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AIRPLANE SUPERCHARGERS.

By

W. G. Noack.

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A I R P L A N E S U P E R C H A R G E R S.*

By

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The ever-increasing demands on the airplane during the war, with regard to climbing speed and ceiling, necessitated the installation of engines of constantly increased power, while the carrying capacity and speed at a serviceable altitude did not proportionately increase. The reason for this is to be found in the fact that the engine power output decreases with the increase of flying altitude. If, for instance, an airplane is still to be able to fly at an altitude of 5 or 6 km., then the engine must be of about twice the power at sea level that would have been sufficient to keep the airplane in flight in the vicinity of the ground.

The principal reason for the falling off of the engine power is the decrease in the density of the air as the airplane rises. The manner in which this occurs may be seen in Table I,** which gives the average barometer pressures and temperatures during the year, and also the relative pressures. Generally speaking, if y stands for the density of the air, (when leaving out moisture as for every gas), and b signifies the pressure and t the temperature:

$$y = y_o \frac{b}{760} \quad \frac{273}{273 + t} ;$$

in which $y_o = 1.293$ kg/cu.m., the density of the air at $b = 760$ mm. mercury column and $t = 0^oC$.

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* Sonderabdruck aus der Zeitschrift des Vereines deutscher Ingenieure, Jahrgang 1919, Seite 995.

**Also see A. Wagner, "Contributions relating to the Composition of the Atmosphere," III 1919.

TABLE I.

Decrease of the Air Pressure with the Increase in Altitude.

Altitude above Sea level m.	Average air pressure, b mm. mercury.	Average yearly temperature, t_m °C	Relative air pressure $\frac{b}{b_o}$	Average density of the air, y kg/cu.m.	Relative density of the air $\frac{y}{y_o}$
0	762	+8.7	1	1.258	1
1000	674.5	+3.9	0.885	1.130	0.900
2000	596	-1	0.782	1.020	0.810
3000	525.5	-5.9	0.689	0.914	0.727
4000	461.5	-11.6	0.605	0.820	0.653
5000	405	-16.9	0.531	0.735	0.584
6000	354.5	-23.7	0.465	0.660	0.524
7000	309.5	-31	0.400	0.595	0.473
8000	269.5	-37	0.357	0.532	0.423
9000	240	-45	0.315	0.489	0.388

If the falling off of the engine power were dependent upon the density of the air alone, then the same relation would hold good for both. This is however not generally the case. As has been shown at the altitude experimental stations, the efficiency of the usual airplane engines falls off considerably faster. The reason for this is to be found first of all in the action of the carburetor. The fuel supply in the carburetor does not decrease in the same degree as the weight of the air inducted at each piston stroke, the fuel mixture becomes too rich and the thermal efficiency is also decreased, because, with the number of revolutions remaining the same, the no-load work of the engine, which is affected by the diminished working pressure but little, remains almost the same; its ratio to the power output however, increases with increased altitude. With the very low temperature prevailing at high altitudes, the inducted air may affect the formation of the mixture unfavorably when not sufficiently heated. For a confirmation of the above we refer to the performance of one of the best of the older German airplane motors* as shown in the curves given in Figs. 1 and 2, in which the power for various inductional temperatures is plotted in relation to the density of the air. If the power of the motor were proportional solely to the density, that is, the pressure and the temperature of the outer air, then all the measured qualities plotted against the density of the air would result in

*"Technische Berichte der Flugzeugmeisterei," Vol.III, 1918.

horizontal lines, for instance, converted from $b = 760$ mm. barometer reading, and $t = 15^{\circ}$ to

$$N_r = N \frac{760}{b} \frac{273 + t}{273}$$

Actually, however, they are curves with a marked downward course. Their deviation from the horizontal thus represents a means of measuring the altitude properties of the engine.

These disadvantages of the airplane engine were of course soon recognized; the remedy was however not introduced until a comparatively late date. Our adversaries were also strenuously engaged with this question.* By improving the carburetors, especially the so-called altitude carburetors, the decrease of the power was made to substantially keep pace with the decrease of the density of the air. By raising the ratio of compression of the engine from between 4.6 and 4.9 to 6.6, and by the improvement of the thermal efficiency which was thereby brought about, an improved adaptation of the airplane engine to the altitude conditions was secured. In the vicinity of the ground the intake of the engine must be throttled in order to avoid self ignition and excessive stress. As the airplane reaches higher altitudes the throttling is gradually decreased, and at heights of from 2 to 3 km. it finally ceases entirely. Up to this point the engine power remains almost the same. Another step in advance is made with engines of extra size, in which the displacement of the piston is increased in comparison with ordinary engines and in relation to the dimensions of the parts of the driving gear. These engines must also be throttled when near the ground in order to keep the average piston pressure so low that the power output does not exceed the nominal power. The supercompression can also be combined with super-dimension. In this way it is possible to maintain the engines at a uniform power up to an altitude of almost 4 km. Beyond this point a falling off of the power is avoided by the use of compressors of superchargers, which will be treated in detail later.

