NASA TECHNICAL NOTE

NASA TN D-5074

PERFORMANCE OF VARIOUS OXIDE-MAGAZINE CATHODES IN KAUFMAN THRUSTERS

by David C. Byers

Lewis Research Center

Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1969

NASA TN D-5074

PERFORMANCE OF VARIOUS OXIDE-MAGAZINE CATHODES IN KAUFMAN THRUSTERS

By David C. Byers

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price $3.00

ABSTRACT

The performance of various oxide-magazine cathodes in the mercury discharge of a Kaufman thruster is presented. Emission current of the final design was 2.0 amperes at a cathode heater input power between about 70 and 80 watts during thruster operation. The emission current was found to follow a thermionic characteristic up to some level of emission, above which other limitations dominate the emission current. The emission current also appeared to be limited at high values of propellant utilization efficiency. Tests with a large variety of chemical constituents led to no fundamental improvements over the initial chemical block type.

PERFORMANCE OF VARIOUS OXIDE-MAGAZINE CATHODES IN KAUFMAN THRUSTERS

by David C. Byers

Lewis Research Center

SUMMARY

The performance of various oxide-magazine cathodes in a 15-centimeter Kaufman thruster is presented. The final design cathode required an input heater power between about 70 and 80 watts and emitted 2.0 amperes of electrons into the mercury discharge of the thruster. The emission current was found to follow a thermionic characteristic up to some level of emission, above which other effects determine the emission current. In general, the emission current increased with discharge potential up to some value and then decreased. The decrease was ascribed to removal of activator by ion sputtering. The emission current also appeared to be limited at high values of propellant utilization efficiency. This limitation at high utilization efficiency was believed caused by some gross change in the cathode plasma sheath.

A large variety of chemical constituents were tested in the chemical block of the "oxide-magazine" cathode. No fundamental improvements over the initial chemical block type were found.

Cathode electrical performance was adequate for the SERT II mission. Preflight test requirements of the thruster system led, however, to the selection of a hollow cathode for the mission.

INTRODUCTION

The SERT II mission (ref. 1) objective is a 6-month endurance test of a 15-centimeter Kaufman thruster (refs. 2 and 3). Development of a low power cathode for the thruster with a lifetime of greater than 6 months is essential to the success of the SERT II mission. Mission requirements impose upper limits of about 3 amperes and 100 watts on the cathode emission current and cathode heater power, respectively.

A variety of cathode types have been studied previously at the Lewis Research Center

and elsewhere. These included the tantalum ribbon cathode (ref. 4), the brush cathode (ref. 5), and oxide-magazine cathodes (ref. 6). Liquid metal (ref. 7) and thin layer oxide cathodes (ref. 8) have also been investigated. Early in the planning stages for the SERT II mission, the oxide-magazine cathode was considered as a prime candidate for further development. This was mainly because

(1) At the time, this cathode had the longest demonstrated lifetime (4179 hr), in a thruster environment (ref. 6)

(2) Relative ease of fabrication

(3) The cathode had promise, with minor improvements, of long term, low power, efficient operation (ref. 6)

The investigation reported herein included variation of basic cathode parameters such as, the constituency of the chemical block and the cathode geometry. In addition, the influence of various thruster performance parameters, such as anode voltage, neutral flow rate, and propellant utilization efficiency on cathode performance were studied.

The cathode was developed to an extent sufficient to meet the electrical requirements of SERT II. However, as is true of most oxide-type cathodes, the oxide-magazine cathode degrades somewhat in performance when exposed to atmosphere between tests. The subsequent imposition of pretest requirements of flight hardware, with repeated exposure to atmosphere, resulted in the final selection of another cathode type, the hollow cathode (ref. 9), for the SERT II mission.

This report has been written to document the results of the oxide-magazine cathode development program for possible future uses. These may include specific use in electric propulsion thrusters subject to different preflight test requirements, or general use in ground operation discharge devices with the same range of plasma characteristics as the Kaufman thruster.

APPARATUS AND PROCEDURE

Permanent Magnet Thruster

The basic thruster utilized was a Kaufman thruster (ref. 2) of the type described in reference 3. Figure 1 shows the major components (e.g., pole piece, magnets, distributor, and a representative oxide magazine cathode). Alnico V permanent bar magnets were used together with the soft iron pole pieces to produce a divergent magnetic field. The centerline axial magnetic field strength decreased from about 3×10^{-3} tesla at the end of the upstream pole piece to about 1×10^{-3} tesla at the screen accelerator grid. The accelerator grid system was the same as used in reference 3. The screen grid was 71 per-

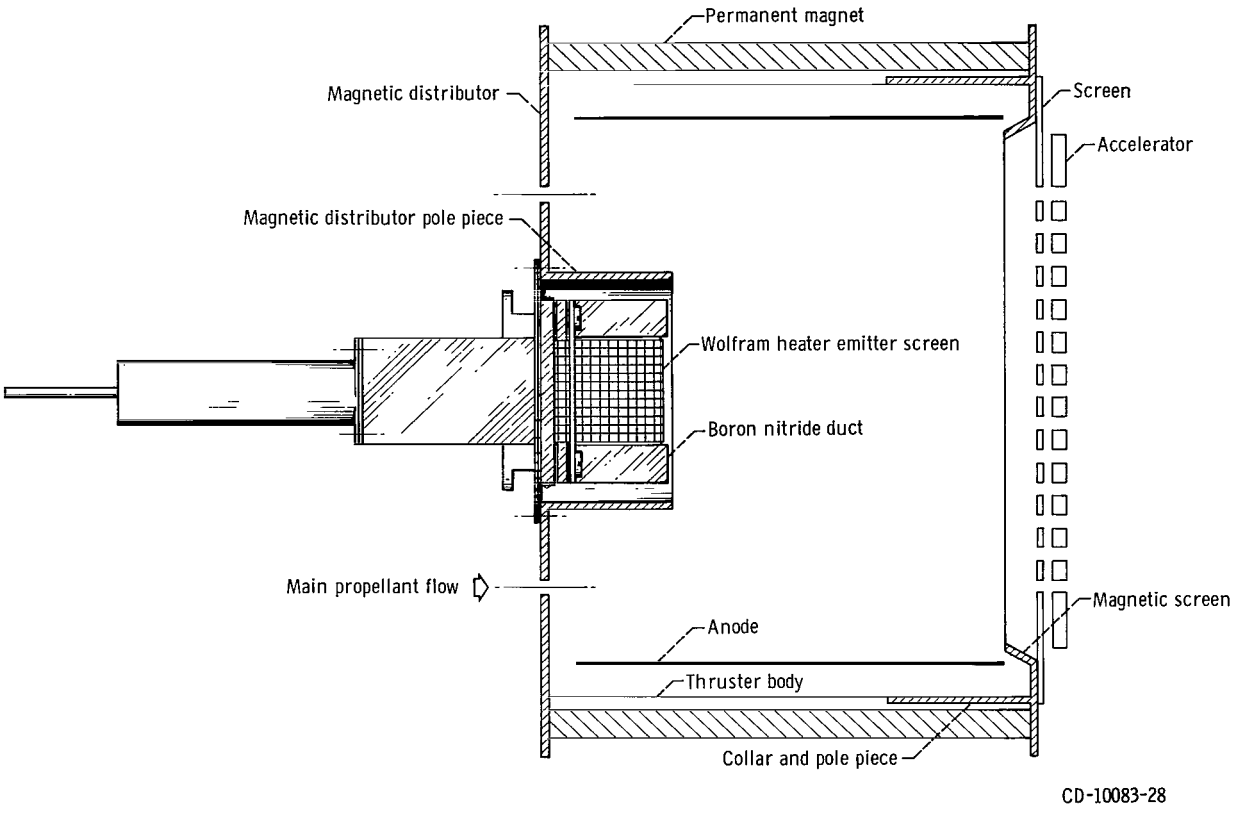


Figure 1. - Fifteen-centimeter diameter Kaufman thruster.

cent open. The essential details of operation of electron-bombardment thrusters have been described in many references (e.g., refs. 2 and 3) and will not be discussed herein.

