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SECURITY CLASSIFICATION Open

SUBJECT Powerplants for VTOL Aircraft: A Preliminary Examination of Y-Axis Centrifugal Fans.

PREPARED BY E.P. Cockshutt and P.J. Lewty

ISSUED TO

SUMMARY:

An analysis is presented of a VTOL powerplant system, comprising several turbojet engines used as gas generators, driving through power turbines a series of centrifugal fans disposed along a common shaft on the wing centerline. For the chosen fan pressure ratio of 2.0, it is demonstrated that a bypass ratio of about 2.0 is desirable to minimize the powerplant system weight to perform a given mission; it appears, however, that the system proposed is almost 50% heavier than a comparable Z-axis fan-in-wing system.

Table of Contents

1.0 Introduction.

Among the various studies of lifting devices for VTOL aircraft by the Mechanical Engineering Division of the National Research Council, both upward-facing (Z-axis) and forward-facing (X-axis) fans have been examined. In this note the third element of the triad is considered - spanwise—facing (Y-axis) fans (a typical arrangement is sketched in figure 1).

The merits of the Y-axis fan are not inconsiderable, and lie chiefly in the mechanical attractiveness of a long, continuous shaft, driven from a single turbine possibly in the fuselage of an aircraft, with several fan units coupled together. The possible disadvantages of the system include the fact that air must be brought in and out of the axial direction in progressing through the lifting machinery.

It is the purpose of this memorandum only to examine a possible arrangement of turbo machinery for a Y-axis configuration. It does not attempt to establish the best method of air intake for the lifting wing (forward-facing, upward-facing, etc), nor does it attempt to establish the method of air exhaust (downward-facing slots, rotating nozzles, etc.).

It has been assumed on the basis of powerplant volume considerations that the Y-axis fan is most suitable for highly loaded lifting systems, i.e., characterized by high efflux velocities and hence low mass flows. This study has been carried out assuming a fan pressure ratio of 2, which corresponds to a nozzle area loading of almost 3000 lbs/ft^2. Space considerations have led to the consideration of centrifugal rather than axial fans. By using the same gas generator as in the previous Z-axis studies, it has been possible to make realistic comparisons of the two schemes.

2.0 Methods of Analysis

The aims of the present analysis were to determine sizes, areas and velocities suitable for achieving the peformance requirements set out above. The following relations were used:

(a) Modified Isentropic Compression

$$\frac{P_2}{P_1} = \left(1 + \eta_c \frac{\Delta T_c}{T_1}\right)^{\frac{\gamma}{\gamma-1}} \qquad (1)$$

(b) Centrifugal Compressor Equation

$$\Delta T = \frac{\sigma p \, (V_{To}^{2} - V_{Ti}^{2})}{2 \, J g_o \, C_p} \qquad (2)$$

(Note that this equation has been generalized to include an incoming tip speed, as well as a leaving tip speed.)

(c) Continuity

$$W = \rho_s \, A \, V \qquad (3)$$

(d) Definition of Mach Number

$$M = V \Big/ \sqrt{\gamma g_o \, R \, T_s} \qquad (4)$$

(e) Adiabatic Flow of a Fluid in a Centrifugal Field

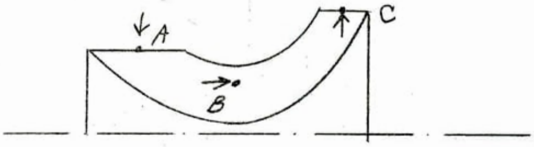
$$T_o - T_i = \frac{V_{To}^{2} - V_{Ti}^{2}}{2 \, J g_o \, C_p} \qquad (5)$$

3.0 Impeller Configuration with Radial Inlet

The idea in using a radial-inflow inlet (see sketch below) for a centrifugal compressor was two-fold:

(a) it appeared to provide a simple method of getting the air distributed and into the rotor, and

(b) it appeared to make possible a very simple rotor construction with untwisted, axial vanes.



Against these advantages had to be weighed the higher tip speeds required (Fig. 2) for a given pressure ratio (Equ.2).

The limiting factor in this design turned out to be the area of the throat of the compressor rotor - station B in the sketch above. Even with a Mach number as high as 0.8, this proved the controlling dimension for the chosen parameters (Fig. 3). One of the reasons for this problem is the appreciable drop in total pressure as the working medium flows inwards against the centrifugal field (doing work on the rotor, which is subsequently put back in on the way out), which results in a low density.

It is probable that the present design - based on the area-mean section - is unduly optimistic in the minimum throat which can be tolerated - since it does not take into account non-uniformities as the flow is turned in the radial-axial plane.

4.0 Conventional Impeller Configurations

By way of comparison with the special impeller described above, a conventional centrifugal impeller with an axial inlet was designed to the same performance specification. Pre-whirl vanes were considered but discarded because of the adverse effects on size of low static pressures as seen above. One important advantage of the conventional compressor is its appreciably lower tip speed for the same pressure ratio (955 ft/sec as compared with 1200 ft/sec above).

Permitting an axial Mach number of 0.5 at inlet, the compressor sees a relative Mach number of 0.825 at the inducer tip, which does not seem excessive for current practice.

The resultant impeller geometry, sketched in figure 4, is clearly much smaller than the radial-inflow arrangement, which was designed for the same mass flow and pressure ratio (Fig. 3).