The purpose of the compressor is to furnish the engine with air of sea level density, no matter what the surrounding atmosphere may be. Up to a certain prescribed altitude there is then the same pressure in front of the carburetor as that prevailing at sea level, and for which the engine has been built.

Three general types of compressors - reciprocal, rotary, and centrifugal, may be considered for this purpose. Reciprocating compressors, as far as is known, have never been tried as they are too heavy and the valves are too complicated.

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* Compare "Zeitschrift 1918" p.61, 816; Engineering, June 28 and July 5, 1918.

Of the rotary compressors, those of the Wittig* and Roots types as well as compressors with revolving vanes were tried, but nothing is known as yet regarding the results. The centrifugal compressor has proved the most suitable up to the present; its construction was taken up by several factories during the last two years of the war and brought to a high state of perfection.

The compressors are, as a rule, driven direct by the engine, mostly at the end opposite the airscrew. It is true that this drive was objected to at first as it was feared that the crankshaft would be endangered by torsion vibrations. However, these fears have so far proved unfounded. In the case of airplanes with several engines, giant airplanes especially, the compressor or supercharger is driven by a special engine and in that case furnishes the air for all the engines. For the airplanes with several engines in a central plant there is also a good solution of the problem. In the latter case the common supercharger can be connected directly with the central plant. As to whether individual superchargers or one common supercharger is better, also whether the drive from the central power plant or from a special motor is to be preferred, has not yet been decided. Each arrangement has its advantages and disadvantages. With single engine airplanes there can of course be only the direct drive from the engine. With giant airplanes carrying a large service crew, the drive from a special engine is better adapted to the air requirements at the various altitudes as it is then always possible to give the compressor engine the number of revolutions corresponding to the air requirements at any given time. The compressor that is coupled with the main engine or with the central plant has, on the contrary, always the same multiple of the number of revolutions of the main engine; it therefore generates pressures which are too high for the lower altitudes and the discharge must be throttled. Thus the amount of energy required for the compressor and the temperature of the compressed air attain their maximum near ground level, and as it is in the lower air strata that the highest natural temperatures predominate, the compressed air reaches the carburetors in a very heated condition at the lower altitudes. Although experiments have shown that most airplane engines can stand temperatures even above 100°C. in front of the carburetor perfectly well, at least for short periods, nevertheless this heating of the fresh air results in a considerable drop in power output. In order to compensate for the latter and in order to generate the driving power for the compressor, it is necessary to furnish the engine with air at greater pressure than sea-level. This causes an overload which is, however, unimportant for the short time necessary for the take-off and for climbing the first few thousand meters.

* Compare "Zeitschrift 1918," p.61, 816; Engineering, June 28 and July 5, 1918.

Figure 3 shows how the engine may be overloaded by the supply of fresh air under high pressure. In these experiments the charging pressures immediately in front of the carburetor amounted to 830, 760 and 720 mm. Hg. (curves 1, 2 and 3), the temperatures of the fresh air, also directly in front of the carburetor, were 40°, 30°, and 8°, the exhaust pressure was unaltered, 736 mm. It is evident that slight pre-compressions are sufficient to secure remarkable power increases and to provide the extra energy for the driving of the supercharger connected with the engine.

The mistaken conception, entertained not only by aviators but also by the engine manufacturers, that the engines are permanently overloaded by the superchargers because of the considerable gain of the airplanes in climbing rate and ceiling, must be contradicted here. As long as the pressure in front of the carburetor is not increased above the pressure at ground level, the engine works mechanically and thermodynamically under the same conditions as on the test stand or in the airplane near ground level. If, however, the altitude up to which the compressor furnishes the full pressure is exceeded, the power of the engine falls off in the same way as occurs with the ordinary engine at its start from the ground. The purpose of the compressor is to raise the flying altitude of the airplane. When the flying is done at these altitudes, the loading of the engine in the vicinity of the altitude limit is exactly as high as with the motor without compressor, only with the difference that the airplane is now at a considerably higher altitude.

