

PRELIMINARY DESIGN OF A DEMONSTRATIONAL
ION ROCKET ENGINE

by

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ABSTRACT

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In order to study the effects of various parameters on the thrust performance of an ion rocket engine, a preliminary analysis was made. After performing this analysis, a preliminary design of an ion rocket engine that can be constructed and used in the laboratory was made.

The design of the engine was subdivided into its three major components: the ionizer, the accelerator and the focuser, and the neutralizer. The theory of each was discussed before the design was attacked.

The ionizer was designed so that the emitter temperature and the cesium feed pressure could be varied causing a variation in the current density of the beam. A method of heating the emitter was devised and the power requirements of the heater were determined.

The accelerator and focuser was designed so that the electrical plate spacing could be varied, creating a measure of control in the thrust of the engine.

The neutralizer was designed so that the neutralization current could be varied in order that conditions of under neutralization, proper neutralization, and over neutralization could be studied in relation to the thrust of the beam.

Since this was only a preliminary design, the parameters obtained were not precise and will only be useful in giving the experimenter an idea of what to expect.

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LIST OF SYMBOLS

A	Atomic weight of an atom or ion. (grams/gram atom)
A_E	Emitter area. (cm^2)
A_0	Universal thermionic emission constant. ($1.2 \times 10^4 \text{amps/cm}^2 \text{ } ^\circ\text{K.}$)
a	Pore radius. (cm.)
Δa	Diffusion length of atoms on the surface of a porous plug. (cm.)
α	Surface adsorption coefficient. (dimensionless)
d	Separation between accelerating plates. (cm.)
D	Separation between ion beam and electron emitter. (cm.)
D_s	Surface diffusion coefficient. ($\text{cm}^2/\text{sec.}$)
e	Charge of an electron. (coulombs)
E	Subscript that refers to the emitter.
\mathcal{E}	Accelerating field. (volts/cm.)
e/m	Charge to mass ratio of an atomic particle. (coul./gram)
F	Accelerating force. (dynes)
$\bar{\epsilon}$	Grey body shape factor. (dimensionless)
g	Gravitational acceleration. (cm./sec^2)
H	Subscript that refers to the heater.

H-S	Subscript that refers to the heat shield.
I	Electrical current. (amperes)
I_s	Surface phase flow rate. (atoms/sec.)
I_v	Volumetric phase flow rate. (atoms/sec.)
J	Current density. (amps./cm ²)
J_T	Total current. (amps.)
k	Boltzmann's constant. (1.38×10^{-23} joules/°K.)
K	Energy. (ergs)
l	Length of a conductor. (cm.)
L	Thickness of a porous plug. (cm.)
m	Mass of an atom. (grams)
\dot{M}	Mass flow. (grams/cm ² -sec.)
p	Pressure. (dynes/cm ²)
p_0	Ionizer feed pressure. (dynes/cm ²)
P	Thrust. (dynes)
q	Rate of heat flow. (calories/sec.-cm ² °K)
Q	Electric charge. (coulombs)
R	Electrical resistance. (ohms)
s	Cross sectional area of resistor. (cm ²)
S	Subscript that refers to the surroundings.
t	Operating time of an engine. (sec.)
T	Temperature. (°K)
v	Ion velocity. (cm./sec.)
V	Electrical potential. (volts)

W	Electrical power. (watts)
W_p	Payload weight. (dynes)
W_t	Total weight. (dynes)
ϵ	Thermal emissivity. (dimensionless)
ϵ_0	Constant defined by: $\epsilon_0 = 1/4 \pi k$. Where k is a proportionality constant in the equation for the force between two charged particles. (9×10^9 dyne $\text{cm}^2/\text{coul}^2$)
ρ	Thermal reflectivity. (dimensionless)
ρ	Volume resistivity. (ohm-cm.)
σ	Surface concentration of atoms. (atoms/ cm^2)
σ	Stefan-Boltzmann constant. (0.1714×10^{-8}) (Btu/ $\text{ft}^2\text{-}^\circ\text{R}^4$)
ϕ	Work function. (volts)
μ_a	Incident atoms. (atoms/ $\text{cm}^2\text{-sec.}$)

NOTE: Although the units of the defined terms are self consistent, there have been deviations from these units in some sections of this paper. The reasons for these deviations were to simplify calculations and to apply reference material without conversion to the cgs system of units.

CHAPTER 1

INTRODUCTION

1.1 History of Ion Propulsion

The concept of ion rocket propulsion is not new. As early as 1906, R. H. Goddard is reported to have speculated on the use of charged particles for propulsion.^{1*} In 1929, Herman Oberth wrote a chapter on a solar powered ion rocket in his book, Wege Zur Raumschiffahrt. Since Oberth's writings there have been many general studies made on ion propulsion systems. All of these studies predicted that ion vehicles would be capable of obtaining higher velocities than those obtainable with chemical rockets having the same payload and gross weight.¹

In January, 1957, the Directorate of Advanced Studies, Air Force Office of Scientific Research, sponsored an analytical study of the ion rocket engine. An experimental research program was initiated in 1958. Both of these programs were carried out by Rocketdyne, a division of North American Aviation Company. "It is believed that the first ions produced in the development of a vehicle propulsion system were generated at the research labora-

*Superscripts refer to references listed at the end of this paper.

tories of Rocketdyne."¹

These studies were followed by programs in several other companies sponsored by agencies of the Armed Forces and the National Aeronautics and Space Agency.¹

At the present time the ion rocket engine is still in the research stage. However, as a result of an increased effort in space research on the part of the national government, more attention is being focused on the ion engine as an interplanetary propulsion device. Current literature indicates that more research is due to follow and rapid technological advances will be made.

1.2 Basic Principles of the Ion Engine

An ion engine can be classified as an electrostatic propulsion device in that it obtains its thrust by accelerating charged particles and ejecting these particles at high velocities. The operation of an ion engine consists of three principle phases. They are: (a) ionization, (b) acceleration and beam focusing, and (c) beam neutralization. A schematic of an ion engine showing each of the three phases is represented in Figure 1.1.

Ionization. Ionization is the first phase of operation of an ion engine. The fuel, usually in vapor form, is taken into the ionizer and ionized. The ionization process consists of the removal of an electron from

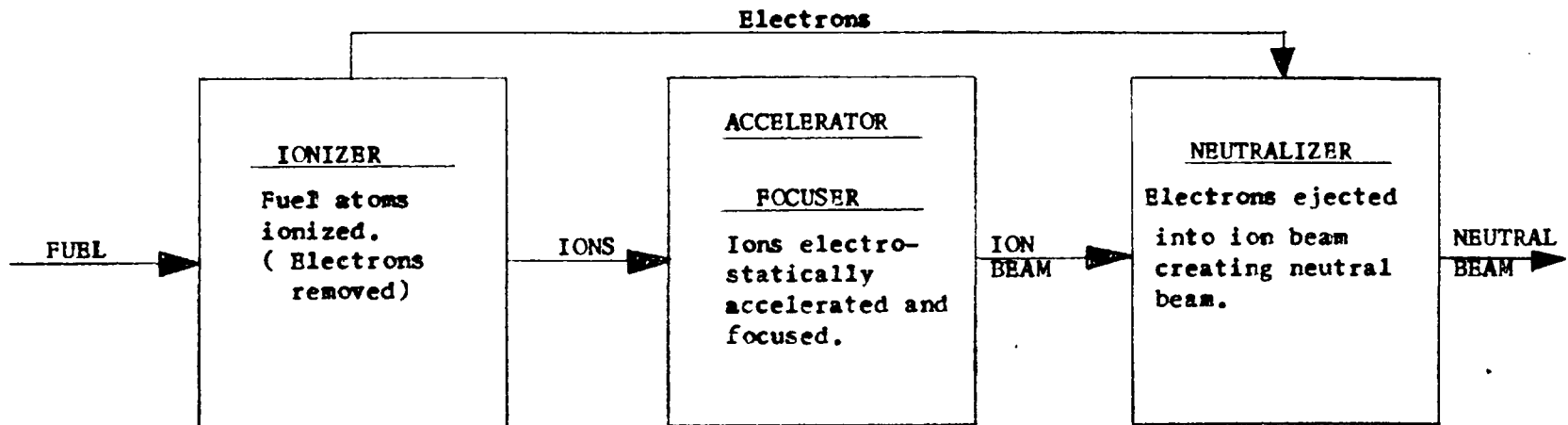


Figure 1.1 BLOCK DIAGRAM OF AN ION ENGINE

each fuel atom creating an ion with a charge of unity. In a later chapter the various methods of ionization will be discussed.

Acceleration and Beam Focusing. The second phase that the atoms (now ions) undergo consists of acceleration and beam focusing. It is by virtue of the accelerated beam that the ion engine develops its thrust. In order to accelerate the ion beam, a force must be applied to each ion in the beam and if this force is originated by the ion engine, an equal and opposite force, or thrust, will be exerted on the engine. Since the ions are electrically charged, there are various methods available by which a force may be applied to the beam.

In order to obtain the greatest thrust for any given engine configuration, the ion velocities must be parallel and directed opposite to the direction of the desired thrust. To accomplish this, the ion beam must be focused or confined to a specific region. Again there are many electrostatic schemes which can be employed to accomplish this task.

Neutralization. Neutralization is the name given to the process of ejecting electrons into the positive ion beam, thereby creating a neutrally charged beam. This is the final phase in the operation of an ion engine. To understand why the beam must be neutralized, the case

of an un-neutralized beam will be considered. As the fuel is ionized, a negative charge will build up on the ionizer as a result of the accumulation of the electrons removed from the atoms in the ionization process. In addition to the negative charge on the ionizer, a positive space charge will form at the exit of the engine as a result of the ion beam being emitted. In a short time the forces exerted by these charges will be equal and opposite to the forces exerted by the accelerating field of the engine. When this condition is reached, the accelerating field will be canceled and the ion beam will not be accelerated. However, if the electrons are electrostatically drawn off the ionizer and ejected into the ion beam, after it has been accelerated, the opposing field will not build up.

1.3 Comparison of Ion and Chemical Engines

To get an idea of the applications of an ion engine, a comparison between an ion engine and a chemical engine must be made. Figure 1.2 shows the differences between ion and chemical engines in thrust to weight ratio, specific impulse, exhaust velocity and specific power.^{2*}

At the present time the thrusts obtainable with ion engines are very small in comparison with the large-

*These terms are defined in the next paragraph.

