2000 sec range (Reference 5). In the thrust range up to several hundred micropounds, little if any overall performance is gained by operating a pulsed plasma device at high Isp. For example, a thrustor providing 300 micropounds of thrust for a total mission-required impulse of 9450 lbs-sec would require 4.7 pounds of propellant when operating at an Isp of 2000 secconds, and 1.9 pounds of propellant when operating at an Isp of 5000 seconds.

In the low thrust range (several micropounds), pulsed plasma engines require only a few watts which makes them highly competitive with the ion engines and the resistojet in cases where power is critical. At present, little data is available on capacitor performance and

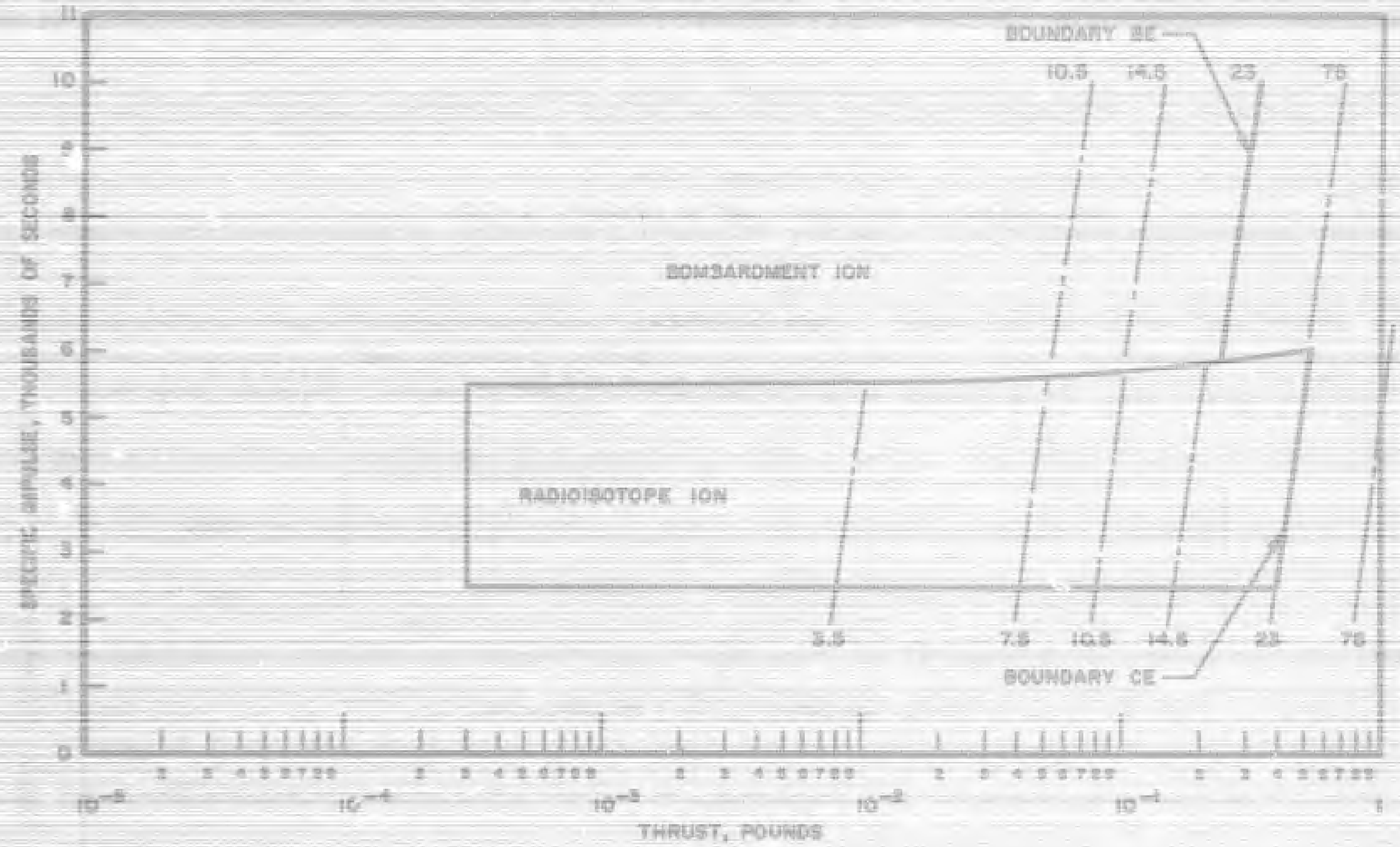


Figure 8. Ion Engine Frontal Diameter (In Inches)

