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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 954

LIMITS OF SINGLE-STAGE COMPRESSION IN CENTRIFUGAL SUPERCHARGERS FOR AIRCRAFT

By K. Kollmann

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LIMITS OF SINGLE-STAGE COMPRESSION IN CENTRIFUGAL SUPERCHARGERS FOR AIRCRAFT*

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SUMMARY

The limits of the single-stage compression in superchargers at the present state of development are determined by five factors:

1) By the rotor material, whose elasticity limit is usually so high that even the highest circumferential speeds used at present have failed to disclose any permanent form changes;

2) By the formation of the flow, which through structural measures (double shrouded rotor, rotating entry vanes, guide vanes) is to be with a minimum loss. Here it is found that the best adiabatic efficiencies are always obtained at well-defined circumferential speeds of around 200 to 260 m/s. Although efficiencies of the order of 80 percent or more are possible at these speeds, experience in the practical operating range, i.e., at circumferential speeds of from 350 to 400 m/s has shown that efficiencies of 70 to 75 percent can scarcely be attained. In consequence, the rated horsepower ceiling obtainable with single-stage compression and admissible air temperatures of around 80° at engine intake is limited to about 6 to 7 km flying height.

3) By the manufacture - the manufacture of double shrouded rotors which produce an especially beneficial supercharger efficiency entails an almost intolerable increase in weight and manufacturing difficulties.

*"Grenzen zur einstufigen Verdichtung in Schleuderladern für Flugmotoren." Luftwissen, vol. 7, no. 3, March 1940, pp. 54-61.

4) By the bearing problem - as the supercharger speed increases the bearing difficulties with plain or roller bearings increase enormously. According to practical experiences, the speed even with roller bearings should be kept below 27,000 to 30,000 revolutions per minute.

5) By the drive method - the rise in revolutions per minute and pressure ratio was accompanied by the development of gear drives with one or more speed changes with their inevitable difficulties, although speed control is absolutely necessary for high take-off power. An infinitely variable speed drive is the ideal solution.

INTRODUCTION

Today's flight range includes any altitude as high as the stratosphere. This calls for highly developed superchargers in order to attain high powers at these heights. The necessary single or multiple stage superchargers thus become structural parts of the engine which have a profound effect on its over-all design.

In a number of engine types the supercharger is mounted behind the engine, the supercharger shaft being a direct extension to the crankshaft or parallel to it. This is of great advantage for the gear drive, insofar as simple spur gears can be used, but this gain is offset by the right angle bends of the air both on the suction and the exhaust side. The Rolls Royce Merlin (fig. 3), for instance, has 2 × 2 right angle bends up to the rotor inlet and two more in the pressure line. Such bends are, naturally, sources of loss which should be absolutely avoided. On the liquid-cooled, in-line Junkers Jumo 211 (fig. 1) and on the Mercedes-Benz DB 600 (fig. 2), the supercharger shaft is perpendicular to the longitudinal axis of the engine and the supercharger is mounted on the side, thus necessitating only one right-angle bend for inducting the air axially into the supercharger rotor.

If, in addition, provisions are made for undisturbed air scoop flow, the total flight dynamic pressure can be utilized for supercharging, which becomes evident in a rise of the rated horsepower ceiling. The amount of this rise by fully utilized flight dynamic pressure is illustrated in figure 4. At a speed of 600 km/h, for instance, it amounts to about 1400 meters.

To keep the losses in the induction lines at a minimum great speed changes should be avoided. The air inducted at around flying speed should reach the supercharger without speed change. The inlet section into the supercharger rotor is thus determined. The developments of the past years, which from the airplane point of view have raised the flying speed enormously, have therefore also exercised a direct effect on the supercharger dimensions. They made smaller inlet openings possible and so improved the supercharger efficiency. The use of a diameter ratio (of the supercharger rotor) Di/Da = 0.5 to 0.6 has hereby proved especially suitable.

The choice of outside rotor diameter (Da) is determined mainly from the pressure head required. The connection of the various quantities : rated horsepower ceiling, boost pressure, tip speed, outside diameter, and rotor revolutions per minute, for different supercharger efficiencies - is seen from figure 5. For equal efficiency (75 percent) and equal speed (25,000 rpm) of the supercharger, a rise from 6 to 10 km in rated horsepower ceiling (boost pressure, 1.3 atm) requires an increase in tip speed from 340 m/s to 420 m/s and of the rotor diameter from 260 mm to 320 mm. The induction temperature itself rises from 110° to 168°. For 60 percent efficiency instead of 75 percent, the values would be as follows:

TABLE I

Efficiency	75 percent		60 percent	
Rated altitude horsepower, km	6	10	6	10
Outlet pressure, atm	1.3	1.3	1.3	1.3
Induction pressure, atm	0.483	0.483	0.483	0.483
Induction temperature, °C	-23	-50	-23	-50
Supercharger, rpm	25,000	25,000	25,000	25,000
Outside diameter of rotor, mm	260	320	290	350
Tip speed, m/s	340	420	380	460
Temperature rise, °C	110	168	136	210
Outlet temperature, °C	87	118	113	160
Adiabatic pressure head, mgs	8,470	12,950	8,470	12,950
Pressure ratio	2.7	4.85	2.7	4.85