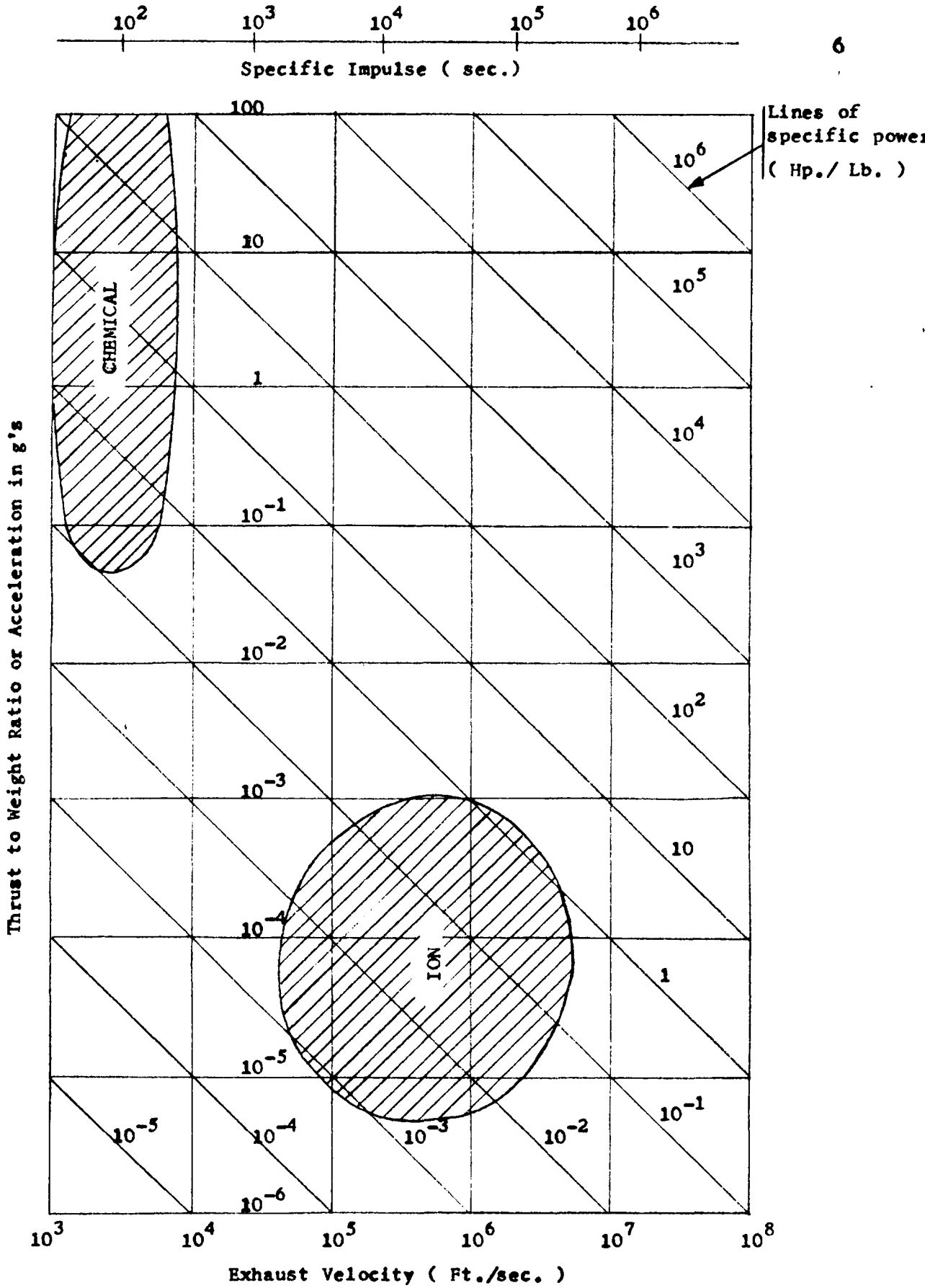


Figure 1.2 REGIONS OF ACCELERATION AND SPECIFIC POWER FOR CHEMICAL AND ION ENGINES.

thrust chemical engines. The highest thrust obtained with an ion engine is approximately one-tenth of a pound while thrusts of over one million pounds are obtainable with chemical engines. The application of an ion engine will depend upon a suitable mission. It is impossible that a device with a thrust on the order of one-tenth of a pound or less could ever propel a vehicle from the surface of the earth into orbit. The gravitational and drag forces encountered in such a mission are far greater than any foreseeable ion thrust forces. However, when missions in a small or non-existent force field are considered, the advantages of an ion engine become more apparent. A comparison of specific impulses and exhaust velocities illustrates the advantage of an ion engine over a chemical engine. The specific impulse is defined as the thrust (P) times the operating time (t) divided by the propellant weight (W_p). For this comparison, the predominant term in the specific impulse relationship is the operating time. While a chemical engine can only operate for minutes, an ion engine can operate for months.² Since the velocity of a vehicle can be expressed as the product of the acceleration and the time the accelerating force is applied, then in the absence of net external forces an engine with a low thrust and a long operating time could eventually have a greater velocity than an engine with a high thrust and

short operating time.

For missions in the immediate vicinity of the Earth and the Moon, accelerations less than 0.01g are too small to be useful.² For missions between Mars and the Sun, accelerations of 0.0001g are sufficient to achieve satisfactory travel times. Interplanetary missions beyond Mars will require thrusts of only 10⁻⁵g.²

An increase of payload fraction is also obtained by the use of an ion engine. Table 1.1 is a comparison of payload fractions for various engine types for a Mars satellite orbit using the same initial weight in an Earth orbit.²

TABLE 1.1

Engine	Payload Fraction (W_p/W_t)
Chemical	9-13%
High Energy Chemical	16%
Nuclear Fission	25%
Ion	32%

W_p = Propellant Weight

W_t = Total Weight

Table 1.2 is a comparison of trip times between ion and chemical engines for various missions.³

TABLE 1.2

<u>Instrument Probe To:</u>	<u>Chemical Engine Trip Time (years)</u>	<u>Ion Engine Trip Time (years)</u>
Jupiter	2.7	1.5
Saturn	6.1	2.5
Pluto Orbit	45.0	3.0

CHAPTER 2

THEORY

The theory upon which the ion engine is based has been known for some time. Its discussion here will be carried out by considering the ionization, acceleration and focusing, and neutralization phases.

2.1 Ionization

There are various methods that can be used to ionize a gas, such as: (1) subjecting the atoms to high temperatures in flames, electric arcs, or contact with hot surfaces, (2) allowing the atoms to absorb energy from photons of light, using either a beam of white or monochromatic light, or (3) bombarding the atoms with energetic electrons.⁴ The most commonly-used method in ion engines is a variation of method (1). This variation is called the contact-potential method. Since it is the predominant method at the present time, it will be the only method discussed in this paper.

Definitions of the terms "work function" and "ionization potential" are essential in understanding the contact-potential method of ionization. The work function of any solid is "the minimum energy which must be given

to an electron in the solid in order to remove the electron from the solid."⁵ Ionization potential is the minimum amount of energy required to ionize the gas (i.e., to remove one electron from each gas atom).⁵ It is known that the internal energy of any substance is a function of temperature. As the temperature increases, so does the internal energy. If a certain substance were to be heated, it could eventually gain enough energy to ionize in the case of a gas or to emit electrons in the case of a solid.

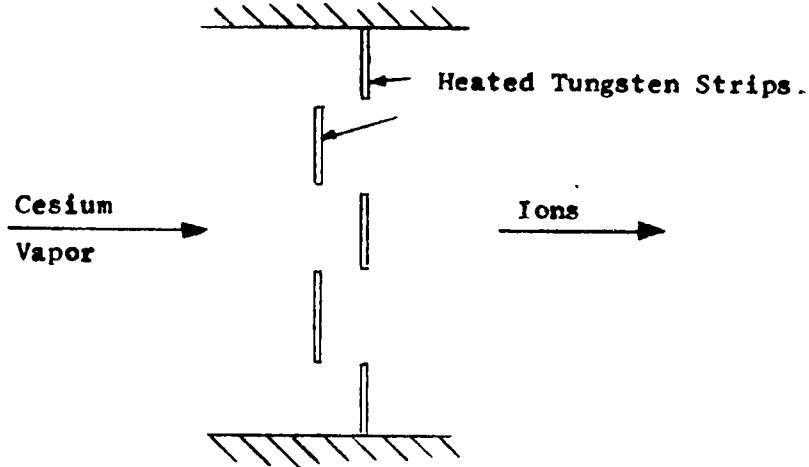
The actual process of ionization depends on an ionizer and a gas to be ionized. The principle requirement is that the ionization potential of the gas is less than the work function of the ionizer.³ If the ionizer is heated to a temperature which yields an energy level less than the work function of the ionizer but greater than the ionization potential of the gas, the gas atoms adjacent to the ionizer will gain energy, by virtue of heat transfer, until they have enough energy to ionize. One electron will be removed from each atom, thus forming positive ions. In general, the energy level needed to release a second electron is greater than twice the energy required to release the first.⁶ In all cases, the second level is greater than the work function of any element,⁶ therefore, only a singly charged ion will be formed.

There are several combinations of gases and ioni-

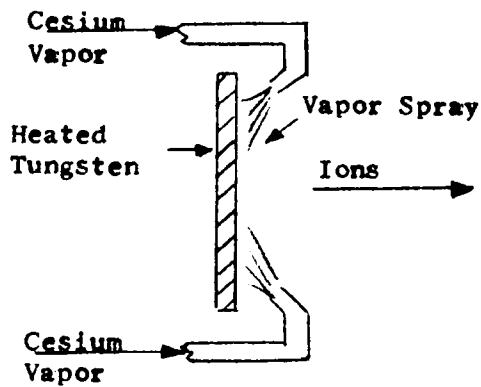
zer materials available but cesium vapor and tungsten are the most commonly used.⁷ Cesium is used because of its high atomic weight and its relatively low ionization potential.⁶ Tungsten is used because of its work function and its thermal and electrical conductivities.⁶ The presence of surface films of cesium on the tungsten reduces the work function of the ionization surface. Therefore, the surface of the ionizer must be lightly covered at any instant.³ To make sure the surface is lightly covered, the ionizer must be maintained at a high temperature so that the film "boils off." The acceptable temperature range of tungsten in which cesium undergoes 100% ionization is from 1700°F to 3200°F.³

There are three basic ionizer types which can be utilized to accomplish contact ionization: Through Feed Ionizer, Reverse Feed Ionizer, and Porous Ionizer.³ (Fig. 2.1). The fundamentals of through feed and reverse feed ionizers are the easiest to understand because the ionization process is just the contact ionization process as previously explained. The tungsten ionizers must be above 1700°F and the cesium must be in the vapor form. The ionization depends solely on the work function-ionization potential relationships. The number of atoms ionized can be easily calculated by use of mass flow equations and the equation of state. Because these methods were not

THROUGH FEED IONIZER



REVERSE FEED IONIZER



POROUS IONIZER

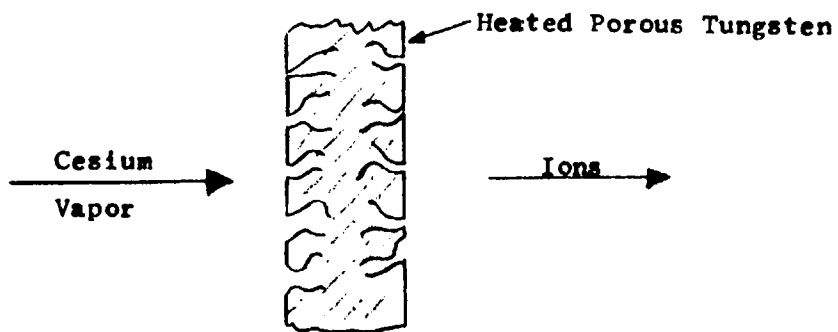


Figure 2.1 SCHEMATIC OF IONIZER TYPES.

considered for the design that follows, a more complete explanation of the through feed and reverse feed ionizers will not be given. A thorough discussion of contact-potential ionization is given in refs. 9 and 10.