Vacuum Facilities

Work was carried out in three separate vacuum facilities that are described in detail in references 10 and 11. Two facilities were 4.5-meter long by 1.5-meter diameter. The third, used primarily for endurance testing, was 18.5-meter long by 7.5-meter diameter. All three facilities utilized oil diffusion pumps with LN_2 cold traps during thruster operation and in all three facilities, the thruster operated in a small test chamber (herein called a bell jar) separated from the main chamber by a 1-meter diameter valve. The bell jar pressures varied from about 2×10^{-5} to 4×10^{-6} torr in the small facilities and between approximately 1×10^{-5} and 5×10^{-7} torr in the large facility during thruster operation. The higher pressures were typical immediately after preheating the cathode. The lower pressures occurred after several hours of thruster operation. Pres-

sures in the main facility were from about a half to a full decade lower than the bell jar pressures in all three facilities. No major differences in cathode performance were noted in the three facilities.

Cathodes

Cathode description. - Figure 2 shows a typical oxide-magazine cathode. This design was, in fact, similar to that used in the endurance tests of reference 6. The major components of the cathode were:

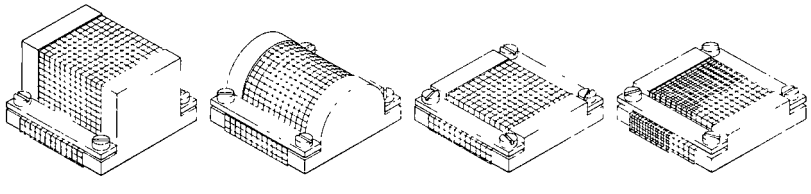
(1) A screen from which the electrons were emitted. The screen, wolfram (tungsten) for nearly all tests, was woven 0.13-millimeter (five-mil) and 0.09-millimeter (3-mil) diameter wire. The smaller wire mesh spacing was 120 per centimeter. The larger diameter wire, which carried the cathode heating current, was spaced at 10 per centimeter. A variety of screen geometries, materials, and mesh sizes were tested and will be described later.

(2) The cathode heater leads. The leads for most of the cathodes described herein were made of wolfram. Wolfram rather than copper leads were utilized in order to minimize the sum of the conduction losses from the screen and the ohmic power loss in the leads themselves.

(3) A boron nitride duct contained the chemical block for earlier tests. High purity alumina was utilized in the latter stages of the program.

(4) The chemical block was, in general, a mixture of a carbonate compound (usually barium carbonate), a reducing material (usually carbon), and a binder (usually stearic acid). It was fabricated in several steps. The various chemicals were first dry mixed by shaking in a set of sieves, where the smallest sieve mesh spacing was 25 per centimeter. The shaking was followed by roll mixing. A slurry was then made, usually with acetone as a solvent. This complex was then formed into a block by cold pressing followed by hydrostatic pressing, usually at a pressure of 4.5×10^{8} Newtons per square meter (6.5×10^{4} psi).

A variety of cathode geometries were investigated in the program. Some of the designs are shown in sketch a. Type A was identical in design to the oxide-magazine cath-



Sketch (a)

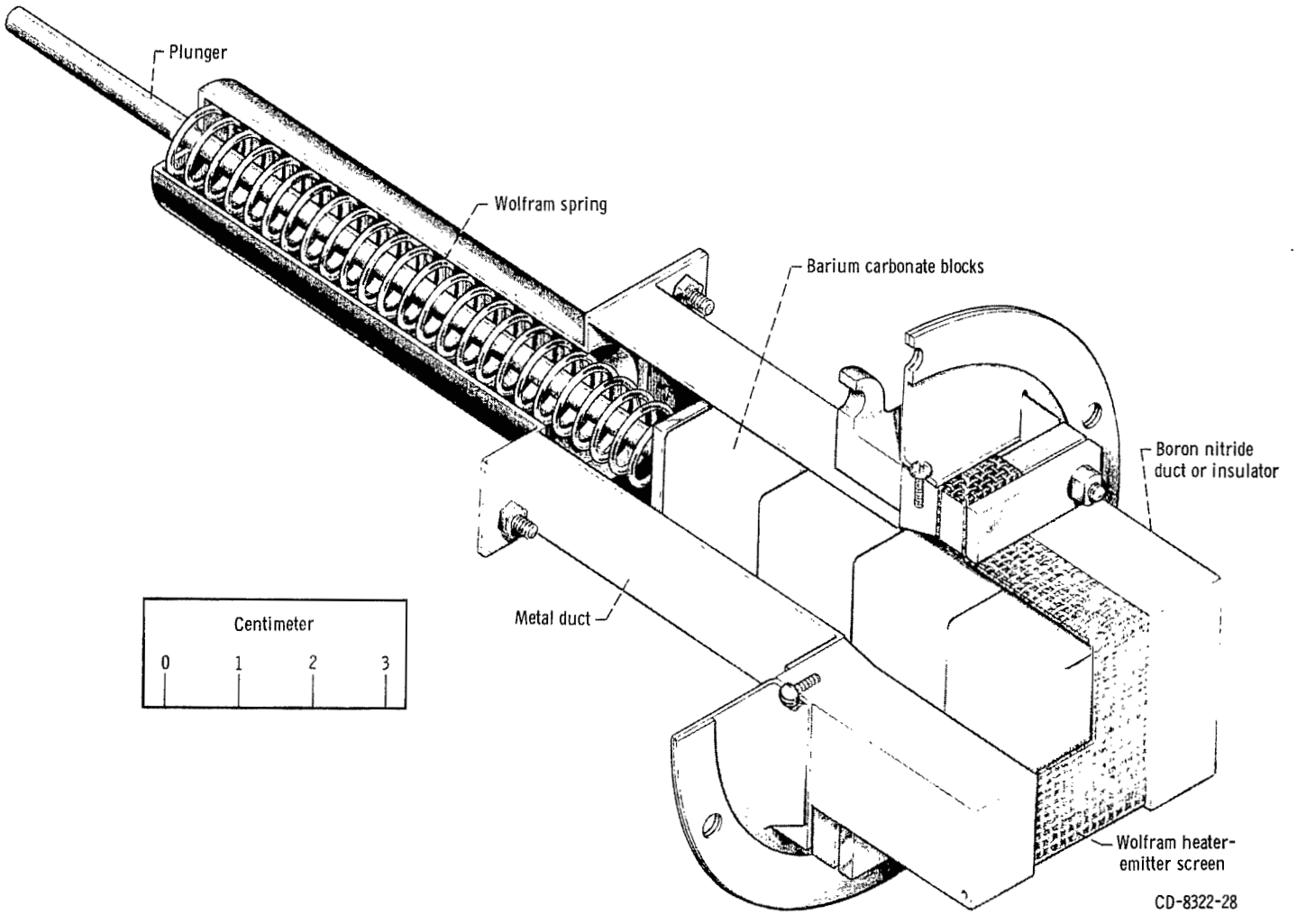


Figure 2. - Typical oxide-magazine cathode.

ode utilized in the endurance tests of reference 6. The other types shown in sketch (a) represent later designs and, for clarity, are shown without heat shielding.

In general, the program direction was to decrease cathode size (i.e., reduce radiative losses). In addition, end losses were reduced by the use of wolfram leads and considerable heat shielding. Cathode type D (the double screen) was a deviation from the general program direction and warrants some explanation. The temperature at which barium and barium oxide are released in sufficient quantities to maintain cathode activation has been estimated between about 1300 and 1500 K (ref. 12). On the other hand, the temperature required for electron current densities of about 0.2 to 0.5 ampere per square centimeter from activated wolfram is of the order of 1050 to 1200 K (ref. 13). Use of the double screen allowed the inner screen to run hotter than the outer screen, due to the radiative shielding of the outer screen. Ideally then, the radiative losses, dominated by the outer screen temperature, would be reduced. In addition, the evaporation rate of activator from this surface is reduced by operation at lower temperatures. All designs utilized the previously described activator feed concept.

Cathode operation. - An ac current, usually 30 to 40 amperes, was passed through the leads and screen during preheat. The screen would, in general, reach a temperature in excess of 1280 K at the preheat values. The chemical block, held in contact with screen by a spring, also became hot. Free barium and barium oxide would then become available, by a process to be described later, and diffuse to the screen. The barium and barium oxide, by lowering the work function of the wolfram, increased emission of electrons from the screen. Ideally then, as the chemical block was consumed a continually replenished source of barium and barium oxide was made available at the screen by the feed action of the spring.

Test Sequence

The thruster was usually operated in the following sequence:

(1) The cathode was preheated for 1.5 hours at an input power sufficient to heat the screen to about 1280 K. The bell jar and tank pressures would rise at the beginning of preheat but would fall to near the initial pressures at the end of 1.5 hours.