While at low rated horsepower altitude the induction temperature, which is usually below 100° C, plays a subordinate part, it becomes important at high rated horsepower altitude and then everything must be done to assure the best supercharger efficiency for the entire operating range of the engine, or else air coolers must be resorted to. Incidentally, the highest antiknock fuels tend toward detonation as the induction temperatures rise. Proceeding from a practical induction temperature of 80° C while disregarding the possible cooling effect of the inlet air before the inlet values as a result of fuel vaporization, the required supercharger efficiency for certain rated horsepower ceiling and boost pressures can be computed. With a 1.3 atm boost pressure and a 6 km rated horsepower ceiling a 78 percent efficiency is still sufficient, but this must be raised to about 98 percent in order to reach a rated horsepower ceiling of 10 km (fig. 6). At the present state of development of centrifugal superchargers, it may be conceded that a 78 percent efficiency can be reached at least within a certain power range of the engine. It is not likely that a 98 percent efficiency will ever be realizable even in the future. In view of the heat stresses of the engines and the knock characteristics of fuels limiting induction temperatures of about 80° C will be necessary. This means that for rated horsepower ceilings above 6 km, the boost air must be cooled, and this fact explains why the 6 km ceiling is at present the usual limit. For exceptional reasons, such as altitude records, the use of air cooling is resorted to, as for instance, is furnished by the Bristol company in the design of a special airplane mounted with a Bristol Pegasus engine. It reached the record height of 16,470 meters (fig. 7), where the atmospheric pressure dropped to 77.8 mm Hg at -49.8° C air temperature. The engine was fitted with a gear-driven supercharger for a rated horsepower ceiling of about 4500 meters, supplemented by a two-stage booster (fig. 8). This booster charger was also engine driven across an extension shaft fitted with control clutches operated by compressed air servomotor. Between the two stages of the additional supercharger the air is cooled in special coolers. Bristol also has another patented intercooler between the separate cylinders.

Whereas, on the one hand, a limitation of air temperature is necessary for reasons of heat stresses, any pressure ratio can be achieved by successive supercharger stages, one behind the other, so as to maintain a certain induction pressure at high altitude.

The installation on the engine and drive of superchargers with several pressure stages will probably always remain a difficult problem, whence single-stage compression to maximum supercharged height will always be attempted.

In the following, the limitations of single-stage centrifugal superchargers is discussed in the light of present-day development.

1. Material of Rotor

According to figure 1, a rise from 6 to 10 km rated horsepower ceiling by equal efficiency requires a 24 percent increase in rotor tip speed. Since the centrifugal forces increase as the square of the tip speed, an increase of about 50 percent in tensile stress in the radial blades of the rotors is involved.

Considerations of weight generally rule out steel as material for rotors. With high-grade light alloys of from 35 to 40 kg/mm^2 (49,700 to 56,800 lb/in^2) yield point and of from 48 to 55 kg/mm^2 (68,300 to 78,200 lb/in^2) tensile strength, it is possible to control the centrifugal forces at high tip speeds. In theory, any material can be utilized which has a ratio yield point to specific weight of the same order as high-duty steel. This value is about 80/7.5 = 10.7 (11,400/7.5 = 15,200) for high-duty steel VCMo 140, while for duralumin DM31 it is as high as 38/2.8 = 13.6. With elektron of about 1.8 g/cm specific weight a strength factor of only 19 to 20 kg/mm^2 (27,000 lb/in.^{2} to 28,400 lb/in.^{2}) is required to equal the safety factor of the best steel. From the point of view of fatigue, however, light alloy is definitely inferior to steel. This difficulty can, however, be overcome by proper design.

The Mercedes-Benz duralumin rotor (fig. 10) weighs only 880 g (1.94 lb), but has given no evidence of permanent form changes at tip speeds up to 450 m/s. Designed in elektron, this weight could be lowered to 668 g (1.47 lb) for practically the same factor of safety. A comparison of the rotor weight of different engines (table II) proves what can be accomplished by proper design.

TABLE II

Engine	Dural (kg)	Elektron (kg)
Mercedes-Benz DB 600	0.880	0.668
Rolls-Royce Merlin	3.0	--
Rolls-Royce Bussard	2.36	--

Unfortunately, there is no method of predicting the stesses in a supercharger rotor. These are largely determined by the centrifugal forces which increase with the square of the tip speed. But the stresses ensuing from the torque transfer to the air are superimposed as bending stresses. And these are supplemented by rhythmically alternating forces, especially in spiral casings, by which as the individual blades of the rotor rush past, force impulses on the tongue of the pressure spiral protruding into the pressure chamber are released on the blades. Suitability or correctness of a design will have to be decided by practical experiments. So far as can be judged, it may be stated that at the moment no limitations of tip speeds exist if the characteristics of the material are properly taken into account in the design. Of course, the many different rotor shapes permit of no generally valid empirical data. Rotor designs as employed on the Jumo 210 211 (fig. 11) must naturally be assessed differently than the conventional rotors (fig. 10). It may be assumed that the Junkers type rotors (fig. 11) are substantially more susceptible to overspeeding, since the self-contained, closed blade channels produce more complicated material stresses.

