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THE HIGH SPECIFIC IMPULSE, ARC-ION SYSTEM

J. S. Luce
J. W. Flowers

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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ABSTRACT

The use of high exhaust velocity in a space vehicle after gravitational forces have been overcome is made necessary by the large mass loss inherent with high thrust low specific impulse devices needed for takeoff (Addendum 1). Increased maneuverability, greater range and larger payloads are obvious advantages which accrue from the development of a successful high specific impulse system.

This report considers a little-explored but promising high specific impulse method: the arc-ion system. The ion source used with this system utilizes an arc for ionization of the propellant and the resultant ions are accelerated electrostatically. The arc system of ionization is adaptable to advanced methods of space-charge neutralization because the arc is transparent to high-energy electrons which can be passed through it. These electrons reduce the positive ion space potential in the accelerating gap and drift spaces.

The achievement of space-charge neutrality in these systems would, in principle, allow beams of very large density to be accelerated. Child's Law sets definite limits to the obtainable current in space charge limited sources. The arc-ion system, however, lends itself naturally to development of new space charge neutralization techniques. If successful neutralization is achieved the system will cover the same specific impulse range as the arc jet, plasma, and ion propulsion methods with one simple device.

Obviously, the recognized ability of ion propulsion to achieve high specific impulse should be enhanced by the laboratory-proven advantages of the arc-ion system. Some of these proven assets are:

A. Any ion species can be accelerated and controlled in the arc-ion system. This includes ions of waste material and any substance that could be obtained from small moons, astronoids, etc., in space and converted to propellant.

B. Large ion emission areas and ion beams in the multi-ampere range have been achieved with arc-type ion sources.

C. The arc-ion system, and certain plasma systems, allow the use of "pumping propellants," such as Ti, Zr, U, and many others, which because of their low vapor pressure at normal temperature permit the construction of low-cost, high-capacity ground testing facilities. Testing engines of <u>any</u> obtainable thrust is, in principle, possible since the <u>propellant itself provides pumping</u>. This important advantage allows the study of the basic physics of extremely large beams which is not possible when high vapor pressure propellants and conventional pumping is used. In principle, pumping propellant facilities will reduce the number of orbital tests necessary. This will result in financial savings, and should appreciably enhance time schedules. Any electric propulsion system can be tested in this manner by utilizing low vapor pressure propellants. The only method excluded would be the cesium contact source, which appears to be inherently restricted to a high vapor pressure propellant.

The flexibility and extensive potentialities of the arc-ion system justify a program at least comparable in magnitude to the cesium contact source.

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THE HIGH SPECIFIC IMPULSE, ARC-ION SYSTEM

INTRODUCTION

Specific impulse is a measure of propellant exhaust velocity (Addendum 1). The specific impulse which can be attained by a thrust system is an extremely important parameter and partially classifies the system. With low specific impulse a high price is paid in the mass loss of the vehicle during acceleration. For a fixed specific impulse the mass loss necessary to attain a given velocity is fixed (Addendum 1). Because of its low specific impulse the chemical rocket mass loss necessary to attain orbit is usually greater than 90 per cent. Any space mission beyond the initial orbit is severely limited if a chemical system is used.

Large thrust systems, such as the chemical rocket, are necessary for passing quickly through the atmosphere or a radiation belt and for directly overcoming the force of gravity. In the region beyond the atmosphere, systems of low thrust may be used, and systems of high specific impulse are essential. Since no known thrust method provides both high thrust and high specific impulse, it is clear that more than one system is necessary for space travel or space missions other than a simple orbit. The chemical system at the present time provides high thrust and will probably remain the most suitable for reaching levels up to 100 or 200 miles above the earth. [1]For more extensive missions where maneuvers are planned, auxiliary thrust systems are necessary and devices which produce higher specific impulse must be provided.

The available specific impulse from the chemical system appears limited to values below about 400 seconds, and is essentially limited by reaction temperature. The specific impulse which can be obtained from the nuclear heat transfer rocket and the arc thermal (arc jet) system is dictated by the temperature limitation of materials used in the vehicle. These systems gain in specific impulse mainly because hydrogen may be chosen for the propellant, while in the conventional chemical system the propellant must be of a higher molecular weight, since it is the product of combustion, e.g., H_2O, CO_2, HF, etc. The Centaur Rocket, which uses oxygen and hydrogen, will provide specific impulse of about 350 seconds, while systems using H_2 F_2 or H_2 O_3, if successful, will provide specific impulse in the range of 400 seconds. It has been estimated that it may be possible to obtain specific impulse values of 600 to 1000 seconds for hydrogen which has passed over the graphite of a very high temperature fission reactor. Recent Rover tests indicate that a specific impulse of at least 600 seconds is feasible. With the arc-thermal system, the propellant can be heated to a higher temperature than is possible with the chemical, or nuclear heat transfer system. Values of well over 1000 seconds have been measured, and values of 2000 seconds appear possible. The nuclear heat transfer rocket will provide a significant increase in specific impulse over that of the chemical system. This will be of great value because of its high thrust and relatively simple construction, nevertheless, greater specific impulse values must be reached for many contemplated missions into space; and for many missions the only realistic possibility appears to be ion or plasma propulsion.

ION THRUST SYSTEM

Ion propulsion is of interest because of its capacity to produce extremely high exhaust velocity and therefore high specific impulse. The acceleration of ions to any desired velocity in a dc electric field, unlike the nuclear, plasma, or arc jet systems, is unrelated to any equilibrium state or thermal heating; for in ion sources, energy is put directly into the ions. The exhaust velocity of an ion of charge e and mass M after it has been accelerated in an electric field through a potential drop ϕ is given by

$$V_{ex} = \sqrt{\frac{2\phi e}{M}}, \tag{1}$$

and the specific impulse

$$I_{SP} = \sqrt{\frac{2\phi e}{M}\Big/g} \text{ seconds.} \tag{2}$$

From these equations it appears that no limits are encountered for any usable specific impulse values. Specific impulse in the ion system can be adjusted to any desired value. [1-10] The advantage of this characteristic has been pointed out in the literature. In Addendum 1 it is shown that for a given thrust the power increases in proportion to specific impulse. It is therefore possible to adjust the specific impulse to achieve an optimum balance between propellant consumption and the power available. This optimum depends on the thrust required and may change significantly during a mission. In general, it will be best to obtain the required thrust with the highest value of specific impulse permitted by the power available. The minimum propellant consumption will be given by a system in which the specific impulse could be varied to suit the thrust requirements of the various phases of the mission.

Ion Thrust

For the ion system, thrust depends upon the magnitude of the positive ion current achieved in the exhaust beam (Addendum 1), and very large ion currents have not as yet been obtained. Electrons present in the exhaust contribute negligible thrust because of their small mass. In the usual considerations of ion acceleration systems, ion currents are assumed to be space charge limited. They then follow an equation of the form:

$$I \sim \left(\frac{e}{M}\right)^{1/2} \frac{\phi^{3/2}}{x^2} \qquad (3)$$

where x is some variable accelerating gap space. The conclusion that space charge limitation is inevitable leads to the following arguments concerning the thrust. For a given ion, adjustment of specific impulse by adjusting ϕ (Eq. 2) affects the ion beam current (Eq. 3), and therefore the thrust. In order to maintain the desired thrust it is possible to adjust specific impulse by a change of ion species, using an ion with a different e/M value or perhaps even a charged colloidal particle. Maximum values of ϕ are chosen for high current (Eq. 3), and e/M are compared, the current required is smaller for an ion of larger mass for a given specific impulse and power. For single ionization, the current ratio is the inverse of the mass ratio. A one-ampere mercury ion beam at a given specific impulse and therefore given thrust and power must be compared with a 200-ampere hydrogen beam at the same specific impulse, thrust and power. For example, with I_{SP} = 10,000 seconds, the hydrogen ion would require a potential ϕ of 50 volts and the mercury ion would require 10 kv. The thrust from each would be the same and the power would be 10 kw. Hydrogen then is essentially ruled

out at the present time because of the large current requirement under the controlling space charge limited conditions.

It is not generally realized that it is theoretically possible to accelerate ions under the condition of complete space charge neutrality (Addendum 2). For this condition, Eq. (3) is irrelevant and the obtainable ion current is extended to a much higher value, if the special requirements of electron velocities and density are achieved. The requirement of neutrality places no demands on the direction in which the electrons move. Electrons which move counter to the ion flow (which occurs with gas neutralization) provide some neutralization but cause an undesirable source drain, thus making it more advantageous to accelerate electrons in the same direction as the ions and provide an ion source with hollow electrodes so that the electrons can pass through the source. It seems very likely that space charge limitations can be at least partially eliminated in this way, and much larger ion currents can be achieved. High thrust is an obvious result of large ion current. Another advantage lies in the flexibility which high current would permit with respect to the power supply, to the ion species, to the specific impulse, and finally to the possibility of a universal thrust system. The arc-ion source under the condition of space charge neutrality appears to have these potentialities and should be pursued with vigor. Controlled neutralization should provide improvements that justify re-evaluation of the potentialities of ion propulsion; also, if a controllable ion current of great density can be achieved, its application certainly will not be confined to space propulsion alone.

Ion Source Types

Ion source development for propulsion of space vehicles can be divided into two broad categories based on the method of ion production: (1) surface ionization, and (2) arc ionization.

Surface Ion Sources

In the surface-ion source, cesium is the propellant generally used. The selection of cesium is a result of several considerations. Ion emission occurs when the ionization potential of an atom is less than the work function of the surface material from which the atom leaves. A tungsten surface may be heated sufficiently, and its work function is large enough to allow the needed ionization process with cesium which then provides an ion of fixed charge and mass.

Arc Ion Sources

Arc-ion sources, in which propellant ionization occurs in an arc, take a number of forms; and many new configurations appear possible. The duoplasmatron or von Ardenne source is of this type. Lesser known are the grid ion sources used in isotope separation processes. Both of these sources employ magnetic fields; and other source types using a magnetic field appear promising. Intense arcs operating from hollow cathodes in longitudinal magnetic fields seem particularly attractive for source work, since auxiliary high-velocity electrons can be passed through the cathode.

For space propulsion, the largest effort to date appears to have been made with the surface ionization system, and some comparison of this source and the arc source is worth consideration. Two characteristics have led to considerable interest in the surface contact system, i.e., low power requirements for ionization, and high ionization efficiency. However, while the

power requirements for ionization are small, power losses through radiation tend to nullify the advantage because of the large surface areas required. Arc-ion sources have achieved equal ionization efficiency; so it is possible that no net advantage may exist for either in the ionization process. The arc-ion source achieves much higher current density with the possibility of still higher ion density with improved charge neutralization. It is not evident that these improvements can be made in the contact ionization sources.