(2) With a typical cathode the discharge would initiate upon introduction of mercury into the discharge chamber. For most tests the starting voltage (i.e., voltage between the anode and cathode) was supplied by two power supplies connected in parallel. This arrangement provided a high starting voltage which was made to drop to some low, nominally constant value, at low emission currents. The volt-ampere characteristic was con-

trolled by means of a load resistor. The voltage was constrained to drop quickly to some low value (about 30 V) in order to prevent ion sputtering damage to the cathode.

(3) After the discharge was initiated, the discharge current would increase for about 1.5 hours at fixed discharge potential and cathode heating power. This behavior will be referred to as conditioning and was found to be a necessary part of each test. After conditioning, the discharge voltage and cathode power were adjusted to obtain the desired levels of ion beam current. Tests were then conducted, typically for from 2 to 6 hours, after which cathodes were visually inspected.

RESULTS AND DISCUSSION

This cathode investigation was carried out in conjunction with a thruster optimization program. As a consequence the cathode ambient environment (e.g., pole piece, magnetic field strength, etc.) was varied extensively throughout the program. The cathode electrical requirements remained constant, however, and most data were taken at emission currents of about 2 amperes and discharge voltages less than 35 volts. The values of thruster propellant mass flow rate were generally between 0.250 and 0.350 equivalent amperes. All data presented in this report were taken with an operating thruster, unless otherwise noted.

The cathode performance can be studied as a function of two sets of variables: pure cathode parameters and thruster performance parameters. The major cathode parameters varied were the chemical constituency of the activator block, the screen size and shape, and the cathode heater power. The major thruster performance parameters discussed are discharge potential, neutral propellant flow rate, and propellant utilization efficiency. The various parameters, especially the thruster variables, are strongly interrelated. For clarity, this paper will discuss these variables separately as follows:

(1) Chemical effects

(2) Preheat and conditioning effects

(3) Effects of cathode heater power and cathode geometry

(4) Effects of various thruster performance parameters

(5) Poisoning and facility effects

(6) Effects of vibration tests

Occasionally throughout the program some difficulty was experienced in obtaining repeatable cathode operation. Cathodes which utilized one specific batch of carbonate mixture in the activator block, for example, required anomalously high powers to initiate a discharge and also would not condition properly. Chemical analyses revealed no major

constituent deviation in these chemical blocks. Variation in cathode performance in a thruster environment seems, however, to be typical of the oxide cathode regardless of the dispensing mechanism or geometry (e.g., see refs. 6 and 8). The data presented herein for the most part were selected as typical of a given cathode system. Usually several tests were made with cathodes of nearly the same type and a general level of performance was noted. As will be discussed later, cathodes would sometimes exhibit anomalously high (good) emission characteristics. Cathode data exhibiting apparent anomalies, either very low or high emission characteristics, will be pointed as such when presented.

Chemical Effects

The chemical basis of operation of the oxide-magazine cathode is fundamentally the same as that of the brush cathode (ref. 5). Free barium and barium oxide (herein after referred to as the activators) are provided by a two-step conversion and reduction process. Upon initial heating barium carbonate is converted:

$$BaCO_3 \rightarrow BaO + CO_2 \tag{1}$$

This reaction is followed by the slower reduction reaction.

$$BaO + C \rightarrow Ba + CO \tag{2}$$

The free barium and barium oxide, made available by reactions (1) and (2), interact with the wolfram screen and enhance emission.

As mentioned in reference 14, a variety of other reactions can take place. If, for example, the carbon dioxide cannot escape freely from the chemical block, carbon (reducing agent) could be depleted by the following reaction:

$$BaCO_3 + C \rightarrow BaO + 2CO \tag{3}$$

The standard chemical block, based on the information of reference 14, contained a stoichiometric supply of free carbon for reaction (2). The standard block also contained about 2 percent stearic acid (by weight) as a binder. A binder was added to facilitate handling of the chemical block. The binder is driven off at much lower temperatures than associated with the reactions (1) and (2).

Variations of reducing agent, binder, and wetting agent. - The amount and type of reducing agent was varied. It was found that the barium carbonate block would not acti-

vate without some free carbon present. Three tests were made with twice stoichiometric carbon. In two tests the cathode failed to activate and the third activated very poorly. No substantial difference in performance was noted between 1 and 1.5 stoichiometric carbon supply in the carbonate blocks. In addition, tantalum and wolfram were tried as reducing agents in separate blocks. The cathodes using these blocks did not activate. This result is similar to the findings of reference 14.

The emission properties of the cathode were found to be rather sensitive to both the amount and type of binder. Tests were made with stearic acid varied between 0 and 8 percent by weight. The cathode either did not activate or exhibited very poor emission characteristics with both 0 and 8 percent stearic acid. Acceptable performance was obtained with 2 and 4 percent stearic acid. Two tests with polyvinylacetate as a binder and Aerosol - OT as a wetting agent also failed to activate.

Variation of carbonate. - The bulk of the tests were made with the barium carbonate mixture. A few tests were made with R-500 and Radio mix (R-500 and Radio mix are commercial names for triple carbonate mixtures). Radio mix was the basic carbonate for the brush cathodes of references 6 and 8. No cathode utilizing carbonate mixtures other than pure barium carbonate activated well. In all but two of these tests the carbonate mixtures failed to activate at all. The reason for the failure of the mixed carbonates to activate well is not known.

It should be pointed out that the oxide-magazine cathode is significantly different from the brush cathode in some respects. In the oxide-magazine cathode the screen shields, to some extent, the chemical block from the discharge plasma. The chemical compound, on the brush cathode is, however, directly exposed to the discharge plasma. Possibly ion bombardment is necessary to activate R-500 and Radio mix and this may explain why the more exposed brush cathode operated much better than the oxide-magazine cathode with these carbonates.

In sum, no chemical or screen material variation led to significantly improved performance over the original mixture and screen types utilized in reference 6. Included in the variations, in addition to those mentioned above, were the use of nickel and tantalum screens, bakeout of the chemical block in various atmospheres and vacuum conditions, and variations of wetting agents.

Preheat and Conditioning

As mentioned earlier, each cathode was preheated for about 1.5 hours previous to initiating a discharge. Failure to preheat led to several undesirable effects. A large pressure rise would occur upon application of the cathode heater power. This in turn resulted in frequent high voltage breakdowns between the accelerator grids. Also arcs

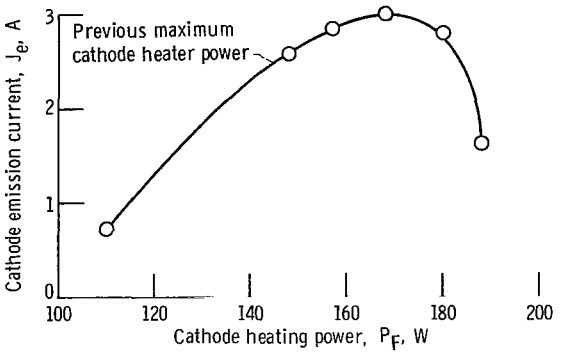


Figure 3. - Emission current as function of cathode heating power. Ion-chamber discharge potential, 25 volts; type A cathode.

would occur between the cathode and the anode. Both breakdown types were apparently due to the high pressure ($>10^{-4}$ torr) in the discharge chamber.

In addition, as the cathode power was raised above the preheat level, or the previous maximum operation level, the measured cathode emission current would increase slightly and then decrease strongly. Figure 3 shows this effect. In addition to the decrease in emission, the facility pressure would increase. This is probably due to the fact that the increase in operating temperature with heating power caused an increase in the gas released from the chemical block. This gas could degrade, or poison, the cathode. In general, when cathode operation was restricted to values of cathode power less than the preheat (no discharge) value, no degradation of emission with power was noted.

Some mass spectrometer data were taken in a bell jar facility during a simulated preheat. The results were essentially those expected on the basis of the postulated chemical reactions (eqs. (1) and (2)). Large peaks with atomic mass values of 44 (CO_2) and 28 (CO) were observed upon application of cathode heating power. Other large peaks such as 18 (H_2O) and 16 (probably CH_4) were also observed at preheat start. After about 1 hour the predominant peak was CO while the CO_2 peak was less than 1 percent of its original value. The rapid decrease in the CO_2 (relative to CO) peak occurred since the reaction rate of conversion of barium carbonate is significantly faster than the reduction of barium oxide (ref. 15).

