ELECTRICAL PROPULSION SYSTEM FOR SPACE SHIPS

WITH NUCLEAR POWER SOURCE

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PART I

Theoretical Considerations

1) Introduction

An interplanetary voyage between an artificial earth satellite and a satellite orbit around Mars is possible with techniques available today[1). A propulsion system as known from earthbound rockets, using the chemical reaction between a fuel and an oxidizer as energy source, would be sufficient to power the space ship. However, all chemically propelled rocket vehicles have by necessity a very high initial mass as compared to their payload. A ship capable of traveling from an earth satellite to Mars and back to the earth satellite with a payload of 25 tons requires an initial mass of the order of 3500 tons. A reduction of this high take-off mass is possible only if the exhaust velocity of the propellant is considerably increased.

Higher exhaust velocities, and, consequently, lower take-off masses, can be obtained if the propellant particles are accelerated by electrical fields instead of chemical combustion[2). A study of the principle features of an electrical propulsion system and of the application of such a system to interplanetary space ships was published in an earlier report[3). In that study, solar energy and steam-electric turbogenerators were chosen to produce electric power.

In the present study, the principles of electric propulsion systems are investigated further, particularly in view of optimum dimensioning of initial mass, total power, and driving voltage. In addition to the general requirement of low initial mass, a further requirement has been introduced in the form of a lower limit to the initial acceleration of the ship. This requirement appears necessary in order to facilitate capturing maneuvers into the Mars and earth satellite orbits. Design data for a space ship with 150 tons payload and 2 years total travel time, based on this optimization study, are presented. In space ships of this magnitude, a nuclear power reactor as primary energy source appears somewhat lighter than a solar generator with the same power output.

2) Summary

A propulsion system for space ships is described which produces thrust by expelling ions and electrons instead of combustion gases. Equations are derived for the optimum mass ratio, power, and driving voltage of a ship with given payload, travel time, and initial acceleration. A nuclear reactor provides the primary power for a turbo-electric generator; the electric power then accelerates the ions. Cesium is the best propellant available because of its high atomic mass and its low ionization energy. A space ship with 150 tons payload and an initial acceleration of 0.67×10^{-4} G, traveling to Mars and back in a total travel time of about 2 years, would have a take-off mass of 730 tons.

List of Symbols

CGS-units are to be used in all formulae of this paper with the exception of voltages and currents, where volts and amperes should be used.

α = specific power of power plant, erg sec^{-1} g^{-1}

a_f = final acceleration, cm sec^{-2}

a_i = initial acceleration, cm sec^{-2}

c = velocity of light, cm sec^{-1}

E = energy, erg

h = Planck's constant

i = current density, amp cm^{-2}

I = total ion current, amp

L = total power for acceleration of ions, erg sec^{-1}

μ = ionic mass, g

e = electric charge of ion, amp sec

M_o = total initial mass, g

M_F = propellant mass, g

M_L = total payload, g

M_P = total mass of power plant, g

ν = frequency of photonic radiation, sec^{-1}

τ = total time of propulsion, sec

Th = total thrust, g cm sec^{-2}

U = voltage, volts

V_{ex} = exhaust velocity of ions, cm sec^{-1}

x = distance, cm

3) General Comparison between Chemical and Electrical Propulsion Systems

One significant difference between electrically propelled ships and ships with chemical combustion engines is that electrical ships require a special power source to provide power for ion acceleration. Since an electrical propulsion system develops only a relatively small thrust, the system will stay in operation during the whole flight. At first, the thrust accelerates the ship. At a proper time, the thrust unit reverses its direction and decelerates the ship down to the velocity adequate for the capturing maneuver in the planetary orbit. The most convenient figure to characterize an electrical propulsion system is, therefore, not the cut-off velocity, but the acceleration of the ship. This acceleration increases linearly with time since the propellant mass decreases at a constant rate.

For a general appraisal of the capabilities of an electric propulsion system, as compared to a chemical system, it is convenient to introduce the "specific thrust" of the system, defined as the thrust per unit power, and measured in dynes erg^{-1} sec, or kg thrust per kw power. This magnitude indicates how much power the generator must deliver into the jet in order to produce a given thrust. From the specific thrust the acceleration of the ship can be found if the values for propellant mass, mass of power plant and structures, payload, and specific power of the power plant (in kw power per kg mass) are known.

An expression for the specific thrust, Th/L, may be derived in the following way:

The total kinetic energy contained in the jet is

$$E = \frac{1}{2} M_F V_{ex}^2 \qquad (1)$$

The power associated with this energy is

$$L = \frac{1}{2\tau} M_F V_{ex}^2 \qquad (2)$$

and the thrust

$$Th = \frac{1}{\tau} M_F^{\tau} V_{ex} \tag{3}$$

The specific thrust is therefore

$$\frac{Th}{L} = \frac{2}{V_{ex}} \tag{4}$$

TABLE I

Comparison of Various Propulsion Systems

Propulsion System	Specific Thrust kg / kw	Total Initial Mass / Dry Mass	Total Initial Mass / Payload	Initial Acceleration G
Chemical	7.15×10^{-2}	70	140	5×10^{-2}
Electric I	1.47×10^{-3}	1.2	6.0	0.4×10^{-4}
Electric II	2.35×10^{-3}	2.0	4.85	0.67×10^{-4}
Photonic	3.33×10^{-7}	1.0	2.0	0.8×10^{-8}

It has been pointed out that a propulsion system could be built which ejects photons instead of material particles [4]. Assuming photons as a propellant, we find

$$E = \sum_N h \nu_N$$

and

$$L = \sum_N \frac{h\nu_N}{\tau}$$

The momentum of a photon is

$$\rho = \frac{h\nu}{c}$$

and therefore the thrust exercised by a flow of photons

$$Th = \frac{d}{dt} \sum_N \rho_N = \sum_N \frac{h\nu}{c\tau}$$

The specific thrust becomes herewith

$$\frac{Th}{L} = \frac{1}{c} \tag{5}$$

Table I contains the specific thrust, the ratio of total mass to dry mass, the ratio of total mass to payload, and the initial acceleration for space ships with four different propulsion systems: a chemical system using nitric acid and hydrazine; an electric system as proposed in Reference 3); an optimized electric system as proposed in this report; and a system in which the propellant consists of photons instead of mass particles.

The table shows that electrically propelled space ships have mass ratios and initial accelerations which are not unreasonable. Photonic propulsion systems, however, do not appear promising as long as photons must be reduced by one of the power generating systems known today, for example, a heat-producing nuclear reactor. Only if an entirely new process should be discovered which transforms mass directly into radiating energy other than through temperature radiation, a photonic propulsion system would become competitive. Even then, the photons should have such a wavelength that they can be bundled and directed by reflecting surfaces. Photons in the range of X-rays and gamma rays could be used only with a low utilization factor.

4) Deviation of Equations for Optimized Design Parameters

The initial acceleration of a space ship is a function of the thrust and the initial mass:

$$a_i = \frac{Th}{M_o} \tag{6}$$

Introducing Eqs. (2) and (3) into Eq. (6), we obtain

$$Th = \sqrt{2\ M_F\ L\ /\ \tau} \tag{7}$$

and

$$a_i = \frac{1}{M_o} \sqrt{2\ M_F\ L\ /\ \tau} \tag{8}$$

The total initial mass of the ship is equal to the sum of propellant mass M_F, payload M_L, and mass of power plant, structures, and ion thrust chambers, M_P:

$$M_o = M_F + M_L + M_P \tag{9}$$

Assuming that all component masses of the power plant mass M_P are proportional to the power L of the propulsion system*), we may define a "specific power" α of the power plant

$$\alpha = \frac{L}{M_P} \tag{10}$$

This figure is assumed to be a constant for a given type of power plant, for example, a power plant consisting of a nuclear reactor and a turbo-generator. Eqs. (9) and (10), when introduced into Eq. (8) yield

$$a_i = \frac{\sqrt{2\ M_F\ L/\tau}}{M_F + M_L + L/\alpha} \tag{11}$$

Eq. (11) implies that an optimum propellant mass $M_{F\ opt}$ exists for which the initial acceleration a_i is a maximum, if the other figures in Eq. (11) are kept constant. As will be shown later, the travel time of an electric space ship from earth to Mars is of the order of one year. This time varies only slightly with the initial acceleration a_i, so that for the present purpose, the travel time τ may be considered constant. The maximum initial acceleration $a_{i\ max}$ may then be found by letting

$$0 = d\ a_i/d\ M_F$$

and solving for $M_{F\ opt}$. A short calculation yields

$$M_{Fopt} = M_L + M_P \tag{12}$$

*) This assumption is only an approximation. Actually, M_P does not increase linearly with L, but more slowly.

and, with Eq. (9),

$$M_o = 2\, M_{F opt} \tag{13}$$

Eq. (13), when entered into Eq. (8), gives a simple formula for the maximum initial acceleration obtainable by an electric space ship with optimized ratio of propellant mass to total mass:

$$a_{i\ max} = \sqrt{L/t\, M_o} \tag{14}$$

Since $M_F = \frac{1}{2} M_o$, the final acceleration a_f attained immediately before total propellant consumption is

$$a_{f\ max} = 2\, a_{i\ max} \tag{15}$$

Eq. (14) may be rewritten with Eqs. (10), (12), and (13):

$$a_{i\ max} = \sqrt{\alpha\, M_P \,/\, 2\tau\, (M_P + M_L)} \tag{16}$$

This equation indicates that the highest initial acceleration a_h obtainable with an electric space ship for either $M_L \rightarrow 0$ or $M_P \rightarrow \infty$ and therefore $M_o \rightarrow \infty$ is merely

$$a_f = \sqrt{\frac{\alpha}{2\tau}} \tag{17}$$

This highest possible initial acceleration a_h depends only upon the specific power of the power plant and the total travel time.