5.0 Fan Installation Arrangements

Having established an impeller geometry suitable for a pressure ratio of 2.0 and a mass flow ratio of 43 lbs/sec, the next part of the study consisted of attempting to establish weight and size data for an installed unit. After several evolutionary steps, the arrangement shown in Figure 5, was selected on the basis of light weight. A unit is seen to comprise two impellers back-to-back, drawing their airflow from inlet plenum chambers, and discharging to a pair of radial, vaned diffusers. Each diffuser, discharging at a Mach number of about 0.2, empties into an outlet plenum, which subsequently supplies lifting and/or thrusting nozzles. The resulting unit size is 44" diameter by 44" long, and is estimated to weigh 200 lbs.

6.0 System Performance Studies

A series of cycle calculations was performed, with the aim of establishing the optimum split of lift between the hot main gas stream and the cold air through the fans. For these calculations, a conventionalized gas generator was assumed with the following cycle parameters:

Compressor P.R = 9.0
η_c = .85
% Bleed = .02

Combustor T1T = 1300°K
PL = .05
η_{cc} = .98

Turbine η_T = .85
η_M = .99

This corresponds very closely to the gas generator assumed in previous studies of the Z-axis (fan-in-wing) system. A series of turbine-fan combinations were subsequently fitted to the gas generator, successively removing more energy from the hot stream and transferring it to the fan stream. These components were specified as follows:

Fan $PR = 2.0$

$\eta_F = .80$

$PL = .05$

Fan Turbine $\eta_T = .85$

$\eta_M = .99$

The independent variable examined was the bypass ratio, which was allowed to increase until no further energy was available from the main stream, - a value just over 3 in this case. The cycle studies yielded specific thrusts of the main and fan streams, and were thus used to generate airflow requirements for the two streams; these results are seen in Figure 6. A typical cycle calculation is shown in Figure 7, which uses the NRC cycle calculation programme described elsewhere (Ref. 1 and 2).

It will be seen that between bypass ratios of 2 and 3, there is very little change in specific fuel consumption, as an increasing amount of thrust is generated by the fans at the expense of the main stream. A weight analysis is required to assess the relative desirability of fan stream and main stream thrust.

7.0 Mission Weight Analysis

The cycle performance data presented above were used to compute total system weights (powerplant + hovering fuel), for a conventional VTOL mission used in previous studies (Ref. 3). The assumptions made and the results derived are summarized in Table I, along with comparable data for a Z-axis fan-in-wing arrangement.

Increases in bypass ratio were produced by using successively larger numbers of the standard fan indicated above; changes in gas generator mass flow were accommodated by keeping the number constant at 4 gas generators, and changing their mass flows. It is seen in Figure 8 that minimum system weights occur between B=2 and B=2.5, although the curve is very flat; for installation simplicity a value of B=1.85 comprising 10 tandem fan units has been accepted as typical of the system.

The weight of the powerplant system is disappointingly large, the minimum value being about 34% of the aircraft all-up-weight. The comparable value for the Z-axis fan-in-wing arrangement was about 24%, so the present Y-axis arrangement is appreciably inferior on this criterion. There is of course the possibility that the Y-axis arrangement, combined with wing surface flow control, may show a superior cruising fuel consumption; experiments currently proceeding in the Gas Dynamics Laboratory should shed some light on this question.

A brief look at a lower fan pressure ratio (1.75 instead of 2.0) was taken with the results shown in Figure 9. A slightly lower system weight is computed, provided the bypass ratio rises to about 3.0; the optimum is however only marginally superior.

8.0 Conclusions

1. The Y-axis arrangement considered herein, with centrifugal fans of pressure ratio 2, produces system weights appreciably higher than the Z-axis fan-in-wing arrangement, (34% of aircraft gross weight, as opposed to 24%).

2. The use of a radial-inlet type of compressor leads to an appreciably larger impeller, and hence a more bulky installation.

3. The lightest combination of fans and gas generators was with a bypass ratio of about 2.0, in which case about 60% of the lift was generated by the fans and 40% by the hot mainstream efflux.

9.0 REFERENCES

1. Chappell, M.S. Cockshutt, E.P. "A Comprehensive Method for Calculating Turbojet and Turbofan Design -Point Performance" CASI Journal, Vol. 10, No. 6, June 1964.

2. Cockshutt, E.P. "A.B.C. Turbojet and Turbofan Design-Point Program: Description and Documentation" Internal Memorandum dated 10 September 1964.

3. Cockshutt, E.P. Galitzine, N. "The Fan-In-Wing Powerplant System for VTOL Aircraft" CAI Journal, Vol. 6, No. 9, November 1960.