Assets of the Arc-Ion Source

Some proven assets of the arc-ion source are:

Propellant versatility

Long accelerating electrode life

Large controllable ion currents

High efficiency

Pumping propellants

Propellant versatility. In principle, any substances including waste products and material available in space can be converted to forms that are usable as propellants in arc-ion sources. It is interesting that the isotopes of 55 elements have been ionized and separated by this system; furthermore, a combination of elements may be ejected simultaneously. The ions of hydrogen and uranium have often been accelerated together in experiments conducted during World War II. When the various waste problems in space travel are considered, these characteristics should be a distinct advantage.[11] The possibility of refueling during flight using material from astronoids or small moons can be seriously considered with arc-ion sources. Successful use of these available propellants would certainly greatly enhance the usefulness of electrical propulsion.

Long accelerating electrode life. Erosion of accelerating electrodes constitutes a problem which is receiving considerable attention.[12] It has been shown experimentally that with proper attention to focusing, erosion by the primary beam is not a decisive factor when an arc type source is used. It is clear that no appreciable amount of scattering occurs in the accelerating gap at the densities that have been obtained, provided that heavy ions are used. Data of this type do not appear to be available for contact sources, but it is probable that the same basic principles apply.

Large controllable ion currents. The ion current which can be drawn from an arc type source has so far been much greater than that from the contact source, which is basically limited by space charge, not only in the accelerating gap, but also at the contact surface. Ion currents in the multi-ampere range are common with arc sources and much larger currents can, in principle, be achieved by further reducing the space charge limitation. There appears to be no obvious way of increasing the current in contact sources.

High efficiency. Arc sources of several types have achieved an efficiency (neutral particles in, versus ions accelerated) in excess of 90 per cent. This is not surprising when the blocking effect of the arc is considered. This question of efficiency is, however, a region where a great amount of misinformation exists. In principle, the arc and contact sources should operate at about the same propellant efficiency.

Arc-ion source development logically should proceed along two lines. One is the immediate development of an intense source capable of a small, dense, well-collimated beam.[13-15] The von Ardenne or duo-plasmatron ion source under development in several laboratories serves this purpose quite

well (Fig. 1). There appears to be little justification for an intermediate program; the next phase logically should be an ion source development capable of producing the maximum current needed to accomplish any contemplated mission, together with a study of the basic limits on ion currents. Grid type ion sources, while not ideally suited to space propulsion, are an example of the potentialities in this field (Fig. 2 and Addendum 3). At the present time insufficient effort is being expended on achieving large ion beams. Once a practical high current source has been produced, it can easily be scaled down if the need arises, and also permit control of thrust and choice of ion type.

While there are numerous problems associated with the development of a successful ion thrust device, the major one undoubtedly is control of space charge. [16] Several methods have been studied. These include neutralization by charge exchange, injection of electrons before ion acceleration, and injection after the ions are accelerated. All methods of neutralization deserve study, since space charge forces represent the most formidable problem in ion propulsion and must be well understood in order to anticipate the conditions in space. Of the systems under study, the attempt to eliminate space charge forces by electron injection both in the regions of acceleration and in field-free regions is particularly interesting.

The condition of complete space charge neutrality does <u>not</u> necessarily imply the absence of an applied electric field which can accelerate positive ions. [17] One can propose a class of electron velocity distributions in a voltage gap in which positive ions are accelerated, electrons are decelerated

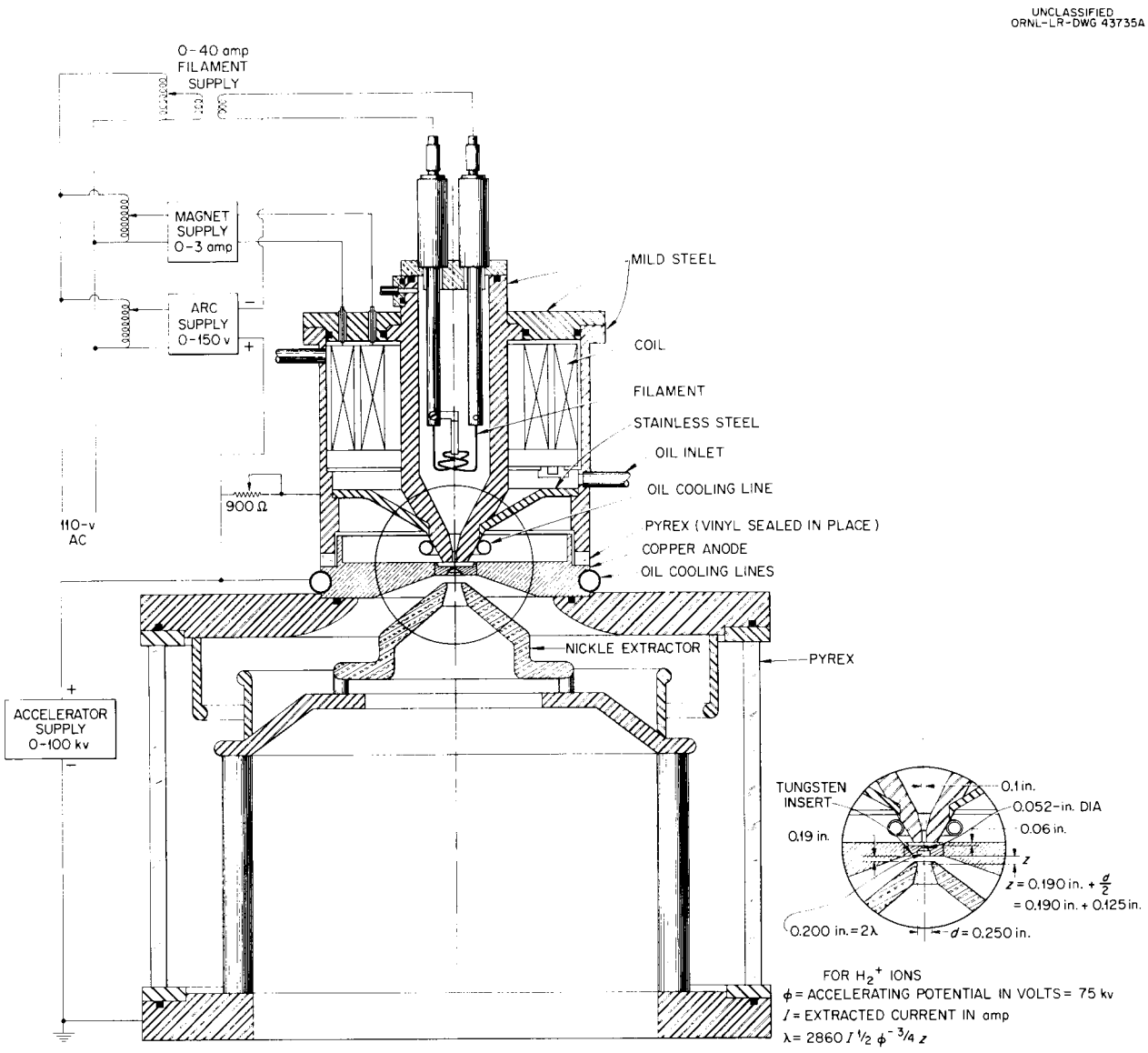

Fig. 1. Duo-Plasmatron Ion Source.

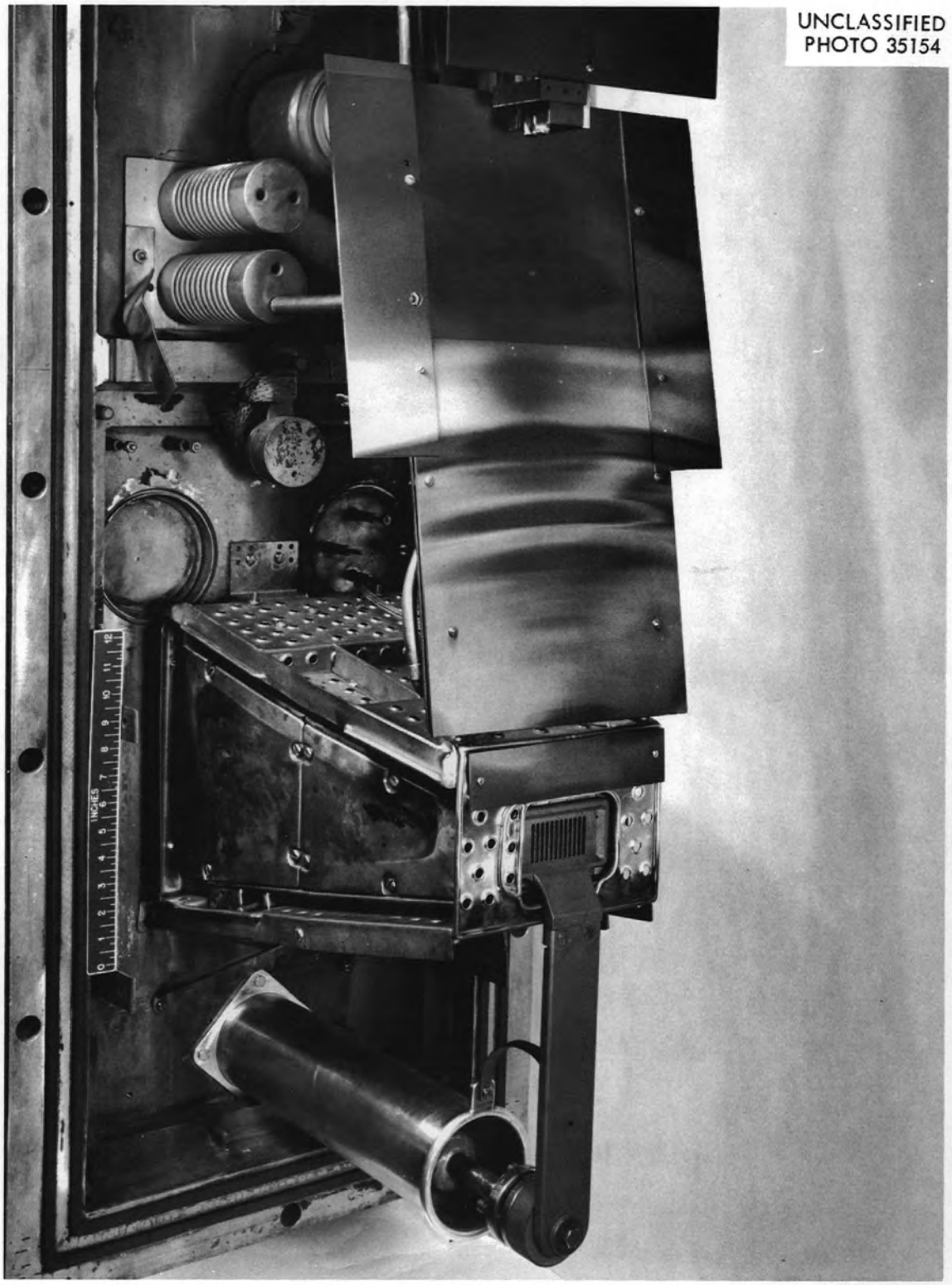

Fig. 2. Grid Ion Source.

and reflected, and no space charge forces arise. Consider the diagram (Fig. 3) with the acceleration of a positive ion beam coming from the left. At the left, the ion density is high and the velocity is low. At the right, the ions have high velocity and low density. If electrons are injected into the gap, the accelerating field for positive ions decelerates the negative electrons, as shown by the dotted mirror image of the ion potential. Thus electrons with suitable velocity distributions will be decelerated and reflected throughout the ion accelerating region, providing an electron density distribution similar to the ion distribution, and charge neutrality is achieved through the gap. Achieving these conditions in an accelerator suitable for ion propulsion does, of course, require new concepts which are now being studied to a limited extent.

