NACA-LEWIS FLIGHT PROPULSION LABORATORY INSPECTION

October 7 - 10, 1957

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PROPULSION RESEARCH FOR HYPERSONIC AND SPACE FLIGHT

The purpose of this discussion is to acquaint you with some aspects of research conducted at the NACA Lewis laboratory on aircraft propulsion systems for continuously powered steady flight at hypersonic speeds. This area of study is differentiated from the research on powerplants for ballistic vehicles that operate for relatively short periods of time and at varying flight speed and altitude.

Let us first orient ourselves with the flight regimes to be considered by referring to figure 1, which shows altitude in miles and flight speed in thousands of miles per hour. The narrow shaded area represents the region or corridor in which continuous steady flight is considered aerodynamically feasible.

The lower boundary of this corridor is established by the maximum temperature that the surfaces of an aircraft can be allowed to reach without jeopardizing structural integrity. The high temperatures are generated by a body flying at high speed because the air at the leading edge of the body is brought to rest abruptly, causing a sudden rise in pressure, resulting in a corresponding rise in temperature. This local temperature is called the stagnation temperature. Thus the faster a body moves, the higher the stagnation temperature. For example, at a flight speed of 2500 miles per hour, the stagnation temperature is about 1000°F, at 5000 miles per hour it is about 4300°F, and at 15,000 miles per hour the stagnation temperature is well over 15,000°F.

When the stagnation temperature is high, the airframe will, of course, absorb a large quantity of heat, especially at low altitudes where the air is very dense. However, at the same time the hot surfaces radiate much of this heat to space and consequently the surface reaches a stabilized or equilibrium temperature that is considerably lower than the stagnation air temperature. Thus, along the lower boundary of the corridor, the equilibrium surface temperature would be over 2000°F. At higher altitudes the air is less dense and therefore the heat transferred to the body is less. Since radiation of heat away from the surfaces is not affected by changes in altitude, the equilibrium surface temperature decreases to a safe value. For example, the equilibrium surface temperature along the center of the flight corridor is about 1500°F. Therefore, structural considerations preclude continuous flight at low altitudes and high flight speeds.

The upper boundary of the corridor of continuous flight is defined by a region where the air density is too low to provide sufficient lift to sustain level flight with a practical airplane geometry. This can be illustrated by considering the airplane configurations shown in figures 2 and 3. The airplane shown in figure 2 was designed to operate at a flight speed of 3400 miles per hour at an altitude of about 17 miles. It carries a useful payload and has considerable flight range. The airplane shown in figure 3 was designed to have the same gross weight and to fly at the same airspeed but at an altitude of 21 miles. In order to sustain level flight the second airplane requires a wing four times as large and engines twice as large as the first airplane. The additional structural weight of the wing and engines so restricts the fuel load that it has only one-fourth the range of the first airplane. Thus, continuous steady flight in the region above the flight corridor becomes very inefficient.

As flight speed is increased to about 18,000 miles per hour, the upper limit disappears, since the vehicle need not depend on aerodynamic lift to maintain flight but is, instead, supported by centrifugal force as it orbits around the earth. If the orbital speed is increased sufficiently a vehicle can be projected beyond the earth's gravitational field into space.

This, then, establishes in a broad sense where we can and cannot expect to fly and therefore defines the areas in which research on propulsion systems needs to be done. Research on turbojet engines, indicated by the present flight area in figure 1, at airspeeds up to 2700 miles per hour (Mach No. of 4.0) is discussed in another presentation. This discussion will be focused first on the major problems encountered with ramjet engines operating at speeds from 2700 miles per hour to 4600 miles per hour and secondly on special propulsion considerations for flight in space beyond the earth's atmosphere.

Some of the ramjet engine problems and some of the facilities being developed to conduct this research are discussed in the following presentation.

As use of the ramjet engine is extended to speeds as high as 3000 to 4500 miles per hour, there are two principal propulsion system problems that arise. One is, as you might expect, cooling of the engine parts, and second, is the effective conversion of the energy released by the burning fuel into useful thrust. We will review these problems for you and indicate briefly the extent to which we have begun to do research in these areas.