The propellant consumption, M_P/τ , may be expressed as a function of the voltage which is applied to accelerate the ions, and the total power contained in the jet. Since the ion current I is given by

$$I = \frac{M_F}{\tau} \cdot \frac{e}{\mu} \tag{18}$$

and since

$$L = U \cdot I \cdot 10^7 \tag{19}$$

we obtain

$$\frac{M_F}{\tau} = \frac{\mu}{e} \cdot \frac{L}{U} \cdot 10^{-7} \tag{20}$$

or

$$\frac{M_{Fopt}}{\tau} = \frac{\mu}{e} \cdot \frac{L}{U_{opt}} \cdot 10^{-7} \tag{21}$$

Introducing Eqs. (13) and (21) into (14), we obtain the maximum initial acceleration $a_{i\ max}$ as a function of the optimum voltage U_{opt}:

$$a_{i\ max} = \frac{1}{\tau} \sqrt{\frac{e}{2\mu} U_{opt} \cdot 10^7} \tag{22}$$

or

$$U_{opt} = 2\frac{\mu}{e} \tau^2 a_{i\ max}^2 \cdot 10^{-7} \tag{23}$$

Eqs. (13) and (21) yield the optimum voltage U_{opt} as a function of the total initial mass and the total power:

$$U_{opt} = 2\frac{\mu}{e} \cdot \frac{L\tau}{M_o} \cdot 10^{-7} \tag{24}$$

The current associated with the optimum voltage is given by

$$I_{opt} = \frac{L}{U_{opt}} \cdot 10^{-7} = \frac{e}{\mu} \cdot \frac{M_0}{2\tau}$$

or, with Eqs. (12), (21), and (23):

$$I_{opt} = \frac{e}{\mu} \cdot \frac{M_L}{\tau(1-2\tau a_i{}^2{}_{max}/\alpha)} \tag{25}$$

The total power contained in the jet is found from Eqs. (12), (21), and (23)

$$L = \frac{M_L}{1/2\,\tau a_i^2{}_{max} - 1/\alpha} \tag{26}$$

and the total initial mass from Eqs. (12), (13), and (26):

$$M_0 = \frac{M_L}{1/2 - \tau a_i^2{}_{max}/\alpha} \tag{27}$$

This equation gives the lowest possible take-off mass M_0 of an electric space ship when payload M_L, the total travel ~~time~~ τ, specific power α, and the desired initial acceleration a_i are given.

5) Basic Design Considerations

The design of a space ship will begin with basic assumptions regarding the payload M_L, the specific mass of the ions μ/e, the total travel time τ, the specific power α of the power generating plant, and the initial acceleration a_i as required by navigational considerations.

The payload M_L includes the crew members and their personal equipment, the living quarters, and the equipment needed for the exploration of Mars' surface, such as landing crafts, ground vehicles, etc. An expedition to Mars will consist of several space ships, and the total landing equipment will be distributed among them. Some of the ships will be cargo ships which carry propellant for the one-way trip only. The passenger ships will carry a total payload of about 150 tons each; the cargo ships, 300 tons each.

The propellant material must be selected so that it can be ionized easily. Furthermore, its atomic mass μ should be large in order to make driving voltage U_{opt} large (Eq. (23)). The latter is necessary because of space charge effects in the ion thrust chambers (see par. 13). Two different propellants, Rubidium and Cesium, will be considered in this study. Cesium is superior to Rubidium, but Rubidium is more easily obtainable in large quantities than Cesium.

The travel time for an interplanetary voyage, for example from earth to Mars and back, depends only little upon the details of the propulsion system. A chemically propelled ship will enter after a short period of propulsion into an elliptical trajectory around the sun with its perigee in the earth's path and its apogee in Mars' path. During most of its travel time, it will coast on this ellipse. The voyage from earth to Mars will last 260 days [1]. An electrically propelled ship with its low acceleration must spiral around the earth for some time until it has sufficient speed to detach from the earth's gravity field. Having entered into an ellipse around the sun, it will continue to gain speed. Its trajectory will, therefore not be elliptical, but will stretch out into a wide spiral around the sun. This portion of the ship's voyage will be shorter than the corresponding portion of a chemically driven ship's voyage. At a predetermined point between earth and Mars, the ship will reverse the direction of its thrust chamber and begin to decelerate. When it is close enough to Mars, it will enter into a narrow spiral around the planet and descend to the desired orbital altitude. The travel time of an electrical ship from earth to Mars as described in this study will be of the order of one year, depending only slightly upon the initial acceleration a_i. Total travel time for the round trip will be a little less than twice as long.

The specific power of the power source α should be as high as possible (Eqs. (11), (17), (26), and (27)). Its magnitude depends upon the method of power generation, upon safety factors, and upon the skill of the designer. The masses of power plant, structural members, and ion thrust chambers are combined in the power plant mass M_P. It will be shown in paragraph 15 that for a nuclear power source as proposed in this study, a specific power of the order of 0.1 kw per kg mass may be expected.

The initial acceleration of the ship, a_i, should be large to facilitate capture maneuvers in the Mars satellite orbit. The ship must be able to execute velocity corrections within a sufficiently short time. It is assumed that an acceleration of 0.1 cm sec^{-2} or approximately 10^{-4} G near the Martian orbit is adequate for safe capture procedures into an orbit around Mars. A velocity change of plus or minus 85 m sec^{-1} per day would be possible with this acceleration. The initial acceleration a_i would then be 0.067 cm sec^{-2}, the final acceleration a_f upon return into the earth satellite orbit, 0.133 cm sec^{-2} (Eq. (15)). If part of the payload is detached in the Martian orbit, the acceleration on the way home will even be greater.

The total take-off mass of a space ship, expressed as a multiple of the payload, M_o/M_L, is plotted in Fig. 1 as a function of the initial acceleration a_i (Eq. (27)). Parameters are specific power α and total travel time τ .

The total power necessary for the jet, L, expressed as the ratio L/M_L, is plotted in Fig. 2 as a function of the initial acceleration a_i (Eq. (26)). Parameters are again specific power α and total travel time τ .

The optimum voltage U_{opt} is plotted in Fig. 3 as a function of the initial acceleration a_i (Eq. (23)), with the ionic mass μ and the total travel time τ as parameters.

The principle design data for a space ship may be taken from these diagrams. One representative example of a space ship will be described in the next paragraphs. Its data are marked with circles in Fig. 1, 2, and 3.

Part II - Design Features of an Electrically Propelled Space Ship

6) General Remarks

An electrically propelled space ship needs a power-generating plant to provide the electric power for the ion current. The primary energy source may be the sun as described in an earlier report[3], or a nuclear reactor as studied in this report. In either case, a thermodynamic heat cycle is used to transform the heat energy of the source into mechanical energy, and electric generators to transform the mechanical energy into electrical energy. The overall efficiency of such a system is of the order of 10 to 20 percent. All other methods to transform heat into electrical energy which are available would yield a considerably smaller output power for the same total mass.

A block diagram of the entire propulsion system is shown in Fig. 4. It begins with a nuclear reactor which produces heat power. A radiation shield keeps gamma-rays and neutrons away from the rest of the ship. The heat from the reactor is transferred by a suitable coolant to a heat exchanger which acts as a boiler for the working fluid. The steam from the boiler drives a turbine and is then condensed in a radiation cooler. After condensation, the working fluid is pumped back into the boiler. The turbine is directly coupled with the generator. The generator, which is cooled by a separate cooling system, provides electric power to the thrust chambers. The propellant is kept in the storage tank at such a temperature that its vapor pressure is high enough to feed vaporized propellant at the correct rate into the chambers. After ionization, ions and electrons are accelerated in the thrust chambers by electric fields and expelled at equal rates.

The propulsion system should be as light as possible. It must work reliably and without maintenance over a period of at least 2 years.

All pipes and containers connected with the reactor cooling system, with the working fluid system, and with the generator cooling system must be absolutely leakproof. This condition can be fulfilled only if each of these three systems is completely sealed, with no bearings and sliding surfaces communicating with the outside.

7) Nuclear Reactor

The design of nuclear reactors and associated equipment has been treated in recent publications with remarkable detail[5]. It appears possible to lay out, on the basis of published data, a nuclear propulsion system at least to such an accuracy that a fairly reliable estimate of mass, size, and performance data of a system for a required power output can be made. The design chosen in this study is by no means the only one possible. Components and methods have been selected mainly with regard to low mass, simplicity, and long-time operation capabilities.

The total power output of the reactor is tentatively assumed to be 100 megawatts. Reasonable figures are then chosen for the temperatures of reactor coolant and working fluid and for the efficiencies of turbine and generator. With these assumptions, the dimensions and masses of the various components of the power generating system can be estimated. The result of this estimation is the "specific power" α of the system, measured in erg sec^{-1} g^{-1}, or in kw per kg. This figure is then used to calculate the total mass M_o and the total power L for a ship for which payload M_L, initial acceleration a_1, and total travel time τ are given (Eqs. (26) and (27)).

