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PERFORMANCE OF AN EXHAUST-GAS "BLOWDOWN" TURBINE ON A NINE-CYLINDER RADIAL ENGINE

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ADVANCE CONFIDENTIAL REPORT

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SUMMARY

Tests were run on an exhaust-gas turbine having four separate nozzle boxes each covering a 90° arc of the nozzle diaphragm and each connected to a pair of adjacent cylinders of a Pratt & Whitney R-1340-12 nine-cylinder radial engine. The total turbine nozzle area was 8.44 square inches. This type of turbine has been called a "blowdown" turbine because it recovers the kinetic energy developed in the exhaust stacks during the blowdown period. The purpose of the test was to determine whether the blowdown turbine could develop appreciable power without imposing any loss in engine power arising from restriction of the engine exhaust by the turbine.

At an engine speed of 2000 rpm and an inlet-manifold pressure of 33.5 inches of mercury absolute, the turbine power varied from 9 percent of engine power with a turbine exhaust pressure of 28 inches of mercury absolute to 21 percent of engine power with a turbine exhaust pressure of 7.5 inches of mercury absolute. The engine power was decreased a maximum of 1 percent by the presence of the turbine at the lowest turbine exhaust pressure as compared with the engine power delivered with a conventional collector ring discharging to an equal exhaust pressure. No engine-power loss was imposed by the presence of the turbine with turbine exhaust pressures greater than 20 inches of mercury absolute. The engine air-flow rate was not affected by the presence of the turbine.

The use of a blowdown turbine and a conventional turbosupercharger connected in series is briefly discussed. An analysis is presented relating the test data to the mean jet-velocity data for the NACA individual-stack jet-propulsion system.

INTRODUCTION

At the time of exhaust-valve opening, the pressure of the gas in the cylinder of an internal-combustion engine is considerably above atmospheric pressure; the gas is therefore capable of doing an appreciable amount of work by further expansion. When the cylinders are exhausted to a collector discharging either to the atmosphere or to the nozzle box of a conventional exhaust turbine, the kinetic energy produced at the end of the exhaust stacks by the difference between cylinder pressure and collector pressure is dissipated as heat in the collector. A turbine that converts this kinetic energy into shaft work has been called a "blowdown" turbine because it recovers the kinetic energy developed in the exhaust stacks during the blowdown period.

With a suitable piping arrangement and turbine nozzle area, the power delivered by the blowdown turbine may be obtained with little or no decrease in engine power resulting from exhaust-pipe restriction. The maximum net power can be attained by discharging the exhaust gas from each cylinder into the turbine buckets as a separate jet and permitting each cylinder to exhaust to the turbine outlet pressure.

Several satisfactory exhaust-system arrangements exist. In one arrangement each cylinder may be connected to a separate nozzle. This arrangement would require a large total nozzle area and would result in an excessively large turbine size. The turbine size may be reduced approximately one-half at the possible cost of a slight loss in turbine power by connecting each nozzle to two cylinders having nonoverlapping exhaust periods. In such an arrangement, the exhaust discharge of each cylinder would still be a separate event. Paired exhaust stacks, however, must be carefully designed to avoid an appreciable kinetic-energy loss at their juncture.

In present aircraft engines, the connection of more than two cylinders to a single nozzle would result in a considerable mechanical and design difficulty or, in some engines, would result in an overlap of the exhaust periods with a resultant increase of the engine back pressure.

The present report describes the results of tests of a blowdown turbine in which each nozzle served two cylinders that have nonoverlapping exhaust-valve-opening periods. The object of the tests was to determine the amount of power from the blowdown turbine and the effect of the presence of the turbine on engine power. The tests were conducted at the Aircraft Engine Research Laboratory of the NACA at Cleveland, Ohio, from November 1943 through January 1944.

APPARATUS AND METHODS

Construction of the blowdown turbine. - A diagrammatic drawing of the blowdown turbine used in the NACA tests is shown in figure 1. The turbine was constructed from a standard General Electric type B turbine wheel and bearing assembly and four nozzle boxes. Each nozzle box has an exit area of 2.11 square inches and covers a 90° arc of the nozzle diaphragm. This exit area was chosen by the use of the methods and data of reference 1 as the area that would impose no power loss on the engine at its rated operating conditions. The exit of each nozzle box is divided into nine nozzles by flat vanes sufficiently long to guide the exhaust-gas flow at the inlet and discharge ends.

A drawing of one of the nozzle boxes is shown in figure 2. Photographs of a nozzle box and the nozzle diaphragm assembly are reproduced in figure 3. The entire turbine was enclosed in a metal housing with four inlet pipes that extended through sliding glands to the outside of the housing. A labyrinth seal gland for the turbine shaft was provided around the opening between the inside of the housing and an evacuated fore chamber. Leakage of air through this gland was reduced to a negligible amount by adjusting the pressure difference between the labyrinth stages to 0 ±0.1 millimeter of water by means of an air-operated jet pump in the line connecting the evacuated fore chamber to the altitude-exhaust system.

Test setup. - The blowdown turbine was connected to eight of the nine cylinders of a Pratt & Whitney R-1340-12 engine by means of four pipes having Y-shaped branches connected to adjacent cylinders. The gas from the turbine discharged to the laboratory altitude-exhaust system. The gas from the ninth cylinder discharged directly to the altitude-exhaust system. The engine air was supplied directly from the room to the carburetor through a duct provided with a measuring orifice. A photograph of the test setup is shown in figure 4.

The turbine power was absorbed by a water-brake dynamometer. Turbine torque was measured by a spring scale. The turbine speed was measured with a condenser-type tachometer. The accuracy of the turbine-power measurements was within ±1.5 percent. The temperature of the turbine exhaust gas was measured with a quadruple-shielded chromel-alumel thermocouple.

The power of the engine was absorbed by a separate water-brake dynamometer. Engine torque was measured with a balanced-diaphragm torque meter of the type described in reference 2. Engine speed was measured with a magnetic-drag type of aircraft tachometer. Engine air flow was measured by a head meter with a thin-plate orifice installed according to A.S.M.E. specifications for flange taps. Measurements of engine power are estimated to be accurate within ±1.5 percent. Engine fuel flow was measured with a sharp-edged-diaphragm density-compensated rotameter. Air-flow and fuel-flow measurements are estimated to be accurate within ±1 percent. Temperatures of engine air, rear spark-plug gasket, and carburetor air were measured with iron-constantan thermocouples. Pressures of engine inlet and turbine exhaust were measured with mercury manometers. Pressures in the air-flow system were measured with water manometers.

Tests. - The tests herein described were run at an engine speed of 2000 rpm. The tests consisted of calibrating an engine with an exhaust collector and measuring the engine power and the turbine power with the blowdown turbine in place.

Most of the tests were run at full engine throttle at an inlet-manifold pressure of approximately 34 inches of mercury absolute. Exhaust pressure was varied from 7.5 to 29 inches of mercury absolute. In the turbine-power tests the turbine speed was varied. Additional tests with the turbine were run at part engine throttle, at engine inlet-manifold pressures of 24 to 19 inches of mercury absolute, a turbine exhaust pressure of 7.5 inches of mercury absolute, and with variable turbine speed.

Methods of reducing test data. - A preliminary analysis of the operation of a blowdown turbine predicted that the power output P_{max} at the optimum turbine speed is given by a relation of the form

$$550\ P_{max} = \frac{1}{2} M_t \overline{V}_e^{\,2} \eta_{max} \qquad (1)$$

where

η_{max} efficiency of turbine (including bucket losses but excluding nozzle losses) at optimum blade-to-jet-speed ratio

M_t mass flow of exhaust gas to turbine, slugs per second

$\overline{V}_e$ mean jet velocity at turbine-nozzle exit, feet per second

Equation (1) was obtained by assuming that the instantaneous turbine bucket efficiency is a parabolic function of the instantaneous blade-to-jet-speed ratio and is independent of the Mach number. The analysis (as shown by equation (1)) indicates that the term $\frac{1}{2} M_t \overline{V}_e^{\,2}$ is a measure of the available power. The conditions are almost exactly satisfied by single-stage impulse turbines unless the

Mach number becomes too high at which time the buckets choke and the instantaneous efficiency is reduced. The mean efficiency $\bar{\eta}_t$ of the blowdown turbine with any operating conditions, therefore, has been defined as the ratio of the turbine power output P_t to the available power by means of the equation

$$\bar{\eta}_t = \frac{1100\ P_t}{M_t \bar{V}_e^{\,2}} \tag{2}$$

Because the turbine was connected to eight of the nine cylinders of the test engine, the mass flow of gas through the turbine was therefore assumed to be eight-ninths of the total mass flow of exhaust gas M_e.

The mean jet velocity $\bar{V}_e$ was computed from the data obtained for a 25-inch straight stack (see fig. 10 of reference 1) as a function of p_eA/M_t where

p_e turbine exhaust pressure, pounds per square foot

A effective nozzle area, square feet

The effective nozzle area to be used for calculating p_eA/M_t branched stacks is determined by multiplying the area per stack by the number of cylinders connected to the turbine. The effective nozzle area of the stacks used was 16.86 square inches.

The power-output data for the engine and turbine shown in figure 5 were corrected to a constant carburetor-air temperature and engine inlet-manifold pressure. Engine power and mass flow of combustion air were assumed to vary inversely as the square root of the absolute carburetor-air temperature and directly as the first power of the inlet-manifold pressure.

The corrections of turbine-power data to the basis of constant engine inlet pressure were made by a method derived from the analysis of reference 1. A similar method was used to account for the variation in turbine power with the total mean turbine-inlet-gas temperature. The details of these corrections are described in the appendix.

RESULTS AND DISCUSSION

Power output of the engine and turbine. - The power delivered by the Pratt & Whitney R-1340-12 engine, discharging its exhaust to a standard collector and the power delivered by the engine discharging its exhaust to the blowdown turbine, is shown in figure 5 together with the turbine power obtained at the optimum permissible turbine speed. At the lowest turbine exhaust pressures the turbine speed was limited to the rated speed of 21,300 rpm. A larger power output could have been obtained at a higher turbine speed. The data in this figure were corrected to a carburetor-air temperature of 90° F and an engine inlet-manifold pressure of 33.5 inches of mercury absolute.