The power of an engine with compressor is also somewhat increased by another cause, not involving a correspondingly increased absolute piston pressure. The reduction in the pressure of the outer air causes the exhaust back pressure to be diminished, the engine furthermore works under air pressure during the suction stroke, thus converting the delivery of the compressor into useful work. These two circumstances increase the useful piston pressure, and consequently the power output, at the altitude of 5,000 m. to the extent of almost one atmosphere or about 12.5%.

In order to calculate the power required for the supercharger, Fig. 4 may be used. As the superchargers are not cooled and in consequence of their small dimensions, substantial losses in the clearance of the impellers, in the pressure compensation, and in the stuffing boxes, must be taken into account, with the result that the compression curve is a polytrope lying above the adiabatic curve. For the purpose of a general survey, the compression ratios for $\frac{b_o}{b}$ for the various altitudes are also plotted. The values of b have been taken from Table I. Fig. 4 also shows the expenditure of power for the adiabatical compression of 1 kg/sec. of air having an initial temperature corresponding to the mean yearly temperature t_m.

The output of airplane engines (when referred to the piston displacement) amounts, generally speaking, to from 1 to 1.1 h.p. per liter, the inducted weight of the air from 3.5 to 3.6 kg. per h.p./hr. From this we get the expenditure of energy with adiabatic compression of the fresh air in relation to the output of the engine at the various pressure ratios or altitudes. The actual expenditure of energy is increased by the losses in supercharger and drive. Detailed tests with a supercharger built by Brown, Boveri & Co. in Mannheim for 1100 to 1200 h.p. engine output (that is, a delivery of about 4200 kg/hr. and a pressure ratio of 1.2) had an efficiency of 65% referred to the adiabatic curve and converted to -15° initial temperature. With later models 68% was attained, even with smaller quantities of air.

The addition of the pressure connection does not, for the most part, require any substantial alteration of the engines, so that their standardized production is not interrupted. The most favorable engine for the purpose is the 260 h.p. Daimler engine. Its one piece carburetor and common air suction tube made possible the immediate attachment of pressure connection. It was only necessary to consider whether it would be more advantageous to take the air from the atmosphere direct or through the engine crankcase passage. With the 260 h.p. Daimler engine the air is inducted through a channel under the crankcase, and then through a quarter bend to the carburetor in order that it will be heated and that oil draining off into the oil sump will be cooled. The temperature of the inducted air is raised 15° to 20° above the temperature outside. This results in raising the final temperature of compression in the supercharger. As, with the supercharger in operation, the air is more than sufficiently heated in consequence of the compression; even with the very lowest outside temperatures, it seems advisable to take it direct from the atmosphere as is done with all other engines. With the 260 h.p. Daimler engine this was however not possible at first because when the weather was warm the air current alone was not sufficient for cooling the crankcase. The lubricating oil in it was heated to between 85 and 95° C., became too thin, and did not reach the piston pins. This was remedied by circulating the oil through an oil cooler by means of a gear pump driven from the cam shaft by a flexible shaft, the cooler forming a part of the engine housing.

The air reaches the carburetor direct from the pressure connection. The carburetor itself needs no alteration as long as the ground level pressure to which it is adjusted is not exceeded to an appreciable extent. The space above the float, or the float chamber overflow, also the container from which the carburetor directly receives the fuel, are to be connected with the pressure pipe of the supercharger by a compensating tube, as the same pressure must prevail above the float and in the fuel tank as at the pressure connection of the supercharger. All the carburator openings must be closed so that no leakage of fuel is

is possible. A light detachable cap is fitted over the float valve stem guide. The guides of the inlet valves are always sufficiently airtight so that no special provision is necessary at that point. In order to render back firing harmless it is advisable to fit relief valves of generous size in the piping between the pressure connection of the supercharger and the carburetor. The wall between the last two stages of the supercharger is, above all, endangered during violent back firing.

In the case of one common supercharger for several engines, each engine has a connecting piece (Fig. 5) usually an aluminium casting with a large blow-off valve (a cap held in place by several springs), a throttle valve for shutting off the compressed air (missing in Fig. 5), and an automatic air suction valve. The suction valve permits the intake of air direct from the atmosphere as long as the supercharger is not working; when, on the contrary, the supercharger is furnishing air of higher pressure than that outside, then the valve closes. The connecting piece is connected to the float chamber by a pressure compensation tube. Special attention must be given to the fuel discharge. The utmost care must be taken to prevent an overflow of fuel at the nozzle from running into the tube connections (which in giant airplanes are built into the lifting surfaces and are of considerable length) as during back firing they might explode and endanger the airplane. For this reason the connecting piece is provided with a fuel drain cup having a drain cock or small opening so that the misplaced fuel can drain off. The loss of air thus occasioned is unimportant. An open U tube filled with mercury is the most suitable means for measuring the pressure of the central superchargers. On it is a millimeter scale which shows the different pressures appertaining to the various altitudes. For single superchargers on small airplanes, low pressure gauges are used, which show either the absolute pressure or the pressure in excess of the pressure outside. In the first case the pressure of the air in front of the carburetor is always adjusted to one atmosphere. In the second case the regulation for the various altitudes is according to a special graduation of the altitude indicator.