Even so, it is maintained that the material for rotors available at the present time does not restrict the development of superchargers with highest possible compression, since it is possible with light alloy rotors to reach tip speeds of more than 450 meters per second.

1470 ft/sec.

2. Aerodynamic Points of View

Attainment of the velocity of sound presents, as far as can be judged at present, no definite limitation. In practice, however, the possibilities of one-stage compressions are to a certain extent narrowed down by the aerodynamic effects. In figure 12, the characteristic field of the experimental supercharger developed by the DVL is illustrated. This supercharger was systematically developed to a maximum efficiency by optimum design of every single part. The double shrouded rotor was, to improve the inflow conditions, fitted with special rotating entry vanes, whose entering edges were designed for shock-free air entry. The discharge blades and the adjoining pressure spiral themselves were, after a number of tests, of the most beneficial shape. On studying the characteristic field of this supercharger it will be noted that the maximum efficiency, amounting to about 83 percent, is located at around 200 to 220 m/s. As the revolutions per minute increase the efficiency drops rapidly, so that for air volumes of around 1.4 to 1.5 m^3/s and around 27,000 rpm as encountered in practice, efficiencies of from 68 to 70 percent can be counted on.

On comparison of this characteristic field with that of other centrifugal superchargers, it is found that - independent of the supercharger design - the best efficiencies always range between about 200 to 260 m/s. Remodeling the supercharger alters the absolute value of the best efficiency but not its position in the characteristic field.

This characteristic phenomenon is also evident on the Mercedes-Benz DB 600 supercharger with a maximum efficiency of 68.5 percent at 245 m/s rotor tip speed (fig. 13).

Another fact, when comparing characteristic fields of different superchargers is that, while the best efficiency in the 220 m/s tip speed range with optimum design of all parts affecting the supercharger efficiency can be raised to about 80 percent, the attainable improvements in the practical range of from 350 to 400 m/s are quite small. For the DVL supercharger (fig. 12) the best compression efficiency was around 83 percent, or a gain of 15 percent over the DB 600 supercharger. At tip speeds of the order of 380 m/s, however, the best efficiency in both cases drops to 68 percent. This action of the superchargers is naturally dependent upon the phenomena of flow. Unfortunately, the individual factors, such as number of blades, shape of impeller, friction losses, gap losses, etc., are not amenable to definite mathematical treatment; hence the efficiency curve cannot be plotted beforehand.

So, at the present state of supercharger development, the best possible efficiency ranges between 70 and 75 percent, referred to the practical operating range. For a limiting induction temperature of 80° C this means that single-stage compression will give compensation up to a maximum altitude of 6 to 7 km.

Not until the maximum efficiencies of as high as 80 to 83 percent are realizable at high tip speeds will it ever be possible to raise the present limit of rated horsepower altitude.

3. Manufacture

The best efficiencies of from 80 to 85 percent of the DVL experimental supercharger (fig. 14) were achieved with a rotor whose blade passages were shrouded on both sides. But manufacturing difficulties and considerations of weight make it questionable whether or not this is justified in comparison to the single shrouded impeller without entry vanes and which presents no manufacturing difficulties. The possible gain in compression efficiency of such designs is limited in any case to relatively low tip speeds which are of no great practical interest.

Moreover, the weight of the double shrouded type will always be from 50 to 100 percent heavier than for the single shrouded type.

4. Bearings

To insure small supercharger dimensions and low structural weight, the speed of the supercharger shaft will always be the maximum consistent with the shaft bearings. An empirical rule for roller bearings is given by the product of shaft diameter in mm with rpm. This product should not exceed 500,000 to 600,000, i.e., a 25 mm shaft mounted on roller bearings will run satisfactorily at 20,000 to 24,000 rpm. Speeds in excess of this are possible, but require extreme care in the fitting of the bearing and its lubrication. The practical limit of operation seems to be of the order of 30,000 rpm (reference 1). (See also NACA T.M. No. 945.)

Plain bearings with special bronzes, partly with floating bushings are also used. However, for taking up axial thrust the use of roller bearings should, in general, be simpler. Sealing the shaft against oil should also be possible by simpler means (labyrinths, piston rings, etc.) with roller bearings which generally use much less oil than plain bearings.

Unfortunately, the bearing stresses (longitudinal and transverse) induced by the rotor cannot be estimated, so that bearing ventilation and break-down must be established for every case by special tests. But even for plain bearings no generally applicable data can be given regarding clearance and choice of material. It is certain, however, that on the basis of past experimental work and experience the requirements can be met with sufficient operating safety. But even then it requires further study and research to raise the present limit of 27,000 to 30,000 rpm to still higher rpm.

5. Supercharger Drive (Gears and Clutches)

The rise in pressure ratio obtainable in a single supercharger stage entails a substantial increase in the supercharger power which the engine must transmit by mechanical drives and clutches to the supercharger. With a compression efficiency of 70 percent, for instance, the provision of 1.3 atmosphere absolute at 6 km absorbs about 12 to 13 percent of the engine power. The power loss near the ground is thus very considerable unless a variable-speed drive is provided. The clutches are generally of the multiple-disk type operated by oil-controlled pistons or centrifugal force. The shift from low to high gear is usually effected by hand. Some airplane engines are already fitted with such multiple-speed gears for the supercharger drive (reference 2).