<u>Effect of the turbine on engine power</u>. - At the lowest turbine exhaust pressure, the power of the engine exhausting to the blowdown turbine was slightly smaller (1 percent) than the power of the engine discharging to a standard collector at a pressure equal to the turbine exhaust pressure. As the exhaust pressure increased, the power loss with the turbine operating decreased. For exhaust pressures greater than 20 inches of mercury absolute there was no measurable power loss. No measurable change in engine-air weight flow was caused by the presence of the turbine. The brake horsepower shown in figure 5 was obtained with the air to the carburetor supplied directly from the room. The pressure drop through the air-measuring orifice and duct was 3 inches of mercury and the carburetor pressure was 26 inches of mercury absolute. In order to determine the net power at altitude it is necessary to subtract the supercharger power required to obtain a carburetor-inlet pressure of 26 inches of mercury. Because this power would be the same for the two cases in figure 5 at any given exhaust discharge pressure, it does not affect the comparison, which reveals the negligible effect of the presence of the turbine on the engine power.

With respect to its effect on engine power, the blowdown turbine is similar to the Büchi exhaust-gas turbine (reference 3). In both systems the exhaust piping is arranged to avoid producing back pressure on the cylinders toward the end of the exhaust stroke and particularly during the valve overlap or scavenging period. No attempt is made in the blowdown turbine to provide a resonant or tuned exhaust-stack system sometimes mentioned in connection with the Büchi system.

The ratio of the brake mean effective pressure to the inlet-manifold pressure $bmep/p_m$ plotted against the ratio of the exhaust-discharge pressure to the inlet-manifold pressure p_e/p_m is shown in figure 6.

References 1 and 4 showed that the effect of an exhaust restriction on engine power is determined by the value of the ratio $v_d n/A$ where

v_d displacement volume, cubic feet

n engine speed, revolutions per second

For this turbine the effective nozzle area was 0.132 square foot (for nine cylinders). At an engine speed of 2000 rpm the value of $v_d n/A$ was therefore 196 feet per second. A loss in engine power from 2 to 3 percent was expected at the lowest exhaust pressure for this value of $v_d n/A$. (See reference 4.) Because the loss was less than predicted, it must be concluded either that the Pratt & Whitney R-1340-12 engine is slightly less sensitive to exhaust-pipe restriction than the Wright 1820-G engine used for the tests of references 1 and 4 or that the blowdown turbine exerts a favorable suction effect during the last part of the exhaust stroke when the velocity of flow through the exhaust system is small.

Turbine power output and speed characteristics. - The turbine power output (fig. 5) as measured, using the exhaust gas from eight of the nine cylinders, varied from about 9 percent of engine power at a turbine exhaust pressure of 28 inches of mercury absolute (p_e/p_m = 0.84) to about 21 percent of engine power at 7.5 inches of mercury absolute (p_e/p_m = 0.22). At the lowest exhaust pressure, the turbine power output varied through a range of about 9 percent of turbine power with the amount of leakage into the turbine housing around the four turbine-inlet pipes. The data at this exhaust pressure (7.5 in. Hg absolute) are not considered entirely satisfactory. The ratio of the turbine power output to engine power output at constant engine speed increases with a decrease in the ratio p_e/p_m.

The variation of turbine power output with turbine speed for constant engine power output is shown in figure 7. These curves are similar in shape to the power-speed curves of single-stage steady-flow impulse turbines. The blowdown-turbine power output is nearly independent of speed near the maximum power output. A deviation in speed of 10 percent from the optimum speed reduces the power output only approximately 1 percent.

The carburetor-inlet pressure for these tests averaged 26 inches of mercury absolute. This pressure could be provided at high altitude by passing the gas from the blowdown turbine to a conventional turbosupercharger of proper size operating at a nozzle-box pressure of approximately 26 inches of mercury absolute. The blowdown-turbine power output with a discharge pressure of 26 inches of mercury absolute would be approximately 10 percent of the engine-shaft power on the basis of utilizing the exhaust gas from eight of the nine cylinders. If all the exhaust gas were utilized in the turbine, the power would be increased one-eighth larger and would amount to $11\frac{1}{4}$ percent of engine power. It is evident therefore that, even in a power plant equipped with a turbosupercharger, an appreciable gain in power and economy can be obtained by installing a blowdown turbine between the engine and turbosupercharger. This arrangement is only one of a number of possible applications of the blowdown turbine; further study is required to determine the most advantageous application.

At a turbine exhaust pressure of 26 inches of mercury absolute, the blowdown turbine imposed no loss in engine power. (See fig. 5.) At a given set of engine conditions, the mean jet velocity from a single exhaust stack or a branched exhaust stack increases when the exit area is reduced. (See references 1 and 4.) A greater total power output could therefore be obtained from the turbine and engine by the use of nozzles small enough to produce a small loss in engine power. The percentage gain in power provided by the blowdown turbine in the application under discussion will increase with an increase in the inlet-manifold pressure for constant exhaust pressure.

The speed of the turbine for the maximum output with an exhaust pressure of 26 and an inlet-manifold pressure of 33.5 inches of mercury absolute is approximately 16,000 rpm. (See fig. 7.) This speed is about 75 percent of the rated turbine speed; hence, the centrifugal stress in the buckets is only 56 percent of the centrifugal stress at rated speed. When the inlet-manifold pressure is increased to 52 inches of mercury absolute with the exhaust pressure of 26 inches of mercury absolute, the optimum turbine speed is approximately the rated speed.

When the blowdown turbine and a conventional turbosupercharger are used in series, the blowdown turbine may be geared to the engine. Aircraft engines are operated at high speed for emergency power output and at successively reduced speeds for rated-power and cruising-power operation. With approximately constant blowdown-turbine exhaust pressure, the nozzle-jet velocity decreases approximately in the same proportion as the engine speed. A blowdown turbine geared to the engine crankshaft with a fixed-ratio gear train will therefore operate at nearly optimum speed for each engine power output.

Mean turbine efficiency. - The variation of the mean efficiency $\bar{\eta}_t$ of the blowdown turbine, defined by equation (2) with the blade-speed to mean-jet-speed ratio, is shown in figure 8. (The maximum turbine efficiency is obtained at a turbine pitch-line velocity of approximately 0.4 $\overline{V}_e$.) The greatest mean efficiency attained is approximately 72 percent.

For the lowest turbine exhaust pressures, the mean efficiency decreases as the exhaust pressure decreases. With a turbine exhaust pressure of 7.5 inches of mercury absolute, the instantaneous peak value of the ratio of the impact pressure in the nozzle to the turbine exhaust pressure may be as great as 7 or 8. (See fig. 12(b) of reference 1.) The pressure ratio for the greatest efficiency of a type B turbine is appreciably lower than 7. For pressure ratios lower than that for the greatest efficiency, the bucket efficiency is nearly constant but, for greater pressure ratios, it decreases appreciably. A lower mean turbine efficiency is, therefore, to be expected for low turbine exhaust pressures.

The value of $\overline{V}_e$ used for the computation of the mean turbine efficiency was that measured for a 25-inch straight stack. (See fig. 10 of reference 1.) Previous tests with an exhaust stack having a side branch had shown that the mean jet velocity $\overline{V}_e$ was smaller than the velocity for a straight stack or a curved stack. (See fig. 4 of reference 3.) The branched-stack jet-velocity data gave mean turbine efficiencies greater than 90 percent; the diagram efficiency of the turbine, excluding all losses, is only 86 percent. The peak mean efficiency of the blowdown turbine was expected to be about 80 percent. The mean jet velocity for the stack arrangement used in the blowdown turbine, therefore, is probably greater than the velocity for the branched stack tested in reference 3 but may be less than that for a straight stack.

The variation of the maximum mean turbine efficiency is shown in figure 9 as a function of the jet-velocity parameter p_eA/M_t. The correlation is not satisfactory for the lowest exhaust pressures (low p_eA/M_t). A small, but variable, leakage occurred from the turbine into the turbine housing through the packing glands around the inlet pipe and caused a corresponding variation in the pressure p_w behind the wheel at the lower turbine exhaust pressures. The turbine output apparently varies with the pressure p_w.

The maximum turbine output per pound of exhaust gas and the estimated optimum turbine pitch-line velocity is shown in figure 10 as a function of p_eA/M_t. At the lowest values of p_eA/M_t, the turbine power is that obtained at rated turbine speed (21,300 rpm) rather than at the optimum speed. The turbine-power data obtained with full-open engine throttle form a smooth curve except for two points at the lowest value of p_eA/M_t. (See the preceding discussion of fig. 9.)

The efficiency and power data obtained at part engine throttle fall below the full-throttle curve. When the turbine data are corrected for the variation of turbine inlet-gas temperature with engine power, the two sets of data are in good agreement.

The mean turbine efficiency $\bar{\eta}_t$ is a measure of the ability of the turbine to recover kinetic energy at the nozzle exit. This efficiency is larger than the efficiency attained with the same buckets in a conventional turbine because the available energy is usually computed with the condition of the fluid at the nozzle inlet and losses are suffered in the nozzles. These losses are not considered in defining the mean efficiency of the blowdown turbine.

The greatest work recovered by the blowdown turbine was approximately 30 percent of the work that is theoretically available to an ideal machine in the expansion of the exhaust gas from its pressure in the cylinder at the time of exhaust-valve opening to the prevailing atmospheric pressure.

Effect of the blowdown turbine on exhaust-gas temperature. - The variation of the exhaust-gas temperature at the turbine outlet with turbine power for an exhaust pressure of 7.5 inches of mercury absolute is shown in figure 11. The temperature measured with a quadruple-shielded thermocouple was assumed to be the total turbine exhaust-gas temperature. The mean total gas temperature at the turbine inlet was computed by adding to the measured turbine-outlet temperature the temperature difference corresponding to the power per pound of gas removed by the turbine. The computed total inlet temperature was not quite constant. Small variations of the fuel-air ratio occurred during the tests. The effect of fuel-air ratio on total temperature at the turbine inlet is included in figure 11.

The effect of engine power on the total turbine inlet-gas temperature at a fuel-air ratio of 0.075 is shown in figure 12. The exhaust-gas temperature increases with engine power because the heat rejection per pound of exhaust gas from the engine and its exhaust piping to the cooling air is greater at low engine power. The correction of the part-throttle turbine data to constant exhaust temperature was made from these data.

Condition of the blowdown turbine after tests. - During the tests the blowdown turbine was operated for a total time of approximately 24 hours. Although a small stretching of the buckets occurred, the stretching was less than that normally experienced in conventional exhaust-gas turbine operation with the same inlet-gas temperature. One bucket showed a deformation of the shroud due either to bucket vibration or to initial bending stresses. (See fig. 13.)

The turbine buckets apparently ran quite cool, as suggested by the appreciable lead deposits found on the exit side of the buckets. Cool running of the buckets was expected because the buckets are exposed to the hottest exhaust gas for a short time and to the coolest exhaust gas for a relatively long time. The lead deposits are shown in figure 14. These lead deposits are an index of flow conditions because solid particles tend to accumulate in regions of separation of flow. Streaks in the lead deposits show the direction of flow of the gas over the buckets.

