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PERFORMANCE CHARACTERISTICS OF A JUNKERS JUMO 211F ENGINE SUPERCHARGER WITH A DVL FULLY SHROUDED IMPELLER AND SCROLL DIFFUSER

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ADVANCE RESTRICTED REPORT

PERFORMANCE CHARACTERISTICS OF A JUNKERS JUMO 211F ENGINE SUPERCHARGER WITH A DVL FULLY SHROUDED IMPELLER AND SCROLL DIFFUSER

By J. Austin King and Harold Klein

SUMMARY

A German supercharger from a Junkers Jumo 211F engine was tested by the NACA. The supercharger differed from conventional American superchargers in that it had a fully shrouded impeller, which discharged through a very short vaneless diffuser into a scroll-collector case.

Tests were run at impeller tip speeds from 400 to 1200 feet per second at increments of 100 feet per second for a wide range of air flows. Tests were made with and without the casing lagged in order to determine the effect of heat transfer. Impeller-tip surveys were taken to determine the impeller efficiency. An analysis of the scroll collector is presented together with dimensional drawings of the supercharger assembly.

At a tip speed of 800 feet per second the supercharger showed a peak adiabatic efficiency of 76.5 percent, a peak pressure coefficient of 63 percent, and a peak impeller efficiency of 82.3 percent. The characteristic curves of the supercharger were flat over a wide range of air flows. It was impossible to make the supercharger surge at the low speeds; at the high speeds surging occurred only at extremely low load coefficients.

INTRODUCTION

Most present-day superchargers use impellers having only a rear shroud. A fully shrouded impeller would be expected to have less eddying in the blade channels and no circulation of air from one channel to the next. Thrust loads on a fully shrouded impeller should also be considerably less than on the half-shrouded type. In 1937 a German aeronautical magazine published an article by Werner von der Nüll (English translation available as reference 1) in which photographs and test results of a fully shrouded impeller developed by the Deutsche Versuchsanstalt für Luftfahrt (DVL) were given. Efficiencies of over 82 percent were reported for the supercharger using this impeller. Since that time much controversy has existed as to the actual value of a fully shrouded impeller. In 1940 Kollmann of Germany published a report (reference 2) in which he maintained that the highest efficiency of a fully shrouded impeller was obtained at tip speeds of about 725 feet per second. Although these efficiencies were high, the efficiencies at higher tip speeds were no greater than those obtained with a half-shrouded impeller. In a later report (reference 3) von der Nüll presented performance curves with efficiencies of 80 percent at tip speeds of 1000 feet per second. The Bristol Aeroplane Company Limited of England is manufacturing superchargers with fully shrouded impellers, but unpublished tests by the NACA indicated no appreciable gain in performance for this design over more conventional types.

Several experimental fully shrouded impellers have been made in the United States but their performance has generally been about the same as that of a half-shrouded impeller. Also, difficulty has been experienced in manufacturing the impellers from solid forgings and no built-up impellers that will withstand the centrifugal forces have yet been constructed. The NACA has tested a fully shrouded impeller having approximately the same flow passages as one of the most efficient production-type American impellers; the inducer of the standard impeller was not exactly reproduced owing to machining difficulties. Preliminary, unpublished results, however, indicate that the shroud does not appreciably improve performance.

Although fully shrouded impellers were tested and highly recommended in Germany in 1937, it was not until the fall of 1942 that the NACA obtained a DVL supercharger with a fully shrouded impeller from the Bureau of Aeronautics, Navy Department. At the request of the NACA Special Subcommittee for Supercharger Compressors, performance tests were conducted at the Langley Field laboratory on the supercharger in order to compare the results with those of American production-type superchargers. The supercharger is, in general appearance of scroll and bearing mountings, quite similar to that used in the Junkers Jumo 211A described in reference 4. It is probable that the Germans simply substituted the fully shrouded impeller for the inefficient box-type impeller used with the Jumo 211A.

The fully shrouded supercharger has no conventional diffuser; the air from the impeller discharges through a very short vaneless diffuser into the scroll, or volute, which performs the functions of a collector. It has long been known that collectors of this type greatly increase the operating range between the maximum and the minimum load coefficients of a supercharger; they have not been used in this country because the vaned-type diffusers have proved more efficient. In the tests of the Jumo 211A (reference 4) it was not determined whether the low efficiency (a peak of 59 percent) could be attributed to the box-type impeller, to the scroll, or to both.

This report presents the results of the tests on the DVL supercharger from the Junkers Jumo 211F engine, together with photographs, drawings, an analysis of the scroll design, and a comparison of the DVL supercharger with American superchargers.

APPARATUS AND METHODS

Supercharger

The supercharger tested was designed by the DVL for use in a Junkers Jumo 211F engine. Because the design has features that depart considerably from conventional American practice, a detailed examination of the construction is presented.

Figure 1 is a photograph of the supercharger completely assembled and figure 2 is a drawing of the assembly made from measurements of the unit. The complete supercharger weighs only 20 pounds, is small and compact, and is designed to supply an engine of about 1000 horsepower.

The impeller assembly is shown in figure 3. The impeller is a 12-blade fully shrouded wheel of 8.897-inch outside diameter. It is machined from a magnesium-alloy blank and has a coating of some bronze material probably for protection against corrosion. The air passages have well-filleted corners. The passage surface is quite rough with scratches left by grinding. In addition to the three oil-seal rings a baffle is provided to reduce air leakage about the back of the impeller. The use of six pins to fasten the impeller and the inducer to the shaft is a departure from the usual American practice of using splines or keys. Figure 4 is a detailed drawing of the impeller. The aluminum-alloy inducer is separately machined and is held to the impeller by a lock nut and two pins. The concave surfaces of the blades are quite rough, but the convex surfaces are smoother. A sketch of the inducer with over-all dimensions is given in figure 5.

The impeller discharges into a scroll collector case through a very short vaneless diffuser. Figure 6 is a photograph of the inside and the rear of the scroll. Drawings of the scroll collector and passage are shown in figure 7. A front and a rear view of the front cover is shown in figure 8. The original scroll-collector outlet had been broken; the flange and the duct shown in the photograph were faired into the scroll for the tests. Both the front and the back walls are recessed for the impeller shrouds. These recesses were apparently designed to reduce disk friction rather than to promote a smooth entrance into the diffuser because the inner walls of the impeller are not flush with the diffuser walls. (See fig. 2.) A groove is provided for the projecting baffle ring on the back of the impeller.

As can be seen from figure 8, three streamline struts immediately in front of the impeller support the front bearing, which is a split-race ball bearing that locates the impeller axially with practically no end play. The streamline nut shown in figure 1 was machined to cover the bearing that had been broken. The rear bearing is a roller bearing.

Test Setup

The supercharger was driven by an electric dynamometer through a step-up-gear arrangement. At the highest speeds an automobile engine was coupled to the dynamometer to provide additional power. The straight inlet duct was 6 inches in diameter and 17 diameters in length. (See fig. 1.) The scroll discharged into an outlet duct $3\frac{1}{2}$ inches in diameter and 15 diameters in length. The entire duct was lagged with sheet asbestos and 1/2 inch of felt. For the tests with the supercharger lagged, a wooden box lined with insulating board was installed over the supercharger. The inlet and the outlet throttling was accomplished by butterfly valves.

Measurements

Air-quantity measurements were taken at the inlet with a 10.13-inch circular flat-plate orifice connected to a large orifice tank. The pressure drop across this orifice was measured to 1/10 millimeter of alcohol with an NACA micromanometer. The air temperature at the orifice was measured with a mercury-in-glass thermometer.

Temperatures and static and total pressures were taken in the inlet duct 2 diameters from the entrance flange of the supercharger. In the outlet duct, temperature and total-pressure and static-pressure measurements were taken after 12 diameters of straight-pipe flow. All thermocouples, pitot tubes, and static taps were installed in pairs as a check against erroneous readings. In order to determine the impeller efficiency, a total-pressure tube was installed 1/4 inch from the impeller tip (fig. 3(a)). Surveys were taken at four points equally spaced in an axial direction, which were located by dividing the distance between the walls into four equal parts with the points as the centers of these parts.

Pressures were measured with a bank of mercury manometers and corrected to a mercury temperature of 32° F. Wall static taps of 0.020-inch bore were used for the static-pressure measurements, and calibrated pitot tubes were used for the total-pressure measurements. The pitot tubes were mounted to allow rotation for obtaining the true total pressure in the event of air rotation in the pipe. The total-pressure tubes were set 1/3 diameter into the pipe.

The temperature measurements were taken with calibrated copper-constantan thermocouples having a common cold junction immersed in melting ice. Voltages were measured with a potentiometer equipped with an external spotlight galvanometer.

The impeller speed was set at the desired value with an electric tachometer and a speed strip in combination with a neon light operating from a line frequency of 60 cycles. The speed was checked at frequent intervals by an electric counter and a stop watch. All measurements and computations were made in accordance with the methods of references 5 and 6. The over-all accuracy is estimated to be ±1 percent.

RESULTS AND DISCUSSION

Figure 9 shows the adiabatic efficiencies of the supercharger for tip speeds from 400 to 1200 feet per second at intervals of 100 feet per second. The over-all efficiency has peak values from 72 to 76.5 percent. The highest impeller efficiency measured was 82.3 percent at a tip speed of 800 feet per second. The pressure coefficients of the supercharger for all the tip speeds tested are shown in figure 10. The peak over-all pressure coefficient was insensitive to the speed inasmuch as it varied from only 61 to 63 percent for the range of tip speeds investigated. The pressure coefficient was low because the impeller had only 12 blades. The impeller pressure coefficient has peak values from 67 to 72.5 percent for tip speeds of 800, 900, and 1000 feet per second, the range of speeds for which impeller-tip surveys were taken. The technique for determining the impeller performance is not so accurate as that for determining the over-all performance of the supercharger. The impeller performance, however, is a guide to a qualitative comparison of impellers. The overlapping range of tip speeds of 800 and 900 feet per second with and without lagging indicate that lagging has little effect on performance.

In order to determine the possible advantages of the front shroud it was planned to machine off the front shroud after these tests were completed and test the same impeller as a half-shrouded impeller. Because the supercharger failed, however, the performance of the impeller must be evaluated from total-pressure measurements at the impeller tip and comparison with other impellers similarly tested by the NACA. The results of the measurements at the impeller tip indicate that the maximum peak efficiency of the DVL impeller is 82.3 percent. Several American impellers including the NACA fully shrouded impeller have shown efficiencies greater than 90 percent. Although no conclusions can be drawn from this comparison as to the value of a front shroud, the DVL impeller is seen to have no remarkable performance characteristics.

Figure 11 shows the total pressure ratio p_{2_t}/p_{1_t} as a function of the nondimensional load coefficient Q_1/nD^3 for the various Mach numbers tested, where D is the impeller-tip diameter in feet. The maximum ratio measured was 2.22 but the peak at this Mach number was not attained because of power limitations. The adiabatic work per pound of air H_{ad} and the efficiency contours for the supercharger are presented in figure 12. The optimum efficiency of the supercharger occurs at a tip speed of approximately 800 feet per second and a load coefficient of 0.091.

A comparison of the collector losses of the DVL supercharger with those of the most efficient production-type vaned diffuser and the most efficient experimental vaneless diffuser tested by the NACA is given in figure 13. The ordinate is

$$\frac{\eta_{ad_i} - \eta_{ad_o}}{\eta_{ad_i}}$$

where

η_{ad_i} impeller adiabatic efficiency based on impeller-tip surveys

η_{ad_o} over-all supercharger adiabatic efficiency based on outlet measurements

Also

$$\eta_{ad_i} = \frac{H_{ad_i}}{H}$$

and

$$\eta_{ad_o} = \frac{H_{ad_o}}{H}$$

where H is the increase in total enthalpy in foot-pounds per pound of air.