To help the cooling problem, we will compare the external aircraft surface temperatures with those of uncooled engine parts. We will take as an example a flight at a speed of 4000 miles per hour where the stagnation temperature is 3000°F. At these conditions, the temperature of the outer surface of the engine drops rapidly from 3000°F at the leading edge to 1000°F along the rear portion of the nacelle. This is because the external surface radiates heat to the surrounding atmosphere. However, the internal surface temperatures remain close to the air stagnation temperature of 3000°F, because these surfaces cannot radiate to the cold external environment. When the temperature of the gases is further raised by combustion of fuel, the internal surfaces become correspondingly hotter, approaching 5000°F.

It is well to recognize that any metal surface within the engine would melt at these high temperatures; these surfaces must therefore be cooled. Our analyses tell us that the best technique is to cool the surfaces with fuel, then subsequently to burn the fuel in the engine combustor.

Let us now turn to the other problem of ramjet flight at high speeds, that of producing thrust when the fuel burned. As flight speed and thus inlet air temperature of the ramjet are increased, we find that less and less temperature rise can be produced by burning the fuel. It has been estimated that at a flight speed of 6300 miles per hour the temperature rise drops to zero. We might infer that at this speed the engine does not produce thrust. This is not necessarily true, and the explanation lies in the molecules of the exhaust gases.

When fuel is burned, carbon and hydrogen of the fuel combine with oxygen in air to form carbon dioxide and water vapor. Let us look at the behavior of the carbon dioxide molecule, for example, as we go to higher and higher flight speeds. At the higher speeds the temperature of this molecule is raised to a point where the bonds holding the carbon and oxygen atoms together are weakened and finally broken. This is called dissociation. These bonds are initially very strong and a great deal of energy is required to break them. Thus, we find that the heat added goes to break the molecular bonds rather than to increase the temperature. Furthermore, as long as these bonds are broken, this energy is not available to produce thrust, and we would therefore expect the engine thrust to be reduced. For example, at 5000 miles per hour we obtain only one-half of the theoretical thrust if there is no recombination of these dissociated atoms within the engine.

The recombination proceeds as the temperature of the gas is lowered by expansion in the exhaust nozzle. However, time is required for this process, and an extremely short exhaust nozzle may not provide sufficient time for the recombination to occur. A longer exhaust nozzle will provide more time for recombination and hence should develop higher thrust. Our research will tell us how much of this energy can be recovered and allow us to determine an engine configuration having the highest possible flight speed. These problems, cooling the engine and the recombination of dissociated gases, are fruitful areas for research. Let us now consider the facilities required for these investigations.

Some research on these problems is being done in flight with rocket boosted models. This technique is essential to show whether new systems are practical or to collect data on flight environment for the aircraft or engine. However, flight testing becomes impractical for studying these research problems in great detail. Therefore, a facility is required in which we can provide hypersonic streams at stagnation temperatures of 3000° or 4000°F.

Because the air temperatures required are above the melting temperature of metals used in conventional heat exchangers, new methods of heating the air must be utilized. Two such methods are being used currently at this laboratory to provide the required temperature and velocity conditions. One method utilizes a rocket motor to supply the hot gas, and the other method uses a bed of hot ceramic pebbles to heat the air.

In our rocket tunnel we have utilized a 5000-pound-thrust rocket motor to provide a high-temperature hypersonic stream. The 4000°F gases are expanded through a nozzle into a 15-inch-diameter test section in which models up to 5 inches in diameter can be placed. This facility has been in operation for 15 months and has been an extremely useful tool in our initial cooling research. The rocket tunnel does have one disadvantage, which is that the composition of the rocket exhaust gas is different from that of the air. Although an excess of oxygen is supplied so that the gases will contain the proper fraction of oxygen normally present in air, large quantities of water vapor are also present in the rocket exhaust gas. Therefore, a need exists for a facility which has a supply of uncontaminated air at these temperatures.

Such a source of hot air will be provided for our high-speed ramjet research by pebble-bed heaters. One such heater is currently being readied for initial operation and construction of a second heater will begin in one of our altitude chambers shortly. The principle of the pebble-bed type of heater is to store heat in a material which can withstand extremely high temperatures. Both of our heaters will be packed with about 10 tons of aluminum-oxide pebbles to provide this reservoir.

The beds are first heated to the working temperature by passing combustion products of a gas flame through the bed from top to bottom. When the bed has been heated, a gas burner is shut down and cooled air is passed through the bed from bottom to top. In passing through the bed, the air is heated to the temperature of the pebbles and is then expanded through a hypersonic nozzle into the test section. Both of our facilities will be large enough to permit installation of engines up to about 16 inches in diameter. Operating temperatures up to 3200°F will be possible. It is anticipated that these pebble beds will operate for periods of 3 to 5 minutes before the temperature of the test air begins to fall and the test must be terminated. Research engine configurations are now being designed for installation in these facilities, so that the cooling and dissociation problems may be investigated.

