PRACTICAL SUBSONIC RAM JET DESIGN

A ram jet engine is a device from which usefuI thrust can be obtained by creating a velocity difference between the atmosphere entering the ram jet body and the same quantity of air leaving the ram jet body. This velocity difference between entrance and exit air is accomplished by the addition of heat to that portion of the airstream flowing through the ram jet body. Burning liquid fuel inside the ram jet body is one means of adding heat to a ducted airstream and is the only method with which this monograph will be concerned.

The ram jet engine is composed of three major components: a body structure, fuel injection system, and a flame stabilization system. A poor design of any one of these parts will nullify a good design of the other components. In order to build a good performing engine all three components must be of proper design because of their close relation and dependence upon each other.

BODY STRUCTURE
(Diffuser)

The body of a subsonic ram jet engine is an open duct composed of a divergent nozzle (called a diffuser), a combustion chamber, and a convergent nozzle (usually called the nozzle). (SEE FIG #1)

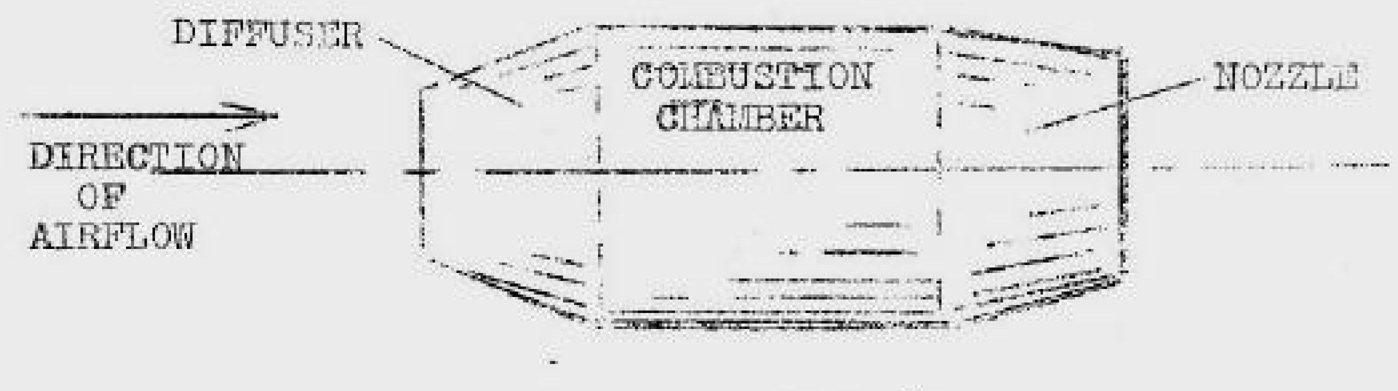


FIG #1

The amount of thrust or push desired from the ram jet engine at a given speed determines the size of the diffuser entrance area. The larger the diffuser entrance area the greater the thrust.

The following figure #2 is a plot of average net thrust available per one square inch of diffuser entrance area. versus the operating velocity of the ram jet engine.

As an example, suppose a designer desires to design a ram jet engine for a small ram jet helicopter which requires engines at the rotor tips to produce a net thrust of thirty-five pounds per engine. This helicopter is to be equipped with rotors twenty-three feet in diameter and operate at a RPM of 665. Since the engines are attached to the rotor tips the operating velocity of each engine will be equal to rotor tip speed which may be calculated as follows:

Rotor Tip Velocity (ft/sec) = pi x diameter x RPM/60
= 3.1416(23)(665)/60
= 800

THRUST
(pounds per
square inch

of Diffuser
entrance area)

Referring to Fig #2 the designer roads a net thrust of 3.5 pounds available per square inch of diffuser entrance area at an operating velocity of 800 ft/sec.

To construct a ram jet engine producing a net thrust of 35 pounds at an operating velocity of 800 ft/sec., the diffuser entrance should have ten square inches of area.

The ratio of diffuser entrance area to diffuser exit area varies from three to four for most subsonic ram jet designs. The most widely used value being three and one-half. Using this value the diffuser exit area will be thirty-five square inches. Therefore, the diameter dimensions for the example ram jet engine diffuser will be:

$$\text{Entrance Diameter } m = \frac{\text{Area} \times 4}{\text{pi}} = \frac{10(4)}{3.14} = 3.56 \text{ inches}$$

$$\text{Exit Diameter} = \frac{35(4)}{3.14} = 6.67 \text{ inches}$$

The length of the diffuser depends upon the designer's choice of one of two probable configurations. A hollow cone frustum is the easiest of the two configurations to fabricate but is longer in length than the other configuration which consists of a hollow cone frustum with a curved insert (See Fig #3). The latter configuration is used in most commercial ram jet designs because its shorter length offers less drag (resistance to movement through the atmosphere).

NOTE: Curved insert allows the use of a larger cone angle (between 10 and 30 degrees)

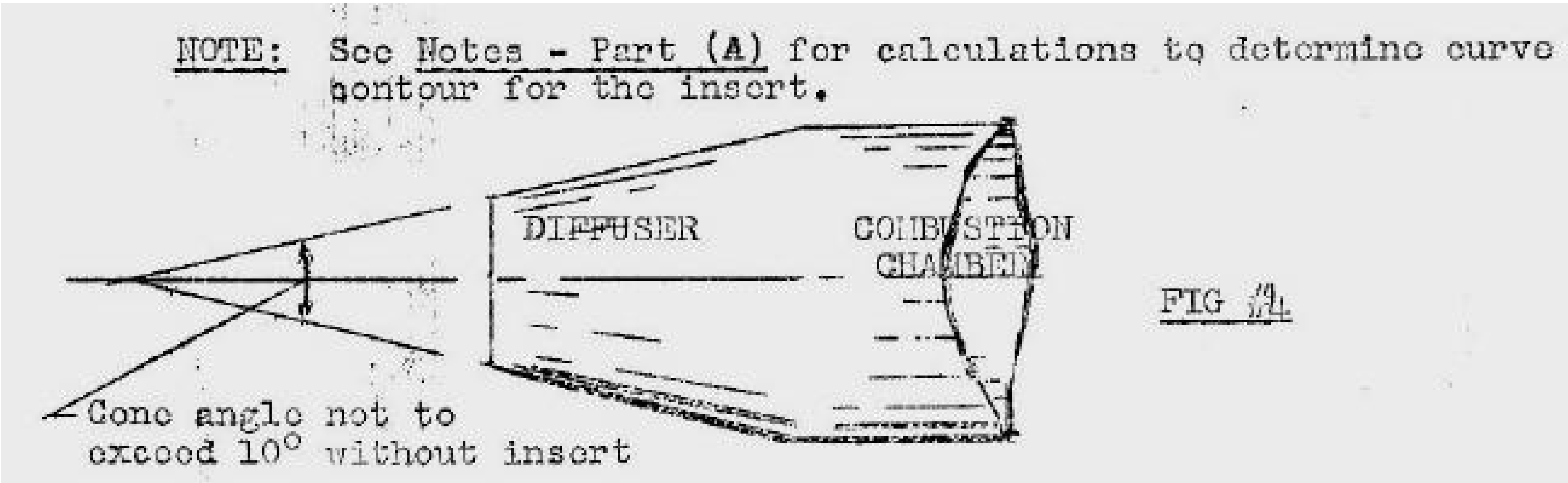
The cone angle of a diffuser without thc curved insert should not exceed ten degrees (SEE Fig #4) or the efficiency of the diffuser will fall below an acceptable limit. A simple mathematical equation for calculating the cone length for a diffuser with an insert may be stated as follows:

$$\text{Diffuser length} = \frac{\text{Diffuser Diameter @ Exit} - \text{Difuser Diameter @ Entrance}}{0.525}$$

For the example engine, diffuser length will be:

$$\text{Diffuser Length} = \frac{6.67 - 3.56}{.525} = \text{Approximately 6 inches}$$

NOTE: See Notes - Part (A) for calculations to determine curve contour for the insert.