Therefore,

$$\frac{\eta_{ad_i} - \eta_{ad_o}}{\eta_{ad_i}} = \frac{H_{ad_i} - H_{ad_o}}{H_{ad_i}}$$

where the subscripts are the same as previously defined. Because H_{ad_i} is the useful energy input per pound of air to the diffuser and H_{ad_o} is the useful energy output per pound of air, the quantity plotted is a measure of the percentage loss in the diffuser or the scroll in question. The losses in the scroll are between 10 to 15 percent over most of the range; the curve is fairly flat, which indicates that the losses increase only moderately for very small and very large volume flows. The diffuser losses obtained from unpublished data on the NACA 6° equivalent-cone vaneless diffuser of 34-inch diameter vary from about 15 to 10 percent and decrease slightly with increasing load coefficient Q_1/n. The data for a typical vaned diffuser obtained from the tests run with the NACA fully shrouded impeller indicate a minimum loss of 14 percent; the losses increase sharply with an increase in Q_1/n. The vaneless diffuser and the scroll collector have losses that are fairly constant over a wide range of load coefficients, whereas the vaned diffuser has a sharply defined operating point and increased losses with distance from this point. The impeller often operates at a larger load coefficient than that for optimum operation for the diffuser, which results in a lower over-all efficiency than might otherwise be expected.

A scroll-type collector cannot be evaluated in terms of a diffuser because the collector discharges the air at such a high velocity that little or no diffusion takes place. The velocity in the outlet duct is plotted as a function of Q_1/n for each tip speed (fig. 14). During tests on the DVL scroll, outlet-duct velocities as high as 750 feet per second were reached, whereas this velocity at the operating point of the supercharger installed on the engine was approximately 400 feet per second. This outlet velocity is much higher than the velocity of 200 to 300 feet per second existing in American engine induction systems. From the consideration of friction losses low velocities are advantageous. It is probable, however, that these losses are not particularly objectionable in the Junkers engine because no outlet carburetor is used and the manifold from the scroll outlet to the intake valves is short and free from bends. In the engine-supercharger combination, the maximum permissible velocity of the air leaving the supercharger is a compromise between the diffuser and the induction losses. In many diffuser or collector designs, the losses in a diffuser might be greater than the losses due to the high velocity in the induction system. Further tests on engine-supercharger combinations are necessary to determine the relative importance of these factors.

Another point noted in these tests deserving comment is the peculiar surging characteristics of the DVL supercharger. The supercharger would not surge at low speeds; at the high speeds surging occurred only at very low load coefficients with certain conditions of boost. During a small range of load coefficients in the medium loads a peculiar resonant wailing sound was noticed. This wailing occurred at each speed and only for certain values of load coefficient. In a few tests in which the impeller was run without an inducer no resonant sound was encountered, which would indicate that the flow through the inducer caused the wailing sound. The pressures were steady during this wailing.

Inasmuch as the use of a scroll diffuser without vanes in aircraft-engine superchargers is untried in American practice, a detailed description of the scroll design is presented. The polar equation for a logarithmic spiral is

$$r = ae^{\theta \tan \alpha}$$

where a is a constant equal to the radius when $\theta = 0^\circ$ and α is the constant angle between a tangent to the spiral and a tangent to the circle at the same radius with the tangents drawn through the point of intersection of the two curves. When the logarithms of both sides of the equation are taken,

$$\log_e r = \log_e a + \theta \tan \alpha$$

The equation is linear if $\log_e r$ is plotted against θ. When the distance from the center of the impeller to the outermost point in the scroll passage is plotted in this form, the scroll is seen to be a logarithmic spiral except for a small section at the beginning (fig. 15). The abscissa of the curve corresponds to the angle shown in figure 7. Calculations show that α is equal to about $3\frac{1}{2}^{\circ}$. The cross-sectional areas of the scroll determined by planimetering the sections in figure 7 are plotted against the angle θ in figure 16. This area was taken as bounded by the walls of the scroll and a line connecting the two points where the front and the rear walls cease to be parallel. The points lie on a straight line, which proves that the passage area increases uniformly around the circumference.

In figure 17 the over-all performance of the DVL supercharger is compared with the most efficient impeller-diffuser combination in actual production that has been tested by the NACA and with the most efficient centrifugal supercharger of any type tested at the Langley laboratory. This supercharger was equipped with an NACA vaneless diffuser but the combination is not now used in aircraft. The DVL has an efficiency equal to that of the conventional type but about 4 to 6 points lower than that of the experimental one. The pressure coefficient of the DVL supercharger is about 3 points higher than that of the experimental supercharger and about 6 points lower than that of the production-type supercharger.

SUMMARY OF RESULTS

The DVL is admittedly an excellent supercharger with the added advantage of compactness and comparative lightness in weight for the size engine with which it is used. The desirable characteristics of the scroll-type collector suggest further research on this supercharger. The performance characteristics of the DVL supercharger as compared with those of production-type American superchargers are summarized as follows:

1. With the DVL supercharger, peak adiabatic efficiencies from 72.0 to 76.5 percent were obtained, which are equal to the performance of the most efficient production-type American superchargers.

2. Although the fully shrouded impeller showed high efficiencies, these efficiencies are no higher than those obtained with several American impellers tested by the NACA.

3. Peak pressure coefficients from 61 to 63 percent were obtained, about 5 points lower than the pressure coefficients obtained with most American superchargers. The higher exit velocities might prove objectionable with present engine intake systems.

4. The surge characteristics of the DVL are excellent; an unusually wide range of load coefficients was covered without surging.

5. The cross-sectional area of the scroll-type collector increases uniformly with angle; the outer periphery (curvature) is based on a logarithmic spiral.

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2. Kollmann, K.: Limits of Single-Stage Compression in Centrifugal Superchargers for Aircraft. NACA TM No. 954, 1940.

3. von der Nüll, W.: The Maximum Delivery Pressure of Single-Stage Radial Superchargers for Aircraft Engines. NACA TM No. 949, 1940.

4. Oldberg, Sidney, and Ball, Thomas M.: Design Features of the Junkers 211B Aircraft Engine. SAE Jour. (Trans.), vol. 50, no. 11, Nov. 1942, pp. 465-483.

5. NACA Special Subcommittee on Supercharger Compressors: Standard Procedures for Rating and Testing Centrifugal Superchargers. NACA ARR, Feb. 1942.

6. Ellerbrock, Herman H., Jr., and Goldstein, Arthur W.: Principles and Methods of Rating and Testing Centrifugal Superchargers. NACA ARR, Feb. 1942.

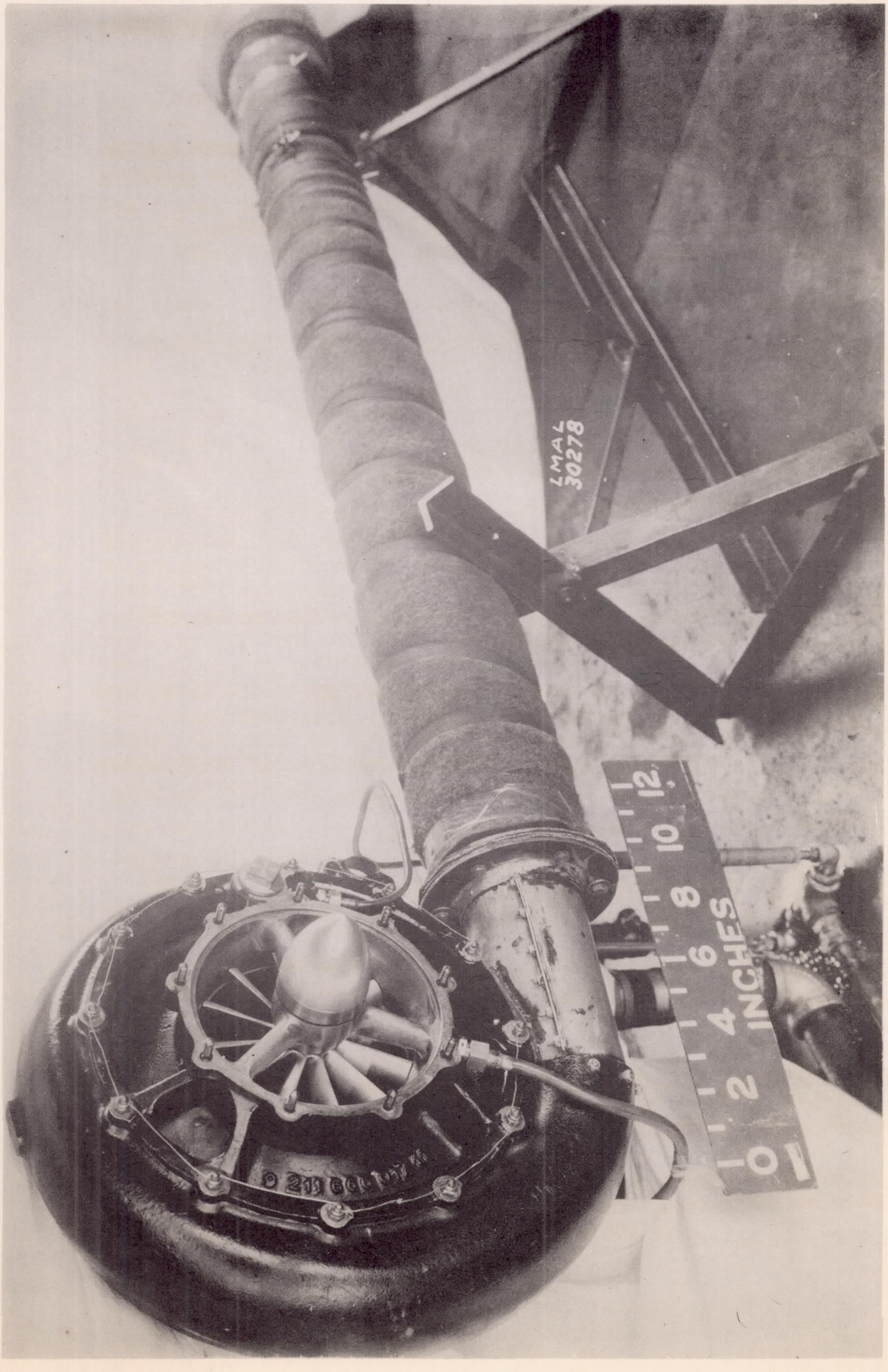

Figure 1. - Supercharger from Junkers Jumo 211F engine assembled for testing.