Before space flight can become a reality, propulsion systems which can operate at conditions beyond the earth's atmosphere must be studied. The Lewis laboratory is currently making preliminary investigations to check the feasibility of some future engine systems at speeds as high as 25,000 miles per hour, and at altitudes extending into outer space. However, many difficult problems must be solved before actual engines will be flying this fast and this high.

At present, it appears unlikely that any one engine will fully meet the requirements for a complete space mission. For example, at altitudes of about 40 miles, the atmospheric density becomes so low that air breathing engines become inoperative; thus space engines must be capable of functioning at near vacuum or vacuum conditions. Consequently, space flight might be divided into several steps - each powered by a suitable propulsion system. The first few steps would involve a vehicle leaving the earth's surface and reaching an orbital velocity of 18,000 miles per hour at an altitude of approximately 300 miles. The next part of the trip would be the acceleration of the vehicle to an escape velocity of about 25,000 miles per hour and entry into space flight. Once there, the craft could shut off its motor and coast at its escape velocity - influenced only by the gravitational forces from other bodies.

However, studies indicate that a low-thrust engine would be useful in this region. Despite the small accelerations which such an engine could develop, these velocity changes could add up to substantial speeds at the end of long travel times. For example, if a 10 ton vehicle in outer space were powered by a 10 pound thrust engine for one month, it would increase its original velocity by over 25,000 miles per hour. Upon its return, the vehicle would re-enter the earth's atmosphere, and its propulsion units would be subjected to the high stagnation temperatures associated with re-entry flight.

Under these conditions, the behavior of matter changes markedly. (Fig. ____ Effect of Temperature on Molecular Structure of Nitrogen) This figure illustrates the effect of temperature on the molecular structure of nitrogen, the principal constituent of air. In the vicinity of 7000°F, nitrogen molecules divide or dissociate. This is illustrated on the lower right where a nitrogen molecule is breaking up into its component atoms. Now a nitrogen atom is composed of a relatively heavy nucleus surrounded by planetary electrons. At higher temperatures, atomic collisions occur and some of the electrons may separate from an atom, and it then becomes an ion. This process is known as ionization. At temperatures of about 15,000°F, the resulting mixture contains neutral atoms, free electrons and positive ions. This state of matter is called "Plasma". Temperatures of this order may be found in a shock wave preceding a hypersonic vehicle re-entering the earth's atmosphere. Let us examine a device which can simulate these extreme temperatures.