The processes involved in a porous ionizer are more complex than the processes involved in a reverse feed or a through feed ionizer. However, once the ions are formed by the porous ionizer, there are no obstructions in the ion's path as there are in the other two methods. With high ion velocities (10^5 m/sec. or greater) obstructions in the beam will cause problems in beam focusing and control. For this reason, a porous ionizer was chosen for this design.

Vapor Flow Through the Interior of a Porous Plug

The assumption will be made that the cesium atoms will not become ions while they pass through the interior of the porous plug, but only after they reach the external surface where "the conditions of low surface coverage and the presence of an accelerating field are met."¹¹ For a model of the porous tungsten, a structure of long parallel tubes of length (L) and radius (a) will be used. (Fig. 2.1).

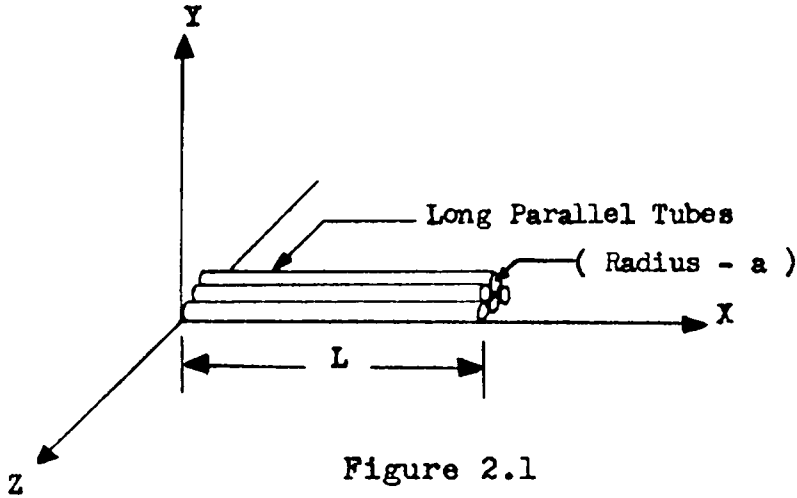


Figure 2.1
Porous Plug Model

The flow through the structure, at constant temperature, will consist of a volumetric flow diffusing under a pressure gradient dp/dx and a surface phase diffusing along the wall under a gradient of surface concentration $d\sigma/dx$. The flow rate for the volumetric flow is given by:¹¹

$$I_v(x) = -\frac{8}{3} \frac{\pi a^3}{(2\pi m k T)^{1/2}} \frac{dp}{dx} \quad (2.1)$$

Where: k = Boltzmann's constant.

m = mass of cesium atom.

T = temperature of tungsten.

The diffusion equation for the surface is given by:¹¹

$$I_s(x) = -2\pi a D_s \frac{d\sigma}{dx} \quad (2.2)$$

Where: D_s = diffusion coefficient.

If local equilibrium is assumed, the two phases are coupled

by the adsorption isotherm: $p = p(\sigma, T)$. For the region near the exit ($x = L$):¹¹

$$P/(2\pi mkT)^{1/2} = \sigma/\tau_a \quad (2.3)$$

Where: τ_a = residence time of atom on the surface in the limit of vanishing coverage.

Therefore:¹¹

$$\left(\frac{I_v}{I_s}\right)_{x \rightarrow L} = \frac{4}{3} \frac{a^2}{D_s \tau_a} = \frac{4}{3} \left(\frac{a}{\Delta a}\right)^2 \quad (2.4)$$

Where: Δa = Diffusion length, $(D_s \tau_a)^{1/2}$,
of cesium atoms on tungsten surface before ionization occurs.

The following table by Nazarian and Shelton (ref. 11) presents experimental data and the extrapolation of the data in ref. 12.

TABLE 2.1

Cesium vapor-Tungsten combination

T°K	τ escape (sec)	τ travel (sec)	D_s (cm ² /sec)
600	1100 x 10 ⁻¹³	11 x 10 ⁻¹³	0.016 x 10 ⁻⁴
800	59	9.5	0.28
1000	9.8	8.5	0.95
1200	3.0	7.7	1.6
1400	1.3	7.1	2.1
1600	0.7	6.7	2.4

It should be noted that at temperatures above 1600°K, D_s is almost insensitive to temperature.¹¹

τ_a can be calculated by the following equation:¹¹

$$\tau_a = 3.6 \times 10^{14} \exp(-62 + 3238/T) \quad (2.5)$$

Where T = temperature of the porous plug.

Expressed in tabular form:¹¹

TABLE 2.2

T°K	τ_a (sec)	Δa (microns)
1000	45	650
1200	0.23	60
1400	4.5×10^{-3}	10
1600	2.3×10^{-4}	2

If the values of Δa are introduced into equation (2.4), the data in table 2.3 is obtained.

TABLE 2.3

Pore Radius a (microns)	Percentage Cesium Atoms Lost* Directly Through Orifices of Porous Tungsten (Theoretical)			
	1000°K	1200°K	1400°K	1600°K
50.0	1	56	98	100
10.0	0	5	57	97
5.0	0	1	25	89
1.0	0	0	1	25
0.8	0	0	1	18
0.6	0	0	0	11
0.4	0	0	0	5
0.2	0	0	0	1

*The term atoms lost refers to the atoms that pass through the pore orifices without being ionized.

Table 2.3 shows how the pore size must decrease as the temperature is increased so that there will not be an increase in the number of atoms lost through the pores.¹¹

The manner in which the pressure and the surface coverage influence the flow through the porous plug can now be examined. For steady state, the following expression is obtained.¹¹

$$I = \frac{1}{L} \left[\int_0^L I_V(x) dx + \int_0^L I_S(x) dx \right] \quad (2.6)$$

Substituting equations 2.1 and 2.2 into equation 2.6 and integrating from $x = 0$ to $x = L$ with end conditions given by:¹¹

$$\begin{aligned} p(0) &= p_0 & \sigma(0) &= \sigma_0 \\ p(L) &= 0 & \sigma(L) &= 0 \end{aligned}$$

$$\text{We find: } I = I^* (1 + \alpha) \quad (2.7)$$

$$\text{Where: } I^* = \frac{8}{3} \frac{\pi a^3}{(2\pi m k T)^{1/2}} \frac{p_0}{L} \quad (2.8)$$

$$\alpha = \frac{3}{4} \frac{D_s \sigma_0 (2\pi m k T)^{1/2}}{a^2 p_0} \quad (2.9)$$

Integrating equation 2.6 again from $x = 0$ to $x = x$:

$$\frac{x}{L} = \frac{(1 - p/p_0) + \alpha (1 - \sigma/\sigma_0)}{1 + \alpha} \quad (2.10)$$

By combining the adsorption isotherm $p = p(\sigma, T)$ with equation 2.10, the pressure and coverage can be calculated for given values of p , T and α .¹¹

If the assumption is made that the tube services an external area πR^2 with $R = 3a$, which is realistic for porous materials, and if it is assumed that all of the surface flow will be emitted as ion current, the relationship for the ion current density can be written:¹¹

$$j = \frac{e I^* (1 + \alpha)}{9 \pi a^2} = \frac{8 e a p_0 / L}{27 (2 \pi m k T)^{1/2}} (1 + \alpha) \quad (2.11)$$

For any desired current density and design conditions (a & L), a value of the feed pressure p_0 and the dimensionless quantity α can be calculated by the application of the following iteration process. α is assumed to zero and a value of p_0 is calculated. Once p_0 is found, σ_0 can be found by the use of equation 2.12 and figure 2.2:

$$\mu_a = (2 \pi m k T)^{-1/2} \text{ atoms/cm}^2 \text{ sec.} \quad (2.12)$$

μ_a = number of atoms incident on the plug.

With p_0 , σ_0 , D_s , a , m , & T known, α can be determined by the use of equation 2.9. With the value of α considered, the current density given by the right hand side of equation 2.11 will be greater than the j specified. A systematic reduction of p_0 must be made. The corresponding variations in α must be calculated until the right side of equation 2.11 will give the desired value of j . In many cases the value of α originally calculated will be so small that its effect on equation 2.11 may be neglected.

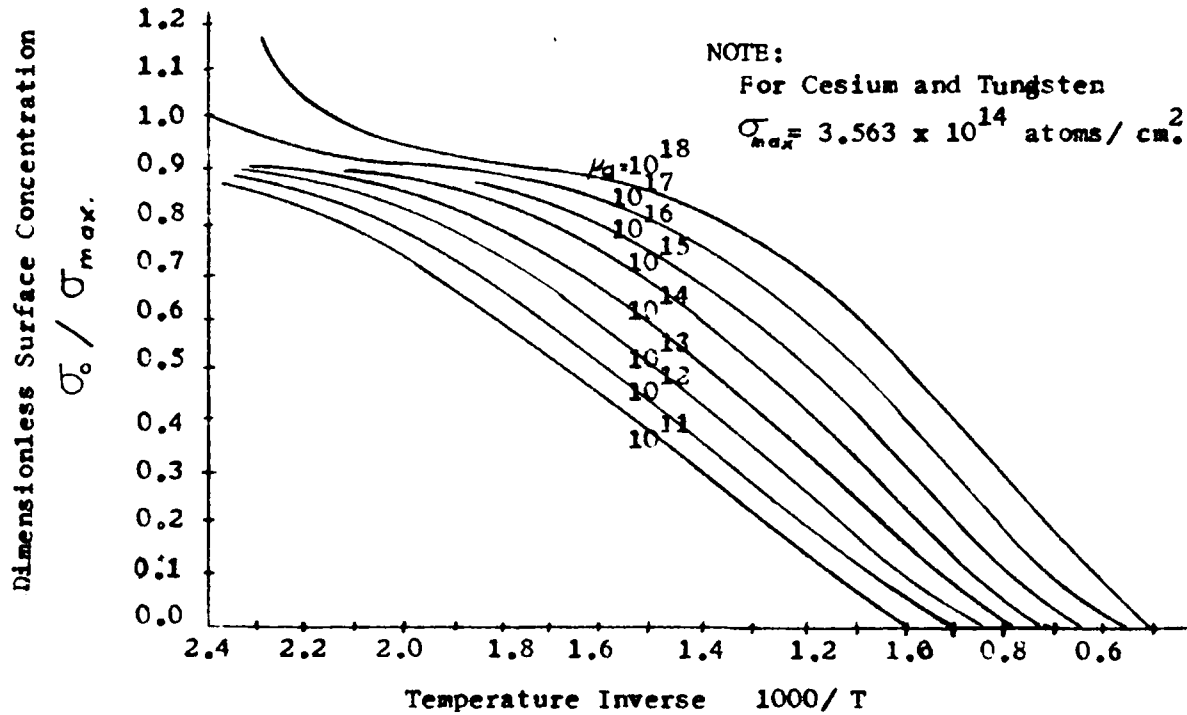


Figure 2.2 DIMENSIONLESS SURFACE CONCENTRATION VERSUS TEMPERATURE INVERSE FOR VARIOUS NUMBERS OF INCIDENT ATOMS.

2.2 Acceleration and Beam Focusing

Acceleration. The acceleration of ions can be accomplished by the application of an electric field. The velocity of electrostatically accelerated ions is given by:¹³

$$v = \sqrt{2 V_s e/m} \quad \text{cm./sec.} \quad (2.13)$$

$$v = 13.8 \sqrt{V/A} \quad \text{km./sec.} \quad (2.14)$$

Where: V_s = accelerating potential in statvolts.
(300 volts = 1 statvolt).

e/m = charge to mass ratio in esu/gram.