Although automatic control has not been attempted so far, future developments will undoubtedly lead to it. Beyond that, attempts will be made to replace multiple-speed drives by infinitely variable speed drives. And a number of contributions to this end have already been made. They are partly based on friction gears, partly on hydraulic equipment. Thus, the Junkers had fitted the Gt4 engine with an infinitely variable speed drive which, however, proved unsuccessful (reference 3). Even the number of foreign patents are evidence of the interest displayed on this subject. A solution of this problem would at the same time remove the competition between suction-side and pressure-side control (reference 1, p. 285).

The advantage of pressure-side control is above all based on structural reasons. The dimensions of the throttle become smaller, which is important for its operation by the boost-pressure regulator. Since the low pressures on the suction side of the supercharger merely correspond to the velocity head of the air in the inlet section - it may even become high pressure by dynamic pressure utilization - the oil-sealing difficulties of the supercharger shaft drop into the background. Then the simplest type of seal, the labyrinth, can be successfully employed even for high pressure heads.

With correct supercharger design and correspondingly favorable characteristic field (flat curve for rpm, wide efficiency maximum) untoward effects can also be avoided in operation. For instance, for the characteristic curves plotted in figure 14, the points for supercharger operation at rated horsepower height (N) and at sea level by suction side (B_S) and pressure side (B_D) boost-pressure control are those shown in the plat (reference 1, fig. 11).

The operating point is purposely placed at sea level by suction-side control in the region of maximum supercharger efficiency and maximum adiabatic pressure head, which brings out the conditions for suction-side control in an especially favorable light. The rated horsepower height itself was assumed at 4 km. This is equivalent, according to practical flight tests to a difference of about 10 percent in supercharger (weight), so that in operating point N the volume of air inducted amounts to about 1.48 kg/s, at point B_S and B_D to about 1.35 kg/s each. At different adiabatic efficiencies the supercharger output per kg/s of inducted air is for B_D as shown in table III.

TABLE III

	B_S	B_D		
		60 percent	65 percent	68 percent
N . . . . hp/kg	150	172	159	150
ΔN. . . . . hp/kg	-	22	9	0
Δt. . . . . °C	95	110	100	96

With 68 percent adiabatic efficiency, the conditions in point B_D are already the same for supercharger power input and temperature rise of charging air by suction- and pressure-side control.

It is not right to start a comparison of pressure- and suction-side control from the sea-level point for suction-side control and to assume it also as the sea-level point for pressure-side control. Such a supercharger is absolutely of the wrong dimensions for an engine whose air required is so large that the sea-level point of pressure-side control coincides with the sea-level point of suction-side control. On the contrary, it is necessary to proceed - for a given engine and supercharger design - from the operating point at rated horsepower height. Without accurate knowledge of its characteristic curves it is impossible to judge what type of supercharger control is more economical. As the example indicates, if the supercharger is correctly designed, it is possible to achieve, even with pressure-side control, a condition of no power loss at sea level. On superchargers with multispeed drives the sea-level operating point in the low speed can be placed, even with pressure-side control, in the range of maximum supercharger efficiency, so that usually some advantage over the suction-side control can be gained.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

REFERENCES

1. von der Null, Werner: Ladeeinrichtungen für Hochleistungs-Brennkraftmaschinen, insbesondere Flugmotoren. ATZ, 1938, p. 286, fig. 12.

2. Luftwissen Jahrg. 1938, vol. 5, no. 1, p. 22, fig. 4.

3. Die Luftwacht, May 1935, no. 5, pp. 169-71.

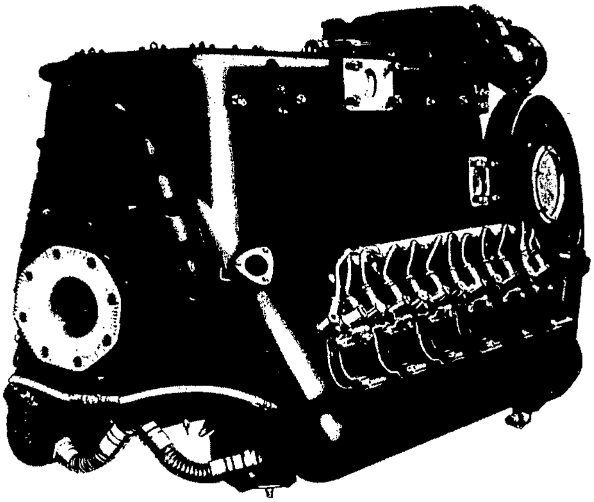


Figure 2.- Mercedes-Benz DB600 airplane engine.

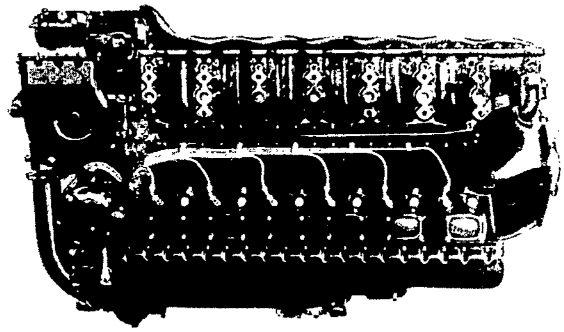


Figure 1.- Junkers-Jumo 211 airplane engine.