It was found necessary to condition the cathode for about $1\frac{1}{2}$ hours in the mercury discharge to reach equilibrium cathode emission levels. Two techniques of conditioning were utilized. These techniques differed in the arrangement of the discharge power supply output characteristics. In the first technique the discharge was lit on initial tests by raising the discharge voltage to between 40 and 50 volts and turning on the neutral propellant flow. The anode supply was essentially voltage regulated, hence the conditioning sequence consisted of a rise in anode current at nearly constant discharge voltage. As shown in figure 4 with this technique, the emission current usually rose quite quickly for

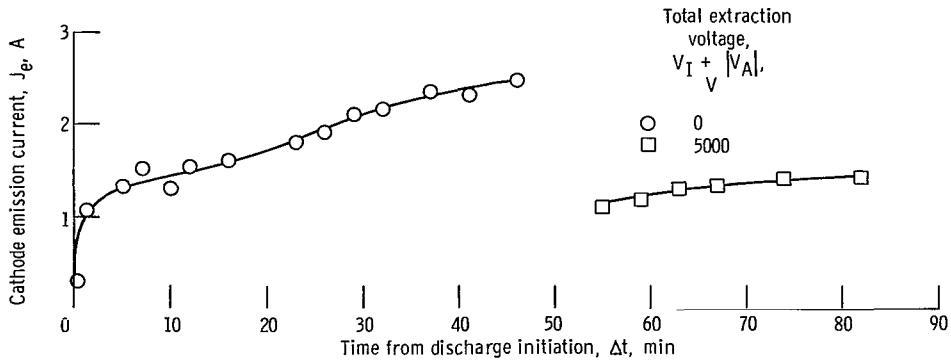
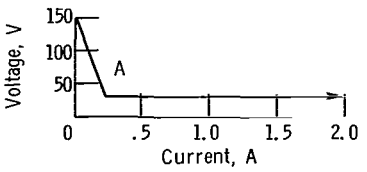


Figure 4. - Typical cathode conditioning curve. Cathode type A; ion-chamber discharge potential, 30 volts.

about 3 to 5 minutes. This rise was followed by a slow increase in emission current for time periods of about 1 to 2 hours. Optical pyrometer measurements indicated that the cathode temperature was essentially constant (to within measurement accuracy) during the initial emission current rise time. Typically the temperature would rise about 15 to 30 K during the 1 to 2 hour slow rise in emission current. The nominal values for emission current and anode voltage at the end of the 2 hour rise were about 2 to 2.5 amperes and 25 to 35 volts. Figure 4 also shows that the emission current decreased by about a factor of two when the extraction voltage was applied to the accelerator grids. The effect was noted for all cathode designs utilized in the program. It is seen, however, that the time rate of change of emission current was not significantly affected when the extraction voltage was applied.

The adverse effect of extraction voltage on emission current was noted throughout the program. The application of extraction voltage would lower the emission current by a factor of about two to three (fig. 4). The general effect of extraction voltage on the discharge plasma was studied in reference 16. Application of extraction voltage lowered the electron (and, hence, ion) densities by greater than a factor of three on the axis of the thruster (i.e., the location of the cathode). In addition, the electron temperature distribution was shifted to higher energies. Although no information exists, it is also likely that the electric fields of the discharge plasma are a function of the extraction voltage. The drop in plasma density might serve to increase the cathode sheath length, and, hence, lower the space charge current limit for the cathode.

Occasionally the discharge would not initiate with an applied discharge voltage of 40 to 50 volts. In order to provide for a more reliable start up, a second conditioning technique was used which consisted of auxiliary discharge supply, with appropriate resistors and diodes, in parallel with the normal voltage regulated discharge supply. The auxiliary supply provided 150 volts for initiation of the discharge and insured very reli-



(b)

able startups for the duration of the program. The volt-ampere characteristic of the two supply system is shown in sketch (b).

At start-up, the discharge voltage established by the auxiliary supply was constrained to follow a load line similar to that shown in sketch b. The anode voltage was constrained to reach the low voltage (point A in sketch b) at an anode current greater than 0.1 ampere in order to avoid a starting instability. The starting instability was quenching of the discharge plasma if the discharge voltage load line was too steep. The discharge potential, as established by the auxiliary supply, would usually drop down to the potential of the main discharge supply in a few minutes. A slow increase in emission current for about 1 to 2 hours would then occur, quite like the initial start-up characteristic of the one supply system (fig. 4). However, with the two supply system, the brightness temperature rose quite quickly during the initial portion of the conditioning curve. This was probably due to some high energy ion bombardment of the cathode screen. These high energy ions have a larger effect on temperature than in the first conditioning technique. Subsequently, the brightness temperature rose in about the same fashion as for the first conditioning sequence.

The exact explanation of the slow, 1 to 2 hour, conditioning is not known. Possibly the observed temperature rise caused the increase in emission current (see fig. 6 of ref. 14). On the other hand, it has been mentioned that some self-poisoning of the cathode may exist (fig. 3). If this were the dominant effect it would be expected that as the various gas species were driven off the cathode would gradually increase emission with time. It was noted in the mass spectrometer study that many mass peaks reached their equilibrium values in a time of order 1 to 2 hours.

Effects of Cathode Power and Geometry on Emission

The parameters selected to compare cathode performances were emission current Je, input power P_F, and cathode brightness temperature T_B. The emission current reported herein is the sum of the electron current actually emitted and any ion current incident on the cathode screen surface. It is, of course, impossible to differentiate between these two sources of current with a meter in the cathode circuit. (Discussion of the

possible magnitude and importance of the ion current incident on the screen surface will be deferred to a later section of the report.) Comparison of the specific emission (A/cm^2) and power density (W/cm^2) is more usual in the literature of oxide cathodes. However, a number of factors, such as selection of the appropriate area of the complex surface of most cathodes, make such comparison somewhat arbitrary.

The brightness temperature of the cathode screen should be a linear function of the fourth root of the input power if the power balance of the cathode screen is essentially radiation dominated. Figure 5 shows that the temperatures were, in fact, quite linear with the fourth root of heating power for a number of cathodes and over large ranges of power. A so-called "flower" cathode (ref. 8) is included for reference. It was also found that the discharge potential did not affect the brightness temperature at potentials less than 30 volts. As mentioned previously, however, above 30 volts, the brightness temperature did vary with discharge potential.

These observations suggest that the power balance of the oxide-magazine cathodes of this study are essentially radiation dominated. It is known that the power balance of some thermionic emitters is strongly affected by the ion current from the discharge plasma incident on the cathode surface (ref. 17). This dependence is usually associated, however, with systems wherein the discharge current densities are many times larger than those of interest in this study. The information of later sections will indicate that some

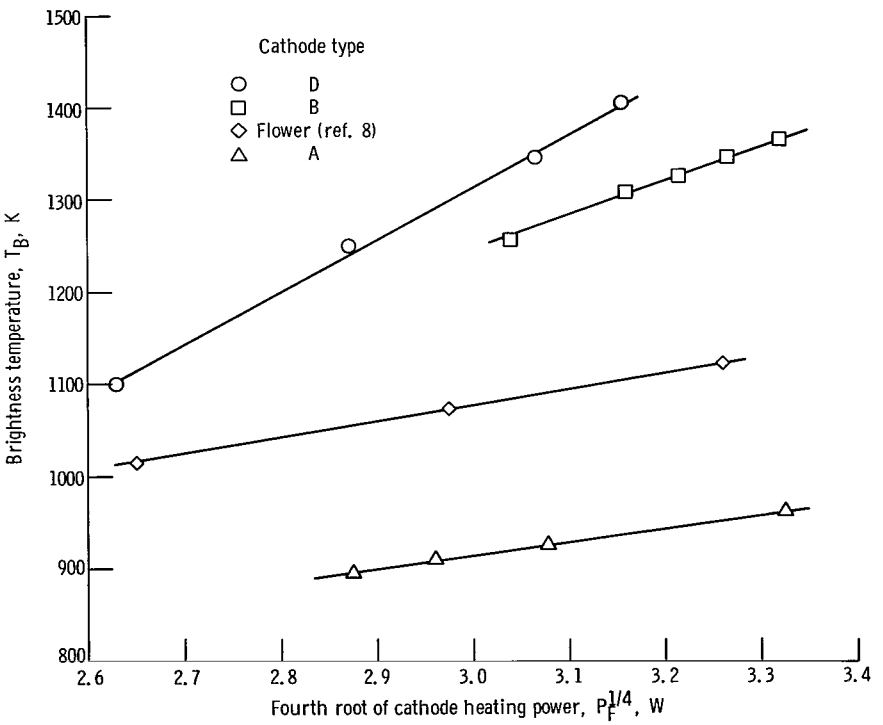
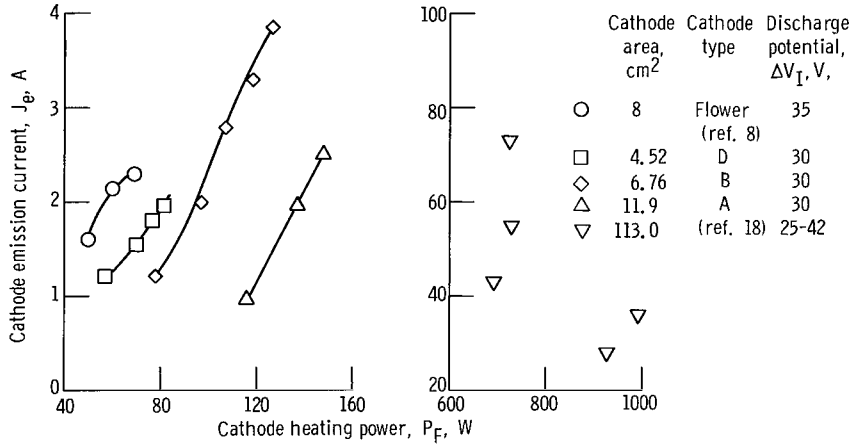