In addition to the oscillatory electrons needed in the accelerating region it is also necessary to accelerate a stream of electrons (Addendum 2) through the entire system, which will emerge with about the same velocity as the positive ions. Successful dc charge neutral electron guns have been developed which easily achieve a density of 5×10^{10} electrons per cc at any velocity needed for neutralization (Fig. 4); and an ion source with the necessary hollow electrode configuration which permits electrons to pass through the source has also achieved successful operation. If combining the two succeeds, space charge neutralization will be realized throughout the system (Fig. 5). The conventional method of injecting electrons after ion acceleration does not eliminate space charge forces during and immediately after acceleration.

While charge-to-mass ratio is often considered to be of significance in ion acceleration and heavy ions and colloids are being investigated, it can be shown that the power-to-thrust ratio for a desired specific impulse

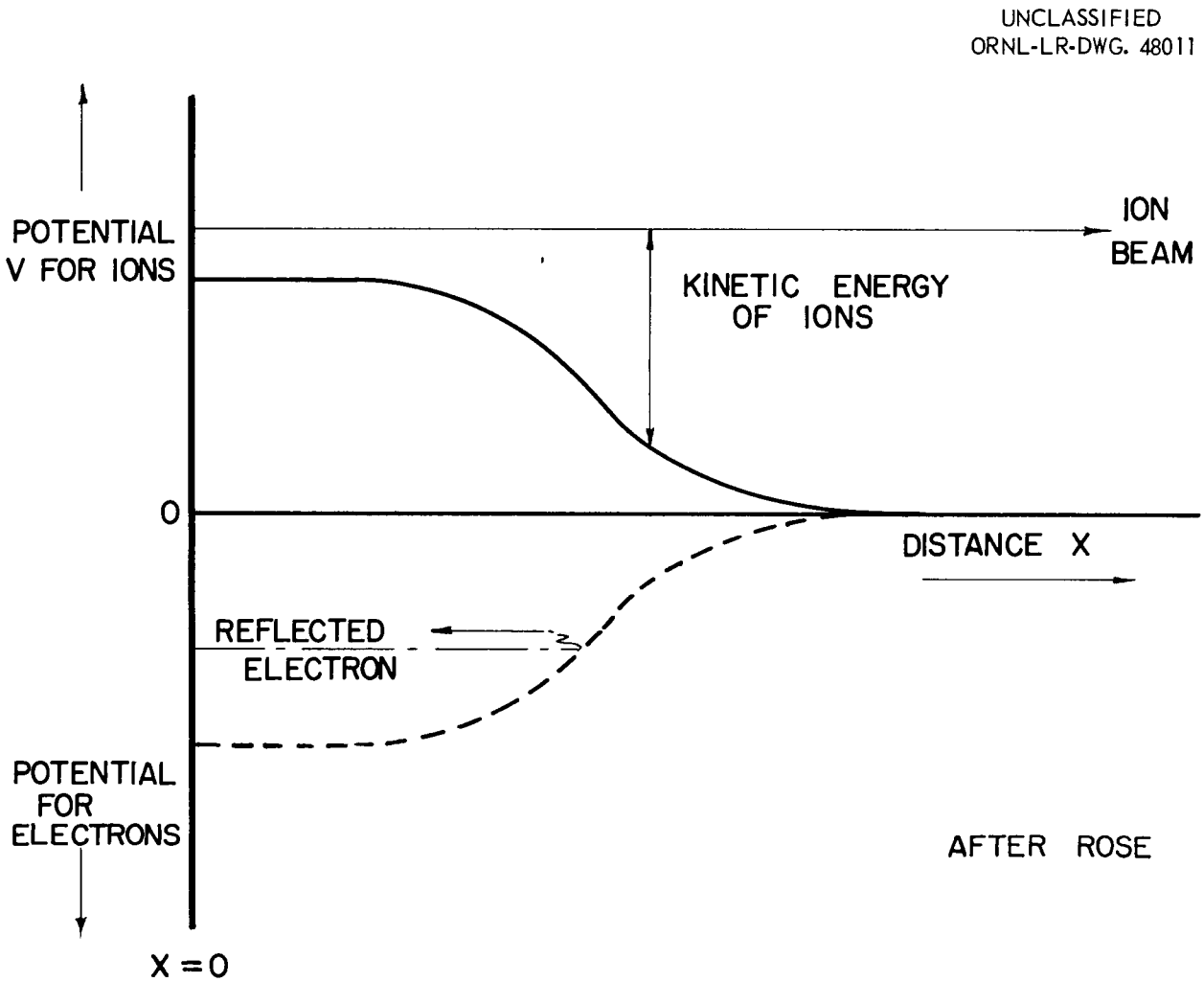

Fig. 3. Potential Diagram for Ions and Electrons.

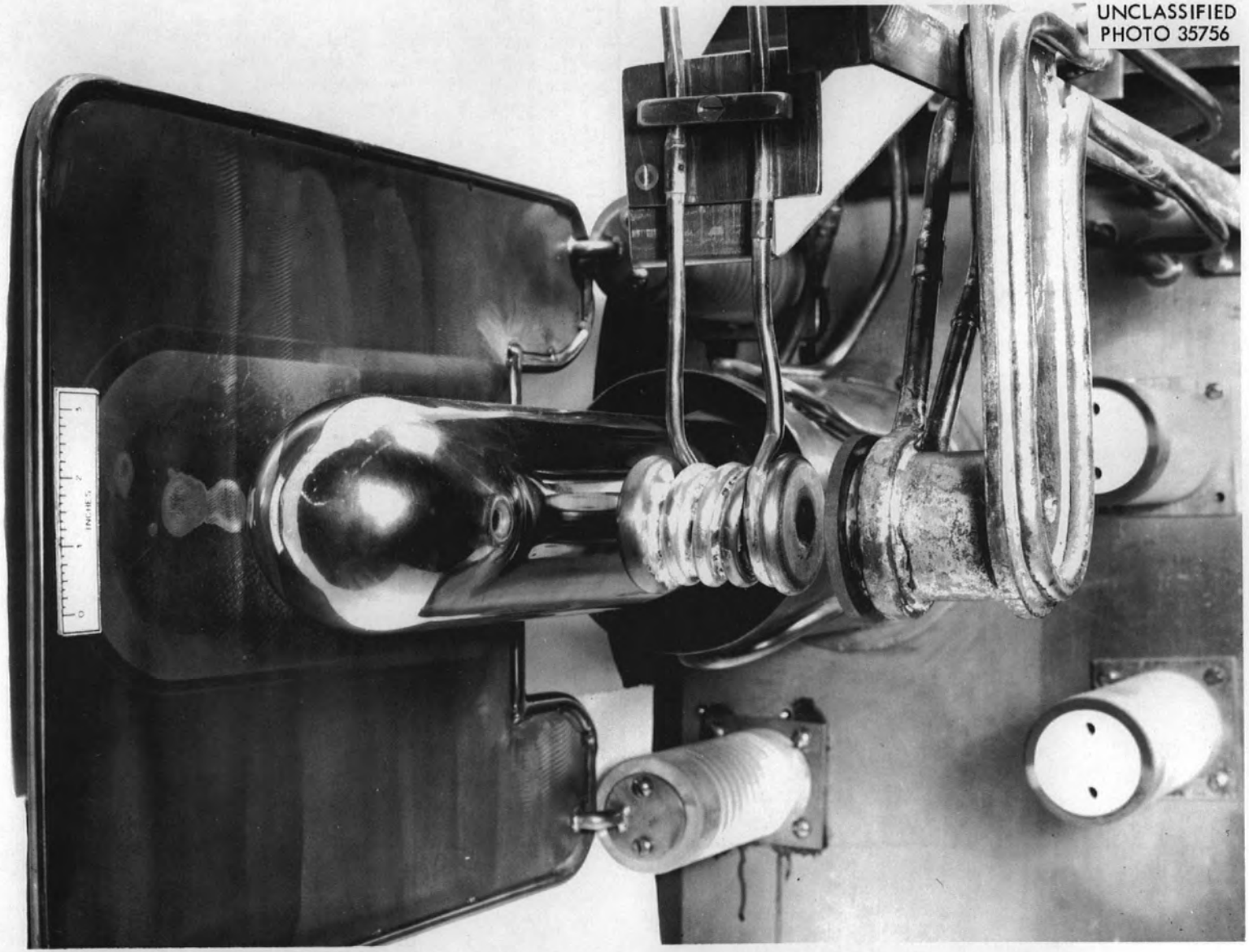

Fig. 4. Electron Gun.