The flow in a blowdown turbine is similar to that in a Holzworth explosion turbine; the problems arising from blade vibration and thermal erosion due to the rapidly varying gas temperatures are therefore similar. (See reference 5.)

Numerous small local deformations of the leading edges of the buckets (fig. 15) and trailing edges of the nozzle-box guide vanes (figs. 3(b) and 16) were noted. These deformations apparently resulted from the action of large solid particles in the gas stream. The wheel-nozzle clearance was originally set at 0.11 inch but owing to warping the clearance was not maintained. Actual contact of the wheel and one nozzle occurred at one time during tests, as shown by polished spots on the buckets and nozzles. The deformation of nozzles caused by thermal expansion is a serious problem because each nozzle must be connected to a separate tail pipe.

The leading edges of the buckets were rounded or eroded more than in previous tests with the same type wheel at approximately the same total turbine-inlet exhaust-gas temperature with steady flow. This rounding could have been caused by mechanical erosion by solid particles in the gas stream or, as seems more likely, by the thermal erosion caused by the extremely rapid alternate heating and cooling of the bucket leading edges. Thermal erosion can be reduced by using round-nosed buckets to increase the ratio of internal heat-transfer area to external heat-transfer area.

The total damage to the turbine was not serious and did not interfere with the tests.

CONCLUDING REMARKS

The results of the tests of a blowdown turbine on a Pratt & Whitney R-1340-12 engine, conducted to determine whether appreciable power could be developed by the blowdown turbine without affecting the engine power through exhaust restriction, at an engine speed of 2000 rpm and an inlet-manifold pressure of 33.5 inches of mercury absolute showed that:

1. The blowdown turbine developed a power equal to 9 percent of the engine power with a turbine exhaust pressure of 28 inches of mercury absolute and 21 percent of engine power with a turbine exhaust pressure of 7.5 inches of mercury absolute.

2. The engine power was decreased a maximum of 1 percent by the presence of the turbine as compared with the conventional exhaust collector ring discharging to an equal pressure. No engine-power loss was imposed by the presence of the turbine with turbine exhaust pressures greater than 20 inches of mercury absolute.

3. After a total test time of 24 hours no evidence of failure from bucket vibration was observed.

4. Some evidence of erosion of the leading edges of the buckets was noted.

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APPENDIX - CORRECTION OF BLOWDOWN TURBINE POWER FOR VARIATIONS IN ENGINE OPERATING CONDITIONS

The mean turbine efficiency $\overline{\eta}_t$ has been defined by the equation

$$\overline{\eta}_t = \frac{1100\ P_t}{M_t \overline{V}_e^2} \tag{2}$$

where the mean jet velocity $\overline{V}_e$ is a function of the parameter $p_e A/M_t$. The results of the present tests showed that the maximum values of $\overline{\eta}_t$ were sufficiently independent of the value of $p_e A/M_t$ within the range of variation required for small corrections that equation (2) may be used to predict the effect of changes in operating conditions on turbine power.

The data on turbine power output (shown in fig. 5) was corrected to the basis of constant carburetor-air temperature and constant inlet-manifold pressure by the following steps:

(a) Compute the corrected engine-air and exhaust-gas mass flows

(b) Compute $\overline{\eta}_t$ from equation (2) using the uncorrected mass flow and $\overline{V}_e$ from figure 10 of reference 1

(c) Compute $(M_t)_{corr}$ from the equation

$$(M_t)_{corr} = M_t \frac{(M_e)_{corr}}{M_e}$$

(d) Compute $(\overline{V}_e)_{corr}$ from figure 10 of reference 1 using the corrected turbine exhaust-gas flow

(e) Compute $(P_t)_{corr}$ from an inverted form of equation (2)

$$(P_t)_{corr} = \frac{(M_t)_{corr} (\overline{V}_e)^2_{corr} \overline{\eta}_t}{1100} \tag{3}$$

The part-throttle data in figures 9 and 10 have been corrected to the basis of full-throttle exhaust-gas temperature by the following method:

The theory of exhaust stacks developed in reference 1 shows that the mean jet velocity, $\overline{V}_e$ is a function of the gas temperature and the parameter p_eA/M_t. The mean jet velocity decreases with a decrease in temperature for constant p_eA/M_t. In the application of a correction to the turbine output and efficiency for variations in temperature, $\overline{V}_e$ was assumed to vary with temperature according to the relation

$$\frac{\overline{V}_e}{\sqrt{R_e\overline{T}_e}} = f\left(\frac{p_eA/M_t}{\sqrt{R_e\overline{T}_e}}\right) \tag{4}$$

where

R_e the gas constant of the exhaust at the test fuel-air ratio

$\overline{T}_e$ mean exhaust-gas temperature, $^{\circ}F$ absolute

The relationship expressed in equation (4) was inferred from equation (15) of reference 1.

The following steps are involved in the correction of turbine efficiency:

(a) Compute p_eA/M_t and find $\overline{V}_e$ from figure 10 of reference 1

(b) Compute $(p_eA/M_t)_{corr}$ from the equation

$$\left(\frac{p_eA}{M_t}\right)_{corr} = \frac{p_eA}{M_t}\sqrt{\frac{R_s\overline{T}_s}{R_e\overline{T}_e}}$$

where

$\overline{T}_s$ mean exhaust temperature to which basis the data is being corrected, $^{\circ}F$ absolute

R_s corresponding gas constant

(c) Compute the jet velocity $\overline{V}_e'$ from figure 10 of reference 1 corresponding to $(p_eA/M_t)_{corr}$

(d) Compute

$$(\overline{V}_e)_{corr} = \overline{V}_e' \sqrt{\frac{R_e\overline{T}_e}{R_s\overline{T}_s}}$$

If the fuel-air ratio is a constant, $R_e = R_s$ and the correction may be based solely on temperature; otherwise the variation in fuel-air ratio should be included.

(e) Compute the corrected efficiency $(\overline{\eta}_t)_{corr}$ from the equation

$$(\overline{\eta}_t)_{corr} = \overline{\eta}_t \left(\frac{\overline{V}_e}{(\overline{V}_e)_{corr}}\right)^2$$

The following steps are involved in the correction of turbine power:

The turbine power and pitch-line velocity are corrected to the conditions corresponding to $(p_eA/M_t)_{corr}$ for which the mean jet velocity is $\overline{V}_e'$. The corrected values are indicated by primed symbols.

(a) Compute P_t' from the equation

$$P_t' = P_t \left(\frac{\overline{V}_e'}{(\overline{V}_e)_{corr}}\right)^2$$

(b) Compute the corrected pitch-line velocity u' from the equation

$$u' = u \frac{\overline{V}_e'}{(\overline{V}_e)_{corr}}$$

where u is the turbine pitch-line velocity, feet per second.

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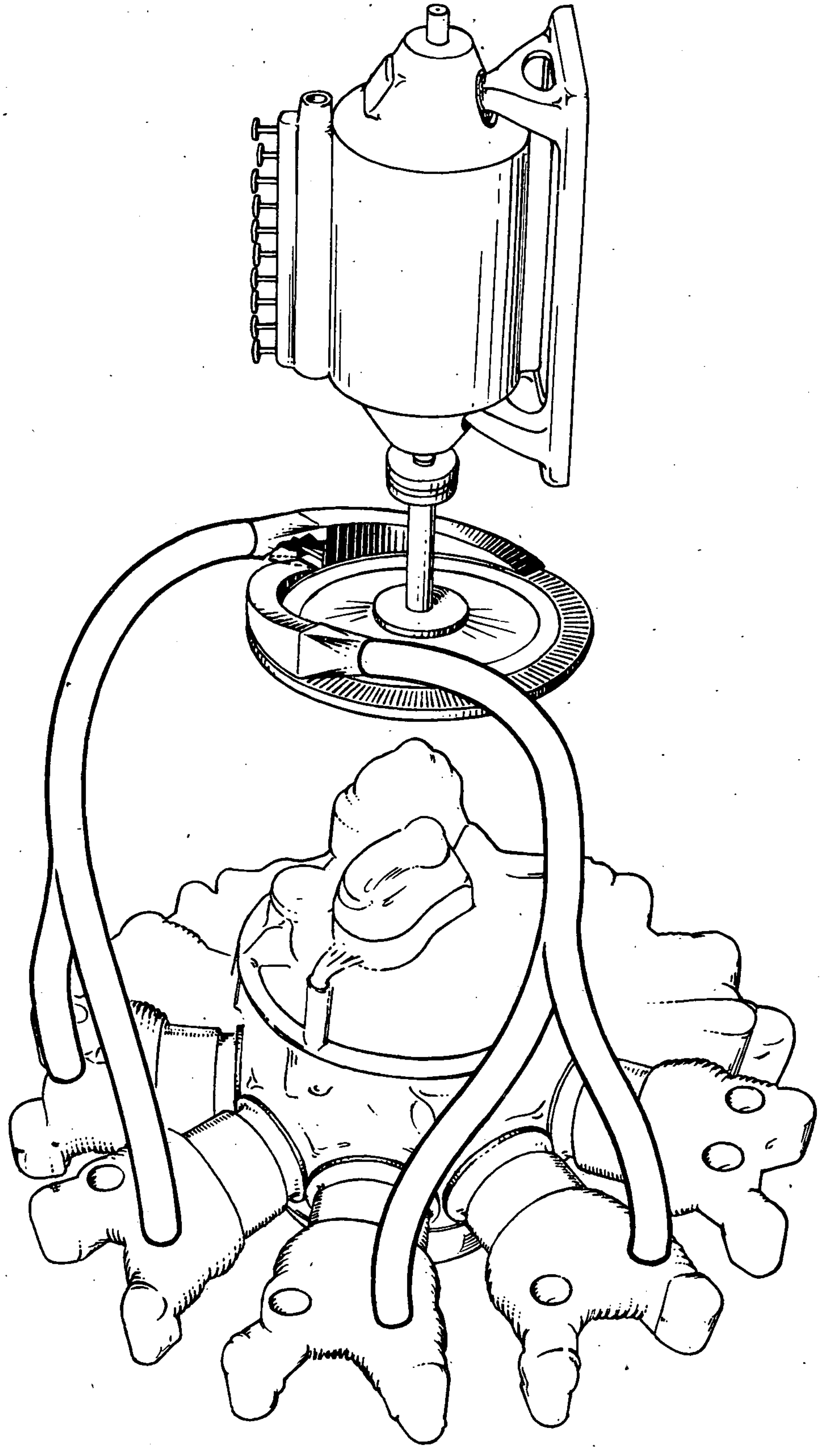

Figure 1. - Diagrammatic drawing of a blowdown turbine for a nine-cylinder radial engine with dynamometer load.