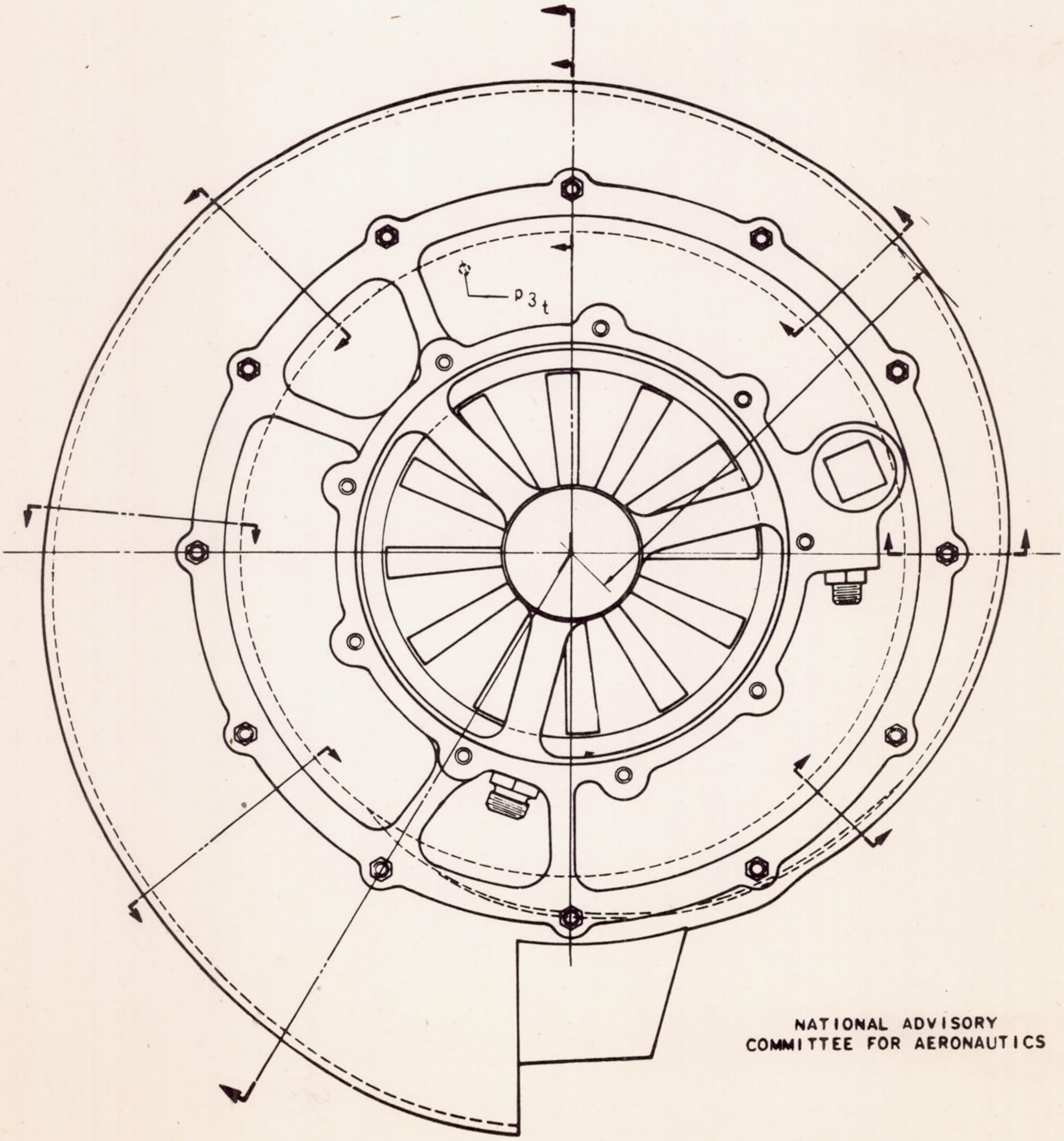

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Figure 2. - Assembly of supercharger from Junkers Jumo 211F engine.

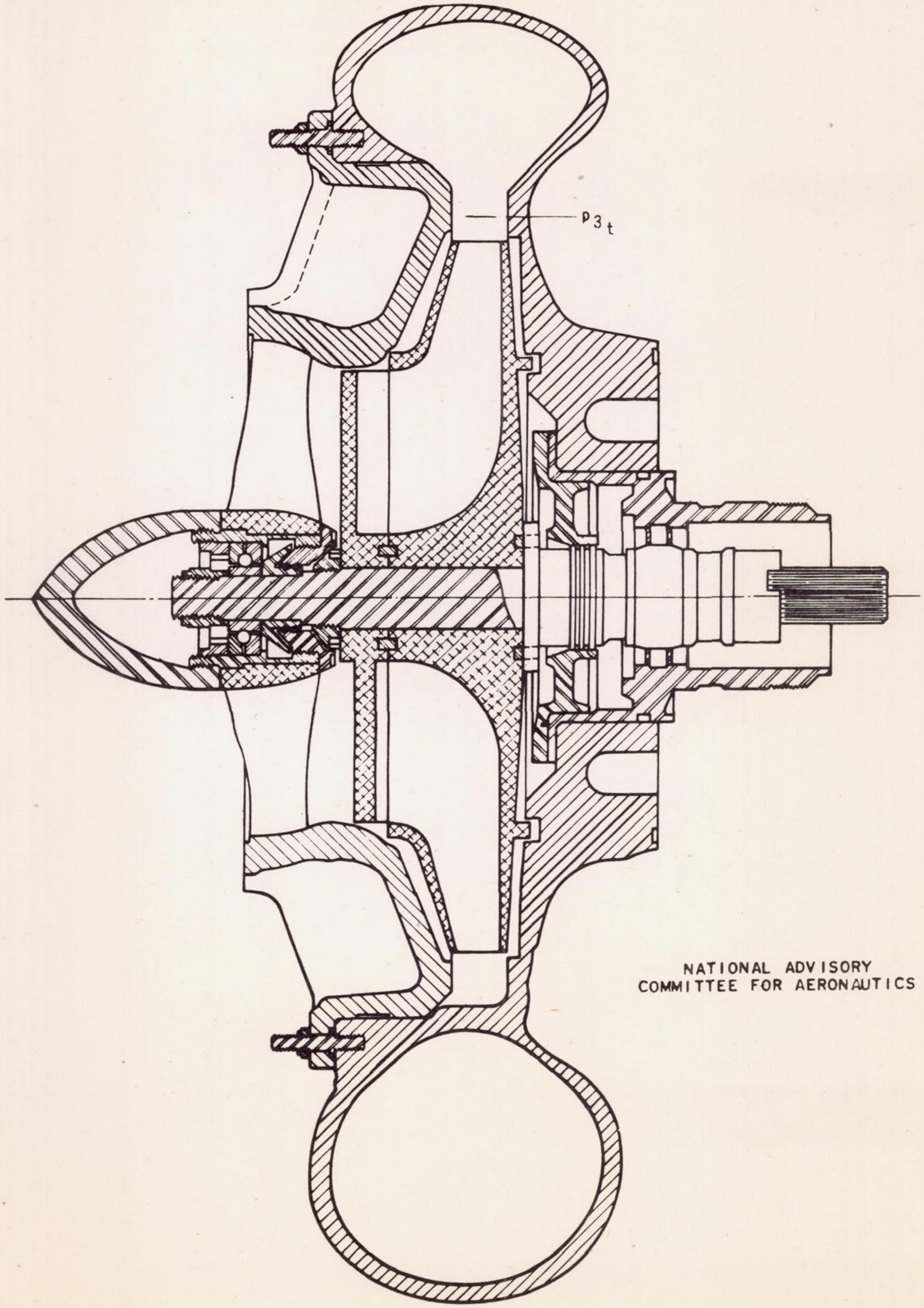

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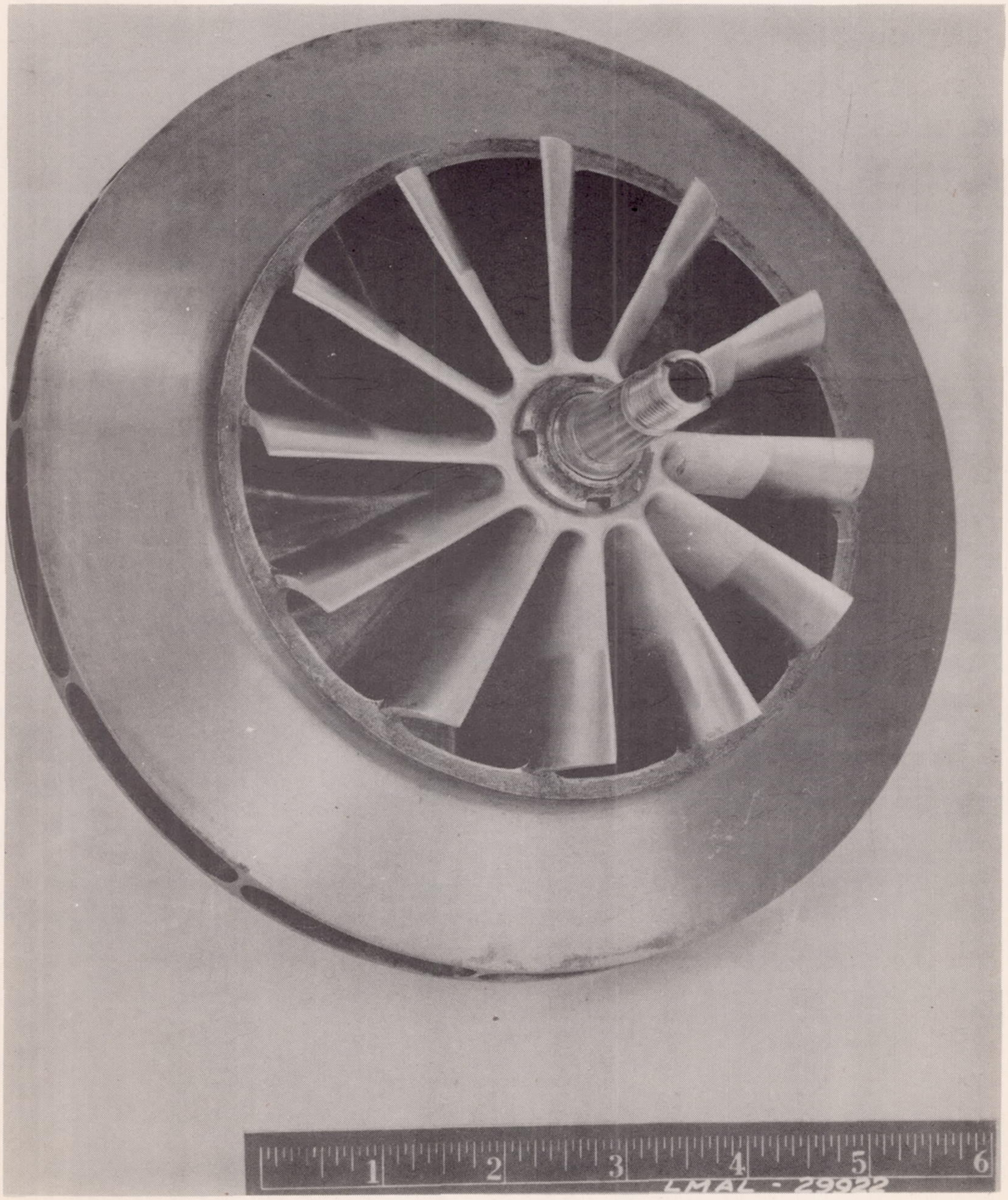
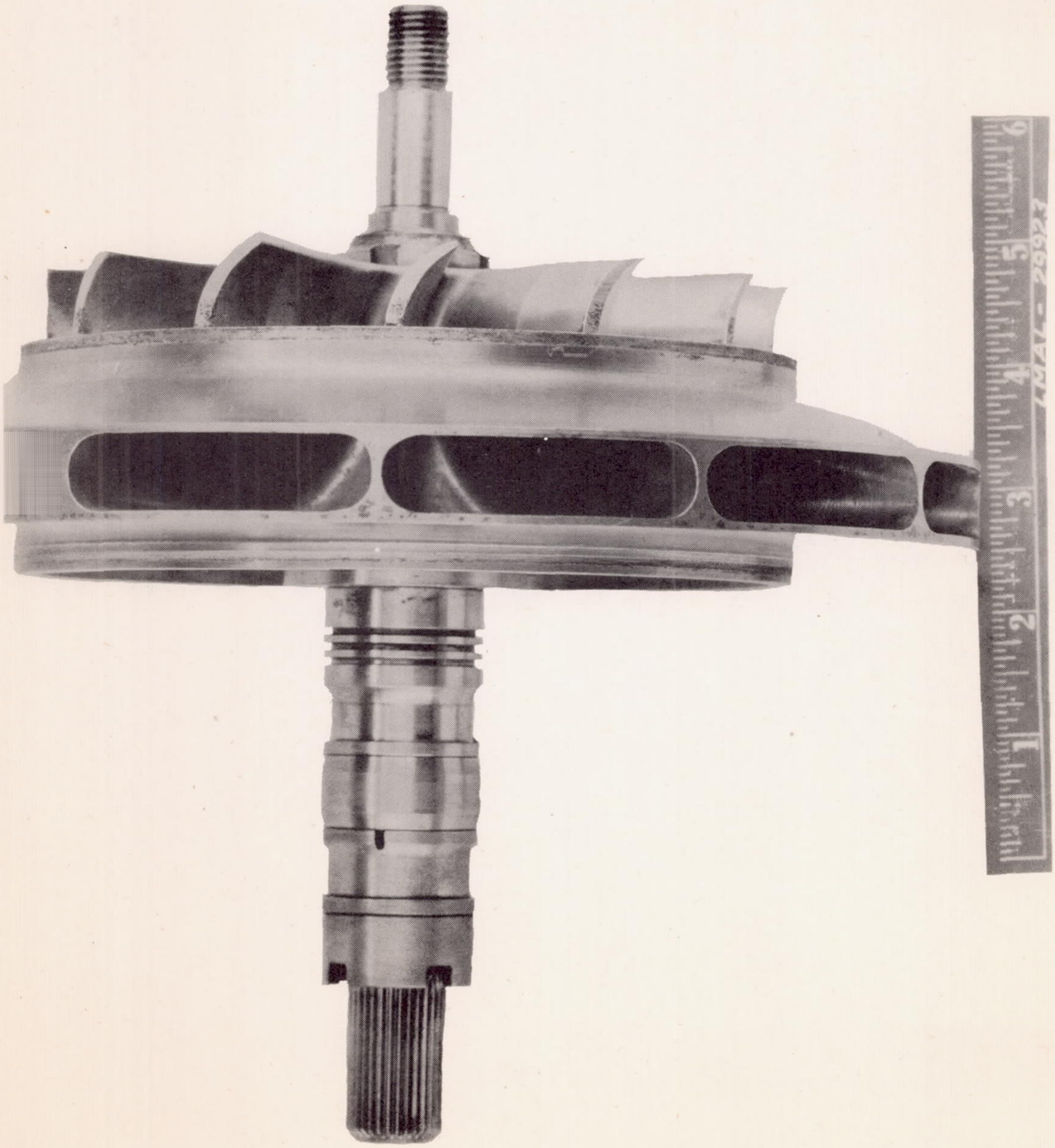
Figure 2. - Concluded.