Combustion Chamber

The combustion chamber is merely a hollow cylinder with a diameter equal to that of the diffuser exit diameter. Its length is usually determined by trial and error. However, a good "rule of thumb" is make the combustion chamber length approximately three times the diffuser entrance diameter.

The combustion chamber for the example engine will be a cylinder 6.67 inches in diameter and 10 inches long.

Nozzle

The exit nozzle, which is located downstream from the combustion chamber has its entrance diameter equal to the diameter of the combustion chamber. Nozzle exit diameter is dependent upon combustion chamber temperature and can be determined mathematically. Such mathematical treatment is beyond the scope of this monograph. A good "rule of thumb" that the practical designer can use to obtain this dimension is make the nozzle exit area approximately 1.4 times greater than the diffuser entrance area. The nozzle exit area is a critical dimension and this value can best be determined by trial and error (varying the area until the highest thrust value is obtained). However, the above stated empirical factor will give a reasonably close value.

For the example engine the exit diameter of the nozzle will be:

$$\text{Exit Diameter} = \frac{10\,(1.4)(4)}{3.14} = 4.22 \text{ inches}$$

The length of the nozzle is not critical and is usually no greater in value than the entrance diameter of the diffuser.

From the information obtained in FIG #2 and the above stated empirical factors, the designer will construct the body of his ram jet engine to the dimensions shown in FIG #5, if he desires an Engine that will produce thirty-five pounds of thrust at an operating velocity of 800 foot per second.

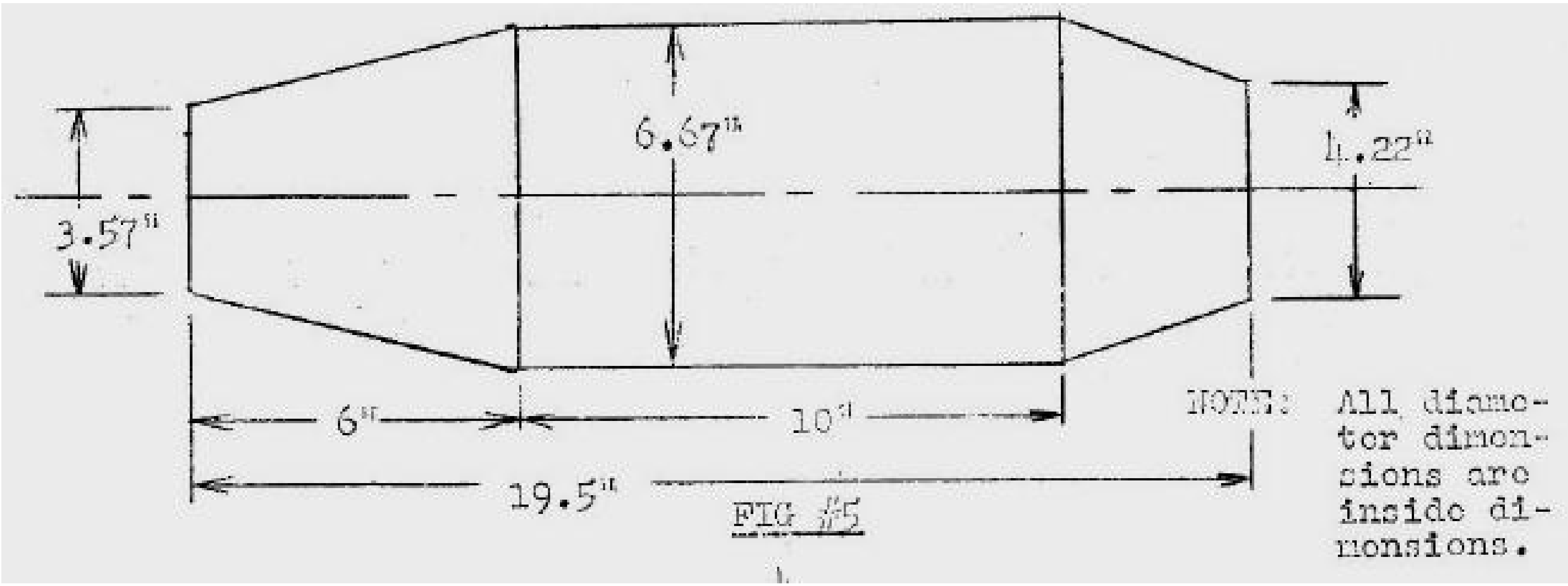


FIG #5

Material

The recommended material for fabrication of ram jet engine shells would be Type 310, 321, or 347 stainless steel, Typo 347 being the most suitable of the three. A sheet thickness of 16 gage could meet strength requirements for engine shells up to a maximum diameter of 7 inches. If a base plate is employed in the body structure (see description below) 20 gage sheet stock may be used to fabricate the diffuser, combustion chamber, and exhaust nozzle.