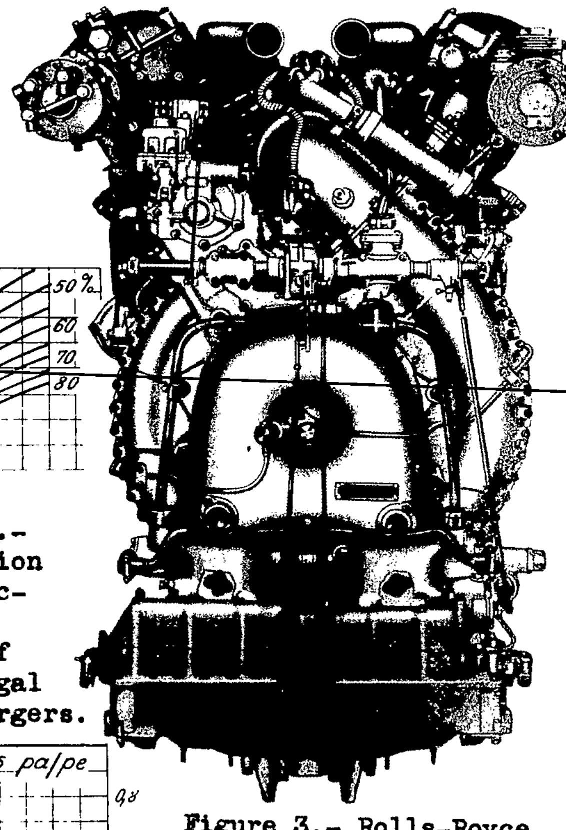


Figure 3.- Rolls-Royce Merlin engine-supercharger side.

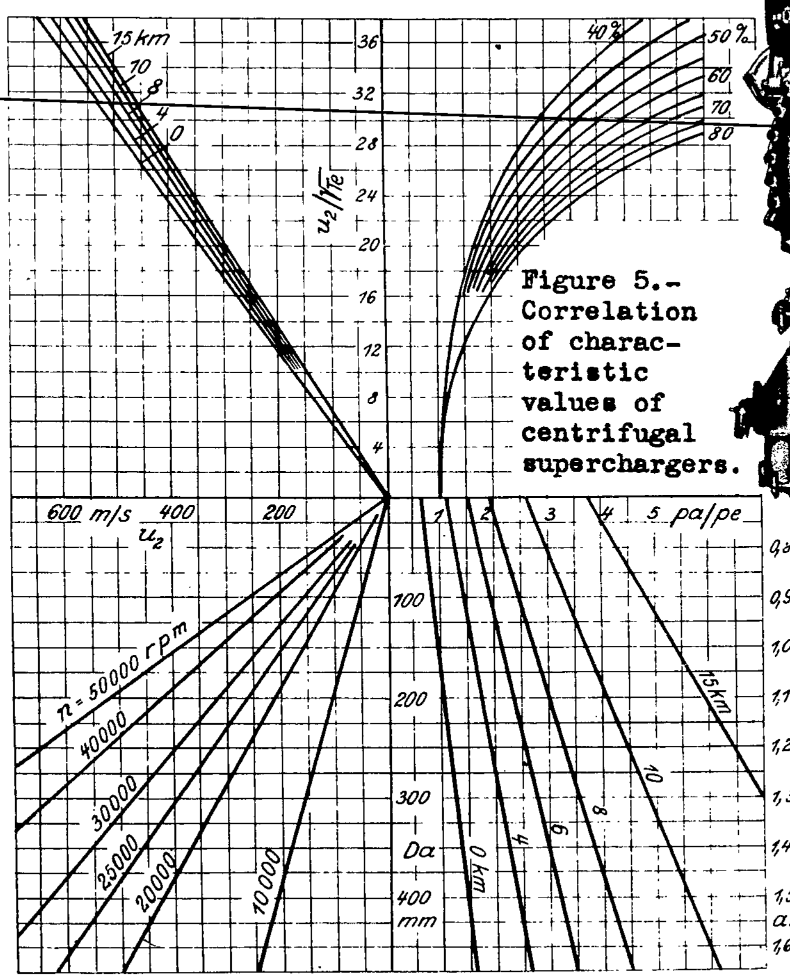


Figure 5.- Correlation of characteristic values of centrifugal superchargers.