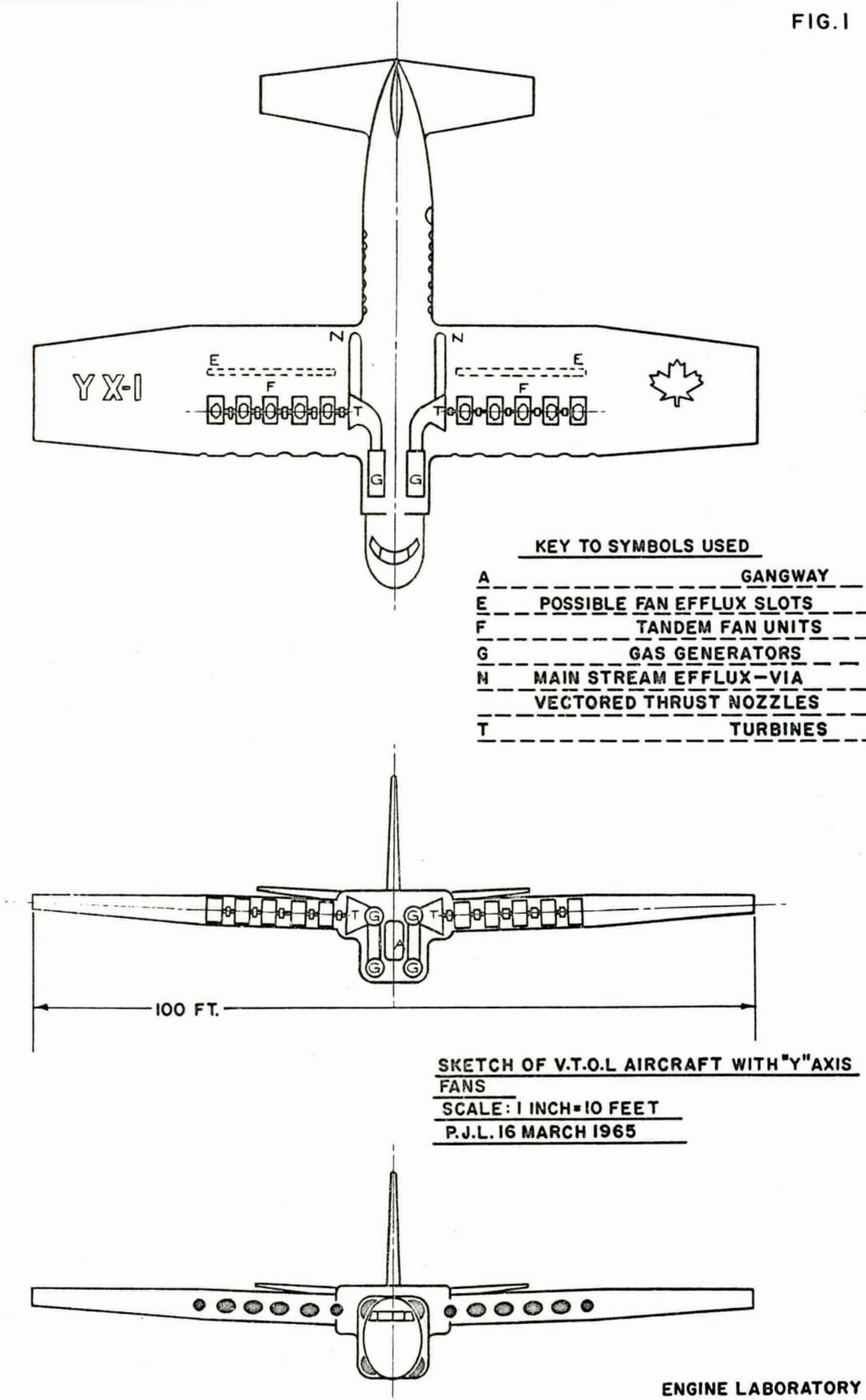
TABLE I

VTOL AIRCRAFT MISSION

Aircraft Gross Weight	40,000 lb.
Installed Thrust (33% Reserve)	53,300 lb.
Payload	10,000 lb.
Hovering Duration	10 min.
Fuel Allowances - Tankage	3%
Reserve	15%
Cruising Range	500 mi
Cruising Altitude	20,000 ft.
Cruising Speed	0.6 Mach
Cruising Lift/Drag Ratio	15

Y-AXIS FANS		Z-AXIS FANS
1.85	Bypass Ratio	17.0
2.0	Fan Pressure Ratio	1.143
480 (÷4)	Gas Generator Mass Flow	197 (÷8)
860 (÷20)	Fan Flow	3,350 (÷8)
6,500 (÷4)	Gas Generator Weight	5,200 (÷8)
2,000 (÷20)	Fan Weight	2,400 (÷8)
1,000	Turbine Weight	
9,500(23.8%)	Powerplant Weight	7,600(19.0%)
4,240(10.6%)	Hovering Fuel	1,780(4.5%)
13,740(34.4%)	Powerplant+Hovering Fuel	9,380(23.5%)

FIG. 1



KEY TO SYMBOLS USED

A	GANGWAY
E	POSSIBLE FAN EFFLUX SLOTS
F	TANDEM FAN UNITS
G	GAS GENERATORS
N	MAIN STREAM EFFLUX—VIA VECTORED THRUST NOZZLES
T	TURBINES