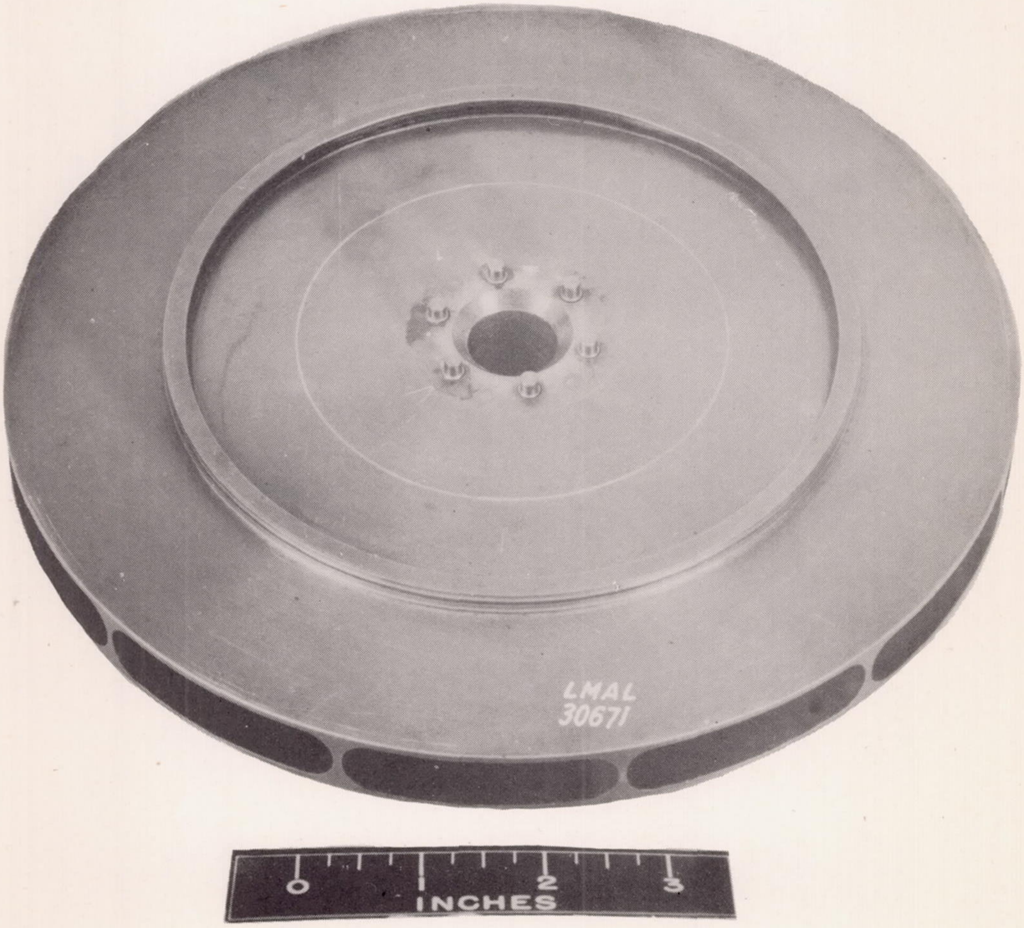
(a) Front view.

Figure 3. - DVL fully shrouded impeller of supercharger from Junkers Jumo 211F engine.



(b) Side view.

Figure 3. - Continued.



(c) Rear view.

Figure 3. - Concluded.

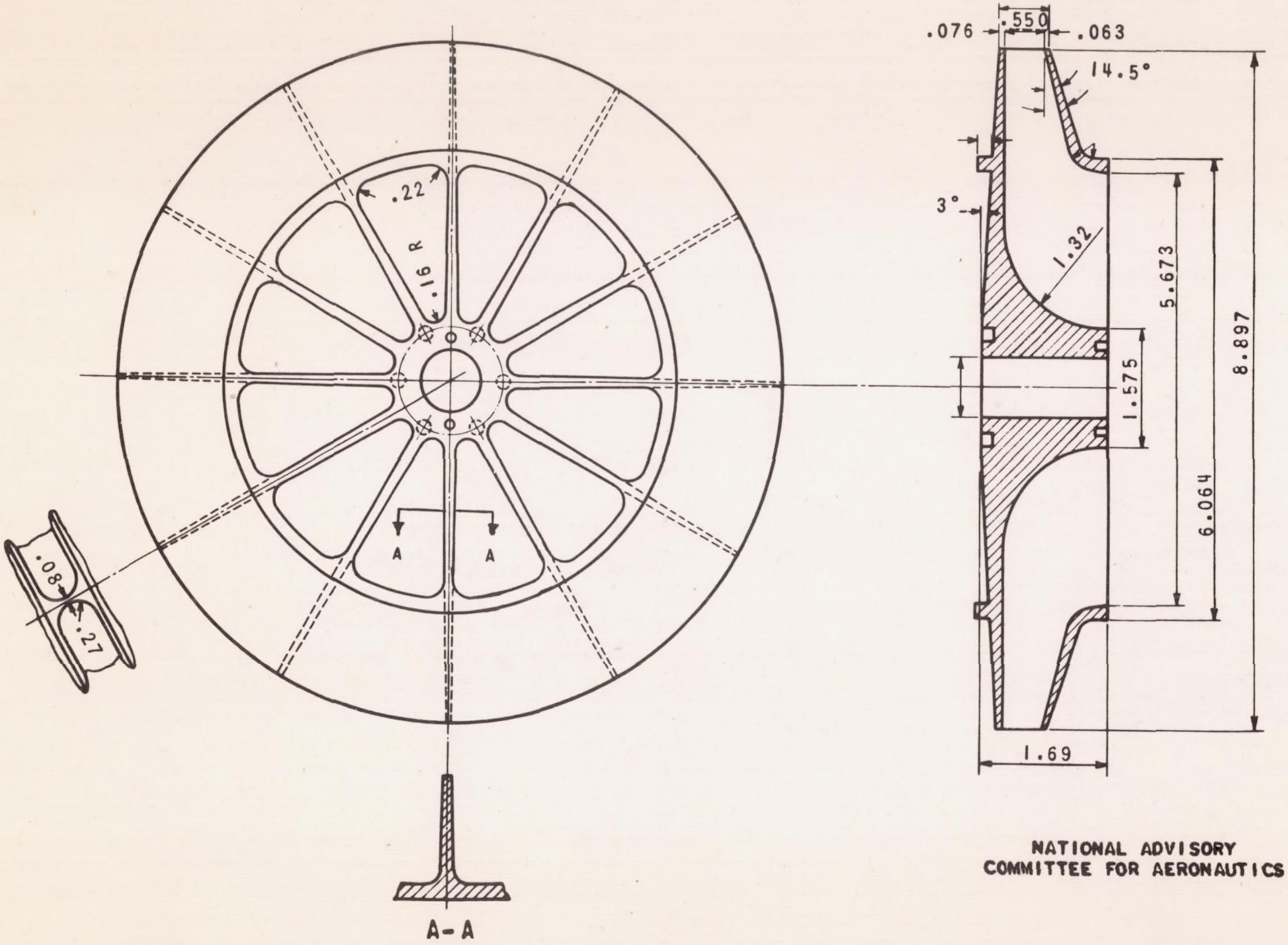


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Figure 4. - Dimensions of DVL impeller of supercharger from Junkers Jumo 211F engine. All dimensions in inches.