$$\eta_{ad} = \frac{H_{ad}}{u_2^2/g}$$

$$u_2 = \sqrt{\frac{g}{\eta_{ad}} \cdot R \cdot T_e \cdot \frac{K}{K-1}\left[\left(\frac{pa}{pe}\right)^{\frac{K-1}{K}} - 1\right]}$$

$$\frac{pa}{pe} = \left[\frac{\eta_{ad} \cdot \frac{u_2^2}{g}}{R.T_e \cdot \frac{K}{K-1}} + 1\right]^{\frac{K}{K-1}}$$

$$u_2 = \frac{D_2 \pi . n}{60}$$

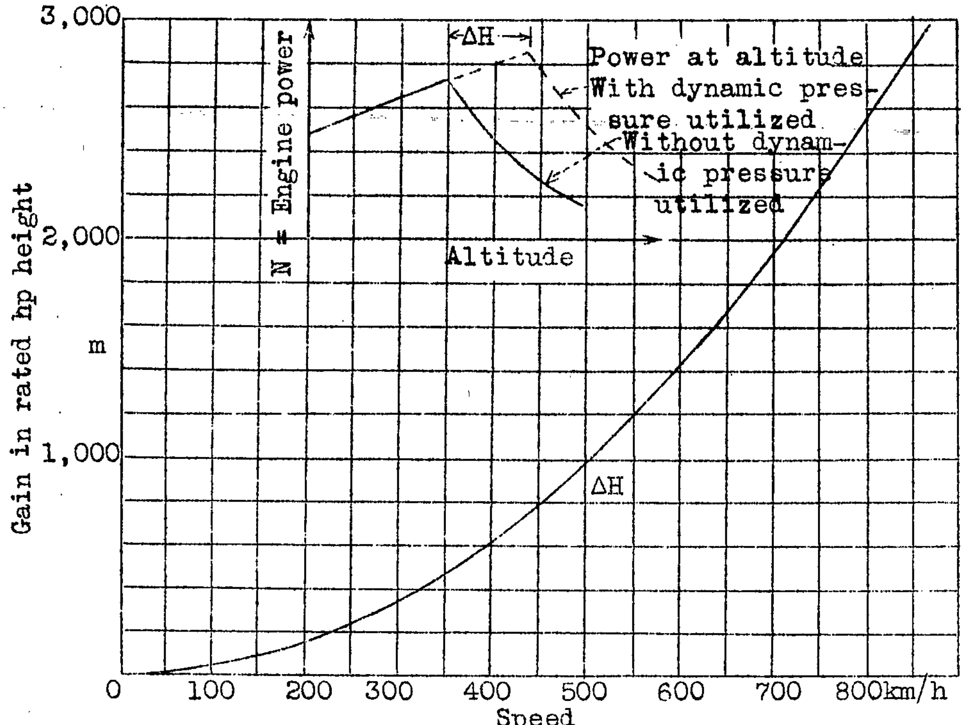
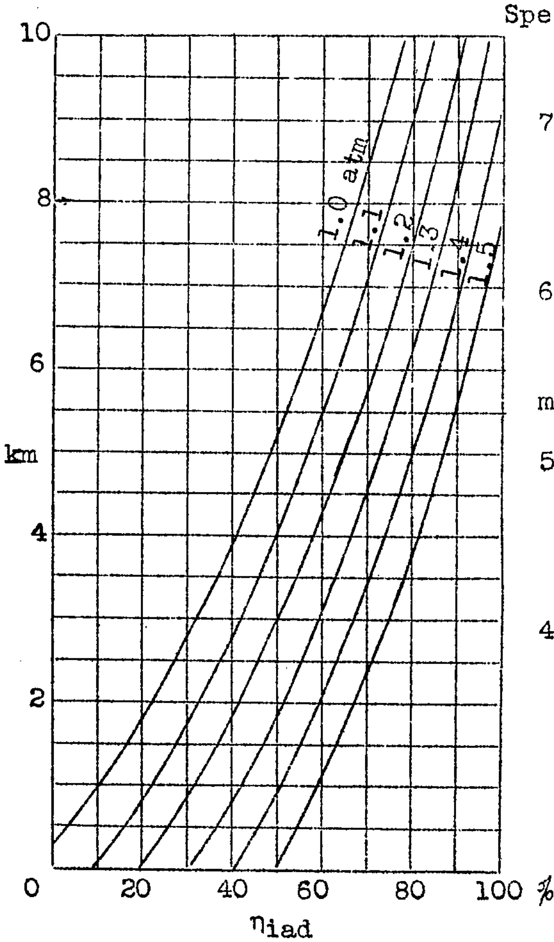


Figure 4.- Height gain at different flying speeds



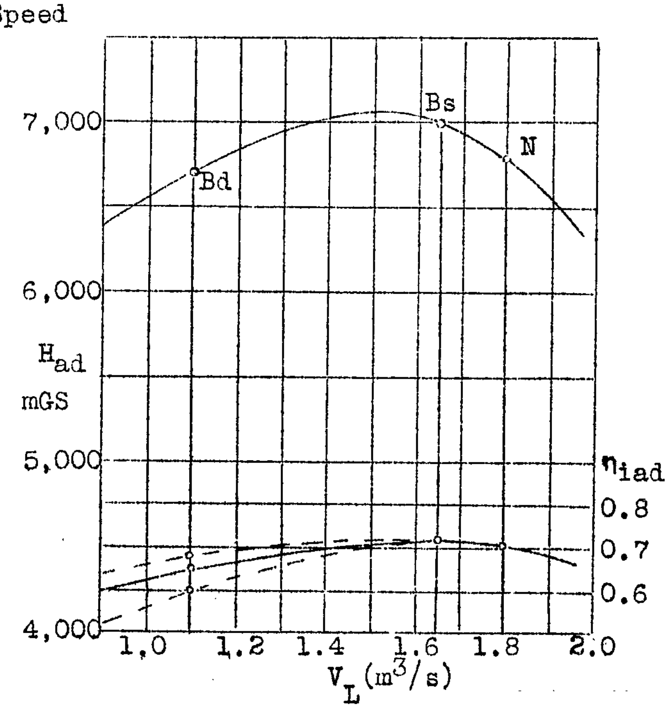


Figure 14.- Characteristic curves of a centrifugal supercharger.