Figure 5. - Effect of cathode heating power on brightness temperature.

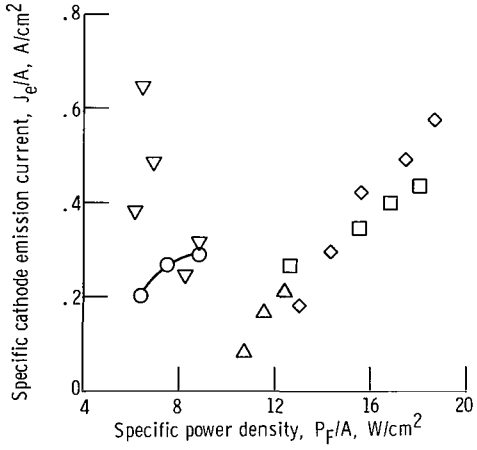
ions are incident on the cathode screen. It is assumed, however, that the power delivered to the screen (effectively the total incident ion current times the cathode sheath drop) is not significant in the cathode power balance.

The brightness temperature of the cathode screen was a function of the screen's history. The brightness temperature of a cathode at a fixed heating power was found to decrease by as much as 50 K when exposed to atmosphere between successive tests. The drop in temperature seemed permanent. The cathode would not return to its original temperature power curve when operated for long time periods over large ranges of power and discharge potential.

The power-emission curves for several cathode types are shown in figure 6(a). The specific power-emission curves for the same cathodes are shown in figure 6(b). The



(a) Total emission current as function of total cathode heating power.



(b) Specific cathode emission current as function of specific heating power.

Figure 6. - Cathode emission characteristics.

"flower" cathode and the large oxide-magazine cathode of reference 18 are also shown. The discharge potential was 30 volts for these data, except where noted. The data were taken, however, at a variety of neutral flow rates, propellant utilization efficiencies, and thruster electrical and geometric conditions. These parameters all influence cathode emission. They are strongly interrelated and will be discussed separately later.

Figure 6 shows that for the cathodes of this program, the power requirements increased with larger cathode screen area (frontal). The cathode emission density as a function of specific heating power (W/cm^2) was approximately the same for all the cathodes of this study. More striking are the very high current densities at low power densities for the large cathode of reference 18 and the "flower" cathode (ref. 8). In substance, the cathodes of reference 18 were scaled up versions of a type B cathode. A catenary screen shape and a somewhat heavier mesh than the screens of this study were utilized. Although not shown in figure 6, the emission currents of a type B cathode which utilized the same mesh as the large cathodes were lower than the type B cathodes that used the standard mesh. In addition, the chemical block of the reference 18 cathode was substantially the same composition as the standard block of this program. It is unlikely, therefore, that the very high values of specific emission current densities of the reference 18 cathodes result from a major chemical difference.

Variations in end losses and varying degrees of localized emission might, however, explain the differences in emission current densities. Conduction end losses become a larger fraction of the total power loss as the cathode size is decreased. Due to improved heat shielding and reduction of conduction losses by use of tantalum heater leads, the measured brightness temperatures became more uniform as cathode size decreased. The temperature of cathode type A, for example, varied by about 90 K across the front face in approximately a linear fashion. The brightness temperature of type D was, however, uniform to within about 20 K over approximately 90 percent of its wolfram surface. Strongly localized temperatures have been observed in other oxide cathode types, such as the brush (ref. 5). An extreme case of localized emission also occurred with one cathode of type A. This cathode was inadvertently overheated by the application of powers in excess of 350 watts. Large irregular amounts of activator material were deposited on the downstream side of the wolfram screen as a result of overheating. This cathode subsequently operated at very low power levels of the order of 20 to 30 watts. The existence of localized emission can then lead to anomalously high values of emission current for a given input power. Localized emission is undesirable, especially from the standpoint of lifetime. Local overheating, possibly due to high local emission, led to failures in several brush cathodes (ref. 5). Although not certain, it is also possible that the heater failures of the thin oxide layer cathodes of reference 8 might be attributed to localized overheating. No oxide-magazine cathode failed due to open or short circuits in heater

leads. This included several tests of greater than 100 hours duration and the several thousand hour tests of reference 6.

Figure 7 shows the emission current plotted as a function of the inverse fourth root of input power for a tantalum ribbon and a type D cathode. These data are typical of the other cathodes tested in the program. It is seen from the right portion of the plots that both curves tend to be linear (on a semilogarithmic graph) at lower levels of power. To

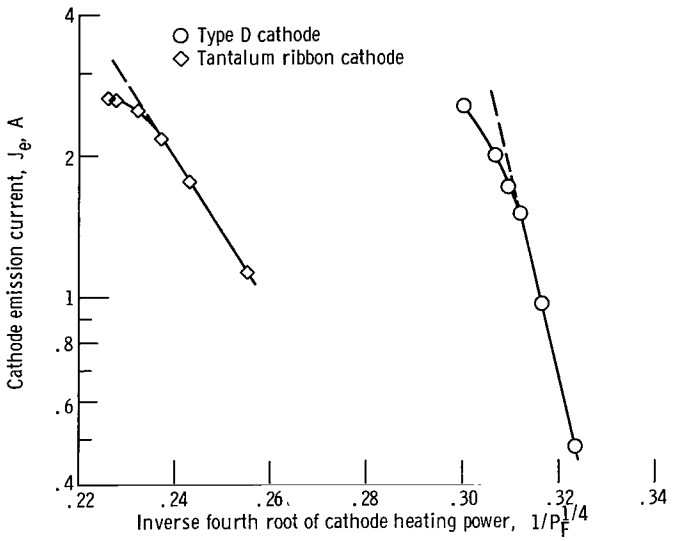


Figure 7. - Effect of cathode heating power on emission current. Ion-chamber discharge potential, 30 volts.

the left the emission increased at a slower rate and became smaller than predicted from thermionic relations such as the Richardson and Duschman equations (ref. 19).

The deviation of the emission curve from thermionic predictions might be due to a number of reasons, such as (1) gross changes in the overall cathode sheath, or; (2) the effect of nonzero initial electron velocities on the usual space charge limitations; or (3) the effect of ion current incident on the cathode screen.

References 20 and 21 discuss the space charge current between plane diodes under the assumption of nonzero initial electron energy. In particular, reference 21 discusses this problem directly in terms of the energy of the electron and the initial potential energy. These energies should roughly correspond to the energy equivalent of the temperature of the screen and the potential drop in the cathode sheath, respectively. The wolfram screen temperature is nominally 1100 K ($\approx$0. 1 V) while the cathode potential drop is about 30 volts. The ratio of initial to potential energy is then less that about 10^{-2}. Figure 2 of reference 21 indicates that the increase in unipolar electron current is very small with this energy ratio, certainly less than 10 percent. It is seen, however, from

figure 7 that rather large increases in emission current still occurred even after the emission current deviated from a thermionic characteristic. It would seem then that the deviation of the emission curve from a thermionic characteristic is not due to the initial energies of the emitted electrons.