The reactor chosen in this design is a homogeneous, fast neutron reactor consisting of natural uranium with its U-235 content enriched to about 1.7%. No moderator or reflector is necessary. The heat energy is removed by a system of molybdenum pipes through which NaK alloy is pumped. Molybdenum has a high melting point, high heat conductivity, and a relatively small neutron absorption cross section. It is essential that the mechanical contact between the uranium metal and the molybdenum pipes be as perfect as possible to facilitate the heat transfer between the uranium and the cooling system, and to avoid points of high temperature within the reactor. NaK is liquid from + 19°C on; no preheating will, therefore be necessary before the power plant can start to operate. The boiling temperature of NaK at atmospheric pressure is 820° C. NaK is non-corrosive against molybdenum. Since it is a metallic alloy, it can be pumped very conveniently by an electromagnetic pump without any moving parts. NaK has a comparatively high heat conductivity, high heat capacity, and low neutron absorption cross section.

The heat power that can be removed from a uranium reactor by such a cooling system is of the order of 260 watts per cm^3. This figure determines the size and mass of the reactor. The reactor shape should be as close to a sphere as possible to minimize the surface through which neutrons can escape. Also, it should be such that little shielding area as possible is required. Fig. 5 shows the proposed design. The reactor is surrounded by a cooling jacket in addition to the cooling pipes in its interior. The control rods consist of boron encased in molybdenum tubes. Their positions within the reactor are servo-controlled. The power level at which the reactor operates as well as its temperature are determined only by the position of the control rods and by the amount of heat power removed by the coolant. Although the control of a fast neutron reactor is more difficult than that of a slow neutron reactor, a fast reactor has been suggested in this study because it can be built lighter and smaller (i.e., with less shielding area) than a slow reactor.

If the total power to be delivered by the reactor is 100 megawatts, the required uranium volume is 0.4 m^3. To be conservative, this volume is increased to 0.6 m^3. Its mass is about 12 tons. During an operating time of 2 years, a total amount of about 76 kg of uranium, both U-235 and U-238 will be burned*). The temperature within the reactor will be of the order of 1100° C. The NaK enters the reactor at a temperature of about 500° C and leaves it with about 800° C. The reactor contains 600 cooling pipes, each with an inner diameter of 1.8 cm and a length of 1 m. About 300 kg of NaK per second will flow through the reactor with a velocity of 2.7 m sec^{-1}.

8) Radiation Shield

A reactor of the present type, working on a power level of 100 megawatts, produces about 7.5×10^{18} neutrons per second and about 1.5×10^{19}

*) U-235 is split preferably by slow neutrons; U-238 is split only by fast neutrons above 1 MeV energy.

gamma rays per second. Although the larger part of them is absorbed within the reactor itself, the working nuclear reactor is an extremely strong radiation source which must be shielded from the rest of the ship. Gamma ray attenuation depends only on the total mass per cm^2 inserted in the path of the rays, independent of the atomic number. Neutrons must be slowed down at first by an element of low atomic number; subsequently, they can be absorbed by an element with large cross section for slow neutrons. In the present design, a radiation shield of metallic beryllium is proposed. With a thickness of 180 cm, it absorbs enough of the gamma rays. At the same time, it slows down the fast neutrons so that they can be absorbed by a thin layer of boron. In addition to radiation protection by shielding, attenuation of the radiation density is also obtained by removing the reactor as far as practicable from the sensitive parts of the ship. Both the gamma rays and the neutrons obey the inverse square law of attenuation. Also, with a larger distance between the reactor and the rest of the ship, the necessary area of the radiation shield becomes smaller. The total mass of a radiation shield as illustrated in Fig. 5 is about 30 tons. It reduces the radiation intensities of a 100 megawatt reactor at the place of the living quarters to about 10 fast neutrons per second per cm^2, and about 100 gamma rays per second per cm^2. These values are permissible according to AEC standards.

9) <u>Heat Exchanger</u>

The NaK coolant becomes radioactive when it flows through the working reactor. A heat exchanger is therefore applied in which the NaK transfers its heat to a working fluid suitable for operation of a steam turbine. The working fluid will not become radioactive since it is not exposed to the strong neutron radiation. There are 3000 tubes in the heat exchanger with a total length of 1800 m and an inner diameter of 1.3 cm. The backflowing coolant is pumped by an electromagnetic pump which works on the principle of a d-c electromotor, the NaK simply substituting the armature. To produce a flow of 300 kg NaK per second, the pump consumes about 100 kw of electric power.

10) <u>Working Fluid and Turbine</u>

The working fluid must have its boiling point in the proper temperature range. In the present proposal, a vapor pressure of about 20 atmospheres has been assumed at a temperature of 600 C. The fluid must still be liquid at a temperature of the order of 10° C, because otherwise the power plant could not be started in space without preheating equipment. Furthermore, the working fluid must be noncorrosive against container walls and also against the interior of the generator with which the vapor will communicate. It is very desirable that the working fluid have lubricating properties for the bearings of the turbine, the generator, and the feed pumps. The best choice for the working fluid will probably be one of the silicone oils. The steam drives a low pressure, multi-stage turbine with a high expansion ratio. After leaving the turbine, the steam condenses in a disk-shaped condenser which dissipates its heat by radiation. After condensation, the working fluid is pumped back to the heat exchanger by completely sealed, motor-driven pumps. Assuming a working fluid with a specific heat of about 0.4 cal per g per deg C, a heat of vaporization of 100 cal per g, a density of 1 g per cm^3, and a condenser temperature of 280° C, about 100 kg per sec must flow through the turbine. The feed pumps will consume a total power of about 200 kw. The total amount of working fluid within heat exchanger, pipes, turbine, condenser, and pumps will be about 8 tons.

11) <u>Condenser</u>

The temperature of the steam should be as high as possible to make the thermodynamic efficiency high. The outlet temperature of the turbine, which is equal to the condenser temperature, should be as low as possible for the same reason. However, a low condenser temperature means a large condenser and therefore a large total mass for the power plant. It has been shown in the above cited report that for each steam temperature there exists an optimum condenser temperature which makes the total mass of the power plant a minimum. In the present study, the condenser temperature is assumed to be 280°C. The steam pressure at this temperature should be not larger than about 0.1 atmospheres so that the condenser walls can be thin. The orientation of the ship in space is always such that the sun's radiation does not hit the cooling areas of the condenser. Under this condition, both sides of the disk emit heat without absorbing solar radiation. The diameter of the condenser will then be about 100 m. It is constructed of titanium which has the highest stress-to-mass ratio known. Wall thickness is 0.5 mm, and thickness of the disk about 5 cm near the center and 1 cm near the rim. The whole disk is subdivided into a number of sectors, each of which has an inlet valve and an outlet valve. In case a meteor should punch through the condenser wall, the valves of the damaged sector close automatically. The hole can then be welded even though the powerplant continues to operate. All the other vulnerable parts of the space ship will be protected by a "meteor bumper," i.e., a thin sheet of metal a few cm above the surface of the parts. Such a device is very efficient in dissipating the kinetic energy of small meteors. If a larger meteor should afflict a severe damage to some part of the ship, the crew would have to abandon that ship and board one of the other ships in the fleet. It is estimated that such an accident will occur with an almost negligible probability only.

12) Generator

The generator housing forms an integral unit with the turbine housing and the rest of the steam system without any moving parts reaching the outside. To keep the generator as simple, light, and reliable as possible, a three-phase, a-c generator is chosen. Since the load for the generator is practically constant, and since the voltage need not be very constant, permanent magnets are applied to produce the generator field. An auxiliary d-c generator with commutator and slip rings for field excitation is then unnecessary. Rectification of the a-c current is achieved by sealed mercury rectifiers. The generator will be cooled by a disk-shaped oil cooler. If the generator efficiency is 94%, and if a total electric output of 20,000 kw is assumed, the cooler must dissipate by radiation an amount of 1,250 kw. For a cooler temperature of 150° C, the diameter of the disk must be about 20 m. The mass of the generator can be estimated on the basis of figures for oil-cooled aircraft generators. Assuming 2.2 kg per kw for the generator with turbine and rectifiers, the total mass of the 20,000 kw plant will be 44 tons. The cooler with coolant will have a mass of about 4 tons.

The theoretical efficiency of the turbine alone, with an inlet temperature of 600° C and an outlet temperature of 280° C, would be 37%. In this study, a real overall efficiency of turbine, generator, and rectifiers of 20% has been assumed.

13) Powerplant Assembly

Reactor, shield, heat exchanger, turbine, generator, condenser, oil cooler, and the living quarters for the crew will be arranged in axial symmetry as shown in Fig. 6. As soon as the turbine with the generator begins to turn, the rest of the ship begins to rotate in the opposite direction. According to the law of reaction, this rotation of the ship will persist as long as turbine and generator turn, irrespective of any frictional or electromagnetic forces between the ship and the rotor of the turbo-generator. The angular velocity of the ship, which is determined by the turbine speed and the ratio of the moments of inertia, is about 3 revolutions per minute. The designer of the ship can choose this angular velocity to some extent by selecting the speed and moment of inertia of the turbo-generator. The rotation of the ship is imperative for the operation of the condenser. The centrifugal force causes the condensate to separate from the steam and to accumulate at the outer edge of the disk, from where it can be pumped back to the heat exchanger. The feed pumps must be located at the outer edge of the disk. The centrifugal force will also be welcomed by the crew members in the living quarters as a substitute for gravity.

