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RAM JET PROPULSION

By Abe Silverstein

Flight Propulsion Research Laboratory
Cleveland, Ohio

June 1947

CLASSIFICATION CHANGED TO UNCLASSIFIED
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LECTURE FOR

NEW DEVELOPMENTS DIVISION
AIR COMMAND AND STAFF SCHOOL, AIR UNIVERSITY
MAXWELL FIELD, ALABAMA

January 30, 1947

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INTRODUCTION

Over a decade ago it became apparent that flight through and above the sonic speed would require propulsive powers many times greater than was or could be made available with any of the existing propulsion devices. Many believed that the "so-called" sonic barrier would not be pierced, whereas others took comfort in the paradox "that if God can build an immovable barrier, why cannot he also create a large enough force to move it?" Those of good faith have triumphed, and in the past several years flight at supersonic speeds has been accomplished with two different propulsive devices - the rocket and the ram jet. The rocket has been discussed in detail in another paper and this lecture will be concerned largely with the ram-jet engine, showing how the characteristics of the engine are adapted to the propulsive requirements for supersonic flight, describing the present state of ram jet development, and indicating the nature of the problems that remain to be solved.

THE PROPULSION PROBLEM IN SUPERSONIC FLIGHT

Researchers in the physical sciences are impressed repeatedly by certain providential solutions for difficult problems in which the requirements established by the problems are met step by step in the solution. Such a solution is provided by the ram jet for the problem of supersonic propulsion.

It is well known that the power required for propelling a body of fixed dimensions is proportional to the product of drag coefficient C_D, and the cube of the flight speed. The drag coefficient, which serves to define for the aerodynamicist the nature of the flow over the body, varies with the flight Mach number, and a typical variation for a ram-jet missile is shown in figure 1. The drag coefficient reaches a maximum at or about the sonic flight speed and decreases from this peak value at higher supersonic speeds.

If the power requirements are calculated for the aerodynamic body, for which data are shown in figure 1, at speeds of 500 miles per hour and 1500 miles per hour, the power at the higher speed will be tripled because of the threefold increase in the value of C_D, and further increased 27 times because of the cubed ratio of the flight speeds. The power required is therefore increased 81 times and if, in a typical case, 2000 thrust horsepower is required to sustain sea-level flight at 500 miles per hour then 162,000 thrust horsepower is required at 1500 miles per hour.

The disparity between powers of this magnitude and those available from reciprocating engines and turbojet engines now in service is obvious. The characteristics of typical service engines as they are now applied at subsonic flight speeds is shown in figure 2. The subsonic characteristics of the ram jet are added as a point of interest, although it is to be emphasized that the ram jet has little or no merit for propulsion at low flight speeds.

The reciprocating engine is definitely limited in its power potentialities by the low air handling capacity of engine cylinders of practical dimensions. The turbojet and turbine-propeller engines have thus far been limited in power output by the temperature limitations of the turbine materials.

The ram jet combines the favorable characteristics for developing large powers of handling a large mass of combustion air, and of providing the possibility for burning fuel in the air at or near stoichiometric temperatures.

RAM JET PERFORMANCE CHARACTERISTICS

The ram jet is one of the simplest engines that has yet been conceived for aircraft propulsion (fig. 3). There are no mysteries associated with the cycle on which the engine operates or with the manner in which the power is delivered.

The ram jet, in common with all other types of engines, derives its power from the expansion of gases that have been burned under pressure. The combustion occurs at almost constant pressure as compared with the constant volume combustion that occurs in the reciprocating engine.

Compression of the fuel-air mixture before burning is accomplished by converting the dynamic pressure of the air moving relative to the ram jet to a static pressure in the combustion chamber. This process is analogous to the rise in pressure in an open-ended airspeed tube when it is moved through the air. No moving parts are utilized in the compression or expansion cycle. The expansion cycle, in which the useful work is done, is accomplished by means of a nozzle in which the combustion gases are accelerated, because of their higher temperatures, to a final velocity that is higher than the velocity of the air which entered the engine.

The difference in the momentum of the gases leaving the nozzle after they have reached equilibrium with the surrounding atmosphere and the momentum of the air entering the engine is a measure of the ram-jet thrust. The power of the ram jet is simply the thrust multiplied by the flight velocity. The efficiency is in a large measure determined by the temperature ratio achieved in expansion of the hot gases between the combustion chamber pressure and the ambient discharge pressure (Carnot cycle efficiency). The higher the expansion ratio through the nozzle, the higher is the efficiency.

In order to show clearly why the ram jet is adapted so ideally to supersonic propulsion, it is necessary to develop an elementary relation for its thrust. As previously mentioned, the thrust of the ram jet is equal to the change in momentum of the mass of gas passing through the engine; that is (see fig. 4)

$$F_n = m_a\ (v_5 - v_o)$$

in which

F_n = net thrust

m_a = mass airflow

v_5 = final gas speed

v_o = flight speed

If we assume for simplification that the engine operates without losses and all second order effects are neglected, it can be shown that

$$v_5 = \sqrt{\frac{T_3}{T_2}}\ v_o$$

in which T_3 is the total temperature at the discharge of the combustion chamber and T_2 is the temperature at the combustion chamber inlet. If we replace the term $\sqrt{\frac{T_3}{T_2}}$ by the symbol $\sqrt{\tau}$, then

$$v_5 = \sqrt{\tau}\ v_o$$

Substituting in the original expression for the thrust,

$$F_n = m_a v_o\ (\sqrt{\tau} - 1)$$

By definition m_a can be replaced by $\rho_o v_o A_o$, in which A_o is the area of the cross section of the mass of air entering the inlet of the ram jet at free stream conditions, ρ_o and v_o. Then

$$F_n = \rho_o v_o^2 A_o\ (\sqrt{\tau} - 1)$$

$$= 2\ q\ A_o\ (\sqrt{\tau} - 1)$$

$$= C_f\ q\ A_o$$

in which q is the dynamic pressure $1/2\ \rho_o v_o^2$ corresponding to the flight speed and C_f is the thrust coefficient.

A similar expression can be written for the drag of the body which is being propelled, that is,

$$D = C_D\ q\ A_o$$

in which C_D is the drag coefficient.

In comparing the equation for the thrust and drag, it will be noted that both increase directly with the dynamic pressure; that is, as the square of the flight speed. For propulsion it remains only necessary for the value of the thrust coefficient $C_f = 2\ (\sqrt{\tau} - 1)$ to be larger than the drag coefficient C_D. Experimental investigations have already shown for certain ranges of Mach numbers that C_f can be maintained larger than C_D.

To avoid confusion in the analysis of data presented in missile literature, attention is called to the fact that no consistent terminology has yet been adopted for the areas on which the coefficients C_D and C_f are based. In the usual case the drag coefficient C_D is not given in terms of the area A_o, but for wing missiles it is based on the wing area S as, for example, in figure 1. The thrust coefficient C_f is generally expressed in terms of the combustion chamber area A_2 (see fig. 4).

The power available for propulsion from the thrust of a typical ram jet and the power required due to the drag of the airplane shown in figure 5 illustrate the matching of the engine and the airplane. With increase in airplane speed, the thrust of the reciprocating engine decreases, the thrust of the rocket remains essentially constant, the thrust of the turbojet engine increases above a speed of 300 miles per hour but at a rate less than the first power of the velocity, whereas the thrust of the ram jet increases as the square of the speed, thereby matching the rise in airplane drag.

For flight at a constant Mach number and varying altitude, both the airplane drag and the ram jet thrust are proportional to the altitude pressure; that is, when the altitude pressure is one-half sea-level pressure, both the airplane drag and the ram jet thrust are halved. The effect of altitude on the ram jet horsepower is illustrated by experimental results obtained in the NACA Cleveland altitude wind tunnel on a 20-inch-diameter ram jet (fig. 6). An output of 35,000 horsepower was obtained at sea-level operation at a Mach number of 2, whereas at 40,000 feet altitude the power delivered was approximately 6500 horsepower.

Thus far no mention has been made of the engine fuel consumption. At low flight Mach numbers the fuel consumption, expressed in pounds of fuel per thrust horsepower-hour (fig. 7), is high because of the low compression ratio in the cycle. For example, at the sonic speed the fuel consumption is 2.5 pounds per thrust horsepower-hour. The engine economy improves rapidly with increase in Mach number and at a Mach number of 2 the fuel consumption decreases to less than 1 pound of fuel per thrust horsepower-hour. This value is comparable to the fuel consumption at military power of our best reciprocating engines and is about equal to the fuel consumption of the turbojet engine at high subsonic Mach numbers. The specific impulses of the ram jet, expressed in pounds of thrust per pound of fuel per second, is from 6 to 8 times that of a rocket at a Mach number of 2. The high specific consumption of the ram jet at low flight Mach numbers decreases its usefulness as an engine for subsonic propulsion.

A major weakness of the ram jet is the zero thrust at take-off. An auxiliary engine or launching device will be required to accelerate the engine to a Mach number of from 0.4 to 0.5, after which the thrust of the engine may be adequate for acceleration to supersonic speeds. It may be found that launching Mach numbers higher than 0.5 will be required unless control of the inlet and outlet dimensions can be provided.

As a possible solution for the take-off problem of a supersonic airplane, a composite engine consisting of a turbojet and a ram jet in series appears attractive. Extensive analytical and experimental investigations of the turbo-ram jet engine have been conducted at the NACA Cleveland research laboratory during the past year which show that this composite engine has excellent performance characteristics up to flight Mach numbers of approximately 2. A schematic arrangement of such an engine is shown in figure 8. Additional fuel is burned in the hot exhaust gases of the turbojet engine in order to bring the temperature of the gases leaving the engine to a temperature of approximately 4000° F. Since this fuel is burned behind the turbine, the principal limitation of the power output of the turbojet engine is avoided.

Substantial take-off thrust is provided and the thrust at a Mach number of 2 is about equal to that of the ram jet alone (fig. 9). The specific consumption of the composite engine (fig. 10) is higher than that of the turbojet alone, but is sufficiently low to provide a practical solution to the problem of attaining high thrust through the range of Mach numbers from take-off to a Mach number of 2. The specific consumption of the turbo-ram jet engine approaches that of the ram jet at a Mach number slightly above 2. For missile application, where it may be desirable to avoid the weight and complexity of a turbojet installation for take-off assist, the use of booster rockets is probably a better solution.

Some consideration should be given to the range of ram jet powered aircraft. This problem has been analyzed by members of the Langley Field staff of the NACA (fig. 11), and it has been found that flight ranges of between 1500 and 1800 miles now appear possible for ram jet powered missiles. In one calculation it was assumed that the fuel weight was equal to half of the gross weight of the missile and that the wing loading was chosen at different altitudes so that the missile flew at an altitude corresponding to its maximum lift-drag ratio. The results for this calculation are shown in figure 11 on the curve marked W/S (optimum wing loading).