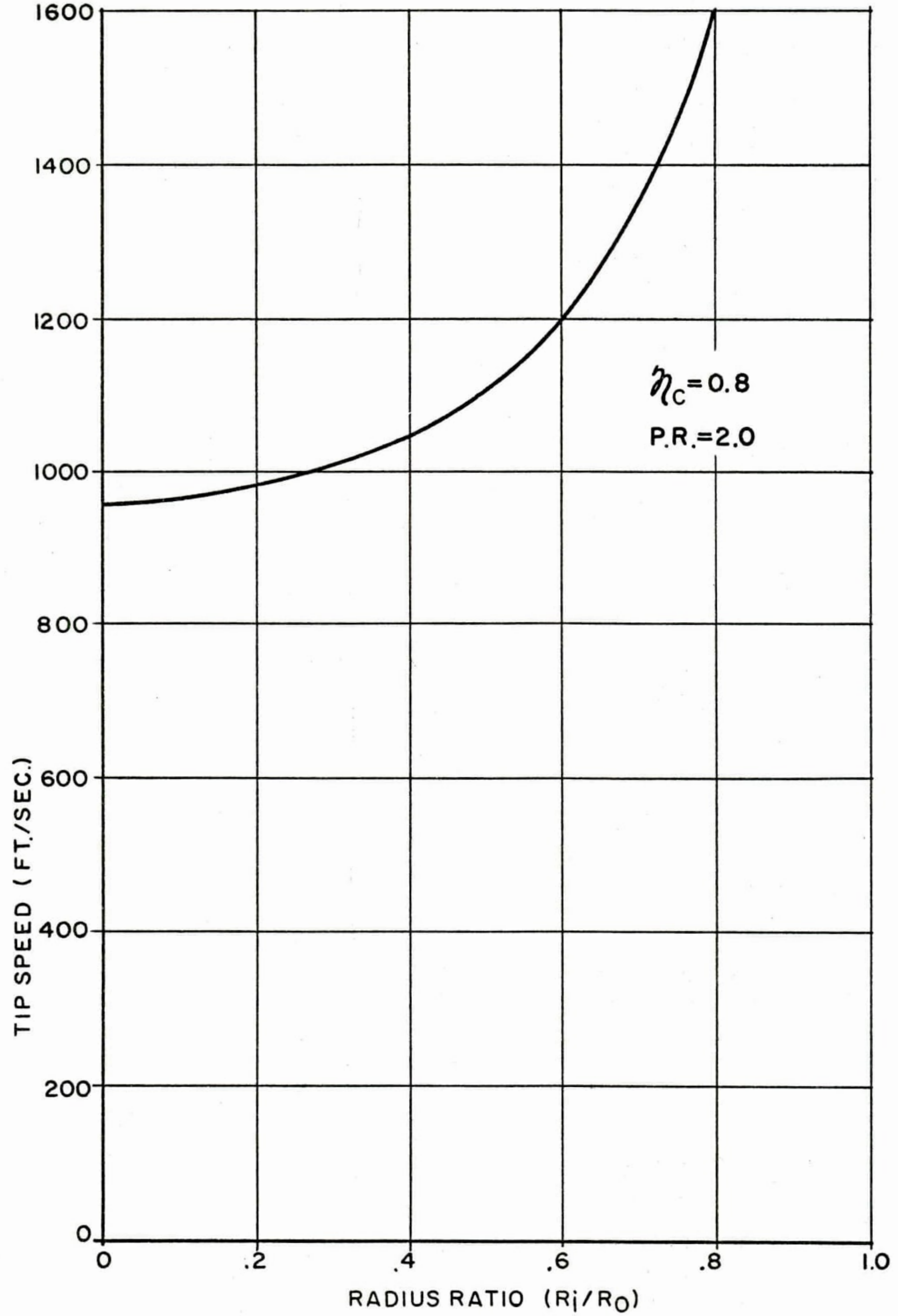
SKETCH OF V.T.O.L AIRCRAFT WITH "Y" AXIS FANS