As shown in Fig. 6, the condenser will have the shape of an annulus outside the toroidal living quarters. The generator cooler is mounted in the same plane as the condenser, but inside the living quarters. The two cylindrical walls of the living quarters will have reflecting surfaces to reduce the influx of radiating heat from the cooler and condenser surfaces. The total mass of the living quarters with all equipment, including scientific instruments, food, oxygen, and crew members, is assumed to be 50 tons.

14) Ionization Chambers and Thrust Chambers

The ionization of the propellant is a major problem of an electric propulsion system, The propellant atoms must ionize easily with a method that works with high efficiency. The ionization procedure must be as simple as possible, and it must be capable of working for years without cleaning or other maintenance.

The one method of ionization which meets all of these requirements almost perfectly is the ionization of alkaline atoms at incandescent surfaces. If an alkaline atom strikes a hot platinum surface, it looses its outermost electron to the metal and bounces off as an ion. The efficiency of this ionization, i.e., the probability of an atom to become an ion upon impact with the platinum surface, is almost 100 percent. The vapor pressure of the propellant within the ionization chamber must be so low and the total platinum area so large that every atom has the chance to strike the hot surface at least once on its way through the chamber. The accelerating field for the ions is immediately adjacent to the ionization chamber. Fig. 7 shows a cross section through ion chambers, thrust chambers, and electron-emitting chambers. A more detailed description of the ionization and thrust chambers has been given in the above-cited report. Current density, thrust chamber dimensions, and accelerating voltage cannot be chosen at will. The largest current which can flow through a chamber of given cross section and length under a given voltage is determined by Schottky-Langmuir's space charge law. The same law governs also the conditions under which a jet of charged particles can leave a thrust chamber and fly out into space. In particular, it states that a continuous stream of ions can leave a chamber only if the charges of the particles are neutralized at a short distance behind the exit orifice of the chamber. If this distance is x, the accelerating voltage U, and the mass and charge of the ions μ and e, then the maximum current density i which can be maintained through the chamber is given by the equation

$$i = 1.77 \cdot 10^{-10} \sqrt{\frac{e}{\mu}} \; \frac{U^{3/2}}{x^2} \qquad (28)$$

The neutralization of the ions can be achieved by emitting electrons from electron chambers which are closely interlaced with the ion chambers. Ions and electrons will then recombine at a distance of 1 or 2 cm behind the exit orifices. Ions and electrons must be expelled at equal rates anyway in order to keep the ship electrically neutral. The contribution of the electrons to the total thrust is negligibly small due to their small mass. Their accelerating voltage will be chosen just large enough to produce the desired electron current; about 100 volts will be enough.

The main part of the electric current will flow from the ion chambers through the generator to the electron chambers. Two small auxiliary power sources, as shown in Fig. 4, are needed to maintain the correct potential differences between the rear electrodes and the ion and electron chambers. Their currents are determined only by the relatively few electrons and ions which hit the rear electrode. Their voltages are chosen so that the effective accelerating voltage, i.e., the potential differences actually passed by the ions in the ion thrust chambers and by the electrons in the electron chambers, assume the desired values. These effective potential differences are smaller than the voltages between the chambers and the rear electrodes. The power to be delivered by the main power source is given by the ion current and the effective potential differences passed by ions and electrons.

On the basis of data derived in the above cited report, the total mass of an assembly of electric thrust chambers as underlying the present study will be of the order of 45 tons. About 1,200 kw of electric power is required to heat the platinum surfaces inside the ionization chambers. Current density through the rear orifices will be about 0.8 mA cm^{-2}. Under the assumption that recombination of the electrons and ions takes place at a mean distance of 1.3 cm behind the rear electrode, the minimum driving voltage which allows a current density of 0.8 mA cm^{-2} with Cesium ions is found from Eq. (28) to be 3,900 volts. The voltage actually applied for ion acceleration must be not smaller than this minimum voltage.

15) Dynamics of Space Ship

Thrust chambers, ion chambers, and propellant storage tank are combined in one structural unit (Fig. 6). The thrust chambers must always point into a direction opposite to the foreward direction of the ship. Since the radiation coolers of the ship must always have a definite orientation with respect to the sun, the thrust chamber unit must be able to assume any direction independent of the orientation of the ship. To meet this requirement, it is sufficient to give the thrust chamber unit one rotational degree of freedom, i.e., rotation around the longitudinal axis of the ship, as indicated in Fig. 6. A small electric motor is required to compensate for frictional forces between the rotating ship and the thrust unit; the latter points always into a direction tangential to the trajectory.

The vector of the thrust force must point through the center of the ship's gravity, because otherwise a torque would be exercised on the ship in addition to the force of propulsion. This condition must be fulfilled when a payload is attached to the ship, for example, a landing craft for Mars, and it must still be met after this payload has been unloaded. For this reason, the expendable payload will be mounted to the thrust chamber unit in such a way that the payload's center of gravity coincides with the center of gravity of the ship itself.

A change of the orientation of the ship in space will be effected by two fly wheels mounted on the thrust chamber unit. If one of the fly wheels turns in one direction, the axis of the ship will turn in the opposite direction. Since these movements need not be fast, the masses of the fly wheels and the electric motors for their operation can be small. No gyroscopic effects will be noticed when the orientation of the ship is changed by means of the fly wheels because the angular momenta of the turbo-generator and of the ship are equal and opposite. However, the bearings of the turbo-generator will experience lateral forces during a change of the ship's orientation.

The ship will carry a small auxiliary power source for the time when the reactor is not in operation, particularly before take-off and during the time when the ship coasts on an unpowered orbit around Mars. Power for the living quarters, for instruments, and for the attitude control system will be needed during this time. Also, the coolant pumps and feed pumps must be operated, at least on a low power level, before the nuclear power system can be started. A total of about 50 kw may be required for these purposes. This power will be furnished by a solar generator, consisting of a large number of silicon diodes. Electric power is developed by such a generator directly from absorbed solar radiation. A set of storage batteries will provide power during the periods when solar radiation is absent. The generator is mounted in a plane vertical to the plane of the condenser; the ship will not be in rotation when the solar generator must operate. For an electric power output of 50 kw, the solar generator will have an area of about 400 m^2. Its mass will be about 2 tons.

16) <u>Masses of Propulsion System Components</u>

A list of the major components of the propulsion system as described in the previous paragraphs is given in Table II. The sizes of the various components are based on a total reactor heat power of 100 megawatts.

TABLE II

Component Masses of Powerplant for 20 Megawatt Electric Power Output

Uranium	12	tons
Radiation Shield	30	"
Heat Exchanger	1.5	"
Coolant Pump	0.2	"
Coolant (NaK)	0.5	"
Working Fluid	8	"
Pumps for Working Fluid	1.8	"
Condenser	40	"
Turbo-electric Generators & Rectifiers	44	"
Cooler for Generator with Pump & Coolant	4	"
Thrust Chambers	45	"
Auxiliary Solar Generator	2	"
Total	189.0	"

With an efficiency of the turbo-electric generator and rectifiers of 20%, a total electric power of 20,000 kw will be available. Out of this power, about 1,200 kw are needed to heat the platinum surfaces in the ion chambers. About 400 kw will be contained in the electron jet which does not contribute noticeably to the thrust. Another 400 kw is supposed to be required for coolant pumps and feed pumps, and for auxiliary equipment such as fly wheels, friction-compensating motors, air purification plant, heating and refrigerating units for the living quarters, instruments, and facilities for the crew. This leaves a total of 18,000 kw available for the jet. With a total power plant mass of 189 tons (Table II), the specific power of the powerplant will therefore be 0.095 kw per kg or 9.5 $\times 10^5$ erg sec^{-1} g^{-1}.

17) Design Data of Representative Space Ship

Column 1 in Table III contains the data which underly, as primary assumptions, the design of a representative space ship. On their basis, the design and performance data in Column 2 were calculated with the equations of Part I. These figures show that with presently known techniques a space ship for a trip to Mars and back, carrying a total payload of 150 tons, could be built with a total take-off mass of not more than 730 tons.

TABLE III

Design and Performance Data of Representative Space Ship

Column 1
Basic Assumptions

Total travel time	6.3×10^7 sec	2 years
Payload	1.5×10^8 g	150 tons
Ionic mass (Cesium)	2.2×10^{-22}g	
Specific power	0.5×10^5 erg/sec g	0.095 kw/kg
Initial acceleration	6.7×10^{-2} cm/sec^2	6.7×10^{-5} G

Column 2

Calculated Design Data

Total initial mass	7.3×10^8 g	730 tons
Propellant mass	3.65×10^8 g	365 "
Power plant mass	2.15×10^8 g	215 "
Total power production	11.45×10^{14} erg/sec	114.5 megawatt
Total electric power	2.29×10^{14} "	22.9 "
Power contained in jet	2.06×10^{14} "	20.6 "
Driving voltage	4880 volts	
Total ion current	4220 amperes	
Diameter of condenser	1.15×10^4 cm	115 meters
Total length	0.85×10^4 cm	85 "
Exhaust velocity	8.4×10^6 cm sec^{-1}	84 km per sec
Thrust	4.85×10^7 dyn	49.5 kg

F I G U R E S

R : Nuclear reactor

S : Radiation shield

HE : Heat exchanger

T : Turbine

G : Generator

C_1 : Condenser

C_2 : Cooler for generator

r_1 : Main rectifier

r_2 : Auxiliary rectifiers

r_3 : " "

I : Ion thrust chamber

E : Electron thrust chamber

L : Living quarters

Th : Thrust unit

Cs : Propellant storage tank (Cesium)

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H. Preston-Thomas, J. B. I. S. 11, 173,(1952).