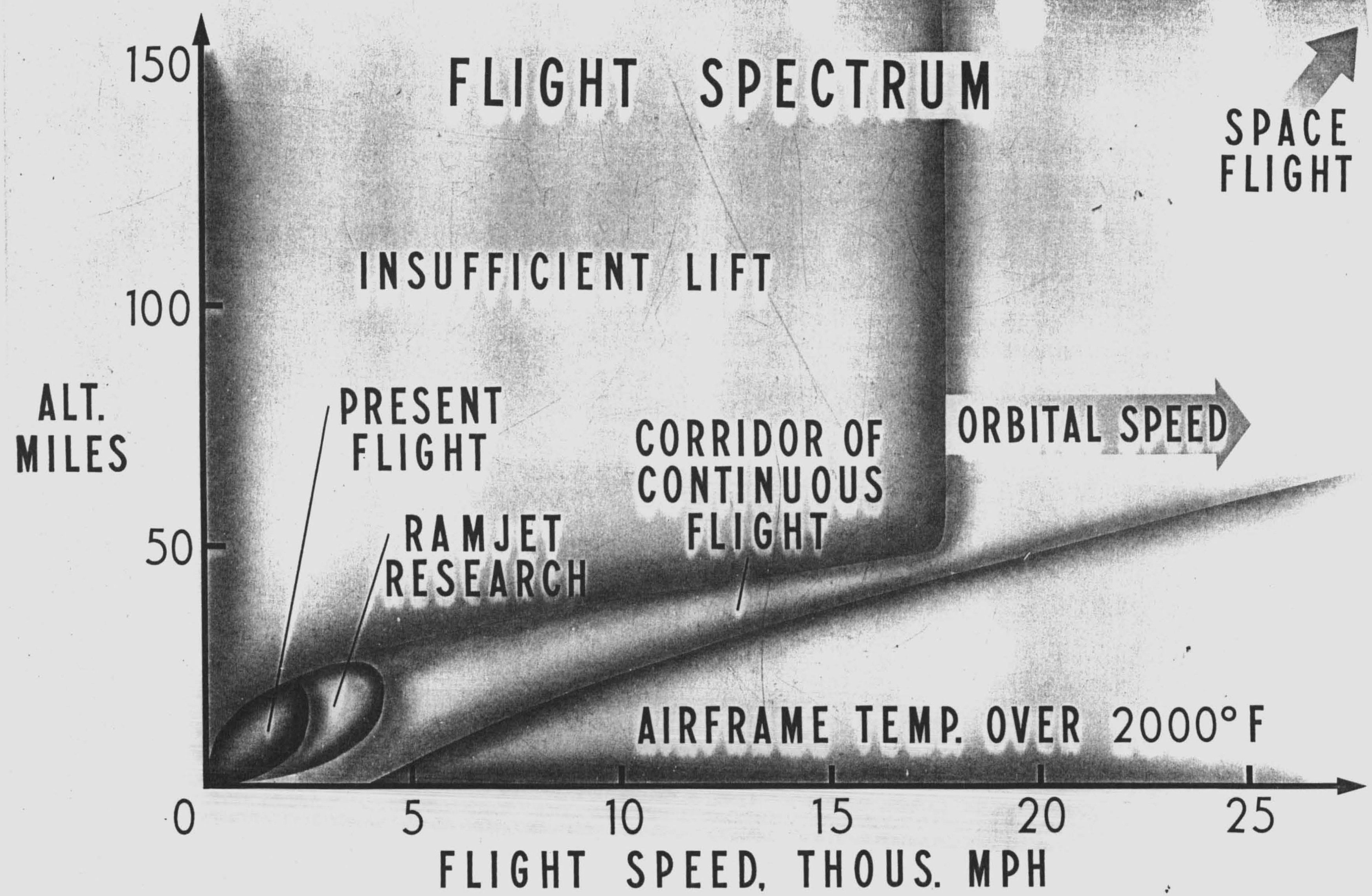
It is known that a high current electric arc operates at much higher temperatures than found in ordinary chemical combustion. The details of an arc or plasma jet are shown in this figure (Plasma Jet). There are two electrodes - the cathode rod and the anode nozzle. An electric arc can be struck between these elements similar to that found in anti-aircraft searchlights. Now, if a working fluid such as nitrogen is injected into the arc chamber, it will confine the discharge and provide raw material for the high temperature plasma. As the fluid passes through the anode nozzle, it will be accelerated, forming a plasma jet where temperatures can reach as high as 30,000°F. This figure illustrates what happens to a steel body in the plasma jet. These are the same conditions which this body would encounter if it re-entered the earth's atmosphere at hypersonic speeds.

If we add a hypersonic nozzle to the plasma jet, we will have an arc tunnel as shown in this chart (arc tunnel). A test model in this high speed, high temperature stream will enable us to study hypersonic re-entry problems such as that of cooling vehicle surfaces. A distinct advantage of such a facility is its ability to run for long periods of time at elevated speeds and temperatures. This suggests that the arc tunnel itself is a potential propulsion device of the future.

Let us compare its merits with those of today's rocket engines. Jet thrust is proportional to mass flow rate and jet velocity. If the product of these factors can be increased, the resulting thrust will go up. But, increased mass flow means that more propellant weight must be carried. The alternative is to find ways of increasing jet velocity. Conventional chemical rockets have large mass flows and jet velocities as high as 6,000 miles per hour. On the other hand, a plasma jet may theoretically give jet velocities five times as great. With this higher value, we can get the same thrust with much less propellant weight to carry. But if even longer controlled flights in space are planned, we will need engines with still greater jet velocities. One possibility is the charged particle accelerator or the ion rocket.