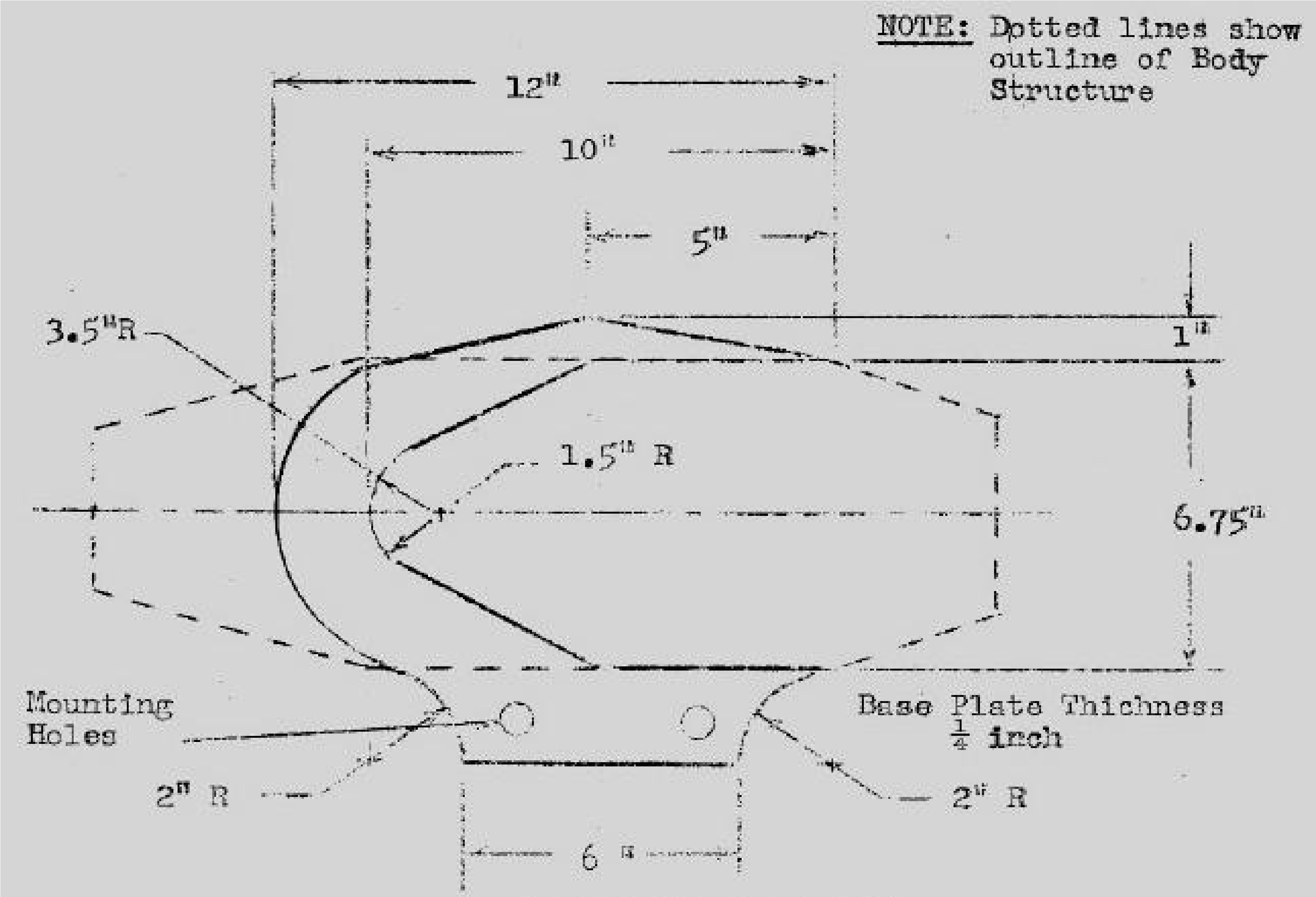
Construction

Commercial ram jet shells are fabricated from manufacturing processes such as stamping, spinning, etc., which the average experimenter can not afford. The recommended construction procedure for most experimenters would be to roll the combustion chamber from sheet stock into a hollow cylinder and roll the diffuser and exhaust nozzle into cone frustums. Then join all three parts by welding. Extreme care should be employed in welding these parts together so as not to cause warpage and distortion in the body structure. All welding beads should be ground to a smooth finish. A smooth finish inside the engine shell is extremely important.

Base Plate Construction

During operation, the high combustion temperature and centrifugal force cause the body structure to warp out of round and seek a "tear drop" shape, thus destroying the performance of the engine. To prevent such warpage a base plate may be welded to the combustion chamber prior to welding the diffuser and exit nozzle to the combustion chamber.

A base plate for the example engine may have the following dimensions as shown in Figure #6.



BASE PLATE (TOP VIEW)
FIG #6

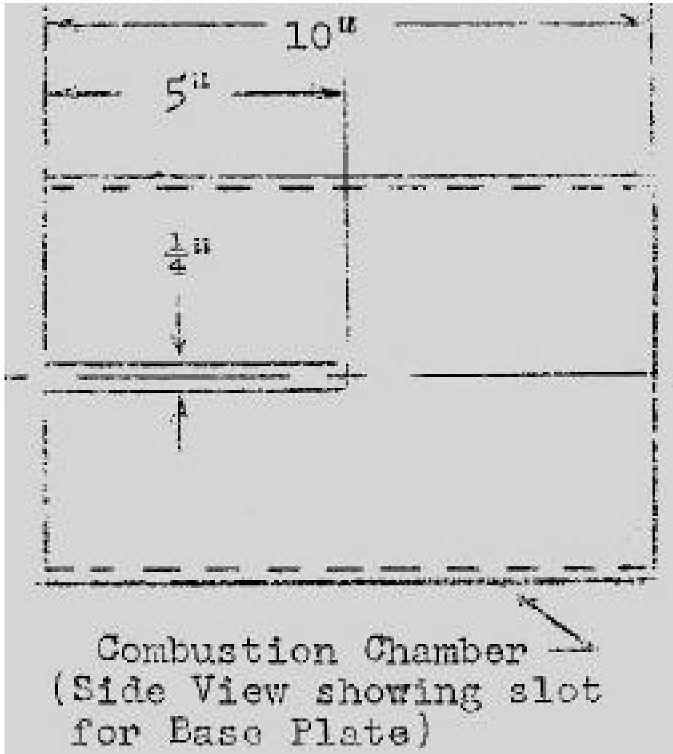


Fig #7

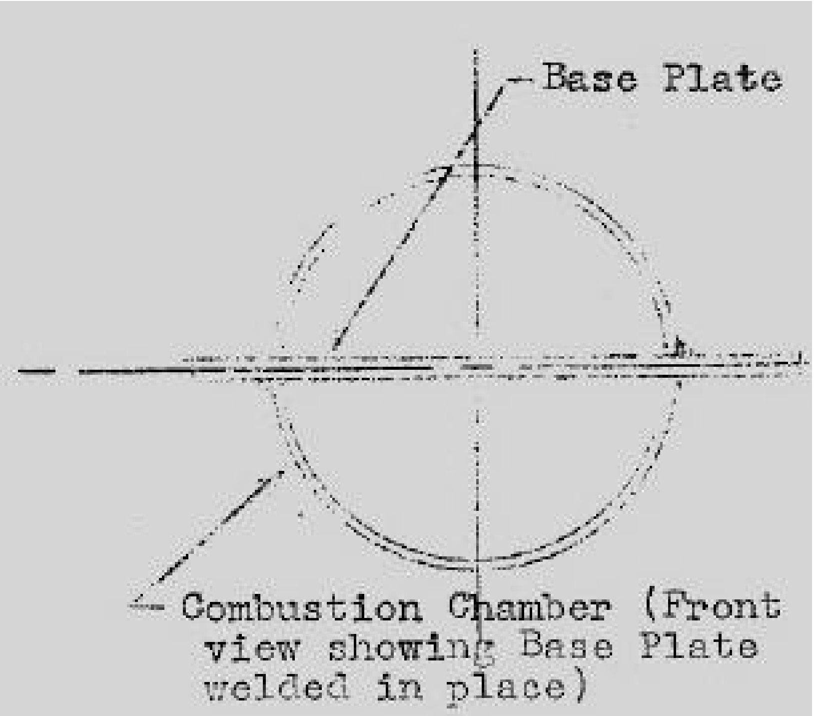
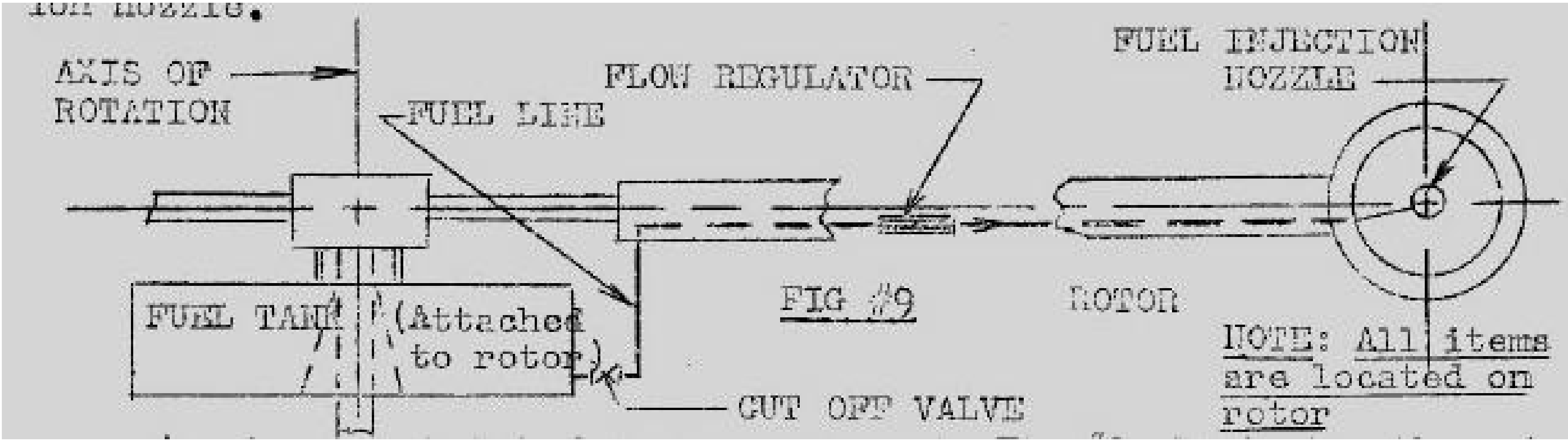