Surprisingly small improvements in range resulted from increases in flight altitude. However, the calculations revealed that at the very high altitudes an extremely small airplane could perform the same mission for which a large airplane would be required at sea level. The dimensions at different altitudes were found to be proportional to the density of the atmosphere. Numerous assumptions were necessarily required for this preliminary range calculation and further research may indicate methods for substantially increasing the range.

STATUS OF RAM JET RESEARCH AND DEVELOPMENT

The ram-jet engine development is primarily in the research phase, although industry programs sponsored by the armed services are making good progress in their attack on some of the problems associated with the production of flight engines. Research is being actively prosecuted at government laboratories and universities throughout the country.

Four principal research techniques are used, namely:

1. Subsonic and supersonic wind tunnel tests

2. Ground stand blower installations

3. Flight test beds

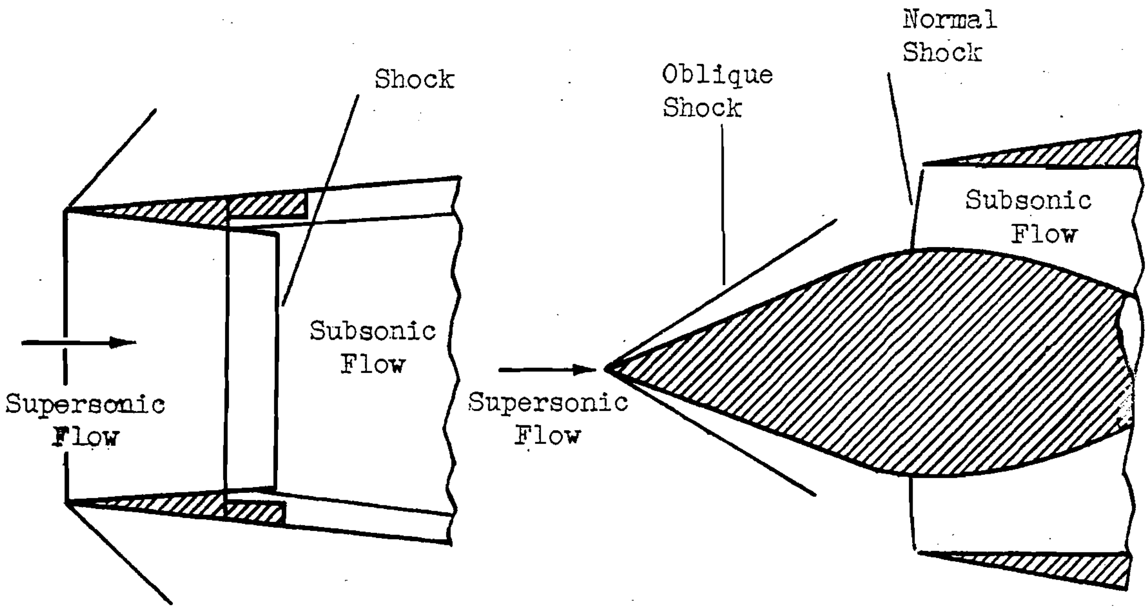
4. Free flight with rocket assisted take-off

Engine research requires detailed study of the characteristics of the engine components and the evaluation of the performance and operational characteristics of the complete engine. A review of research activities at the NACA Cleveland Flight Propulsion Research Laboratory may aid in clarifying the present status of ram jet development and delineate the problems to be solved. Research problems and techniques used for their investigation will therefore be summarized in the following paragraphs.

Supersonic Diffusers

The attainment of high ram jet efficiencies requires that the compression accompanying the diffusion of the supersonic flow ahead of the inlet to subsonic flow in the combustion chamber be achieved with a minimum loss of total pressure of the stream. Since deceleration of a supersonic to a subsonic flow is accompanied by a shock, and since the total pressure loss across a shock is a minimum when the flow ahead of the shock is at sonic speed, the prime objective of all supersonic diffusion is to provide a means for reducing the Mach number of the flow to as close to $M = 1$ as possible before a normal shock is allowed to occur.

Several geometric arrangements have been suggested for this purpose, such as the convergent-divergent diffuser and the oblique shock diffuser.



Convergent-Divergent Diffuser   Oblique Shock Diffuser

The characteristics of these and other types of supersonic diffusers are being actively investigated at the Cleveland laboratory, and a diffuser has been developed for use at a Mach number of 1.85 in which a loss of only 4 percent of the free-stream total pressure occurs. The efficiency of this diffuser is higher than that of any type of mechanical compressor.

In supersonic research a most useful tool is the schlieren apparatus that enables regions of the flow field in which density gradients are occurring to be clearly outlined. Typical schlieren pictures showing the flow at the entrance of a diffuser with one and two oblique shocks are shown in figures 12 and 13. The increase in density behind the oblique shocks is shown by the shaded areas and the location of the normal shock near the inlet is clearly disclosed.

As the flight Mach number is increased, the losses across the supersonic diffuser tend to increase and at a Mach number of 3 it is possible for as much as 50 percent of the total pressure of the free stream to be lost in the supersonic diffuser. In a large degree the successful application of supersonic ram jets at high Mach numbers will be dependent on research efforts which enable the diffuser losses to be decreased. The reduction of the nose drag of the supersonic missile associated with the formation of oblique shocks at the ram jet inlet also remains as an important research problem. Much research effort will be required in the next few years to provide solutions for these important problems.

Combustion

The problem of achieving stable combustion with high combustion efficiencies in ram jet combustion chambers over a wide range of flight speeds and altitudes represents one of the most difficult phases of ram jet development. The fuel to be burned in the ram jet at high Mach numbers is measured in terms of 10 thousands of pounds per hour and the heat release per unit volume in these combustion chambers is many times higher than in any other types of burner equipment. The difficulties associated with combustion are increased by the requirement that devices installed in the ram jet combustion chamber to promote stable and efficient combustion are necessarily limited to those producing relatively low pressure losses.

Many research projects are now in progress at the NACA Cleveland laboratory to investigate the fundamental factors affecting the combustion process, such as the inlet-air pressure, temperature, and velocity, and the fuel-air ratio of the combustion gases. The nature of the turbulence required downstream of the flame-holding device in order to promote stable and efficient burning at high combustion speeds is also being investigated. Thus far a basic understanding of the effects of varying the fundamental combustion parameters has not been established and the design of combustion chambers is largely based on cumulative experience.

A typical installation of a ram jet combustion chamber for combustion studies is shown in figure 14. Combustion air is provided for this experiment by a blower ahead of the combustion chamber inlet. The combustion temperatures are measured with water-cooled rakes at low combustion temperatures and are calculated from measurements of gas samples taken in the exhaust for temperatures above which thermocouples are now available. The measurement of temperatures in the range of 3000° and 4000° F offers a difficult research problem in itself and instruments for this purpose are badly needed.

Equipment is available at the Cleveland laboratory for investigating the effects of variations in the inlet pressure and temperature of the combustion air on combustion efficiency. It is found in general that decreasing the pressure or the temperature at which combustion occurs reduces the combustion efficiency. The attainment of high efficiencies at high altitudes therefore presents a more difficult problem than at sea level. Caution must be used in interpreting research results obtained under sea level test conditions unless they are subsequently checked at altitude conditions.

An important variable in the combustion process is the velocity of the air at the entrance to the combustion chamber. Successful burning under altitude conditions with the types of flame-holding devices now in use has not been accomplished at combustion inlet velocities much above 200 or 250 feet per second. Fortunately, analysis indicates that it is not desirable to greatly exceed these speeds since the pressure losses due to the acceleration of the gases during the combustion process are approximately proportional to the square of the combustion chamber velocity.

The combustion study provides one of the most interesting phases of ram jet research and a large effort will be required in the next few years to establish the problem on a sound fundamental basis.

Fuels

The large fuel consumption of the ram jet introduces a special fuel problem. Stated briefly, this problem is one of finding volume enough in the supersonic airplane to carry the fuel. The volume requirements for the fuel present a more serious problem than the weight of the fuel.

Since the drag of supersonic bodies is so high, it is extremely undesirable in long-range missiles to increase the frontal areas of the fuselage, which appears to be the most logical place to carry the fuel, to a size sufficient to carry the conventional hydrocarbon fuels. Thus far all research on ram jets and performance evaluations have been made using gasoline or related hydrocarbons as a fuel. Research is in progress, however, for the development of fuels having a higher heating value per unit volume than the hydrocarbon fuels.

No obvious solution to this problem appears to exist. Analysis shows that the metals and their hydrides may offer promising solutions. For example, beryllium has a heat content of 3,110,000 Btu per cubic foot, as compared with gasoline which has 840,000 Btu per cubic foot. The use of beryllium as a fuel would therefore reduce the volume of the storage space required in a long-range aircraft to approximately one-fourth of that required for gasoline. Unfortunately, beryllium is scarce and expensive and is used here simply to illustrate the characteristics desired of a fuel.

A further advantage results from the use of a fuel such as beryllium which has a higher stoichiometric temperature than gasoline. Because of the temperature rise associated with the compression of the gases in the inlet of the ram jet, the value of the possible temperature ratio across the combustion chamber T_3/T_2 decreases with increasing Mach number. For example, with gasoline as a fuel the maximum value of the ratio of T_3/T_2 (τ) decreases from a value of over 6 at sea level static conditions to a value of 3.8 at a Mach number of 3. Since the thrust coefficient is proportional to the value of $\sqrt{\tau}$ (see thrust coefficient equation), its value will decrease at higher Mach numbers. With beryllium, at a Mach number of 3, a value of τ of 6.5 can be reached. Comparisons of the thrust for these two fuels at a Mach number of 3 is shown in figure 15. Because of the high energy requirements of the supersonic ram jet, the use of atomic energy appears particularly attractive.

Performance Evaluation

An important phase of ram jet research is the evaluation of the over-all performance and operational characteristics of the complete engine, in which the losses occurring in the cycle are integrated. From these results the theoretical and actual performance of the engine can be compared and a basis established for aircraft design.

The NACA Cleveland altitude wind tunnel provides an excellent research tool for this purpose, and the internal performance of ram jets has already been established over a range of altitudes up to 47,000 feet and at Mach numbers up to 2. The wind tunnel has been so designed that the pressure in the tunnel can be reduced to 50,000 feet altitude conditions by exhausters, and the temperature can be reduced to -50° F by refrigeration, so that accurate altitude simulation is achieved.

A ram jet installation in the altitude wind tunnel is shown in figure 16. The 20-inch-diameter ram jet was suspended beneath a wing supported at its tip by the tunnel balance system. Air at conditions corresponding to the altitude and Mach number to be simulated is ducted to the ram jet inlet. The engine exhausts directly into the wind tunnel test section, which for these tests serves primarily as an altitude chamber. Numerous ram jet configurations have been investigated in this manner.