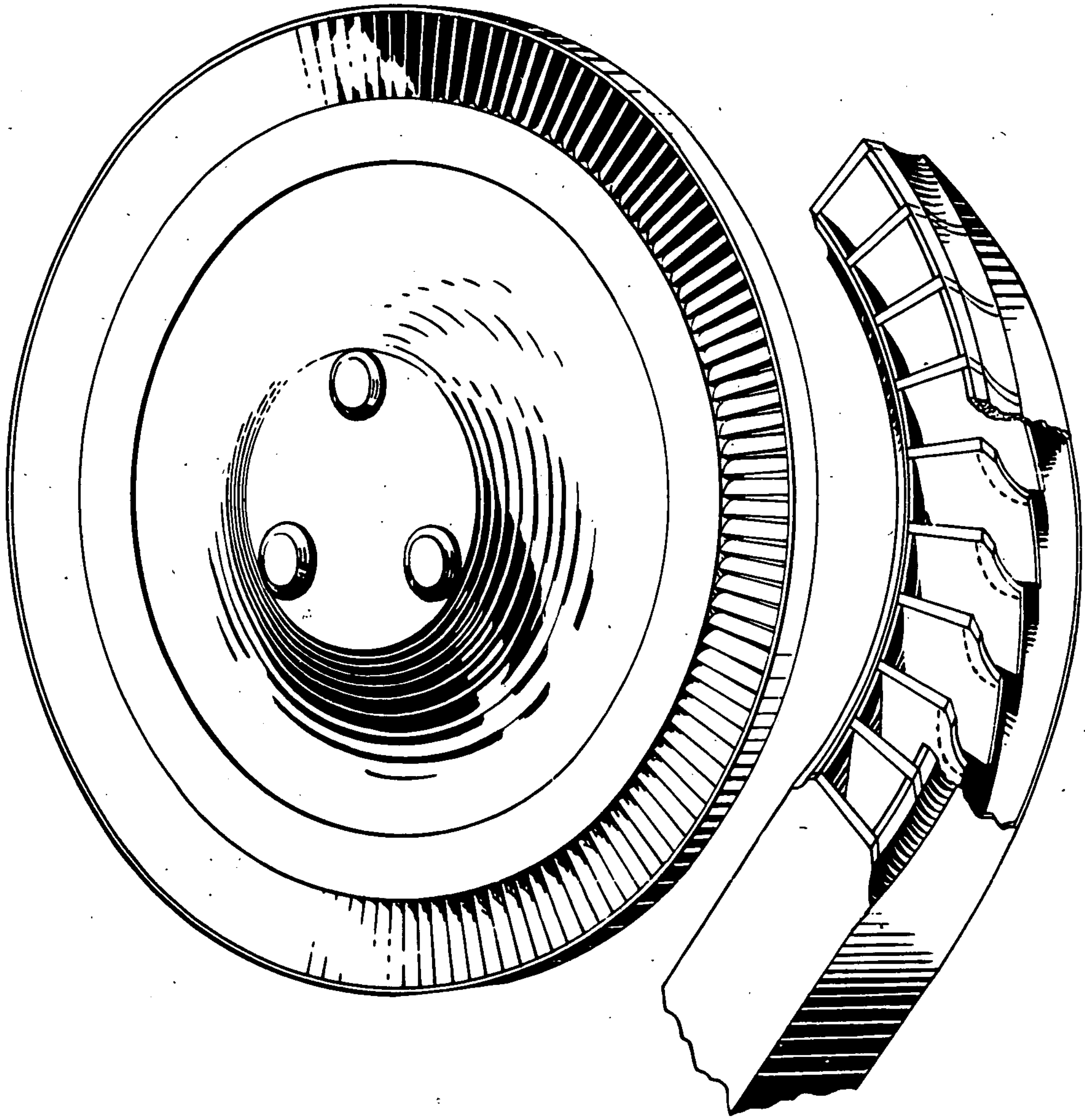

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Figure 2. - Arrangement of guide vanes in blowdown-turbine nozzle box.

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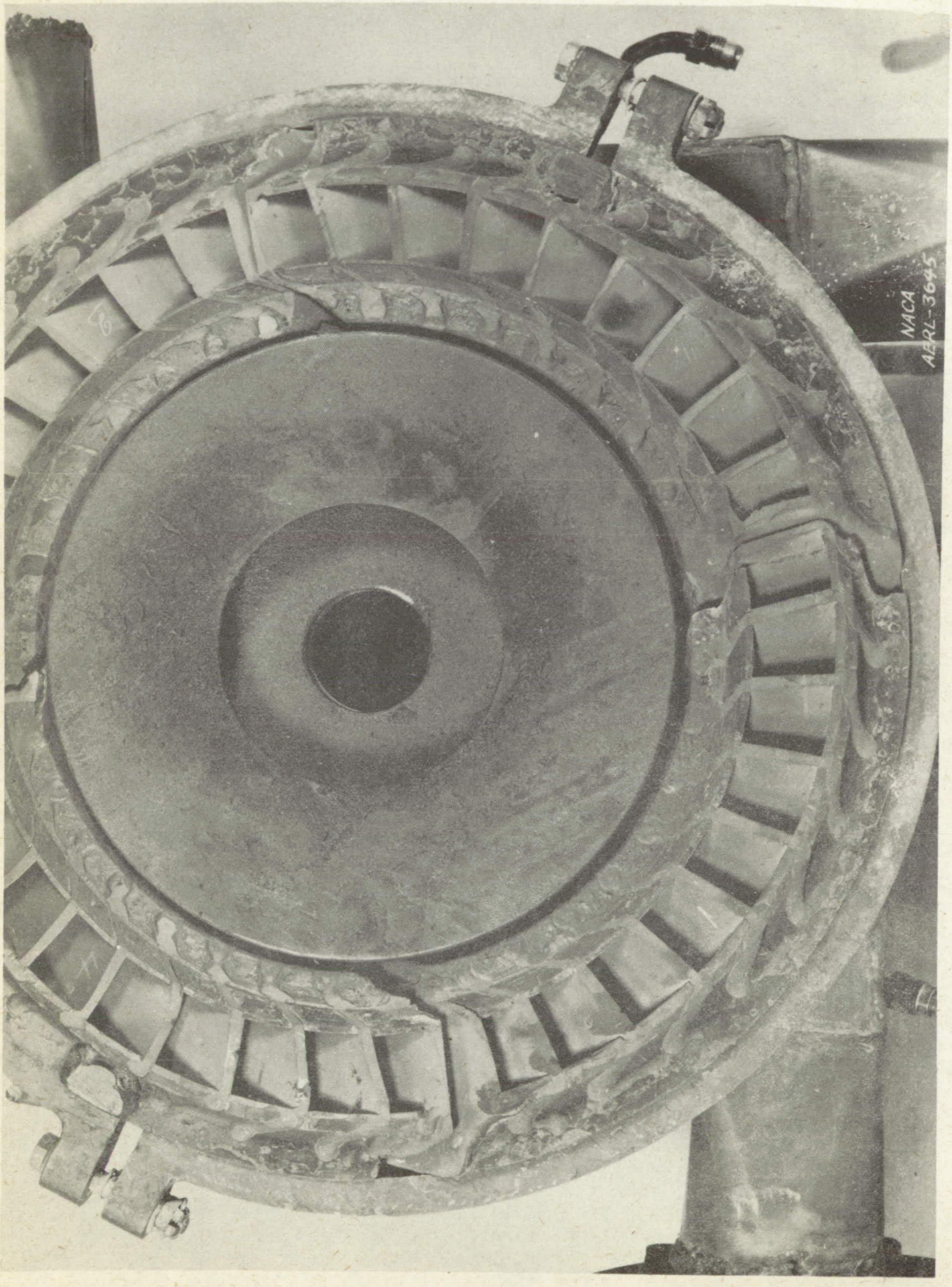
(a) Single nozzle box.

Figure 3. - Nozzle-box assembly of blowdown turbine.



(b) Diaphragm assembly of four nozzle boxes.

Figure 3. - Concluded. Nozzle-box assembly of blowdown turbine.

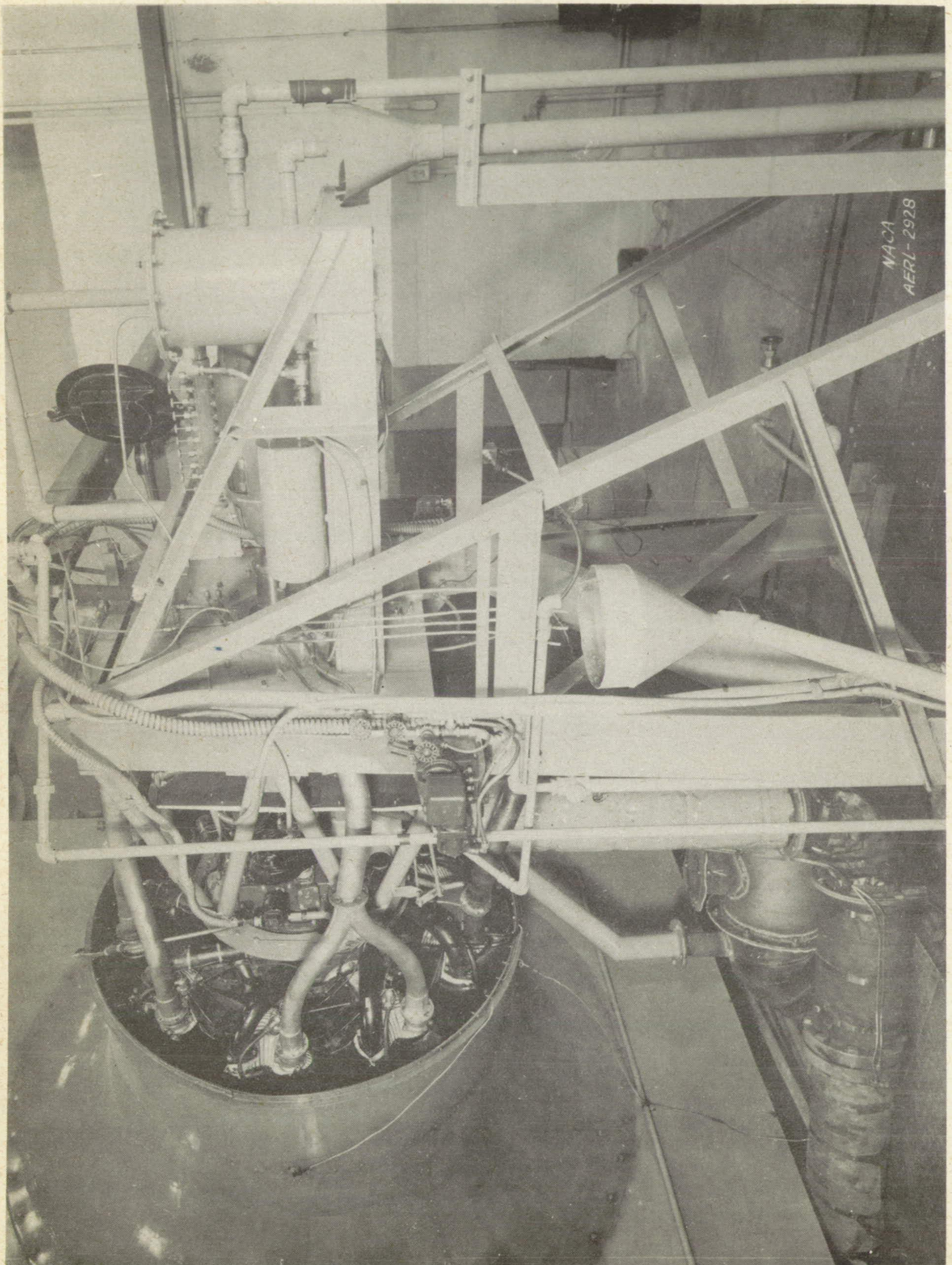


Figure 4. - Engine and blowdown turbine test setup.