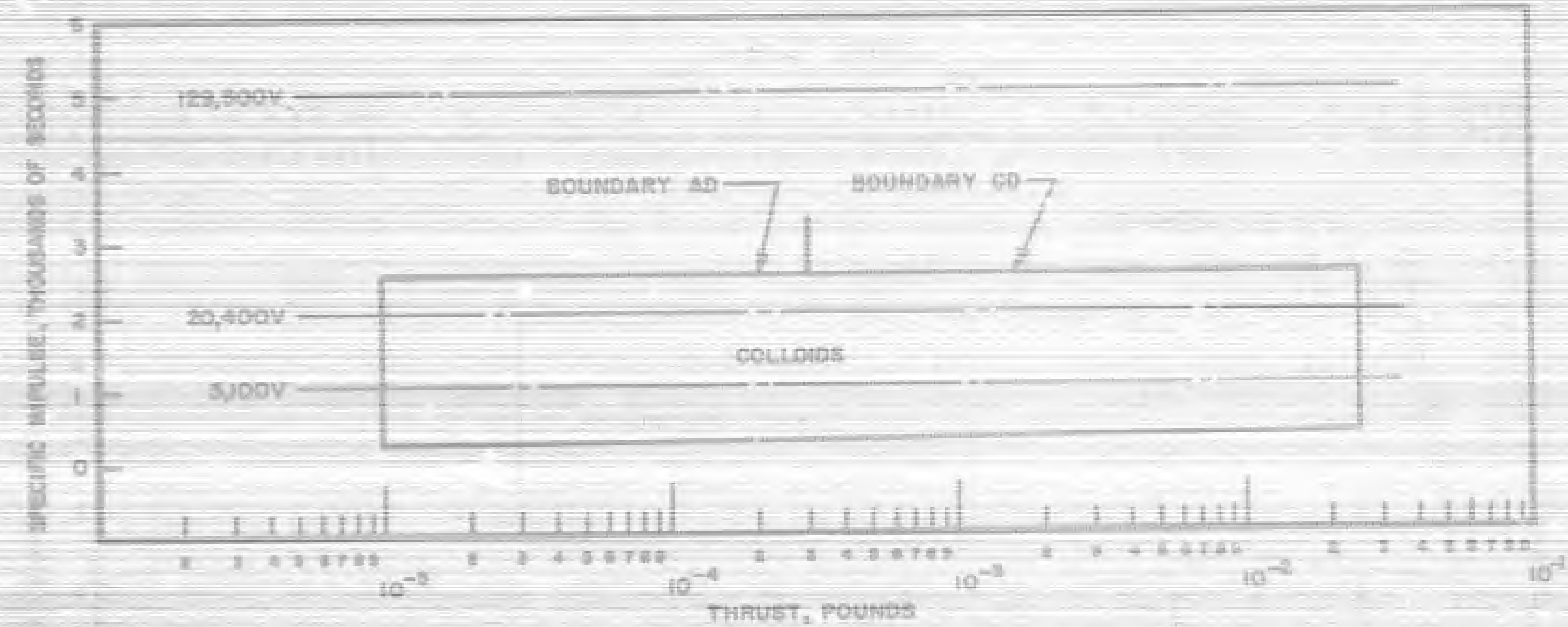


Figure 9. Required Extraction Voltage for Colloid Thrustors

q/m = 10,000 coul/kg

## TABLE III

## CANDIDATE THRUSTORS FOR AREA D

| ENGINE | SPECIFIC IMPULSE REQUIREMENT | THRUST REQUIREMENT | STATE OF DEVELOPMENT |
|---|---|---|---|
| Contact Ion | No | - | - |
| Bombardment Ion | No | - | - |
| Radioisotope Ion | No | - | - |
| Resistojet | No | - | - |
| Colloid | Yes | Yes | Feasibility established |
| Pulsed Plasma | Yes | Yes | Feasibility established |
| Arc | Yes | Upper range, only | Feasibility established, upper thrust range |
| Inductive Accelerator | Yes | Upper range, only | Feasibility established, upper thrust range |
| Radioisojet | No | - | - |

