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# RESEARCH MEMORANDUM

## EXPLORATORY INVESTIGATION OF A HELICOPTER PRESSURE-JET SYSTEM ON THE LANGLEY HELICOPTER TEST TOWER

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## SUMMARY

An exploratory investigation of a helicopter pressure-jet system has been conducted on the Langley helicopter test tower. The effects of tip speed, fuel-air ratio, and pressure ratio on the propúlsive characteristics of the pressure-jet system have been determined for a range of tip speeds from 442 to 559 feet per second, blade-root stagnation-pressure ratios of 1.9, 2.14, and 2.31, and fuel-air ratios from 0 to 0.03. A tangentially mounted burner with a constant-area exit nozzle was used in the investigation. The analysis shows that, for a given pressure ratio and fuel-air ratio, the maximum specific propulsive horsepower and the minimum overall specific fuel consumption should occur at the tip speed at which the propulsive thrust is equal to the air and fuel-pumping term.

Without tip burning, a minimum overall specific fuel consumption of 2.28 pounds per hour per horsepower, based on a conservative estimate of compressor specific fuel consumption, and a ratio of rotor propulsive horsepower to equivalent compressed-air horsepower of about 0.45 was obtained at a stagnation-pressure ratio of 2.31 and a tip speed of 558 feet per second. With burning at a fuel-air ratio of 0.02 at the tip unit, the overall specific fuel consumption was increased about 11 percent and the power ratio was increased to about 1.0.

## INTRODUCTION

In comparison with a shaft-driven helicopter rotor, the jet-driven rotor has the advantage of mechanical simplicity and higher payload to gross-weight ratio with, however, a shorter range or endurance because of the higher specific fuel consumption. Of the various types of tip-mounted engines, the pressure jet, although heavier and more complicated than the other tip-mounted jet engines, such as the ram jet or pulse jet, is particularly applicable to helicopters because of its high thrust to frontal-area ratio and its lower overall specific fuel consumption. With the much smaller tip-engine frontal area for a given engine thrust, the rotor performance is not significantly impaired by the external drag of the tip units, as is the case for pulse- and ram-jet powered rotors. Furthermore, the pressure jet is not subject to the variation in thrust with rotor azimuth angle and rotor-blade angle of attack that is characteristic of other tip-mounted jet units which take air in at the blade tip.

The investigation of the helicopter pressure-jet system is a part of the program devoted to the study of tip-powered helicopter rotors undertaken by the National Advisory Committee for Aeronautics. Other aspects of this program include an analytical investigation of the pressure-jet power plant (ref. 1), the study of ram-jet-powered rotor (refs. 2, 3, and 4), and the study of pulse-jet-powered rotors (ref. 5). The investigation reported in this paper was conducted with a pressure-jet system assembled from available rotor blades, which were limited by structural considerations to tip speeds below 560 fps, and powered by a burner designed, mainly, to operate at very low fuel-air ratios. The use of a burner with stable combustion down to extremely low fuel-air ratios would result in a continuous reduction of power as fuel-air ratio is decreased as compared with the abrupt drop in power associated with conventional burners which flame out at fuel-air ratios of about 0.010. The results of this investigation, therefore, do not represent the maximum capabilities of the pressure-jet system, even by present standards. These results are presented in such a form as to show the effect of the tip speed, pressure ratio, and fuel-air ratio on the performance of a pressure-jet system as determined by the specific fuel consumption, specific propulsive horsepower, propulsive horsepower per unit duct area, and ratio of propulsive horsepower to equivalent air horsepower, and to point out some of the more important relationships that should be considered in the design of such a system.

The data obtained in this investigation are for a fixed-area nozzle over a tip-speed range of 442 to 558 fps, and stagnation-pressure ratios at the blade root of 1.9 to 2.3.

## SYMBOLS

$F/A$ fuel-air ratio

$F_g$ gross thrust of pressure-jet tip unit, $\frac{W_a}{g}\left(1 + \frac{F}{A}\right)V_{j_e}$, lb

| | |
|---|---|
| $F_p$ | propulsive thrust of pressure-jet tip unit, $\frac{W_a}{g}\left(1 + \frac{F}{A}\right)\left(V_{j_e} - \Omega R\right)$, lb |
| $g$ | acceleration due to gravity, 32.2 ft/sec$^2$ |
| $HP_c$ | equivalent compressed-air horsepower, hp |
| $HP_p$ | propulsive horsepower, hp |
| $\bar{M}_R$ | mean duct Mach number at root |
| $p_a$ | ambient air pressure, lb/sq ft |
| $p_t$ | total pressure, lb/sq ft |
| $q$ | dynamic pressure, lb/sq ft |
| $R$ | rotor-blade radius (measured to center line of tip unit), ft |
| $V_{j_e}$ | equivalent jet-exit velocity, fps |
| $W_a$ | weight of air flow per engine, lb/sec |
| $\Omega$ | rotor angular velocity, radian/sec |
| $\eta_w$ | wake efficiency |

Subscripts:

| | |
|---|---|
| 1 | duct root station |
| 2 | duct tip station |
| 3 | inlet to tip unit station |

## APPARATUS

The Langley helicopter test tower is described in reference 6. The only major changes in the tower since the publication of reference 6 are an enlargement of the working area at the base of the tower and the replacement of the Packard Marine Engine by a 3,000-horsepower variable-frequency electric motor drive.

The fuel and ignition system used for these tests is described in reference 2.

## Rotor

A view of the pressure-jet system mounted on the test tower is shown in figure 1. An existing set of rotor blades with a fairly large steel tubular spar to serve as an air duct was used in this investigation. The radius of the rotor was 17.46 feet to the tip of the blade airfoil section and 18.39 feet to the center line of the tip units. The whirling tests of the pressure-jet system were conducted with the rotor operating at zero thrust and the power available to the rotor was absorbed by drag plates mounted inboard of the tip and near the leading edge of the blade. A sketch of the rotor blade, air duct, and tip-unit assembly is shown in figure 2.

## Rotor-Blade Air Duct

The rotor-blade air duct shown in figure 2 consisted of four lengths of constant-diameter tubing. The first length extended from radial station 32.75 to station 42.5 and had an inside diameter of 3.19 inches; the second length extended from station 42.5 to station 154.5 and had an inside diameter of 3.275 inches; the third length extended from station 154.5 to station 194.5 and had an inside diameter of 3.025 inches; and the final length extended from station 194.5 to station 212.18 and had an inside diameter of 2.375 inches.

Static pressure and temperature measuring stations were included in the blade duct at the blade root and at the blade tip.

Nonwhirling tests of the rotor-blade duct shown in figure 2 indicated that the lengths of uniform diameter duct between stations 32.75 and 212.18 had individual friction factors comparable to the friction factor for commercial pipe (0.009 to 0.0035 for Reynolds numbers from $10^4$ to $10^6$).

Figure 2 shows the blade air-duct connection to the tip burner inlet. This type of air-duct connection was used to position the tip burner as far forward as possible in order to reduce the amount of weight necessary to mass balance the tip unit about the spar. After leaving the spar the air was turned forward $45^\circ$ and then aft $135^\circ$ to the burner inlet. A $5^\circ$ expansion was included in the initial part of the turn. A splitter vane was incorporated in the expansion and turning sections to reduce the flow separation in the turn, thereby reducing the pressure loss. In the range of mass flows used, the loss of total pressure between the tip pressure measurement station and the tip burner-inlet pressure measurement station in terms of the dynamic pressure at the tip $\Delta p_t/q_2$ was approximately 1.0.

## Pressure-Jet Tip Burner

The tip burner used in the pressure-jet-driven rotor tests is shown in figure 3. This burner was chosen as a result of a limited development program for pressure-jet burners to obtain a burner with the ability to burn at low fuel-air ratios with reasonable burner life.

Static tests of the tip unit have shown the pressure loss between the tip-unit inlet and exit in terms of the dynamic pressure at the tip-unit inlet $\Delta p_t/q_3$ range from 7.31 to 3.10 for a range of Mach numbers from 0.08 to 0.26.

The main fuel nozzle was located on a faired support upstream of the flame holder. The fuel spray was directed toward a perforated cone located at the front of the flame holder. Since the ratio of the hole area of the perforated cone to the tip-unit cross-sectional area at the inlet to the flame holder was 0.019, most of the air and part of the fuel passed to the outside of the flame holder and entered as secondary air and fuel through the louvers and holes located in the can-type flame holder. At the exhaust nozzle, a clearance of 1/32 inch was used between the outer shell of the tip unit and the flame holder so that approximately 5 percent of the secondary air was used for cooling the exhaust nozzle. The fuel used in this investigation was 80 octane unleaded gasoline and the fuel-flow rate was measured by a vane-type flow meter.

An auxiliary fuel nozzle with a fuel-flow rate of one-third that of the flow rate of the main spray nozzle was located in the apex of the first perforated cone. The auxiliary nozzle sprayed fuel onto and through a secondary perforated cone to provide a local stable burning region at overall low fuel-air ratios. The fuel was ignited by a standard aircraft spark plug located in the flame holder to the rear of the cones.

The flame holder was made of Inconel and was ceramic coated. The second cone was also ceramic coated. In order to prevent distortion of the flame holder by centrifugal forces, stainless-steel spacers were provided at five stations along the flame holder.

The tip unit was alined with the blade airfoil chord and was rigidly supported by an attachment to the blade spar. The supporting structure was enclosed by a fairing. In order to cool the inboard portion of the tip unit outer shell, air scoops were mounted on the fairing. The tip burner was aerodynamically faired into a streamlined nose which extended forward of the leading edge of the rotor blade. The nose of this fairing was weighted to mass balance the tip unit about the blade spar.

## Pressure and Temperature Measurements

The amount of air flow was measured by a survey rake located in a length of uniform duct upstream of the rotary air seal. The survey rake was connected to electrical pressure pickups and the signal was read on calibrated microammeters.

The static pressure at the blade root, blade tip, and inlet to the tip unit was obtained by use of NACA miniature electrical pressure gages described in reference 7. The signal from the pressure gage was recorded on an oscillograph.

Stagnation temperatures at the rotor hub, blade root, blade tip, and inlet to the tip unit were obtained by use of iron-constantan thermocouples. The signal was recorded on a temperature recorder.

## Compressed-Air Supply

A compressed-air source for the pressure-jet units was improvised by bleeding air from the final compression stage of a Westinghouse J34-WE-22 turbojet engine. The maximum pressure ratio obtainable with this installation was about 2.5. The amount of air flow was controlled by a remotely actuated butterfly valve located in the duct near the turbojet engine. The air was ducted to a rotary air seal located above the hub of the rotor. The rotary air seal was connected to the rotor-blade ducts by a length of flexible tubing in order that the rotor blade be free to change pitch and to flap.

# METHODS AND ACCURACY

## Whirling Tests

All whirling tests were made at approximately zero rotor thrust and all measurements were under steady-state operating conditions. The power of the tip units and tower drive motor was absorbed by the rotor and by drag plates which were mounted inboard of the tip and at the leading edge of the rotor blade. The test procedure was to establish a constant rotor tip speed by adjusting the speed of the tower drive motor and then varying the pressure-jet tip-unit thrust and fuel flow through the desired range.

The power requirements of the rotor blades with various drag plate combinations were determined directly from the conventional tower drive measurements. The propulsive thrust of the pressure-jet tip burners is defined as the thrust available to overcome the drag of the blades and tip-burner installation. It was calculated by assuming that the propulsive thrust of the tip burners was equal to the thrust required to drive the blades with tip burners attached minus the tip thrust equivalent of the torque supplied by the electric motor. The tip thrust equivalent of the rotor torque is calculated by dividing the torque supplied by the electric motor by the distance from the center line of rotation to the center line of the tip burners.

The total or gross thrust of the pressure-jet tip unit is defined in equation (1) and consists of the propulsive thrust plus the thrust necessary to accelerate the fuel and air to the tip-unit speed. The latter term is referred to as the air and fuel pumping term.

$$F_g = F_p + \frac{W_a(\Omega R)}{g}\left(1 + \frac{F}{A}\right) \qquad (1)$$

For a given tip-burner inlet pressure, the gross thrust is essentially independent of tip speed except as the centrifugal acceleration may affect the combustion process.

Contamination effects (increase in temperature of the air in which the engine and part of the rotor blade operates caused by the exhaust from the previous engine) were not measured and corrections for these effects have not been applied. However, previous experience indicates that the air-temperature rise due to contamination effects, measured in tests of a jet-propelled rotor having a similar radius and tip speed and operating at zero thrust are usually small and its effect on the blade tip drag may be neglected. (See ref. 3.)

## Nonwhirling Tests

The nonwhirling tests were conducted with the rotor blades mounted on the tower. The tip unit was restrained from rotating by an electrical strain-gage dynamometer which measured engine thrust.

## Estimated Accuracies

The estimated accuracies of the basic quantities measured in the tests are as follows:

| | |
|---|---|
| Rotor torque, ft-lb | ±20 |
| Fuel flow rate, lb/hr | ±2 |
| Rotor angular speed, rpm | ±1 |
| Pressures, lb/sq in. | ±0.6 |
| Temperatures, deg | $\pm 2\frac{1}{2}$ |
| Overall accuracy of plotted results, percent | ±3 |

## RESULTS AND DISCUSSION

The more important parameters affecting the performance of the pressure-jet rotor are tip speed, blade-root stagnation-pressure ratio $(p_t/p_a)_1$, tip-burner fuel-air ratio, and blade-duct Mach number. The effect of these variables on the tip-burner performance will be discussed before proceeding with the discussion of the overall pressure-jet rotor characteristics.

### Tip-Burner Specific Propulsive Horsepower

Some of the tip-burner characteristics are shown in figure 4 as plots of specific propulsive horsepower as a function of rotor tip speed for various fuel-air ratios and root station stagnation-pressure ratios from 1.9 to 2.3. The specific propulsive horsepower is defined as the propulsive horsepower per pound of air per second and is important in determining the compressor requirements and the size of the rotor blade duct.