V = potential in volts.

A = atomic mass of ion. ($A = 1$ for proton)

1 AMU = 1.66×10^{-24} grams.

The Child-Langmuir law for the maximum current density of charged particles that can pass between parallel, plane electrodes with spacing d and potential difference V is given by:¹³

$$j = 5.44 \times 10^{-9} \frac{V^{3/2}}{A^{1/2} d^2} \quad \text{amp./cm}^2 \quad (2.15)$$

The mass flux is given by:¹³

$$\dot{M} = C j m / 10e \quad (2.16)$$

Where: C = ratio of electrostatic to electromagnetic units.¹³

Or:

$$\dot{M} = 5.71 \times 10^{-13} \frac{A^{1/2} V^{3/2}}{d} \text{ grams/cm}^2 \cdot \text{sec.} \quad (2.17)$$

The thrust force per unit area of the beam is given by:

$$F = \dot{M} v \quad (2.18)$$

Substituting in the expressions for v and \dot{M} from equations 2.14 and 2.17:

$$F = 7.85 \times 10^{-7} \frac{V^2}{d^2} \text{ dynes/cm}^2 \quad (2.19)$$

Where d is in cm.

It is seen that the force is independent of A .

This is the thrust per unit area. The total thrust can be calculated by multiplying the thrust per unit area times the total area. It should be noted that the above equations are developed for parallel lines of force between parallel plates. This implies a beam of uniform cross sectional area. However, if the beam were not of uniform cross section, the current density, velocity and force per unit area would vary with the change in area. If the area of the emitter is known, the thrust per unit area at the emitter can be calculated. Therefore, the total thrust can be calculated. Since the lines of force originate on the electrodes and terminate on the beam, the resultant thrust is felt on the accelerating electrodes. If a thrust and voltage are specified, the distance between the electrodes, the

mass flow, the current density and the velocity of the beam can be calculated from equations 2.13 - 2.20.

Focusing. As previously stated in the introduction, beam focusing is a very important phase in the operation of an ion engine. Figure 2.3 will help in explaining the importance of beam focusing.

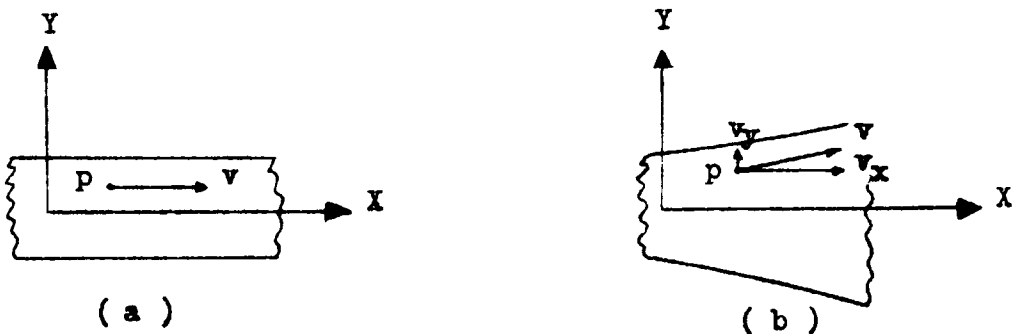


Fig. 2.3

Focused and Unfocused Beam

Beam (a) is an ideally focused beam (all of the ions are traveling in parallel paths). If p is an ion and v is its velocity, the energy of the ion is given by the equation $K = 1/2 mv^2$. The energy expended in the x direction is given by: $K_x = 1/2 mv_x^2$. In beam (a), $v = v_x$ and all of the energy is expended in the x direction. The total energy expended in the x direction can be calculated by summing the energies of all the ions in the beam. Since thrust can be related to energy dissipated, for a given thrust, the

energy required can be calculated.

Beam (b) is a poorly focused beam in that the ions have velocity components in the y direction. In this case, the beam is said to diverge. If $p' = p$ and $v' = v$, the total energy of p' will equal the total energy of p . However, the energy expended by p' in the x direction will be less than expended by p because of the energy that p' expends in the y direction. If all the energies in beam (b) are summed (assuming a symmetrical beam) the energy dissipated in the x direction will be less than in beam (a). Therefore, to acquire a specified thrust, more energy must be supplied to an unfocused beam than to a focused beam. This constitutes an inefficiency that cannot be tolerated when maximum performance is desired.

Two methods that can be used to focus a beam are the use of magnetic fields and the use of electric fields. There are many configurations for each method. The configuration selected depends upon the design parameters such as: emitter configuration, accelerating potential and distance between the accelerating plates. Since all of these configurations are just applications of basic field theory and as a group will not add to the understanding of this paper, there will be no discussion of them. A specific method will be discussed in Chapter 3. If the reader desires to investigate focusing more thoroughly, refs. 14 and 15 would be an

excellent place to start.

2.3 Neutralization

Beam neutralization, if carried out most efficiently, is very complex. A complete discussion of neutralization could comprise a thesis in itself. Since this thesis is primarily concerned with a general, fundamental design, only a crude type of neutralization will be discussed. The method discussed will prove satisfactory for the requirements of the design discussed in Chapter 3.

The simplest method of beam neutralization is to place a hot filament in or very near the beam. "The positive ion beam will pull electrons off a hot emitting grid without further complication of electron accelerating grids according to the needs for neutralization."⁷ In order to completely neutralize the beam, the electron current must equal the ion current. The ion current can be calculated from:

$$J = j A_e$$

Where: A_e = area of the filament.

J = total current

The electron current can be calculated from:⁵

$$j = A_o T^2 \exp \left\{ -\frac{e}{kT} \left[\phi - \left(\frac{e E}{4 \pi \epsilon_o} \right)^{1/2} \right] \right\} \quad (2.20)$$

Where: A_0 = a constant of the filament.

($0.6 \times 10^6 \text{ amp/m}^2 \text{ } ^\circ\text{K}^2$ for tungsten)

T = temperature of the filament.

e = unit of electrical charge.

ϕ = work function of the filament.

k = Boltzmann's constant.

\mathcal{E} = electric field felt by the filament.

ϵ = constant obtained from Coulomb's law of forces between electrical charged particles.

In practice, an electrostatic generator draws the electrons, formed during the ionization process, off of the emitter and feeds them into the filament (see figure 2.4). From the filament the electrons are drawn to the beam and change the ions into atoms, thus neutralizing the beam.⁷

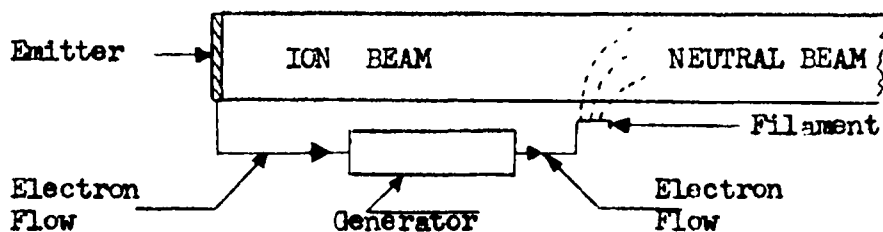


Fig. 2.4

Beam Neutralization

CHAPTER 3

PRELIMINARY DESIGN

3.1 Specifications and Primary Calculations

In the design of an ion engine, as in any other design, certain design specifications and performance requirements must be made. The primary specifications and requirements will be discussed at this point and less important specifications will be discussed as they are approached in the design.

There are three primary requirements or specifications: the thrust, the accelerating potential, and the emitter area. From these three parameters most of the other design parameters can be found. The values selected for these parameters are presently obtainable in the laboratory and are consistent with currently developed engines.

$$\text{Thrust} = P = 0.01\# = 4.5 \times 10^5 \text{ dynes.}$$

$$\text{Accelerating potential } V = 40,000 \text{ volts.}$$

$$\text{Emitter area } A = 0.25 \text{ in}^2 = 1.61 \text{ cm}^2$$

Using these three parameters, the distance between the accelerating plates can be calculated. If the distance between the plates is known, the current density can be calculated.

When the plate spacing and the current density are known, the preliminary design can be made.

The equation for the thrust is:

$$P = FA_e \quad (3.1)$$

Where: F is given in equation 2.19 which is repeated here for convenience.*

$$F = 7.85 \times 10^{-7} \frac{V^2}{d^2} \text{ dynes/cm}^2 \quad (3.2)$$

Then:

$$P = 7.85 \times 10^{-7} \frac{A_e V^2}{d^2} \text{ dynes} \quad (3.3)$$

To find d, equation 3.3 must be rearranged to give:

$$d = \left(\frac{7.85 \times 10^{-7} V^2 A_e}{P} \right)^{1/2} \text{ cm.} \quad (3.4)$$

Substituting in the appropriate values for V, A_e , and P:

$$d = 0.655 \text{ cm.} = 0.262 \text{ in.}$$

Now that d is known, the current density of the beam can be calculated from the following equation:¹³

$$j = 5.44 \times 10^{-8} \frac{V^{3/2}}{A^{1/2} d^2} \quad (3.5)$$

Where: A is the atomic weight of the vapor atoms.

$$(A = 132.9 \text{ for cesium})$$

$$j = 8.53 \times 10^{-2} \text{ amps/cm}^2$$

*It should be recalled that all of the discussion here pertains to a cesium-tungsten combination.

The total current of the beam is equal to the current density times the emitter area. The equation for the total current is, therefore:

$$J = j A_e \quad \text{amp.} \quad (3.6)$$

$$J = 0.137 \quad \text{amp.}$$

3.2 Ionizer

With the current density known, the ionizer can be designed. The ionizer must meet two requirements. The emitter area must be 1.61 cm.^2 as specified in section 3.1, and the emitter must produce a current density of $8.53 \times 10^{-2} \text{ amps/cm}^2$

Emitter. To provide an axial thrust, the emitter will consist of a circular disk of radius r and thickness L (Figure 3.1). Since the face area of this disk must be 1.61 cm.^2 , the radius is 0.715 cm. The thickness of the disk will be arbitrarily selected as 0.0381 cm. ($0.015''$) which corresponds to thicknesses used in currently developed engines.

The temperature of the emitter must also be selected. A value of 1700°F or 1200°K was decided upon. This temperature was selected because 1200°K is the lowest temperature of a tungsten emitter that will result in the ionization of 100% of the cesium atoms.⁸ A higher temperature could have been selected but a greater energy would

be required to maintain this higher temperature while no increase in ionization would occur. Table 2.3 indicates that as the temperature of tungsten increases, smaller pores are required to prevent an increase in the loss of atoms through pore orifices. However, if smaller pores are used, the chances of pore clogging will be increased. Therefore, to reduce the possibilities of pore clogging, the largest possible pores must be used. This means that the lowest possible temperature is desirable. At a temperature of 1200°K, a pore radius (a) of one micron or 1.0×10^{-4} cm. is acceptable.¹¹

Feed Pressure (p_0). The required feed pressure of cesium vapor at the emitter face to provide a specific current density is determined by equation 2.11 which is repeated here for convenience.¹¹

$$j = \frac{8 e a P_0 / L}{27 (2 \pi m k T)^{1/2}} (1 + \alpha) \quad (3.7)$$

As explained, α is at first assumed equal to zero. Equation 3.7 can then be rearranged and solved for P_0 .

$$P_0 = \frac{j (27) (2 \pi m k T)^{1/2} L}{8 e a} \quad (3.8)$$

$$P_0 = 7.85 \text{ mm. Hg.}$$

Knowing the pressure of the cesium vapor and assuming that the vapor atoms adjacent to the emitter are at 1200°K, σ_0 can be found from equation 2.2 and figure 2.2.