reliability as they relate to pulsed plasma devices, but a tradeoff can be made between capacitor reliability and weight and efficiency (Reference 8). A choice will probably be made between the pulsed plasma and the colloid engines eventually, after these engines have progressed further in their development.

## 7. BOUNDARY DE

Figure 10 shows that colloid thrustors, either the slit geometry or the needle array, are size-limited as thrust increases into the medium millipound thrust range. Improvements are expected in colloid thrustor technology to provide larger needle and slit currents and in achieving higher and more uniform q/m ratios. Without these improvements, the colloid thrustor, like the contact and bombardment engines, will be limited in thrust density. Clustering modules of engines will not satisfy size requirements for systems to produce a given amount of thrust. The colloid thrustor, therefore, must yield to the arc and inductive accelerators at the high millipound thrust levels. Thrustor areas were determined based on thrust density capabilities of $30 \times 10^{-6}$ lbs/cm$^2$ and $100 \times 10^{-6}$ lbs/cm$^2$ for present needle geometries and future slit geometries, respectively.

## 8. AREA E

Table IV considers all candidate thrustors for Area E. Ion, colloid, and pulsed plasma engines, collectively, cover the specific impulse range, but none of these is really competitive with the arc and inductive accelerator engines at the very high thrust levels. Clusters of ion engines would be required to provide thrust in the range of 100 mlb and above. In addition, ion devices are generally more complex and present a much larger volume and frontal area than do the arc and inductive accelerator engines.

The arc and inductive accelerator engines are inherently high-power devices. Although the concepts are still largely in the feasibility stage, they indicate considerable potential for thrust requirements of several hundred millipounds and beyond. In the medium thrust region, however, they are not expected to provide any overall performance advantages over the ion engines, even if they are eventually developed to the level of the ion engines. The arc and inductive accelerator concepts will find their greatest applicability in the very high thrust regions of operation. As the technology in high thrust engines progresses, a choice will probably be made between the arc and the inductive accelerator engines, and one will be selected for advanced development.

## 9. AREA F AND BOUNDARIES DF AND EF

These boundaries are based on size and efficiency. Table V shows the candidate thrustors for Area F. Based on specific impulse, the colloid thrustor, pulsed plasma, resistojet, and radioisojet devices are all competitive. At very low Isp values (< 100 secs), the only candidate thrustors are the radioisojet and the resistojet, however, and at thrust values beyond the medium millipound level the only candidate is the resistojet.

The limitations on an ammonia resistojet as a function of gas temperature are shown in Figure 11. These values are given ideally by