Effect of fuel-air ratio.- From figure 4 it may be seen that as the fuel-air ratio is increased, the specific propulsive horsepower for this particular burner will increase up to a fuel-air ratio of about 0.03. For example, at a root pressure ratio of 2.31 and a tip speed of 550 fps, the specific propulsive horsepower will increase from 21 hp/lb/sec at a fuel-air ratio of 0 to 57 hp/lb/sec at a fuel-air ratio of 0.03. These values compare favorably with the specific propulsive horsepower values of reference 1 which indicate that, at a tip speed of 550 fps and a pressure ratio of 2.5, the specific propulsive horsepower increases from 25 hp/lb/sec for a fuel-air ratio of 0 to about 65 hp/lb/sec for a combustion-chamber temperature rise corresponding to a fuel-air ratio of 0.03 and a combustion efficiency of about 90 percent.

If the combustion efficiency remained constant, the specific propulsive horsepower would be expected to increase beyond a fuel-air ratio of 0.03. However, this burner, being designed with a short combustion-chamber length and with special emphasis on burning at extremely low fuel-air ratios, showed very poor combustion characteristics beyond fuel-air ratios of 0.03.

Effect of tip speed.- At a given fuel-air ratio and root stagnation-pressure ratio, the specific propulsive horsepower will be a maximum at the tip speed at which the propulsive thrust is equal to the air and fuel pumping term. This may be shown by using equation (1) to write the equation for specific propulsive horsepower:

$$\frac{HP_p}{W_a} = \frac{F_p}{W_a}\frac{\Omega R}{550} = \frac{1}{W_a}\left[F_g - W_a\left(1 + \frac{F}{A}\right)\left(\frac{\Omega R}{g}\right)\right]\frac{\Omega R}{550} \tag{2}$$

The tip speed at which the specific propulsive horsepower is a maximum may be found by differentiating equation (2) with respect to tip speed and setting the resultant equation to zero. The tip speed at which the specific propulsive horsepower is a maximum will occur when

$$F_p = W_a\left(1 + \frac{F}{A}\right)\frac{\Omega R}{g} \tag{3}$$

From equations (1) and (3) and the definition of propulsive thrust, it can be shown that the rotor tip speed for maximum specific propulsive horsepower will be one-half the equivalent jet-exit velocity of the tip burner. The equivalent jet-exit velocity is the hypothetical velocity that would result if the burner exhaust gases were expanded isentropically from the pressure at the jet exit to atmospheric pressure. Calculations of the specific propulsive horsepower in the vicinity of the maximum point indicate that the curves of specific propulsive horsepower as a function of tip speed are relatively flat and, as indicated by the curves at figure 4, therefore, a wide range of tip speeds may be used without an appreciable sacrifice in specific propulsive horsepower. At a fuel-air ratio of 0 and a root stagnation-pressure ratio of 1.90 the calculated tip speed for maximum specific propulsive horsepower is about 600 fps.

The fuel-air-ratio curves of figure 4(a) indicate that the specific propulsive horsepower reaches a maximum at tip speeds less than 600 fps for fuel-air ratios from 0.005 to 0.015. This premature peaking appears to be due to a decrease in the combustion efficiency at these particular low fuel-air ratios and results from the increased centrifugal force acting on the fuel particles. This will result in a decrease in the jet exit velocity and the propulsive thrust.

Effect of pressure ratio.- The effect of increasing the root stagnation-pressure ratio from 1.9 to 2.3 is shown in figure 4(a-c). As the pressure ratio is increased, the specific propulsive horsepower increases for all fuel-air ratios and tip speeds presented. For example, at a fuel-air ratio of 0.03 and a tip speed of 550 fps, an increase in the root stagnation-pressure ratio from 1.9 to 2.3 increases the specific propulsive horsepower from 42.5 hp/lb/sec to 57 hp/lb/sec.

Effect of duct Mach number.- The friction losses in the blade air duct are primarily dependent upon the duct Mach number. Calculations indicate that, for the range of variables tested, the duct Mach number has a negligible effect on the stagnation-pressure ratio at the inlet to the tip burner for duct Mach numbers below 0.15. As the Mach number is increased, the friction losses increase and the specific propulsive horsepower at a given fuel-air ratio will decrease. The mean duct Mach numbers at the root station are indicated for each fuel-air ratio in figure 4.

The variation in mean duct Mach number at a given fuel-air ratio over the tip-speed range of this investigation was found to be negligible. The mean duct Mach number is defined as the Mach number of a constant-diameter duct having the same friction losses, root stagnation-pressure ratio, and mass flow, as the duct of this investigation.

Considerable caution must be exercised in the application of the experimental performance data of this report in the design of a particular pressure-jet helicopter. The data presented are for a particular pressure-jet system and include the friction losses in the duct, losses in the turn at the blade tip, and losses through the flame holders. For duct Mach numbers below 0.3, the friction losses are roughly proportional to the duct Mach number squared. For example, calculations indicate that at a root stagnation-pressure ratio of 2.31 and a tip speed of 550 fps the reduction in the duct Mach number to a value of about 0.1 by an increase in the duct size (while holding the tip-burner dimensions constant) will increase the specific propulsive horsepower about 18 percent at a fuel-air ratio of 0 and about 4 percent at a fuel-air ratio of 0.03.

## Propulsive Horsepower Per Unit Mean Duct Area

An important parameter in determining the rotor-blade air duct size for given rotor power requirements is the propulsive horsepower per unit duct area. This parameter is plotted in figure 5 as propulsive horsepower per unit mean duct area as a function of tip speed for fuel-air ratios of 0 to 0.035 and root stagnation-pressure ratios of 1.9 to 2.3. As previously mentioned, the mean duct area is defined as the area of a constant-diameter duct having the same friction losses as the rotor-blade duct being tested. For this investigation, the mean duct area is 0.051 square foot which is approximately the area of the center section of the blade ducting.

The effects of the fuel-air ratio, tip speed, and pressure ratio on the propulsive horsepower per unit mean duct area are essentially the same as the effect of these parameters on the specific propulsive horsepower discussed in figure 4.

The effect of increasing the fuel-air ratio will be somewhat less than that shown for the specific propulsive horsepower. The decrease in the effect of fuel-air ratio is due to the use of a fixed-area exit nozzle which has the characteristic of decreasing the air mass flow as the burner temperature is increased.

Mean duct Mach number has a significant effect on the propulsive horsepower per unit duct area. As the Mach number increases, the air mass flow increases, thus increasing the propulsive horsepower per unit duct area. The increase in propulsive horsepower will be somewhat less than the increase in air mass flow because of the increasing friction losses. Operation in the higher Mach number range would not be a realistic condition, however, inasmuch as the friction losses incurred would be prohibitive. Calculation of these friction losses indicate that it is desirable to keep the duct Mach numbers below 0.25.

## Tip-Burner Specific Fuel Consumption

Another important parameter in the evaluation of the pressure-jet-powered rotor is the tip-burner specific fuel consumption. The specific fuel consumption of the tip burner in pounds of fuel per hour per propulsive horsepower is presented in figure 6 as a function of tip speed for various fuel-air ratios and root stagnation-pressure ratios from 1.9 to 2.3. As expected, the specific fuel consumption increases with an increase in fuel-air ratio. An increase in root stagnation-pressure ratio from 1.9 to 2.31 results in a decrease in specific fuel consumption over the entire range of fuel-air ratios. At a given fuel-air ratio and pressure ratio, a decrease in the specific fuel consumption results from an increase in tip speed. The specific fuel consumption should reach a minimum at the tip speed at which the propulsive thrust becomes equal to the air and fuel pumping term. This minimum point will occur at higher tip speeds as the pressure ratio and burner temperature increase.

## Ratio of Propulsive Horsepower to Equivalent Air Horsepower

Another important factor in the evaluation of the pressure-jet-powered helicopter rotor is the horsepower equivalent of the compressed air required by the tip burners. An indication of the tip-burner air horsepower for the configuration tested is shown in figure 7 as plots of the ratio of the propulsive horsepower to the equivalent air horsepower as a function of fuel-air ratio over the tip speed and pressure-ratio range tested. The equivalent air horsepower is computed from the root stagnation-pressure ratio and air mass flow. The curves indicate that the ratio of propulsive horsepower to compressed-air horsepower increase with tip speed for practically all conditions tested. One exception exists in the low fuel-air-ratio range (0.001 to 0.014) at a pressure ratio of 1.9 at which point the curve for a tip speed of 559 fps is slightly below the curve for a tip speed of 502 fps. This decrease in propulsive horsepower is apparently due to the decrease in combustion efficiency at this pressure ratio and tip speed, and has been previously discussed in connection with figure 4(a).

The curves also show that, for the particular pressure-jet rotor tested, with no burning at the tip, the horsepower available to the rotor is about 40 to 45 percent of the power equivalent of the compressed air. It should be noted that the values for a fuel-air ratio of 0 correspond to duct Mach numbers of about 0.3. A reduction in the duct Mach number by increasing the size of the duct within a given blade section will reduce the friction losses and have a significant effect on the performance of the pressure-jet system. For a pressure-jet system with no internal losses and no burning at the tip, the ratio of propulsive horsepower to compressed-air horsepower will be equal to the propulsive efficiency. The propulsive efficiency is defined as the ratio of the thrust power output to the kinetic energy input and is given by the equation

$$\eta_p = \frac{2}{1 + \frac{V_{j_e}}{\Omega R}}$$

Since the maximum propulsive horsepower will occur at a tip speed of one-half the equivalent jet-exit velocity, the ratio of propulsive horsepower to air horsepower will approach 0.67 as a limit if the propulsive horsepower is maintained at a maximum value. In the practical application of a cold pressure-jet rotor, power ratios of about 0.5 should be achieved by the use of good ducting practice and restricting the duct Mach numbers to a maximum value of about 0.20.

The addition of energy by tip combustion increases the value of the propulsive horsepower to air-horsepower ratio. For the particular burner and duct tested, maximum power ratios of about 1.2 were obtained at fuel-air ratios of 0.03 and tip speeds of 559 fps.

## Effect of Whirling on Tip-Unit Thrust

As indicated in reference 3, the combustion efficiency and thrust of a tip-mounted jet power plant is affected by the centrifugal force acting on the fuel particles. In figure 8, a comparison of the whirling and nonwhirling tip unit performance is made in terms of specific gross thrust (lb thrust/lb air/sec) and fuel-air ratio. The total pressure ratios at the tip-unit inlet are equal for both the whirling and nonwhirling conditions. As expected, the specific gross thrust for the two conditions coincide at a fuel-air ratio of zero; however, as fuel is added to the burner the specific gross thrust for the nonwhirling condition becomes greater than for the whirling condition. At a fuel-air ratio of 0.020 and for similar burner inlet pressures the specific gross thrust for whirling averages 8 percent less than the specific gross thrust for the nonwhirling condition. The major portion of this decrease in thrust is probably due to the distortion of the fuel spray pattern by the centrifugal force. (See ref. 3.) This loss could be reduced by modification of the fuel spray pattern or by the use of a radial combustion chamber so that burning could take place along the span of the blade rather than in the chordwise direction.

## Effect of Whirling on the Tip-Burner Inlet Pressure

The centrifugal compression of the air flow in the rotor-blade duct has two significant effects on the capabilities of the pressure-jet system. First, the Mach numbers along the duct will decrease for a given air mass flow and will, thereby, reduce the losses due to friction. Second, the increase in pressure at the tip burner will represent, in part, a recovery of the energy loss due to air pumping. An indication of the effect of whirling on the stagnation pressure may be obtained from figure 9. This figure shows the percent rise in stagnation pressure between the blade tip and blade root and between the inlet to the tip burner and the blade root for a range of mean duct Mach numbers at the root in a nonwhirling duct and a duct with a tip speed of 558 fps. The data given in figure 9 are for a root stagnation-pressure ratio of 2.31.

It may be seen from figure 9 that for a mean duct Mach number at the root of 0.24 and a tip speed of 558 fps, the stagnation-pressure ratio at the blade tip is about 13 percent greater than it would be for a static duct. This value will increase rapidly with tip speed. Calculations have shown that at tip speeds of 700 and 900 fps, the percent pressure rise at the tip for the same conditions as previously stated will be about 20 and 34 percent, respectively, above the tip pressure for the nonwhirling duct.

Figure 9 also gives an indication of the pressure loss through the turn between the inlet to the tip burner and the tip. For example, at a mean duct Mach number of 0.24, the loss in stagnation pressure between the tip and the inlet to the tip unit is about 9 percent for both the whirling and nonwhirling case. A reduction or an elimination of the turning losses would result in an overall increase in the thrust of the tip burner due to the increase in pressure at the inlet to the tip burner.

## Effect of Auxiliary Fuel Flow

The data presented in figures 4 to 8 are for an auxiliary fuel-flow rate of one-third that of the fuel-flow rate of the main fuel nozzle. Some tests have been conducted with no auxiliary fuel flow for a tip speed of 440 fps and for root stagnation-pressure ratios of 1.90, 2.14, and 2.31. The principal effect of eliminating the auxiliary fuel flow was that combustion could not be maintained below fuel-air ratios of about 0.010. At a fuel-air ratio of 0.03, a slight increase in the thrust of the burner with no auxiliary fuel was noted at a pressure ratio of 1.9, no difference in thrust was noted at 2.1, and a slight decrease in thrust was noted at 2.3.

## Power-Off Drag of Tip Units

Tests of the rotor blade with the tip unit removed and a faired tip (extending to the center line of the tip unit) indicate that the tip units have a drag coefficient of 0.0556 based on the maximum frontal area

(0.143 square foot) of the unit. This drag coefficient includes the drag of the tip unit and cooling air scoops.

## Overall Specific Fuel Consumption of Pressure-Jet System

For a true evaluation of the pressure-jet-driven rotor, the entire pressure-jet system (tip-unit—duct—compressor combination) must be considered. The fuel consumption of the system must, of course, include the fuel supplied to the compressor drive as well as the fuel supplied to the tip unit.