The effect of ions that strike the cathode surface is not known exactly. It has been shown (ref. 17) that if the ions do strongly affect the cathode power balance the emission current can be a strong function of the total energy delivered to the cathode by the ions falling through the cathode sheath. In addition, ions falling through the sheath will increase the space charge current transmission capability of a thermionic emitter (ref. 21). It has been stated previously that such ions probably do not significantly affect the cathode power balance (fig. 5), especially at the low discharge currents of interest in this program. It is also assumed throughout this report that, except for the effect of sputtering activator from the cathode surface, ions that strike the cathode surface do not strongly affect the emission current.

It thus seems that the very gradual deviation of the emission curve from a thermionic characteristic is not due to the initial energies of the emitted electrons or the effect of ions striking the cathode. Rather, it appears that some gross change occurs in either the voltage drop or length of the cathode sheath. Further discussion of this effect will be deferred to a later section.

Effect of Discharge Potential

The discharge potential strongly affects the emission current. Figure 8 shows a plot of emission current as a function of discharge potential for a double screen cathode (type D) at three different heating powers. The equivalent neutral flow rate was 286 milliamperes for these data. The gross volt-ampere characteristics of nearly all oxide cathode types tested were quite similar. The emission current would increase with voltage up to some level and then monotonically decrease with discharge potential. This behavior has been observed previously (ref. 6).

As seen from figure 8 the level of discharge potential at which the maximum emission current saturated increased with cathode heating power. This was probably due to the increased activator produced at increased power levels. The maximum emission current would seem to be a function of the rate of activator production and removal. The emission current is probably dominated by the cathode sheath characteristics below its maximum value. As the discharge potential increases, however, the rate of removal of activator by ion sputtering increases. The threshold of mercury sputtering on wolfram occurs between 20 and 30 volts (ref. 4). The emission current then decreases at large discharge potentials due to the lack of sufficient activator.

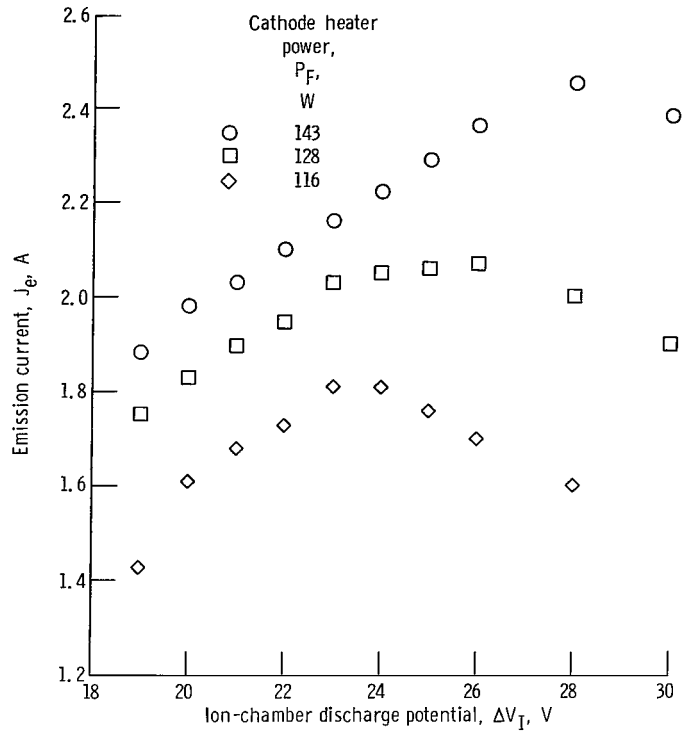


Figure 8. - Effect of discharge potential on emission current. Equivalent neutral flow rate, 286 milliamperes.

One cathode type did not exhibit the trends of emission current with discharge potential shown on figure 8. Three tests were made with a type B cathode on which, for convenience, the sides of the chemical block were not enclosed in a duct. The chemical block was exposed directly to the discharge plasma. The emission current rose with discharge potential up to the maximum values of potential applied (about 65 V). Later tests with a type B cathode in which the sides of the chemical block were enclosed in the duct exhibited emission current-discharge potential characteristics similar to those of figure 8.

It is not known exactly why direct exposure of the chemical block to the discharge plasma should change the volt-ampere characteristic of the cathode. Such a configuration would, however, allow the chemical constituents to freely fall into the discharge chamber and this was not an acceptable design for the program.

The dynamic relation between the levels of emission and activator is seen further in figure 9. These data were taken with a type C cathode. In general, following an increase in discharge potential the emission current would first rise then fall to some lower value in a time of order minutes (regions C to D and I to J on fig. 9). Conversely, when the discharge potential was decreased, the emission current would decrease then rise to some nominally constant value (regions E to F and G to H). This behavior is compatible

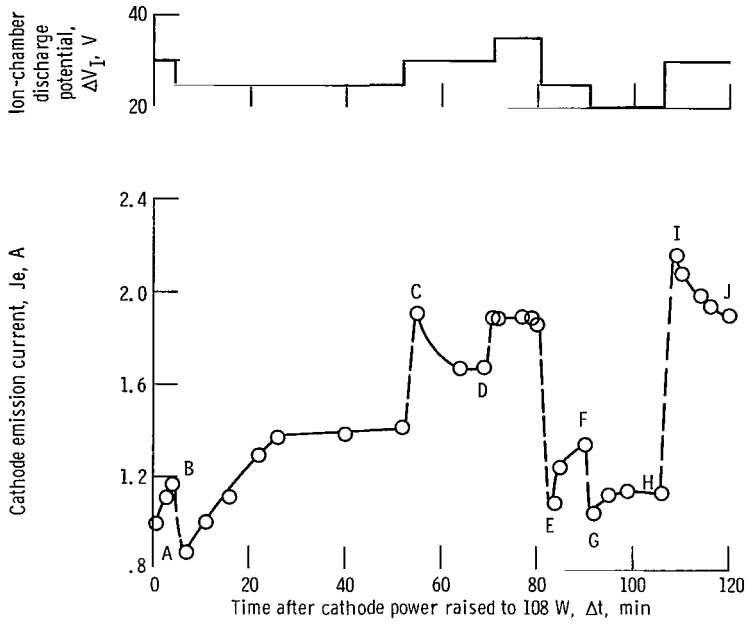
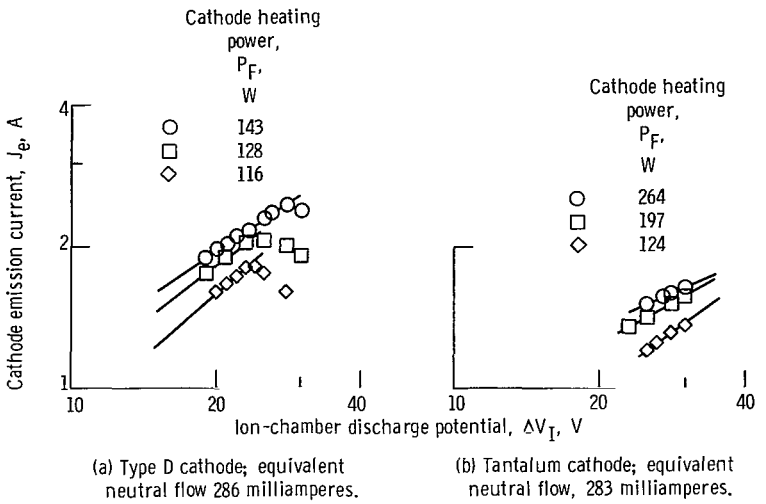


Figure 9. - Effect of time and previous history on cathode emission. Cathode heater power, 110 watts; type C cathode.

with the view that the amount of activator present is a function of the discharge potential. The time for a new equilibrium emission current to be reached is probably a function of the diffusion rate of the activator across the wolfram surface. Calculation of this rate requires, however, exact knowledge of various dynamic rates - such as evaporation rates and total ion sputtering rates. Since knowledge of these parameters is highly qualitative no attempt was made to match the observed equilibration times with any calculated models.

Figure 7 showed that the cathode emission rose with cathode power with a thermionic characteristic up to some limit. The increase in power undoubtedly resulted in an increase of available activator (see fig. 8). Apparently, however, the cathode did not benefit from the extra activator. On the other hand, figures 8 and 9 indicate that the amount of activator is important in the emission process. This seeming contradiction is explained if the activator-wolfram interaction depends on the degree of surface coverage up to some level and then becomes relatively insensitive to the amount of activator.

The emission current of an oxide-magazine cathode might be expected to rise somewhat more slowly than with a three-halves power of discharge potential below emission saturation. This is because, as the voltage is increased, the rate of activator removal is increased and, as seen in figure 8, this can strongly influence the emission current. Figure 10 shows the emission current plotted as a function of discharge potential at various power levels. Figure 10(a) is for a type D oxide magazine cathode and figure 10(b)



(a) Type D cathode; equivalent neutral flow 286 milliamperes.