$$T = \frac{Isp^2 \, g}{2 \, C_p} \qquad (12)$$

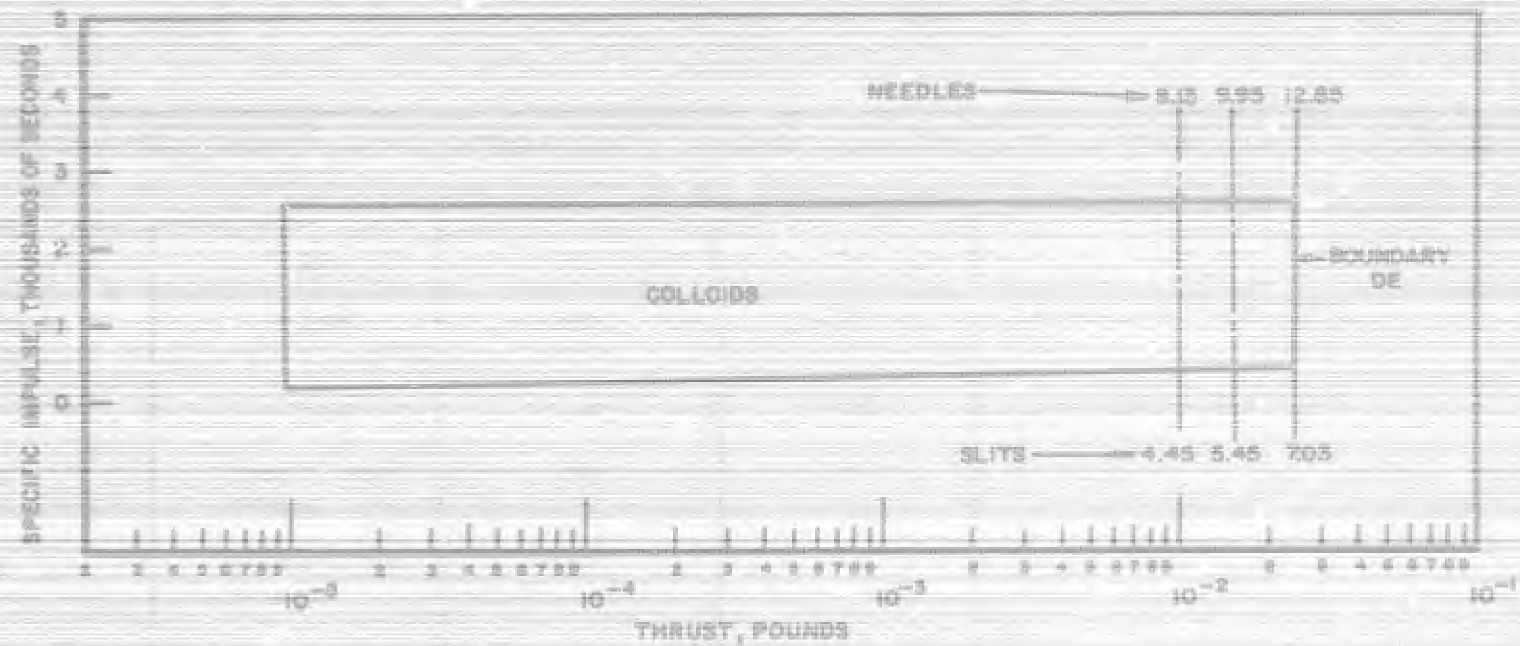


Figure 10. Colloid Thrustor Frontal Diameter (In Inches)