In figure 10, the effect of tip speed on the horsepower specific fuel consumption of the pressure-jet system is presented for fuel-air ratios from 0 to 0.035 and root stagnation-pressure ratios from 1.90 to 2.31. The horsepower specific fuel consumption of the pressure-jet system is computed from the horsepower specific fuel consumption of the tip unit (fig. 6) and an assumed conservative specific fuel consumption for the compressor drive of 0.75 lb/hr/hp and a compressor efficiency of 0.75, thus arriving at a fuel consumption of 1 pound per hour per equivalent air horsepower. The equivalent air horsepower is computed from the root stagnation-pressure ratio and air mass flow.

The curves of figure 10 show the same general characteristic as the curves of figure 6 for the tip-unit specific fuel consumption; namely that as tip speed increases the overall specific fuel consumption decreases. The tip speed for minimum specific fuel consumption for a given fuel-air ratio and pressure ratio will, again, be the tip speed at which the propulsive thrust is equal to the air and fuel pumping term. The curves of constant fuel-air ratio tend to converge with an increase in pressure ratio.

An examination of figure 10 shows an intermingling of the constant fuel-air-ratio curves in the fuel-air-ratio range from 0.01 to 0.03. This is caused by a change in the combustion efficiency with a change in the fuel-air ratio. If the combustion efficiency remained constant, it would be expected that the overall specific fuel consumption would increase evenly with fuel-air ratio.

In figure 10, it may be seen that the minimum overall specific fuel consumption occurs in all cases at a fuel-air ratio of 0. At a tip speed of 550 fps, the specific fuel consumption varies from 2.16 lb/hr/hp at a pressure ratio of 1.90 to 2.28 lb/hr/hp at a pressure ratio of 2.31. It must be remembered that the specific fuel consumption curves of figure 10 include friction losses in the blade duct, the 135° turn, and the flame holders as well as a conservative estimate of the compressor specific fuel consumption. Calculations indicate that at a fuel-air ratio of 0, the specific fuel consumption may be reduced by about 23 percent by eliminating the flame holders, using a good 90° turn, and reducing the duct Mach number to about 0.1. Somewhat smaller gains would be obtained as the fuel-air ratio is increased.

The values of the overall specific fuel consumption given in figure 10 may be compared with the values of reference 1 which indicate an overall specific fuel consumption of 1.50 lb/hr/hp at a fuel-air ratio of 0 and of 2.05 lb/hr/hp at a fuel-air ratio of about 0.03. These values are for a pressure ratio of 2.25, a tip speed of 700 fps, a specific fuel consumption of 0.74 lb/hr/hp for the compressor drive, and a compressor efficiency of 87 percent.

Another interesting comparison may be made between the overall specific fuel consumption of the pressure-jet system and other types of tip-mounted jet engines. The whirling ram-jet and pulse-jet engines, although lighter and less complex, have specific fuel consumptions averaging about 10 lb/hr/hp and 6.5 lb/hr/hp, respectively.

## Remarks on Pressure-Jet Operation

It has been shown in figure 10, that the minimum overall specific fuel consumption of the pressure-jet system occurs for the condition of no tip burning. However, as shown in figure 7, the ratio of rotor propulsive horsepower to compressor-air horsepower is a minimum for this condition. Therefore, in order to determine an optimum pressure-jet system, it is necessary to evaluate the effects of greater compressor unit weight and lower specific fuel consumption of the cold pressure-jet system against the lower compressor unit weight and higher specific fuel consumption of the hot pressure-jet system. Another problem which must be taken into account is that of providing sufficient duct area for the higher air mass flows that are necessary for the cold pressure jet.

The type of mission that the pressure-jet-powered helicopter will perform will also be an important factor in determining the amount of tip burning. Tip burning may be used to increase rotor horsepower at some sacrifice in specific fuel consumption and is, therefore, somewhat analogous to the use of an afterburner in a turbojet powered aircraft. One method of operation for a pressure-jet-powered helicopter is the use of tip burning for maximum performance conditions, with a gradual reduction in the amount of tip burning as the power requirements are reduced until, finally, tip burning is eliminated altogether. This particular type of operation is ideally suited for such helicopters since the maximum power is normally required only for short intervals during hovering and climb conditions.

The overall performance of the pressure-jet rotor is, in addition to the variables discussed in this report, very dependent upon the matching of the air-compressor characteristics to the air-mass-flow requirements of the tip unit.

Since the parameters determining the performance of the pressure-jet-powered rotor are interdependent, the extent to which tip burning will result in increased overall performance will be determined by the particular design and mission and is beyond the scope of this exploratory investigation.

## CONCLUDING REMARKS

An exploratory investigation of a helicopter pressure-jet system with tangentially mounted tip burner, has been conducted on the Langley helicopter test tower. The tests were conducted with a fixed-area exit nozzle over a tip speed range of 442 to 559 fps and at root stagnation-pressure ratios of 1.9, 2.14, and 2.31. Some of the more pertinent findings are as follows:

1. For a given root stagnation-pressure ratio and tip speed, the minimum overall specific fuel consumption of the pressure-jet system investigated is obtained without tip burning. For example, a specific fuel consumption of 2.28 lb/hr/hp was obtained for the particular rotor tested at a root stagnation-pressure ratio of 2.31, a tip speed of 558 fps, and an assumed overall compressor specific fuel consumption of 1 lb/hr/air horsepower.

2. The use of tip burning increases the ratio of propulsive horsepower to equivalent compressed-air horsepower at the expense of increased overall specific fuel consumption of the pressure-jet system. Tip burning at a fuel-air ratio of about 0.02 yields rotor-horsepower to equivalent air-horsepower ratios of about unity and an overall specific fuel consumption of about 2.5 lb/hr/hp at a pressure ratio of 2.31 and a tip speed of 558 fps. This may be compared with the average specific fuel consumption of the whirling ram jet of 10 lb/hr/hp and to the whirling pulse jet with an average specific fuel consumption of 6.5 lb/hr/hp.

3. A comparison of the whirling and nonwhirling specific gross thrust of the tangentially mounted tip burner indicated about an 8-percent loss in thrust due to whirling.

4. An analysis shows that for a given pressure ratio and fuel-air ratio, the maximum specific propulsive horsepower and the minimum overall specific fuel consumption should occur at the tip speed at which the propulsive thrust is equal to the air and fuel pumping term.

5. The analysis also shows that the ratio of rotor horsepower to equivalent compressed-air horsepower is a minimum for the condition of no tip burning. The ratio for the particular rotor tested was about 0.45. With no tip burning the horsepower ratio would approach 0.67 as a limit if the propulsive horsepower were maintained at a maximum value.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 3, 1956.

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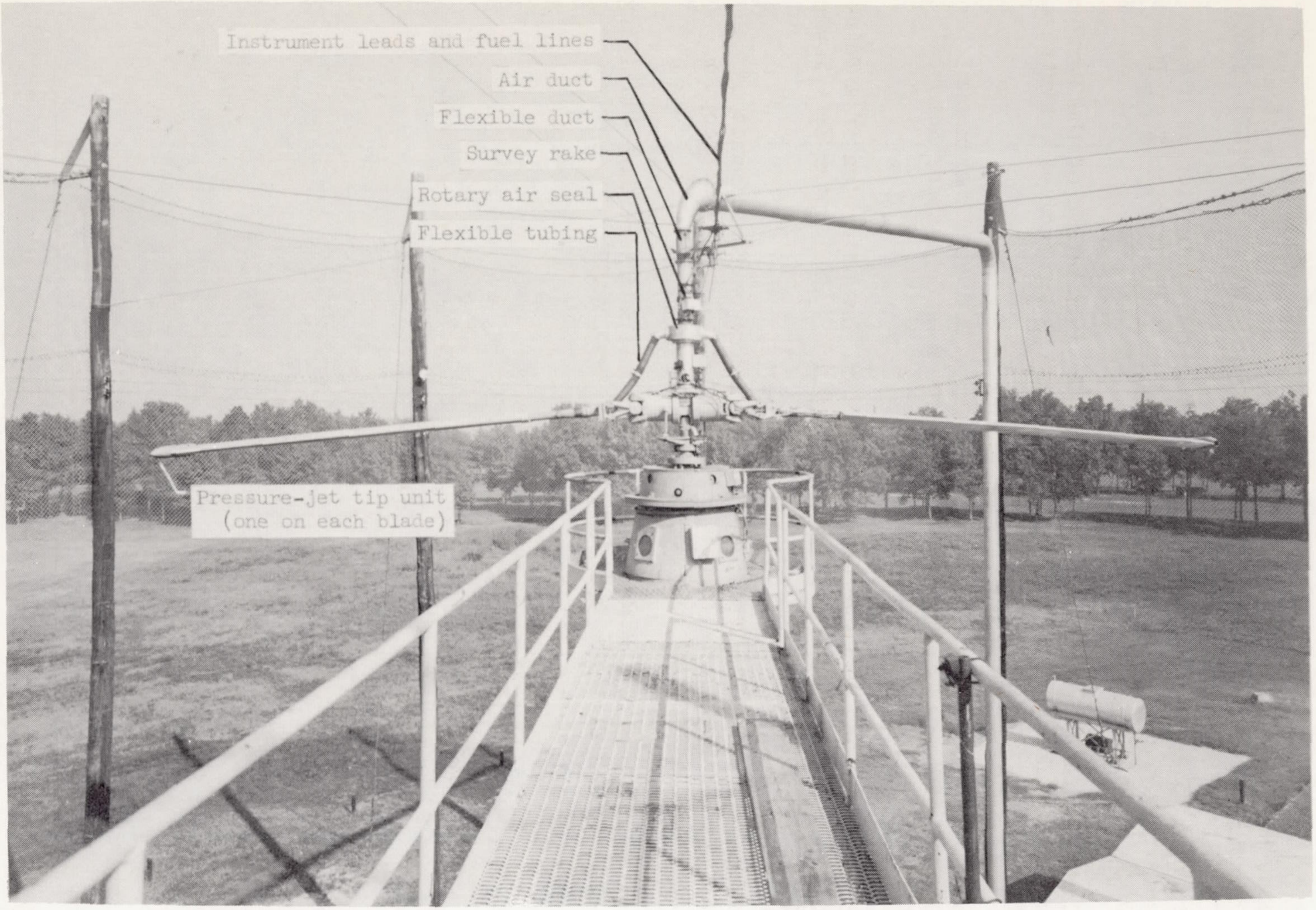


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Figure 1.- View of pressure-jet-powered helicopter rotor mounted on test tower.

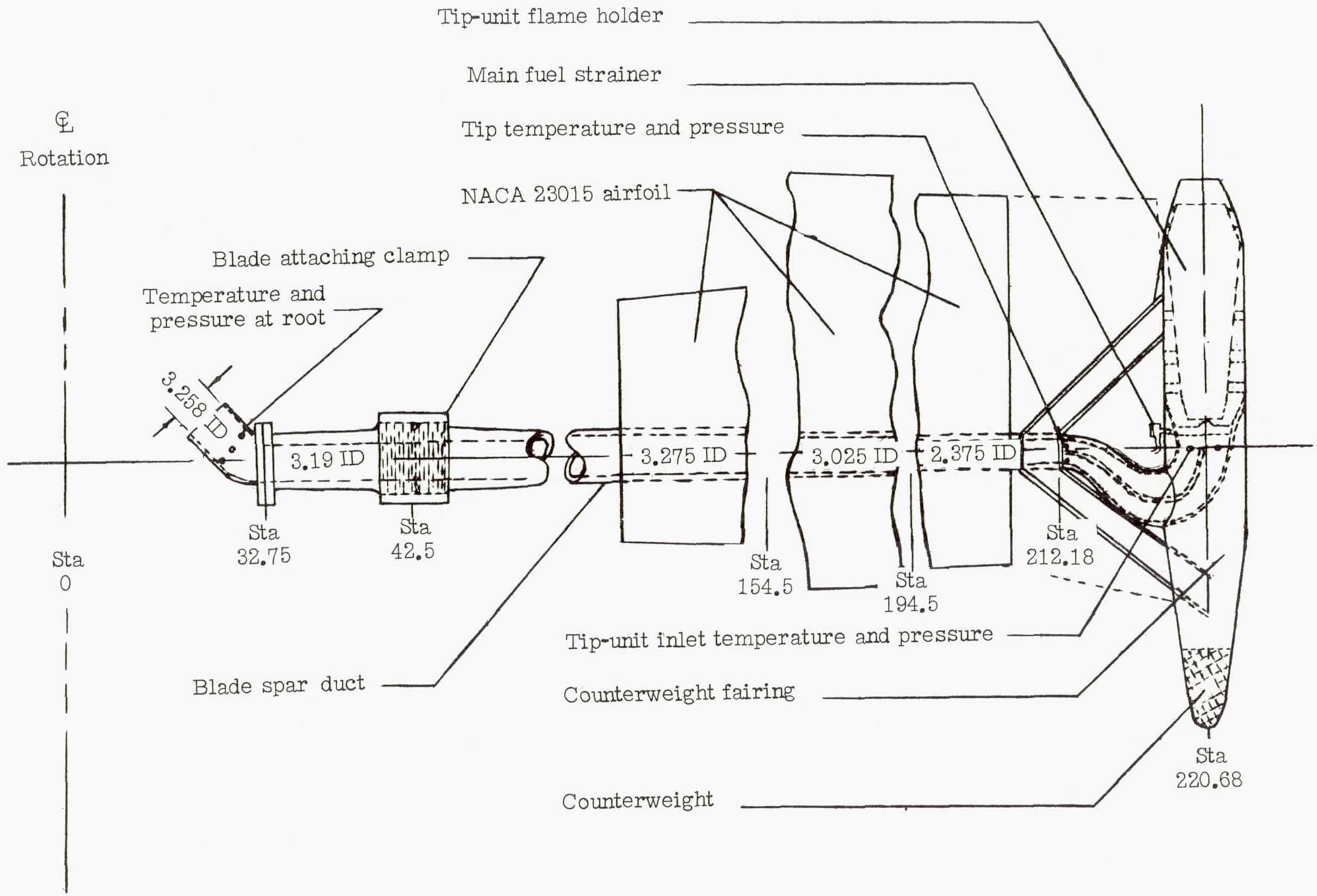



Figure 2.- Sketch of rotor-blade duct and tip unit of pressure-jet-powered helicopter rotor.