SCALE: 1 INCH = 10 FEET

P.J.L. 16 MARCH 1965

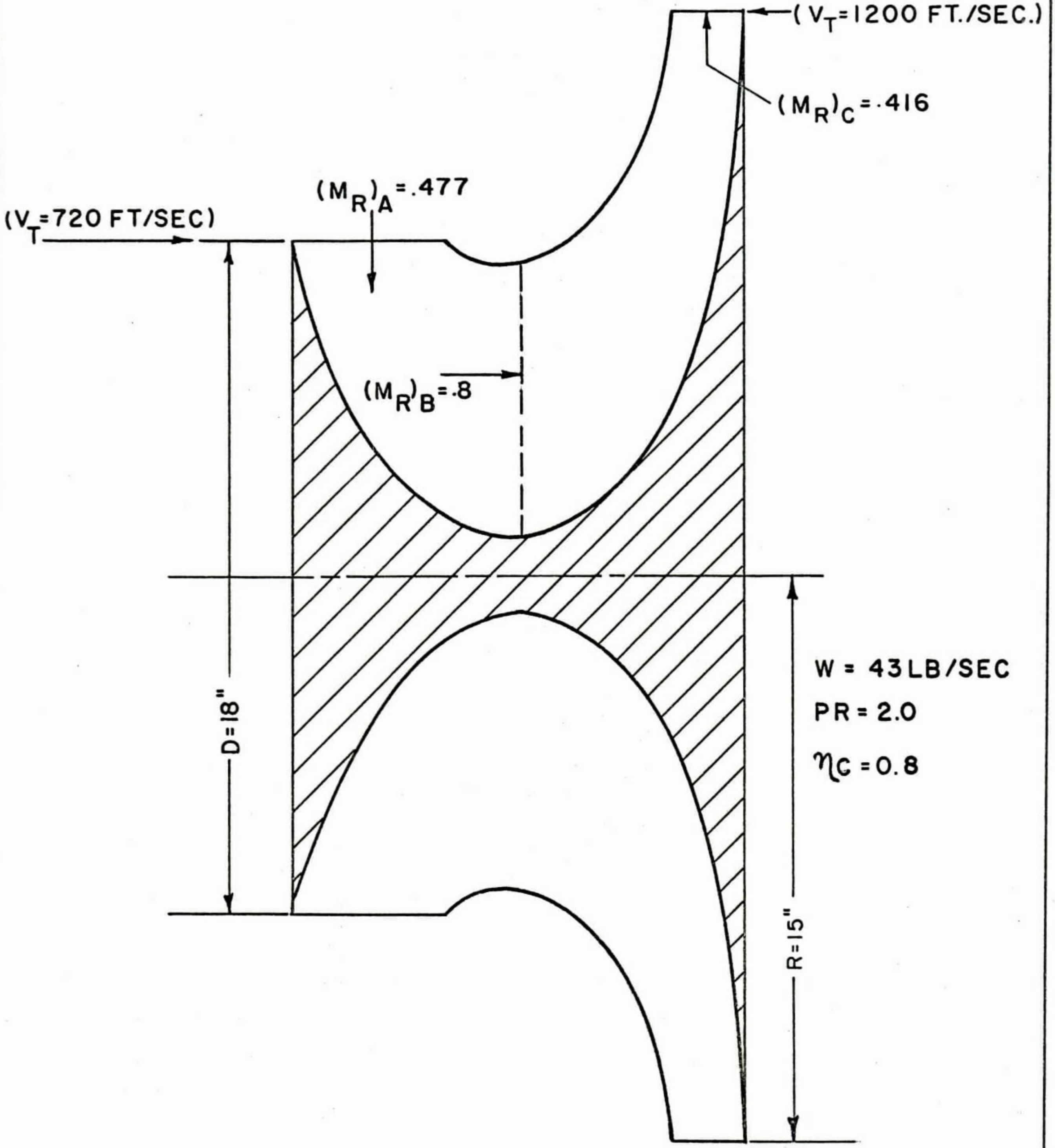
ENGINE LABORATORY
S—275

FIG.2



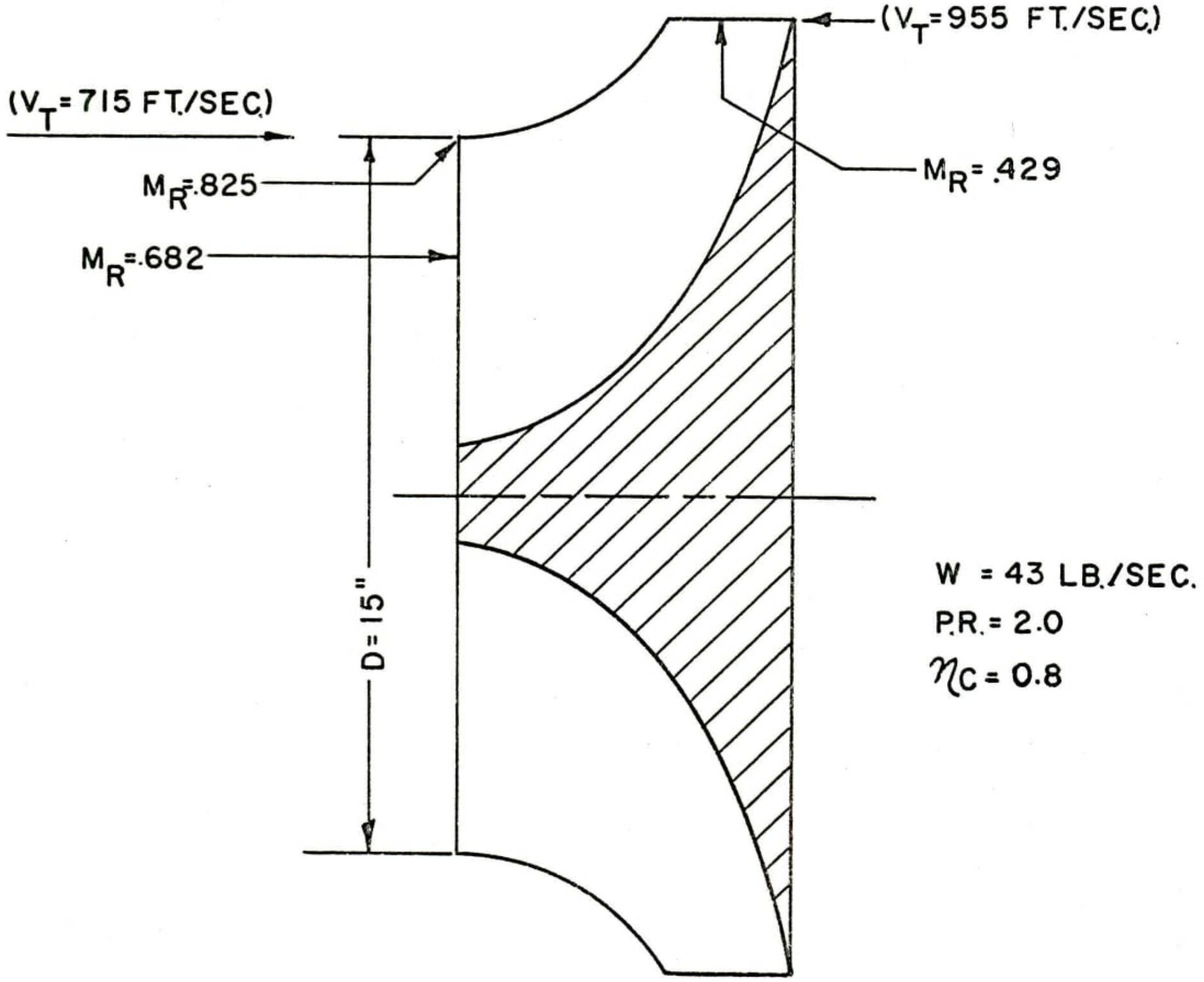
IMPELLER TIP SPEED FOR RADIAL INLETS

FIG.3



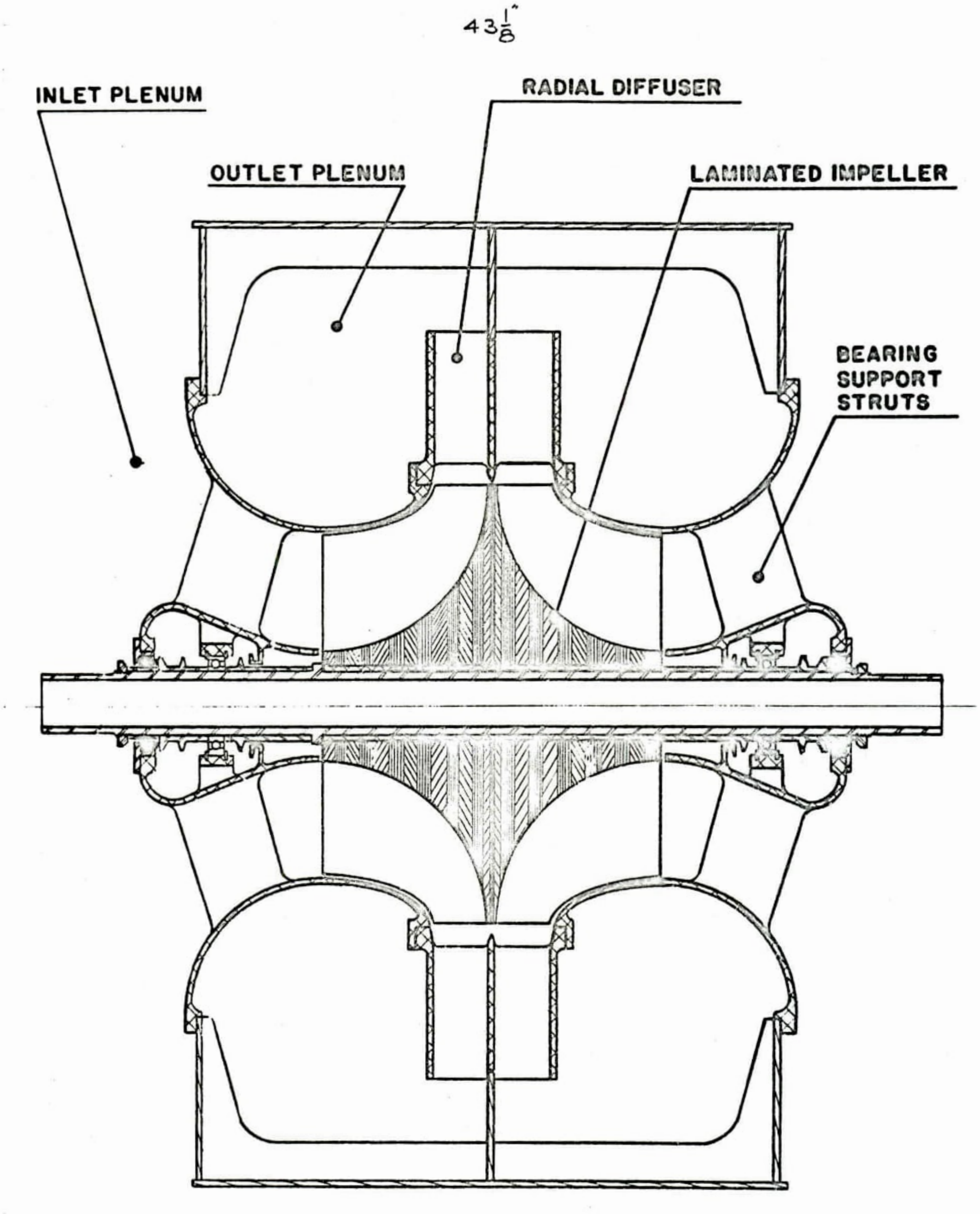
TYPICAL RADIAL-INLET IMPELLER

FIG. 4



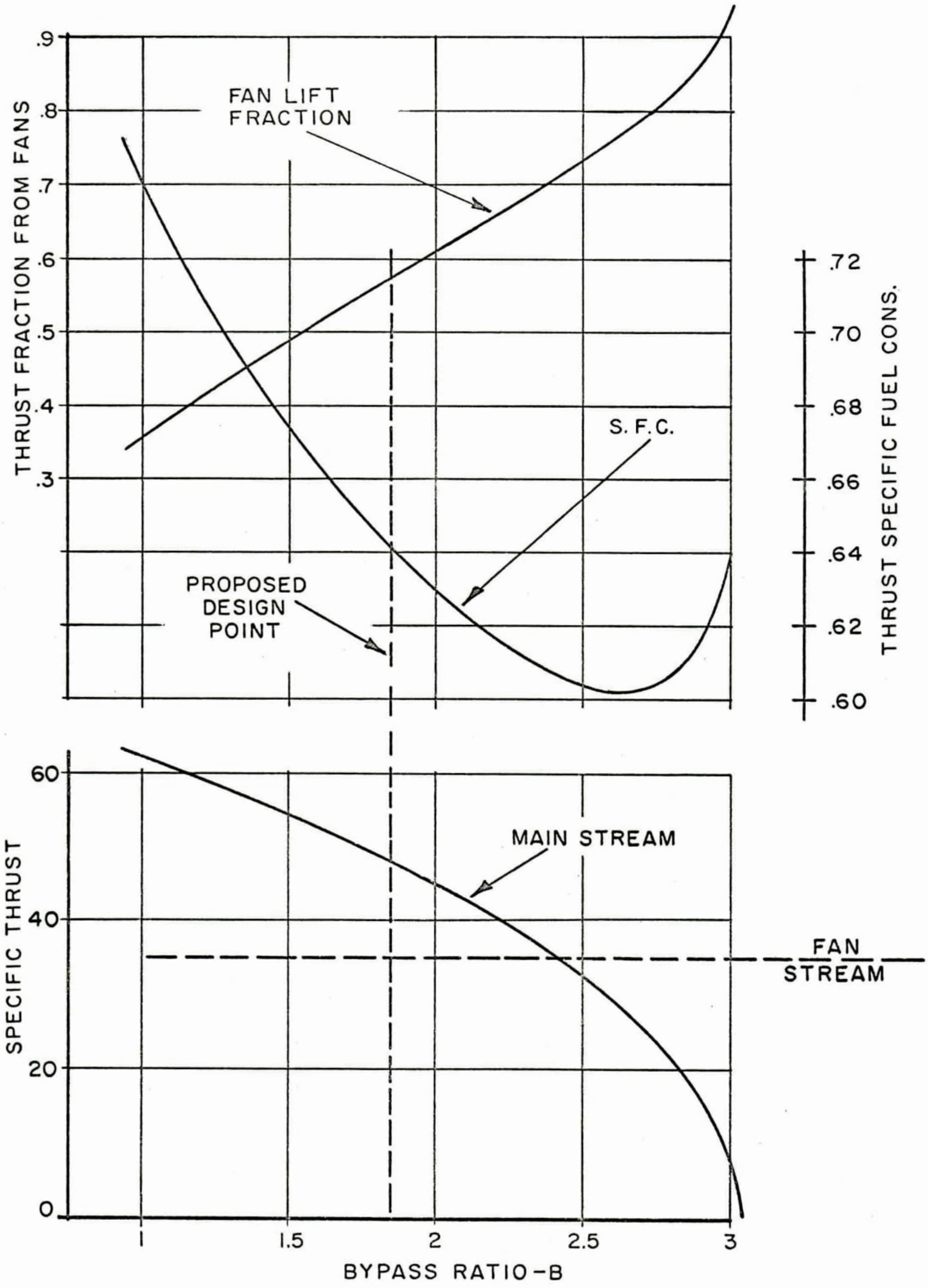
TYPICAL CONVENTIONAL IMPELLER

FIG. 5



PROPOSED FAN ASSEMBLY

FIG.6



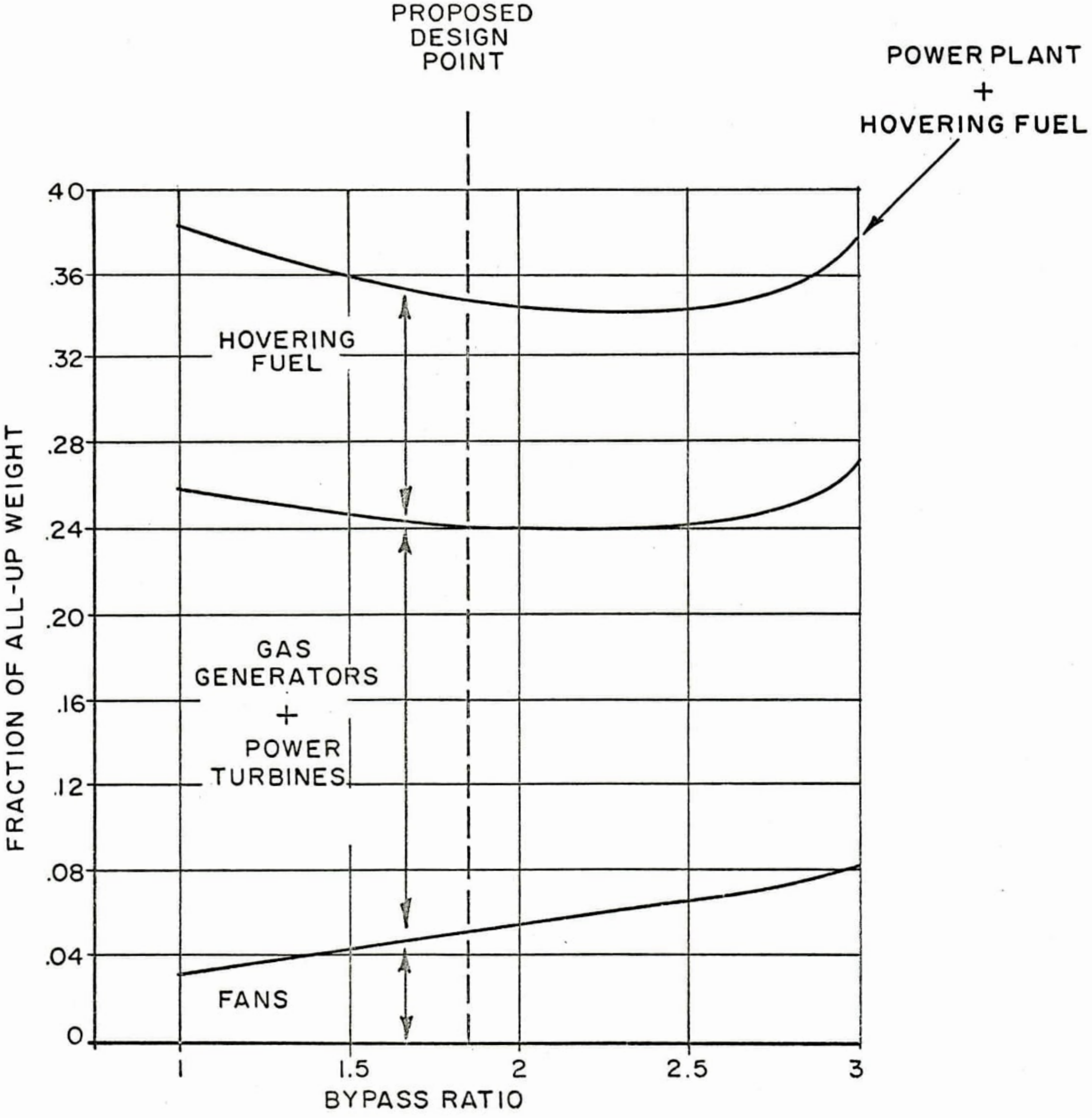
Y-AXIS FAN COMPUTER CYCLES
SLS 913 GAS GENERATOR F.P.R.=2.0

```