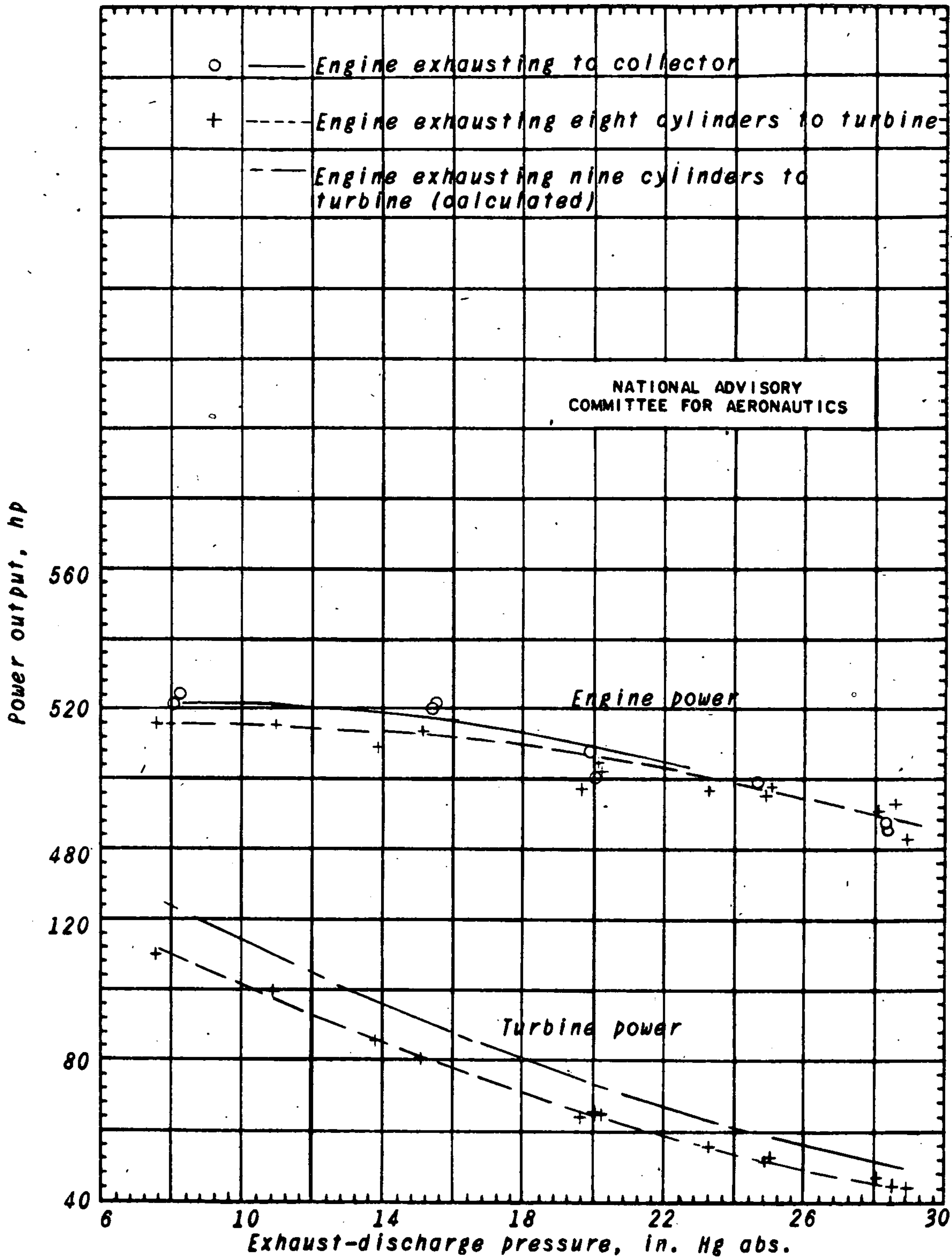


Figure 5. - Power output of Pratt & Whitney R-1340-12 engine and blowdown turbine. Engine speed, 2000 rpm. Data corrected to a carburetor-air temperature of 90° F and an inlet-manifold pressure of 33.5 inches of mercury absolute.

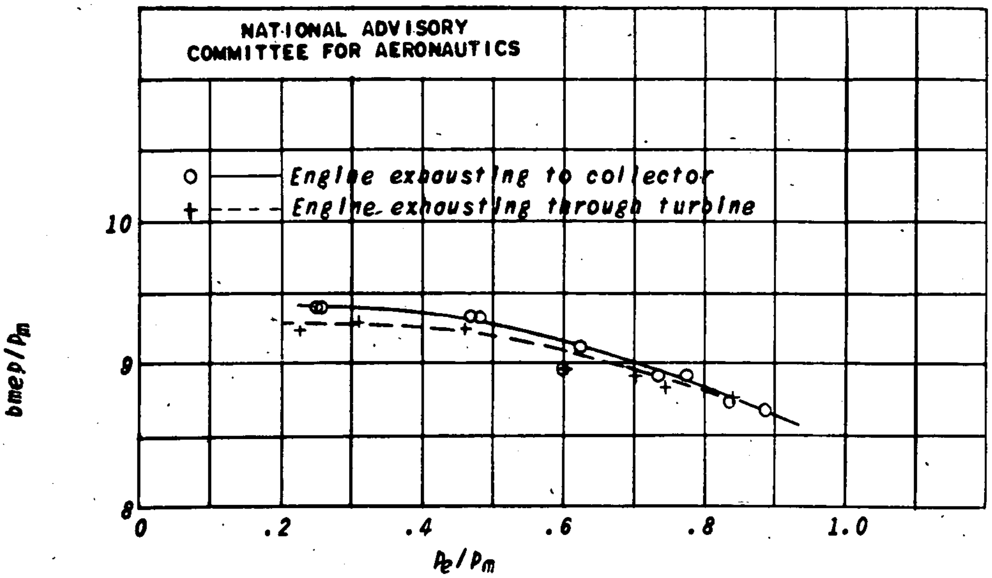


Figure 6. - Effect of blowdown turbine on power of Pratt & Whitney R-1340-12 engine. Engine speed, 2000 rpm; full throttle.

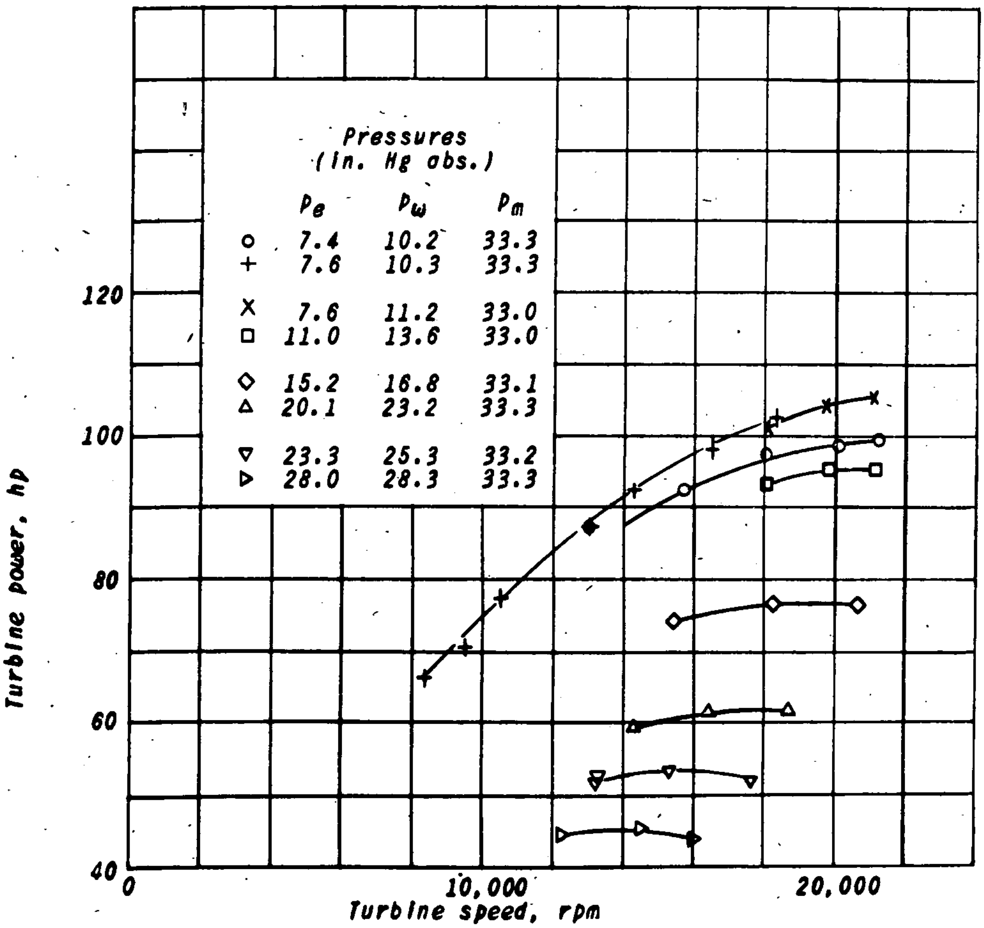


Figure 7. - Variation of turbine power with turbine speed. Engine speed, 2000 rpm; full throttle.