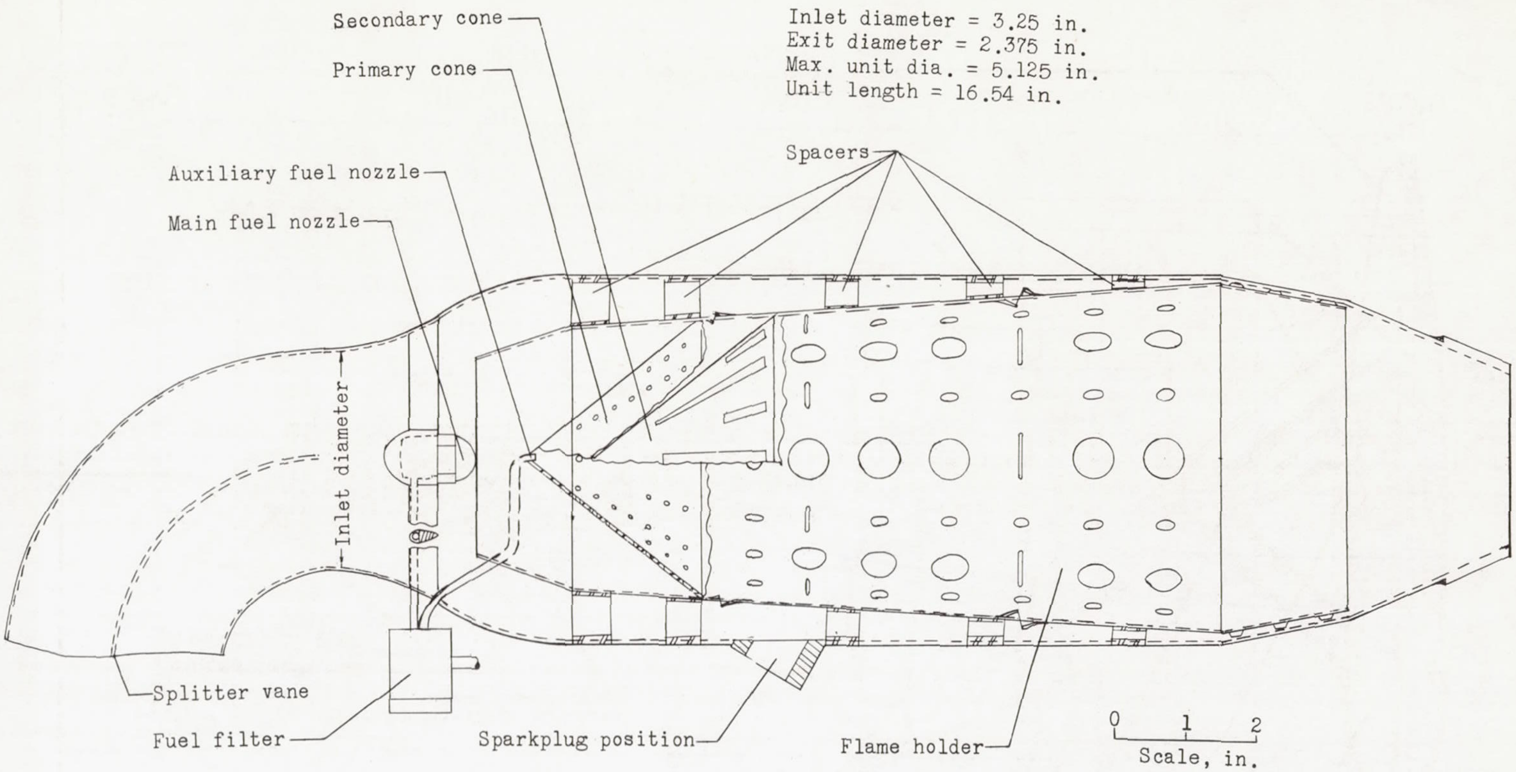
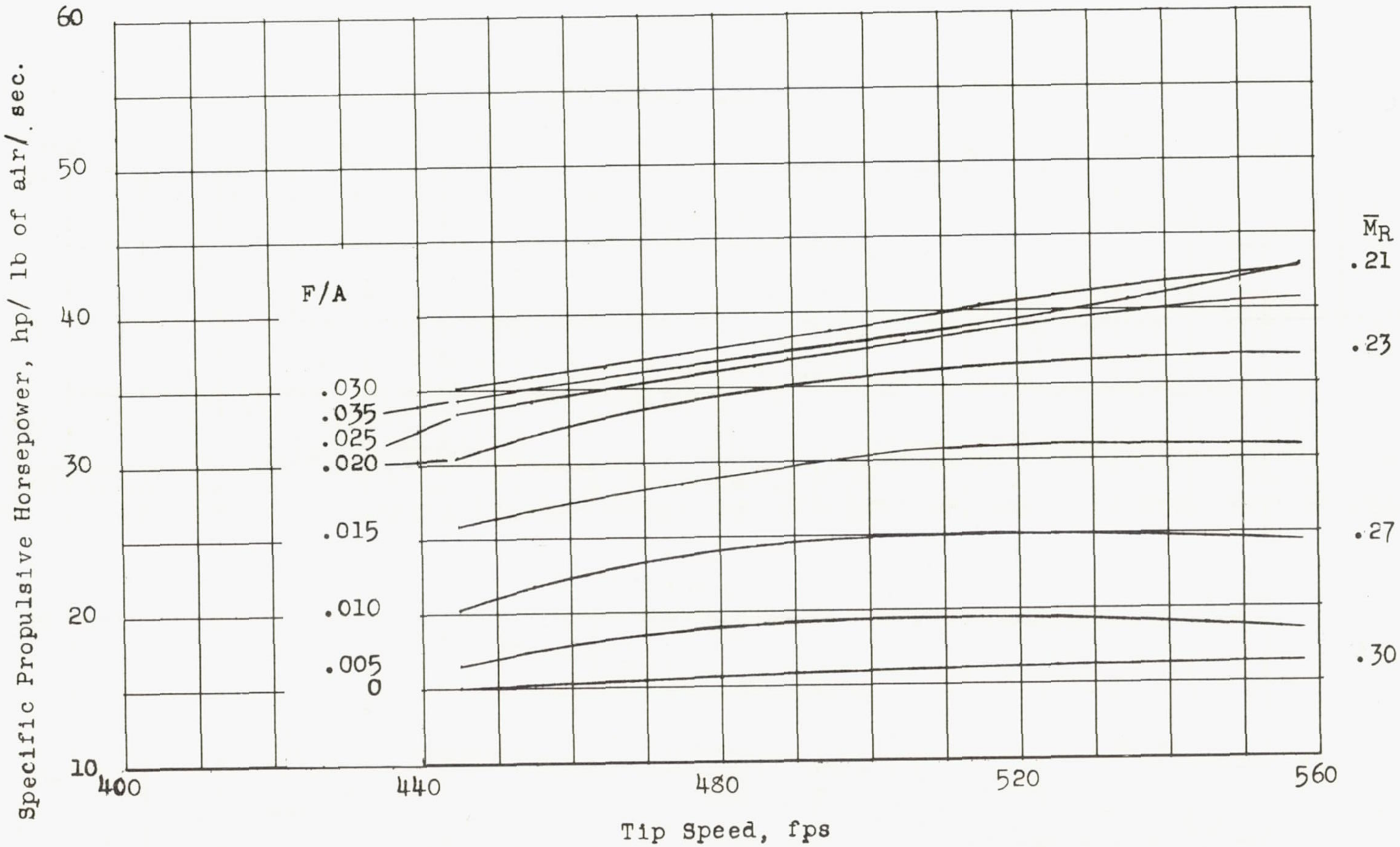
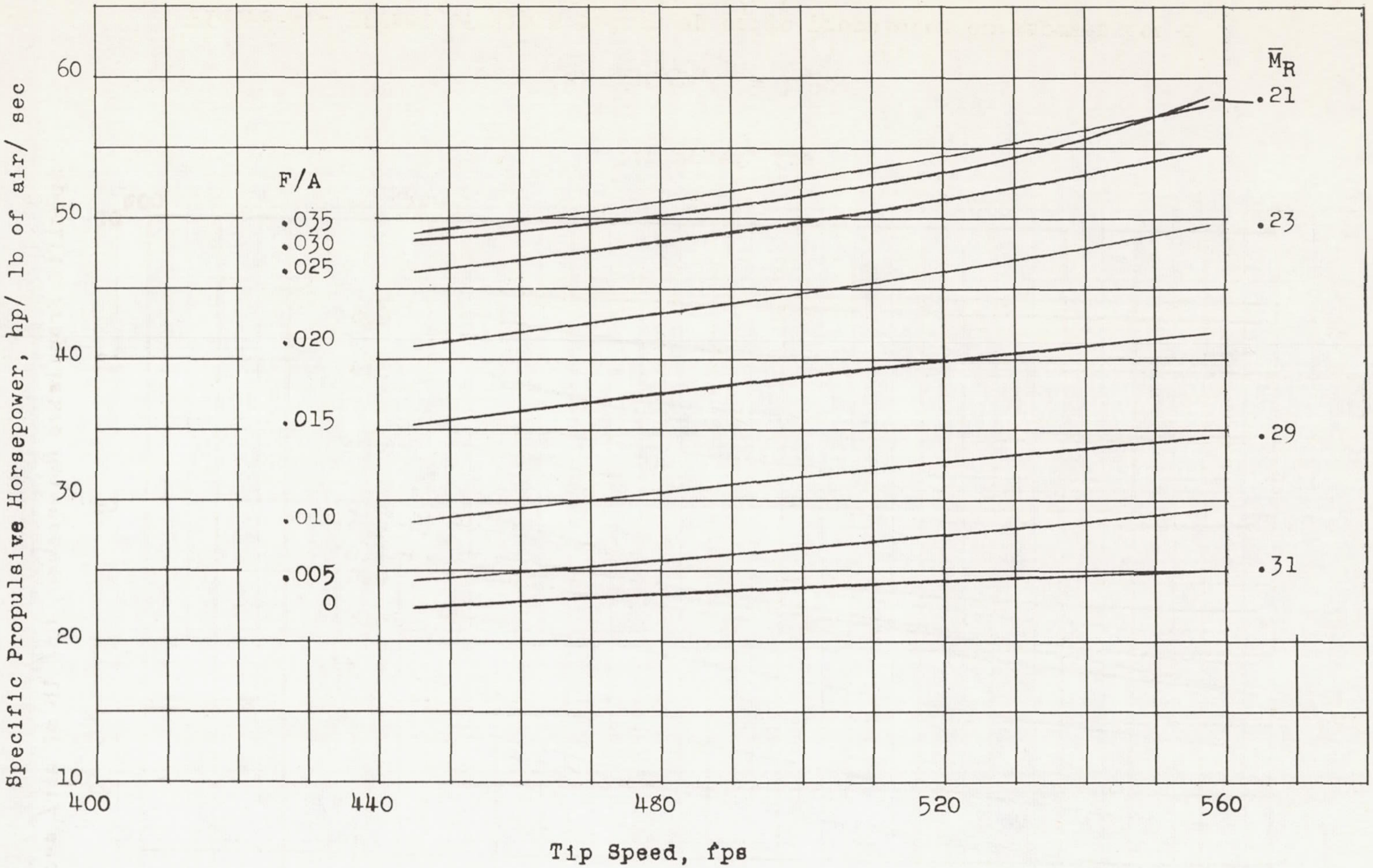



Figure 3.- Sketch of pressure-jet burner.



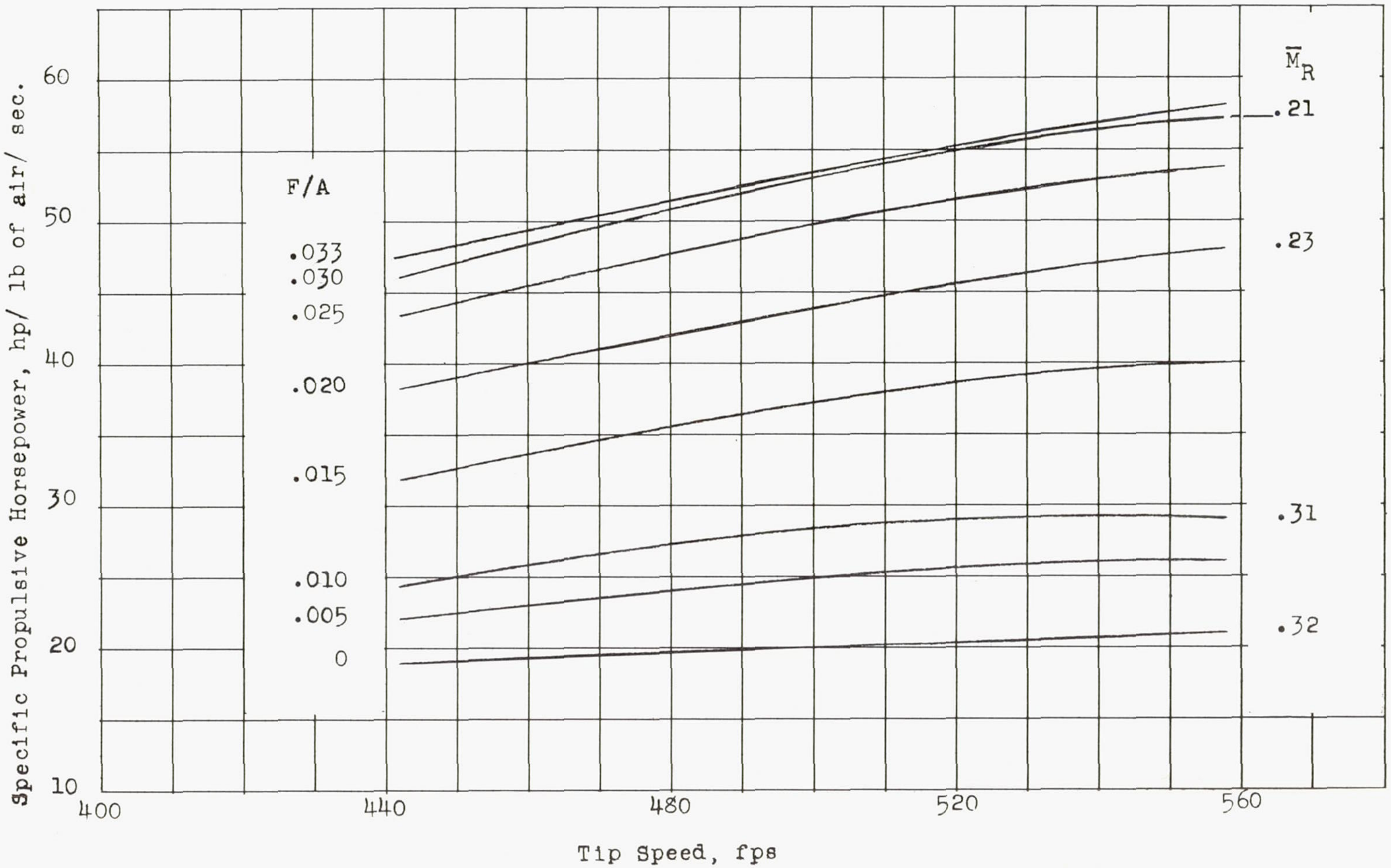

(a) $(p_t/p_a)_1 = 1.90$.