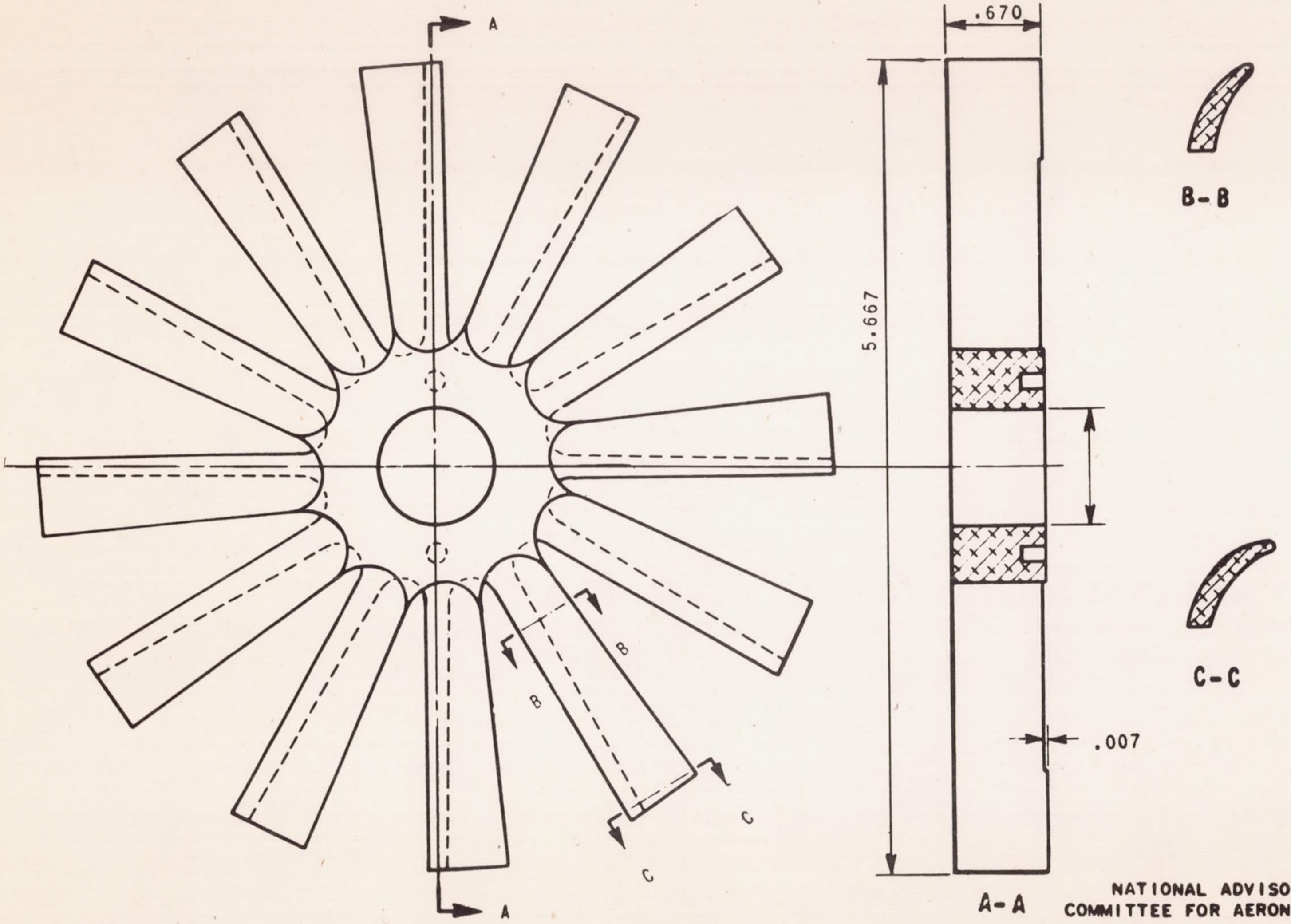

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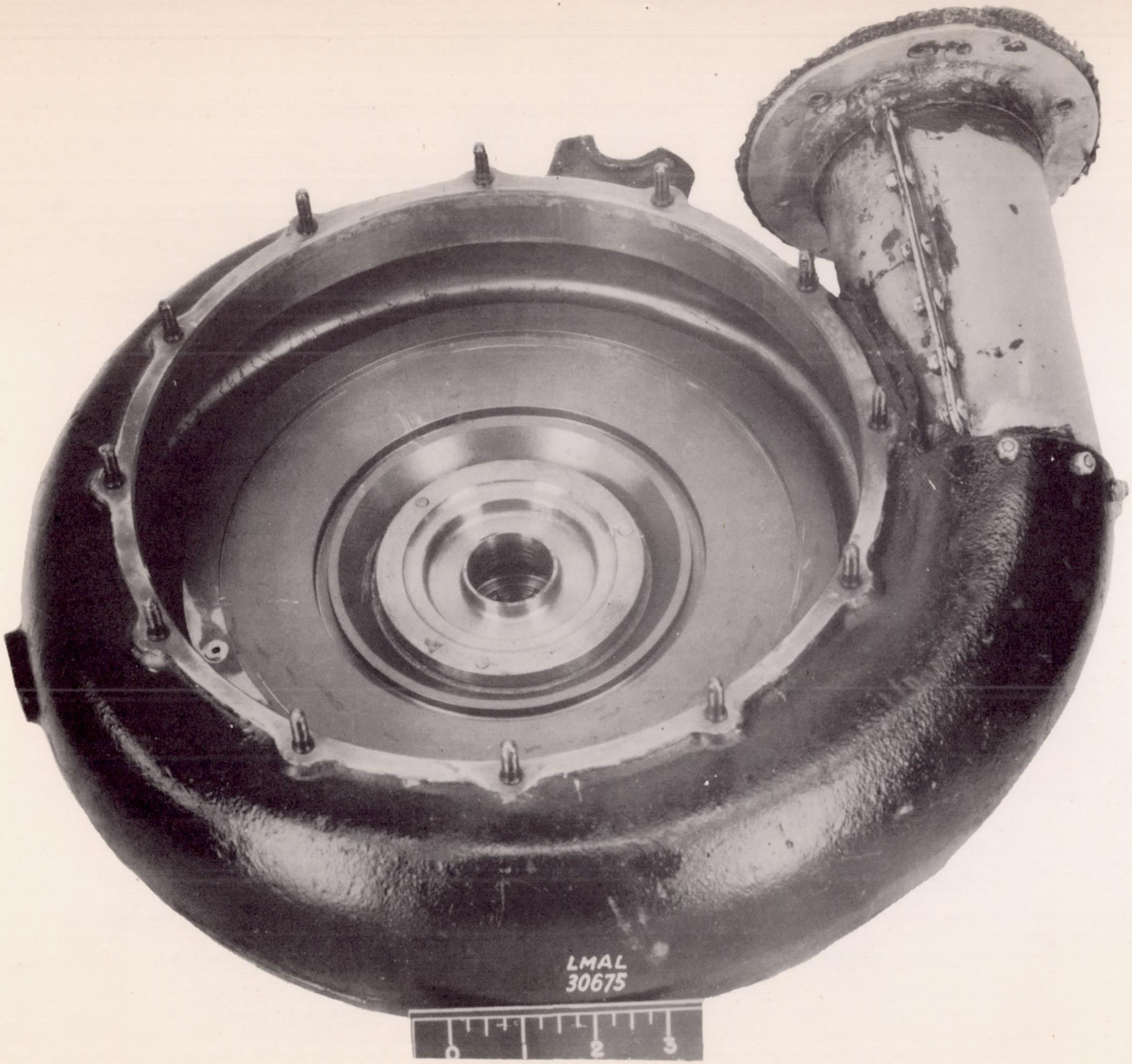
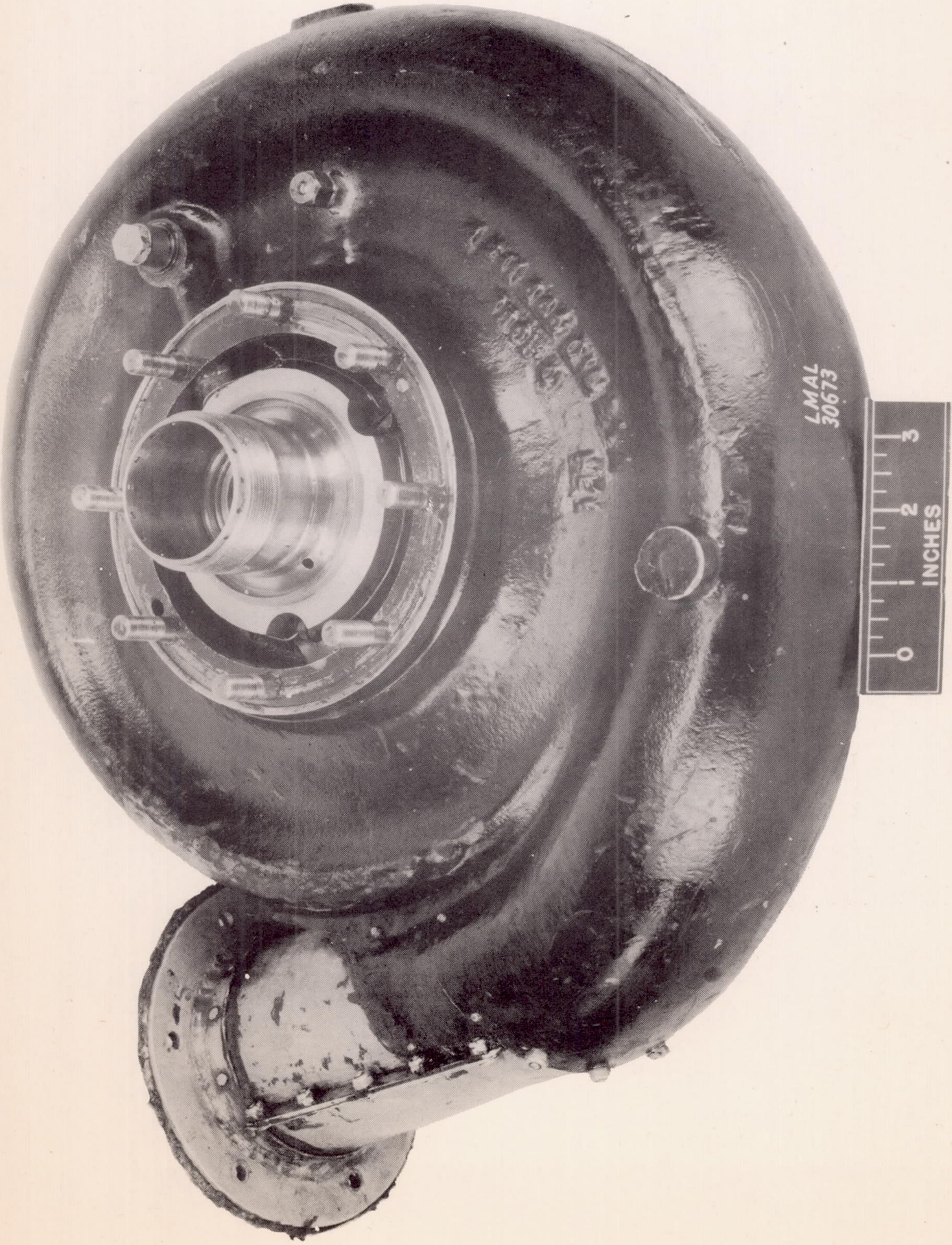
Figure 5. - DVL inducer of supercharger from Junkers Jumo 211F engine. All dimensions in inches.



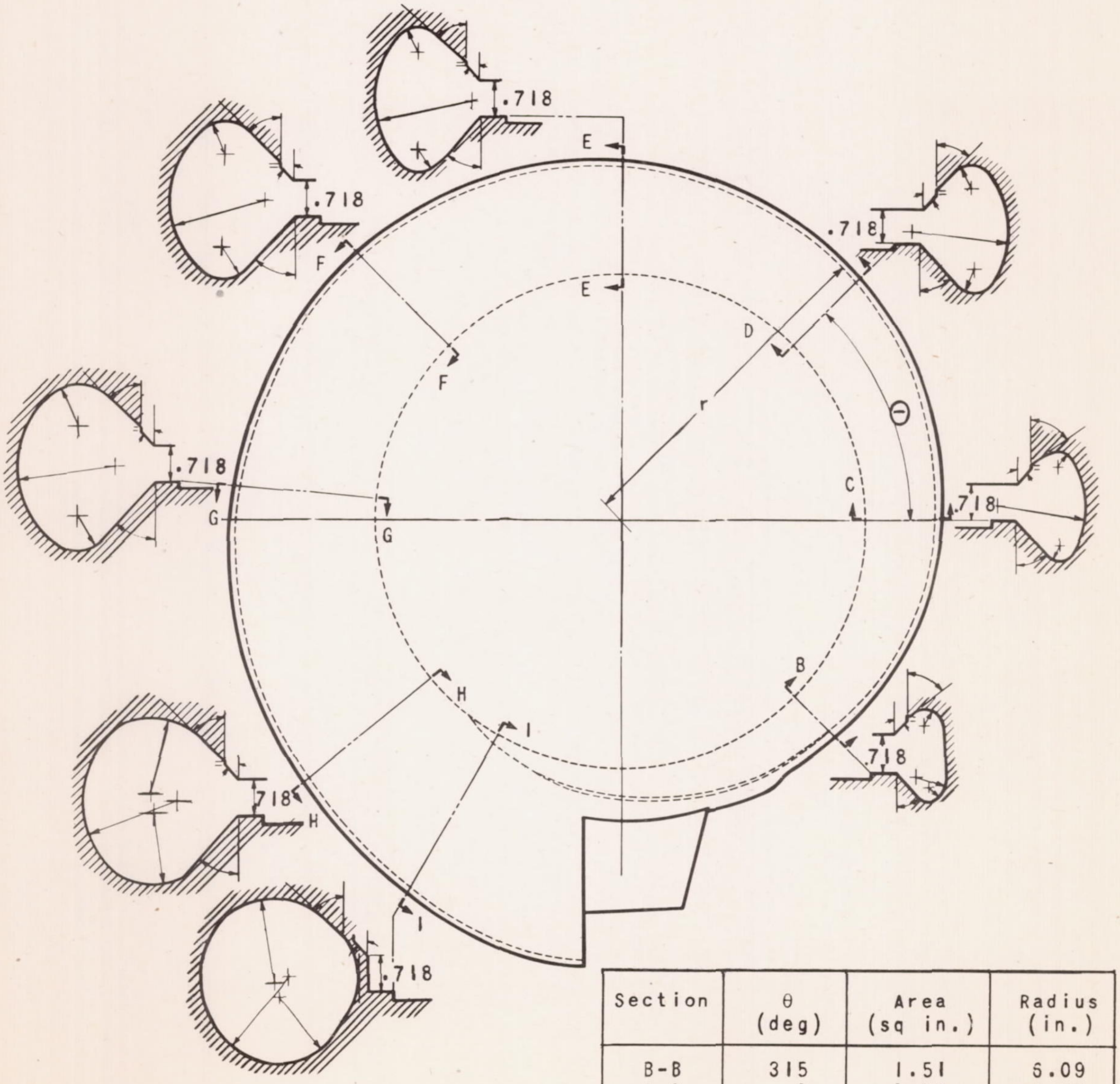
(a) Inside view.