Figure 6.- Attainable rated hp height against supercharger end pressure (for 80°C induction pressure).

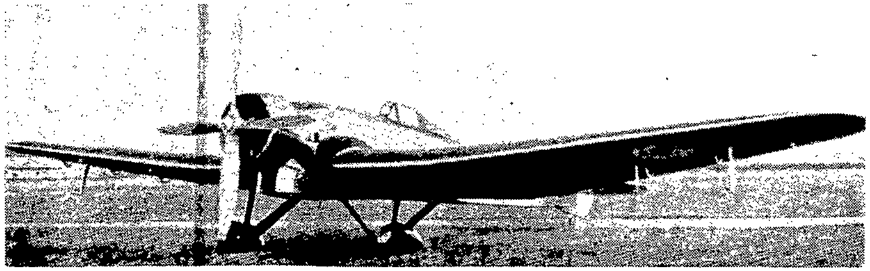


Figure 7.- Bristol altitude record plane with Pegasus XVIII.

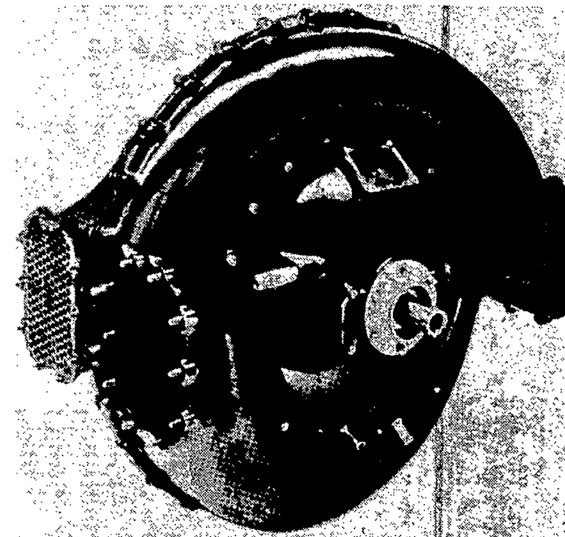
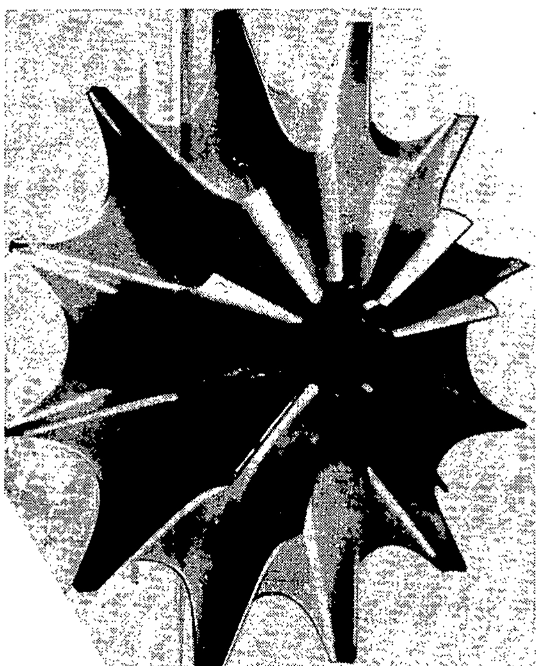


Figure 8.- Booster for Bristol Pegasus XVIII.

Figure 10.- Rotor of DB600-880g



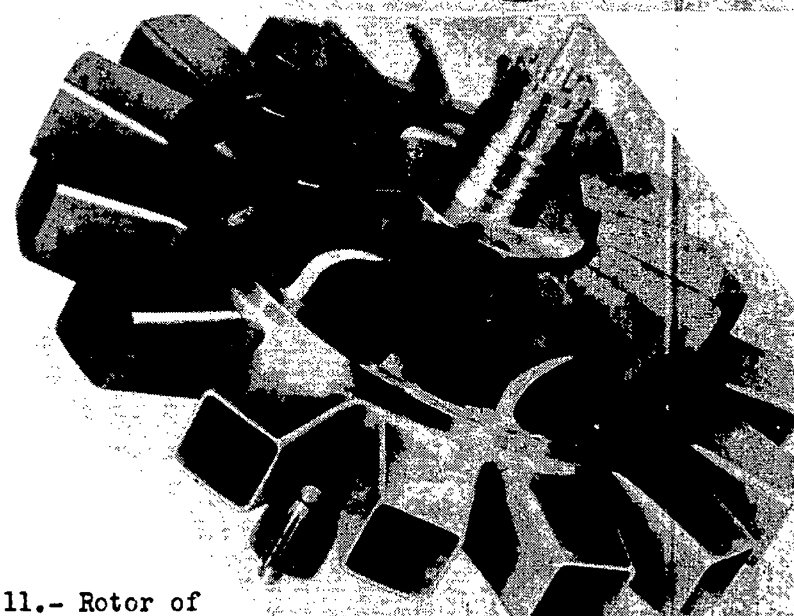


Figure 11.- Rotor of Jumo 210.