Fig #8

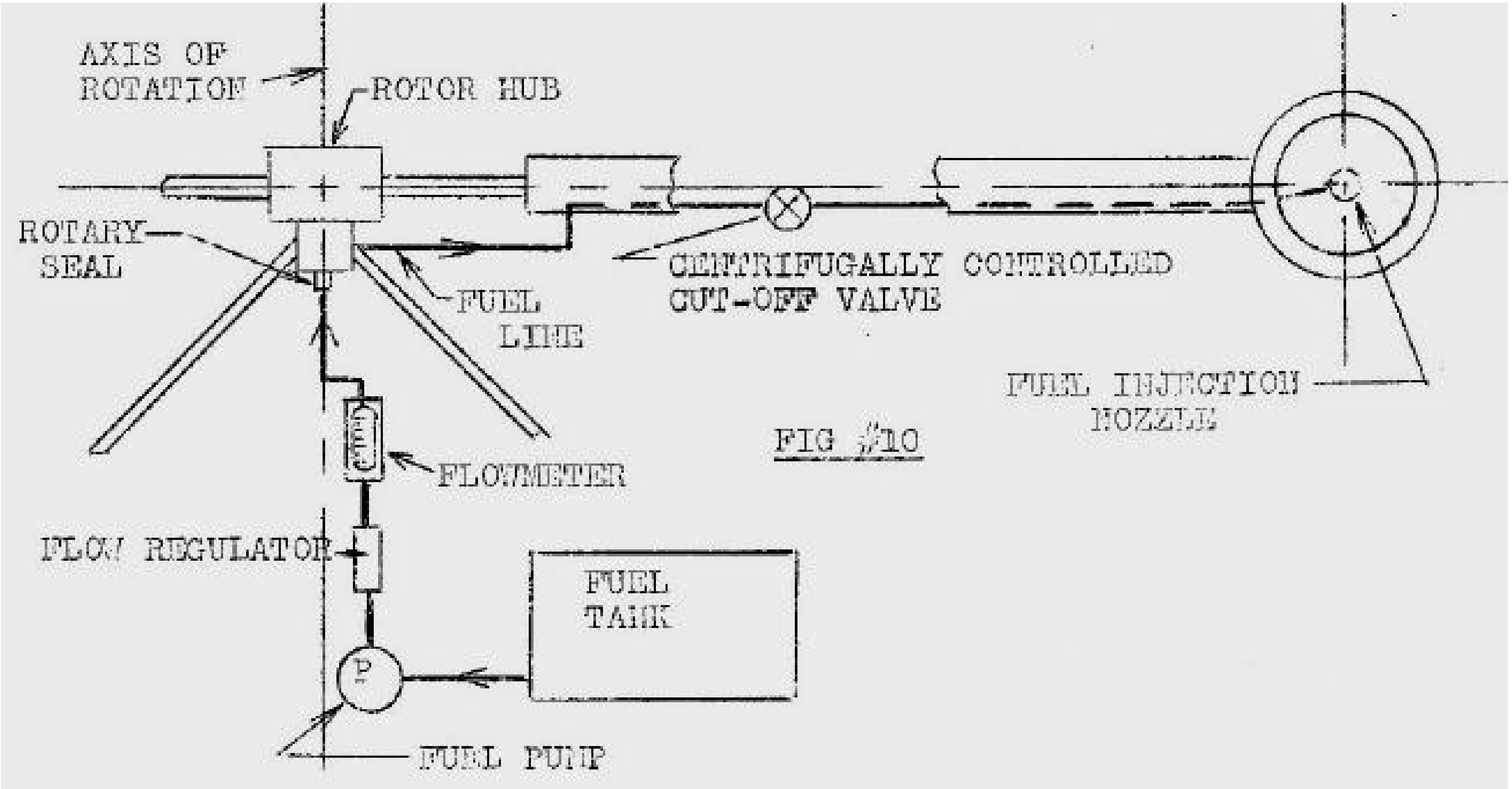
FUEL INJECTION SYSTEM

The fuel injection system includes that part of the ram jet engine which stores and delivers to the airstream entering the engine shell a sufficient quantity of fuel for efficient operation. Figure #9 illustrates the simplest type of fuel system for ram jets propelling a rotor. It should be noted that this system contains only the barest minimum of equipment: fuel tank, cut-off valve, flow regulator, and fuel injection nozzle.



A rotor mounted fuel tank as shown in Fig #9 eliminates the rotary seal and pumping equipment necessary to lift fuel from the fuel tank up to the rotor hub but it complicates rotor stability, works a hardship in refueling and does not provide fuel flow adjustment while the rotor is in operation. Therefore, this system is recommended for test equipment only.

Figure #10 illustrates a more generally used fuel system for ram jet helicopters. A pressurized fuel tank could replace the fuel pump and for light weight designs would be desirable.

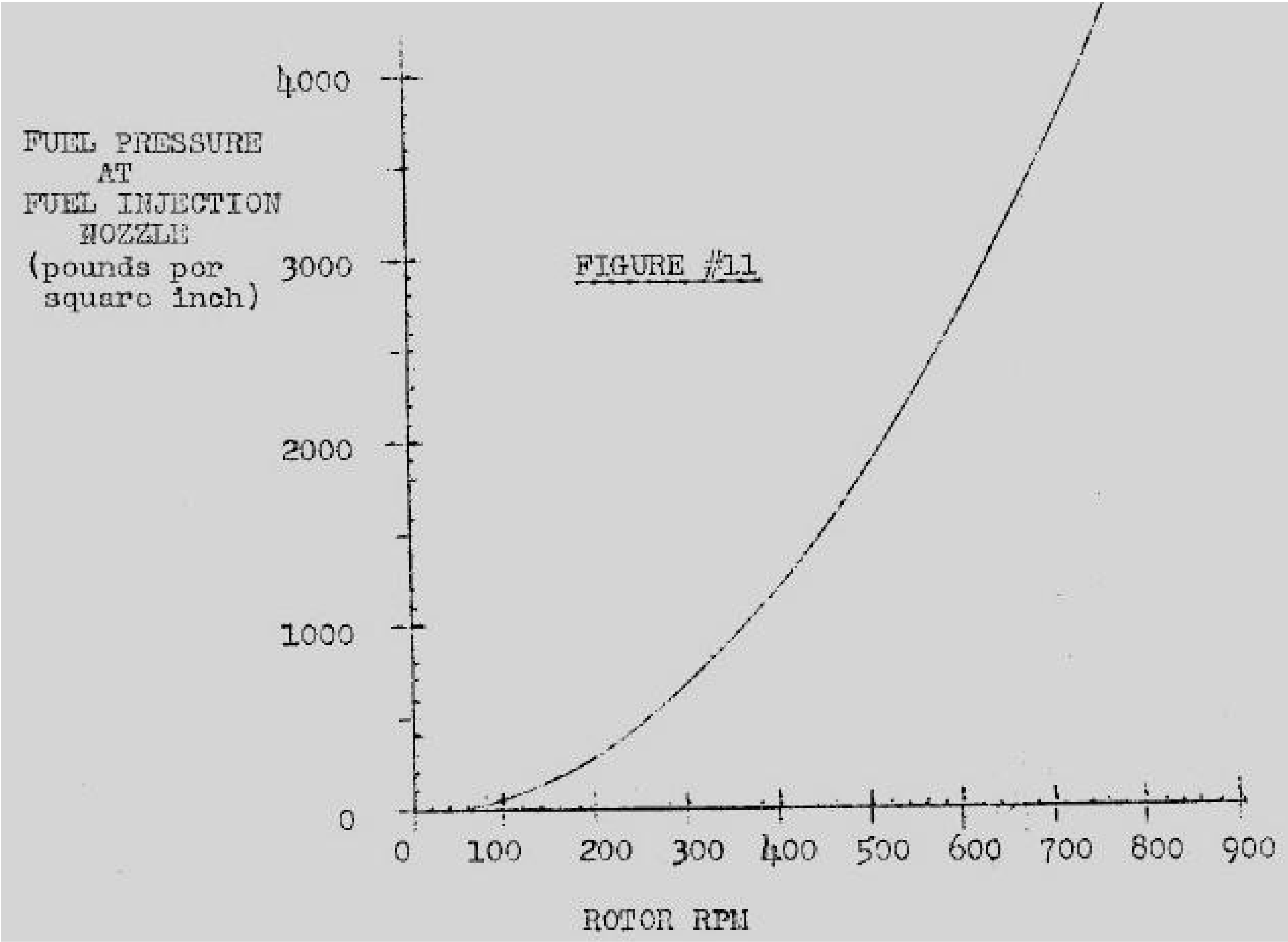


Flow Regulator

An ideal flow regulator should automatically regulate fuel flow for changes in engine velocity, changes in altitude, etc. However, such complicated devices are not essential to the satisfactory operation of small ram jet helicopters. A manually operated needle valve in conjunction with a flow meter can provide reasonably good fuel control. Also, there are flow control devices available commercially that meter a given volume of flow regardless of input pressure. Hays manufacturing Company, Erie, Pa., makes a simple inexpensive "Mesurflo" control which appears to be ideal for use in the fuel injection system described in Figure #9.