Figure 6. - DVL scroll collector of supercharger from Junkers Jumo 211F engine.



(b) Rear view.

Figure 6. - Concluded.



Section	θ (deg)	Area (sq in.)	Radius (in.)
B-B	315	1.51	6.09
C-C	0	2.34	6.50
D-D	45	3.45	6.82
E-E	90	4.50	7.15
F-F	135	5.77	7.50
G-G	175	6.68	7.78
H-H	219.5	7.97	8.20
I-I	240	8.10	8.34

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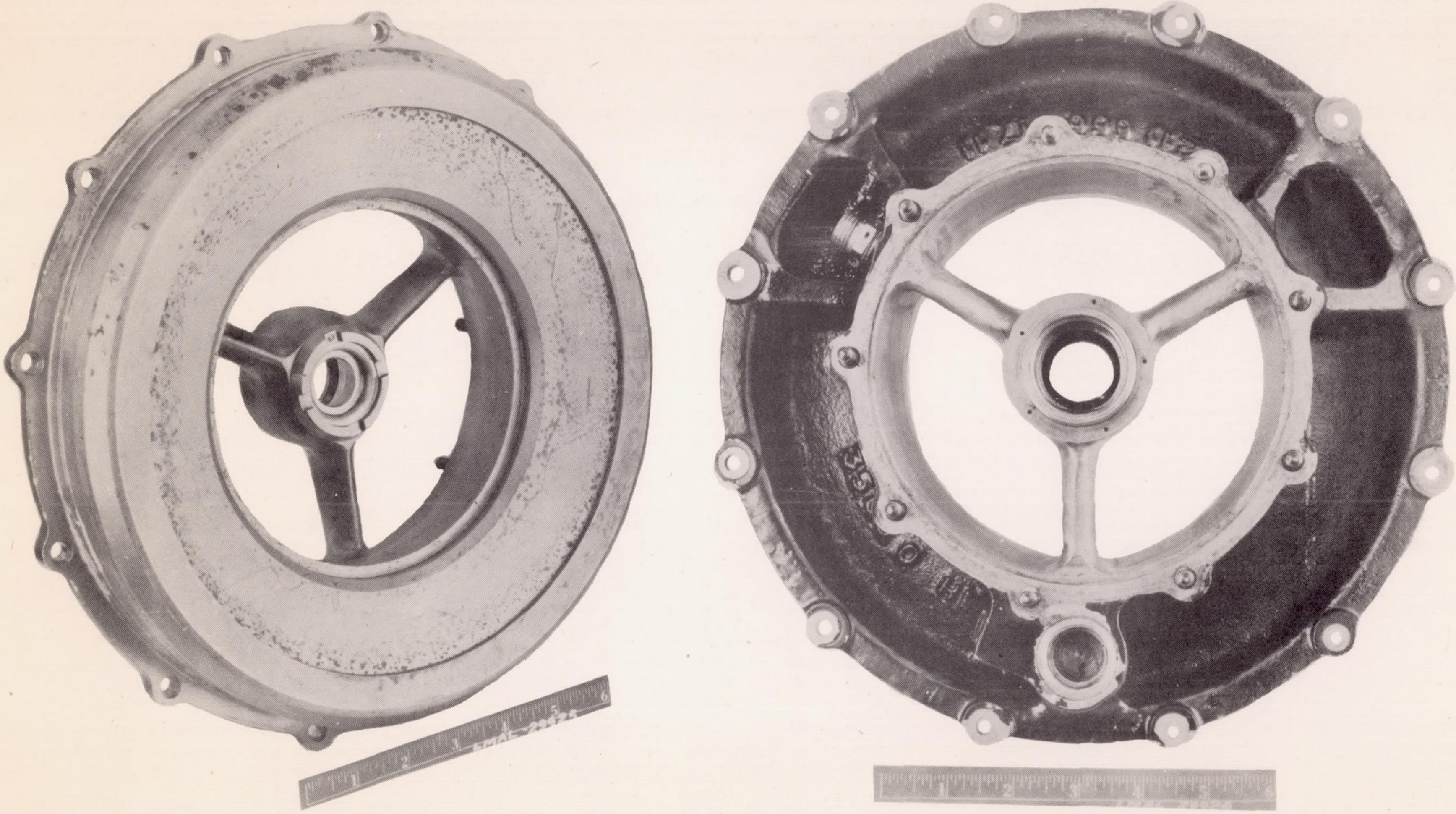
Figure 7. - Dimensions of DVL scroll collector and passage of supercharger from Junkers Jumo 211F engine. All dimensions in inches.



Front view

Rear view

Figure 8. - Front cover of supercharger from Junkers Jumo 211F engine.

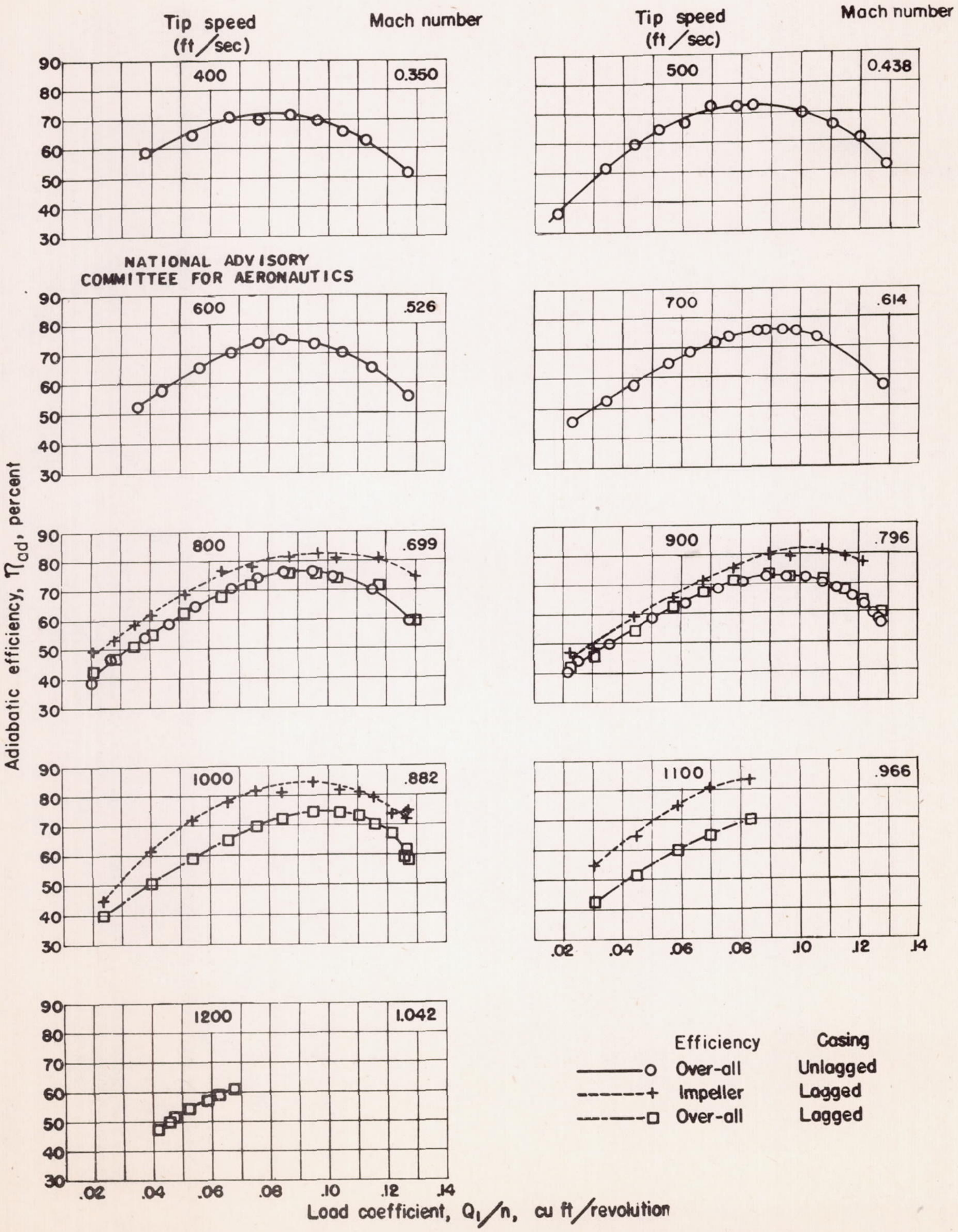


Figure 9.— Adiabatic efficiencies of supercharger from Junkers Jumo 211 F engine.