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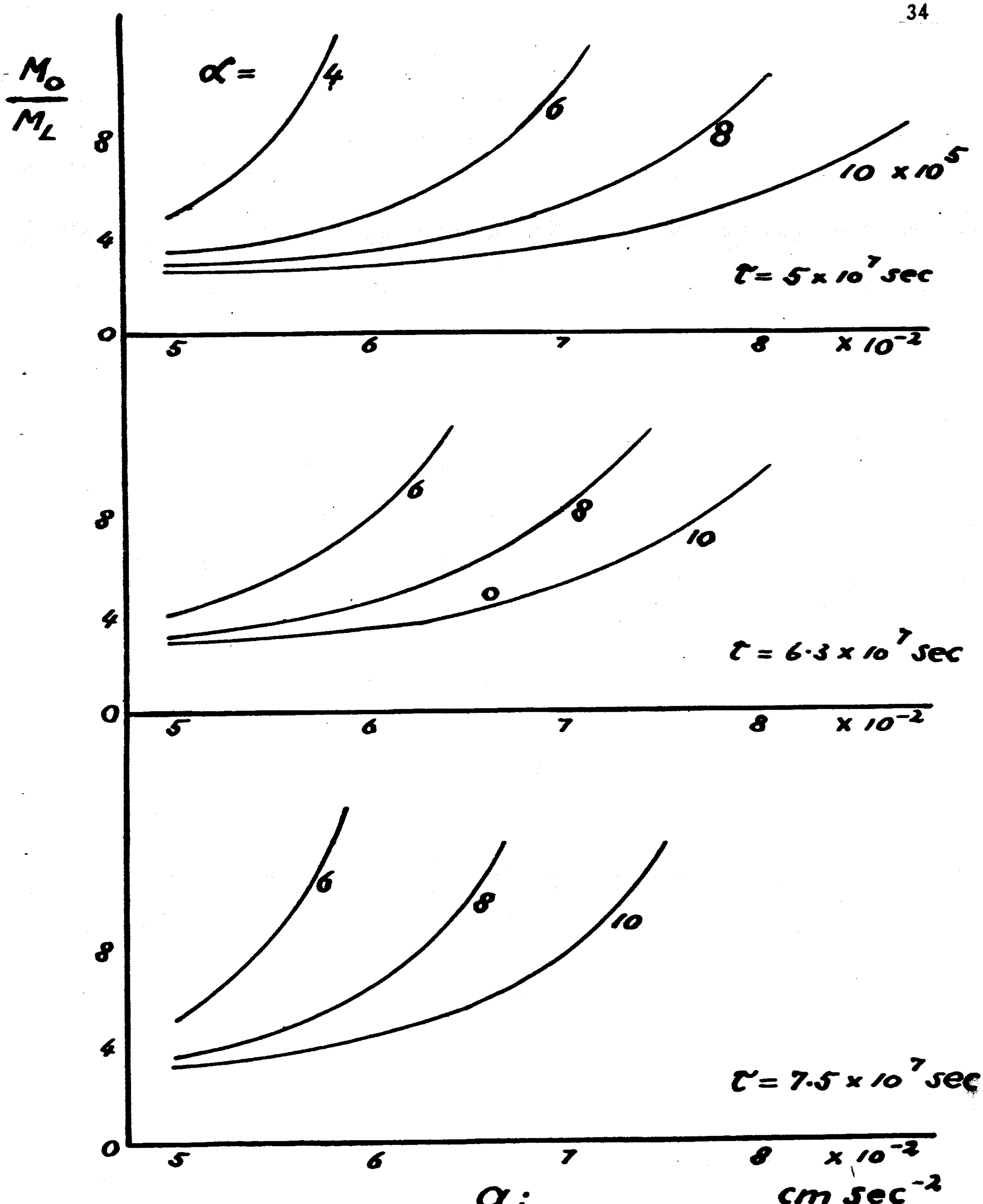
5) The calculations for this study are based on the book INTRODUCTION TO NUCLEAR ENGINEERING by R. L. Murray, Prentice Hall, Inc., N.Y. (1954)



M_o / M_L
$\alpha =$ 4
6
8
10 $\times 10^5$
8
4
$\tau = 5 \times 10^7$ sec
0
5
6
7
8
$\times 10^{-2}$
6
8
10
0
8
4
$\tau = 6{\cdot}3 \times 10^7$ sec
0
5
6
7
8
$\times 10^{-2}$
6
8
10
8
4
$\tau = 7{\cdot}5 \times 10^7$ sec
0
5
6
7
8
$\times 10^{-2}$
a_i
cm sec^{-2}

FIG. 1.

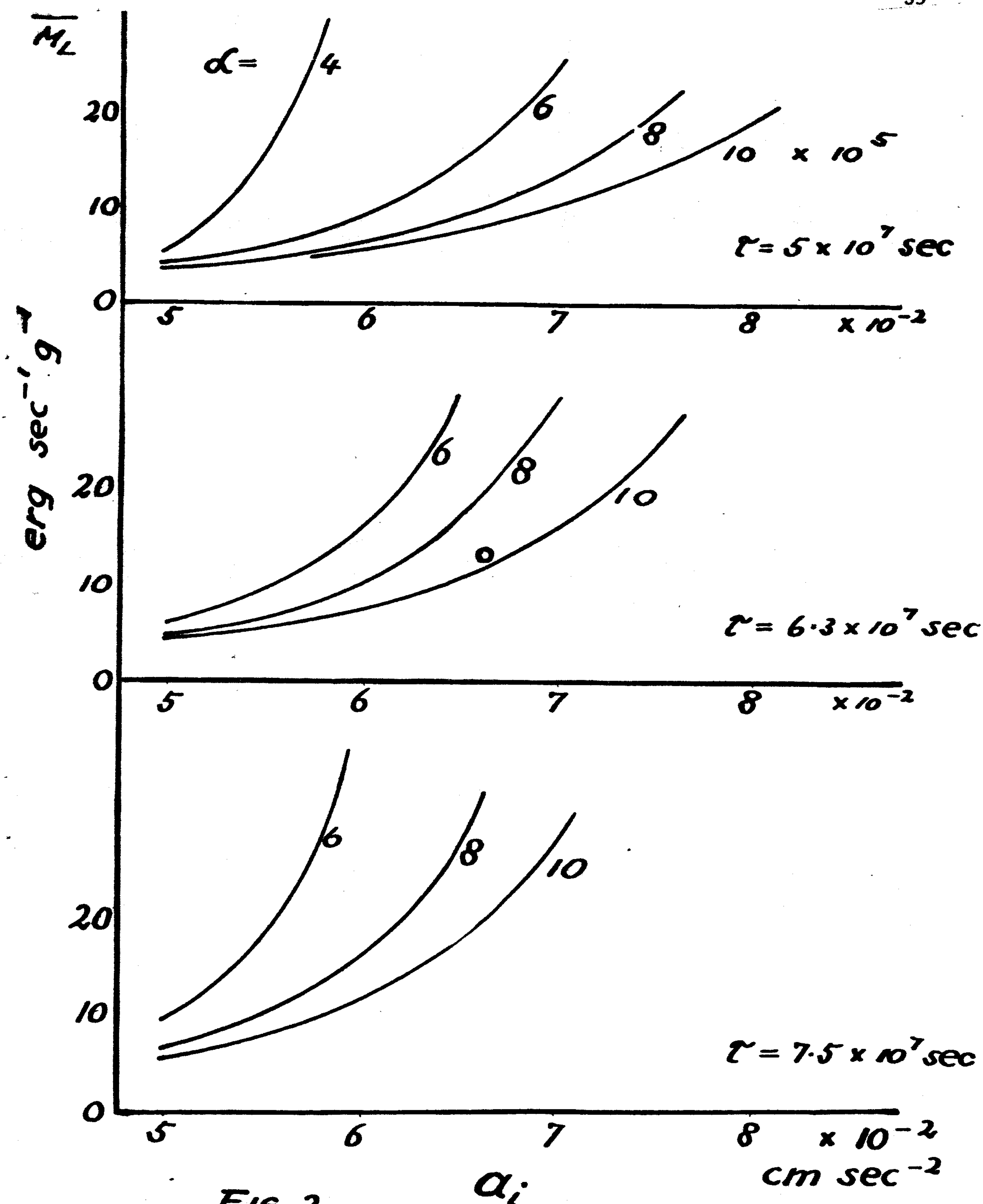

$\overline{M_L}$
$\alpha =$ 4
6
8
10 $\times 10^5$
20
10
0
$\tau = 5 \times 10^7$ sec
5
6
7
8
$\times 10^{-2}$
erg $sec^{-1} g^{-1}$
6
8
10
20
10
0
$\tau = 6{\cdot}3 \times 10^7$ sec
5
6
7
8
$\times 10^{-2}$
6
8
10
20
10
0
$\tau = 7{\cdot}5 \times 10^7$ sec
5
6
7
8
$\times 10^{-2}$
cm sec^{-2}
a_i

FIG. 2.