A typical flame-holding device used to seat the flame and to add turbulence is shown in figure 17. The flame holder, which consists of a grid of V-shaped sections, is fabricated of Inconel. The fuel was introduced for these tests through a series of small orifices drilled in tubes that were arranged in a V pattern near the subsonic diffuser inlet (fig. 18). To provide constant fuel injection pressure at different fuel flow rates, a mechanically driven plunger was used to reduce the number of fuel injection orifices at low fuel flows.

Typical results obtained from the wind tunnel investigations are shown in figures 19, 20, and 21. It has been found that by the use of certain parameters the results obtained at different altitudes may be generalized so that they may be plotted on a single curve. For example, the results on the net thrust curve (fig. 19), which were obtained over a range of altitudes from sea level to 45,000 feet, were generalized by dividing the measured thrust at a given value of the temperature ratio τ by the parameter δ. This generalizing parameter δ is equal to the ratio of the absolute ambient pressure ahead of the ram jet inlet to the absolute static pressure under NACA standard atmospheric conditions at sea level. The use of parameters such as δ provide a great simplification in the experimental investigation of ram jets and enable the altitude performance of the engine to be predicted from sea level tests. The variation of the thrust coefficient C_f with the free-stream Mach number (fig. 20) shows the increase in the thrust coefficient that results from increasing the combustion chamber temperature ratio.

The over-all efficiency of the engine (fig. 21), which is the ratio of the total useful work performed to the heat energy of the fuel burned, increased with the Mach number, but the rate of increase is less at the higher Mach numbers due to the high supersonic diffuser losses. This droop in the efficiency curve will be eliminated when more efficient supersonic diffusers are developed. Analysis of the results of figure 21 showed that the measured efficiency of the engine was only about 70 percent of that which could be obtained for an ideal engine without losses. The direction of further research will be to decrease the difference between theoretically possible efficiencies and those actually realized.

CONCLUDING REMARKS

The ram jet inherently possesses the characteristics required for supersonic propulsion. Experimental investigations have already shown that the theoretical characteristics of the ram jet can be approached in practice and there remains the detailed research on components and complete engines to achieve the highest possible thrust and efficiency.

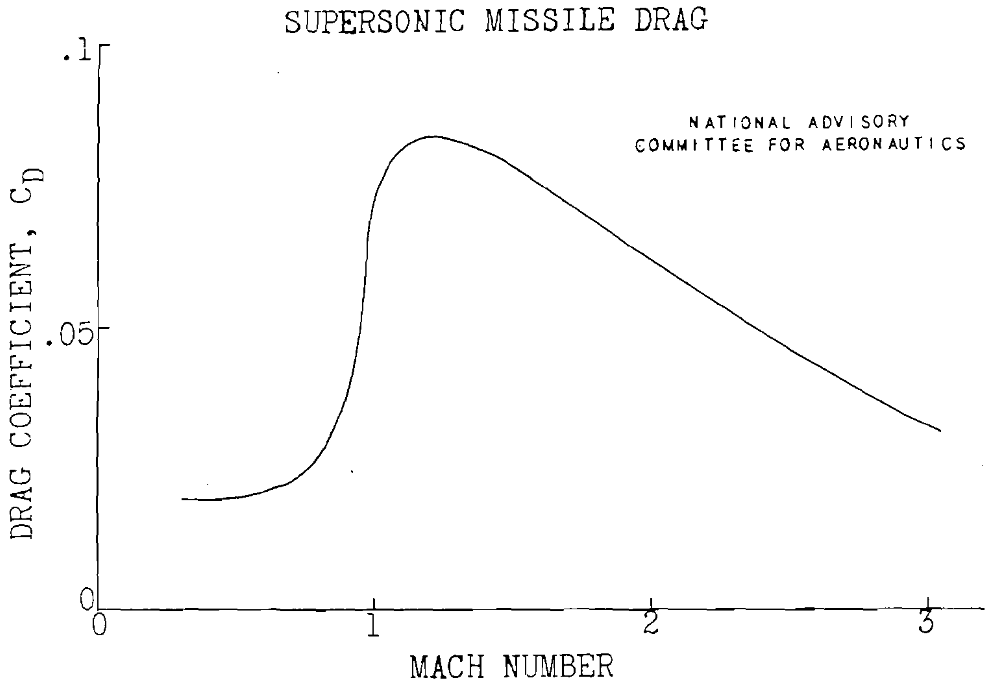


Figure 1.

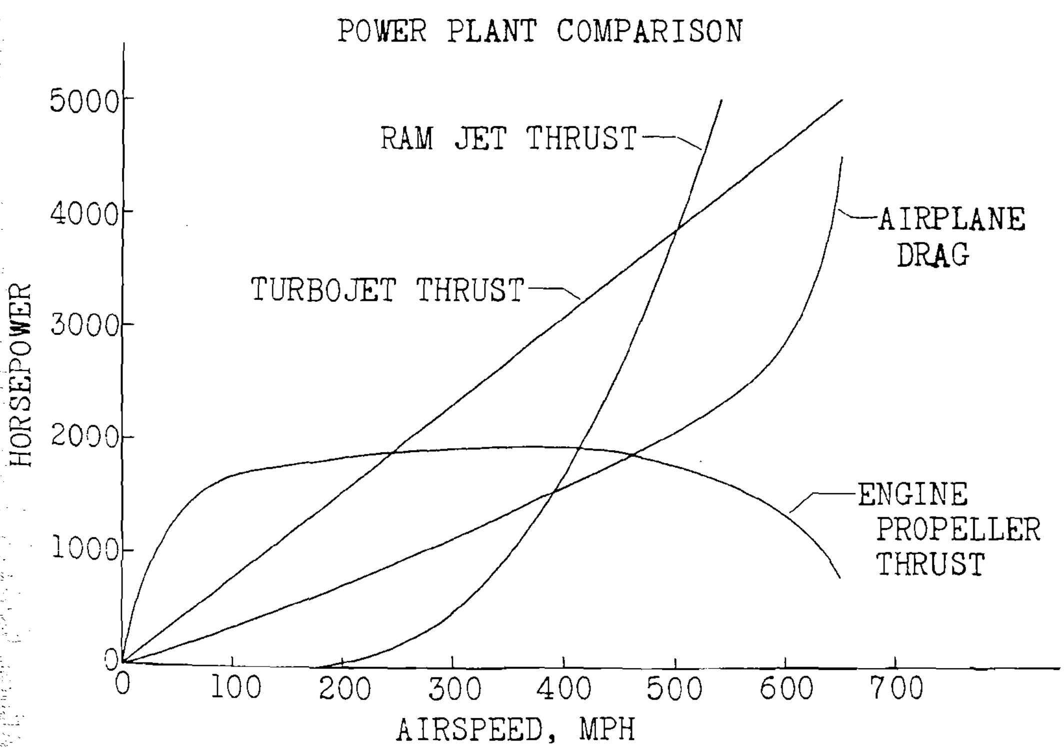


Figure 2.

RAM JET

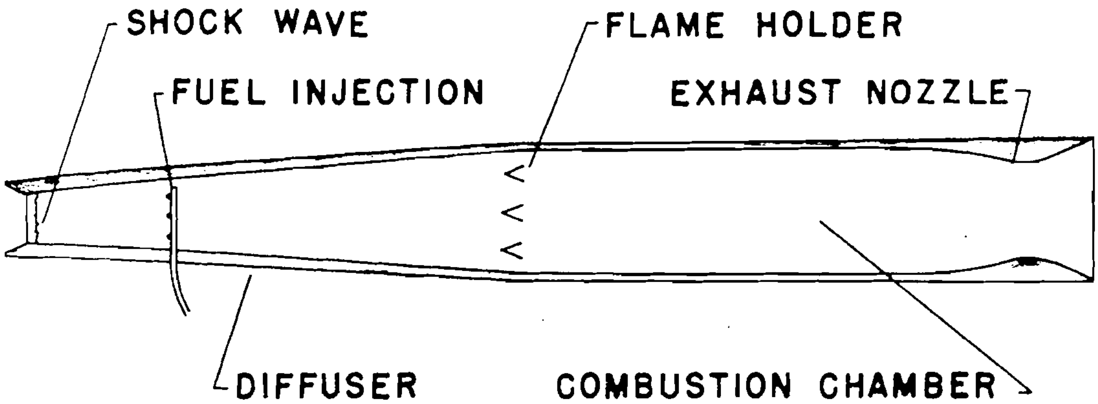


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Figure 3.

SCHEMATIC DIAGRAM OF SUPERSONIC RAM JET

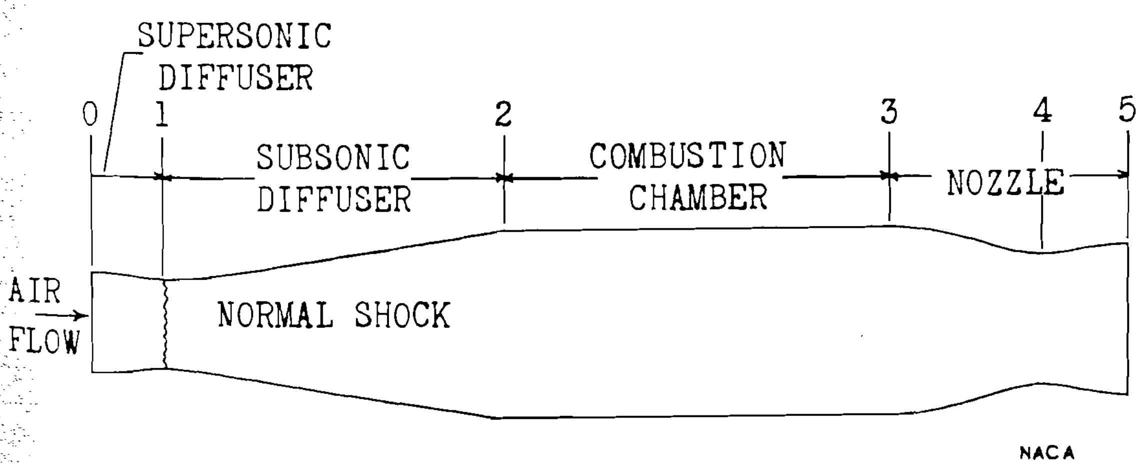

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Figure 4.