          P       T        W        AR         MO     MI      PR     PL      EI      EO      BL -

INLT  1.000   288.1             0.0 FT            0.000                  1.0000

 FAN
COMP
      1.900   366.9   2.0000   0.0000  0.000  0.000   2.000   .050   .8000  0.0000   2.000
COMP
      9.000   579.2    .9800   0.0000  0.000  0.000   9.000  0.000   .8500  0.0000    .020
COMB
      8.550  1300.0   1.0001   0.0000  0.000  0.000   0.000   .050  0.0000   .9800   0.000
TURB
      2.932  1052.6   1.0001   0.0000  0.000  0.000   0.000  0.000   .8500   .9900   0.000
 FAN
TURB
      1.491   916.5   1.0001   0.0000  0.000  0.000   0.000  0.000   .8500   .9900   0.000
NOZL
      1.000   829.4   1.0001   1.2306   .793  0.000   0.000  0.000   .9850  0.0000   0.000
 FAN
NOZL
      1.003   305.8   2.0000   1.1541  1.000  0.000   0.000  0.000   .9750  0.0000   0.000


                MAIN    FAN               INFLOW     F/M THRUST

      THRUST   44.946  34.947             38.282       1.5549

  FUEL FLOW    72.360   0.000    SFC       .6301

-1 2-3-4-5-6-7          614.
```