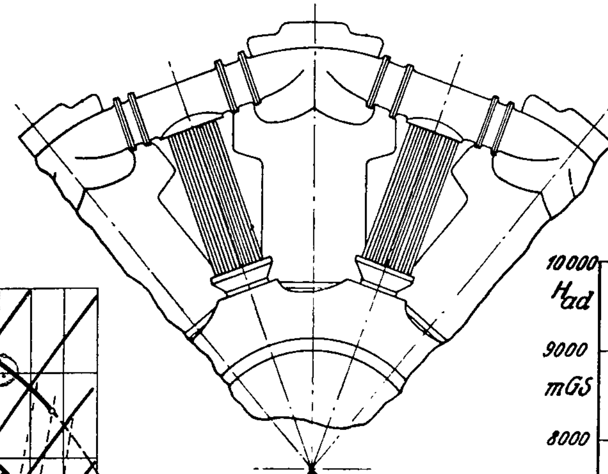


Figure 9.- Intercooler, Bristol patent.

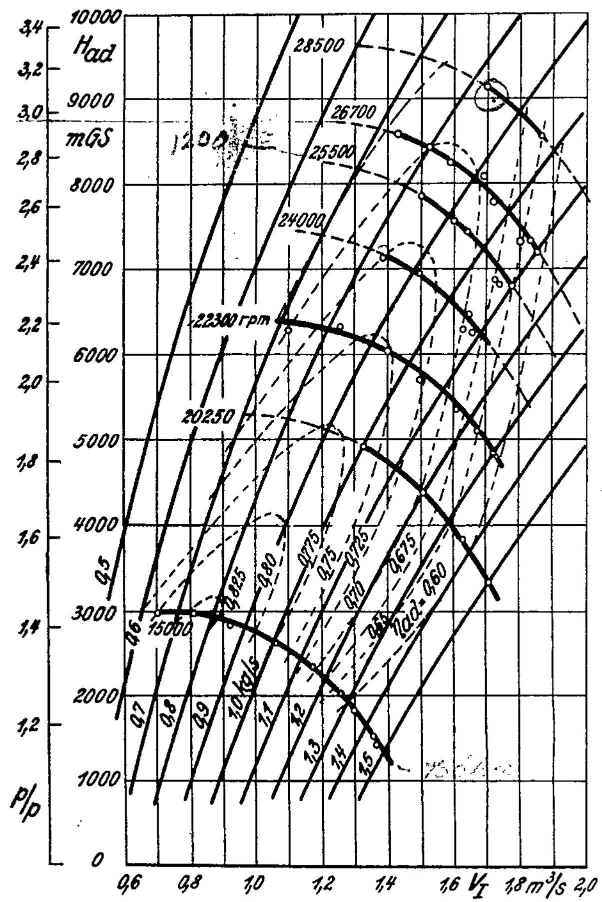


Figure 12.- Characteristic curves of DVL experimental supercharger.

Same as Fig 17; T.M. 839

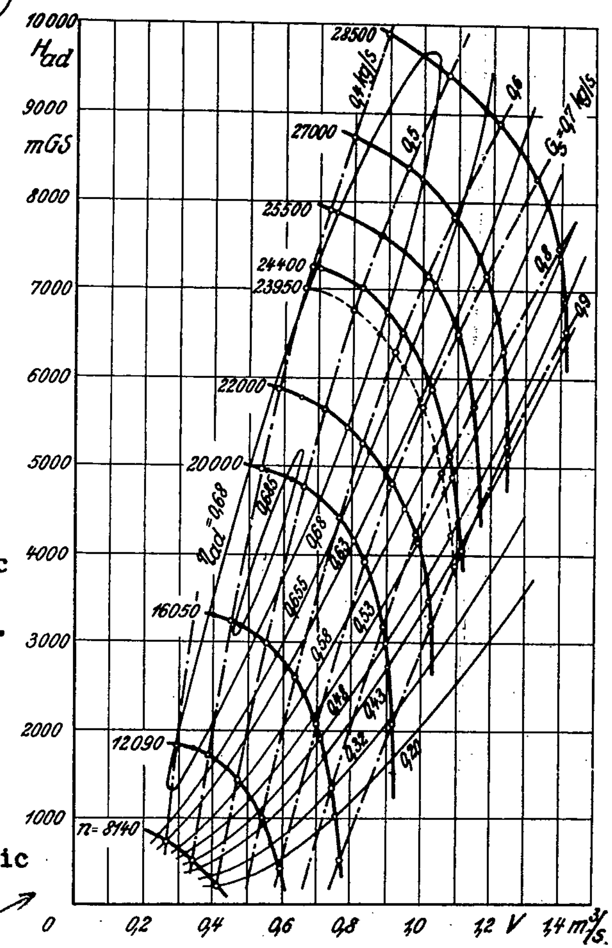


Figure 13.- Characteristic curves for DB600 aircraft engine.