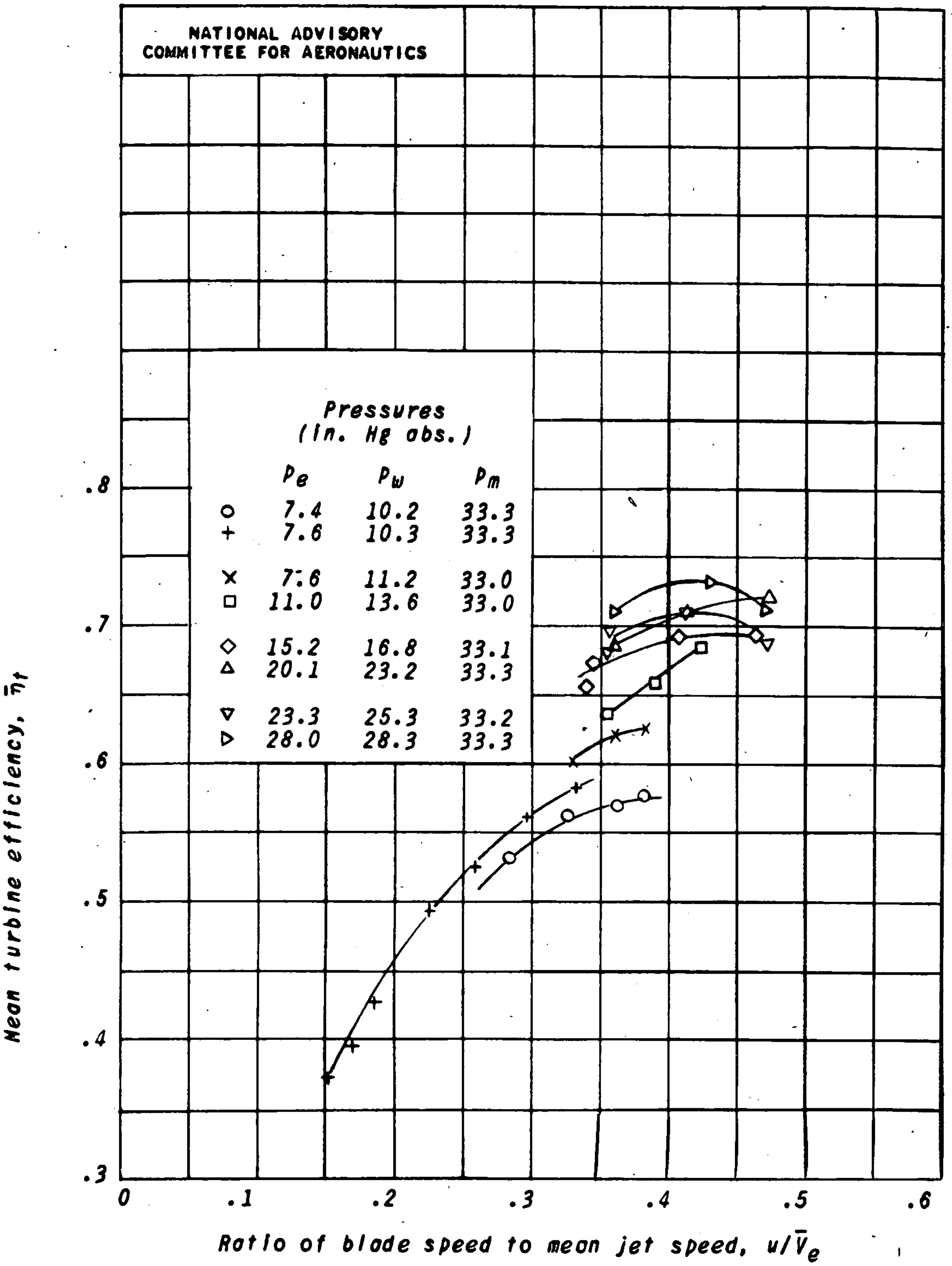


Figure 8. - Variation of mean turbine efficiency with ratio of blade speed to mean jet speed. Engine speed, 2000 rpm; full throttle.

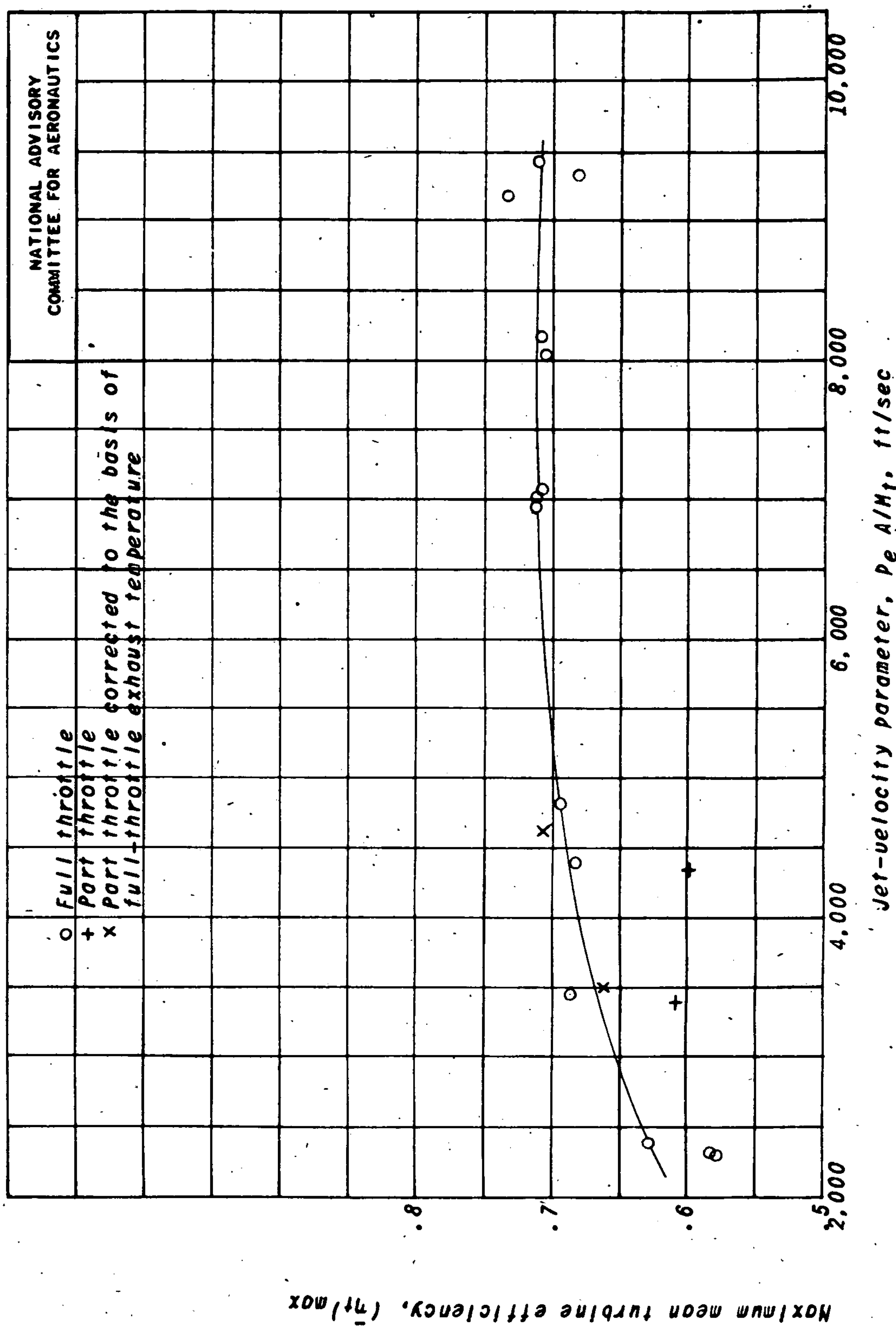


Figure 9. - Variation of maximum mean turbine efficiency with the jet-velocity parameter $P_e A/H_t$.

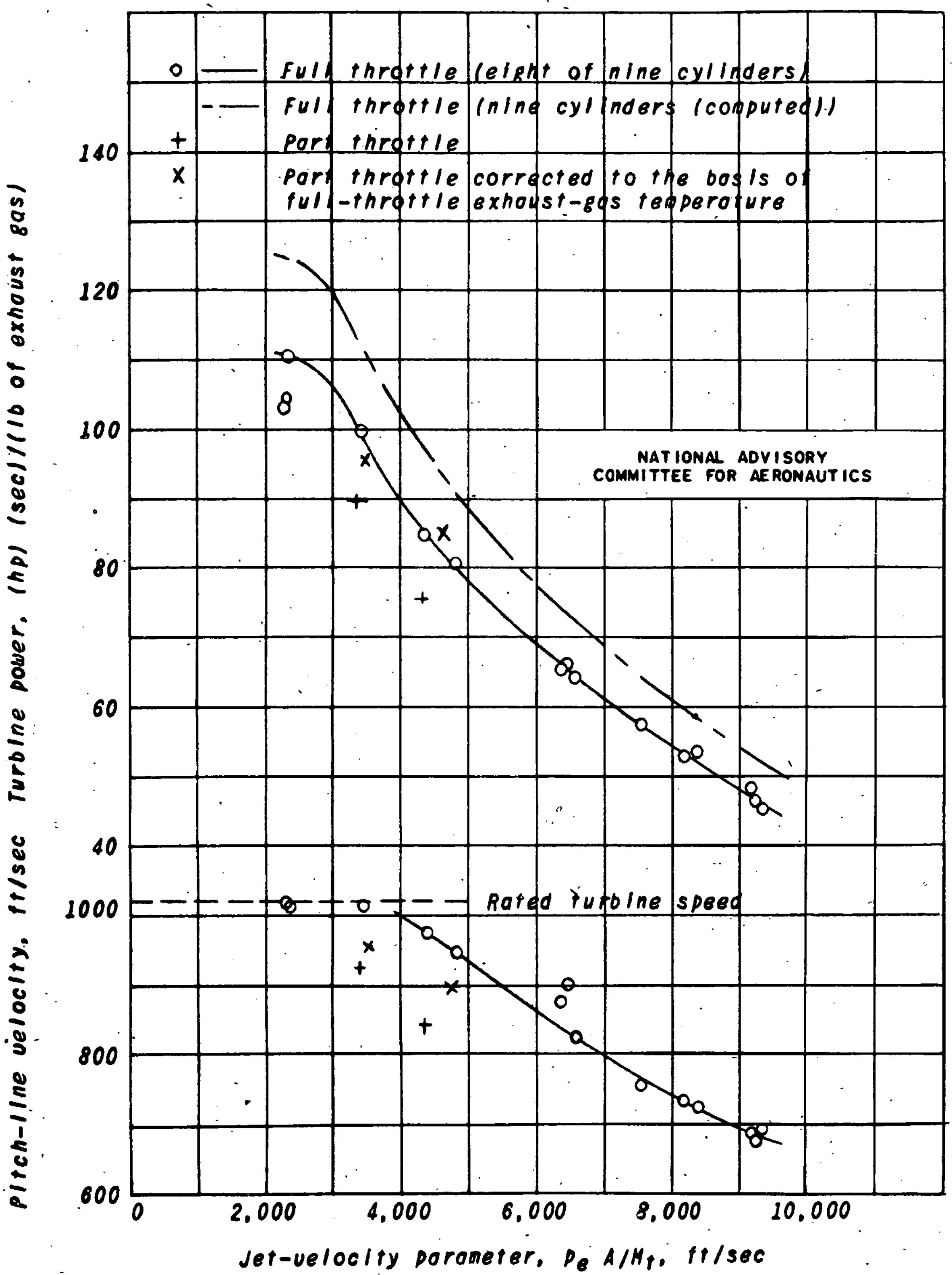


Figure 10. - Maximum turbine power output per pound of exhaust gas and optimum turbine speed. Engine speed, 2000 rpm.