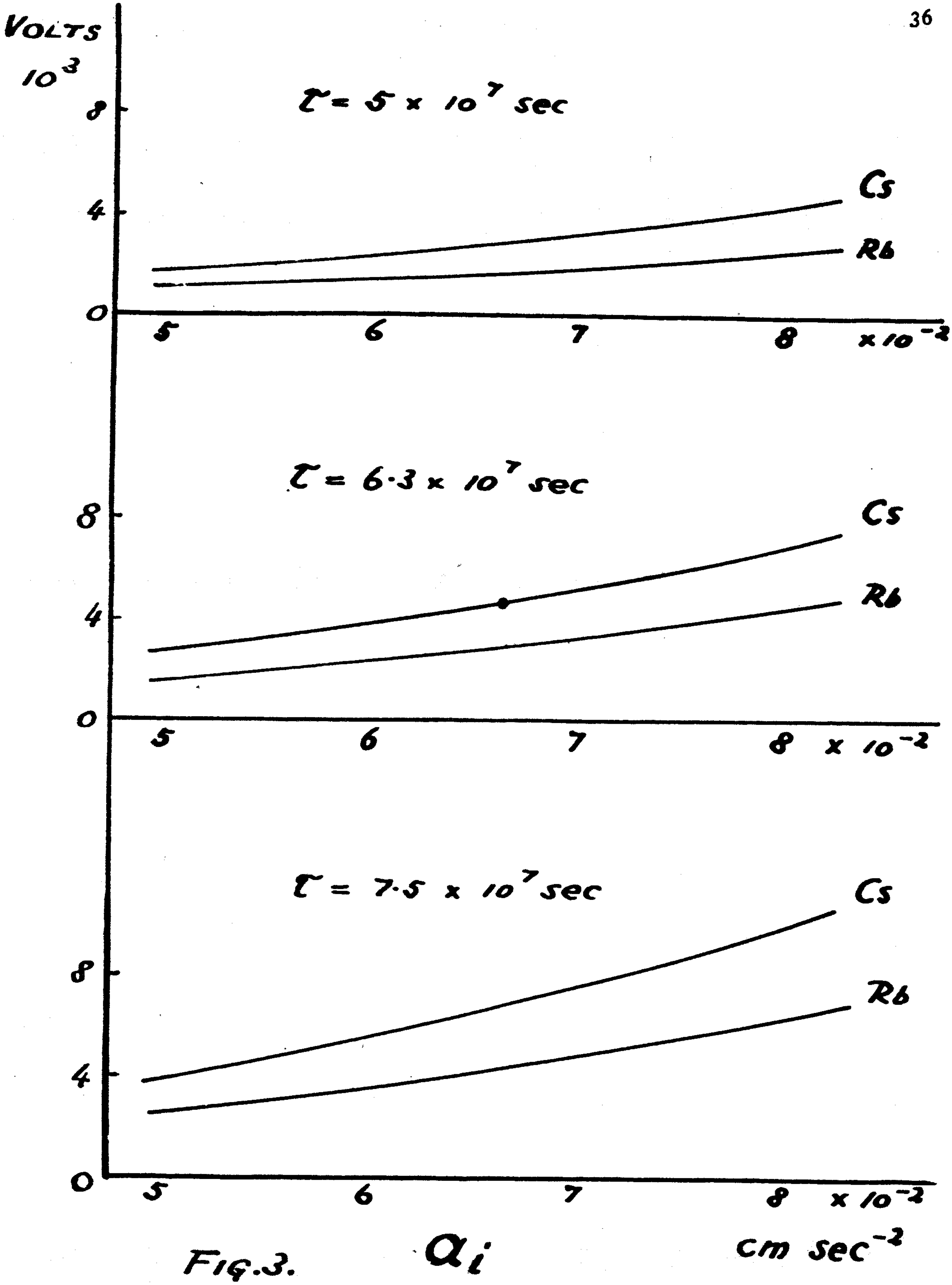

VOLTS
10^3
$\tau = 5 \times 10^7$ sec
8
4
0
Cs
Rb
5
6
7
8
$\times 10^{-2}$
$\tau = 6{\cdot}3 \times 10^7$ sec
8
4
0
Cs
Rb
5
6
7
8
$\times 10^{-2}$
$\tau = 7{\cdot}5 \times 10^7$ sec
8
4
0
Cs
Rb
5
6
7
8
$\times 10^{-2}$
a_i
cm sec^{-2}

FIG. 3.

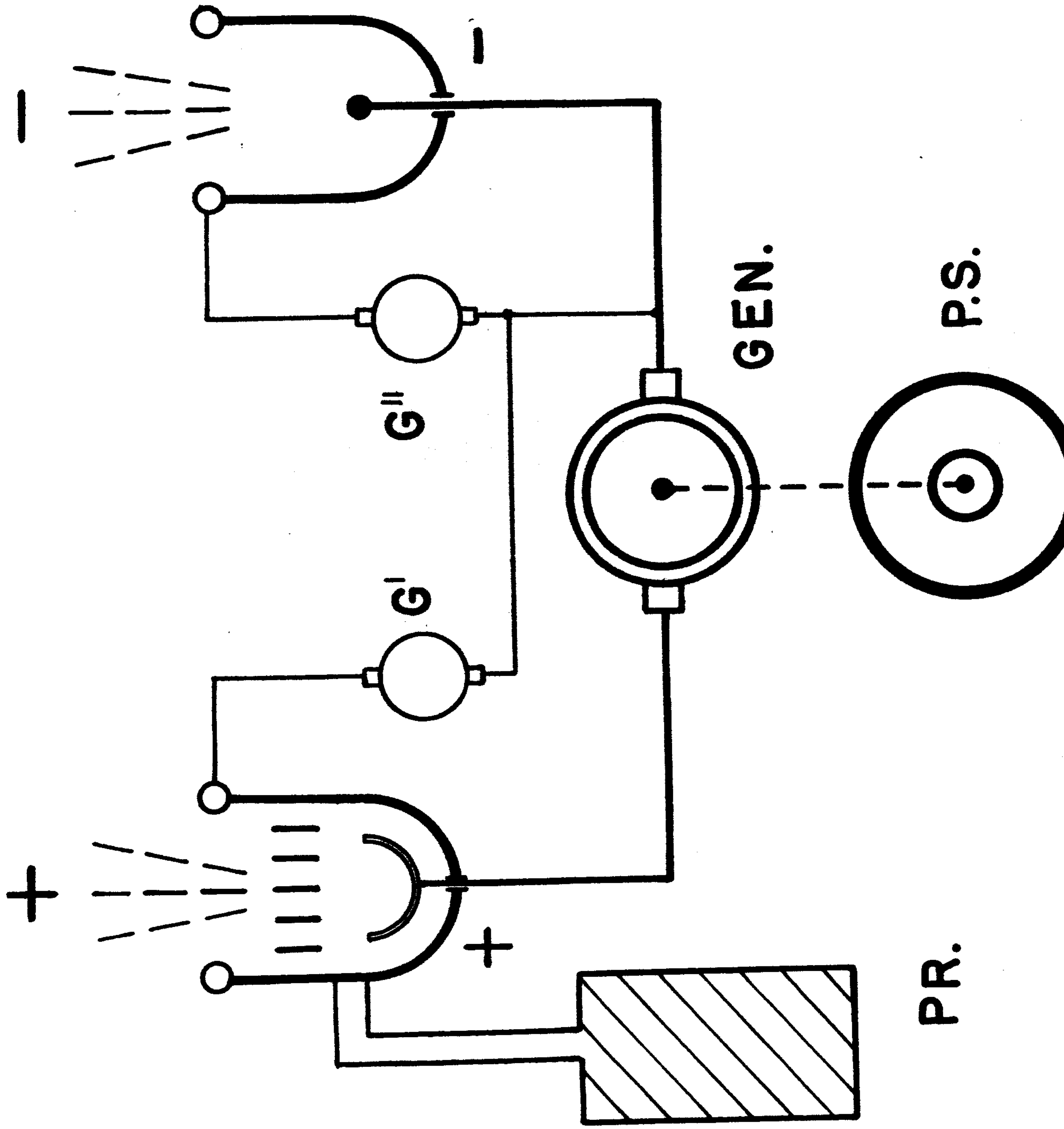


FIG. 4a.