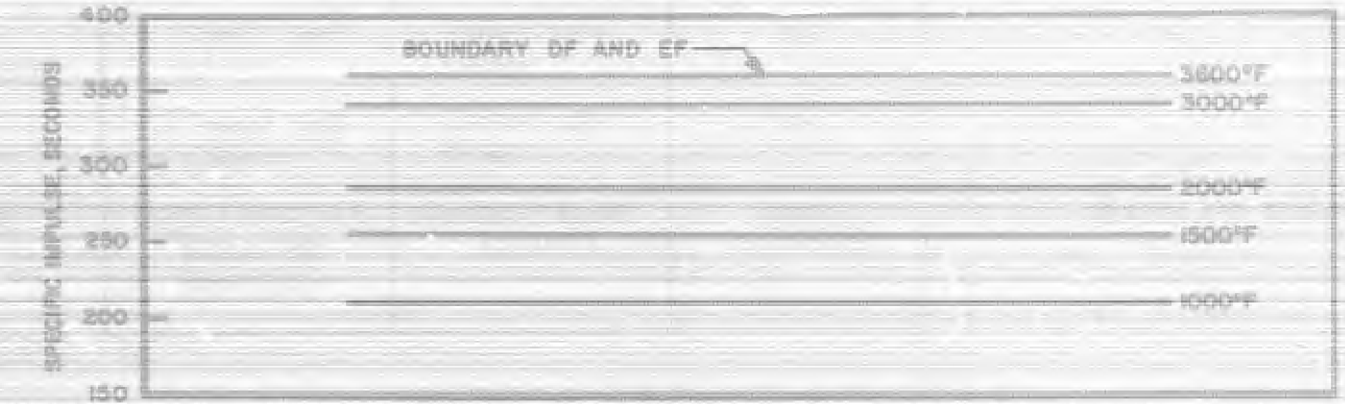


Figure 11. Ammonia Resistojet Gas Temperature

## TABLE IV

## CANDIDATE THRUSTORS FOR AREA E

| ENGINE | SPECIFIC IMPULSE REQUIREMENT | THRUST REQUIREMENT | FRONTAL AREA | STATE OF DEVELOPMENT |
|---|---|---|---|---|
| Contact Ion | Upper range, only | Lower range, only | No | - |
| Bombardment Ion | Upper range, only | Lower range, only | No | - |
| Radioisotope Ion | Upper range, only | Lower range, only | No | - |
| Resistojet | No | - | - | - |
| Colloid | Lower range, only | No | - | - |
| Pulsed Plasma | Lower range, only | No | - | - |
| Arc | Yes | Yes | Yes | Feasibility established |
| Inductive Accelerator | Yes | Yes | Yes | Feasibility established |
| Radioisojet | No | - | - | - |

## TABLE V

## CANDIDATE THRUSTORS FOR AREA F

| ENGINE | SPECIFIC IMPULSE REQUIREMENT | THRUST REQUIREMENT | STATE OF DEVELOPMENT |
|---|---|---|---|
| Contact Ion | No | - | - |
| Bombardment Ion | No | - | - |
| Radioisotope Ion | No | - | - |
| Resistojet | Yes | Yes | Engineering capability established; systems developed in 10 micropound range |
| Colloid | Yes | Lower range | Feasibility established |
| Pulsed Plasma | At upper range | Lower range | Feasibility established |
| Arc | No | - | - |
| Inductive Accelerator | No | - | - |
| Radioisojet | Yes | Lower range | Feasibility established for thrustor in low to medium millipound thrust range |

where

$T$ = gas temperature

$C_p$ = specific heat at constant pressure

The resistojet becomes a radioisojet when the resistive heater element has been replaced with a radioisotope capsule. As in the radioisotope-heated cesium contact ion engine, the radioisotope capsule supplies the thermal energy needed by the engine, thereby reducing the amount of electrical power needed. If a lightweight capsule is designed, significant weight savings can be realized for engines of millipound size or larger. Radioisojets using ammonia and hydrogen as the propellants have been under development for some time and some devices have undergone some testing. (In contrast, the radioisotope ion engine has never been fabricated, although feasibility studies have been made and a simulated radioisotope capsule has been used with an ion engine.)

It is possible that the radioisojets may replace the more conventional resistojets, but the technology is not sufficiently advanced to determine how extensively this type of device may be used. Many factors will influence the use of radioisojets, such as the half-life of the radioisotopes, capsule weight, power density, cost and availability, and biological hazards.

Using hydrogen as the propellant instead of ammonia is not expected to increase the effective specific impulse significantly, since tankage weight becomes an important factor in storing hydrogen. A hydrogen thrustor shows an effective specific impulse advantage at the medium millipound thrust level and beyond, but not at the micropound thrust range (References 2 and 7). Effective specific impulse can be determined from

$$Isp_{eff} = \frac{Isp}{1 + W_{tank}/W_p} \tag{13}$$

where

$Isp_{eff}$ = effective specific impulse, in seconds

$\frac{W_{tank}}{W_p}$ = weight ratio of tank to propellant.

## SECTION IV

## SOME FURTHER CONSIDERATIONS IN SELECTING CANDIDATE THRUSTORS

The Areas of Applicability chart with the candidate thrustors selected for each of the areas of operation is shown in Figure 12. Although this chart shows only five candidate thrustors for the low micropound thrust range, seven could actually be considered: bombardment ion, contact ion, radioisotope ion, colloid, pulsed plasma, resistojet, and radioisojet. These devices cover the range of specific impulse from less than 100 to more than 8100 seconds.