Fuel Injection Nozzle

Design of fuel injection nozzles for ram jets employed on a rotor is complicated by unavoidable high centrifugal force created due to rotation. This force boosts the fuel pressure at the nozzle to approximately 3000 psi. Figure #11 is a plot of fuel pressure at the fuel injection nozzle versus rotor RPM for a nozzle located on a 23 foot diameter. (See NOTES - Part B for further information.)



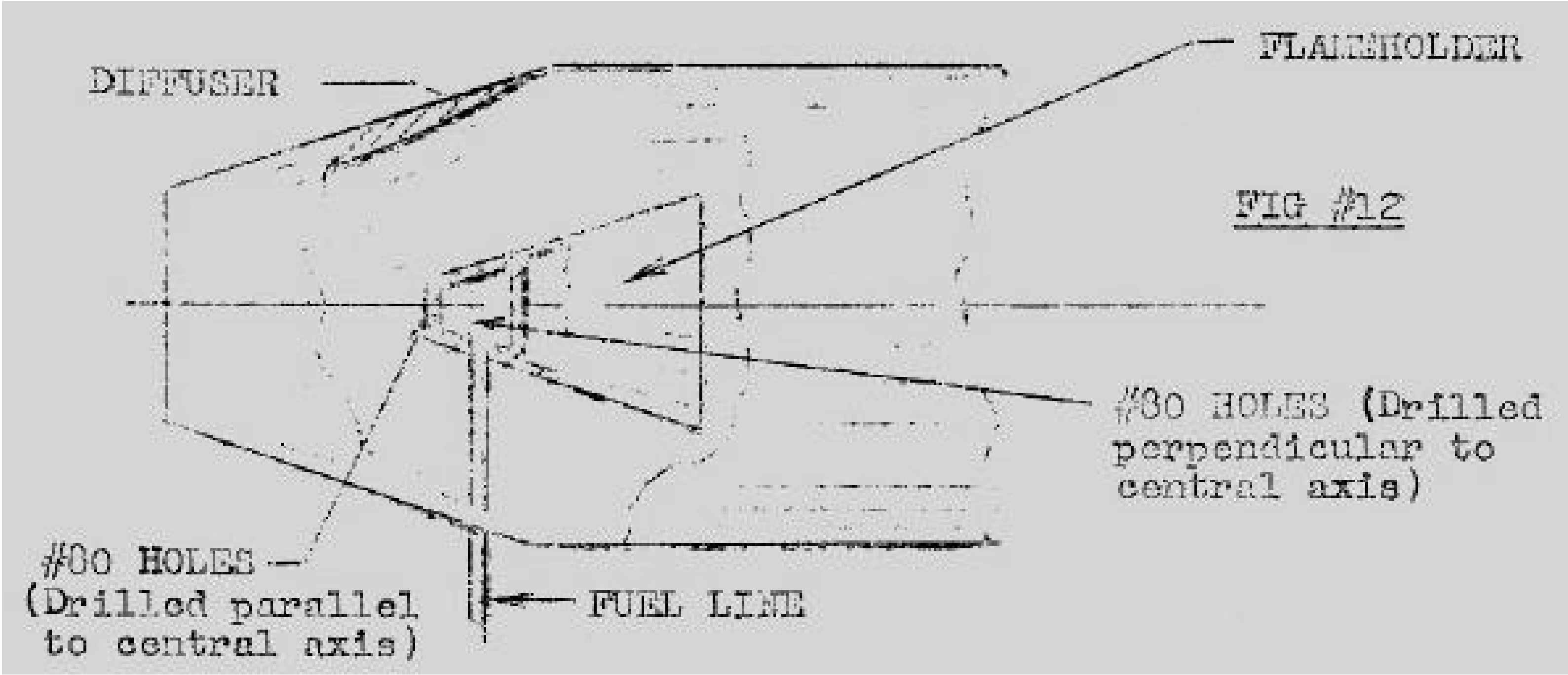
High fuel pressures require extremely small nozzle openings which in turn mean more expense in construction of a nozzle and poorer fuel distribution control. Also, this unavoidable high pressure at the nozzle indirectly affects development costs because expensive high pressure pumping equipment is required to duplicate fuel flow characteristics during static wind tunnel tests.

There are many inexpensive nozzles available commercially that could be used with good results provided the fuel pressure is low. Most of those nozzles are designed and calibrated to operate with fuel pressures in the neighborhood of 100 PSI. Some thought has been given to the possibility of equipping the fuel system with a pressure regulator which would maintain the pressure at the nozzle at 100 PSI regard-loss of rotor RPM. The advantage of being able to use cheaper nozzles, to predict the fuel distribution pattern with more certainty and use loss expensive pumping equipment may not be overcome and disadvantage of added weight, and possibility of pulsation in fuel flow which would cause "rough burning" in the combustion chamber.

Fuel injection designs depend to a great extent upon the design of the flame stabilization system but in general:

> good design requires a uniform mixing of the fuel and incoming airstream with as little disturbance to the air flow as possible.

Such a requirement usually means a centrally located nozzle spraying fuel upstream and in a direction perpendicular to the flow of the airstream. Figure #12 shows this type of nozzle.



The fuel nozzle design shown below in Figure #13 follows the principle stated above and is recommended for a ram jet engine employing a base plate in its body structure. It merely consists of 1/4 inch tubing silver soldered to the front of the base plate and drilled with #80 holes whose axes are perpendicular to the direction of air flow. Those holes are so spaced as to allow a denser fuel flow in close to the center. The exact spacing and number of holes can best be determined by trial and error during testing.