SUPERSONIC AIRPLANE CHARACTERISTICS

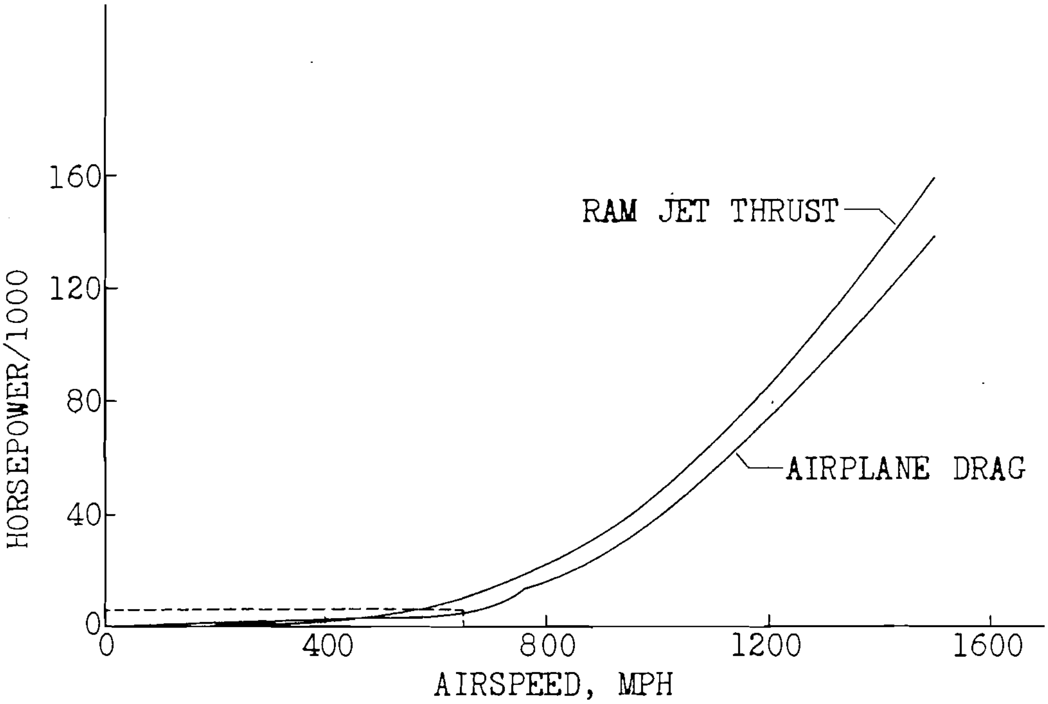

Figure 5.

POWER DEVELOPED BY 20-INCH RAM JET

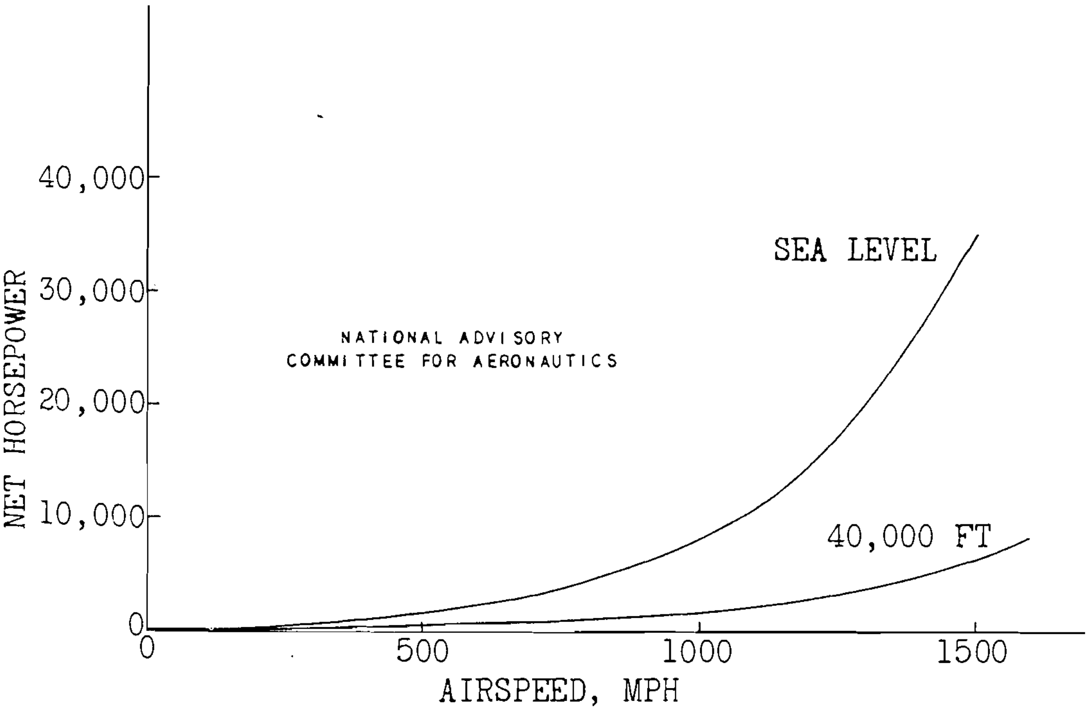

Figure 6

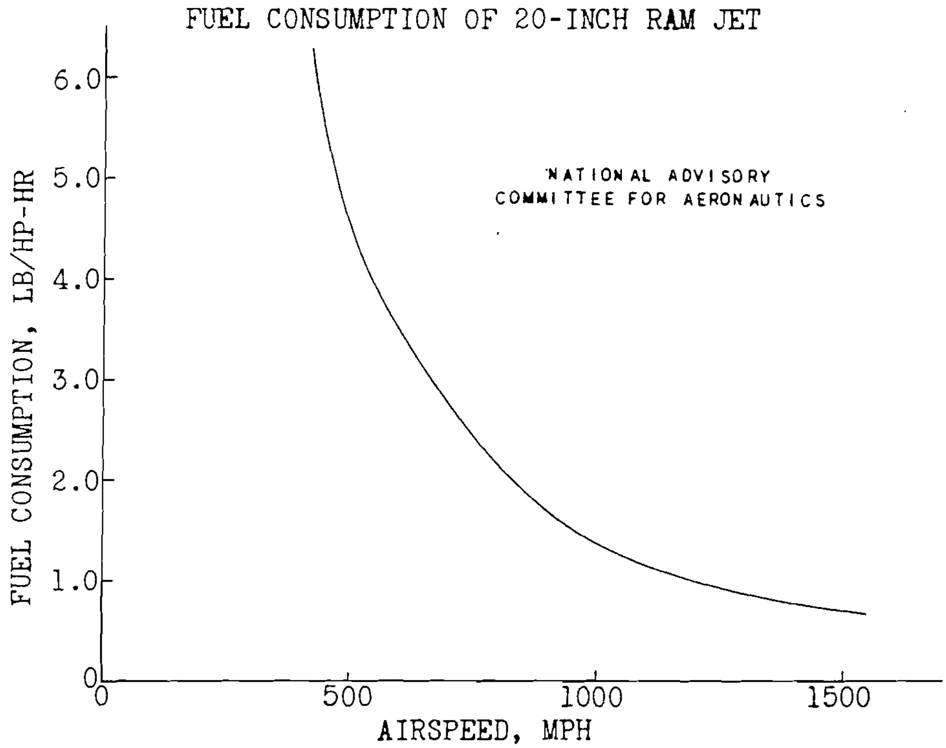

Figure 7.

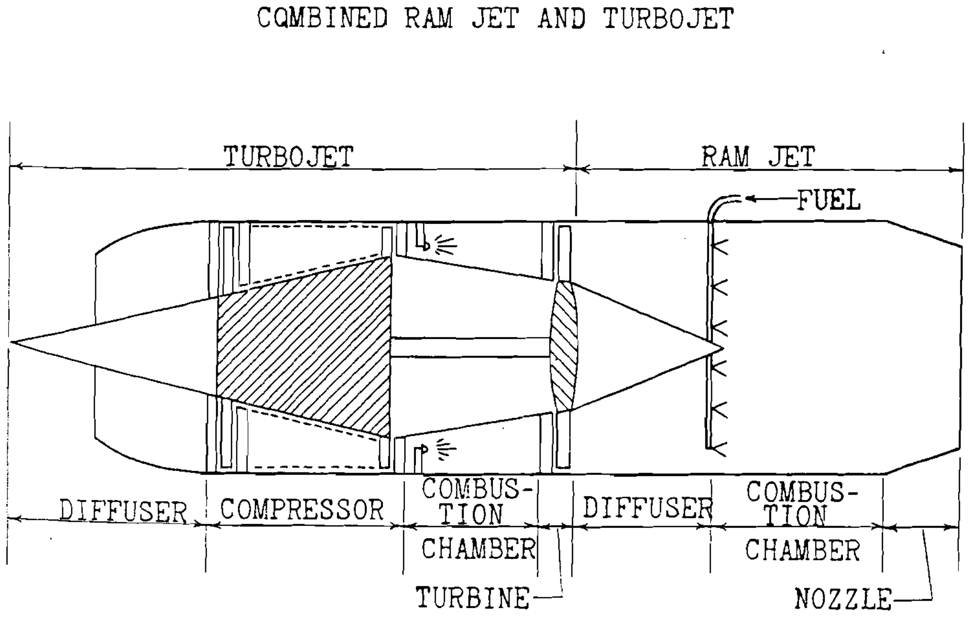

Figure 8.

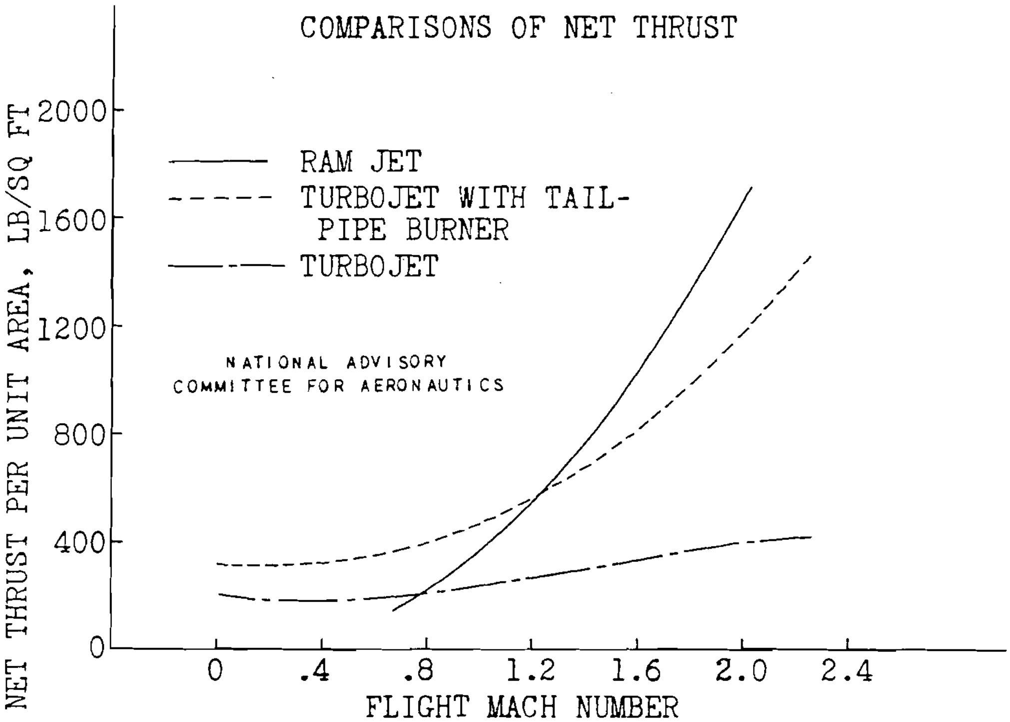

Figure 9.