The question naturally arises as to why so many electric thrustors are needed to provide thrust in the micropound thrust range. The following are some of the factors involved.

The advantages of weight and power savings are readily seen for electric thrustors on missions involving high total impulse, which generally involve thrust requirements in the millipound range and above and thrust times of several months or more. The best thrustor for a specific mission may depend on a number of factors that cannot be determined on the basis of specific impulse and thrust alone. Some missions may be rigidly constrained in the amount of power available to the thrustor, or require rapid cycling of the engine for precise alignment of the satellite. The majority of micropound thrust missions require compromises to be made with the thrustor. No one electric engine system can meet all the mission requirements in the most reliable and efficient manner. Some other thrustor undoubtedly could meet one particular aspect of the mission more effectively. For example, a contact ion engine can perform thrust vectoring easily with one engine, while the resistojet cannot; on the other hand, the resistojet requires less electrical power than the ion engine.

A matrix of performance capabilities of candidate electric propulsion systems can be used in making tradeoffs to obtain the best engine for a particular system. In using such a matrix, the designer would consider the relative importance of mission performance characteristics, such as minimum power, propellant weight, thrust vectoring, thrust trottling, rapid cycling, and possibly others. Each of these performance characteristics would be "weighted" on the basis of its relative imporance in efficiently carrying out a micropound thrust mission. Each candidate microthrustor would then be considered as to its relative capability to accomplish each of the performance characteristics. For example, let us assume that minimum power is judged to have a relative importance rating of 8 out of 10, and the bombardment ion engine scores a relative capability of 3 out of 10 in meeting this requirement; then the score for the bombardment ion engine would be 8 x 3 = 24. This type of scoring would be done for all the performance characteristics and the scores summed up for each candidate microthrustor. Table VI shows how such a matrix might be constructed.

In the matrix example, of the systems performing in the 10 micropound thrust range, thrustor system A had the highest score. Suppose that thrustor A were not as far along in its systems development, however, or that it were not as reliable as some other system. Under these circumstances, the time and cost required to bring the system to the required state of development or standards must be included in the consideration.

A matrix such as is illustrated can be a useful tool for appraising thrustors at the micropound level, but its usefulness decreases as the thrust level approaches one millipound. At this level, propellant weight and power supply weight become more important, and tradeoffs between these two weights as a function of thrust time become critical.