The value of σ_0 arrived at is 1.6×10^{14} atoms/cm².

The value of α is then calculated from the equation:¹¹

$$\alpha = \frac{3}{4} \frac{D_s \sigma_0 (2\pi m k T)^{1/2}}{a^2 p_0} \quad (3.9)$$

At 1200°K, $D_s = 1.6 \times 10^{-4}$ (from table 2.2)

Therefore:

$$\alpha = .00621$$

In comparison with one, α is small enough to be neglected for practical purposes. Therefore, the value of p_0 determined by equation 3.8 is acceptable for the feed pressure at the emitter face. This pressure is the total pressure or the sum of the static pressure and the dynamic pressure. At the entrance of the feed tube, the static pressure will be the same as the total pressure p_0 . Frictional losses will be neglected since the velocity of the vapor in the feed tube is only 0.405 cm./sec. if the tube diameter is one-eighth of an inch. Figure 3.1 is a schematic of the emitter and the feed tube.

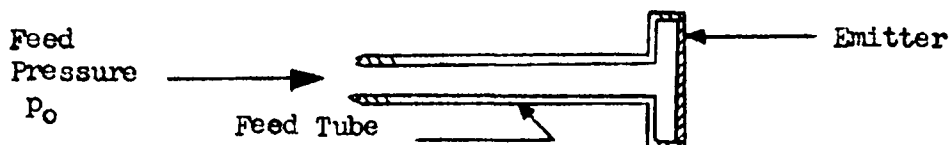


Fig. 3.1

Emitter and Feed Tube

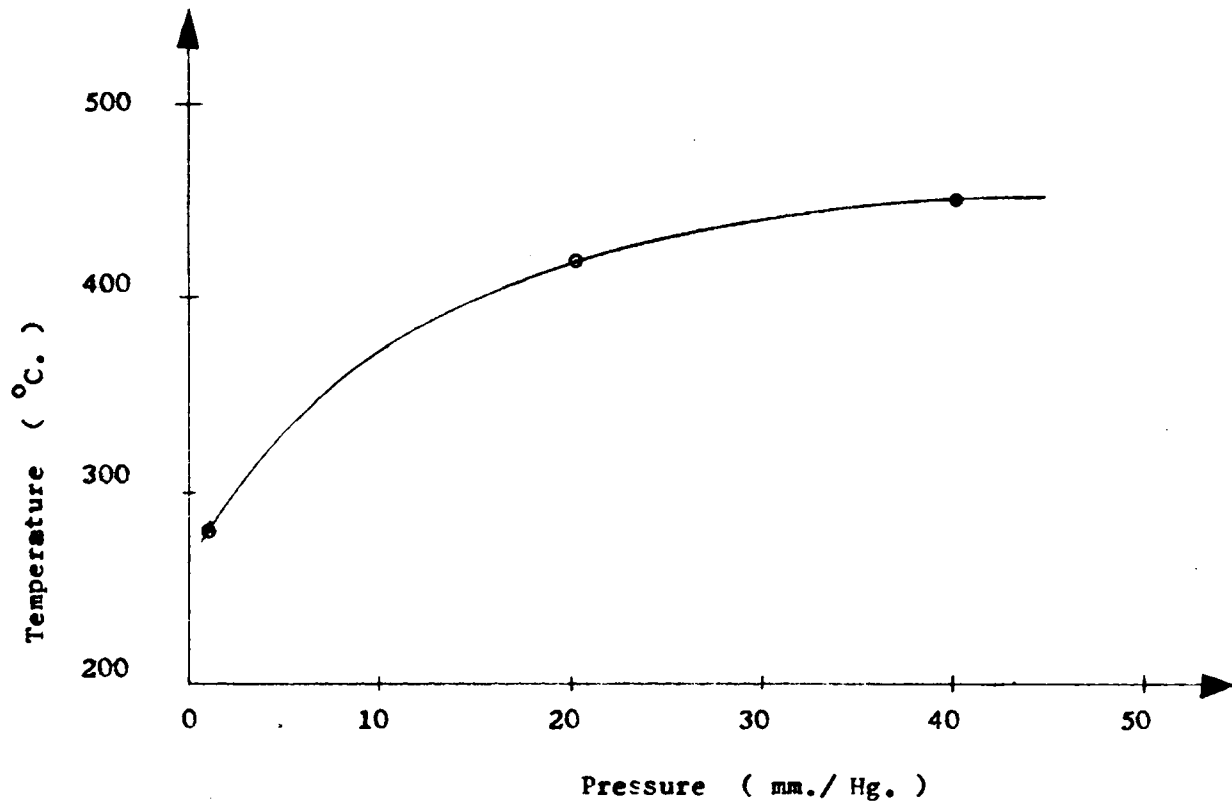


Figure 3.2 EQUILIBRIUM TEMPERATURE vs. PRESSURE FOR CESIUM VAPOR.

Figure 3.2 is a plot of the pressure of cesium vapor versus equilibrium temperature.⁶ From this plot, the equilibrium temperature of cesium at 7.85 mm. Hg. is found to be 360°C. Therefore, to keep the cesium vapor at 7.85 mm. Hg., the vapor must be kept at 360°C. This can be accomplished by some type of thermostatically controlled boiler.

Heater. A method must be devised to heat the tungsten emitter without interfering with either the ion flow or the flow of atoms through the emitter. Figure 3.3 is a diagram of the arrangement decided upon.

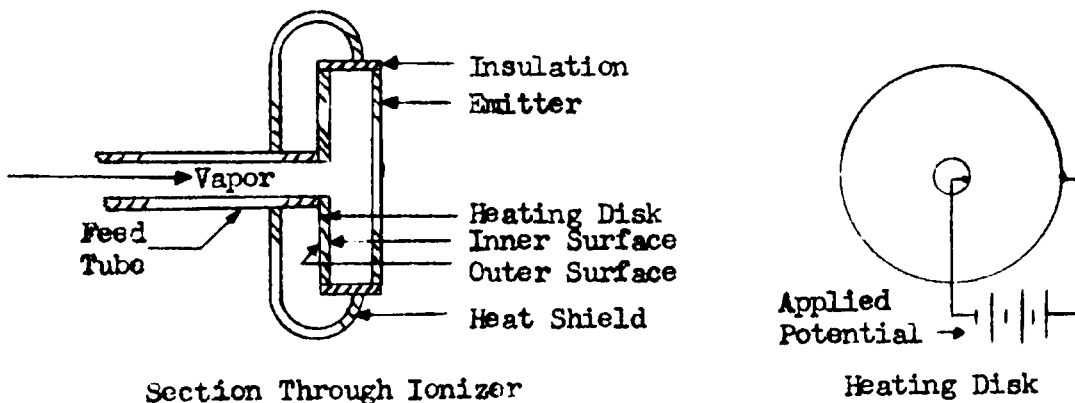


Fig. 3.3

Heater Configuration

The heating disk is made of iron and the heat shield is made of nickel. Iron was selected because of its high melting point and its thermal and electrical conductivi-

ties. Nickel was selected for basically the same reasons and that it has a very low $(0.087)^{16}$ emissivity when highly polished making it an ideal heat shield. The heating disk has an electrical potential applied across it from inner radius to outer radius and the current flowing generates heat in the disk as does the current which flows through an electrical heating coil. The heating disk heats the emitter by radiation and the heat shield is employed to reduce the heat losses by radiation from the outer face of the heating disk.

In this thesis it will be assumed that the heat transfer due to conduction and convection can be neglected in comparison to the heat transfer due to radiation. This assumption is based on three points:* (1) There will be essentially no conduction from the ionizer due to insulation and small conducting surfaces, (2) There will be little convection because of the vacuum outside of the ionizer and the low pressure inside of the ionizer, and (3) The conduction and convection processes are a function of the first power of the temperatures while radiation is a function of the fourth power of the temperatures.

The following equation for the heat transfer by radiation is valid:¹⁷

*Reference to figure 3.5 will aid in the understanding of these assumptions.

$$q_{1-2} = A, \hat{\epsilon}_{1-2} \sigma (T_1^4 - T_2^4) \quad (3.9)$$

Where: q_{1-2} = heat transfer from body 1 to body 2.

A = area of body 1

$\hat{\epsilon}$ = grey body shape factor determined by the geometry of the bodies.

σ = Stefan-Boltzmann constant - 0.1714×10^{-8}
Btu/ft² - °R⁴.

T_1 = temperature of body 1.

T_2 = temperature of body 2.

To find the heat transfer from the emitter to the surroundings, equation 3.9 can be used. The emitter is at 1700°F and the surroundings will be assumed to be at 80°F. The expression $A, \hat{\epsilon}_{1-2}$ for a small grey body in black surroundings reduces to A, ϵ , where ϵ is the emissivity of the grey body.¹⁷ ϵ for tungsten is 0.15¹⁶.

$$q_{1-2} = 9.75 \text{ Btu./hr.} \quad (3.10)$$

This is the heat required to keep the emitter at 1700°F.

To find the temperature drop across the emitter, the following conduction equation will be used:¹⁷

$$\Delta T = \frac{qL}{kA} \quad (3.11)$$

Where: ΔT = temperature difference between the two faces.

q = heat transferred across the emitter.

L = thickness of the emitter. (0.0381 cm.)

A = area of the emitter. (1.6. cm²)

R = thermal conductivity of the emitter. (0.15)

Since steady state conditions prevail, the heat transfer from the emitter to the surroundings is the same as the heat transfer across the emitter, and is the same as from the heating disk to the emitter. If 9.75 Btu/hr. is used for q in equation 3.11 and appropriate values are substituted for the other variables:

$$\Delta T = 0.076^{\circ}\text{F}$$

Essentially the emitter will be at a uniform temperature.

In order to make the heating disk most efficient, the inner surface must radiate as much energy as possible and the outer face must radiate as little as possible. To accomplish this, the inner face will be oxidized giving an emissivity of 0.91 and the outer face will be highly polished giving an emissivity of 0.144.¹⁶ The spacing between the emitter and the heating disk will be specified at 1/16 in. The heat transfer problem can be reduced to the heat transfer between two flat parallel plates, if end effects are neglected. The expression for flat parallel plates is given by:¹⁷

$$A_H \bar{\epsilon}_{H-E} = \frac{1}{\frac{\rho_H}{A_H \epsilon_H} + \frac{1}{A_H} + \frac{\rho_E}{A_E \epsilon_E}} \quad (3.12)$$

Where: ρ = reflectivity

subscript E refers to the emitter.

subscript H refers to the heater.

To find the required temperature of the heating disk:

$$T_H^4 - T_E^4 = \frac{q_{1-2}}{A_H \bar{\epsilon}_{H-E} \sigma} \quad (3.13)$$

When equation 3.13 is evaluated, the following heating disk temperature is found: $T_H = 3000^\circ\text{R}$.

Since the melting point of iron is 3250°R^6 , the heating disk temperature is within safe limits.

The rate of heat transfer from the heating disk to the heat shield and from the heat shield to the surroundings must be calculated. From the heat shield to the surroundings:¹⁷

$$q_{HS-S} = A_{HS} \bar{\epsilon}_{HS-S} \sigma (T_{HS}^4 - T_S^4) \quad (3.14)$$

Where: The subscript HS refers to the heat shield.