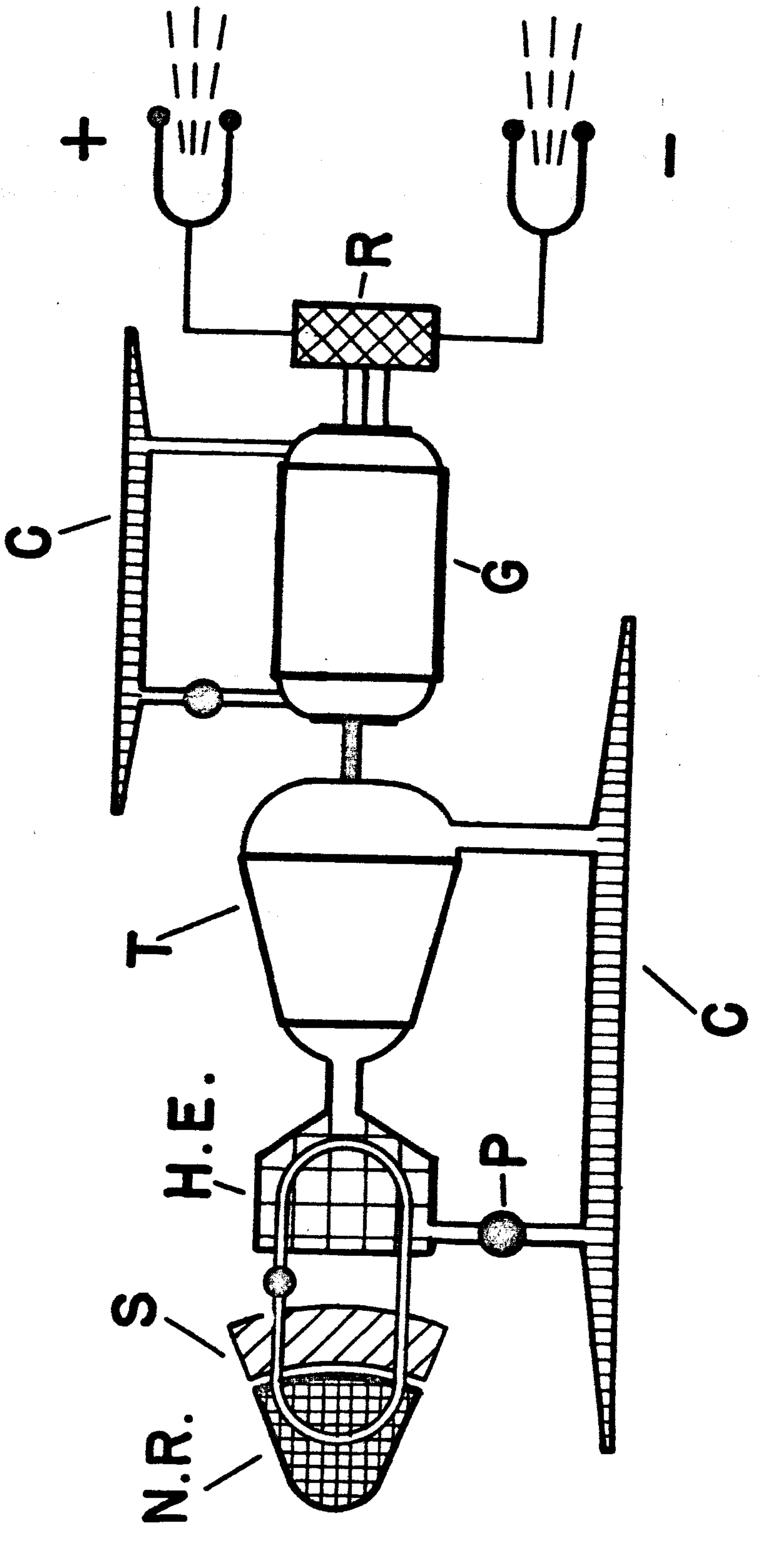


FIG. 4b.

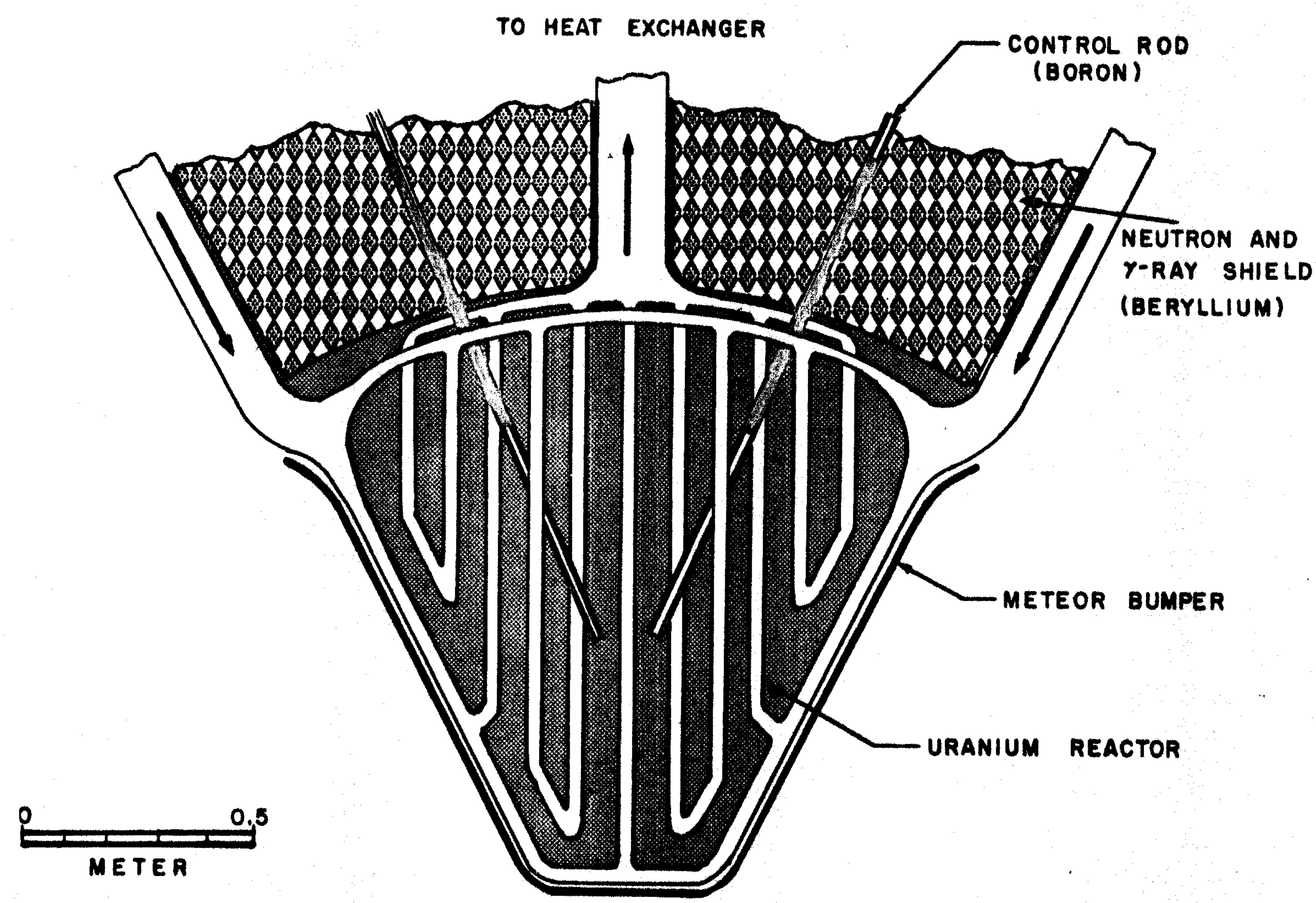

TO HEAT EXCHANGER
CONTROL ROD
(BORON)
NEUTRON AND
γ-RAY SHIELD
(BERYLLIUM)
METEOR BUMPER
URANIUM REACTOR
0
0.5
METER

FIG. 5a

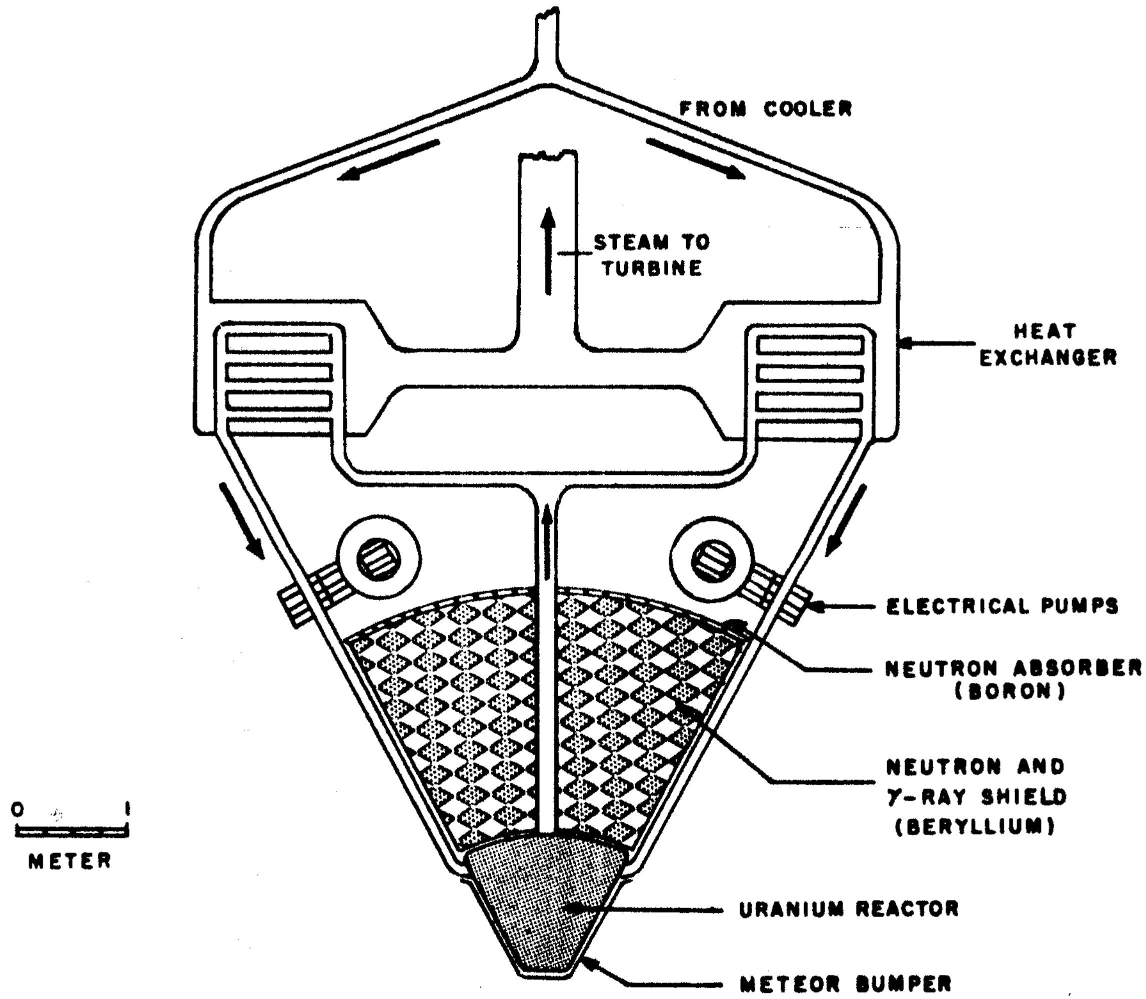

FROM COOLER
STEAM TO TURBINE
HEAT EXCHANGER
ELECTRICAL PUMPS
NEUTRON ABSORBER (BORON)
NEUTRON AND γ-RAY SHIELD (BERYLLIUM)
URANIUM REACTOR
METEOR BUMPER
0
1
METER