Figure 4.- Effect of tip speed on specific propulsive horsepower for a range of fuel-air ratios.



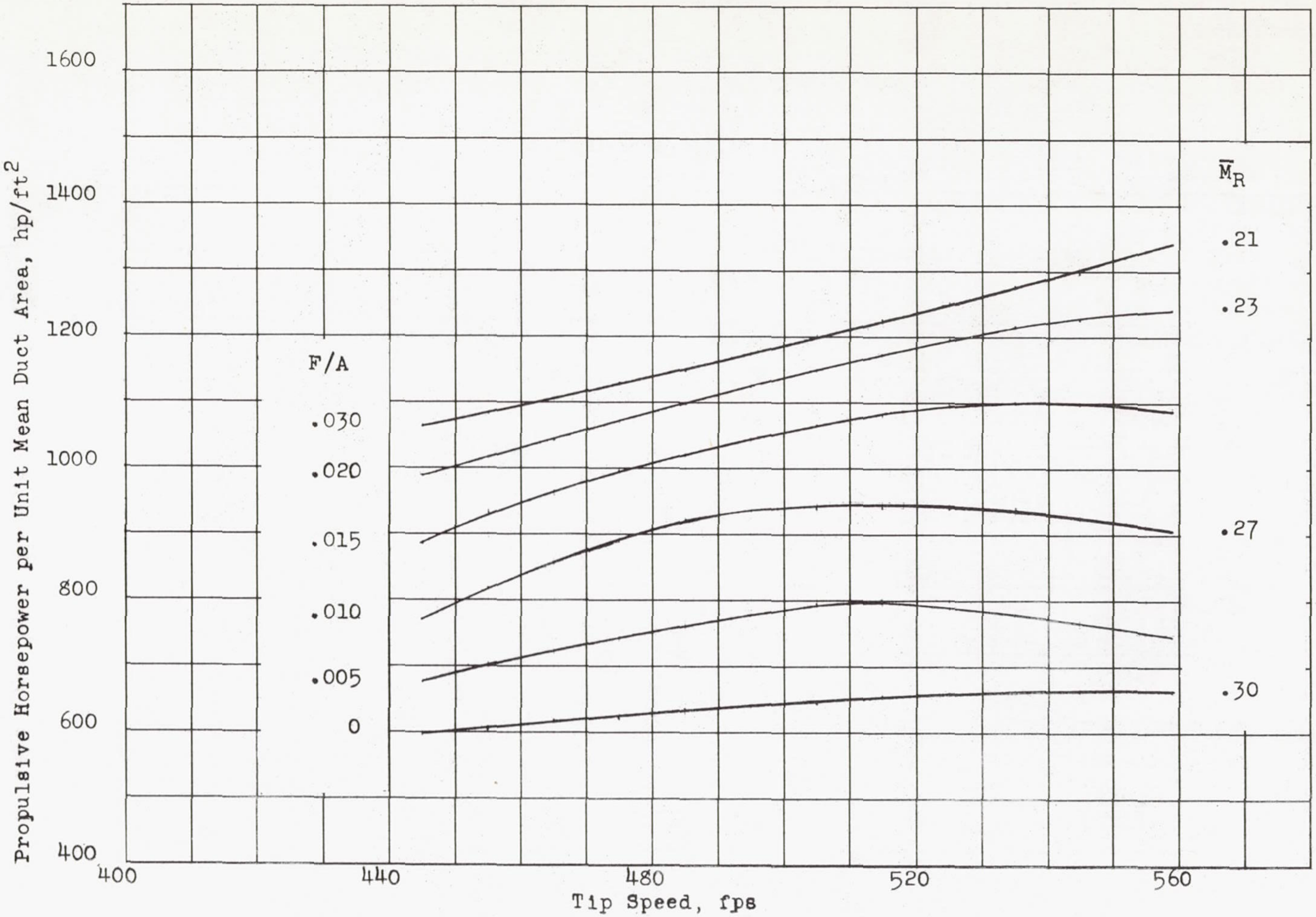

(b) $(p_t/p_a)_1 = 2.14$.

Figure 4.- Continued.



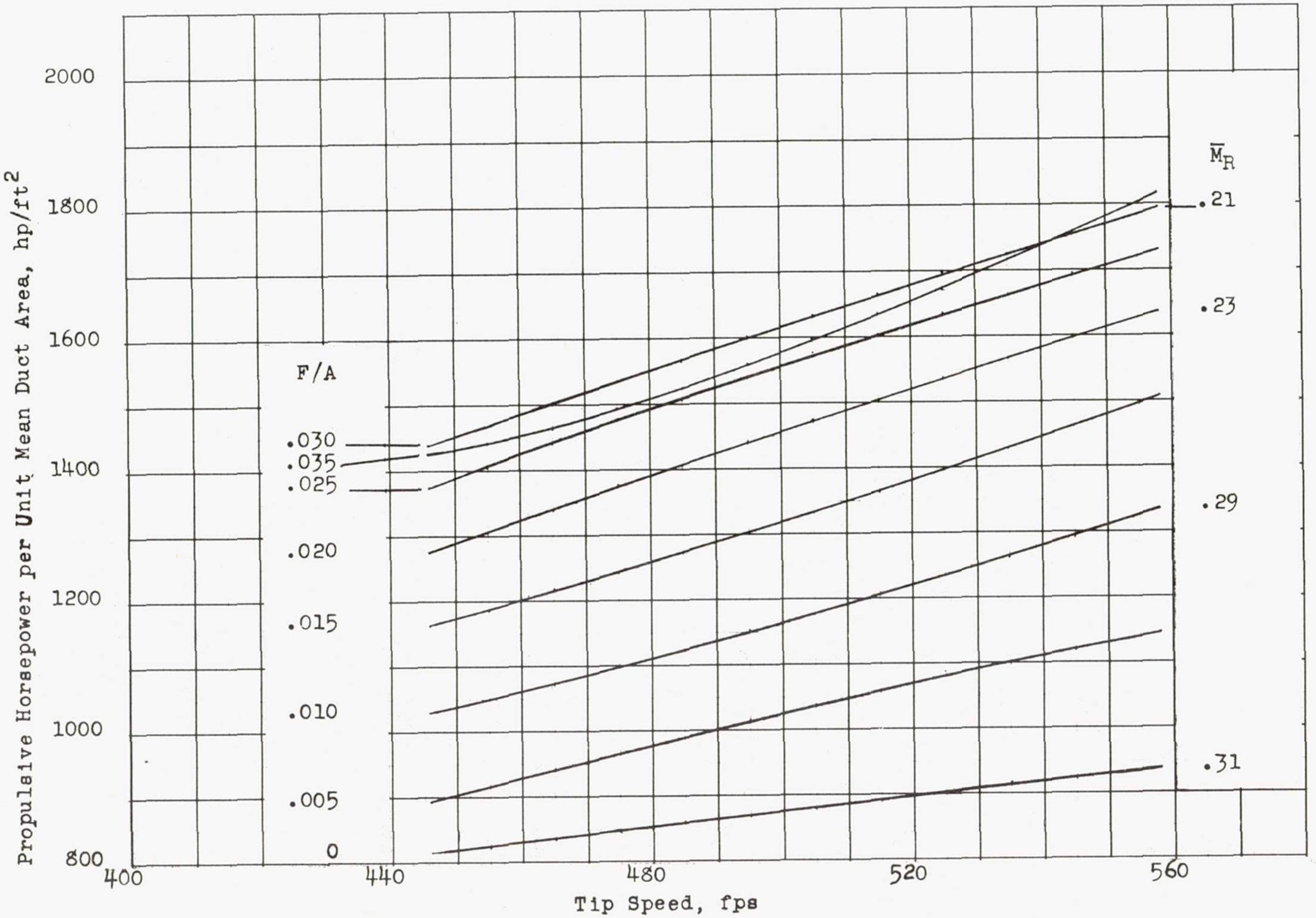

(c) $(p_t/p_a)_1 = 2.31$.

Figure 4.- Concluded.



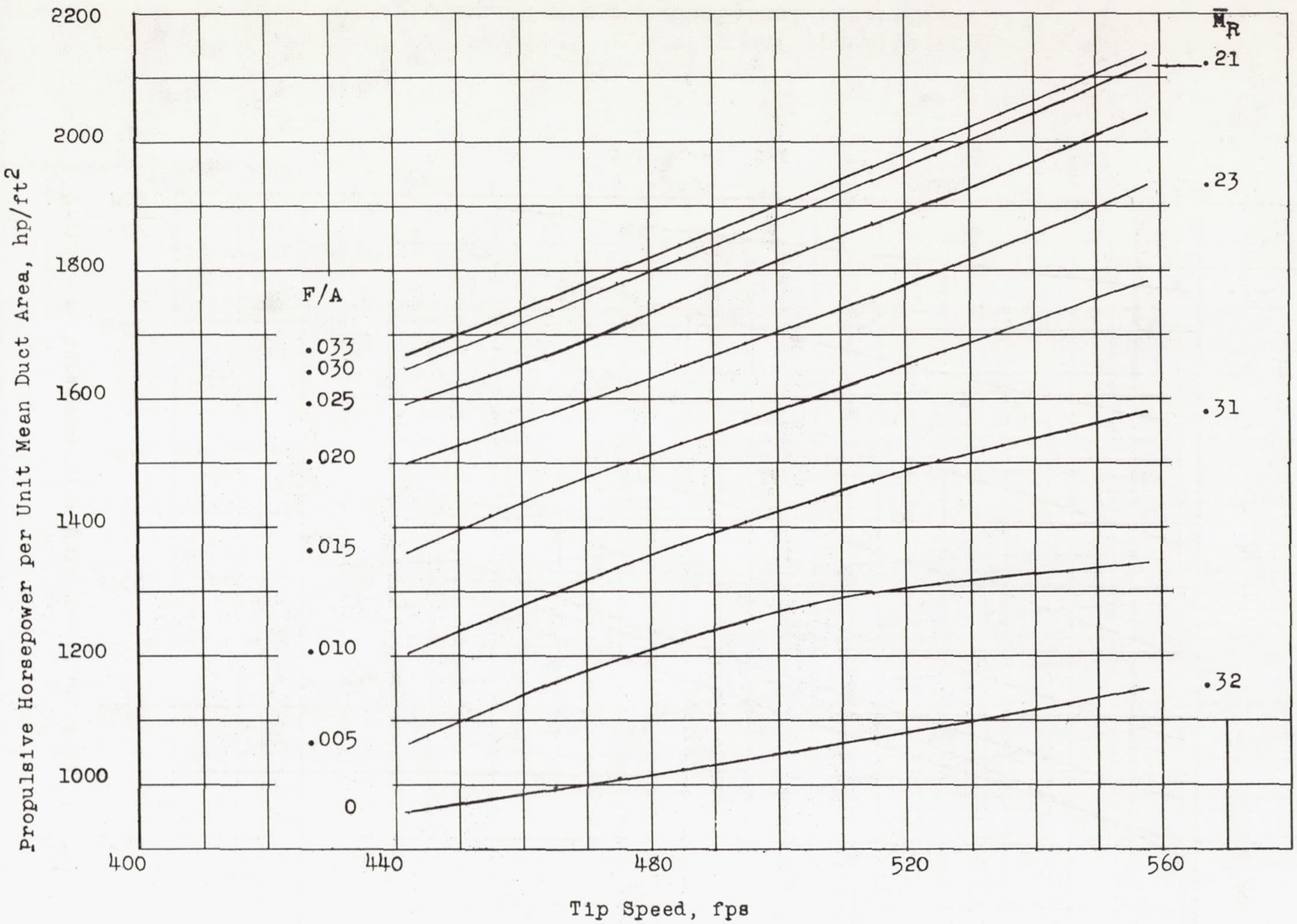

(a) $(p_t/p_a)_1 = 1.90.$

Figure 5.- Effect of tip speed on propulsive horsepower per unit mean duct area for a range of fuel-air ratios.