The subscript S refers to the surroundings.

From the heating disk to the heat shield:¹⁷

$$q_{H-HS} = A_H \bar{\epsilon}_{H-HS} \sigma (T_H^4 - T_{HS}^4) \quad (3.15)$$

In steady state, $q_{HS-S} = q_{H-HS}$.

Therefore:

$$A_{HS} \epsilon_{HS-S} \sigma (T_{HS}^4 - T_S^4) = A_H \epsilon_{H-HS} \sigma (T_H^4 - T_{HS}^4) \quad (3.16)$$

From the geometry of the heat shield it will be assumed that the outer surface of the heat shield is roughly twice the area of the inner surface receiving energy from the heating disk. If the emissivity of polished nickel is 0.087, equation 3.16 can be solved for T_{HS} .

$$T_{HS} = 2220^{\circ}\text{R.}$$

This temperature is safely below the melting point of nickel, which is 3100°R . With T_{HS} known, equation 3.15 can be solved for the rate of heat transfer from the heating disk to the heat shield, yielding:

$$q_{H-HS} = 9.85 \text{ Btu/hr.}$$

To find the total heat loss from the heating disk, equations 3.10 and 3.15 are added.

$$q_T = q_{E-S} + q_{H-HS}$$

$$q_T = 19.65 \text{ Btu/hr.}$$

Converting to watts:

$$q_T = 5.74 \text{ watts}$$

Therefore, to maintain a temperature of 3000°R in the heating disk a power input of 5.74 watts is required.

From basic electrical theory, it is known that:

$$P = I^2 R \quad (3.17)$$

Where: P = power in watts.

I = current.

R = electrical resistance.

and

$$V = IR \quad (3.18)$$

Where: V = voltage.

If R can be calculated, I can be found using equation 3.17 and then V can be determined using equation 3.18. The resistance can be calculated by the following expression:⁶

$$R = \rho \frac{l}{S} \quad (3.19)$$

Where: ρ = resistivity.

l = length of the conductor.

S = cross-sectional area of the conductor.

The geometry of the conductor-heater is shown in figure 3.4.

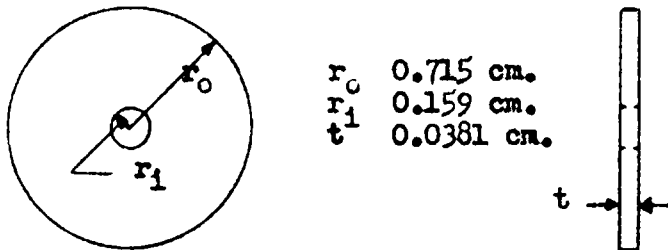


Fig. 3.4

Heating Disk

From the geometry of the disk:

$$l = r_o - r_i = 0.554 \text{ cm.}$$

To arrive at an appropriate value of s , the log mean area will be used.

$$s = \frac{2\pi z (r_o - r_i)}{\ln\left(\frac{r_o}{r_i}\right)} \quad (3.20)$$

In ref. 6, the resistivity at 3000°R is approximately 200 ohm-cm. Then:

$$R = \rho \frac{l}{s}$$

$$R = 1,260 \text{ ohms}$$

And:

$$P = I^2 R$$

$$I = 6.75 \times 10^{-2} \text{ amps.}$$

Finally:

$$V = IR$$

$$V = 85$$

Therefore, if a potential of 85 volts is applied across a disk of iron as previously specified, the disk will heat to 3000°R . The actual resistance of the disk will not be 1,260 ohms when the potential is first applied since resistance is a direct function of temperature. However, as soon as current begins to flow, the disk will begin to heat and its resistance will increase. As the resistance increases, the current will decrease. Finally, an equilibrium

condition will exist and a constant temperature will be maintained.

A cross-sectional diagram of the ionizer is shown in figure 3.6. The bakelite sections are added to provide both thermal and electrical insulation.

3.3 Accelerator and Focuser

In section 3.1 the separation between the accelerating plates was calculated. As stated in the theory, the equations used apply to parallel flat plates. However, parallel flat plates are not the best focusing devices. Figure 3.5 will be useful in understanding why parallel plates are poor focusers.

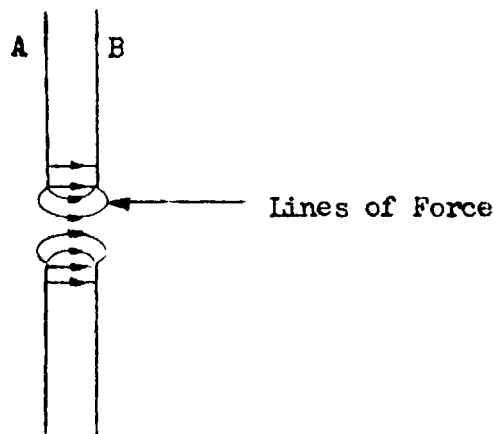


Fig. 3.5

Flat Plate Accelerator

An ion introduced between the plates A and B in the vicinity of the holes will be in the fringe region and will tend to follow the line of force on which it was introduced.

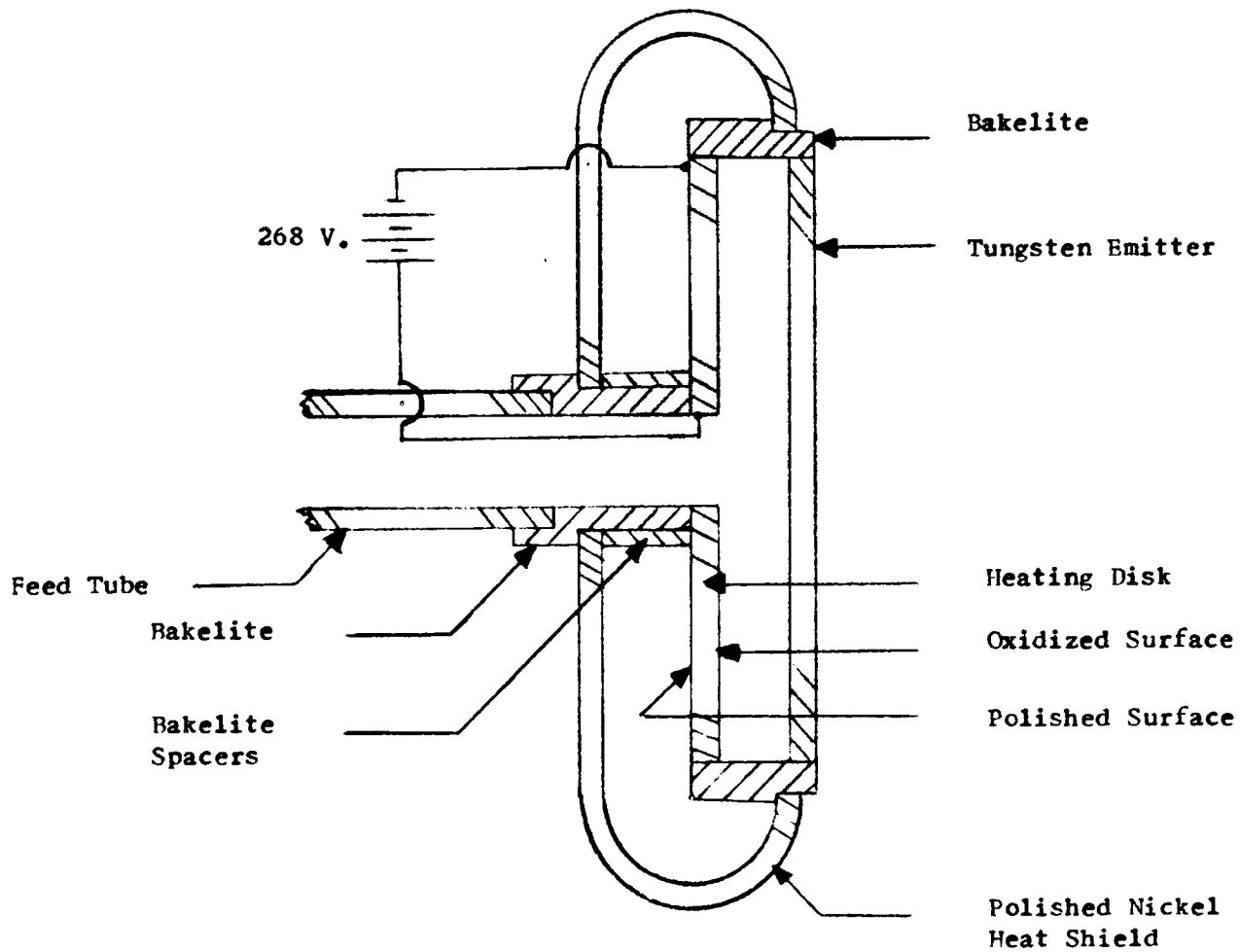


Figure 3.6 IONIZER SECTION.

If the beam is not neutralized in the plane of plate B, ions will diverge due to the curvature of the lines of force. The requirement of completely neutralizing the beam in the plane of plate B creates a complex problem if the neutralizer is to be located at a point outside of the accelerating field. The beam could easily be neutralized if the neutralizer were located between the plates; however, the accelerating length would be reduced and the thrust loss would be greater than if the beam were to diverge.¹³

As stated in the theory, there are many elaborate methods by which the beam can be focused but a simple method will be used in this design. The method decided upon is a modified "Pierce Gun."¹³ (Figure 3.7)

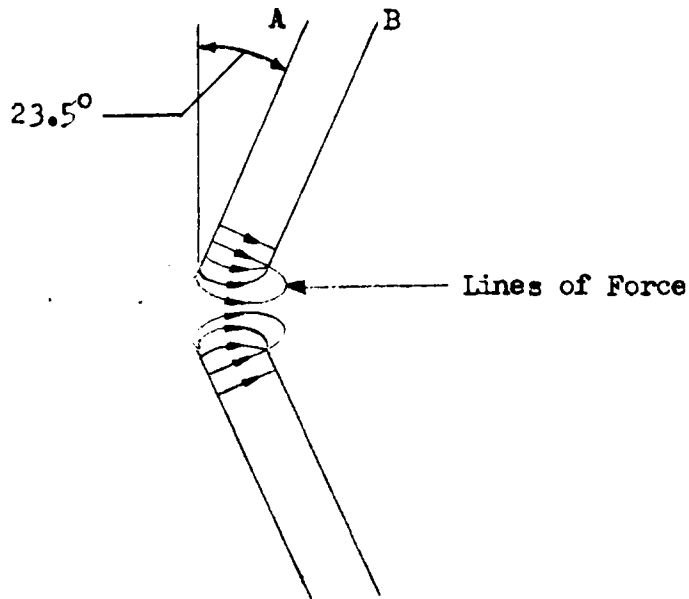


Fig. 3.7

Modified "Pierce Gun"

The modified "Pierce Gun" is used because it is one of the simplest devices that can do an acceptable job of beam focusing. The divergence angle of the beam is unknown to the author but it can be seen from figure 3.7 that the lines of force extend further from the hole before they round off than they do on parallel plates. The problem of neutralization is, therefore, simplified.