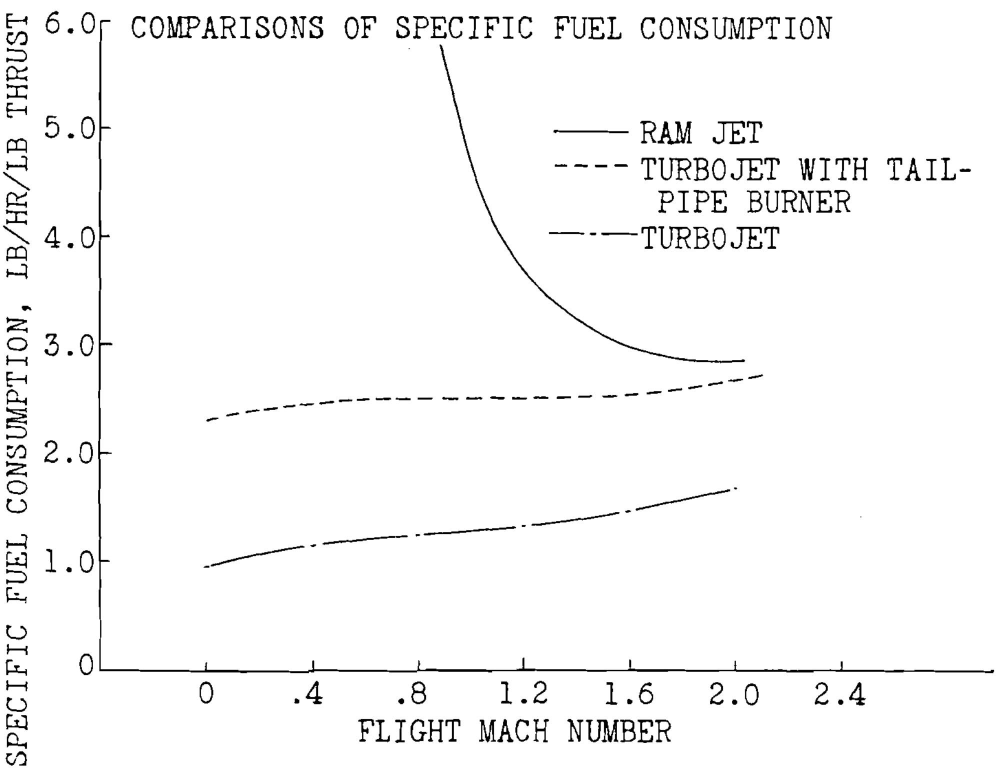

Figure 10.

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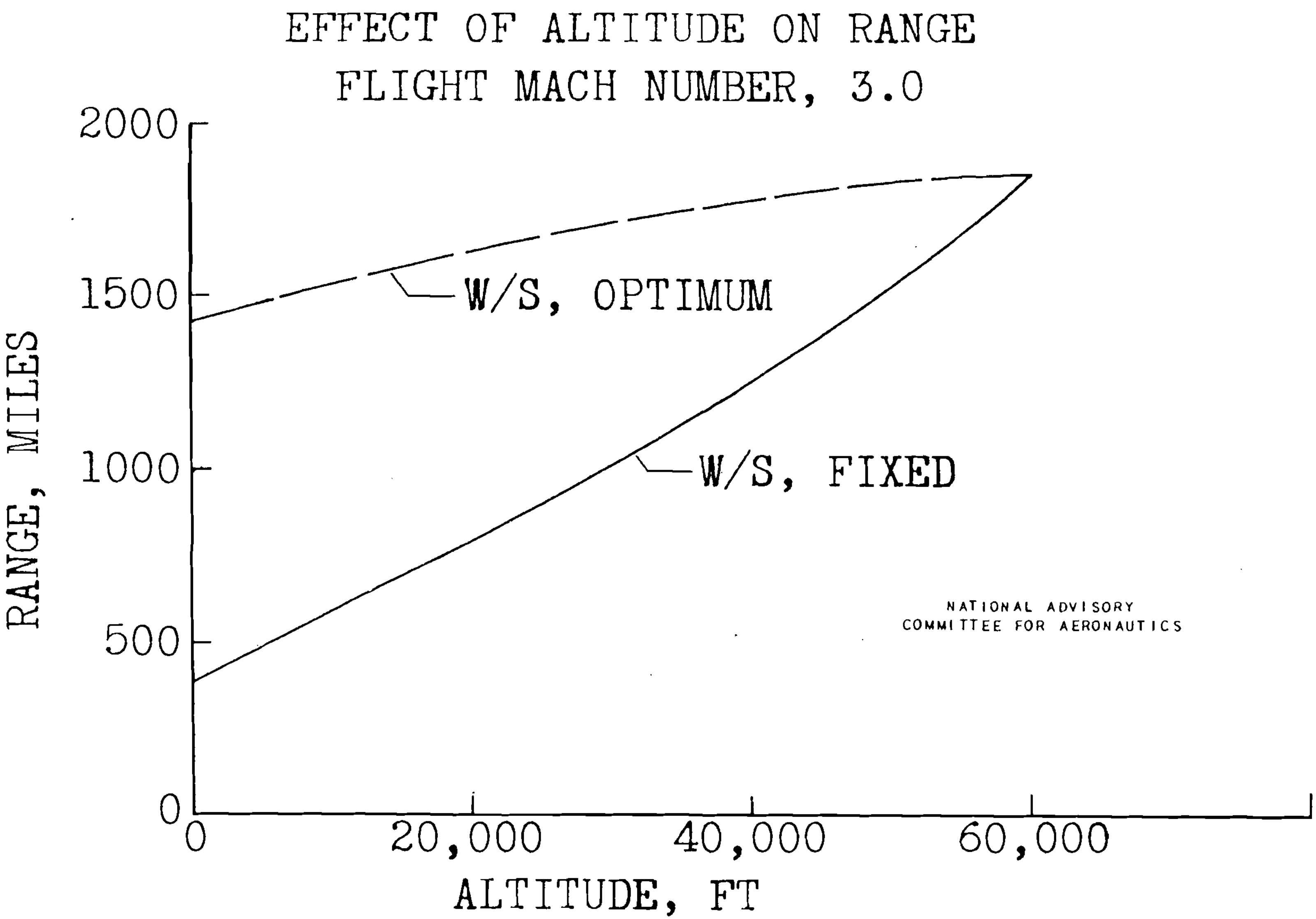

Figure 11.

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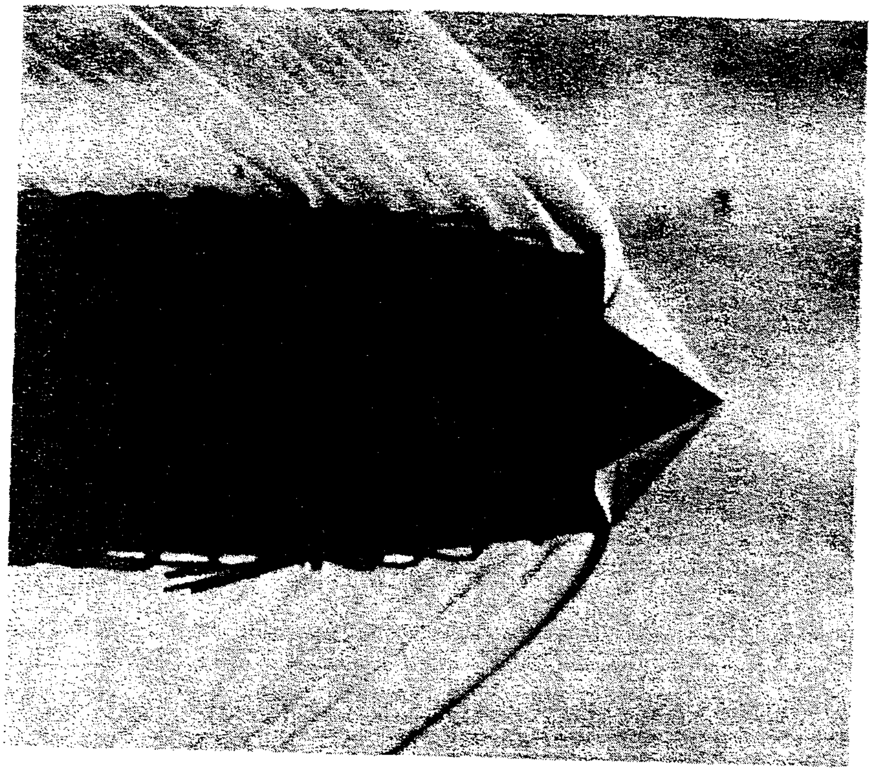

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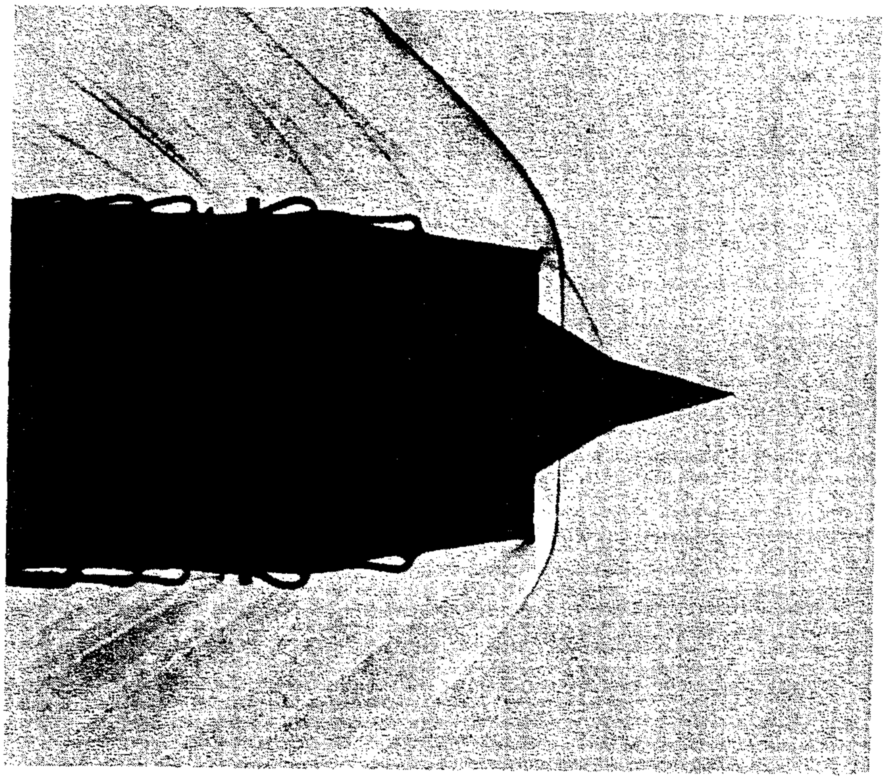
STRAIGHT INLET - 60° CONE
$M_0 = 1.85$

Figure 12.