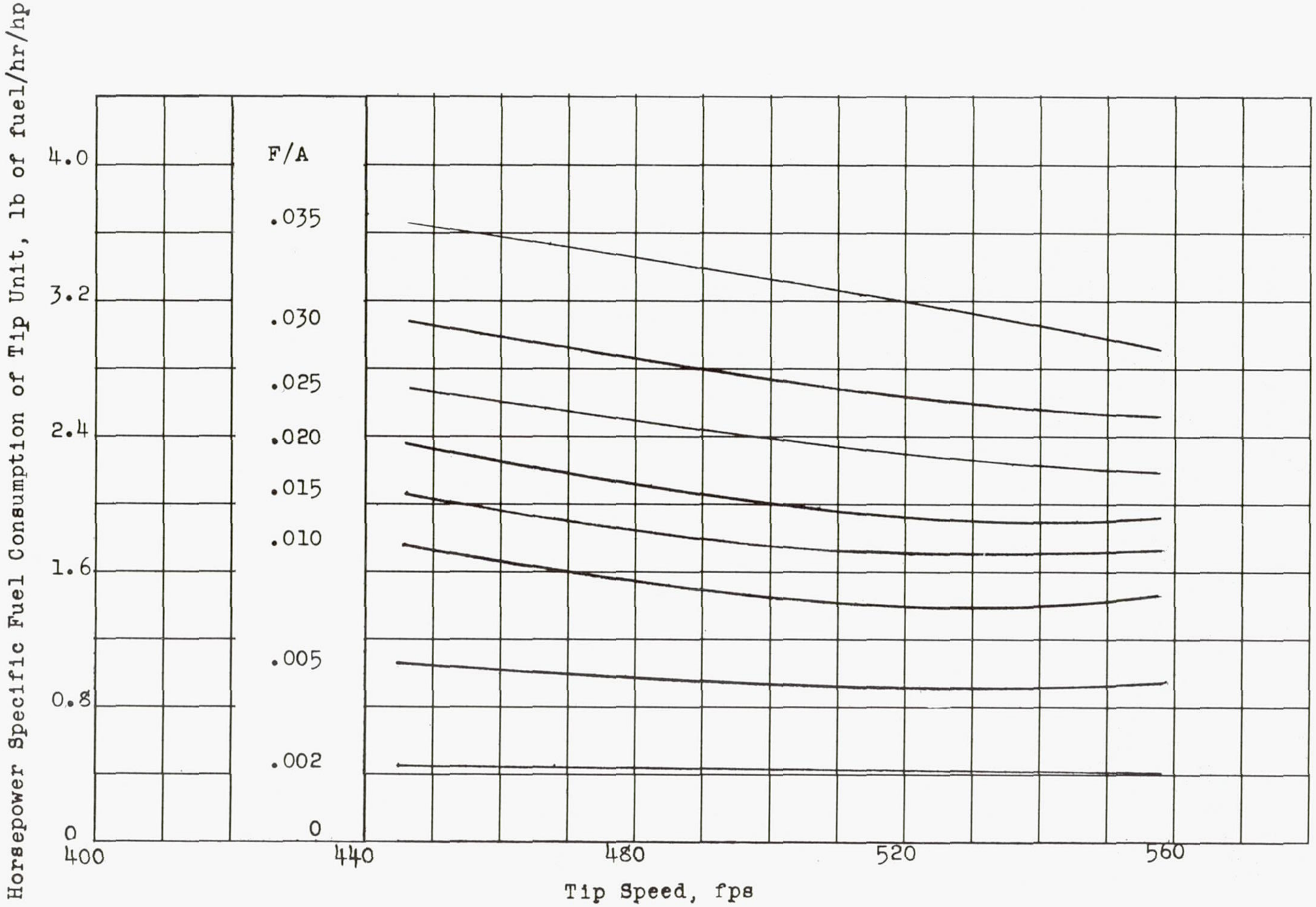

(b) $(p_t/p_a)_1 = 2.14$.

Figure 5.- Continued.



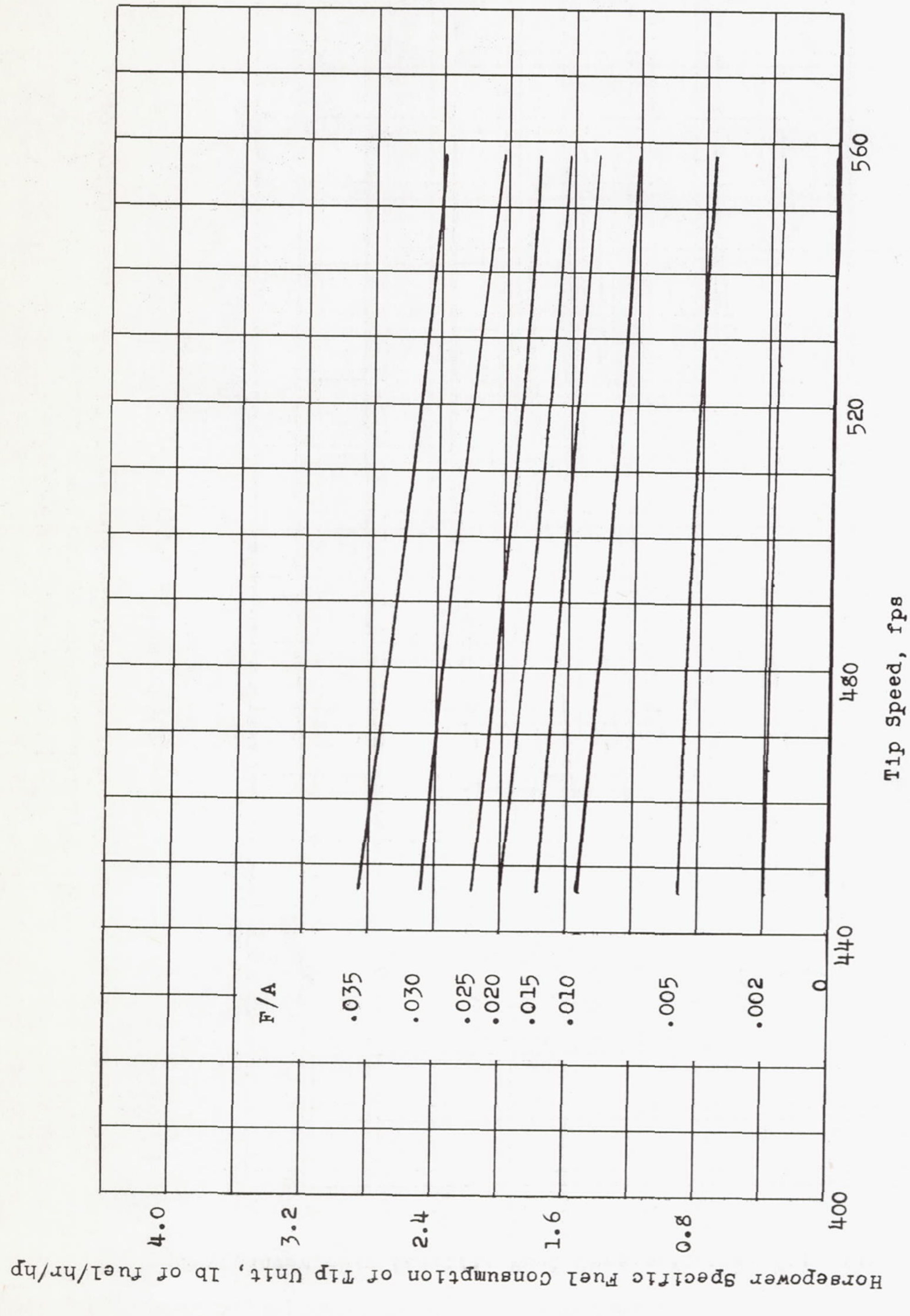

(c) $(p_t/p_a)_1 = 2.31.$

Figure 5.- Concluded.



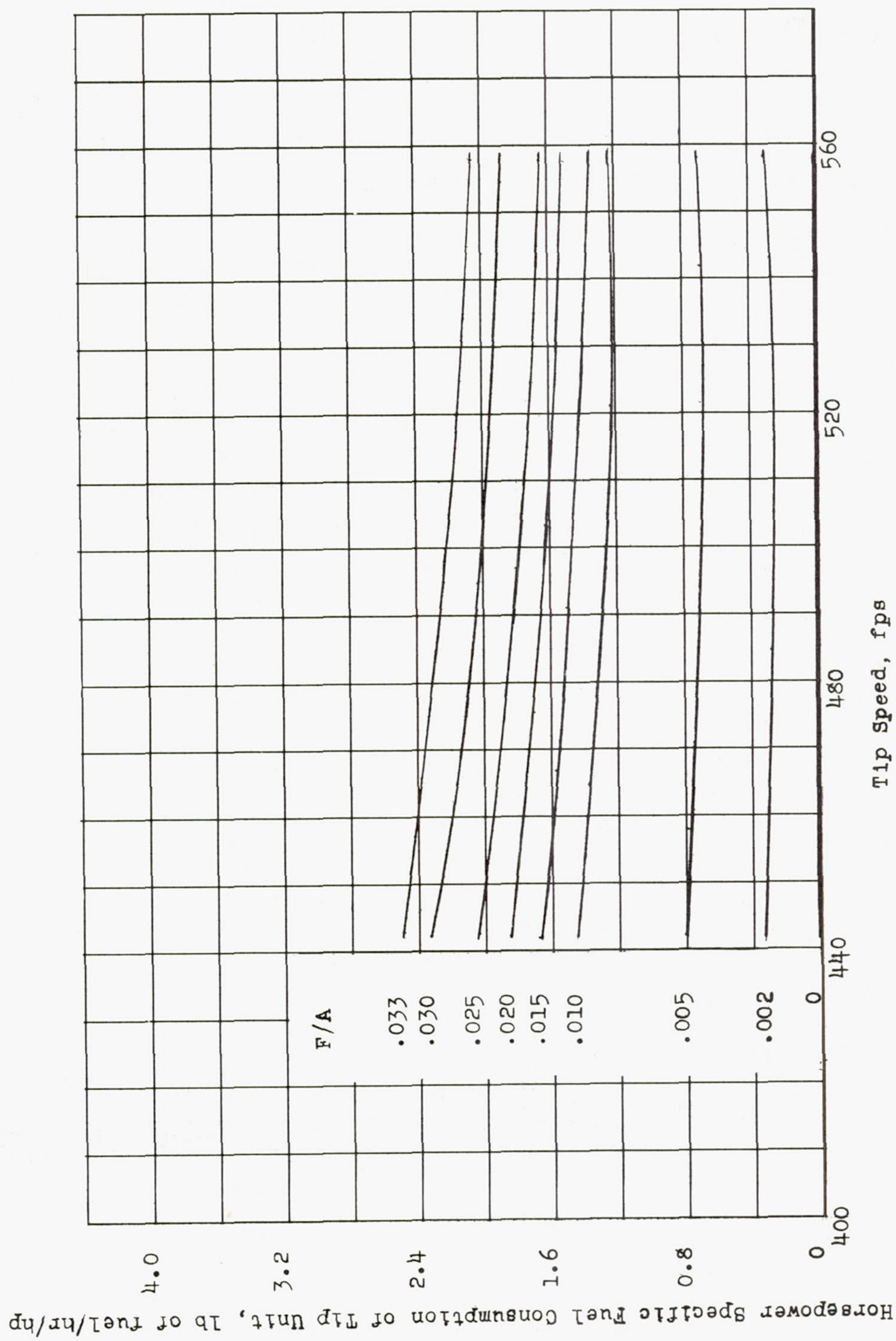

(a) $(p_t/p_a)_1 = 1.90.$

Figure 6.- Effect of tip speed on horsepower specific fuel consumption of tip unit for a range of fuel-air ratios.



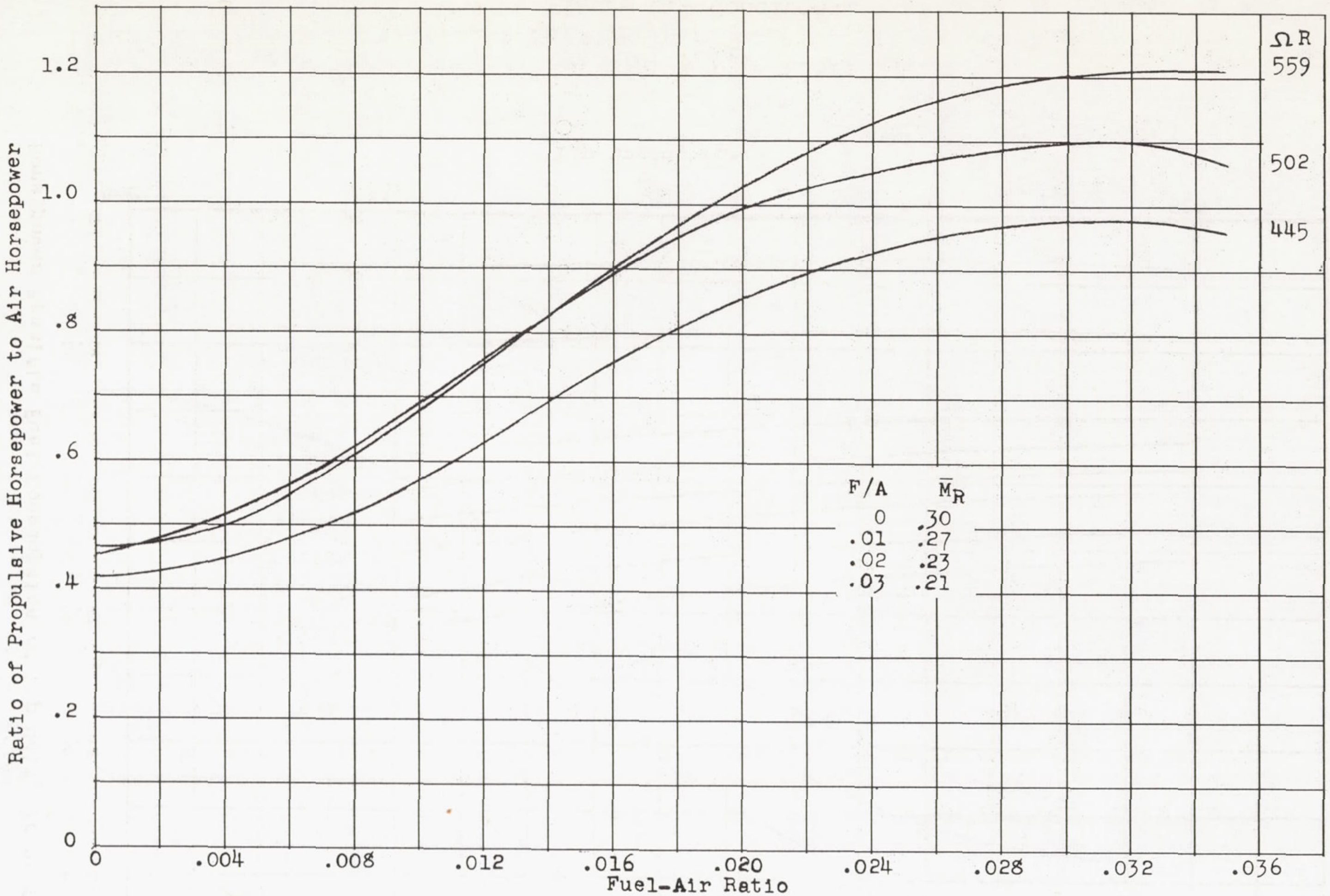

(b) $(p_t/p_a)_1 = 2.14$.