With superchargers driven direct by the main engines, and which always run at the full number of revolutions, the excess pressure at and near ground level (with the exception of the few mm. excess pressure necessary for the compensation of the power consumed by supercharger) must be destroyed by throttling, that is, the delivery of an excess quantity of air must be prevented. The most economical way is to fit the throttle in the supercharger suction pipe as the supercharger will then deliver air of less density. Furthermore, the so-called surging is avoided, because behind the throttle expanded air completely fills the vane spaces and the supercharger works at all altitudes under the conditions for which it was designed, except for the temperature

differences. The opening of the sliding throttle valve for hand operation by Brown, Boveri Co. (Fig. 6) is just large enough to permit the passage of as much air as is required by the engine when running with its full number of revolutions at ground level. The slide valve is operated by means of wires and a lever from the pilot's seat. The lever is provided with a notched guide indicating the various altitudes. For further certainty, the pilot is furnished with one of the above-mentioned low pressure gauges; the hand of the same must indicate one atmosphere or else the same altitude as the hand lever. In order to prevent the engine, before it is running at full speed, from receiving too much air and therefore exploding or stalling, and for the purpose of reducing the number of control levers, the throttles of the supercharger and carburetor may be coupled in such a way that at first only mixture is delivered. If the carburetor is quite open, and the hand lever continues to be shifted, it will stay open and it will be possible to release more air at the supercharger. When shutting off the process is reversed.

In place of operation by hand, automatic regulation may be substituted. This entirely relieves the pilot from controlling the supercharger. Several different forms of apparatus for this purpose, which utilize the expansion of barometric cells under the influence of the decreasing air pressure with increasing altitude, have been proposed by the Propellerbau Lorenzen, Berlin-Neu-Kölln, and by Brown, Boveri & Co., Mannheim.

When the supercharger is driven by a special engine, it is practical to make the rough adjustment of the number of revolutions by throttling the mixture at the driving engine and to make the accurate adjustment by throttling the air at the supercharger. Both throttling arrangements can be manipulated from the pilot's seat, the revolution indicator of the supercharger engine being also visible from the pilot's seat. When idling the main engines, the air withdrawn from the supercharger is reduced almost to the amount required for the supercharger engine. The load of the supercharger thus drops to about 1/3; in order to prevent the supercharger from running away it therefore must be throttled at the same time as the main engines. The supercharger engine is connected to the compressed air pipe in the same way as the other engines.

With the use of a supercharger the fuel system usually undergoes some alterations. Generally speaking, in an airplane, fuel is fed from a gravity tank (its supply being received from a main tank), or with a fuel pump, the excess from which passes back to the main tank through an excess pressure valve. The placing of the main tank under pressure is avoided in consideration of the weight and strength required (at 5 km. altitude the container would be subjected to almost 1/2 atmosphere of excess pressure) and also because of the danger of fire. In the simplest

but most usual case (Fig. 7), the main tank itself is used as a gravity tank. The required excess pressure on the fuel at the carburetor is from 2 to 2.5 m. water column and is generated by the static pressure of the high container. The float and float chamber are subjected to the supercharger pressure, the movement of the float is thus independent of the supercharger pressure as long as the pressure compensation can take place fast enough. For short compensation pipes (for small aircraft) 6 mm. bore is sufficient, for long ones (for giant airplanes) 8 to 10 mm. Special care must be taken to make the pipes and connections absolutely tight.

Fig. 8 shows the design of the fuel system when employing a pump, which may be driven by the engine itself or by some other power and which forces the fuel from the main tank to the carburetor. If the pump delivers more than is consumed, the excess will return through the regulating valve*) which is set for between 2 and 2.5 m. water column. In order also to render the latter independent of the supercharger pressure, the overflow cup and the float chamber of the carburetor are connected by a pressure compensation pipe. The main fuel tanks are subjected to atmospheric pressure only. In order that no supercharger air should reach the main tank, a float valve is inserted between the overflow cup and the main tank. This float valve is also connected with the pressure compensation pipes. Its manner of action needs no explanation. The size of the float is dependent upon the fact that the upward pressure on the float valve must overcome the pressure difference acting on the shut-off valves, the upper side of the latter being subjected to the supercharger air pressure and its lower side to the tank pressure or outside pressure. The most common arrangement of the fuel system for giant airplanes (Fig. 9) is composed of the parts as described. Instead of the excess pressure valve, a drop tank is used there, however.