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STRAIGHT INLET - 30-60° CONE
$M_0 = 1.85$

Figure 13.

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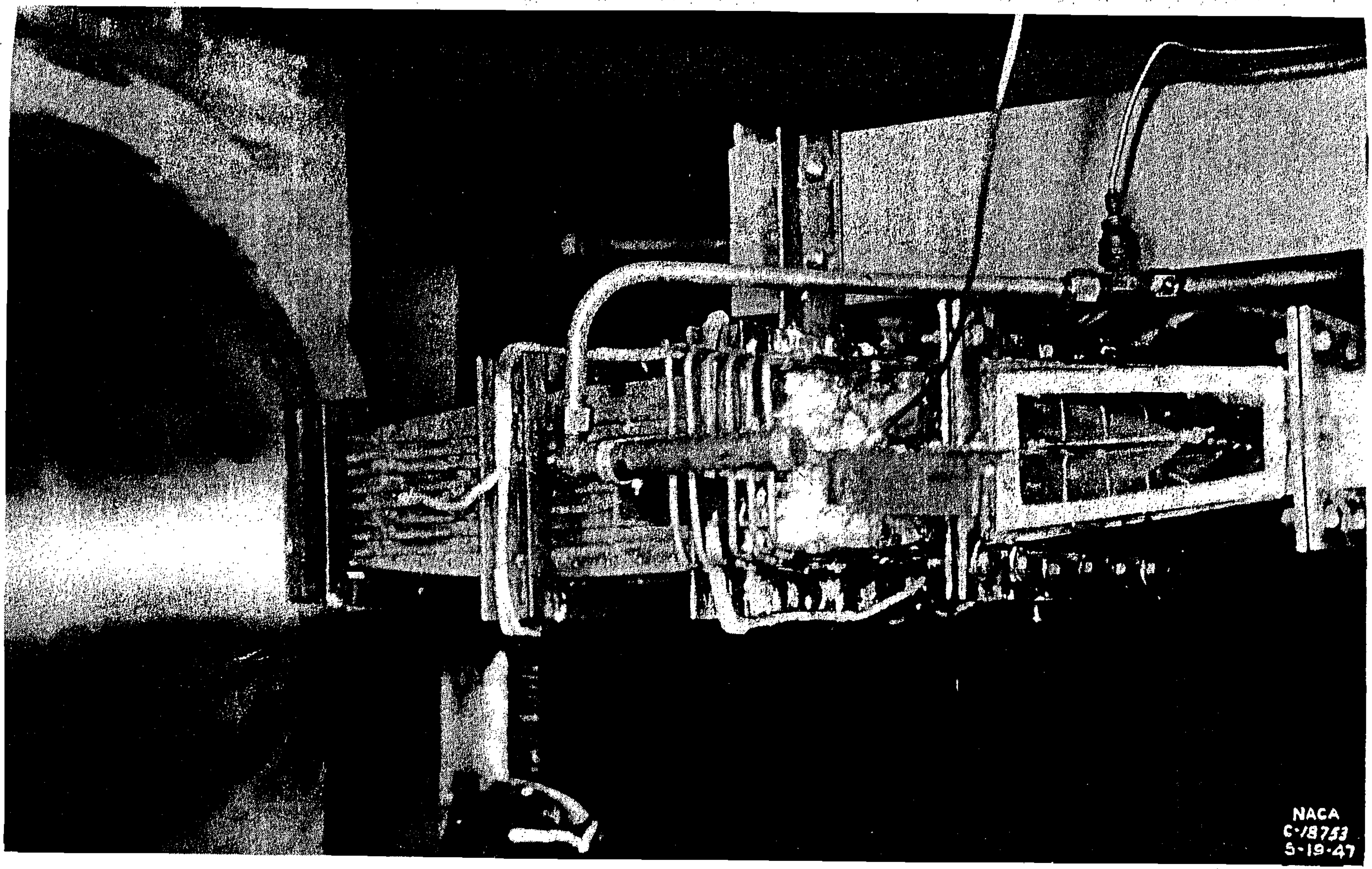

Ram-jet combustion chamber.

Figure 14.

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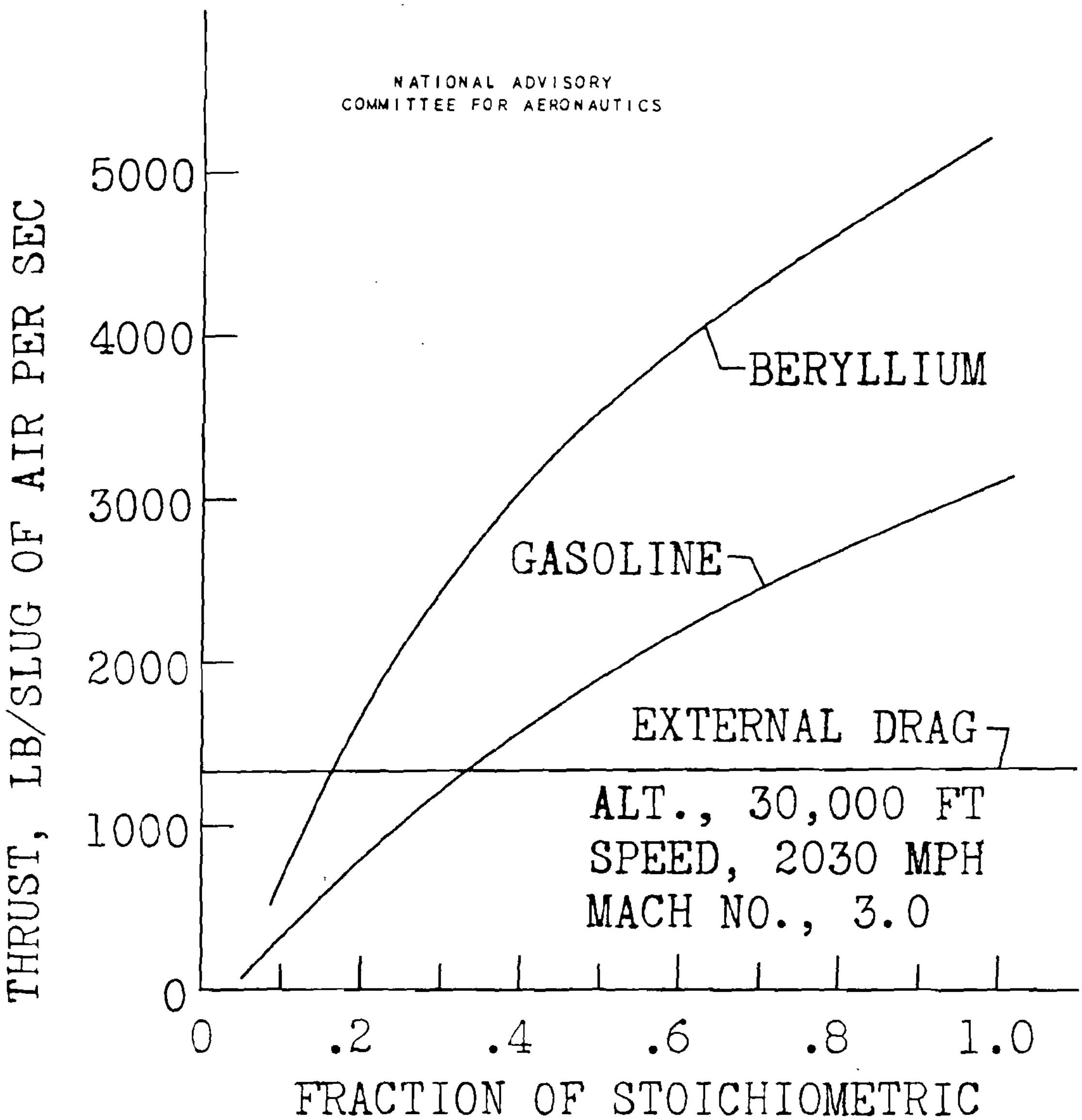
Fig. 14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THRUST, LB/SLUG OF AIR PER SEC
5000
4000
3000
2000
1000
0
BERYLLIUM
GASOLINE
EXTERNAL DRAG
ALT., 30,000 FT
SPEED, 2030 MPH
MACH NO., 3.0
0
.2
.4
.6
.8
1.0
FRACTION OF STOICHIOMETRIC

Figure 15.