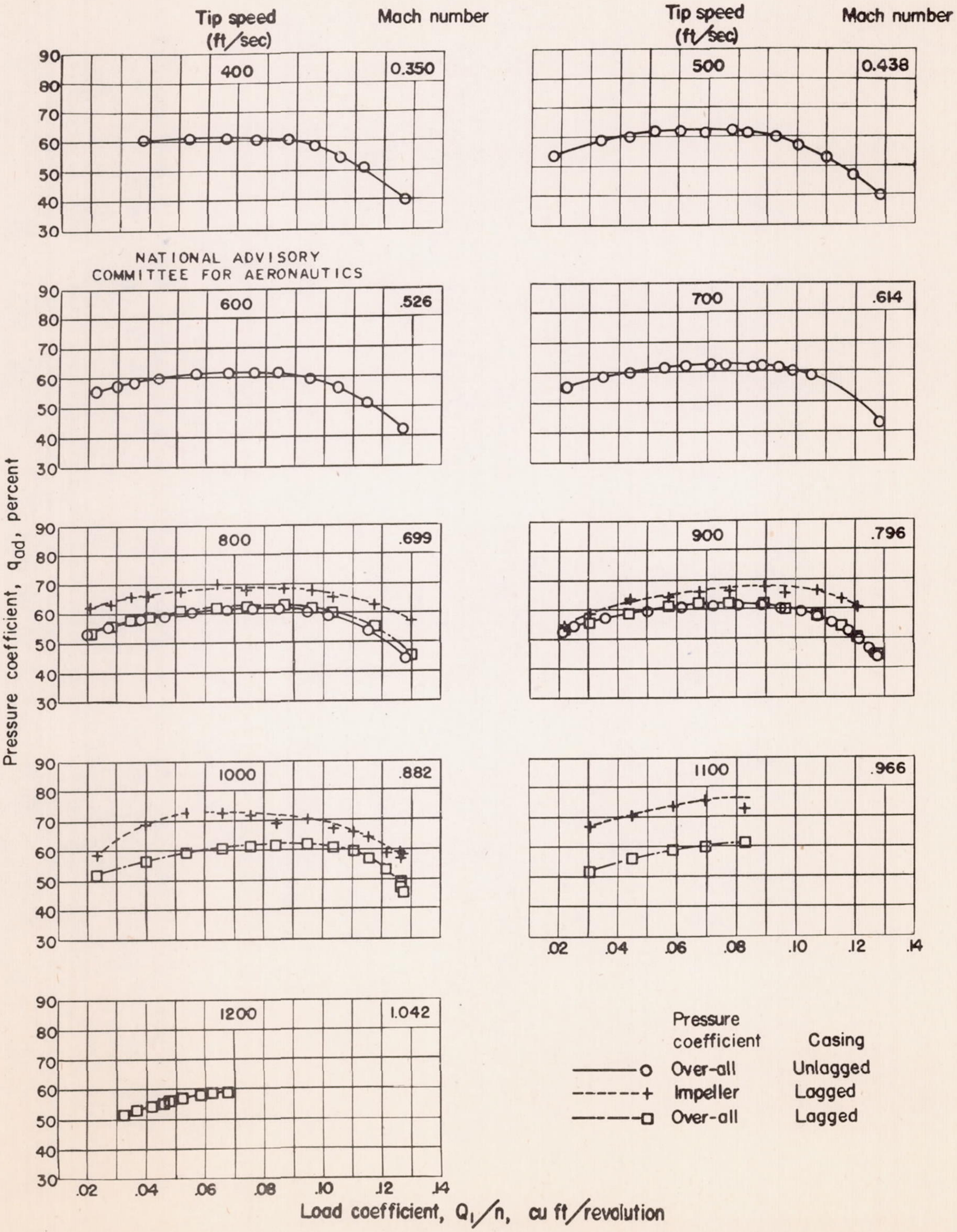


Figure 10.— Pressure coefficients of supercharger from Junkers Jumo 211 F engine.

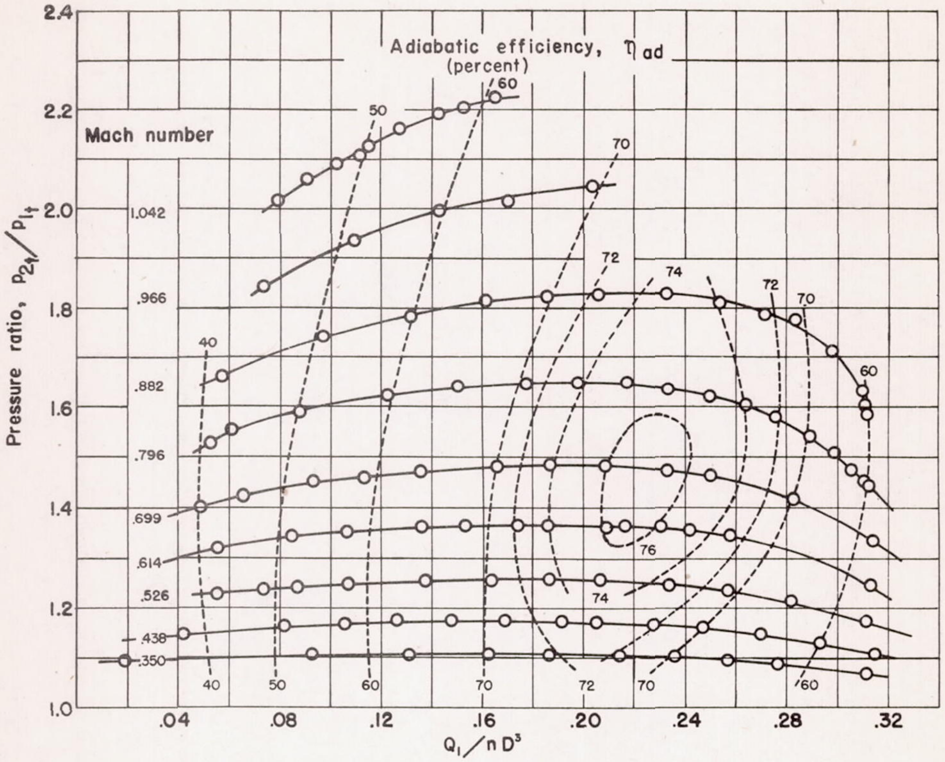


Figure 11.— Pressure ratio of supercharger from Junkers Jumo 211 F engine

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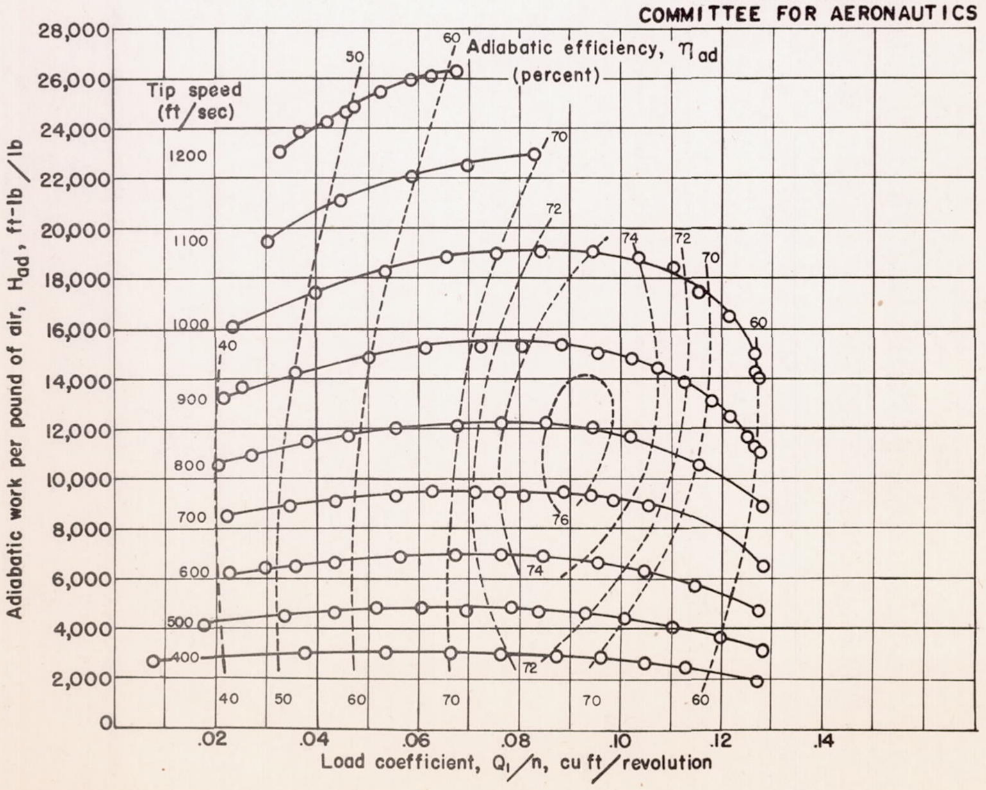

Figure 12.—Adiabatic work of supercharger from Junkers Jumo 211 F engine.

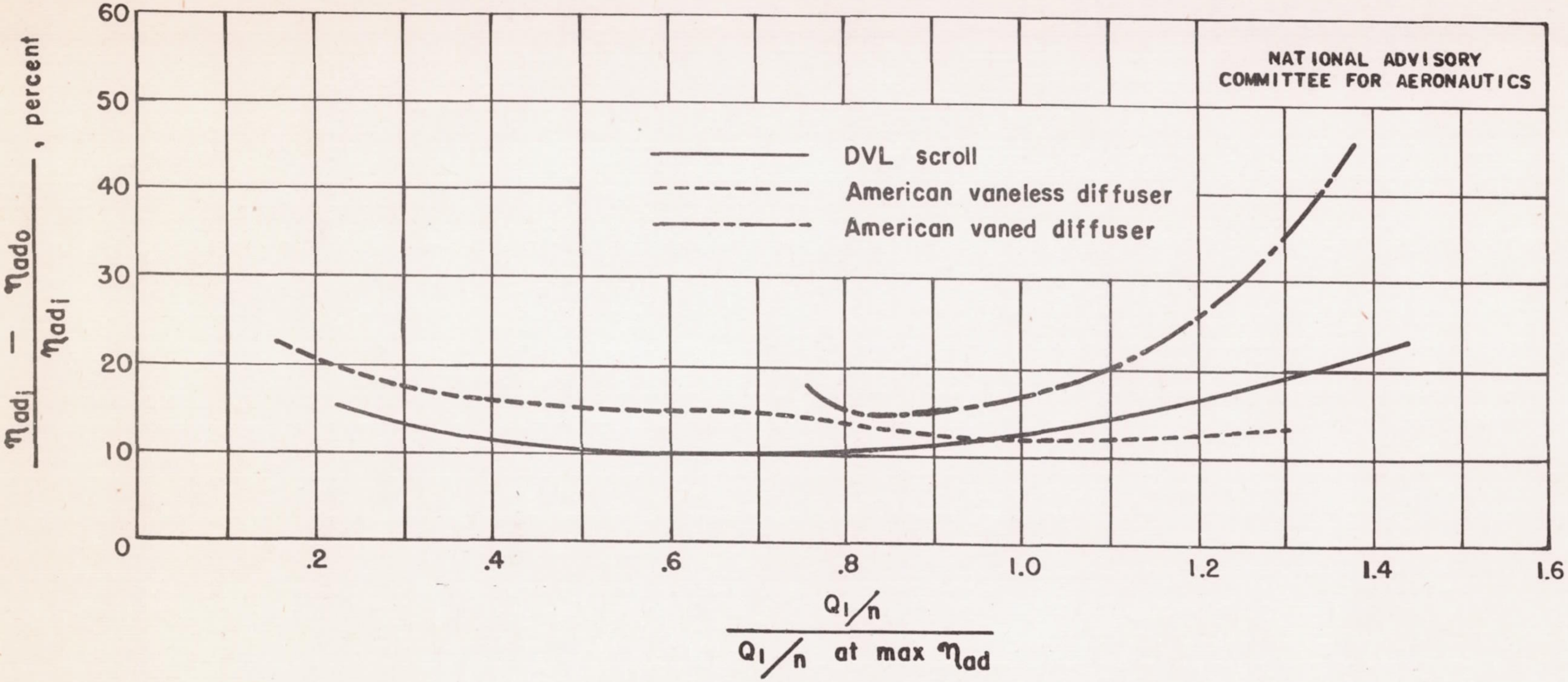

Figure 13.— Comparison of losses in scroll with those in vaned and vaneless diffusers.