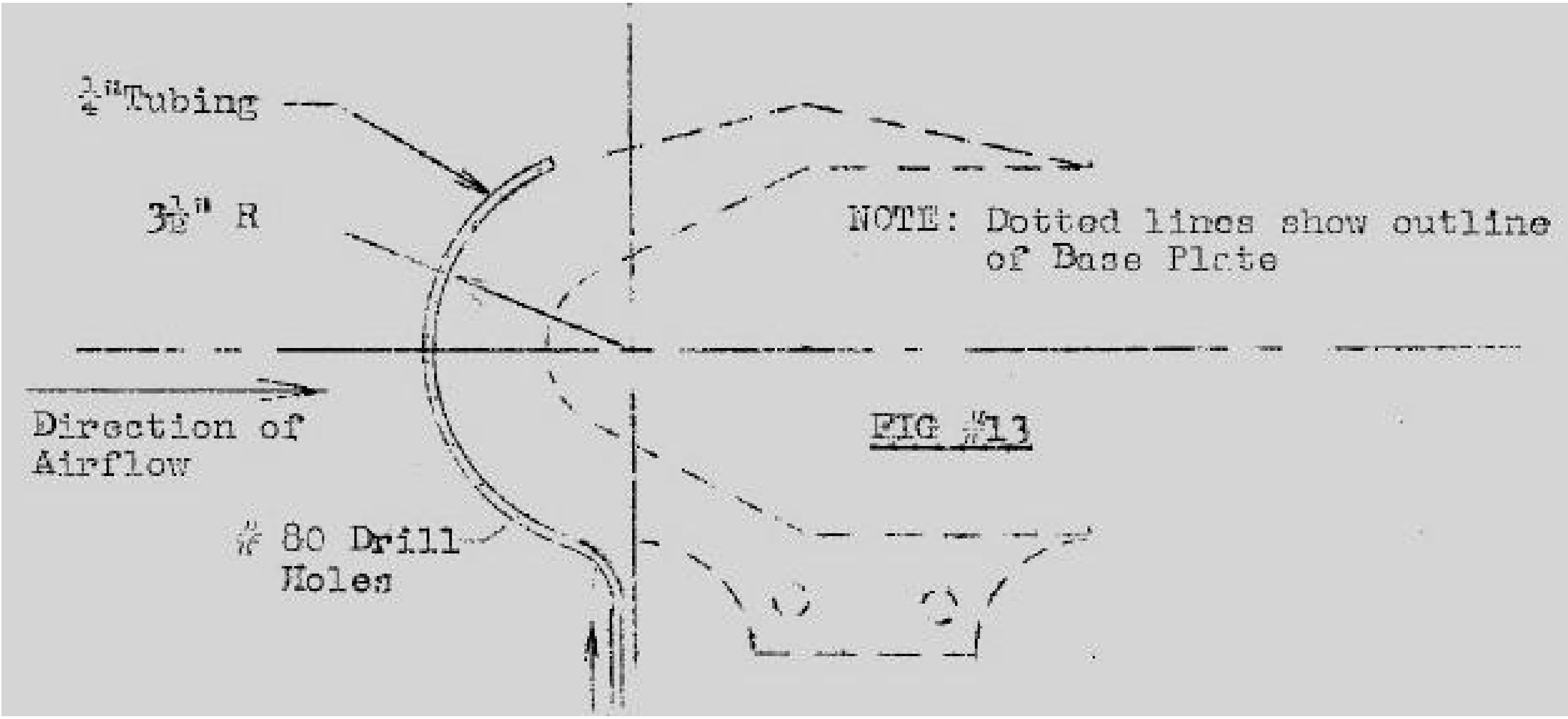


FIG #13

Proper fuel distribution is extremely important. Without proper fuel distribution an otherwise good engine will perform poorly, if at all.

Required Fuel Flow

The required fuel flow depends upon the thrust rating of the engine. Figure #14 is a plot in pounds of fuel required per hour per pound of thrust (S. F. C.) versus operating velocity.

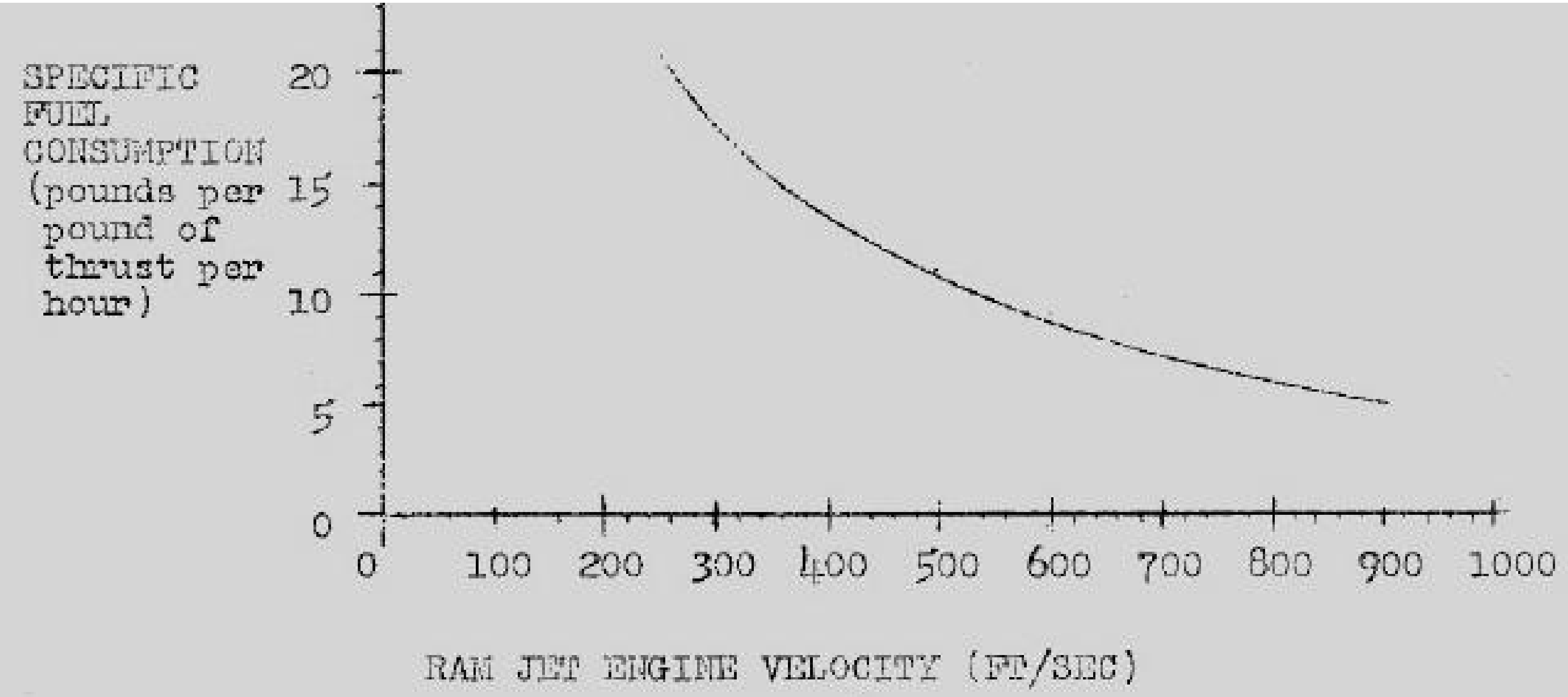


FIG #14

Considering the example engine, the required fuel flow may be calculated by consulting the curve shown in Figure #14. The SFC at an operating velocity of 800 ft/sec is 6. The required fuel flow per engine will be 6 x 35 = 210 pounds an hour (35 gallons). Total helicopter fuel consumption will be 420 pounds (70 gallons). Therefore, the fuel injection nozzle for the example engine must be designed to pass 210 pounds of fuel per hour at operating fuel pressure.

FLAME STABILIZATION SYSTEM
(Flameholder)

In order to maintain flame in any high velocity airstream some means of shielding the flame source is necessary. Such a shielding device is called a flameholder. There are an infinite number of shapes and forms the flameholder may take. Four of the more successful shapes are shown in Figure #15.