This engine differs from the plasma jet in a number of ways. Basically, the ion rocket is an electric particle accelerator while the plasma jet is primarily a heat engine. Although the ion rocket is limited to operation at extreme altitudes, its jet velocity may be 50,000 miles per hour or higher. This chart (Fig.___ Ion Propulsion Device) illustrates a laboratory model of an ion propulsion device. A large number of charged particles are produced in an electric discharge which occurs when a high voltage, direct current arc is struck at near vacuum conditions. These particles can then be accelerated by several means. In this case, they will be speeded up by a transverse magnetic field, and will produce small but useful thrust in outer space where little air exists to impede the vehicle. Fig.___ (Photo of Ion Unit in action) illustrates a small laboratory model of an ion engine in action. Note that a wheel is located in the ion jet for detecting thrust only, and is not a part of the ion engine. By controlling the ion source, and the accelerating magnetic field, we can vary the amount of thrust or push developed. The surrounding bell jar is pumped down to near vacuum conditions.

Development and improved efficiency of such propulsion devices may be one more link in the chain of events leading to future space flight.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ALT. MILES
SPACE FLIGHT
INSUFFICIENT LIFT
PRESENT FLIGHT
RAMJET RESEARCH
CORRIDOR OF CONTINUOUS FLIGHT
ORBITAL SPEED
AIRFRAME TEMP. OVER 2000°F
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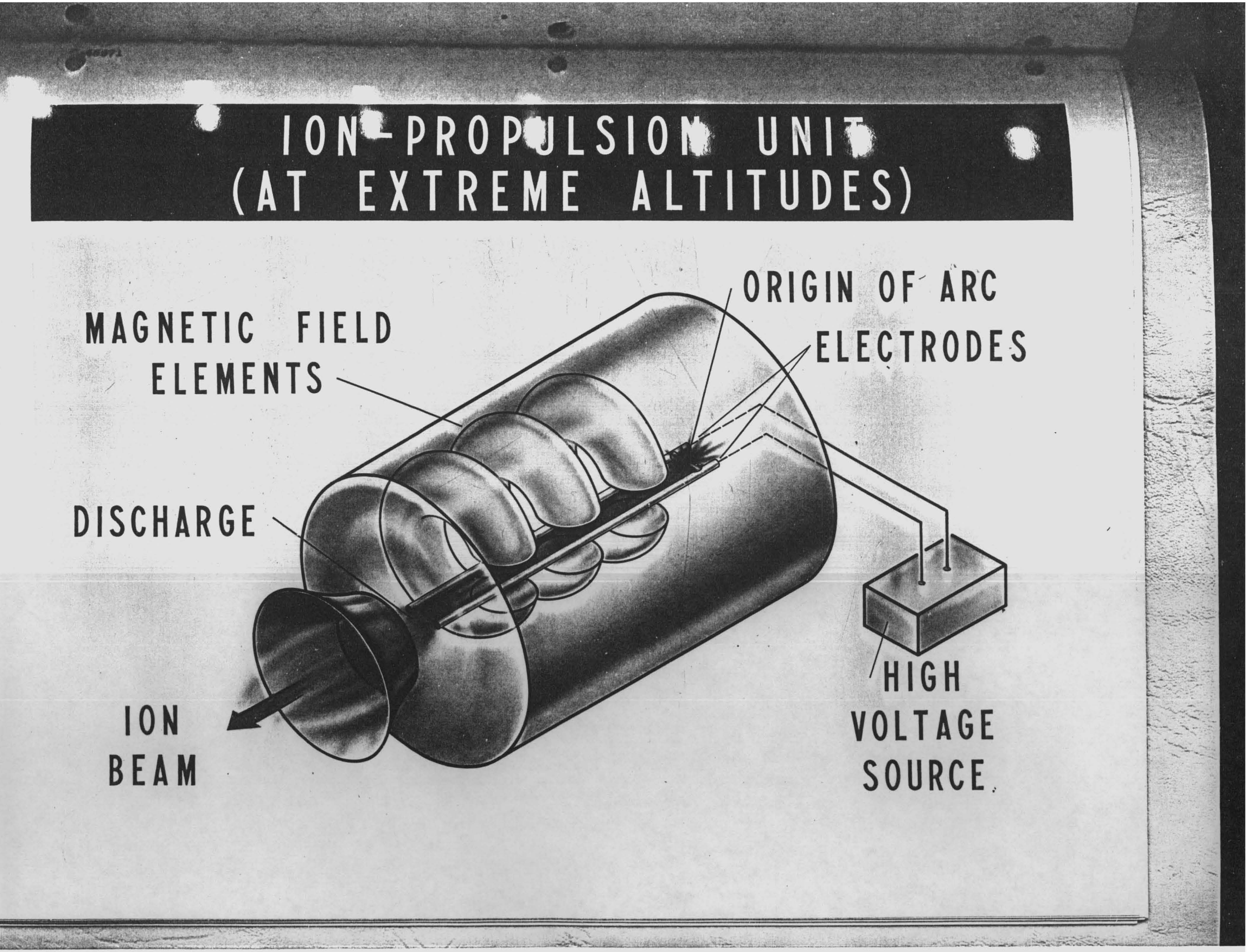
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(AT EXTREME ALTITUDES)
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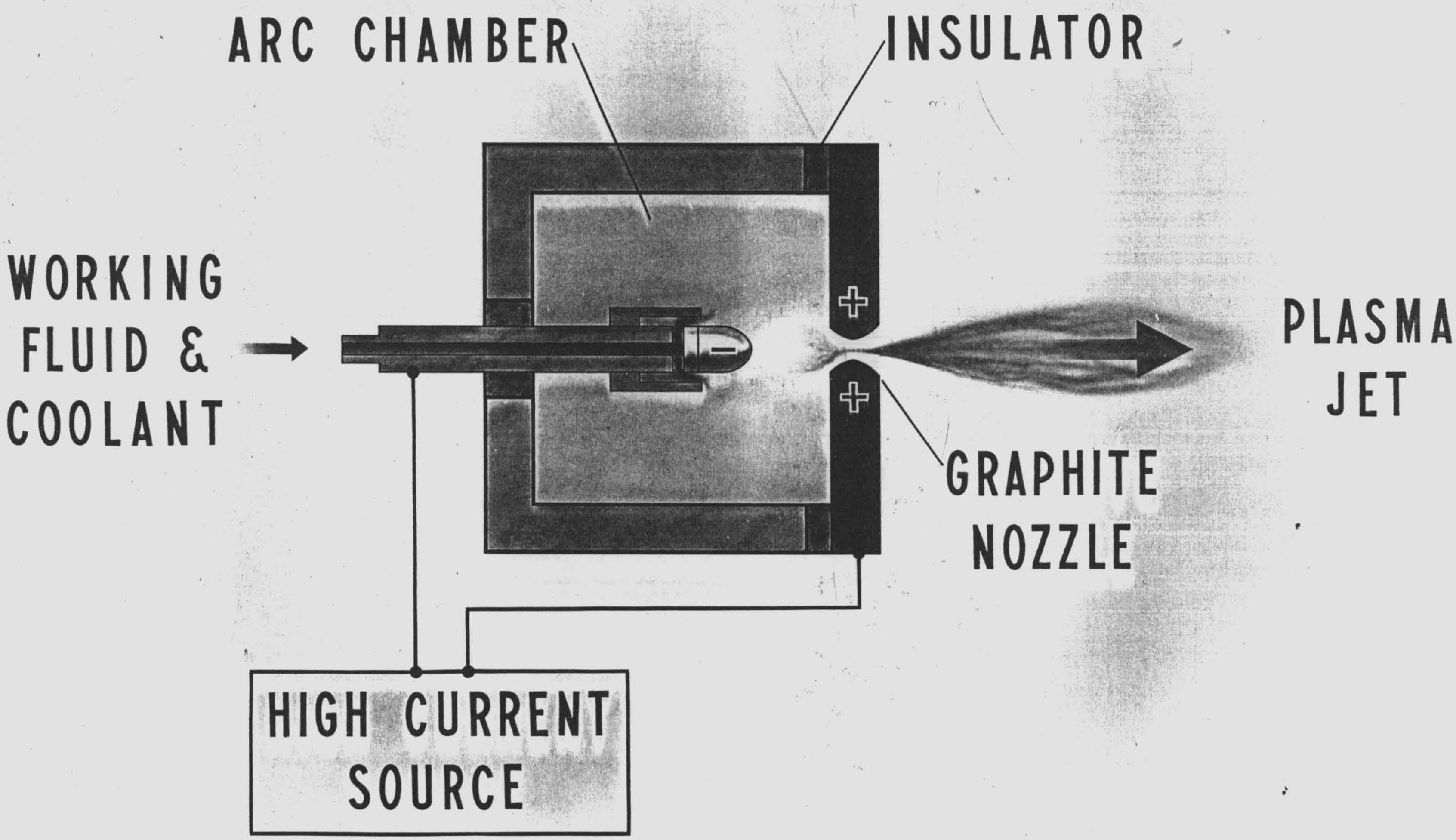
PLASMA JET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