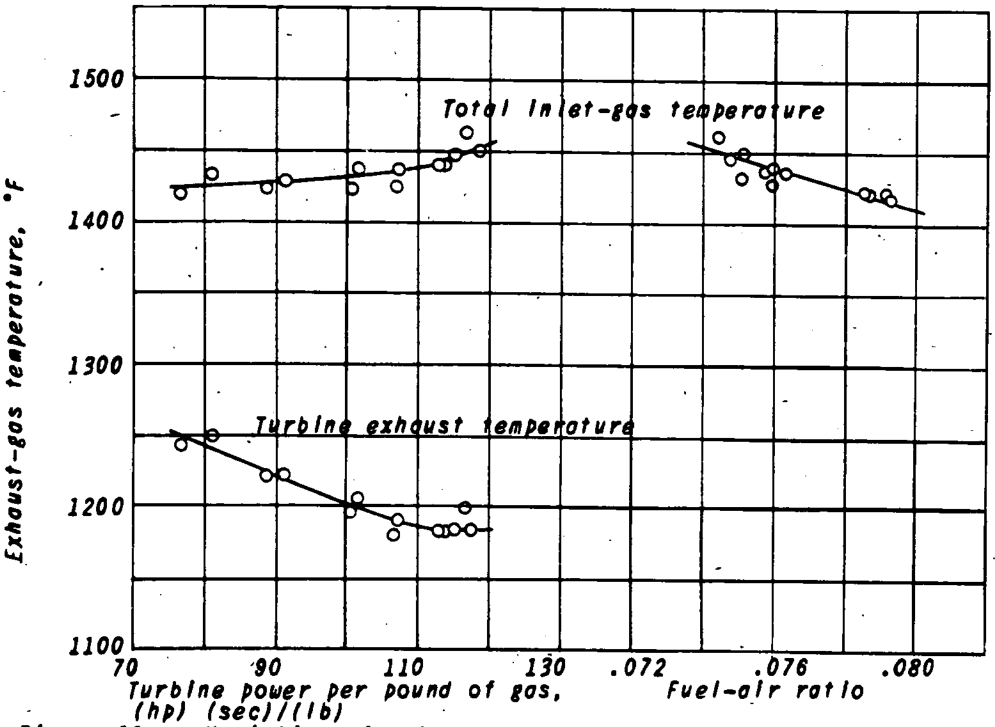


Figure 11. - Variation of exhaust-gas temperature of turbine outlet with turbine power. Average engine power, 513 horsepower; engine speed, 2000 rpm; exhaust pressure, 7.5 inches of mercury absolute.

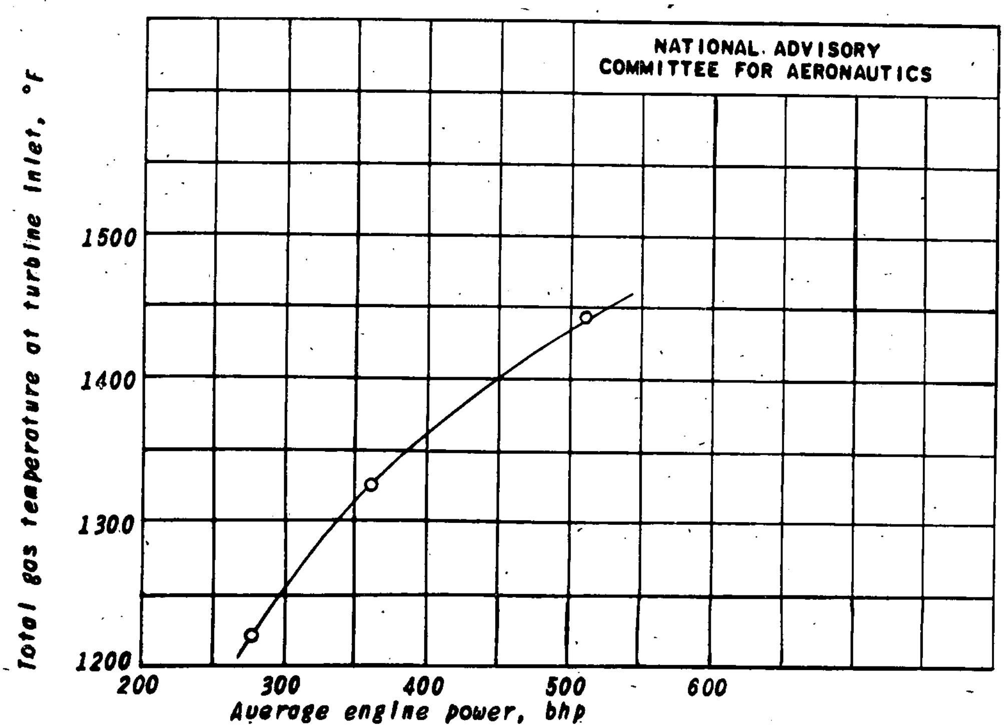


Figure 12. - Effect of engine power on exhaust-gas temperature of Pratt & Whitney R-1340-12. Engine speed, 2000 rpm; fuel-air ratio, 0.075.

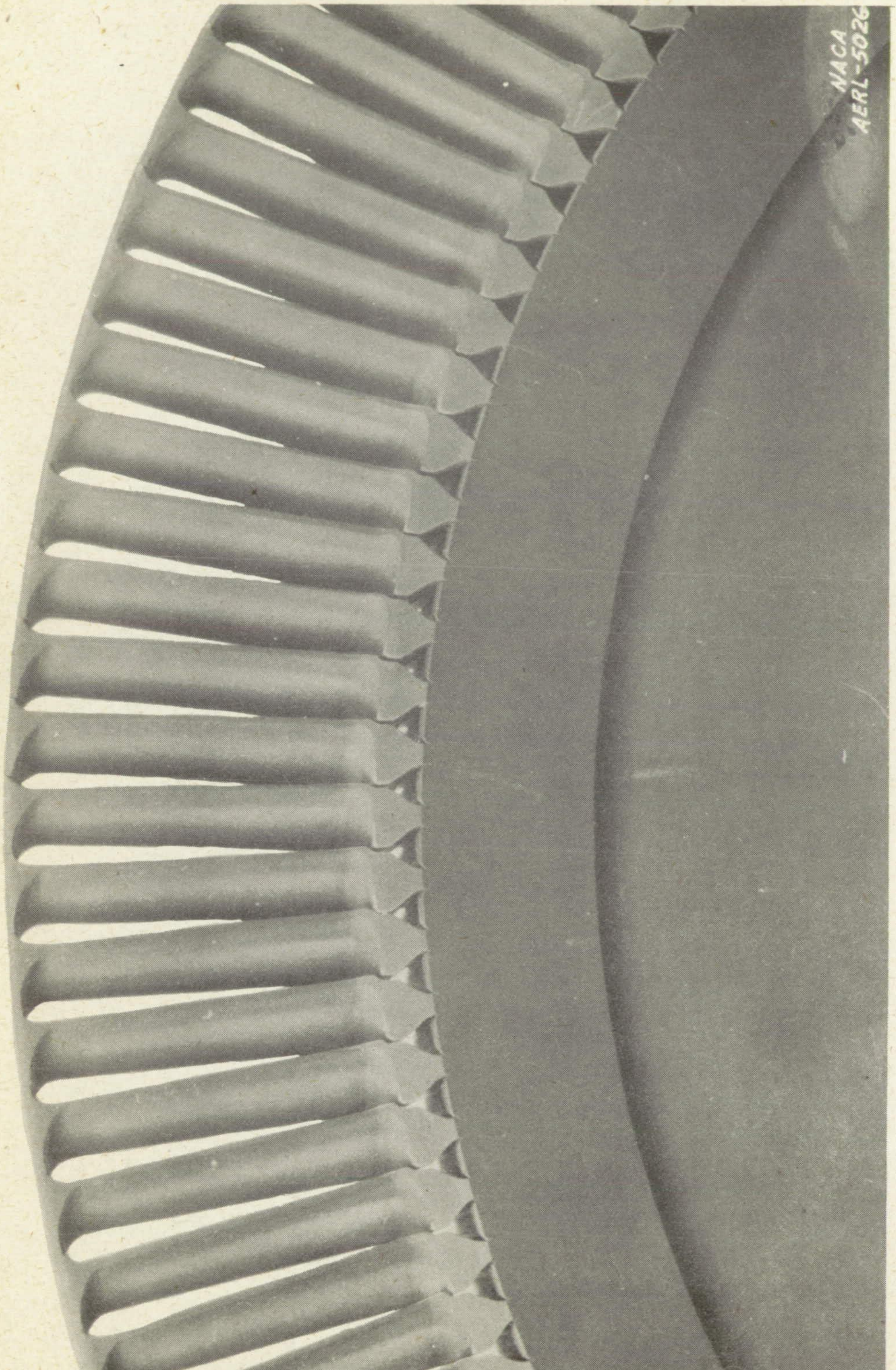


Figure 13. - Deformation of bucket shroud due either to bucket vibration or to initial stresses.