The airplane superchargers described below, and which were in existence at the termination of the war, were for the most part first executions of the designs and doubtless leave room for improvement with regard to weight and space requirements and also with regard to many details.

The first supercharger** of this kind, by Otto Schwade & Co., Erfurt (Figs. 10 to 20) was designed for direct coupling to a 260 h.p. airplane engine and an output of 1000 kg. of air per hour with a maximum compression ratio of $\frac{b_o}{b}$ 1.52, which corresponds to a constant engine output up to an altitude of about 3.5

* The illustration shows the regulating valve by Benz & Co., Mannheim.

** German Reich's patent applied for.

km. It consists of four adjacent chambers. The first of these encloses the gear drive and each of the other three contains an impeller with its corresponding diffuser. The chambers are all co-axial and combined into a single block without horizontal joints. In assembling, an impeller and a housing are put in place alternately and the housings are held together by screws at the circumferences, while the impellers are held on the shaft by means of a nut at the thrust bearing. The chambers are made of aluminum castings, the impellers of special steel. The driving gear has two oppositely located intermediate gear sets running on ball bearings over stationary studs. The impellers revolve at 10,500 r.p.m., the driving gear at 1400 r.p.m., and the intermediate gears at 3500 r.p.m. With the impeller diameter of 250 mm., the peripheral speed amounts to 140 m. per second. The gear wheels are made of chrome nickel steel, case-hardened. The pinion on the supercharger shaft is built integral with a slip coupling consisting of four bronze annulus sectors which are pressed against the coupling box by centrifugal force. This coupling is intended to facilitate the starting of the engine and to protect the driving gear from the violent acceleration shocks when starting, as the coupling does not connect the impellers until the engine has attained a speed of 600 r.p.m. For lubrication of the driving gear the wheels are arranged to dip into an oil bath. Figure 20 shows the supercharger, with the carburetor and float chamber mounted on top as well as the pressure compensation pipe connecting the float chamber with the discharge connection of the supercharger. The supercharger draws air from the bottom of the engine crankcase (which is thereby cooled), and a throttle valve is inserted in the air inlet to the supercharger so that the pressure delivered by the latter can be regulated. The complete supercharger with connections as first executed weighed 47.5 kg., and if we take into consideration that the weight of the 260 h.p. engine is 420 kg. and its output at 3.5 km. altitude is only 170 h.p., and that the driving of the supercharger requires 20 h.p.; then the engine without supercharger would have a unit weight of 2.5 kg/h.p. at this altitude as compared to 1.95 kg/h.p. with supercharger. Superchargers of this kind have been installed in A.E.G. airplanes (see Fig. 21). They are also easily combined with revolving cylinder engines, (see Figs. 22 to 24). In the latter case, the supercharger takes its air directly from the atmosphere and forces it into the inlet pipe which is connected to the tubular crankshaft.

The Brown, Boveri & Co. branch in Mannheim, who even before the war had kept in close touch with their parent house in Switzerland with reference to the construction of turbo-compressors, did the most exhaustive work in connection with airplane superchargers. Their first model was designed for the 1200 h.p. power plants of the giant airplanes (Figs. 25 and 26) and was driven by a Daimler airplane engine which also received its fresh air from the supercharger. With this plant the float chamber of the carburetor of the driving engine is enclosed in a