FIG. 5b

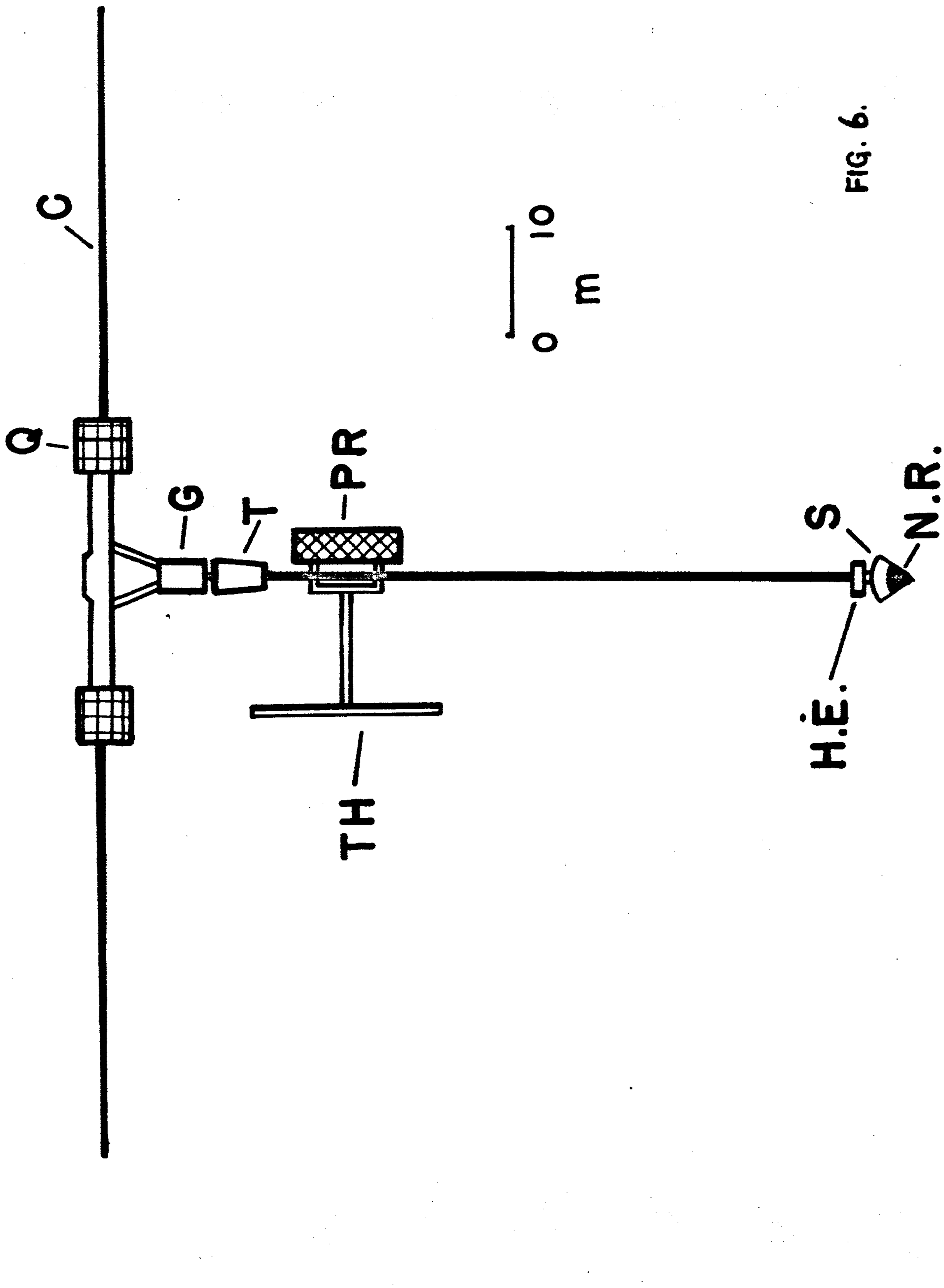


FIG. 6.

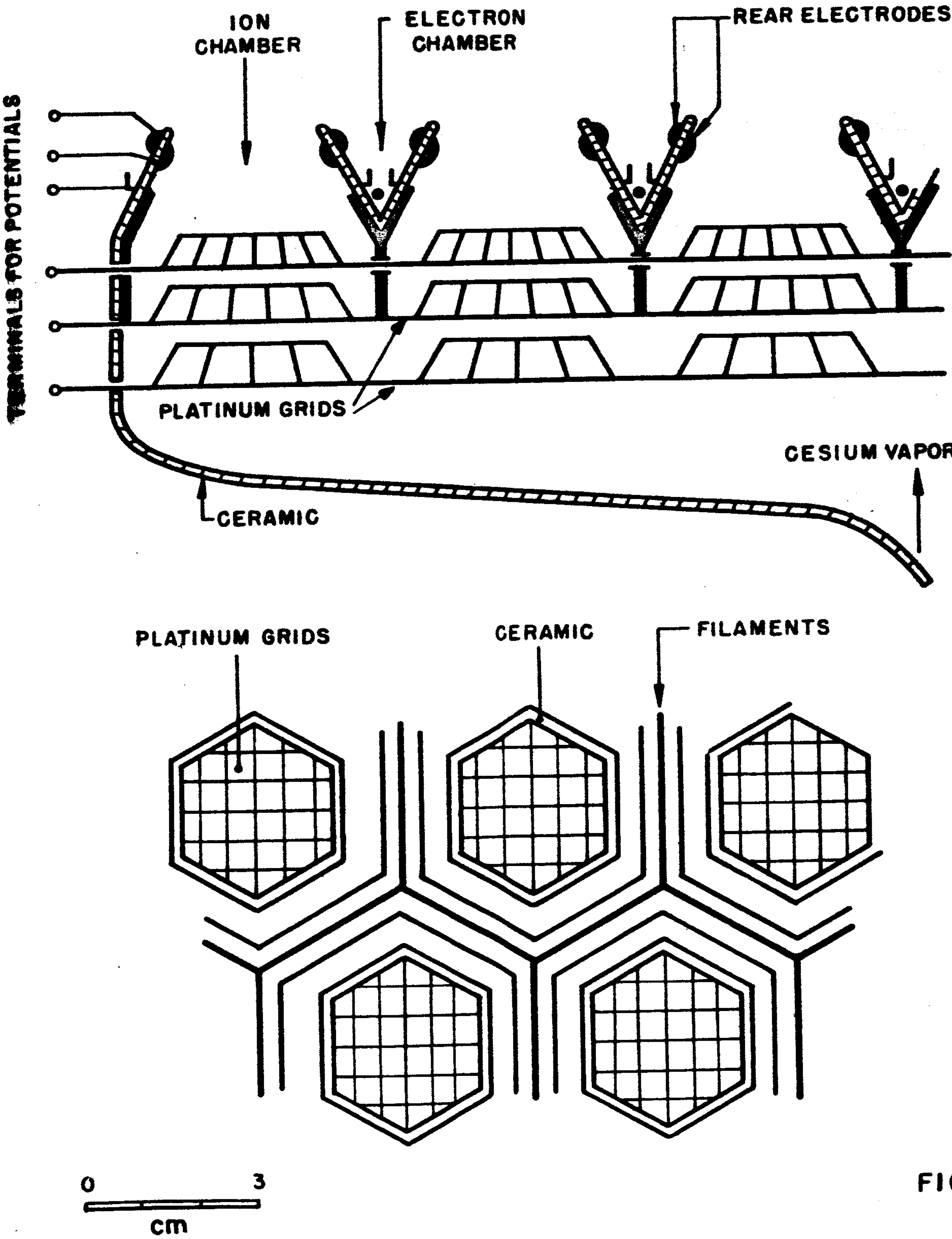

ION CHAMBER
ELECTRON CHAMBER
REAR ELECTRODES
TERMINALS FOR POTENTIALS
PLATINUM GRIDS
CESIUM VAPOR
CERAMIC
PLATINUM GRIDS
CERAMIC
FILAMENTS
0
3
cm

FIG. 7