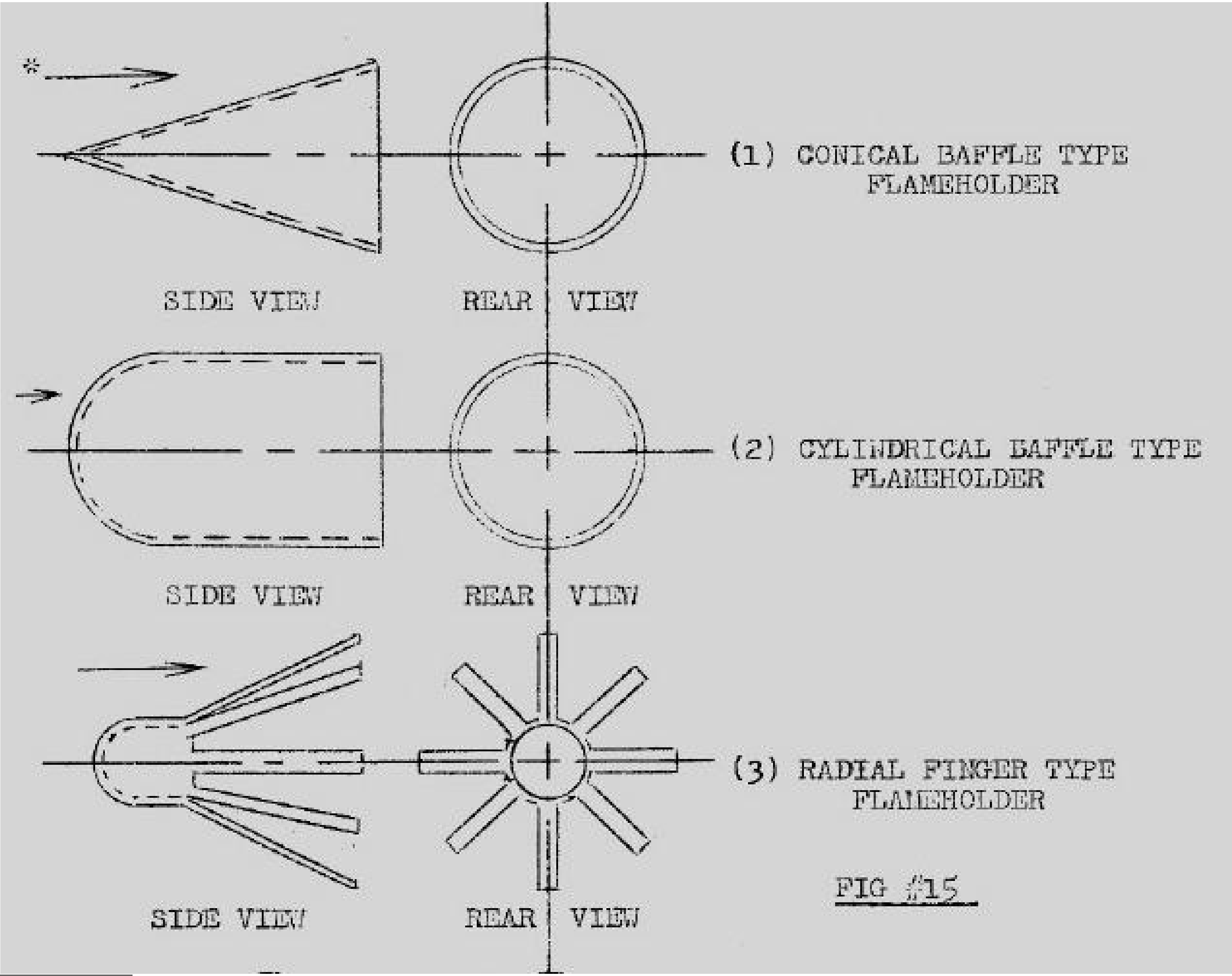
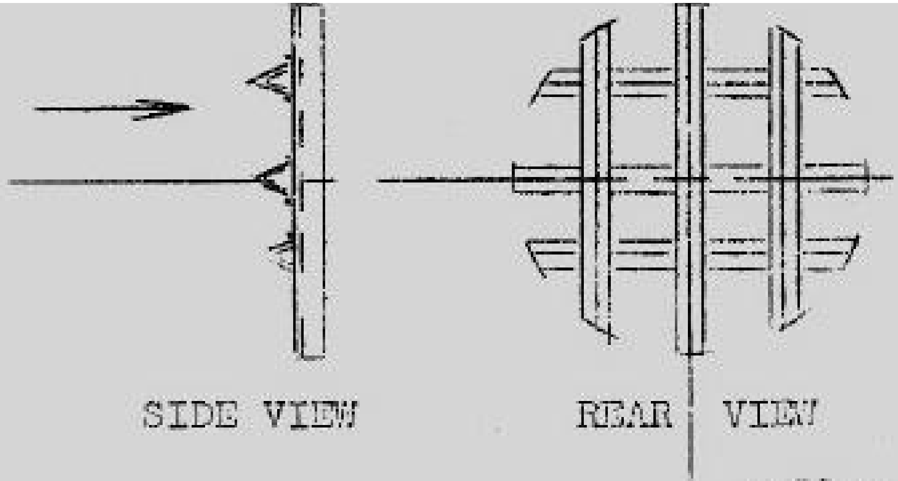


FIG #15



(4) V-GUTTER TYPE FLAMEHOLDER

* Arrow indicates direction of Airflow

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The baffle type flameholders are among the more dependable type flameholders. However, the radial finger or grid type appear to be the most popular in present-day ram jet designs. A baffle type flameholdor operates best with maximum fuel density at the engine's central axis. Taking into consideration the body structure, a conical baffle type, flameholdor appears to be best suited for the example engine. Figure #16 gives the Flameholder dimensions to be used in the example engine.

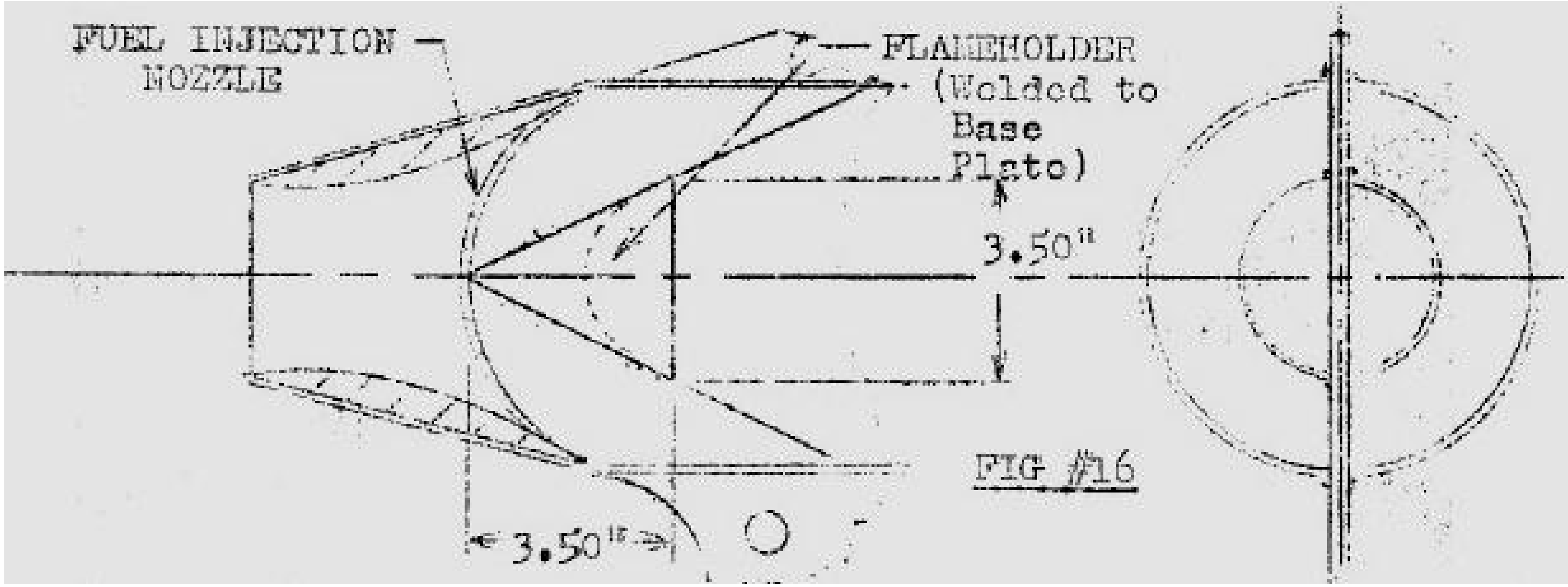

FIG #16

One very important rule to remember in flameholder design may be stated as follows:

> the airflow along the inside wall of the engine shell (this thin layer of air that clings to the wall is called the boundary layer) must not be interrupted by obstructions

because the boundary layer serves as an insulator between the high temperature flame and shell wall. Any interruption usually means hot spots or burnouts in the shell. A violation of this rule is illustrated in Figure #17.