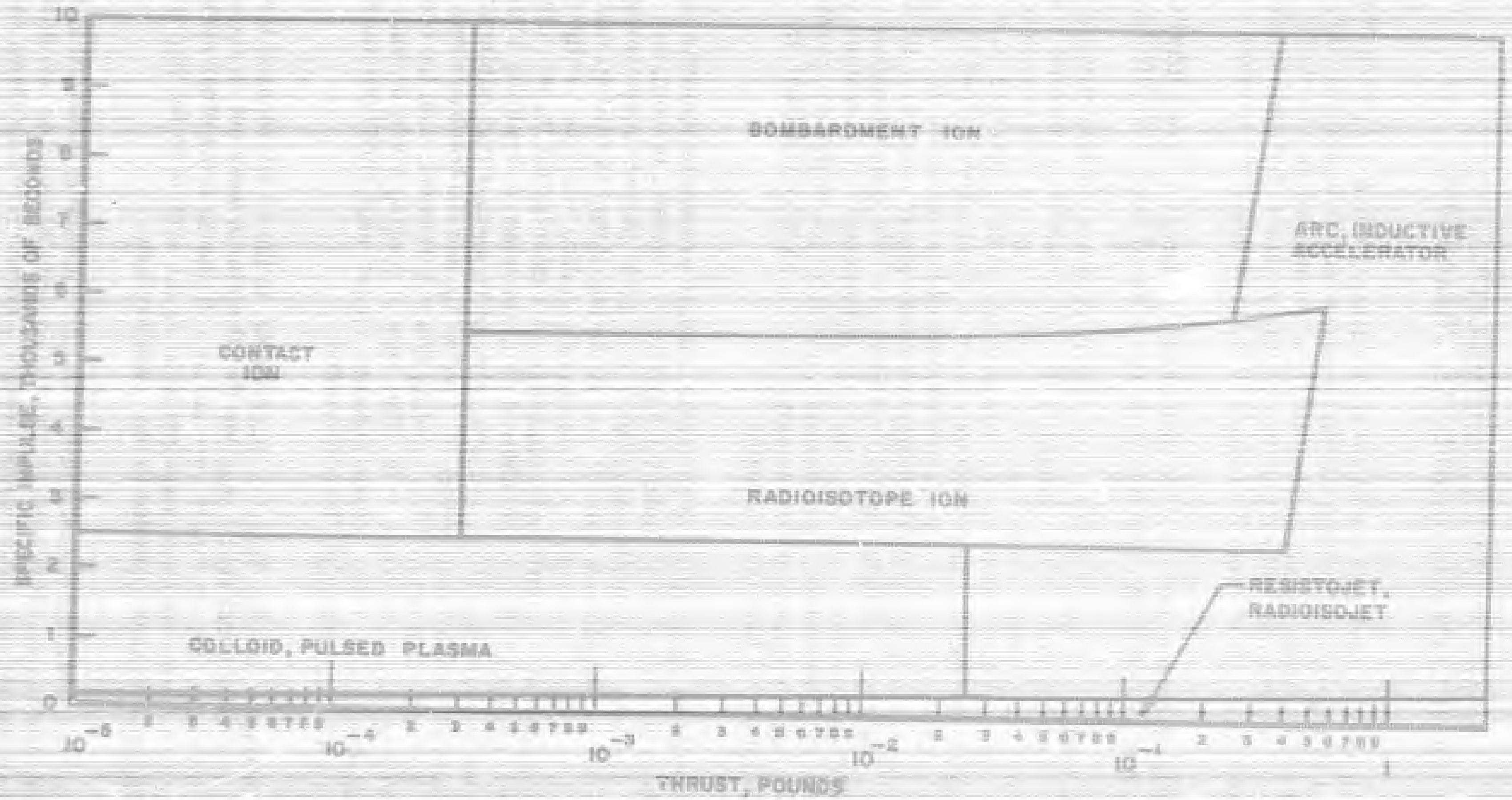
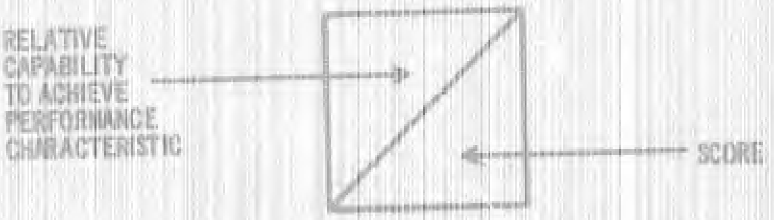


Figure 10. Areas of Applicability for Electric Thrusters

TABLE VI

Matrix for Micropound Thruster Selection 10μ lbs Thrust

| RELATIVE IMPORTANCE | 8 | 10 | 3 | 1 | | |
|---|---|---|---|---|---|---|
| PERFORMANCE CHARACT-ERISTIC / ENGINE | (1) | (2) | (3) | (4) | | TOTAL SCORE / NORMALIZED SCORE |
| (A) | 5<br>40 | 8<br>80 | 2<br>6 | 6<br>6 | | 132<br>10 |
| (B) | 1<br>8 | 2<br>20 | 10<br>30 | 9<br>9 | | 67<br>5.07 |
| (C) | 6<br>48 | 3<br>30 | 7<br>21 | 10<br>10 | | 109<br>8.26 |



## SECTION V

## CONCLUSIONS

The areas of applicability shown in Figure 12 are the same as those shown in Figure 4, but the applicable engines are shown for each area, based on the analysis described in Section III. This plot could be modified by performing a matrix analysis, such as was described in Section IV for the microthrustor area. The matrix illustrated in Table VI could be best formulated by a panel of electric propulsion experts in order to minimize the influence of personal opinions. Performing a complete analysis such as has been described will provide an overall assessment of the performance capabilities of electric thrustors and will further Air Force and NASA confidence in their having selected the best thrustor systems for future advanced developments.