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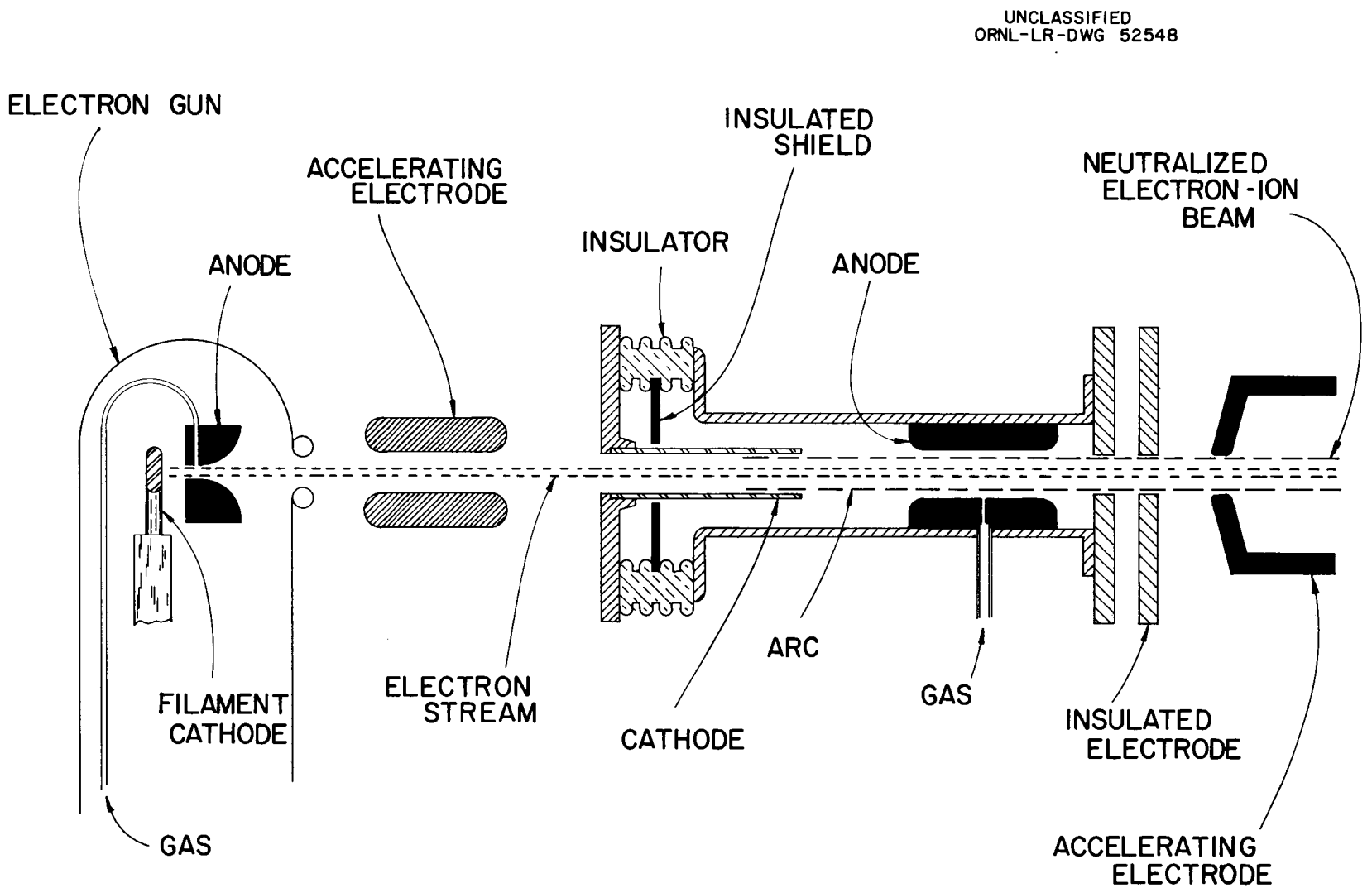

Fig. 5. Neutralized Electron-Ion Source.

is independent of the charge-to-mass ratio (Addendum 1). If future development shows that space charge can be relieved by electron injection through the accelerating region, then a given specific impulse may be achieved by light ions with a high current density and at a lower potential than that required for heavy ions. High-voltage power supply weight could then be reduced as the required voltage is lowered. This advantage must, of course, be weighed against the greater fraction of power required for ionization since the ionization energy per unit mass is greater for light ions. Also, the higher densities that are required will certainly increase collisions and scattering. Sputtering of electrodes should not be drastically increased, however, since the particles will have lower energy, lighter mass, and likely improved focusing with charge neutralization. For the immediate future, however, the system of greatest potential usefulness seems to be an arc type ion source producing large currents of fairly energetic heavy ions.

Pumping propellants. Surface ionization sources using cesium as the propellant are basically limited in capacity to the pumping speed of the facility in which the engine is tested, because of the high vapor pressure of cesium. Multi-million dollar facilities are now under construction for this purpose, but the capacity is fundamentally limited to engines of relatively low current. The arc-ion source and many other systems can eliminate this basic limitation if pumping propellants are used. The use of these very low vapor pressure gettering propellants, such as Ti, Zr, U, and many others, permits construction of economical facilities of enormous capacity. Dissipation of the power in the beam is the limiting factor, not the vacuum pumps. [18]The use of rotating, water-cooled receiving electrodes permits the dissipation of about 10,000 KW total power or 100 KW per square inch of instantaneous area.

The study of the basic phenomena associated with ion and plasma propulsion in space, such as charge neutralization, oscillations, traveling waves, instabilities, etc., is not restricted to any particular ion. The large number of available propellants which can also provide pumping make it possible to do these studies over a wide range of mass and specific impulse. Techniques for outgassing and vaporizing low vapor pressure materials has been extensively and successfully investigated.

Even if the contact source should prove superior for space work, the use of an arc-ion or plasma system operating with pumping propellants provides an opportunity to study the basic problems associated with large plasma and ion streams that would not otherwise be possible without going beyond the earth's atmosphere. Figure 6 is a conceptual drawing of a dual-vacuum facility which uses pumping propellants in the inner volume.

Plasma Thrust Systems

Strong emphasis has been placed on plasma propulsion systems for space work, and there are good reasons for this emphasis. Nevertheless, it appears that plasma propulsion should be approached cautiously because of the unstable nature of such discharges under the usual conditions encountered. Major basic plasma development work is being done in the controlled fusion program of the Atomic Energy Commission, and this program is vigorously supported in four major laboratories. Close cooperation between personnel in the space propulsion and controlled fusion programs is essential to progress in each.

In a plasma thrust system acceleration of both ions and electrons takes place by suitably applied electric and magnetic fields in various combinations, usually transient in nature. The applied fields cause both ions and electrons to move in the same net direction and plasma is ejected from the exhaust.

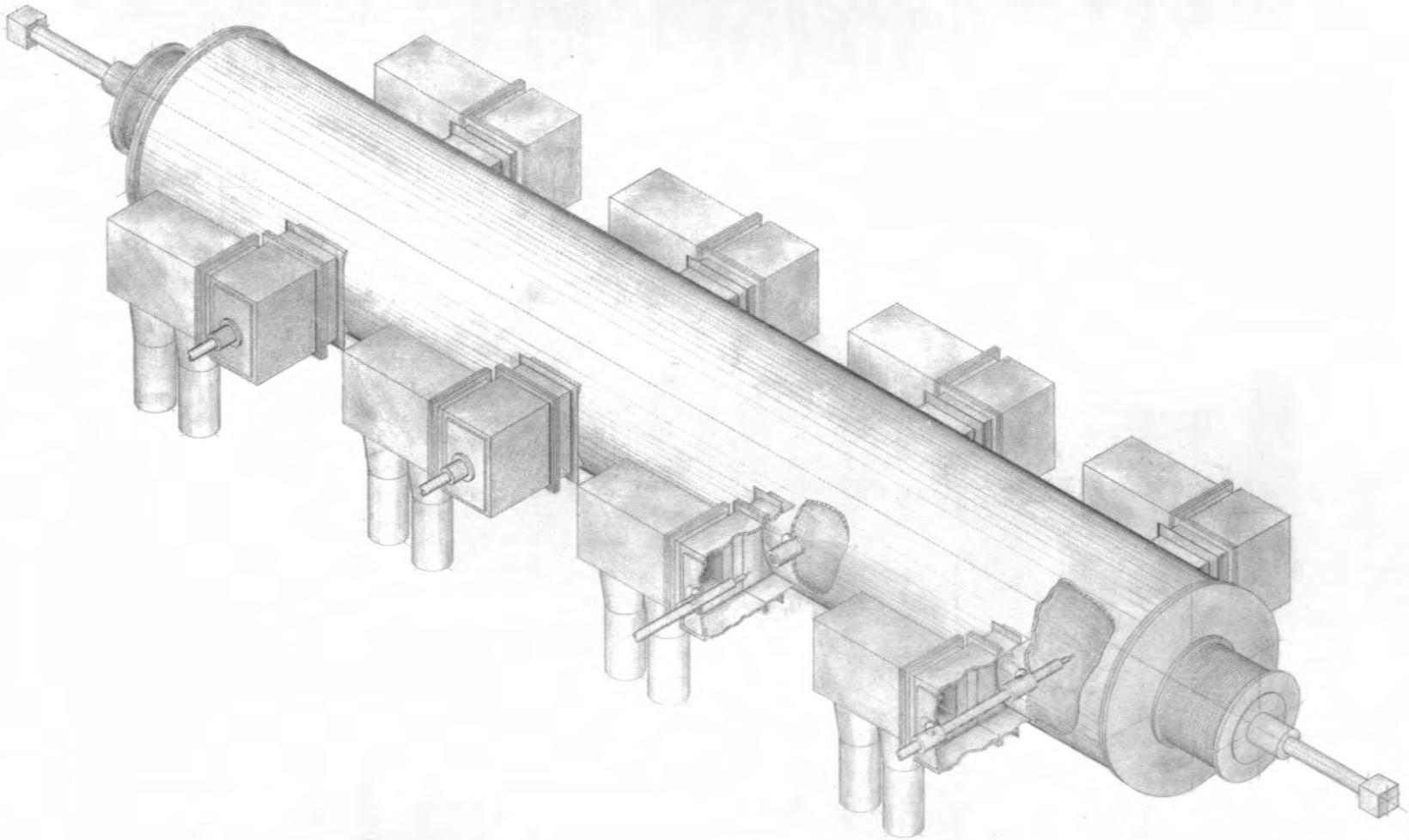

Fig. 6. Conceptual Drawing of Pumping Propellant Test Facility.