box, the latter being subject to supercharger pressure (see Fig. 25), thus rendering the carburetor independent of the outside pressure. At the suction connection of the supercharger is fitted a hand-controlled throttle device (see Fig. 26). The Staaken giant airplanes were equipped with superchargers in the same manner (see Fig. 27). In the middle of the picture may be seen the air pipe leading to the supercharger engine and connected to the box shaped enclosure of the carburetor. The throttle valve for the mixture is hand-operated by means of a chain and sprocket control from the pilot's seat. Figure 28 shows the construction of the superchargers used. In more recent examples of this supercharger (Fig. 29), the suction connection was removed to the driving end so that the incoming stream of cold air might aid in cooling the driving gear. Furthermore, the compressed air conduits, which in the older types had already been divided at the final cell, were, for better guidance of the air stream, now connected to the housing by a practically tangential extension. This supercharger normally furnishes 4200 kg. of air per hr. at 0.52 atmosphere initial pressure and one atmosphere final pressure, the corresponding power consumption being 120 to 125 h.p. The speed of the driving engine is 1450 r.p.m., and that of the supercharger shaft 6000 r.p.m.; supercharger is of the 4 stage type, the impeller diameter being 470 mm., thus the peripheral speed is about 150 m/sec. The housing, driving gear case, inlet pipe connection, and diffuser vanes are all cast of an aluminum alloy. The impellers were made of special alloy steel having a tensile strength of 81 kg/sq.mm. and an elongation of 15%. The ends of the hollow shafts are made of chrome nickel steel with a tensile strength of 76 kg/sq.mm. and an elongation of 16.5%. The gears and pinions are of chrome nickel steel from the Bismarck Works. The bearings at the rotor pinion are subject to great stress and are roller bearings by the Norma Co. The gears were executed with especial care.* The driving wheel has 54 teeth and the pinion 13 teeth with circular pitch of 4.05 π and a face width of 50 mm. When transmitting 125 h.p., the teeth are loaded to $c = \frac{P}{bt} = 113$ kg/sq.cm.^{2}. They are case-hardened and ground on Maag machines. Oil is injected directly between the teeth through two nozzles of 2 mm. diameter, being circulated by a gear pump driven from the small slow speed shaft. The supercharger is connected to the engine crankshaft by a leather block joint (Voith coupling). The complete supercharger with its drive weighs 145 kg. The coupling with a disk fly wheel mounted thereon, which has been found desirable in order to secure a smoother operation and to protect the driving gears against the shocks of the engines, weighs 20 kg.

Another supercharger, having a capacity of 1000 kg/hr. with an initial pressure of 0.56 atmosphere and a final pressure of one atmosphere (Figs. 30 to 32), requires from 28 to 30 h.p. and is designed for direct connection to an engine of from 260

* By the "Zahnradfabrik Friedrichshafen."

to 300 h.p. at 1600 r.p.m. Its impellers make about 10,000 r.p.m. and have a diameter of 290 mm., giving a peripheral speed of 150m/sec. The driving wheels have 82 and 13 teeth of 2.5 π circular pitch and a face width of 25 mm. The dependence of the final pressure upon the amount delivered at the different speeds is shown in Figure 33.

The coupling (Figs. 34 to 36) was specially designed to meet the objections of engine manufacturers to the direct attachment of the superchargers. As a matter of fact, the impeller of the supercharger represents, in spite of its small dimensions, a gyrating mass which, in consequence of its great rotational velocity, has approximately the same kinetic energy as that of the airscrew at the other end of the crankshaft. It was therefore feared that synchronous vibrations might arise in consequence of which the shaft might break. For the large superchargers having their own engine the leather packing at the circumference of the coupling is probably sufficient, nevertheless it is also advisable in this case to reduce the vibrations by means of a flywheel.

For superchargers for single engines, couplings with helical springs were therefore used and which proved successful throughout. In tests made with scribers mounted on the circumference of the two disks, the deflection of the springs was obtained during operation. Shocks were thereby noted corresponding to four times the normal torque. The disks and the springs which transmit the torque form a universal joint, so that the vibrations of the entire supercharger in relation to the engine (which owing to the intense vibrations of the engine and the light wooden frame of an airplane are unavoidable) may be taken care of. The weight of the supercharger with driving gear is 54 kg., the throttle arrangement (Fig. 6) weighs 4-1/2 kg., and the spring coupling weighs 6 kg.

Brown, Boveri & Co. (Mannheim branch), also produced superchargers for 350 h.p. airplane engines and having a driving ratio of 1350 to 10,000 r.p.m. (Fig. 37). The pressure pipe from the supercharger was directed downward and connected to an air cooler of aluminum, which was to be inserted between supercharger and engine. Suction pressure p_1 in relation to the quantity of air delivered for various r.p.m.[1] of the engine, with a constant final pressure p_2 = one atmosphere and constant suction temperature $t_1 = -15^\circ$ C.[2]

Tests to determine whether the installation of this cooling apparatus resulted in an increase in engine output sufficient to justify the additional weight of from 10 to 15 kg. were not completed.

For the giant planes of 1800 to 2000 h.p., yet another kind of supercharger with a special drive by a 160 h.p. Daimler engine had been almost completed, and also a special design of the 1200

h.p. supercharger with vertical shaft which was to be installed in the 1000 h.p. single screw airplane of the Linke Hoffman Works of Breslau and driven direct from a central power plant (see Figs. 39 and 40). The transmission gear between propeller shaft (540 r.p.m.) and supercharger shaft (6000 r.p.m.) is built into the housing of the central power plant.