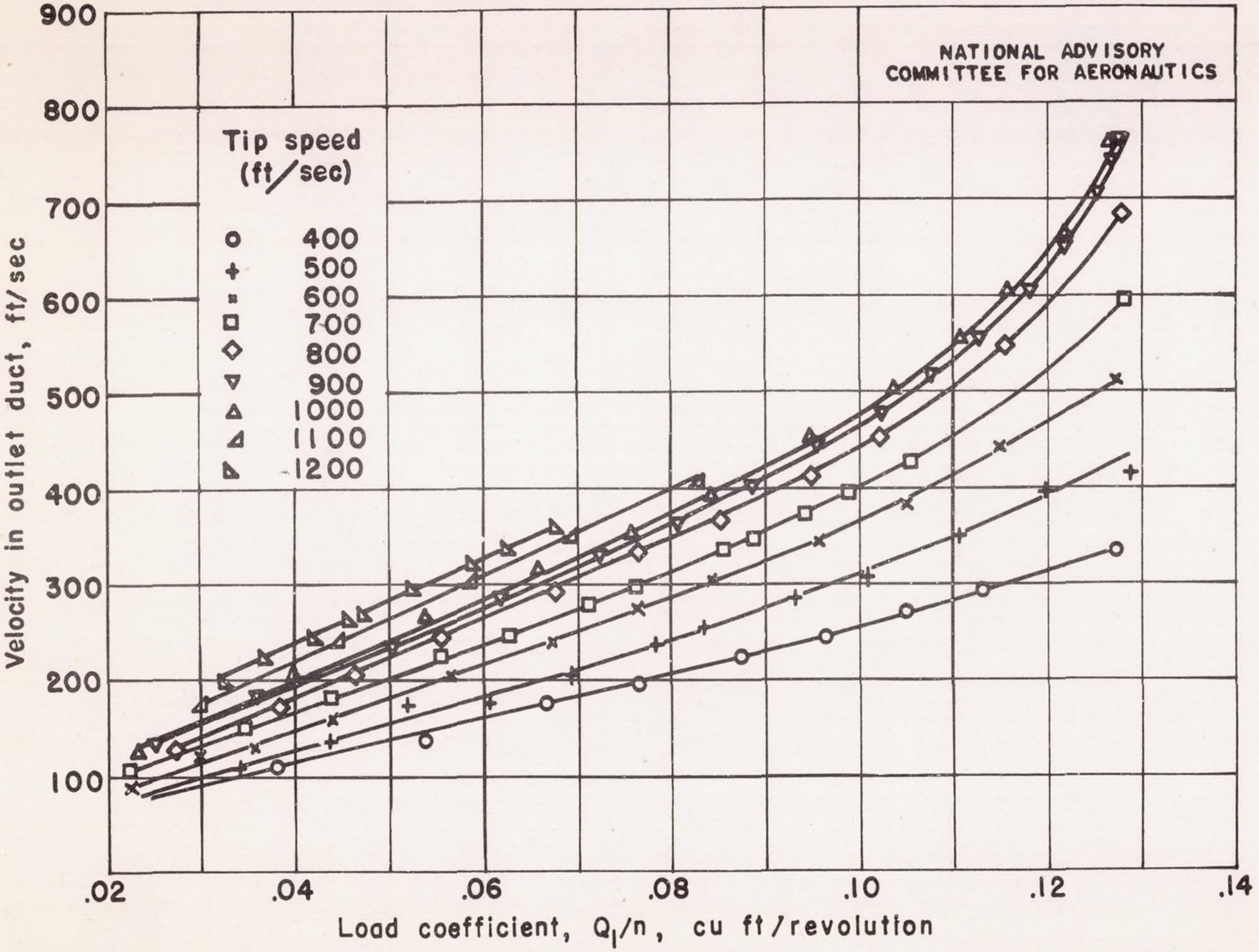

Figure 14.— Velocity in outlet duct of supercharger from Junkers Jumo 211 F engine.

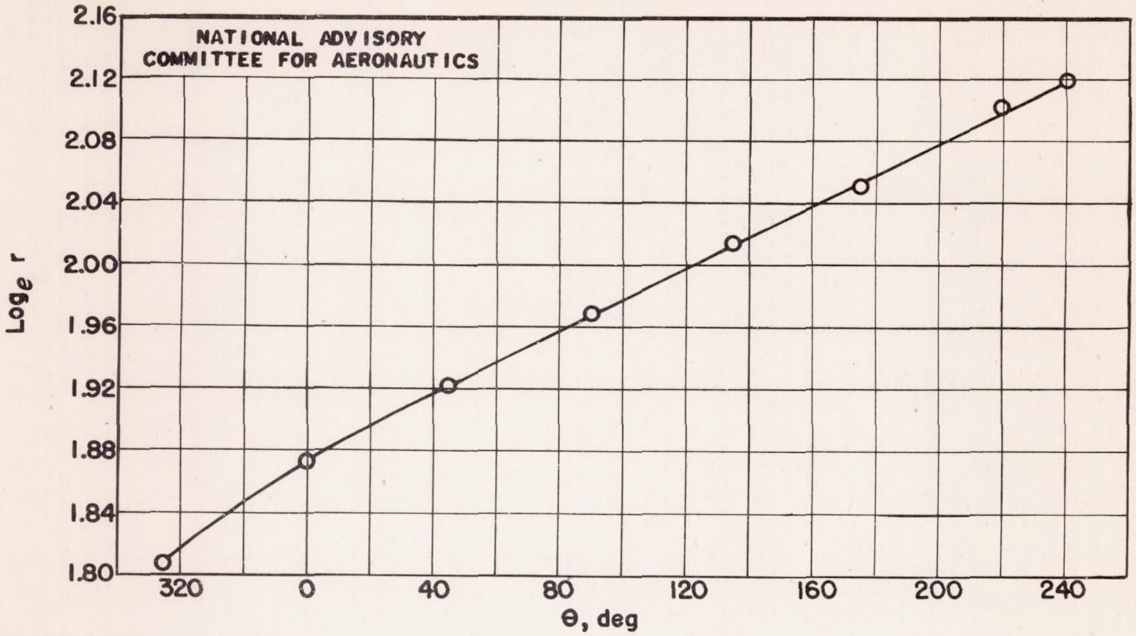

Figure 15.— Logarithm of radius of outermost point in scroll passage as function of angle θ.

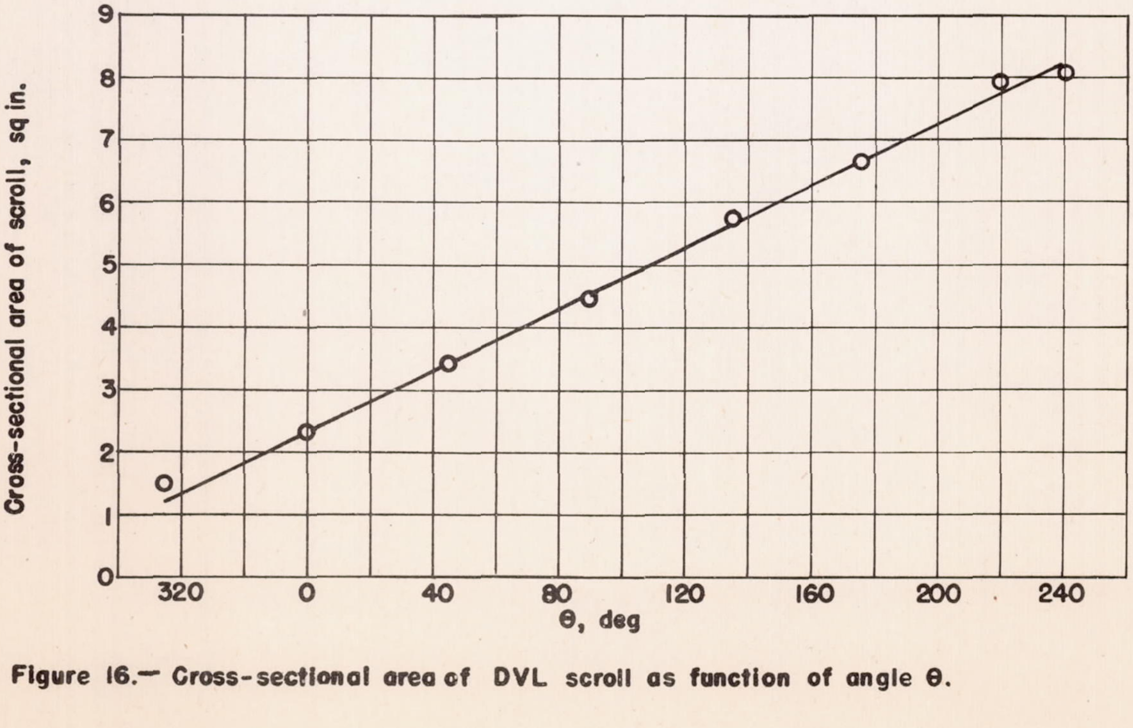

Figure 16.— Cross-sectional area of DVL scroll as function of angle θ.

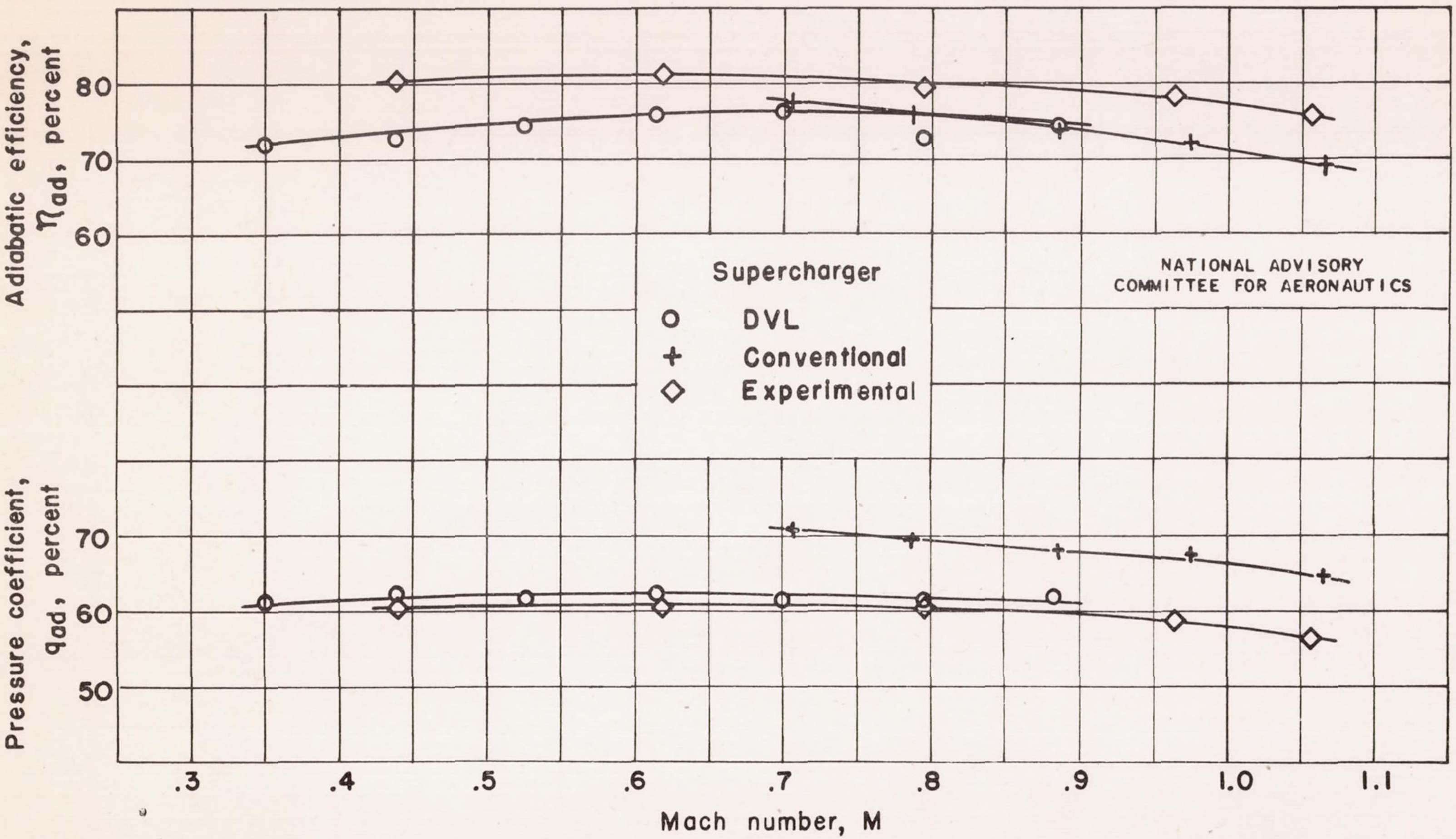

Figure 17.— Peak-performance characteristics of supercharger from Junkers Jumo 211 F engine and American conventional and experimental superchargers.