This process may be seen by considering a region containing ions and electrons in equal numbers. In this region an electric field is established by external means in the presence of a magnetic field perpendicular to the electric field. In such crossed electric and magnetic fields both ions and electrons move with a super-imposed velocity given by

$$\vec{V} = \frac{\vec{E} \times \vec{H}}{\mu_o H^2}$$

where

V = drift velocity of charged particle,

E = electric field,

H = magnetic intensity,

μ_o = permeability of free space,

so that the velocity is at right angles to both the electric and magnetic fields and does not depend on electric charge or mass. Where currents are established in the plasma, volume forces are also set up:

$$\vec{F}_v = \mu_o \vec{j} \times \vec{H}$$

where

F_v = force per unit volume,

j = current density,

and both ions and electrons are accelerated in the same direction perpendicular to the current and magnetic field (Fig. 7). In general, the complete processes are obscure and various instabilities and/or transition processes prevent steady operation. [19]Plasma pulses have been measured

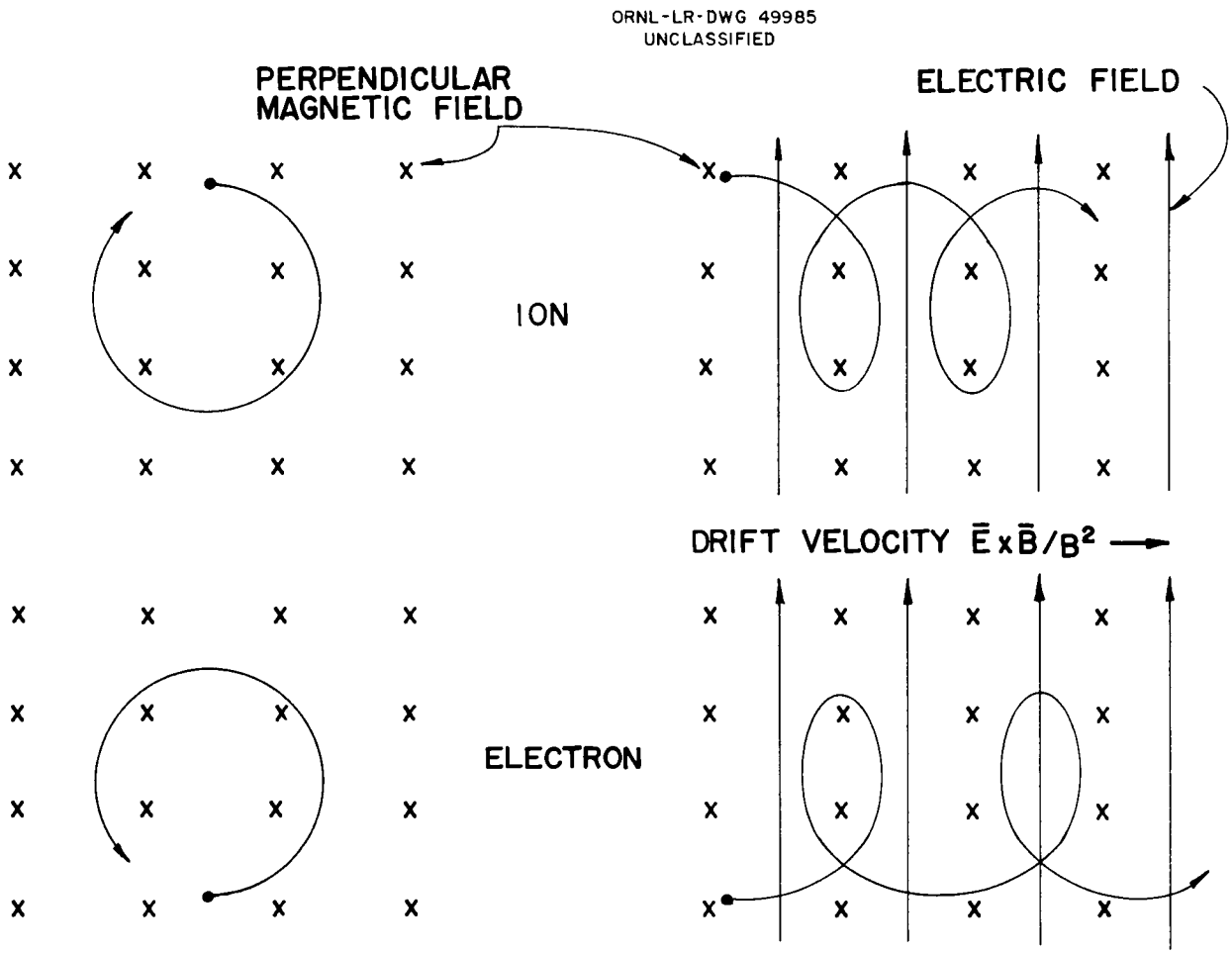

Fig. 7. Charged Particle Motions in Magnetic and Electric Fields.

with velocities as high as 10^7 cm/second giving specific impulse values of the order of 10^4 seconds.[20] A system where both the gas and current are pulsed appears most feasible, since a high value of electric field and current is sustained in the plasma with difficulty due to instabilities and electrical breakdown which are aggravated by excessive gas. Energy storage is usually accomplished by capacitor methods; and matching of the electric load is difficult. The magnetic field also complicates the power supply and reduces efficiency. Complications due to weight and/or storage also arise with the requirements of energy stored by capacitors. The achievable specific impulse is in an interesting range but the thrust that may be obtained is open to speculation. Complications of the power plant indicate that extensive study and development is necessary to produce a practical system. Nevertheless, because of the basic advantage of plasma propulsion, it must be pursued from the long-range viewpoint with emphasis on the fundamental behavior of plasmas.

Again an obvious advantage of the arc-ion system is apparent: there are no basic barriers to the creation of a single device which can operate either as an arc jet, a plasma propulsion system, or an ion propulsion source using direct acceleration by electric fields. A good possibility exists that instabilities will be reduced or eliminated, since both ions and electrons are accelerated directly and cooperative phenomena is not required to produce thrust.

Arc Thermal System

The arc thermal system is also a possible auxiliary system for fast missions of shorter range than those where the ion or plasma system is suitable. Heat transfer, by means of an electric arc, is sometimes called an arc-thermo-dynamic or jet system. The hope for such a thermal system of thrust is centered mainly about the possibility of a twofold increase in specific impulse over that of a nuclear heat transfer rocket. In an electric arc column, gas kinetic temperatures may be attained which are considerably above material limits. This is achieved at the price of electrode erosion and cooling requirements as well as the price of a high-current generator as a part of the power plant with an associated heat sink or radiator where about 80 per cent of the thermal energy is lost.

The arc thermal system provides greater specific impulse due to higher temperature in the arc and the choice of hydrogen as a propellant. In addition, dissociation of free radicals gives higher energy per particle if recombined in the exhaust. For a propellant, such as hydrogen, an immediate advantage in specific impulse is obtained due to dissociation from the molecular to the atomic state. Also, if recombination occurs during expansion, then increased specific impulse occurs. Dissociation of hydrogen occurs to an appreciable extent when temperatures reach the region of 3000°K. Pressure is an important factor; for example, at 3400°K, essentially complete dissociation occurs at a pressure of 10^{-3} atmosphere, while at one atmosphere, the dissociation is about 10 per cent. For atomic hydrogen temperatures of 2000°K, and with 50 per cent of the dissociation energy recovered in exhaust kinetic energy, the specific impulse may reach a value of 2000 seconds.

Some experiments have been reported with laboratory arc systems using argon, helium, and hydrogen. High degrees of excitation and onset of ionization are observed in the exhaust jet. Measurements show the power input to the gas is in directed motion, random motion, and ionization as functions of several parameters, such as pressure and gas flow. Specific impulse appears to be somewhat below expectation; approach to thermal equilibrium is difficult; and proper nozzle design is an important factor. [21] Adam and Camac have reported specific impulse values to 1200 seconds with power efficiency of about 50 per cent.

Overall power efficiency and the required cooling probably constitute a limitation of thrust not inherent in the methods previously considered. System complexity is also a factor because an electric generator must be driven by the energy from a basic power supply. This energy delivered to the arc is converted to heat in the propellant and also to dissociation energy. A number of conversion efficiencies enter into this energy transfer so that overall efficiency is likely to be of the order of 10 per cent for optimistic predictions. The main problem of such a system is the disposal of unusable energy which is released within the vehicle and not removed by the propellant. Such a system cannot be a high thrust system but is actually an intermediate or low-thrust auxiliary device that may be usable in an intermediate specific impulse and thrust range. [22] It is worth noting that the arc jet faces severe competition from the nuclear heat transfer system which has higher efficiency. The arc jet must operate at quite high specific impulse to compensate for its thermal losses where it then begins to compete with plasma propulsion systems. The specific impulse range where the arc jet may prove advantageous is obviously severely limited.

These systems are under study in various laboratories and the nature of the work appears to be non-controversial. It is well, nevertheless, to consider new advancements in the gaseous discharge field; particularly those occurring in controlled fusion research, and to pursue vigorously the basic avenues unfolded. [23] A matter of particular interest is the discovery that very large plasma streams can be accelerated by potentials which exist in arcs of certain types. No auxiliary acceleration is necessary. The use of these energetic arcs should make feasible the achievement of gas heating and plasma propulsion by the same device, thereby adding a decided advantage in power consumption, versatility and range to various space missions (Fig. 8).

A Combined System

A combination of the ion, plasma, and arc thermal systems also appears feasible from the fundamental viewpoint; hence it is necessary to consider this possibility seriously. The arc-ion system employs an intense plasma which operates in a magnetic field. Several configurations are possible; but, for this example, ions are extracted along the magnetic field and the plasma potentials are applied electrostatically, as shown schematically in Fig. 9 (see also Addendum 2). With electron injection, it should be feasible to provide equal ion and electron densities at any desired velocity. The neutral emergence of the accelerated beam from the device constitutes a dc plasma accelerator. The use of acceleration and subsequent deceleration of electrons allows an extremely wide range of electron velocities to be obtained (Fig. 10). Finally, for the arc thermal system the accelerating electrodes can be shifted and replaced by a suitable nozzle, as shown in Fig. 10. The gas is heated in exactly the same way that present arc jets operate. Perhaps the most serious criticism of a variable impulse engine would be related to practical power supply considerations.