The A.E.G. (Hennigsdorf) was also successful with superchargers built in its turbine factory (Fig. 41). This supercharger is driven through an automatic centrifugal clutch of which one member is mounted on the end of the engine crankshaft. This clutch engages only when the engine speed exceeds 600 r.p.m. and then only by the friction of the gripping surfaces. The latter were originally faced with Ferodo fiber, but as this material is difficult to get in Germany, the clutch was converted into a centrifugal type with rocker arms. Between the clutch and the supercharger are inserted a pair of spur gears with a ratio of 1 to 6.9. This is followed by a small intermediate shaft with a square block type universal joint, affording a certain amount of flexibility to take care of slight changes of the bearings and of the vibrations during flight. At the same time this shaft forms a yielding member and a safeguard against fracture, thus protecting the crankshaft in case of rapid acceleration or obstruction within the supercharger.

The three impellers run at 10,000 r,p.m. and consist of steel disks with vanes riveted on. The diffuser case has a horizontal joint through the center. The pressure ratio is 1.7 at full speed which corresponds to a constant output of the engine up to an altitude of 4 km. When attaching the supercharger to the 260 h.p. Daimler engine the usual suction elbow to the carburetor is replaced by a connection piece with automatic valve and throttle valve. The air is drawn through the channel of the crankcase and passes through the swinging valve (which opens automatically) directly into the carburetor, when the throttle device in front of the supercharger is closed. Then the supercharger will be running light. If, on the other hand, the throttle valve is opened the automatic valve will close and the air passes to the engine through the supercharger. The swinging valve can be adjusted to the various altitudes from the pilot's seat by means of a Bowden wire; it can however also be automatically controlled by means of a barometric cell.

The supercharger requires about 10 percent of the engine output, and its weight is 56 kg., including pipes and coupling. In the later models the coupling alone weighs 9 kg., and the weight of the parts necessary for the installation attachment is also 9 kg.

The A.E.G. also made superchargers with separate drive for giant airplanes (Fig. 42).

The Siemens-Schuckert Works also built and tested superchargers which had been designed for direct attachment to the 260 h.p. Daimler engines, in combination with their rotary engines, but full flight trials were forestalled by the signing of the Armistice. The main difference, as compared with the other models of superchargers, is that the spur wheel transmission gear with intermediate wheel is fitted at the propeller end of the crankshaft (see Fig. 43). The compressed air passes to the carburetor through a pressure pipe located outside of the fuselage.

Just ahead of the carburetor is placed a change over valve, which gives the pilot the choice between taking air from the atmosphere through the channel in the crankcase, or compressed air from the supercharger (see Fig. 44). The supercharger is a two stage type and supplies an increase in pressure of 27% at ground level (b 759 mm., t 19°C) when running at 6900 r.p.m. or a peripheral speed of 145 m/sec. The supercharger for the 115 h.p. revolving cylinder engine (Fig. 45) is a 3 stage supercharger and supplies an increase in pressure of 30% at ground level when running at 8600 r.p.m. The power consumption is 11.5 h.p. for 6.5 cu.m. of air drawn in per minute. With its drive this supercharger weighs 28 kg.

With engines of constant output the airscrew problem became one of special importance. With the decreasing density of the air the thrust and the torque of the screw decrease also. But, as the engine with supercharger retains its ground level power output, the speed of the screw is excessively increased. For adapting the power absorbing capacity of the propeller to the density of the air there are various alternatives of which 3 which have already applied will be mentioned here.

First:- By changing the number of revolutions of the screw by means of a variable speed gear, the engine driving two sets of bevel gears of different diameters, whereby a reduction in speed from 1400 r.p.m. to 900 or 1000 r.p.m. may be effected.

Second:- By varying the pitch. Several types of these screws have been tested, but the only one that has actually been used is that designed by Prof. Reissner, and manufactured by both the Helix Propeller Works of Breslau and the Hirth Experimental Construction Station at Cannstatt. This propeller has been installed with two different models of the adjusting mechanism. Blades mounted on a hollow shaft are shifted by means of a rod sliding through the shaft and connected to the blades by a linkwork. Blades mounted on the solid shafts are shifted by moving a ring controlled by a bevel gear mechanism and which is connected with the blades by two links. These propellers are now also arranged for au-

tomatic control by means of a centrifugal governor.

Third:- By changing the number of revolutions by regulating the engine. For this an ordinary airscrew is used but with a greater pitch than usual. As the power absorbed by a propeller increases as the third power of its speed of revolution, but decreases only as the first power of the air density, at an altitude of about 6 km., at which the air density is only about 1/2 that at ground level, the speed of revolution of the propeller needs to be increased in the ratio of $\sqrt[3]{2} = 1.2599$, or by about 36% if its power absorbing capacity is to remain the same at ground level.