(b) Tantalum cathode; equivalent neutral flow, 283 milliamperes.

Figure 10. - Effect of discharge potential on emission current.

is for a tantalum ribbon cathode. These data were taken in the same thruster and at identical cathode positions. The equivalent neutral propellant flow was 286 milliamperes for figure 10(a) and 283 milliamperes for figure 10(b). The tantalum cathode data is presented for comparison because it is free of the influence of activator sputtering, a factor which complicates the oxide-magazine data.

It is seen from figure 10 that the emission current rose considerably slower with discharge potential than a three halves power for both cathodes. In addition, it is seen that as the cathode power level increased the emission current became a less sensitive function of discharge potential. This tendency was noted throughout the program. The slopes ranged from about 0.4 to 1.4. In general the slopes increased with thrusters that tended, due to the geometry utilized, to operate at low values of propellant utilization efficiency.

Effects of Propellant Flow Rate and Utilization Efficiency

The propellant utilization efficiency (η_u) is a basic figure of merit for any thruster system. The parameter is given by the ratio of the extracted ion beam current to the inlet neutral flow rate, expressed in equivalent amperes. The discharge chamber efficiency is measured by the energy expended to form a beam ion (eV/ion). This parameter is essentially the product of the discharge potential and the emission current divided by the ion beam current. The effects of propellant flow rate and propellant utilization efficiency on emission current cannot be easily separated. Variation of the utilization efficiency, at a fixed propellant flow, is usually accomplished by variation of the cathode

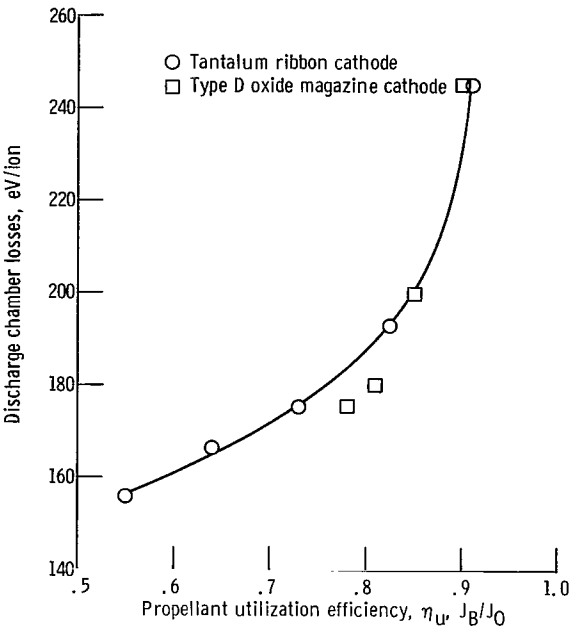


Figure 11. - Discharge losses as function of propellant utilization efficiency. Ion-chamber discharge potential, 30 volts.

emission and/or discharge potential. On the other hand, variation of the neutral flow rate at a constant discharge potential and emission current usually produces variation in propellant utilization efficiency and the discharge efficiency is also sensitive to the thruster electromechanical configuration. The general characteristic, however, is similar for most thrusters.

Figure 11 shows a typical curve for a version of the SERT II thruster. It is taken from figure 11 of reference 3. The data were taken at 30 volts discharge potential. The discharge losses increased due to a faster rate of increase in the discharge current than in the beam current with increases in utilization efficiency.

Figure 12 shows the cathode emission current and propellant utilization efficiency as a function of cathode power at three values of neutral flow rate. The discharge potential was constant for these data. The ion beam current, however, varied with emission current along each curve. It is seen that, at fixed power, the emission current increased with neutral flow rate, while the propellant utilization efficiency stayed nearly constant. The dependence of the emission current on neutral flow rate was strongest at high values of emission current (and propellant utilization efficiency).

To try to differentiate between the effects of neutral flow rate and propellant utilization efficiency on the emission current it is necessary to vary the utilization at a fixed neutral flow, while holding constant the other parameters which are known to affect the emission current, such as discharge potential and cathode power. This type of variation

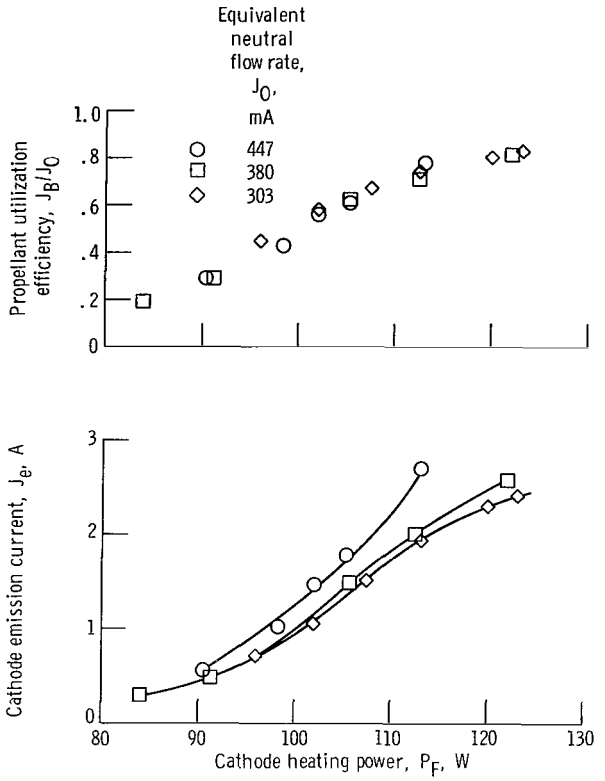
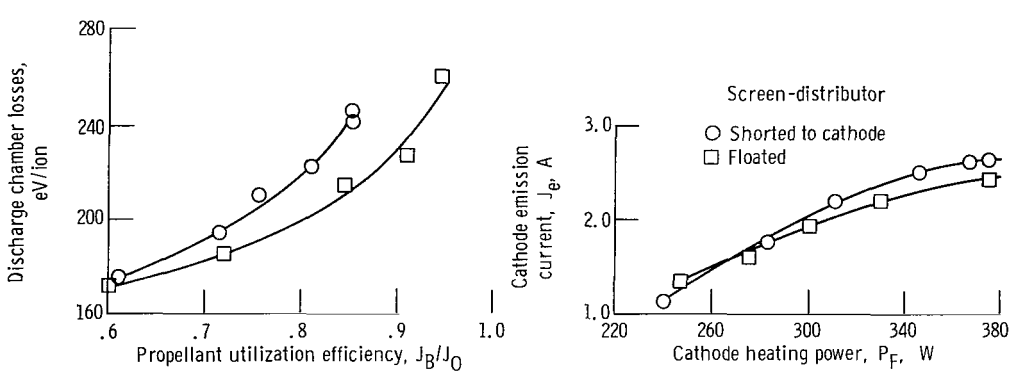


Figure 12. - Effect of neutral flow rate on cathode emission. Ion-chamber discharge potential, 30 volts.

can be accomplished by changes in the screen-distributor plate electrical configuration.

The ends of the ion chamber are bounded by the screen and distributor plates (fig. 1) which could either be electrically floated or shorted to the cathode. It was found that the propellant utilization efficiency increased if the screen distributor was floated. In addition, the state of this component directly affected the emission current. Figures 13(a)



(a) Discharge chamber losses as function of propellant utilization efficiency.

(b) Cathode emission current as function of cathode heating power.

Figure 13. - Discharge losses and cathode emission characteristics. Equivalent neutral flow, 270 milliamperes; Ion-chamber discharge potential, 30 volts.

and (b) show, respectively, a plot of discharge chamber losses as a function of propellant utilization and cathode emission as a function of cathode power for the case of a floated and shorted distributor and screen. The data were taken with a tantalum ribbon cathode, again, to avoid confusion concerning activator removal. The equivalent flow rate was 270 milliamperes and the discharge potential was 30 volts for the data of figures 13(a) and (b).

It is seen that at the lower values of propellant utilization (or cathode power) the two systems are quite similar. At higher values of utilization, however, the ion chamber losses and the emission current for the floated case begin to vary from those of the non-floated case. Figure 12 also showed the relation between propellant utilization and the emission current. The propellant utilization was nearly constant at a fixed cathode power even though the emission current was not.