TYPICAL COMPUTER CYCLE – ASSUMED PARAMETERS UNDERLINED

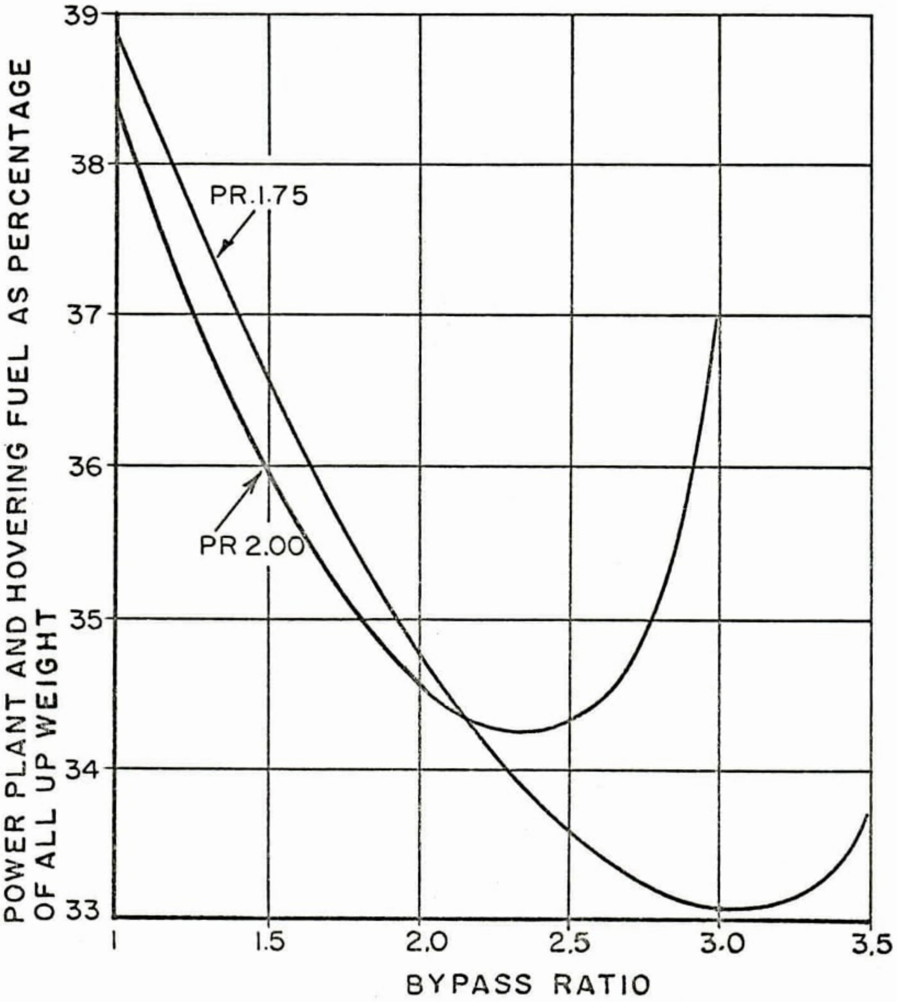
FIG.7

FIG.8



MISSION WEIGHT ANALYSIS

FIG. 9



EFFECTS OF FAN PRESSURE RATIO ON MISSION WEIGHT