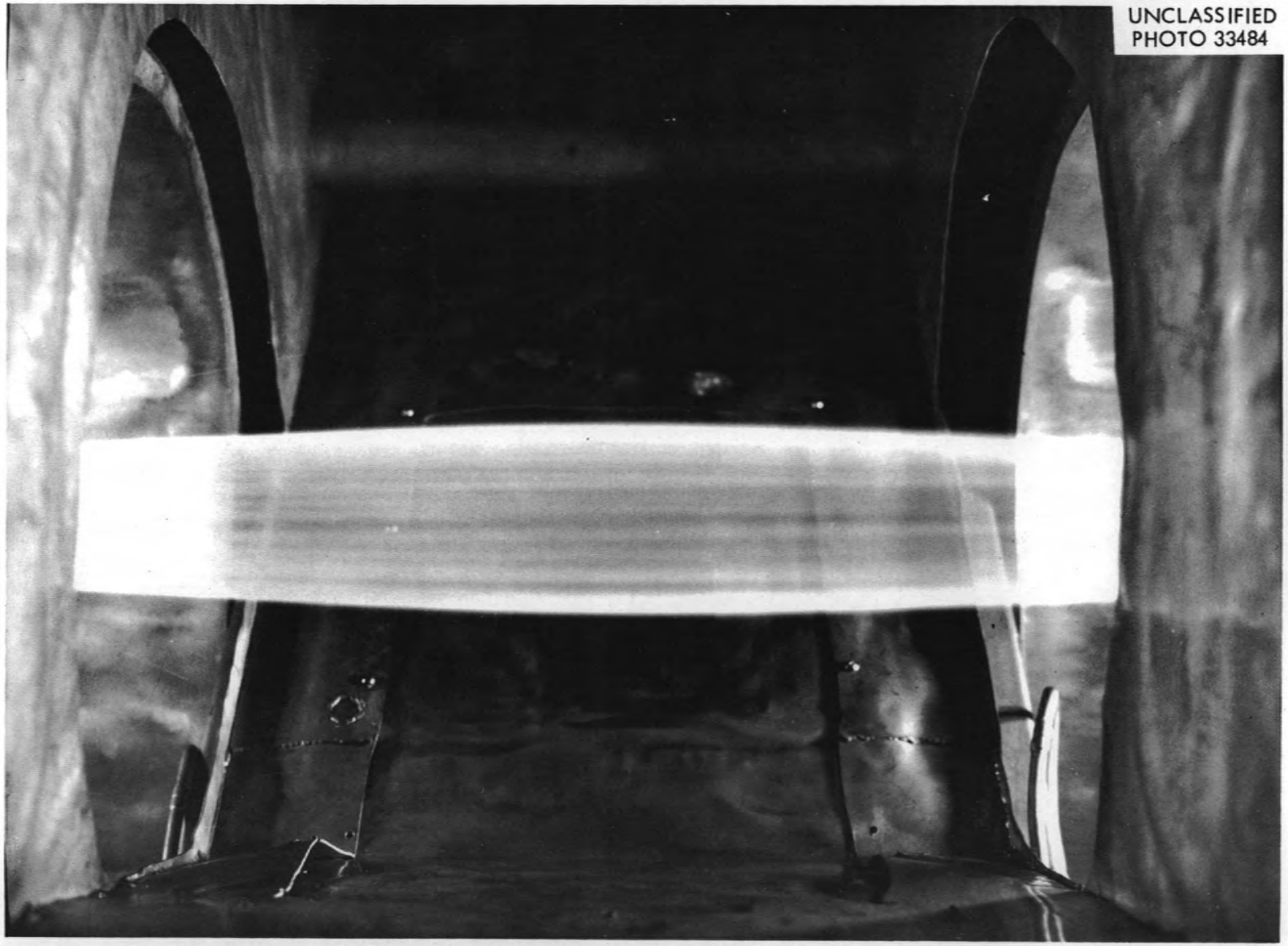

Fig. 8. Energetic Arc.

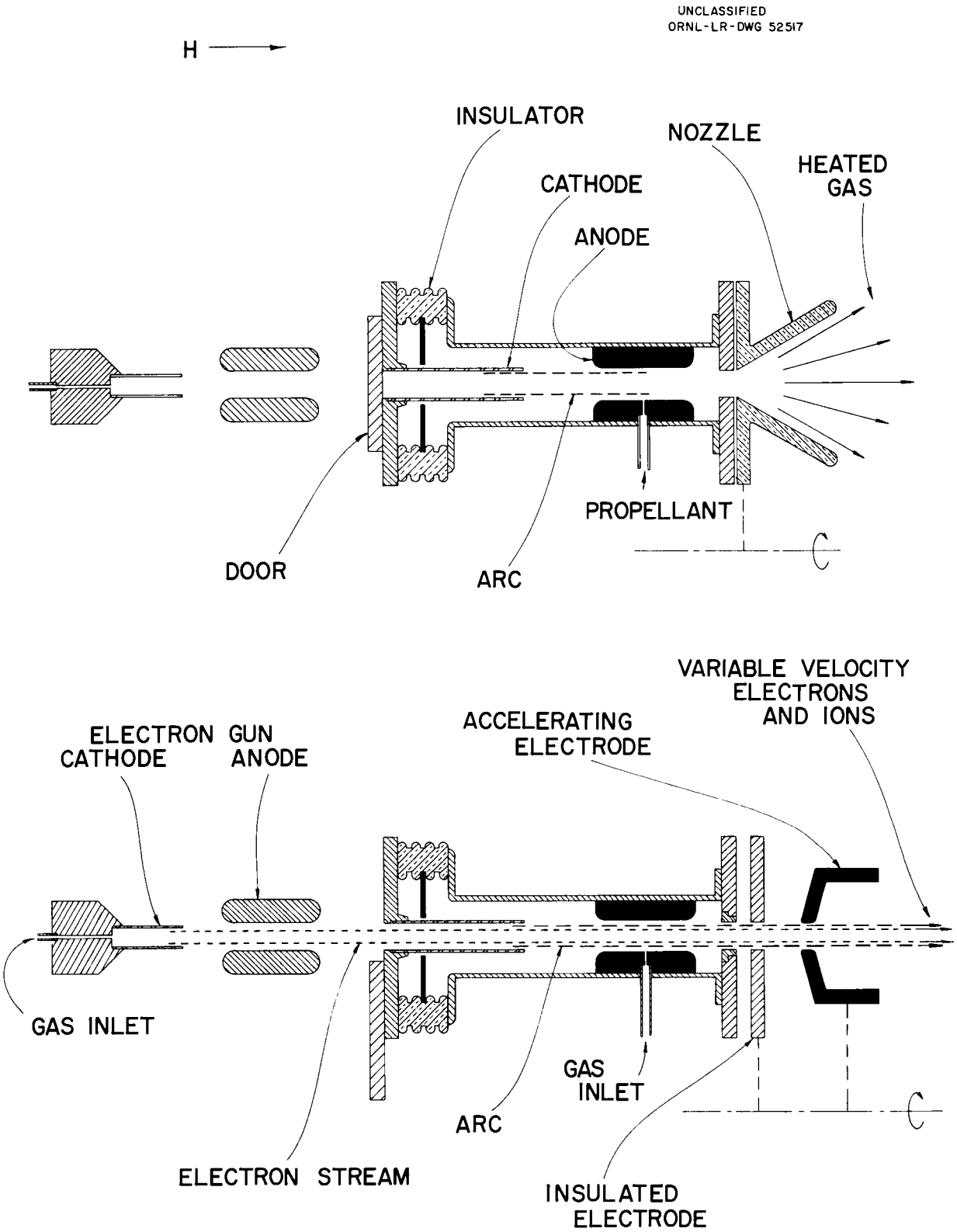

Fig. 9. Variable Specific Impulse System.

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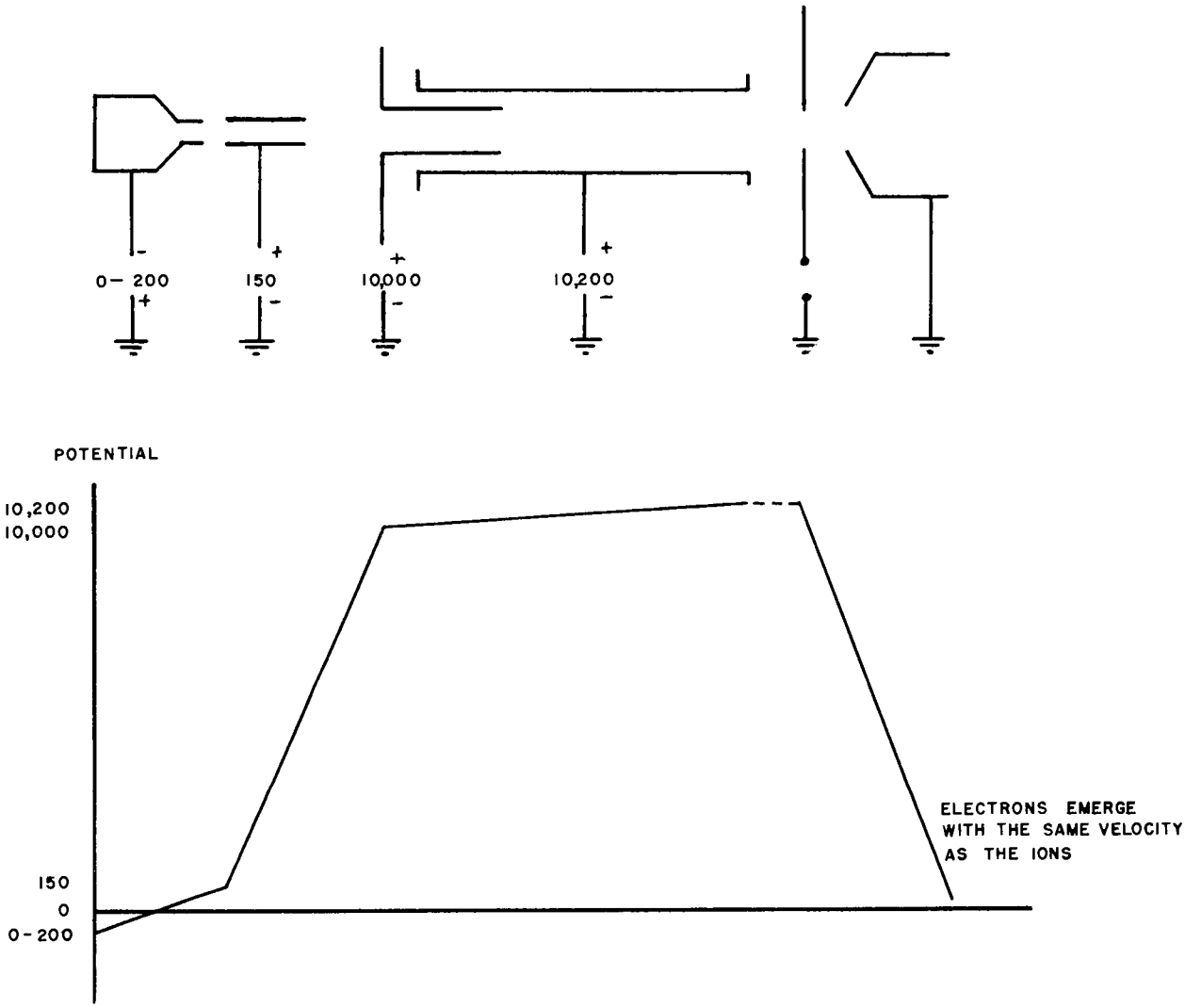

Fig. 10. Potential Diagram of Specific Impulse System.

REFERENCES

1. Moak, C. D., "A New Source for Propulsion of Space Vehicles," ARS Journal 29, p. 868 (1959).

2. Spitzer, L., Jr., ARS Journal 22, p. 92 (1952).

3. Preston-Thomas, H., JBIS 11, p. 173 (1952).

4. Tsien, H. S., ARS Journal 23, p. 233 (1953).

5. Stuhlinger, E., J. of Astronautics (1955-56).

6. Langmuir, D. B., Space Technology Lecture Series, UCLA, February 1958.

7. Irving, J. H., Space Technology Lecture Series, UCLA, February 1958.

8. Cornog, R., First Annual AFOSR Astronautics Symposium, Denver, Colorado, April 1958.

9. Benney, D. J., Jet Propulsion, March 1958.

10. Perkins, F. M., Second Annual AFOSR Astronautics Symposium, Denver, Colorado, April 1958.

11. Fraas, A. P., private communication.

12. Luce, J. S., "Ion Erosion of Accelerating Electrodes in Space Vehicles," 1159-60, ARS Semi-Annual Meeting, May 9-12, 1960, Los Angeles, California.

13. von Ardenne, Manfred, Tabellen der Elektronenphysik, Ionenphysik, und Ubermilroskopie, Deutscher Verlag der Wissenschaften, Berlin (1956).