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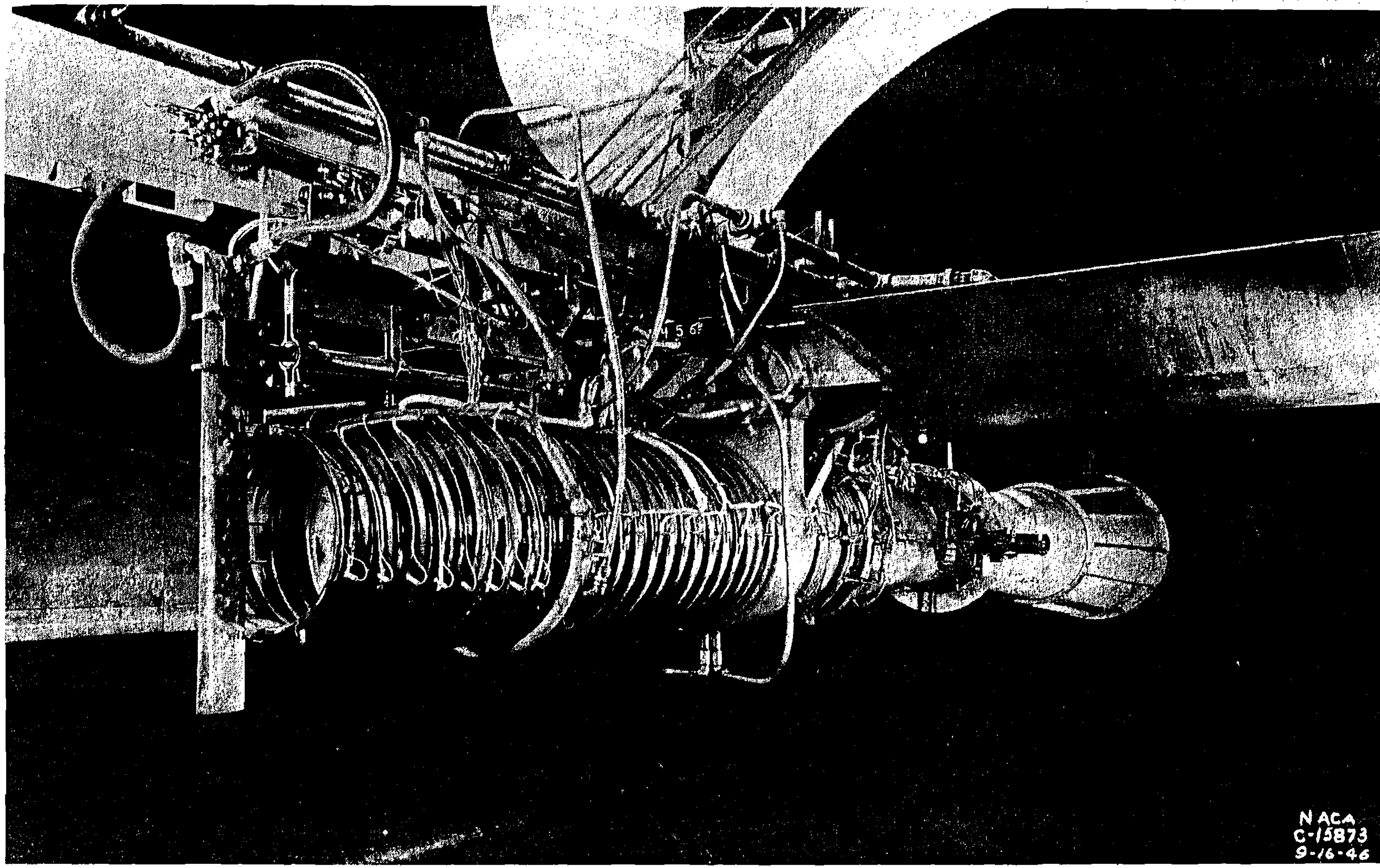

RAM JET INSTALLATION IN ALTITUDE WIND TUNNEL

Figure 16.

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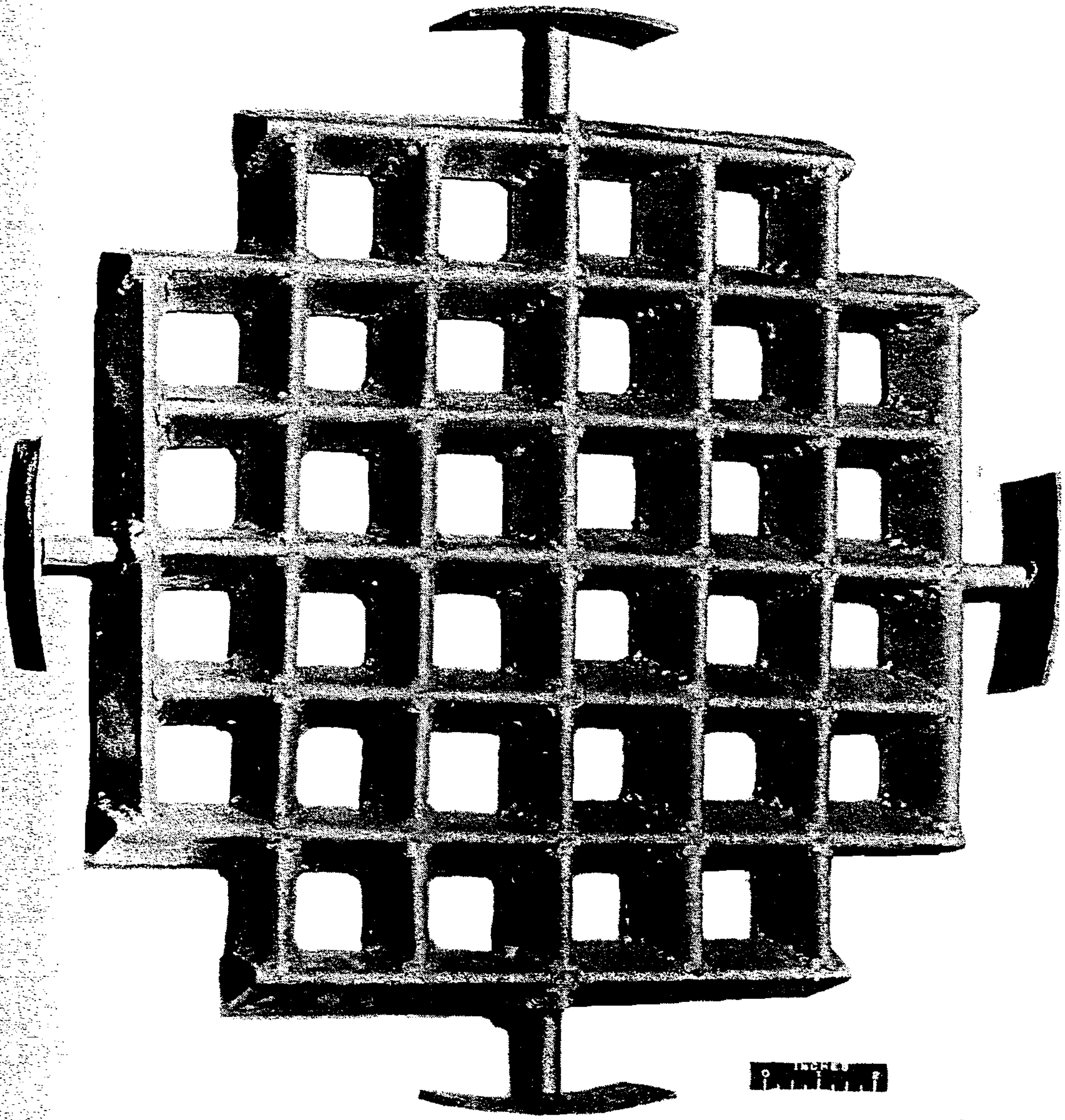
Fig. 16



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CUTTER GRID FLAME HOLDER

Figure 17.

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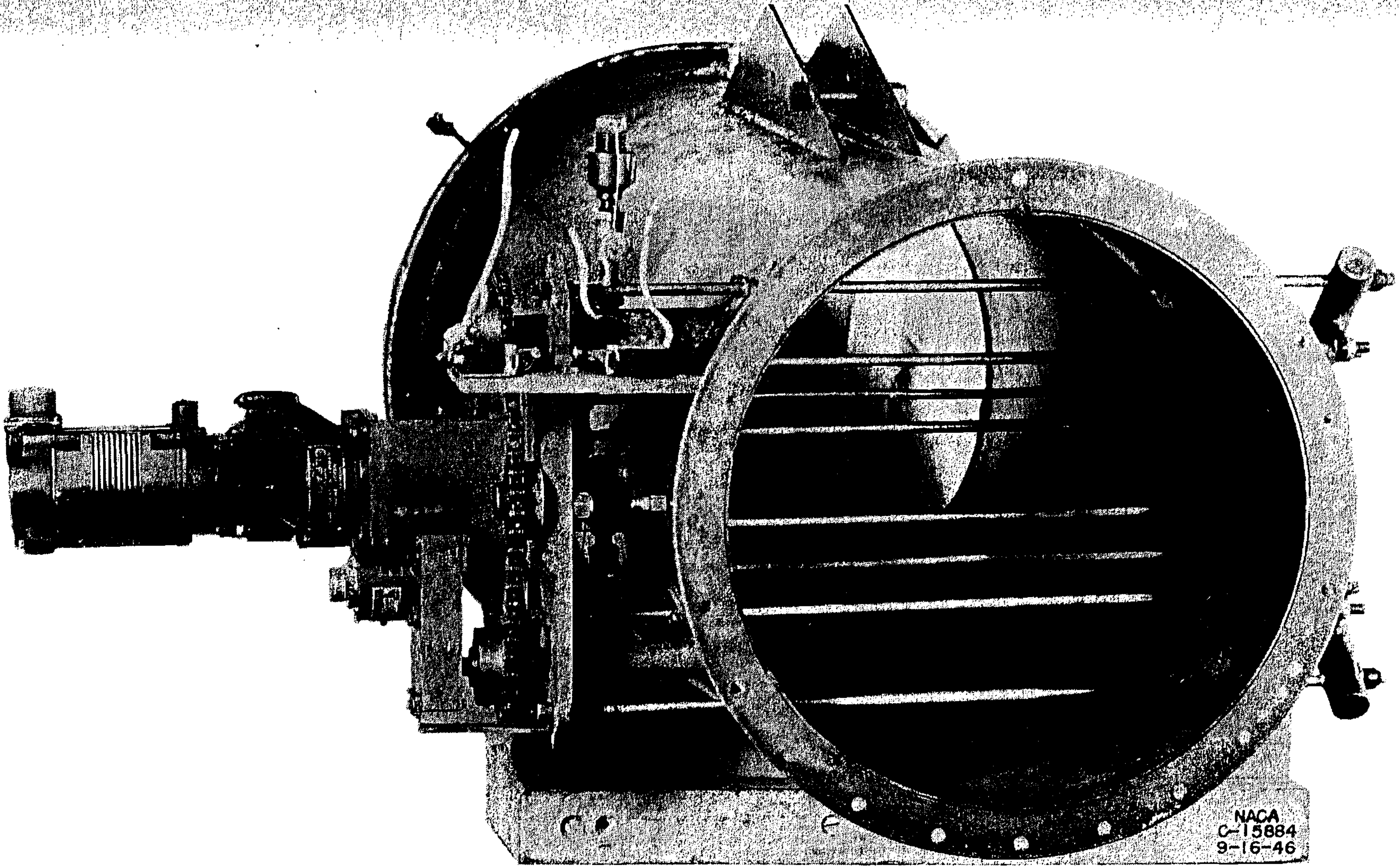

RAM JET FUEL INJECTOR

Figure 18.