Figure 6.- Continued.



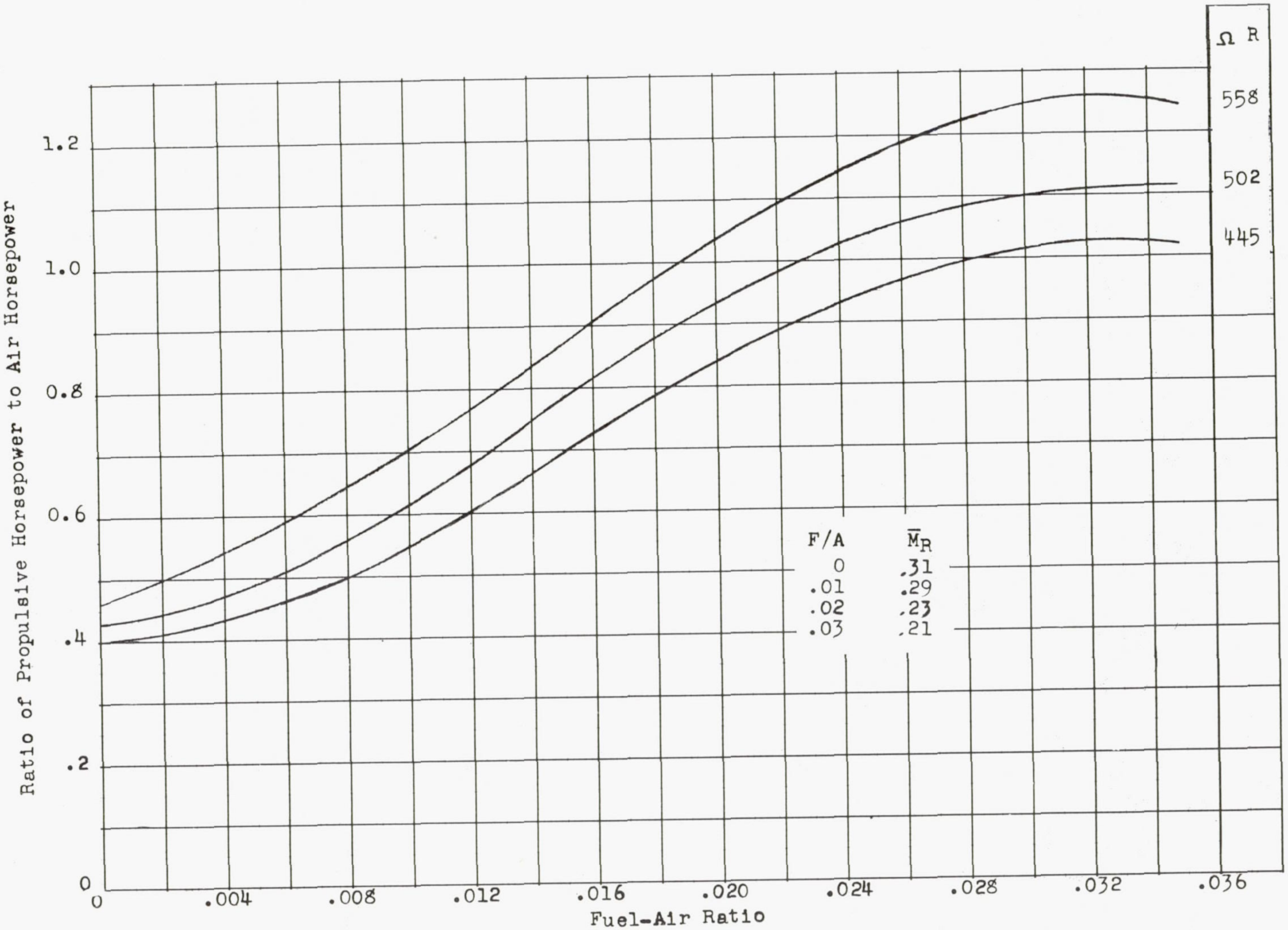

(c) $(p_t/p_a)_1 = 2.31.$

Figure 6.- Concluded.



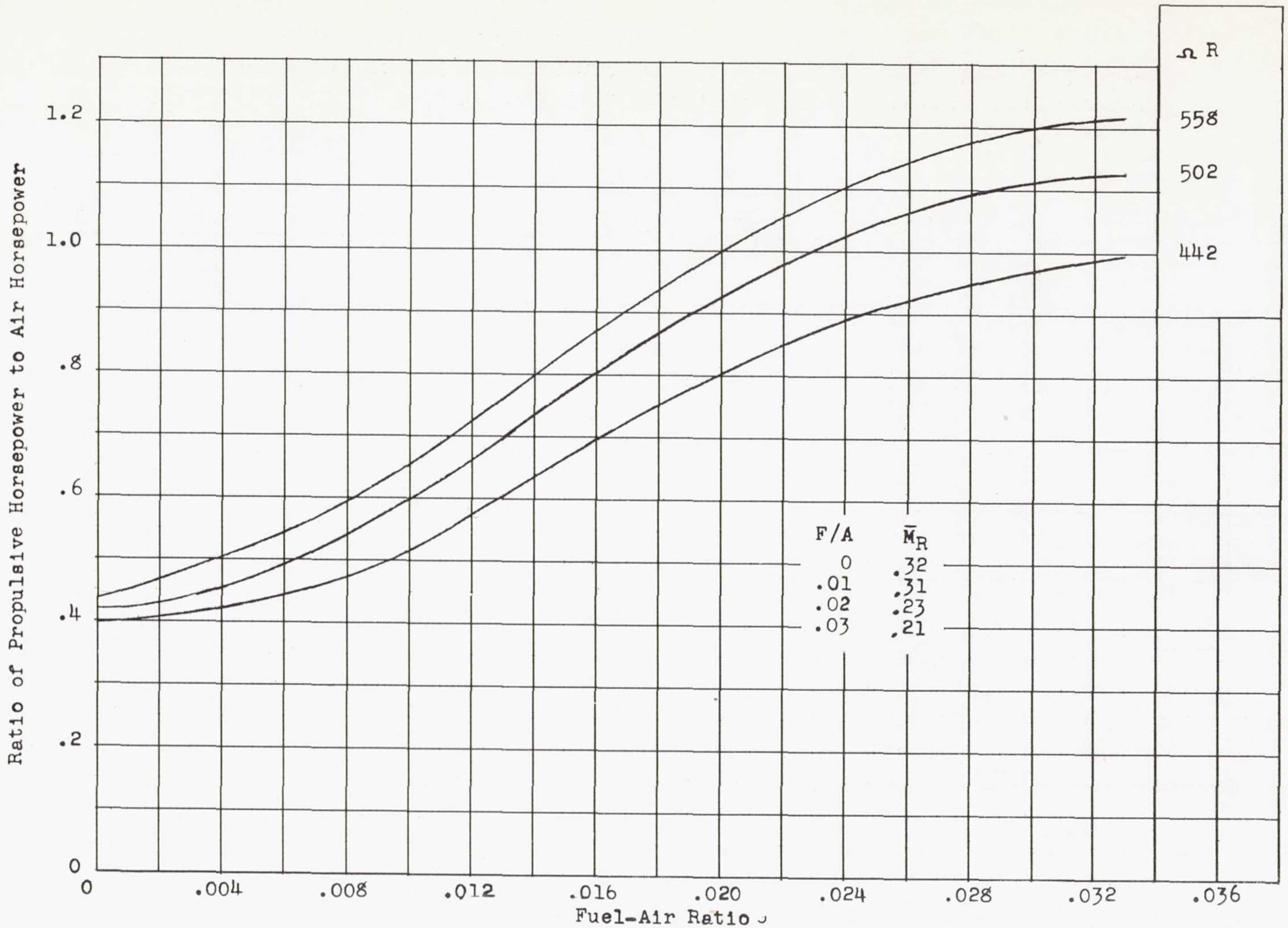

(a) $(p_t/p_a)_1 = 1.90$.

Figure 7.- Effect of fuel-air ratio on ratio of propulsive horsepower to air horsepower for a range of tip speeds.




(b) $(p_t/p_a)_1 = 2.14$.

Figure 7.- Continued.




(c) $(p_t/p_a)_1 = 2.31$.

Figure 7.- Concluded.

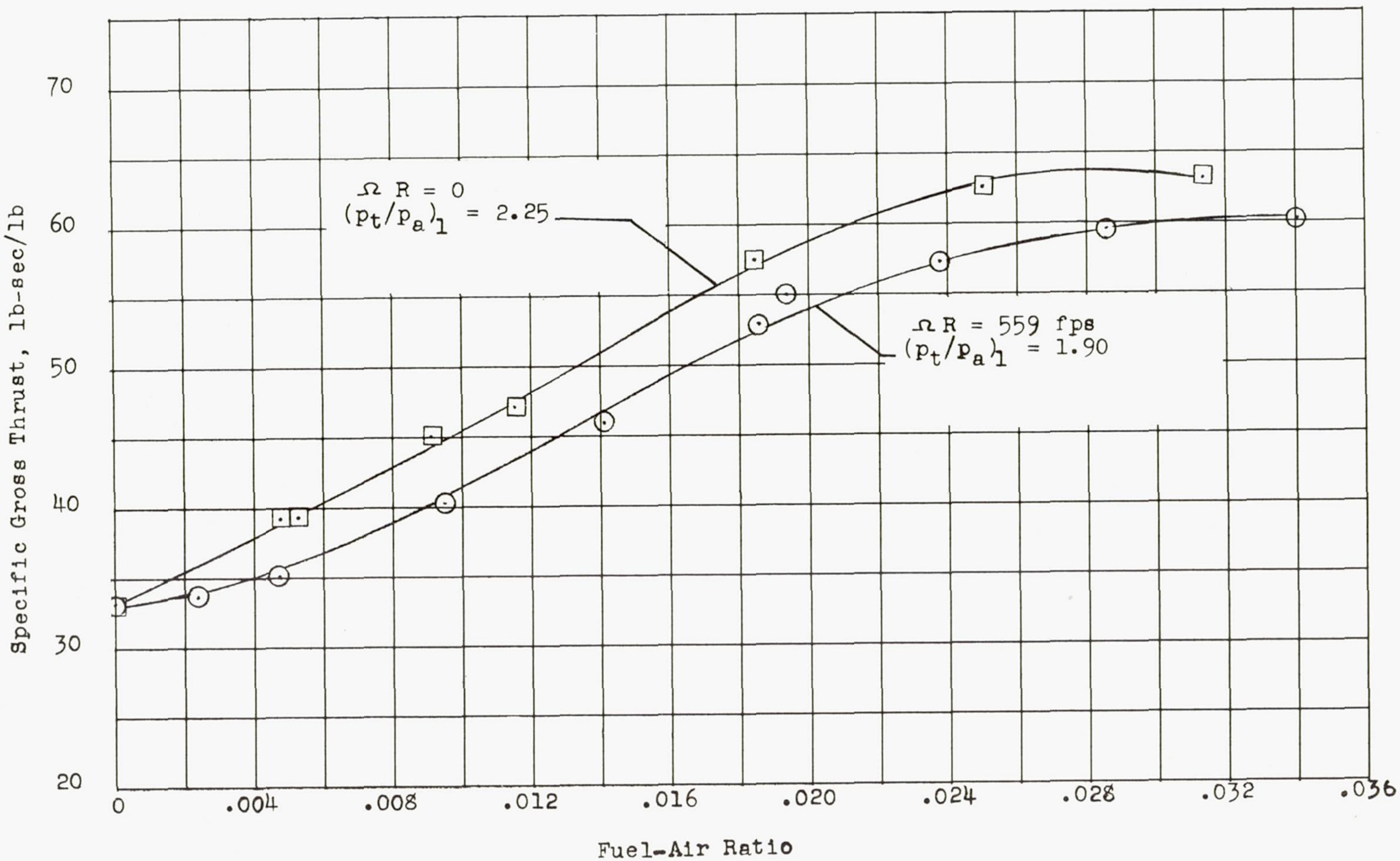



Figure 8.- Comparison of whirling and nonwhirling tip-unit performance in terms of specific gross thrust and fuel-air ratio for equal tip-unit inlet static pressures.