14. Moak, C. D., H. E. Banta, J. N. Thurston, J. W. Johnson, and R. F. King, "Duo-Plasmatron Ion Source for Use in Accelerators," Rev. of Scientific Instr., Vol. 30, No. 8, pp. 694-99, August 1959.

15. Goodrich-High Voltage Astronautics, Inc., Progress Report for the Period May 1, 1960 through May 31, 1960.

16. NASA Research Advisory Committee Report, "Electrical Power Generation and Electrical Propulsion Systems for Spacecraft."

17. Rose, D. J., "Acceleration of a Neutralized Ion Beam," MIT Quarterly Progress Report No. 53, p. 3, April 15, 1959.

18. Matlock, O. D., "Some Engineering Aspects of Energetic Arcs," ORNL CF 60-6-96, Compilation of Material Presented by the Exploratory Physics Group at the Thermonuclear Project Meeting - June 1, 1960.

19. Bostick, W. H., "Experimental Study of Ionized Matter Projected Across a Magnetic Field," Phys. Rev. 104, No. 2., October 15, 1956.

20. Tuck, J. L., and J. Marshall, private communication.

21. Adam, M. C. and M. Camac, ARS Preprint 791-59, presented at the ARS Controllable Satellites Conference, MIT, April 30 - May 1, 1959.

22. Evvard, John C., "Electric Space Propulsion," AIEE Preprint No. 59-1229, October 12, 1959.

23. Luce, J. S., "Studies of Intense Gaseous Discharges," UN/P-1790, Geneva Conference (1958).

ADDENDA

Addenda 1, 2, and 3 provide reference material, supporting arguments, discussion and data not appropriate for the main body of the report. In Addendum 1, an attempt is made to present a more complete development of relationships, such as those concerning thrust, specific impulse, and mass. In particular, specific impulse seems to be initially confusing, and a point of extended discussion. However, for normal usage, specific impulse can simply be considered as a number measuring the exhaust velocity of a rocket or space vehicle.

ADDENDUM 1

SOME DEFINITIONS AND RELATIONS

Thrust

Thrust is equal to the rate of change of momentum imparted by the exhaust. This rate is given by the summation of momentum over all particles exhausted in a suitable time interval divided by this time interval. It may be simplified by considering for a given situation that all particles have equal mass and the same exhaust velocity, and by considering the time interval to be within a suitable finite range. Thrust may then be expressed:

$$F = \frac{m_p \; v_{ex}}{t} \tag{1}$$

where

F = thrust,

m_p = propellant mass exhausted in time t

v_{ex} = exhaust velocity.

This may be written more simply:

$$F = \dot{m}_p \; v_{ex} \tag{2}$$

where

$\dot{m}_p$ = mass flow rate of the propellant.

This rate is averaged over a sufficient given time interval and fluctuations of the rate due to exhaust particle distribution are thereby smoothed. Both $\dot{m}_p$ and v_{ex} are then considered to be constants for a given thrust system.

Impulse, Specific Impulse, Units

For the simplified considerations the impulse is equal to the product of thrust and time:

$$I = Ft \quad . \tag{3}$$

During this time a mass m_p is exhausted and a specific impulse may be expressed as impulse per unit of mass exhausted:

$$I_{SP} = \frac{Ft}{m_p} \tag{4a}$$

This is also seen to be

$$I_{SP} = \frac{F}{m_p} \tag{5a}$$

giving the specific impulse as thrust per unit of mass flow rate. The units of specific impulse depend upon the units of thrust and mass, and some consideration of unit systems seems useful relative to specific impulse. Equations (1) and (2) require absolute units*, which may be either English or metric, while (3), (4a), and (5a) are open to a choice. However, it appears common usage to express the important quantity, the specific impulse in seconds. This is equivalent to choosing a gravitational system of units** in (4a) and (5a) where, for example, both thrust and mass

---

* m_p in pounds, slugs, grams, kilograms, and correspondingly F in poundals, pounds, dynes, newtons. If one is accustomed to the substitution of weight/g for m in equations, such as (1), then in effect a conversion to a gravitational system is being made. See (6) where such a substitution obviously cannot be made.

** m_p in grams, pounds, kilograms and correspondingly F in grams, pounds, kilograms.

are expressed in pounds and specific impulse thus is expressed in seconds (see (6)). For absolute units in these equations, (4a) and (5a), a specific impulse would have the dimensions of a velocity.

On the other hand, if specific impulse is defined as impulse per unit of weight exhausted, then any system of units is suitably converted to yield a specific impulse in seconds.

$$I_{SP} = \frac{Ft}{w_p} \text{ seconds} \tag{4b}$$

$$I_{SP} = \frac{F}{\dot{w}_p} \text{ seconds} \quad . \tag{5b}$$

In any system of units both F and w are forces with the same units, and this definition and set of equations may seem more suitable and consistent with specific impulse measured in seconds. The weight must be the earthly weight as determined in the laboratory where g is the accepted constant or a conversion to this condition. This in effect is then a measure of the mass which is the fundamental quantity of interest.

It is useful to express specific impulse in terms of exhaust velocity. Changing Eq. (1) to a gravitational system of units, it becomes:

$$F = \frac{m_p \, v_{ex}}{g \, t} \tag{6}$$

where g, the acceleration of gravity, is a conversion constant.

Substituting in (4a) one obtains:

$$I_{SP} = \frac{v_{ex}}{g} \text{ seconds} \quad . \tag{7}$$

This usual relation is also the result if Eq. (1) is directly substituted in Eq. (4b). The specific impulse is thus identified with the exhaust velocity.

Velocity and Mass Relations

In free space the equation of motion for a rocket vehicle is given by:

$$mdv = -v_{ex}\ dm \tag{8}$$

where

m = mass of vehicle at time t

v = velocity of vehicle at time t

This integrates to:

$$v - v_o = -v_{ex} \ln (m/m_o) \tag{9}$$

where the subscript o refers to initial conditions and v_{ex} is assumed constant. Assuming an initial velocity $v_o = 0$, the expression may be rewritten using Eq. (7):

$$v = I_{SP}\ g \ln (m_o/m) \tag{10}$$

It is evident from Eq. (10) that any rocket (ion, plasma, jet, etc.,) attains its velocity accompanied by an expenditure of its mass and that the effectiveness of this mass expenditure is a function of the specific impulse (or exhaust velocity). The attainment of a given velocity increment is, from the mass point of view, done more efficiently with the higher

specific impulse system. The decay of mass for a fixed specific impulse can also be seen by writing Eq. (9) with $v_o = 0$ in exponential form:

$$m = m_o \, \mathrm{Exp} \left(- \frac{v}{v_{ex}}\right) \tag{11}$$

Thus it is evident that vehicle mass inherently decays as velocity is increased. This decay is governed by the exhaust velocity, i.e., the specific impulse. When the vehicle velocity has reached a value equal to the exhaust velocity, its total mass (including all its contents) has been reduced to 1/e or .37 per cent of its starting mass. Equation (11) reveals the importance of high exhaust velocity and specific impulse in relation to the ship mass and its payload. For many systems of thrust the ship mass must attain velocities in excess of the exhaust velocity. Equations (10) and (11) show that any velocity is permitted with any value of exhaust velocity or specific impulse. The price, however, of a high ratio of vehicle velocity to exhaust velocity is the resulting small fraction of mass which attains the vehicle velocity.

Ion Terms

(MKS System of Units)

The ion mass flow rate is given by:

$$\dot{m} = i \, (m^+/e) \tag{12}$$

where

i = current,

e/m^+ = charge to mass ratio.

For the ion system, the exhaust velocity is given by:

$$v_{ex} = \sqrt{2\ (e/m^{+})\ \phi} \tag{13}$$

where

ϕ = accelerating voltage.

The thrust from (2) then becomes:

$$F = i\ \sqrt{2\ (m^{+}/e)\ \phi} \tag{14}$$

The electrical power for the beam is:

$$P = i\ \phi \tag{15}$$

and the thrust-to-power ratio may than be expressed as:

$$F/P = \sqrt{(2m^{+})/(e\phi)} \tag{16}$$

Inverting (16), it may be noted that:

$$P/F \sim \sqrt{(\phi/m^{+})} \sim v_{ex} \sim I_{SP} \tag{17}$$

Thus the power required for a given thrust varies directly with the specific impulse.

Equations (10), (11), and (17) indicate the propulsion system parameters to be considered for optimization of the payload capabilities. Higher specific impulse systems can accomplish a mission with a smaller expenditure of mass; however, at a constant thrust, the power required is greater. Optimization then depends on the trade-off between power plant mass and propellant and tankage mass.

ADDENDUM 2

SPACE CHARGE NEUTRALIZATION

In usual cases of small ion beams the ions are extracted from a plasma by an applied accelerating electric field. In the contact source they may be extracted from a heated tungsten surface, but the arc type source is the principal concern here. In the extracting field, charge separation occurs. For ion acceleration a positive space charge appears, and the resultant space charge field tends to counteract the applied electric field. The ion current then follows a space charge equation. This equation for extended plane electrodes gives a current density of the form

$$J = K \left(\frac{e}{M}\right)^{1/2} \frac{V^{3/2}}{x^2}$$

where x is the distance over which a potential V is applied and varies to some extent with V and other factors. K is constant and e/M is charge to mass ratio. Maximum values of V with conditions for minimum x are attempted and breakdown conditions are then approached in the desire to obtain maximum values of J. Breakdown occurs well before saturation of the ion current is reached and the ultimate ion current limit dependent upon ion emission is not nearly achieved. For example, the random ion current density in a reasonable hydrogen plasma of density $N_+ = 10^{14}/cm^3$ and $T \sim 10^4$ is calculated to be of the order of 100 amperes/cm^2. This is at least several orders of magnitude above any known current density at the point of ion extraction, although the plasma density and temperature chosen here are not at any particular limits.

The positive space charge which exists in the accelerating region is probably never entirely free of electrons from some sources. These sources have been little studied and, in general, the behavior is obscure.* However, the need for auxiliary space charge neutralization is evident in an ion beam for densities above 10^8 ions/cm^3.

Electrons enter the space charge region in several ways. They may enter from the background gas or from surfaces where ions strike. They then precess along the beam and if precaution is not taken will strike the source. In transit their effect is beneficial in the sense of reducing the positive space charge. This beneficial effect is considerably reduced in view of "run-away" possibilities and other detrimental effects which must be controlled by reducing the number of such electrons at the various places of origin. Such electrons work toward instability and breakdown. They may also yield x radiation as well as cause progressive deterioration of electrodes, and cause a high drain to the source. In some instances, however, such electrons undoubtedly play a part in achieving partial neutralization and enhancement of ion density with some degree of stability. In many cases these processes contribute to an increased current density, and such effects would be absent in free space, due to the lack of neutral atoms or molecules which are the source of most of these electrons.