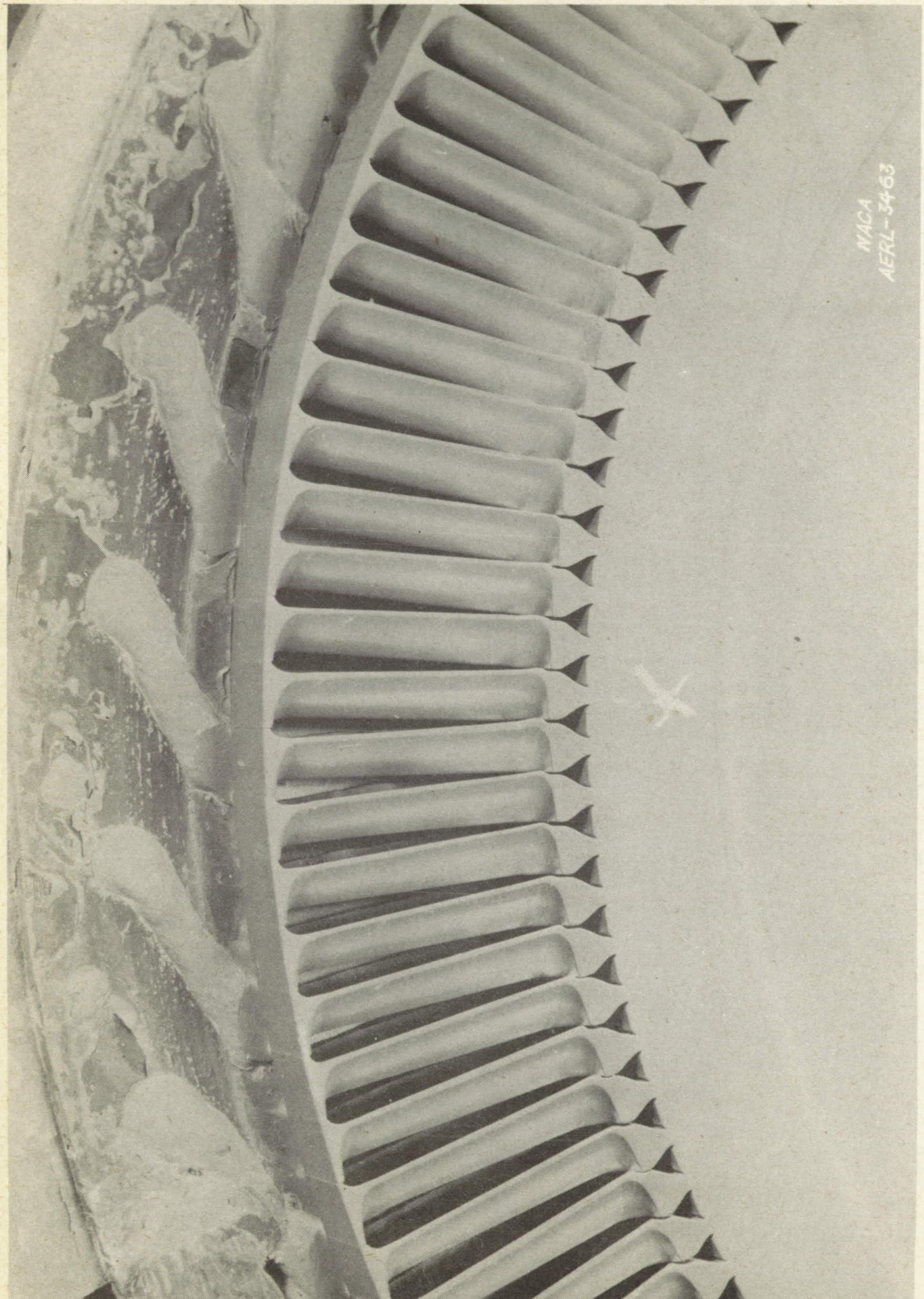


Figure 14. - Lead deposits on exit side of buckets.

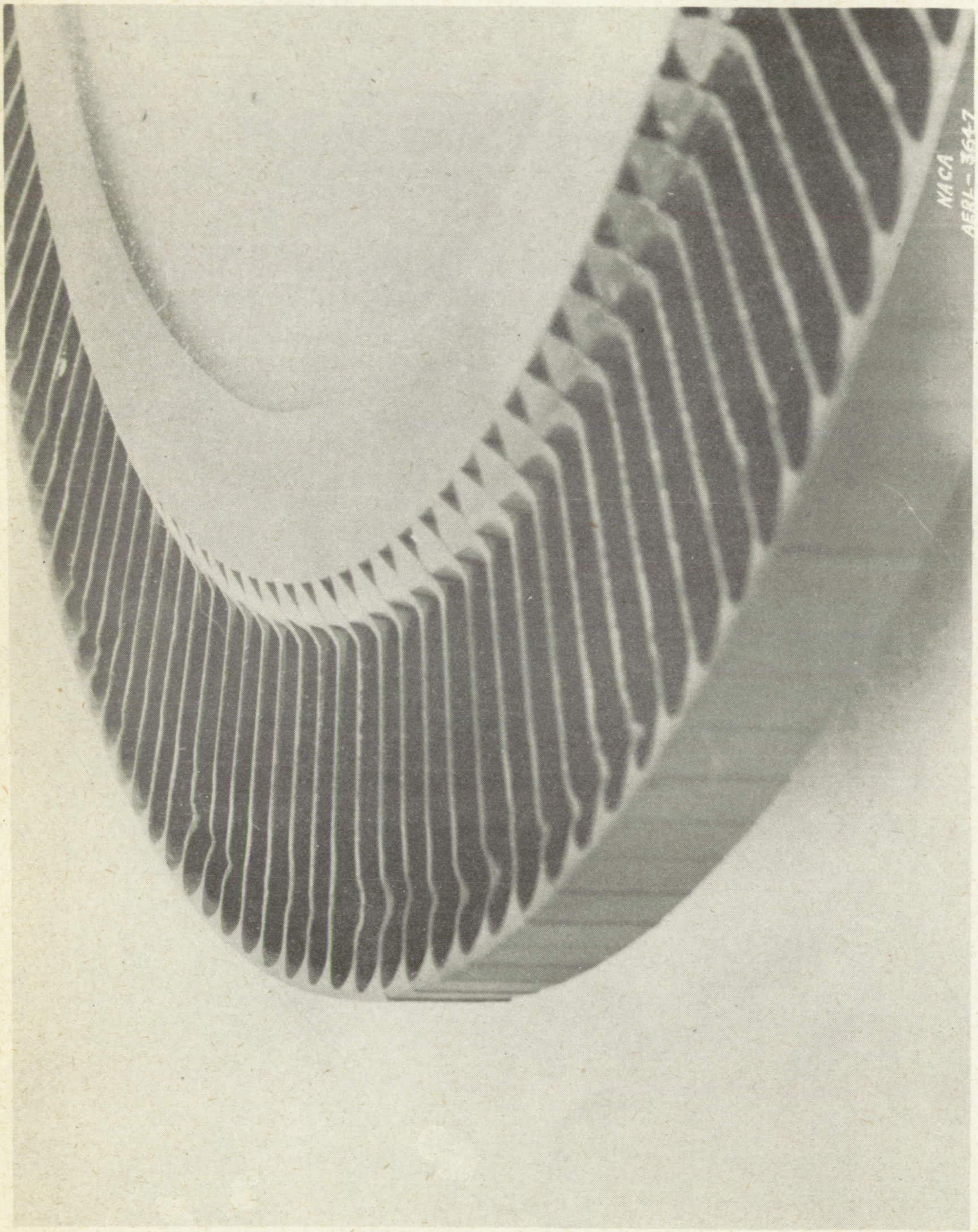


Figure 15. - Erosion and bending of leading edges of buckets.

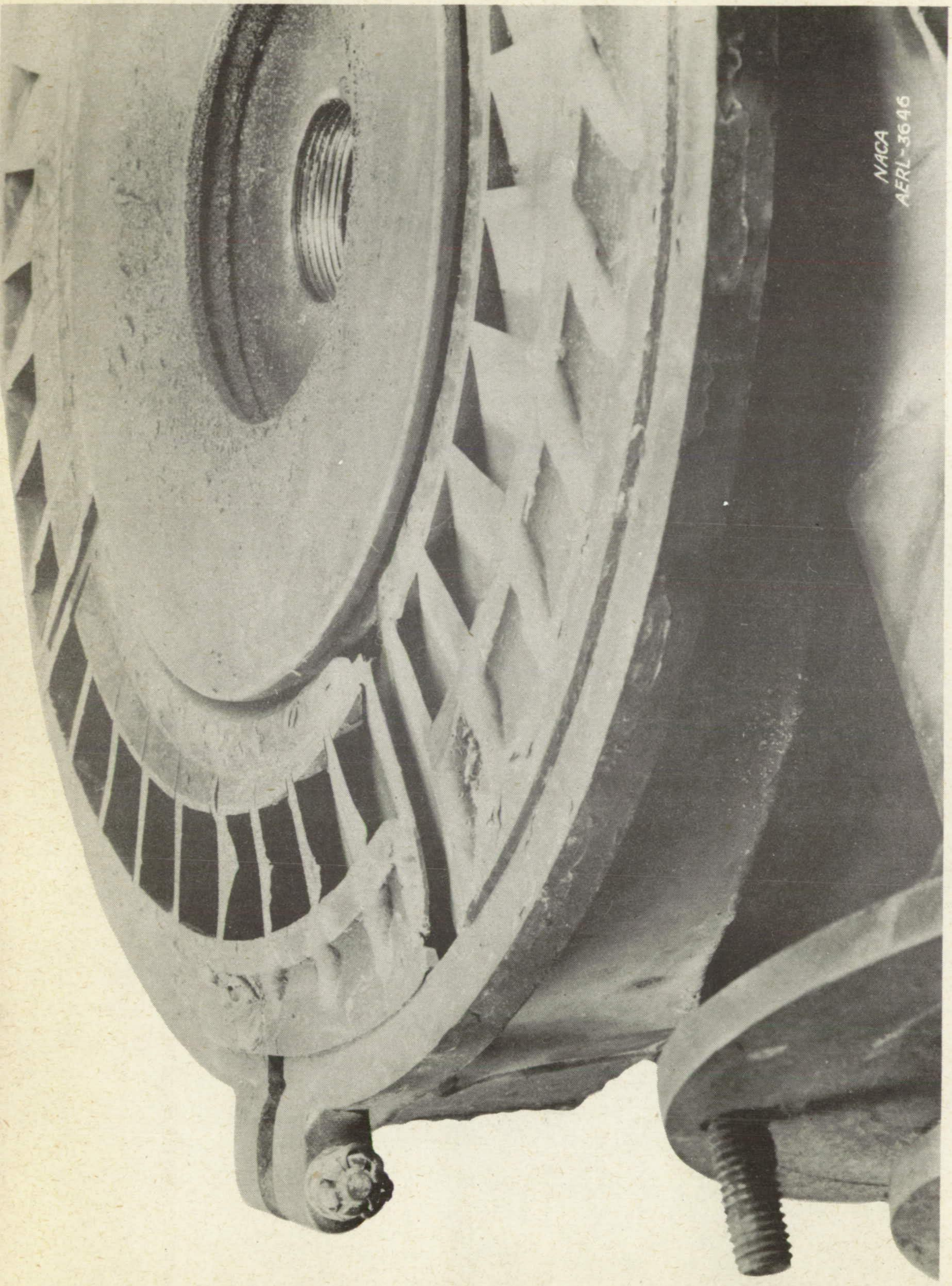


Figure 16. - Damage to turbine-nozzle diaphragm.