In either case, the exact reasons for the relation between propellant utilization efficiency (or various plasma parameters which are a function of utilization) and emission current are not known. It is quite likely, however, that some gross characteristics of the cathode sheath are affected by variation in utilization efficiency. It has been proposed in reference 22 that the increase of discharge chamber losses with propellant utilization efficiency is accompanied by increased ohmic heating losses in the bulk discharge plasma. The ohmic loss is reflected in an increase of the voltage drop across the bulk plasma. If it is assumed that the anode sheath drop remains nominally constant, it is possible that the voltage available for the cathode sheath drop decreases as the propellant utilization efficiency increases. Such a decrease in the cathode voltage sheath drop would produce a space charge limitation of the cathode.

Poisoning and Facility Effects

As previously mentioned, three facilities were utilized to perform cathode tests. The background pressures in all the facilities was considerably larger than those associated with sealed electron tubes of long lifetime. It is not known if these levels of background had a deleterious effect on cathode performance throughout the program. However, the previous remarks on limitations of cathode emission by various thruster parameters indicate that the fundamental limits on cathode performance at high values of emission and propellant utilization efficiency were not of chemical origin.

It was noted that performance would generally degrade if the cathode was exposed to atmosphere after testing. It is not straightforward, however, that this is a poisoning effect. As stated previously, the brightness temperature of the cathode would drop about 50 K after exposure to atmosphere. The apparent degradation in performance may then have actually been a result of a change in emittance of the cathode.

When the bell jar pressure rose during thruster operation the emission current degraded then recovered. In one case, for example, the power required to provide a constant emission current of 1.8 amperes rose by about 15 percent when the ambient pressure rose because of a failure of the cryopump system. Unlike the permanent degradation of performance resulting from exposure to atmosphere, the cathode returned to its original performance level after the pressure dropped to its original value. It was also found that deliberate exposure of the cathode to carbon dioxide resulted in about the same cathode response. Interestingly enough, it was found that exposure to propane for a few minutes during operation degraded the cathode emission for periods greater than 4 hours.

Vibration Tests

Two vibration tests were made with a thruster with an oxide-magazine cathode. Boron nitride was used for the ceramic block. The thruster was vibrated on three axes at sine and random frequencies from 5 to 3000 hertz. Acceleration levels up to 20 g's (200 m/sec^2) were applied. The results of both tests were similar. The major components of the cathode passed vibration tests without structural failure. A fine dust from the chemical block was found in the thruster after both tests. The chemical block is conductive so that the dust deposits could lead to a variety of electrical shorts. The problem could be solved in a variety of fashions, such as a thin covering of some chemical which would evaporate upon application of cathode heating power.

CONCLUDING REMARKS

A study was presented of the performance of oxide-magazine cathodes in a thruster of the SERT II type.

A range of chemical types and concentrations was tested in the chemical block. Some limits on the amounts and types of various chemical constituents such as binder and activator were noted. No significant improvements over the original chemical activator block of reference 6 were noted.

The oxide cathode emission as a function of geometry and cathode power was studied. The power decreased with decreases in cathode size. The lowest value of cathode heating power required to obtain 2.0 amperes emission current (at about 250 mA of ion beam current) was about 70 watts. This power is considerably larger than that required for the same emission current for oxide coated wolfram in nonthruster applications.

The effects of discharge potential on emission were noted. For most cathodes tested the emission current exhibited a maximum with some value of discharge potential. This

effect agreed with previous data (ref. 6) and was felt to be due to activator removal by ion sputtering.

Several disadvantages of the oxide-magazine cathode relative to its use on SERT II or similar missions were noted.

The cathode emission current was found to be sensitive to the neutral propellant flow rate and propellant utilization efficiency. Operation at high propellant utilization efficiency appeared in some way to limit cathode emission. In addition, application of ion extraction voltage reduced cathode emission current by a factor of about two or three.

Some difficulty was experienced in obtaining repeatable performance. In addition, the cathode performance usually degraded when exposed to atmosphere. The latter fact makes preflight testing of the cathode difficult.

The oxide-magazine cathode may, however, be useful in a variety of applications. The lifetime in the plasma environment of ion thrusters has been demonstrated to be greater than 4000 hours (ref. 6). Throughout this program catastrophic failures, typical of many oxide cathode types, were not observed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 21, 1968,
120-26-02-05-22.

REFERENCES

1. Kerslake, William R.; Byers, David C.; and Staggs, John F.: SERT II Experimental Thruster System. Paper No. 67-700, AIAA, Sept. 1967.

2. Kaufman, Harold R.: An Ion Rocket with an Electron-Bombardment Ion Source. NASA TN D-585, 1961.

3. Bechtel, Robert T.: Discharge Chamber Optimization of the SERT II Thruster. J. Spacecraft Rockets, vol. 5, no. 7, July 1968, pp. 795-800.

4. Milder, Nelson L.; and Kerslake, William R.: Evaluation of Filament Deterioriation in Electron-Bombardment Ion Sources. NASA TN D-2173, 1964.

5. Kerslake, William R.: Preliminary Operation of Oxide - Coated Brush Cathodes in Electron-Bombardment Ion Thrustors. NASA TM X-1105, 1965.

6. Reader, Paul D.; and Pawlik, Eugene V.: Cathode Durability Tests in Mercury Electron-Bombardment Ion Thruster. NASA TN D-4055, 1967.

7. Eckhardt, W. O.; Arnold, K. W.; Hagen, G.; Hyman, J., Jr.; Snyder, J. A.; and Knechtli, R. C.: High-Temperature LM Cathodes for Ion Thrustors. Hughes Research Labs. (NASA CR-93771), July 31, 1967.

8. Knauer, W.; and Gallagher, H.: Low Work Function Cathode Development. Hughes Research Labs. (NASA CR-54682), Oct. 1966.

9. Bechtel, R. T.; Csiky, G. A.; and Byers, D. C.: Performance of a 15-Centimeter Diameter, Hollow-Cathode Kaufman Thrustor. Paper 68-88, AIAA, Jan. 1968.

10. Keller, Thomas A.: NASA Electric Rocket Test Facilities. Paper presented at Symposium on Rocket Operations at Simulated High Altitudes and in Space, Arnold Engineering Development Center, Tullahoma, Tenn., June 28-29, 1961.

11. Finke, Robert C.; Holmes, Arthur D.; and Keller, Thomas A.: Space Environment Facility for Electric Propulsion Systems Research. NASA TN D-2774, 1965.

12. Kohl, Walter H.: Handbook of Materials and Techniques for Vacuum Devices. Reinhold Publishing Corp., 1967, pp. 507-509.

13. Kloeffler, Royce G.; Horrell, Maurice W.; and Haragrove, Lee E., Jr.: Basic Electronics. Second ed., John Wiley & Sons, Inc., 1963, ch. 4, p. 113.

14. Kerslake, William R.: Oxide - Cathode Durability in Mercury Electron-Bombardment Ion Thrustor. NASA TN D-3818, 1967.

15. Rittner, E. S.: A Theoretical Study of the Chemistry of the Oxide Cathode. Philips Res. Rep., vol. 8, no. 3, June 1953, pp. 184-238.

16. Strickfaden, William B.; and Geiler, Kenneth L.: Probe Measurements of the Discharge in an Operating Electron Bombardment Engine. Tech. Rep. 32-417, Jet Propulsion Lab., California Inst. Tech. (NASA CR-50623), Apr. 19, 1963.

17. Bade, W. L.; and Yos, J. M.: Theoretical and Experimental Investigation of Arc Plasma-Generation Technology. Part II: Applied Research on Electric Arc Phenomena. Vol. 1: A Theoretical and Experimental Study of Thermionic Arc Cathodes. Avco Corp. (ASD-TDR-62-729, pt. II, vol. 1), Sept. 1963.

18. Nakanishi, S.; and Pawlik, E. V.: Experimental Investigation of a 1.5-Meter Diameter Kaufman Thrustor. Paper No. 67-725, AIAA, Sept. 1967.

19. Cobine, James D.: Gaseous Conductors. Dover Publ., Inc., 1941, ch. V.

20. Langmuir, Irving: The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current Between Parallel Plane Electrodes. Phys. Rev., vol. 21, no. 4, Apr. 1923, pp. 419-435.

21. Howes, Walton L.: Effect of Initial Velocity on One-Dimensional, Ambipolar, Space-Charge Currents. NASA TN D-2425, 1964.

22. Kaufman, Harold R.: Performance Correlation for Electron-Bombardment Ion Sources. NASA TN D-3041, 1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

OFFICIAL BUSINESS

FIRST CLASS MAIL

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546