Electrons may also enter the space charge region from the arc in an ion source. From this direction they must climb a potential energy hill

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* This is somewhat similar to the case of obscure positive ions in electron beams. See, for example, Pierce, J. R., Theory and Design of Electron Beams, pp. 168-170, D. van Nostrand Company, (1954).

at the expense of their energy of motion. For thermal energies of motion they are limited to climb only a few volts in potential; so that thermal electrons in the plasma cannot be effective in neutralization of the space charge region. [19]Relative to velocities which are in general above thermal values, Rose has considered the electron velocity distribution requirement for neutralization during ion acceleration for a simple dc ion current and electric field. He shows that a class of electron velocity distributions can exist in an accelerating gap which permits acceleration of an ion beam without space charge effects.

However, the origin of such electrons and the mechanisms of controlling the supply involves special requirements for high energy acceleration. It has been shown experimentally that electrons required for neutralization can be obtained deliberately from an electron source independent and outside of the arc. For a hollow cathode source they can be suitably accelerated and directed into and through the arc in the source with sufficient energy so that they pass through the high-voltage region of ion acceleration. This is indicated schematically in Fig. I. They may than emerge with the accelerated ions having the same density and velocity, thus producing an electrically neutral beam at the emerging point and beyond. A portion of the electrons of less energy will be stored or trapped for a useful time in an oscillating manner and contribute to charge neutrality throughout the accelerating region. These electrons which are reflected in the ion accelerating field must be drained to regions of high positive potential. Ion acceleration energy and potential relations are shown in Fig. II, and an ion-acceleration, electron-injection system is shown in Fig. I. It thus appears necessary

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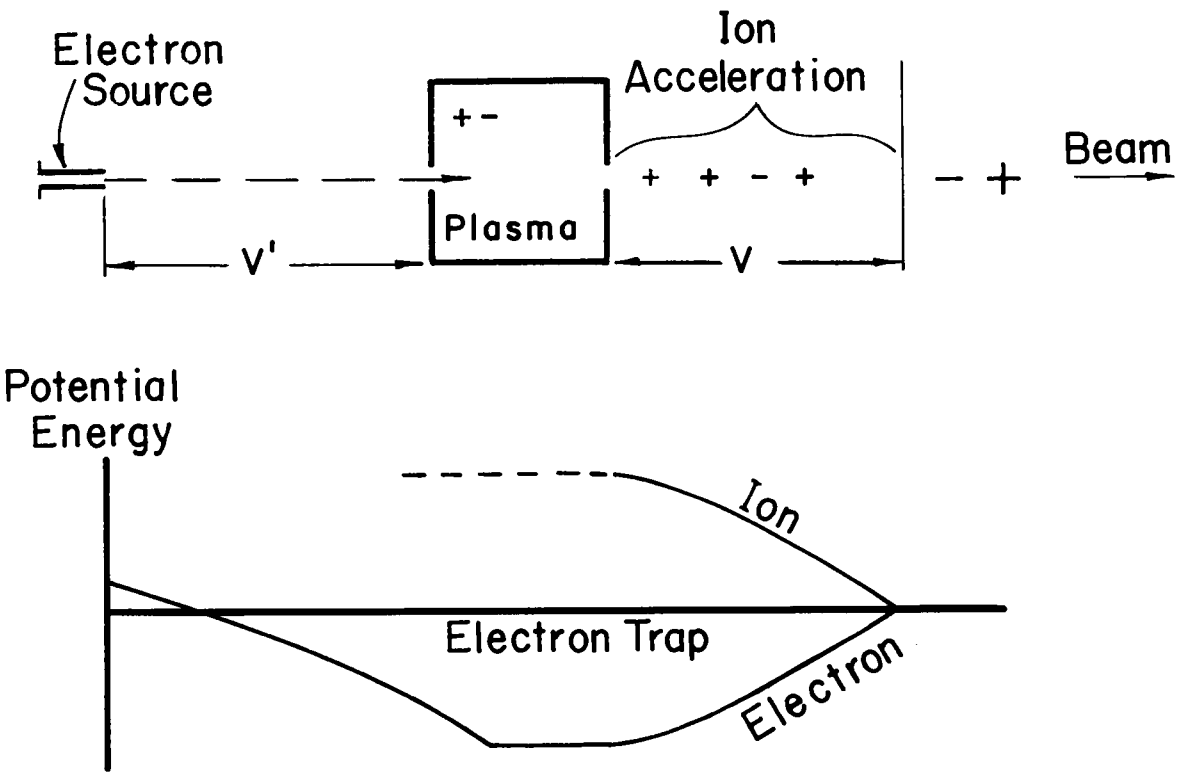

Fig. 1. (Addendum 2) Acceleration Electron Injection.

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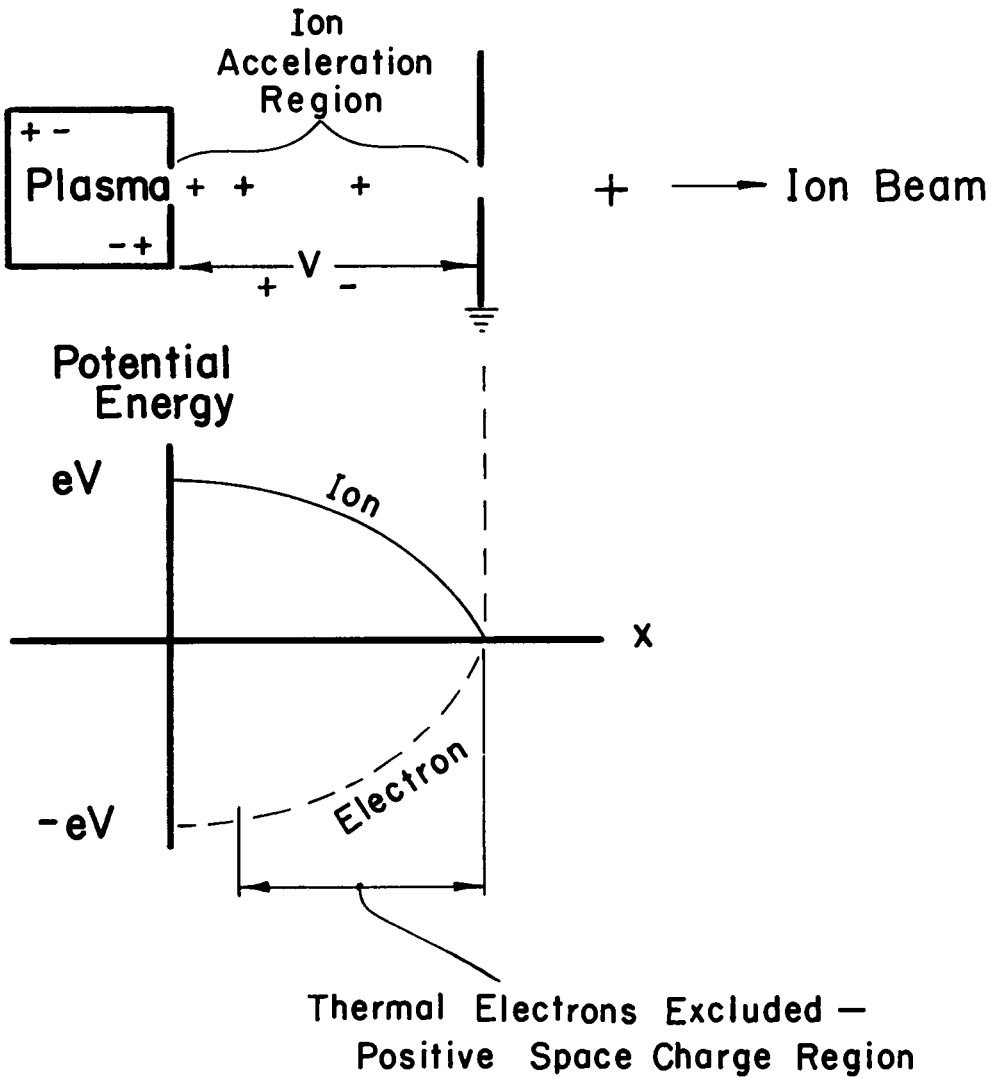

Fig. 11. (Addendum 2) Acceleration Space Charge Limited.

to accelerate an electron beam to a minimum value about as great as the ion beam sought. However, electron beams, although subject to space charge limitation also, are less critical and limited. It is necessary, however, to provide ions for neutralization of the electron beam just as electrons must be provided for neutralization of the ion beam. For a given current, an ion is a much more effective neutralizing particle in drifting through a negative space charge region than the equivalent situation for an electron in a positive region. For a given current density and accelerating potential, the space charge is much greater for an ion beam than for an electron beam. For maximum current it appears practical that electrons be obtained from an electron gun and injected for a stable approach to complete neutralization of all positive regions. The achievement of large ion beam currents should be possible by electron injection and neutralization. Complete neutralization of the emerging ion beam in essence provides a plasma system, in fact a dc plasma system. It is extremely important that these aspects of neutralization be studied, because obscure neutralization such as that occurring from residual gas may provide optimistic laboratory measurements that will not occur in free space.

ADDENDUM 3

GRID ION SOURCES

It may be worthwhile to give some data on characteristics obtainable from ion sources developed for large-scale isotope separation at Oak Ridge. These sources have not been publicized and have little in common with sources usually considered as desirable for space propulsion. However, they do provide an example of the large ion currents which have already been obtained from arc-ion sources.

The following data and calculations are presented for two measured grid ion sources developed at Oak Ridge:[23]

1. <u>Atomic Hydrogen</u> H_+^1

Beam Current I_+	=	5 amperes (+ ion current)
Current Density J_+	=	2 amperes/cm^2
Beam Voltage V	=	2×10^4 volts.

From this, the following is calculated:

$$\text{Propellant Mass Flow} = \frac{1.67 \times 10^{-27}}{1.6 \times 10^{-19}} \times 5$$

$$= 5.2 \times 10^{-8} \text{ kg/sec}$$

Exhaust Velocity	=	1.9×10^6 m/sec
Thrust	=	10^{-2} kg
Specific Impulse	=	1.94×10^5 sec

2. Thallium Tm_+^{169} Singly Ionized

Beam Current I_+	=	12.5 amperes
Beam Voltage V	=	4×10^4 volts
Mass Flow	=	2.2×10^{-5} kg/sec
Exhaust Velocity	=	2.1×10^5 m/sec
Thrust	=	4.7 newtons = .48 kg
Specific Impulse	=	2.15×10^4 sec.

Beam powers are readily calculated, but overall power and efficiency are not calculated because of unrelated magnetic field configurations. These sources were not developed for propulsion or space application, and any relation toward usage in ion thrust motors is only coincidental.

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