Figure 3.8 is a more complete diagram of the accelerating plates. The adjusting screws allow the plate spacing to be varied so the effect of plate spacing on thrust can be determined. The outer diameter of the plates was arbitrarily selected. Unless the outer diameter is of the order of magnitude of the plate separation, the magnitude of the diameter will not effect the fringe region. The bakelite sections are for electrical insulation.

3.4 Neutralizer

As stated in the theory, neutralization can be accomplished by thermionic emission. The equation for the emitted current during thermionic emission is:⁵

$$j = A_0 T^2 \exp \left\{ -\frac{e}{kT} \left[\phi - \left(\frac{eE}{4\pi\epsilon_0} \right)^{1/2} \right] \right\} \quad (3.21)$$

Where the terms are as defined in section 2.3.

The total electron current needed to neutralize the beam is equal to the ion current of the beam. For this design,

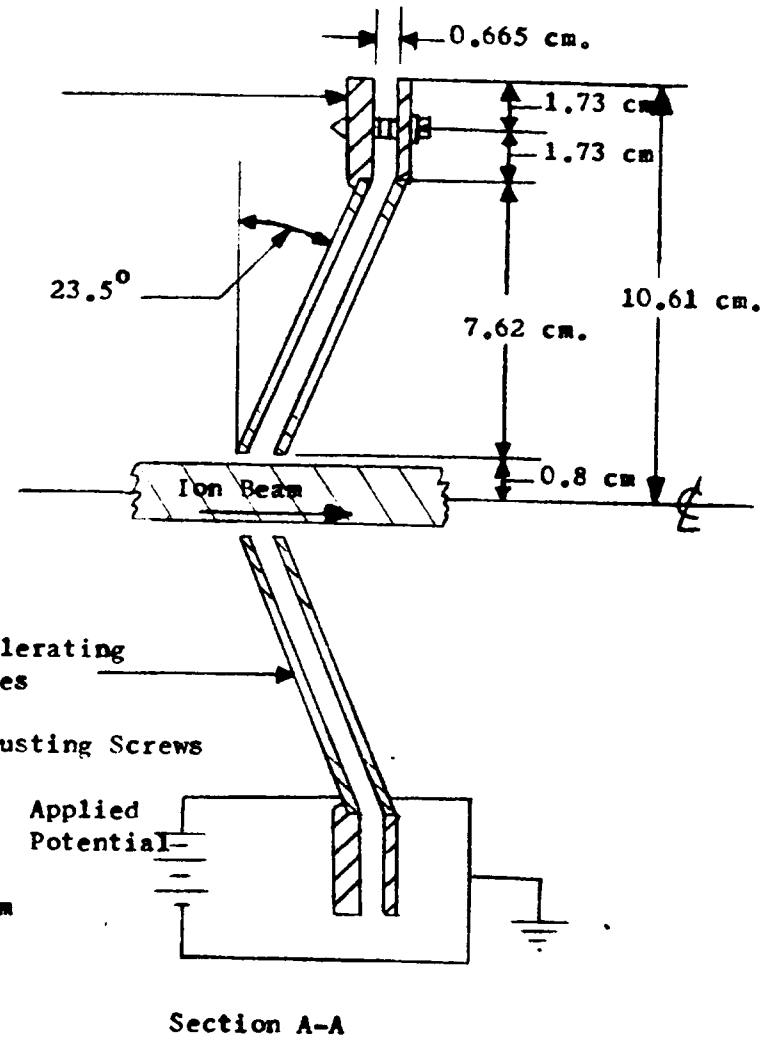
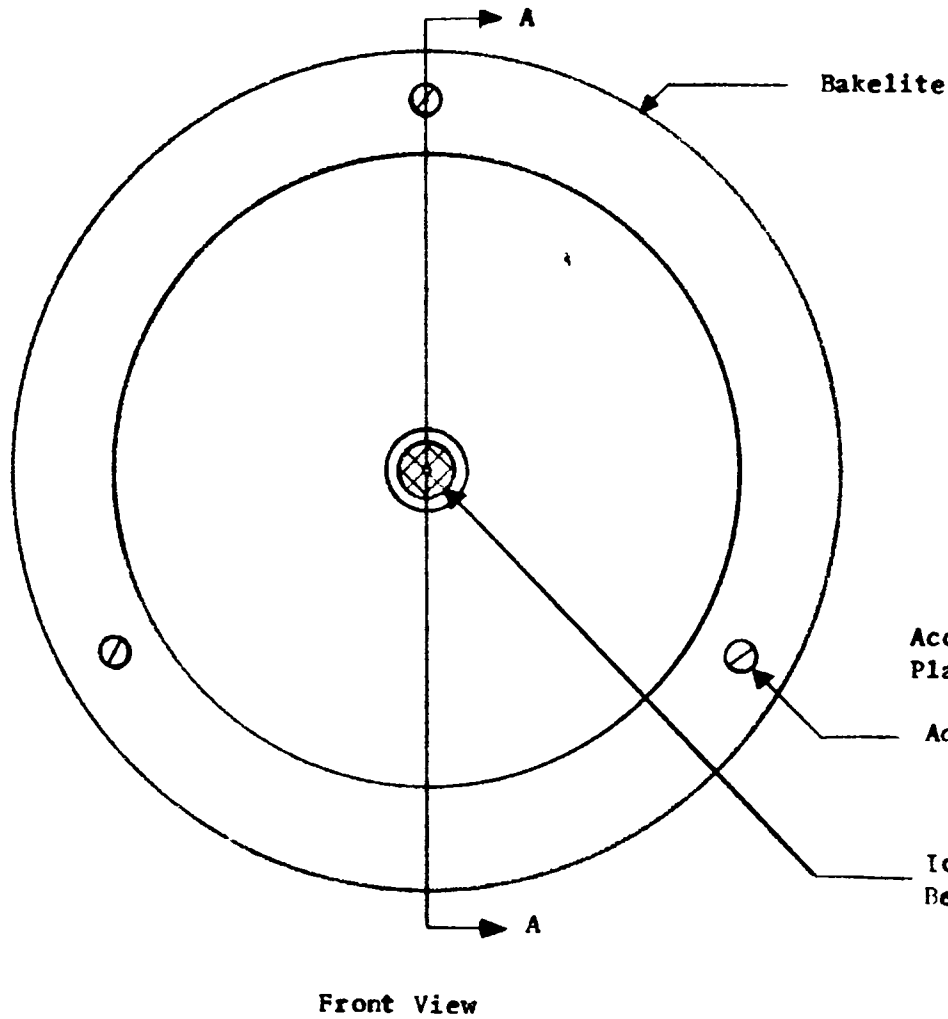


Figure 3.8 ACCELERATING PLATES

the required neutralization current is 0.137 amps. The configuration of the neutralizer is shown in figure 3.9. The radius of the emitter circle is 0.8 cm. Tungsten was selected for the emitter because of its relatively low work function (4.04 volts) and its high melting point. If the beam is assumed to be a solid cylinder with a uniformly distributed charge, an approximation for \mathcal{E} , the electron accelerating field, can be obtained from the following equation:

$$\mathcal{E} = \frac{1}{4\pi\epsilon_0} \frac{Q}{D^2} \quad (3.22)$$

Where: Q is the charge of the segment of the beam within the region determined by the neutralizing emitter.

D is the distance from the beam to the emitter. Once \mathcal{E} is calculated, the emitter temperature T can be calculated by substituting the appropriate values of the variables into equation 3.21 and solving for T .

$$T = 1800^\circ\text{K} = 3240^\circ\text{R}.$$

The rate of heat transfer from the inner surface of the emitter can be calculated from equation 3.9. Assuming the beam temperature is 1140°R .

$$q = 185 \text{ Btu/hr.}$$

This heat flow is the same as the required heat flow from the heater to the emitter. If the distance between the

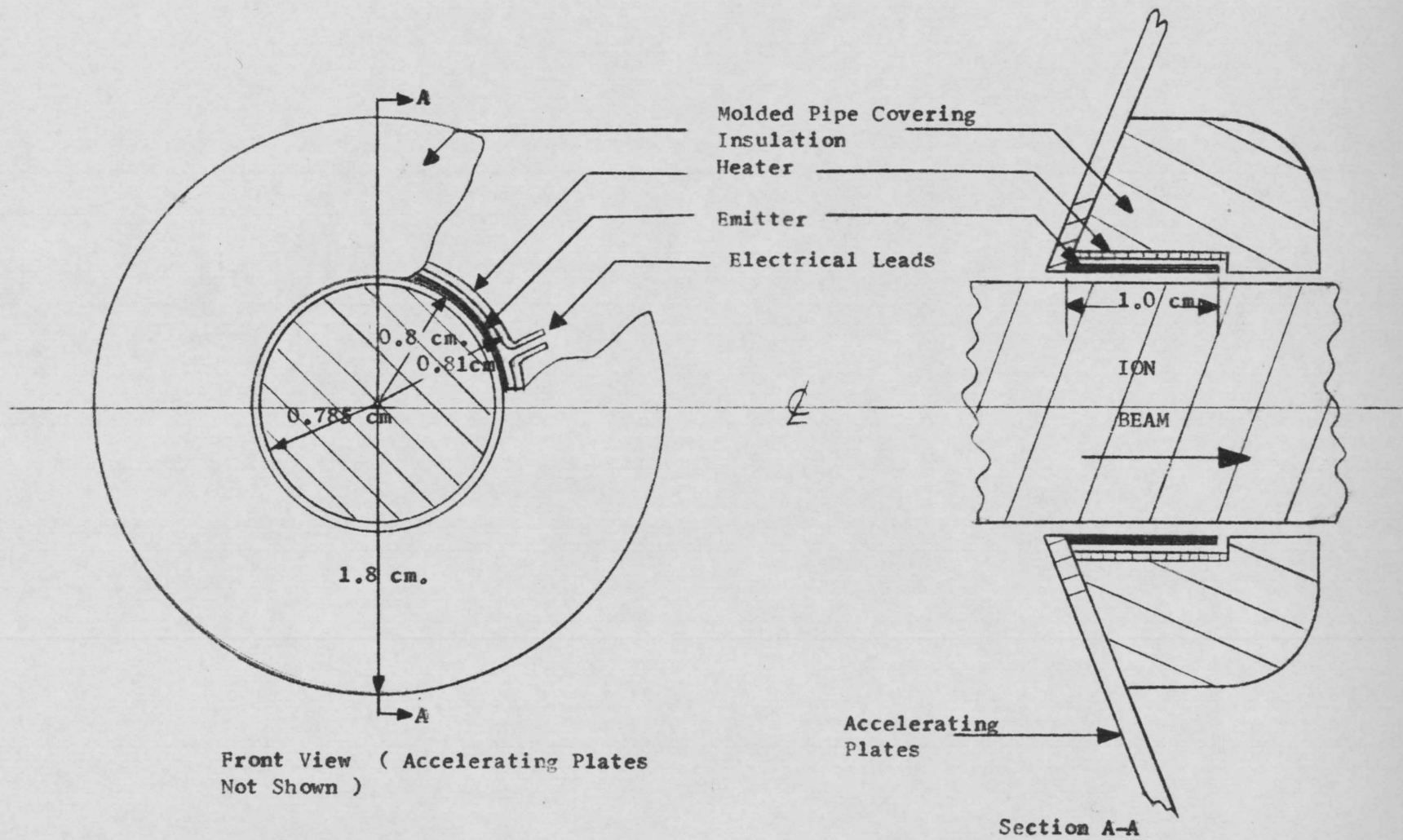


Figure 3.9 NEUTRALIZER ASSEMBLY

emitter and the heater is small in comparison to the radius of curvature of both, equation 3.12 will apply. The equation can be solved for T yielding:

$$T_{\text{Heater}} = 4100^{\circ}\text{R}$$

If the heater is insulated as shown in figure 3.9 and one dimensional heat flow is assumed for simplicity, the rate of heat flow through the insulation can be approximated by:

$$q = \frac{A k}{L} \Delta T$$

If k for molded covering is 0.088 Btu/hr. ft. $^{\circ}$ F, the heat flow is:

$$q = 10.7 \text{ Btu/hr.}$$

Summing the heat flows from both surfaces of the heater:

$$q = 195.7 \text{ Btu/hr.}$$

Converting to watts:

$$q = 56 \text{ watts}$$

Substituting appropriate values for the heater into equation 3.19, the resistance of the heater can be found. The thickness of the heater was arbitrarily selected as 1mm.

$$R = 4950 \text{ ohms}$$

Applying equation 3.17,

$$I = 0.106 \text{ amps.}$$

Placing the values of R and I into equation 3.18,

$$V = 525 \text{ volts}$$

Therefore, if 525 volts are applied to the heater, a heater

temperature of 4100°R will result which will heat the emitter to 3240°R . At 3240°R the emitter will emit 0.137 amps of electron current which is sufficient to neutralize the ion beam.