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Fig. 18

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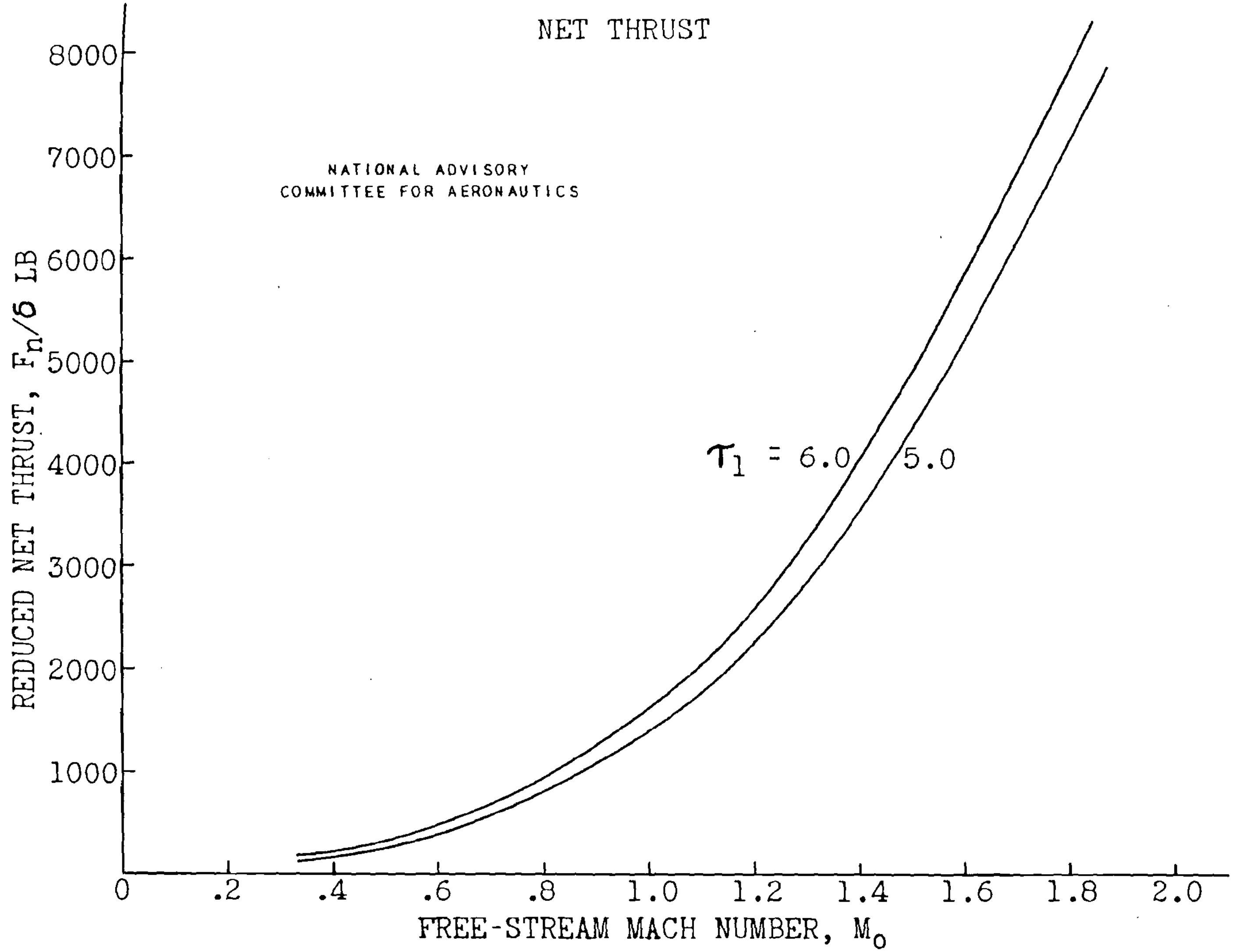

Figure 19.

CONFIDENTIAL

Fig. 19

CONFIDENTIAL

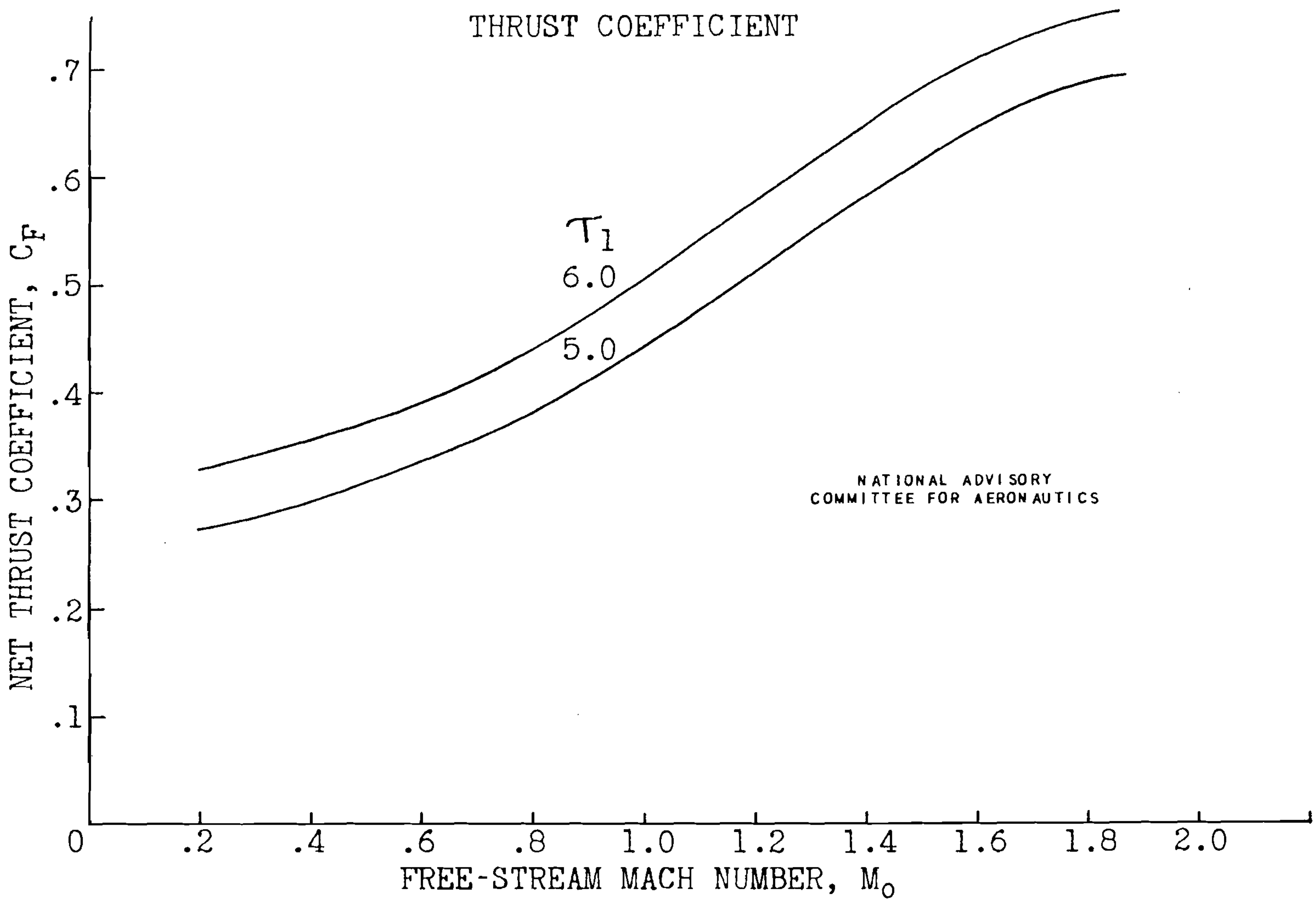

Figure 20.

CONFIDENTIAL

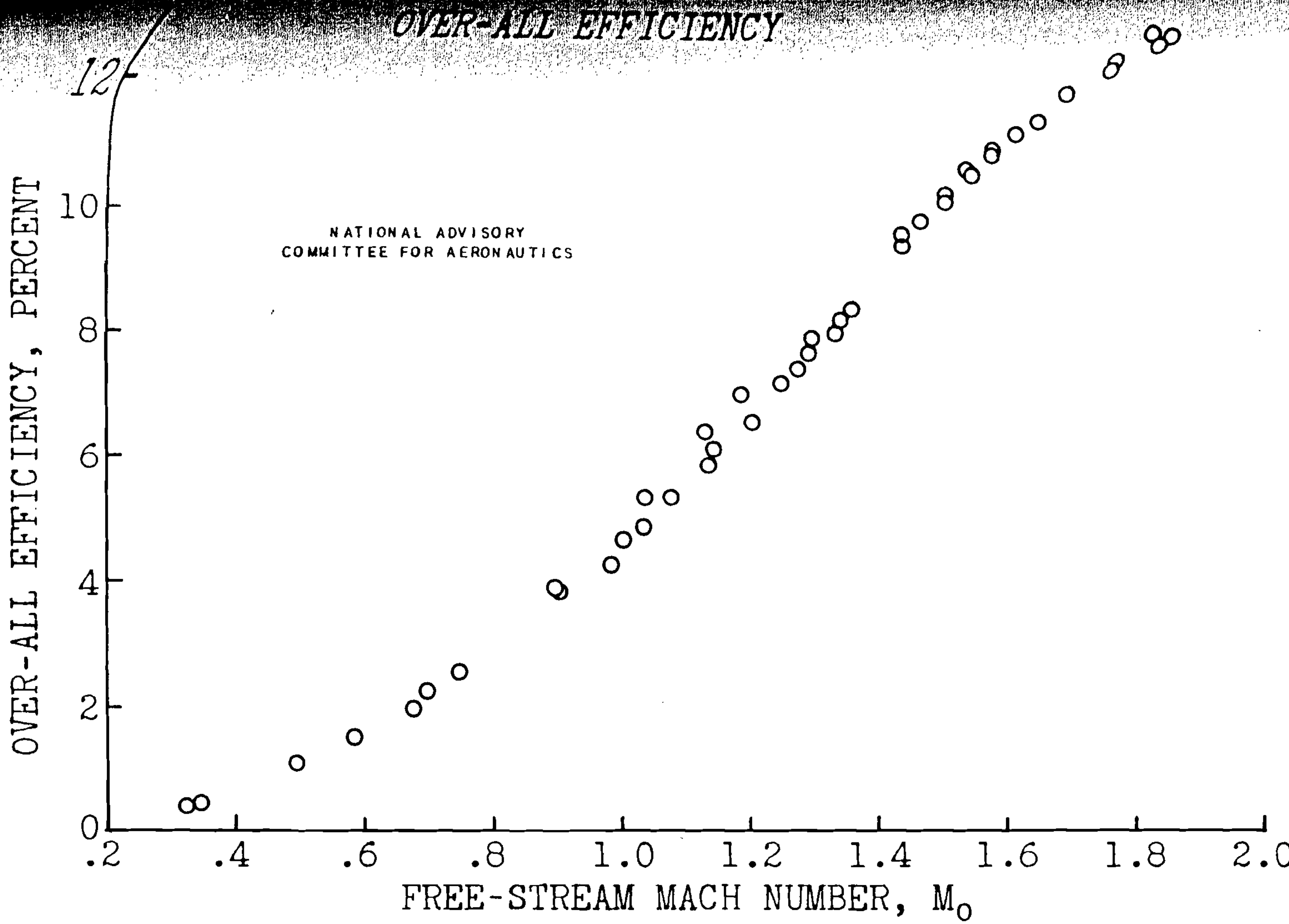

Figure 21.

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