## REFERENCES

1. Program for the Exploratory Development of a Contact Ionization Thrustor, AFAPL-TR-65-68, Electro-Optical Systems, Inc., Pasadena, Calif., under Contract AF33(615)-1530, May 1965.

2. Jack W. Geis, Millipound Thrust Electric Propulsion, AFAPL-TR-66-65, Air Force Aero Propulsion Laboratory, WPAFB, Ohio, September 1966.

3. Jack W. Geis, Ion Engine Diagnostics, APIE-TM-65-13, Air Force Aero Propulsion Laboratory, WPAFB, Ohio, October 1965 (internal document).

4. Exploratory Development of a Contact Ionization Thrustor, Monthly Rpt No. 2 under Contract AF33(657)-1580, Electro-Optical Systems, Inc., Pasadena, Calif for Air Force Aero Propulsion Laboratory, WPAFB, Ohio, June 1964.

5. AFAPL contractual program documents.

6. Telephone conversation, W. J. Guman, Republic Acft Div, Fairchild Hiller Corp., Farmingdale, Long Island, N.Y.

7. David Raspet, 1st Lt, USAF, Supercritical Hydrogen and Oxygen Tankage for Fuel Cell Space Power Systems, AFAPL-APIP-65-TM-9, Air Force Aero Propulsion Laboratory, WPAFB, Ohio, August 1965 (internal document).

## DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>Air Force Aero Propulsion Laboratory<br>Wright-Patterson Air Force Base, Ohio | 2a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED<br>2b. GROUP |

3. REPORT TITLE
AREAS OF APPLICABILITY FOR ELECTRIC PROPULSION SYSTEMS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (Last name, first name, initial)
Geis, Jack W.

| | | |
|---|---|---|
| 6. REPORT DATE<br>SEPTEMBER 1967 | 7a. TOTAL NO. OF PAGES<br>37 | 7b. NO. OF REFS<br>7 |
| 8a. CONTRACT OR GRANT NO.<br>b. PROJECT NO. 3141<br>c. Task No. 314102<br>d. | 9a. ORIGINATOR'S REPORT NUMBER(S)<br>AFAPL-TR-67-80<br>9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) | |

10. AVAILABILITY/LIMITATION NOTICES
This document is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, WPAFB, Ohio.

| | |
|---|---|
| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY<br>Air Force Aero Propulsion Laboratory<br>Wright-Patterson Air Force Base, Ohio |

13. ABSTRACT

An analysis was performed to define the range of specific impulse and thrust covered by most of the electric thrustors in the state-of-the-art to determine their areas of applicability. Candidate thrustors included in the study include the contact ion, bombardment ion, radioisotope ion, resistojet, radioisojet, colloid, pulsed plasma, arc, and inductive accelerator. The results of the analysis are presented in graphic form to show the areas where each of these thrustors indicated quantitative and qualitative advantages. Quantitative parameters considered in the evaluation included efficiency, thrust, specific impulse, size, and lifetime, and qualitative factors included reliability, compatibility and complexity. A sample matrix is constructed for use in making tradeoffs in selecting the best thruster for a specific application.

This abstract is subject to special export controls and each transmittal to foreign governments or foreign nationals may be made only with prior approval of the Air Force Aero Propulsion Laboratory, WPAFB, Ohio.

<table>
<tr><th rowspan="2">14. KEY WORDS</th><th colspan="2">LINK A</th><th colspan="2">LINK B</th><th colspan="2">LINK C</th></tr>
<tr><th>ROLE</th><th>WT</th><th>ROLE</th><th>WT</th><th>ROLE</th><th>WT</th></tr>
<tr><td>Electric Propulsion</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Ion Engines</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Resistojets</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Plasma Engines</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Space Thrustors</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

## INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through

_______________________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through

_______________________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through

_______________________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.