3.5 Conclusions and Recommendations

A complete diagram of the ion engine designed in this thesis is shown in figure 3.10. Table 3.1 represents the specifications of the design in tabular form. It should be noted that in this design many simplifying assumptions have been made. As a result, the design obtained is only preliminary. It is recommended that if such an engine be built, operational plots be made, relating the variations in thrust with the variations in such quantities as: feed pressure, ion emitter temperature, accelerating voltage, accelerator plate spacing, and electron emitter temperature. The thrust can be measured by the use of a hot wire anemometer (the method of measuring the thrust with a hot wire anemometer is given in ref. 18), and the other variables can be measured by a system of ammeters, thermocouples and a voltmeter. The actual integration of the system of measuring equipment into the design will be left to the builder since his objectives will no doubt be different than those of the author.

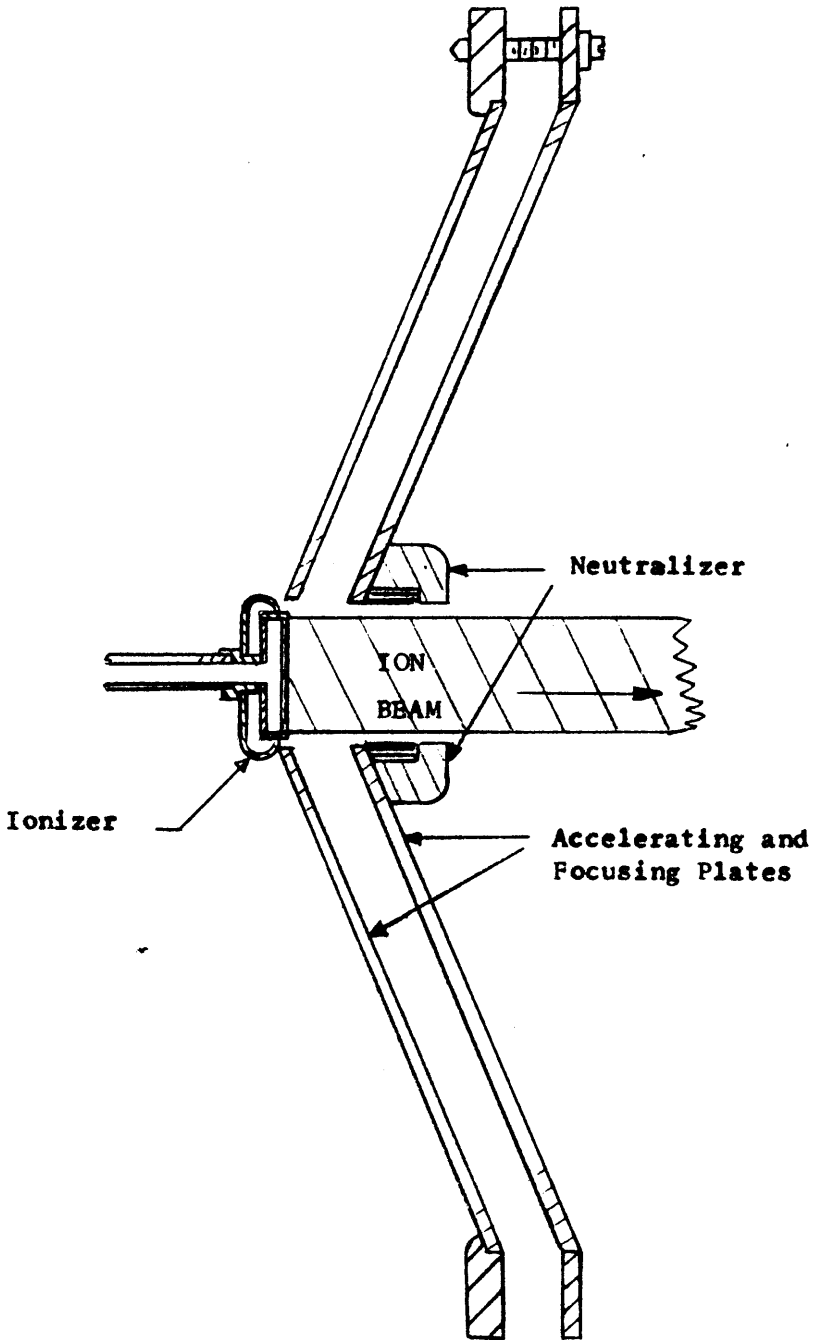


Figure 3.10 ION ENGINE SECTION

TABLE 3.1

Summary of Design Specifications

<u>Ionizer</u>	<u>Accelerator</u>	<u>Neutralizer</u>
<u>Emitter:</u> Material - Porous Tungsten Thickness - 0.0381 cm. Radius - 0.715 cm. Temperature - 1200°K. Pore Radius - 0.0001cm.	Material - Iron Plate Spacing - 0.665 cm. Inner Radius - 0.800 cm. Outer Radius - 7.62 cm. Conical Angle - 66.5°	<u>Emitter:</u> Material - Tungsten Thickness - 0.1 cm. Width - 1.0 cm. Radius - 0.8 cm. Temperature - 1800°K.
<u>Heater:</u> Material - Iron Thickness - 0.381 cm. Inner Radius - 0.318 cm. Outer Radius - 0.715 cm. Temperature - 1665°K.		<u>Heater:</u> Material - Tungsten Thickness - 0.1 cm. Width - 1.0 cm. Radius - 0.81 cm. Temperature - 2280°K.
<u>Heat Shield:</u> Material - Nickel Inner Radius - 0.318 cm. Outer Radius - 0.874 cm.		<u>Insulation:</u> Material - Molded pipe covering
<u>Feed Tube:</u> Material - Steel Inner Diameter - 0.636 cm.		

Electrical Specifications

<u>Ionizer</u>	<u>Accelerator</u>	<u>Neutralizer</u>
<u>Heater:</u> Power - 5.74 watts Current - 0.675 amps. Resistance - 1,260 ohms Voltage - 85 volts	Voltage - 40,000 volts	<u>Heater:</u> Power - 56 watts Current - 0.106 amps Resistance - 4950 ohms Voltage - 525 volts

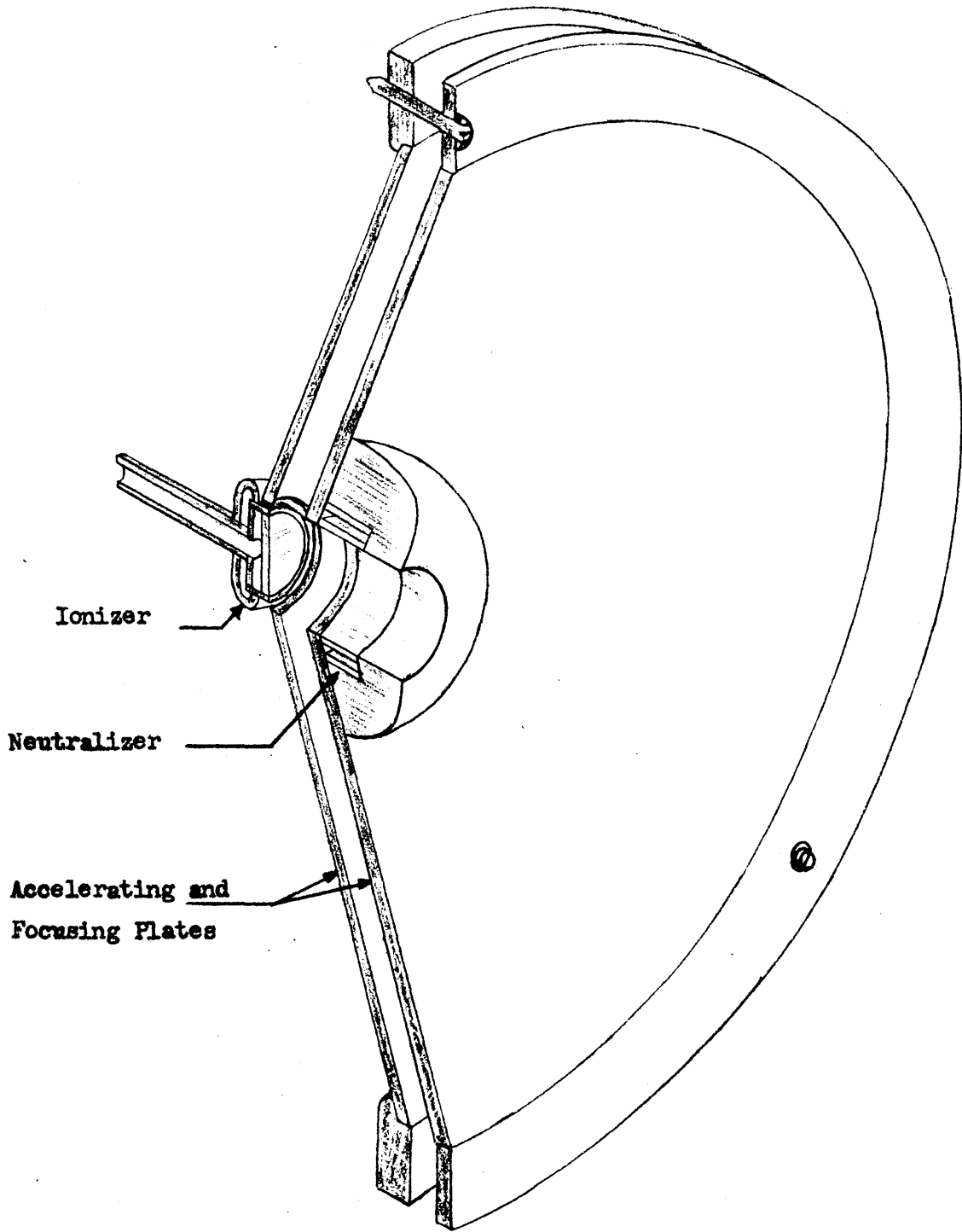


Figure 3.11 ION ENGINE CUT AWAY

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