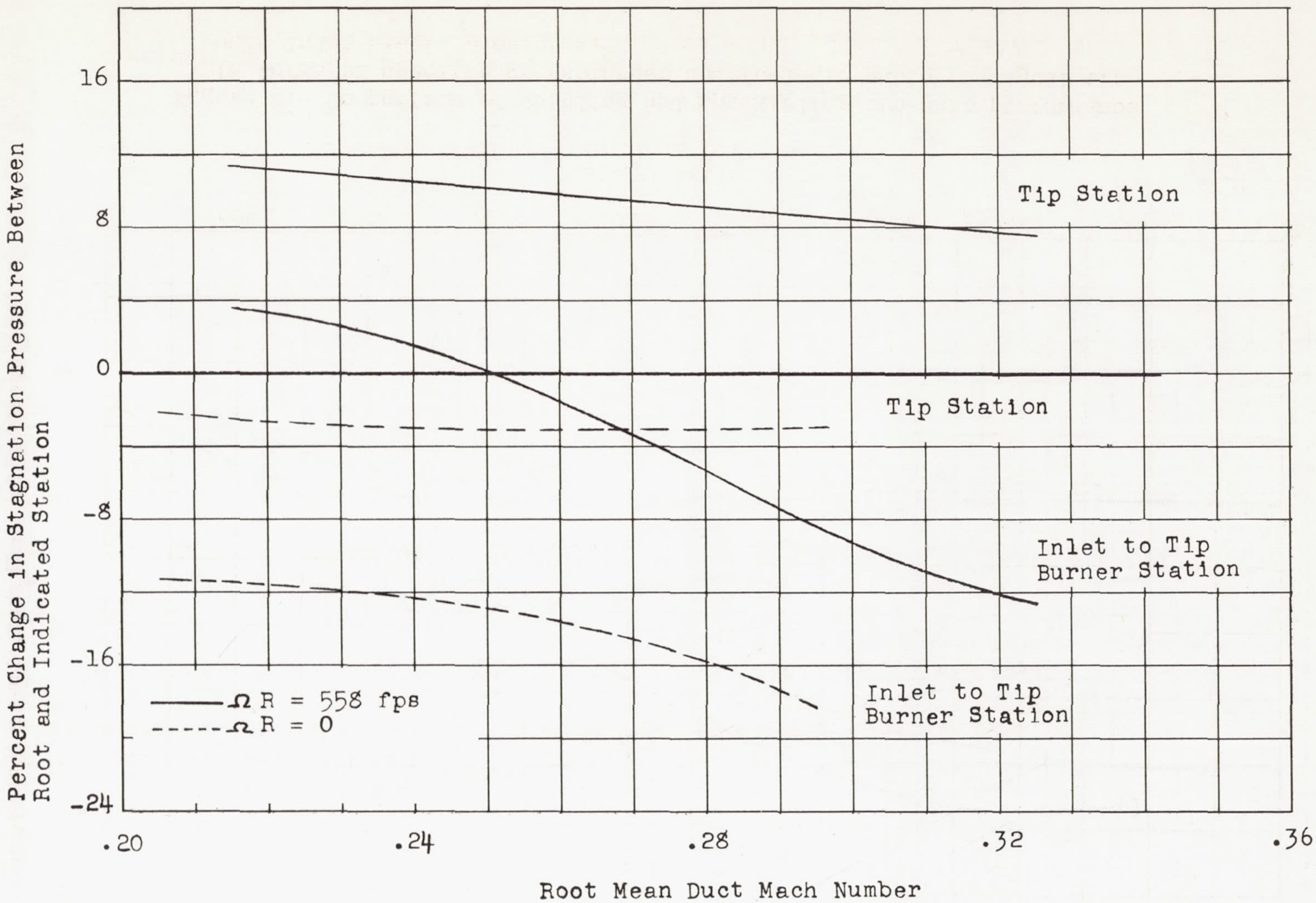
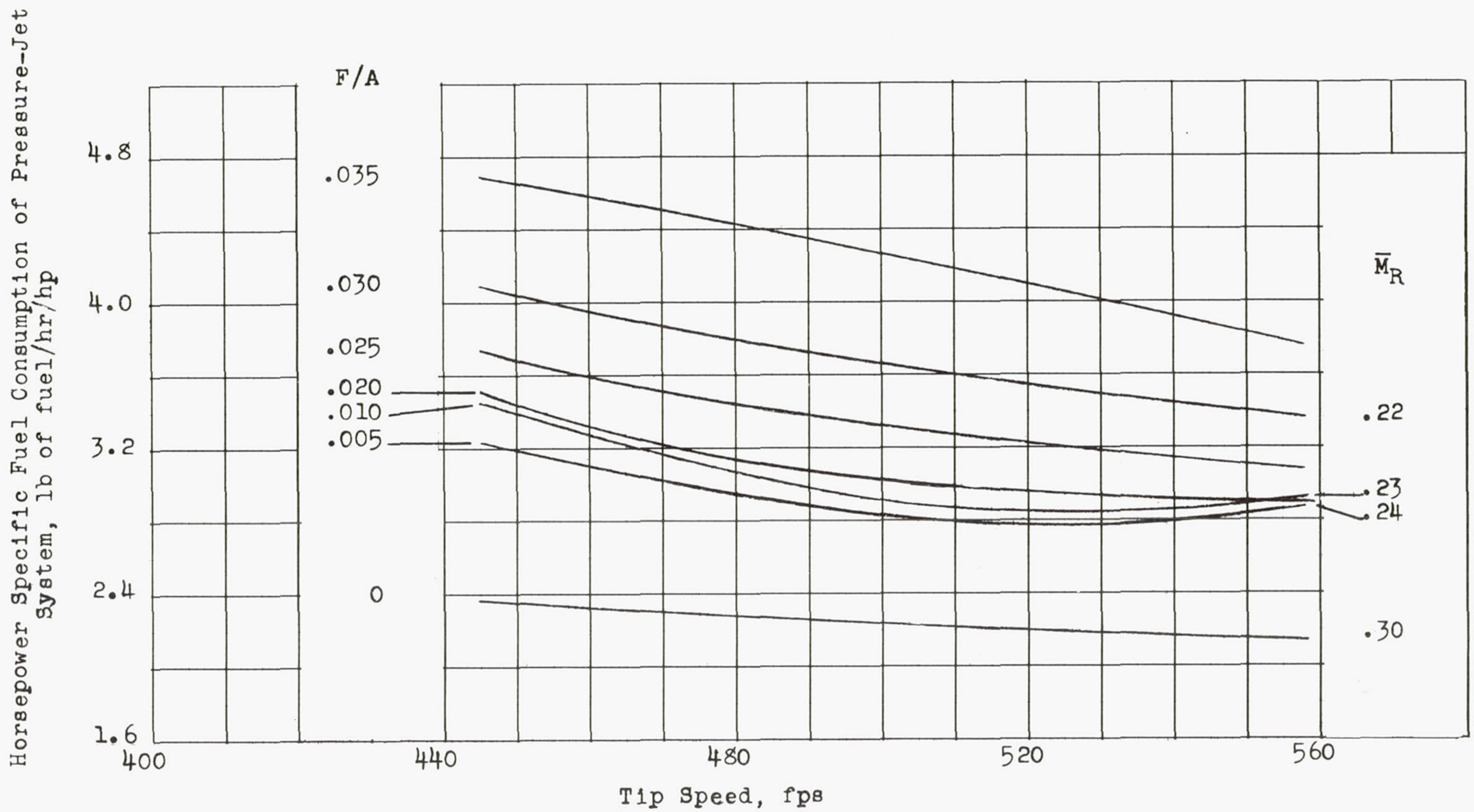
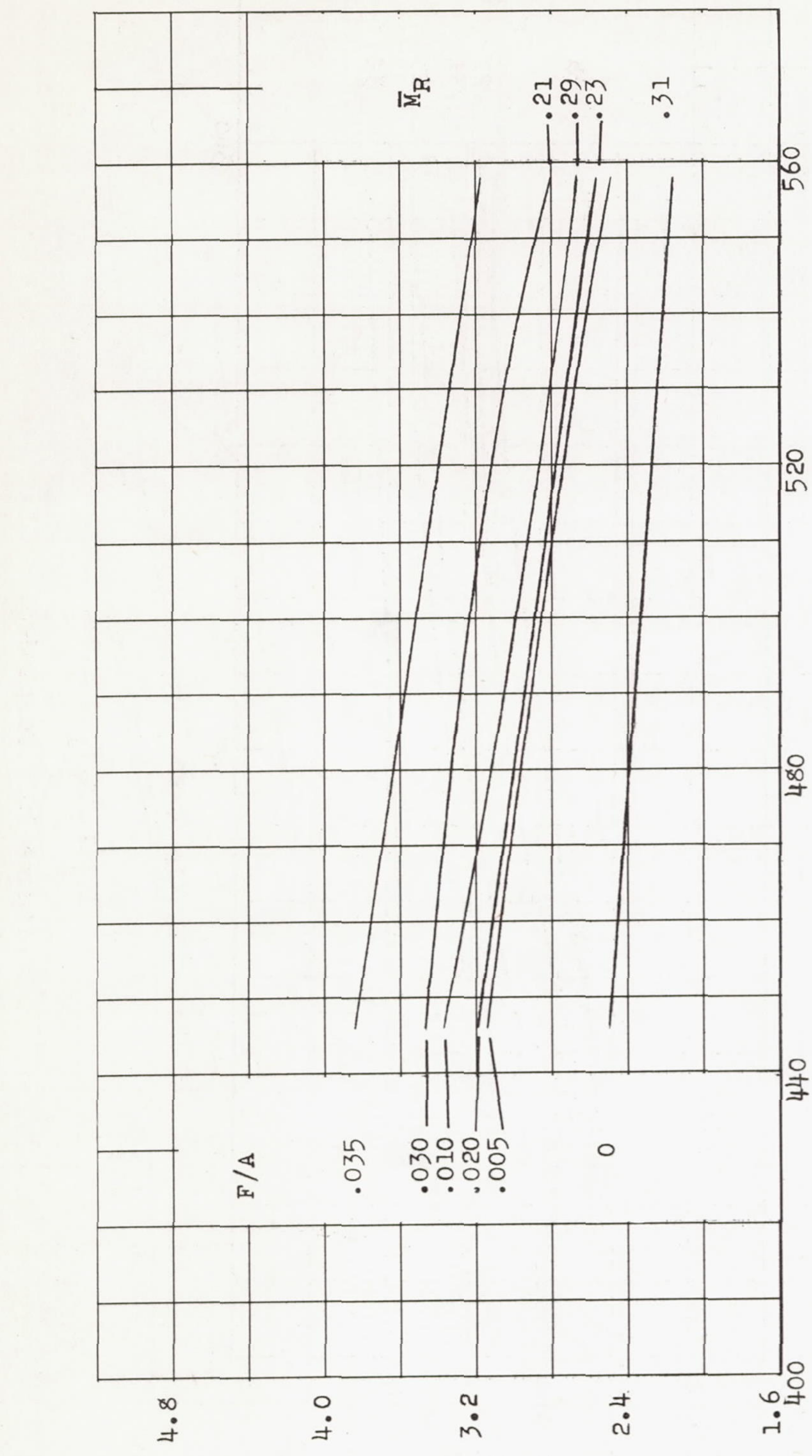



Figure 9.- Effect of root mean duct Mach number on stagnation-pressure change for whirling and nonwhirling conditions. $(p_t/p_a)_1 = 2.31$.



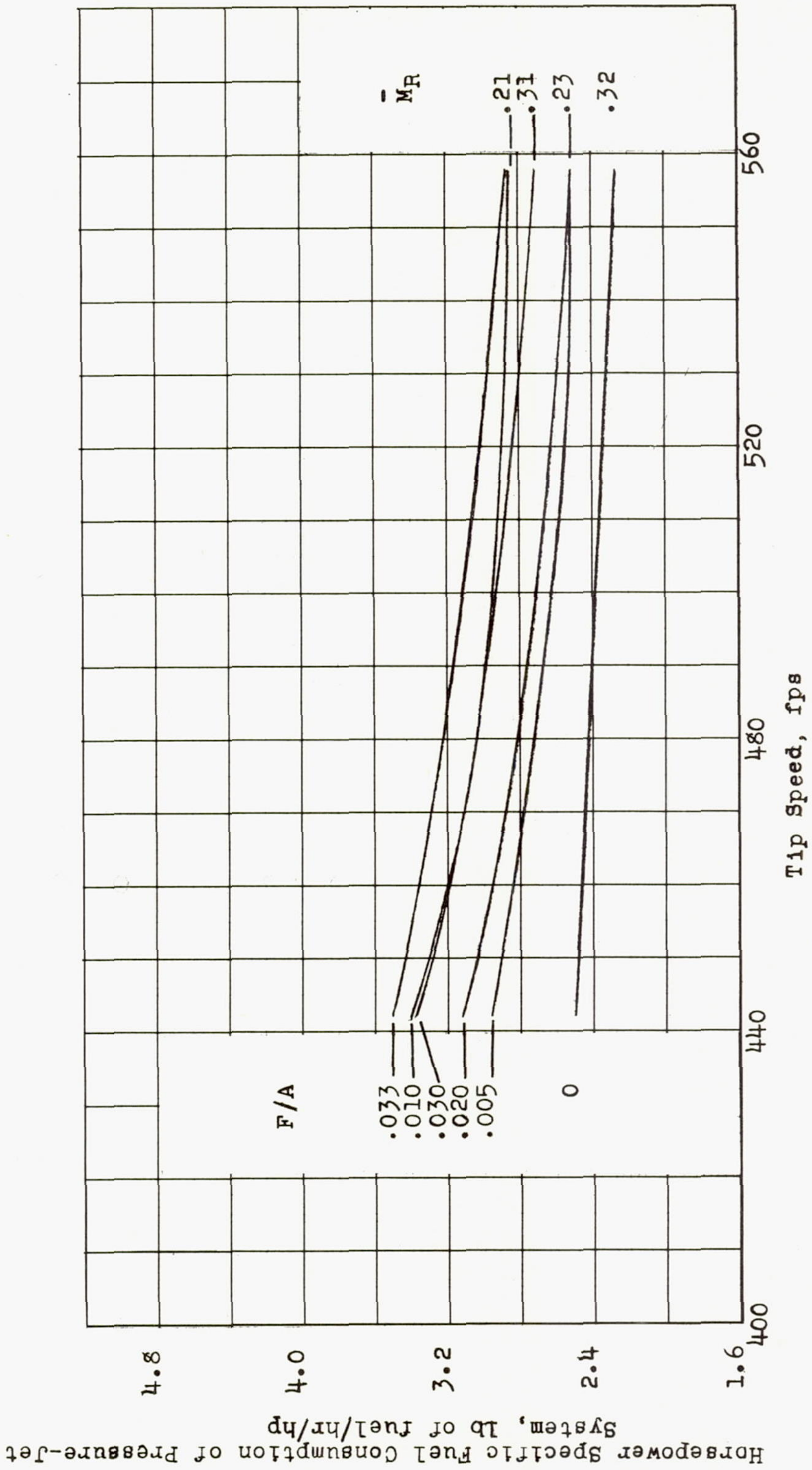

(a) $(p_t/p_a)_1 = 1.90$.

Figure 10.- Effect of tip speed on horsepower specific fuel consumption of pressure-jet system for a range of fuel-air ratios. Compressor-drive horsepower specific fuel consumption, 1.0 lb of fuel/hr/hp.




(b) $(p_t/p_a)_1 = 2.14$.

Figure 10.- Continued.




(c) $(p_t/p_a)_1 = 2.31$.

Figure 10.- Concluded.