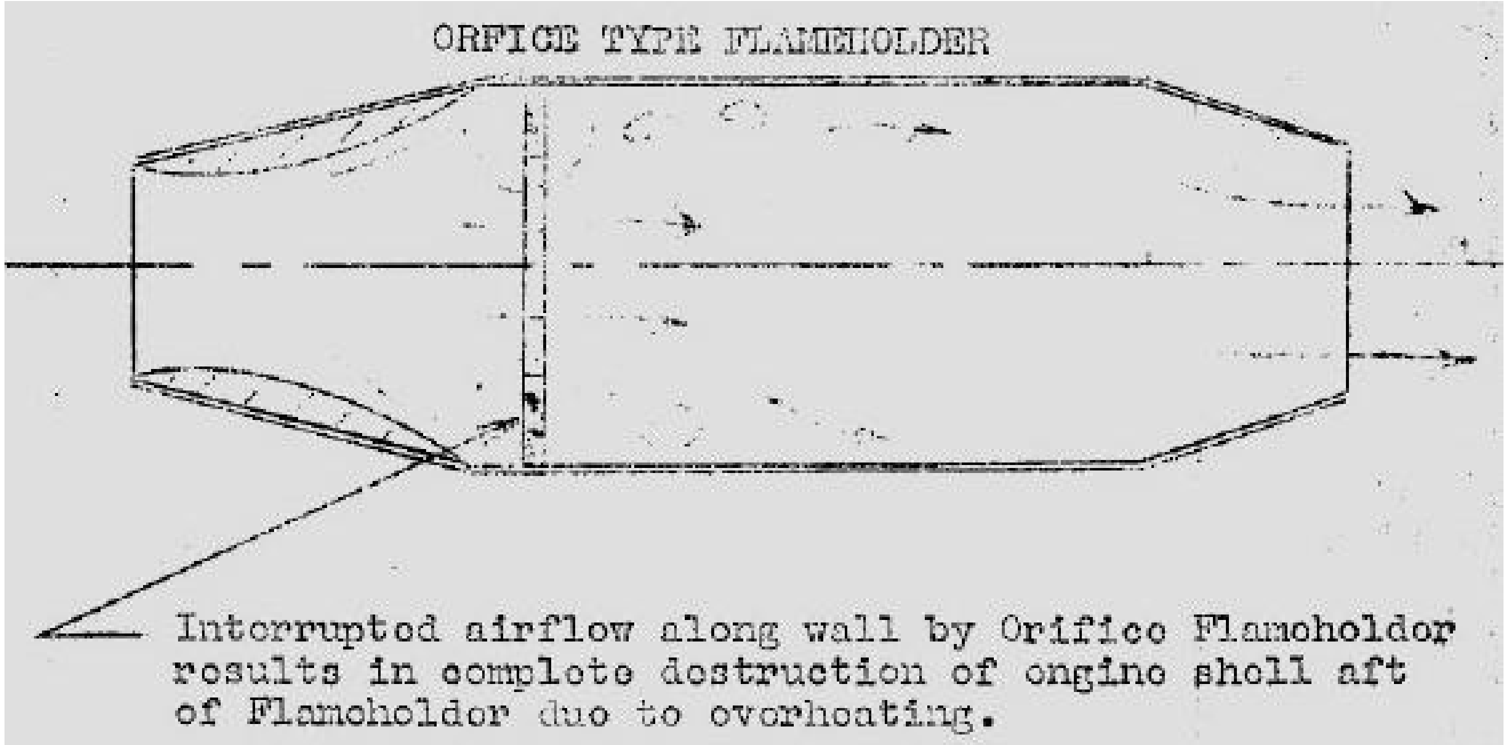

FIG #17

The amount of airstream blockage created by the flameholder directly affects the engine performance. With too little blockage the flame can not be maintained. Too much blockage decreases the thrust available from the engine. The goal of the designer is to maintain combustion over a wide range of fuel flow with as little blockage as possible. A good "rule of thumb" to remember concerning flameholdor blockage is:

> Maximum flameholder cross section area should not exceed thirty (30) percent of combustion chamber cross section area.

Referring to the example engine the area of the base of the flameholder cone should not exceed 30 percent of 35 square inches.

A good comparison factor for indicating the performance of a flameholder is the fuel-air ratio limits at which combustion can be maintained. Each flameholder design has a range of fuel to air mixtures that it will maintain flame. The extremities of this range are usually referred to as lean blowout (the fuel-air mixture at which flame blows out due to too little) and rich blowout (the fuel-air mixture at which flame blows out due to too much fuel). A good flameholdor design should have as long a fuel-air ratio range as possible without offering too much blockage.

Ignitor

In order to ignite the fuel-air mixture that flows past the flame-holder some type of igniter (usually a shielded sparkplug) is required. The exact location of the igniter presents an extremely difficult problem and is determined in most cases by trial and error. Its general location is near the aft end of the flameholder. For the example engine the igniter may be located as shown in Figure #18.

The following equation which was taken from NACA ARR No. L4F26 may be used to determine the curved contour of the diffuser insert.

```
Y = 0.5 D1                                  Where: Y = Vertical coordinate
    -----------------                              X = Horizontal coordinate
    1 + X                                          L = Length of diffuser
        - x (sqrt (A1/A2 - 1))                     A1= Cross section area of diffuser inlet
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L A2= Cross section area of diffuser exit
D1= Diameter of diffuser inlet
D2= Diameter of diffuser exit

Applying the above equation to the example engine we got:

Y = 1.785/1 - .77X

By choosing the X coordinate, the corresponding Y coordinate may be solved for.

The following equation may be used to solve for the fuel pressure at any station along the rotor for a given rotor RPM.

$P = 29.35(N/6C)^2R^2/144$ Where: P = Fuel pressure (1b/sqin)
N = Rotor speed (RPM)
R = Distance Station is from center of rotation (ft)

As an example solve for the fuel pressure at a flow regulator located on the rotor 2 foot from the center of rotation when the rotor is traveling 600 revolutions per minute.

$$P = \frac{29.35(600/60)^2(2)^2}{144} = \frac{29.35(100)(4)}{144} = 82 \text{ lb/sqin}$$

IMPORTANT - PLEASE NOTE

In response to the many inquiries received from purchasers of this monograph, answers to the following questions have been provided.

QUESTION #1: Is this fuel consumption, as quoted in this monograph, too high?

ANSWER: The fuel consumption, as indicated in Fig #14, represents the average values obtainable with subsonic ram jets to date. It is much higher than most people realize, and for this reason, there is much debate among engineers concerning the value of the engine as a propulsive means for helicopters, since it costs the operator approximately $10.00 for fuel to operate a 35 pound thrust ram jet engine an hour. The advocates of ram jets argue, and with good reason that the difference in cost between a ram jet helicopter and a conventional helicopter will more than make up the difference in fuel cost. This is a question each person will have to answer for himself.

QUESTION #2: Why did you choose the value of 35 pounds of thrust for the example engine?

ANSWER: This is an average thrust value that published data indicates the ram jet engines for both McDonnell's and Hiller's ram jet helicopters operate.

QUESTION #3: If I follow the instructions set forth in this monograph, can I be assured of a ram Jet engine operating according to the performance indicated in this monograph?

ANSWER: No! The ram jet engine, at best, is somewhat erratic in operation, and the builder will have plenty of adjusting to do before he can be assured of a satisfactory engine.

QUESTION #4: Do you sell assembled ram jet engines, parts, or kits for making your own ram jet engine?

ANSWER: No. However, such is the plan for the future with the development of an engine having better fuel consumption characteristics.

WARNING: **IF YOU INTEND TO EXPERIMENT WITH RAM JETS, BE SURE YOUR TEST ROTOR IS IN A SAFE LOCATION. A STRUCTURE FAILURE CAN RELEASE A RAM JET FROM THE WHIRLING ROTOR AT SPEEDS EQUIVALENT TO AN ARTILLERY SHELL AND THE PARTED ENGINE CAN DO AS MUCH DAMAGE.**

QUESTION #5: What type of fuel would you recommend for use in a ram jet engine?

ANSWER: Ordinary gasoline or kerosene.

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CONTENT IS TAKEN FROM:

PRACTICAL RAM JET DESIGN

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DECKER ENGINE WORKS

Plasterco, Virginia