With most airplane engines the power curve is rather flat in the vicinity of the customary number of revolutions, below which the torque increases with decreasing r.p.m. With a given screw it is therefore possible to maintain constant power from the ground to an altitude of 6 km., if the speed is changed only from 1200 to 1500 r.p.m. By supplying air at slightly above sea level pressure, we are able to overload the engine somewhat so that the airplane can take off with the engine at 1300 instead of 1200 r.p.m. Generally speaking, screws that are designed for an altitude of 3 km. with regard to density, number of revolutions, and air speed, may be considered adapted for use on engines with constant output up to an altitude of 5 km. Nevertheless, this is a compromise which involves the disadvantage that within the increased engine speed range there is likely to be a critical speed of the engine at which the latter vibrates excessively and causes breakage of fuel oil pipes or water pipes.

In order to better judge the superiority of an airplane which is equipped with a supercharger, we refer to the following:

1) Flying speed:- As the density of the air decreases the resistance to an airplane diminishes, but so also does its carrying capacity. With airplanes equipped with ordinary engines this necessitates an increased angle of the wings, thereby increasing the driving resistance. With constant engine power, it is possible to increase the speed as air density decreases, thus maintaining nearly a constant angle of incidence at increasing altitudes. The velocity v at any given altitude with the prevailing air density y is $v = v_o \sqrt{\frac{y_o}{y}}$, in which v_o, y_o are the corresponding values at ground level.

2) The climbing speed:- The climbing speed remains the same theoretically up to the altitude at which the engine still shows its ground level power. From then on the rate of climb decreases in proportion to the decrease in the density of the air in front of the carburetor.

3) Ceiling:- The ceiling of the airplane continues to be raised until the air in front of the carburetor furnished by the supercharger has become rarefied to an extent which would have served to just barely sustain the airplane without the supercharger.

The foregoing considerations are applicable to airplanes when making flights for the purpose of practical comparison. In Figure 46, as shown, the average ascension curves of a 1000 h.p. giant airplane, with and without a supercharger, but with approximately the same total weight. For the flight shown in Figure 47 the additional output of the supercharged airplane was 130 kg., which corresponds to the additional weight of the two superchargers with accessories.

In this connection, the use of a gas turbine* for driving the supercharger was also advocated. The gas turbine was to use the exhaust gases of one or more main engines. Theoretically there seems to be nothing to prevent this. The available energy also appears to be sufficient even with a turbine of moderate efficiency. However, the additional weight and the lack of simplicity of the engine plant of the airplane are disadvantageous. Difficulties may also be expected from the back pressure on the exhaust gases at the exhaust valves.

The use of a steam turbine instead of the gas turbine might be considered. The heat of the exhaust gases would be sufficient in this case also. But a suitable boiler and condenser are lacking. The airplane supercharger is a child of the war. It was born of the urgent need of continually raising the ceiling of the airplanes higher and ever higher, and of the necessity of using ordinary airplane engines in so doing. These two conditions are largely removed in peace time. For peace time flying altitudes of from 3 to 4 km. will suffice, and for these altitudes the super-compression and super-dimension engine is sufficient. There may however be a notable future for the blower or supercharger with or without exhaust turbine for large engines** in giant airplanes. We might also plan for the future a very large seaplane with a tremendous speed, which would fly at great altitudes for the purpose of utilizing the diminished air resistance at such heights. With such a seaplane the pilot and the engines would be in an airtight compartment in which the air would be maintained at about ground level pressure. These airplanes would be able to fly at altitudes of about 10 to 12 km. and attain a speed of 250 km/hr. and over, so that they would be able to make the trip from Germany to America in less than a day.

* See "Zeitschrift" 1919, p.418, and "Luftpost" 1919, Nos. 13 and 15.

** German Reichs patent No.204630 (A. Büchi) "Zeitschrift für das ges, Turbinenwessen" 1909, p.313.

SUMMARY.

Airplane superchargers and problems connected therewith are discussed: Decrease of the density of the air with increasing altitude, causes of the decrease in engine power with increasing altitude, devices for maintaining constant engine power, super-compression and super-dimension engines, the airplane supercharger, drive and control of the supercharger, the overloading capacity of the engine by means of the supercharger, the pressure compensations at the carburetor, and fuel systems. Various superchargers constructed by Schwade, in Erfurt; Brown, Boveri & Co., in Mannheim; the A.E.G. in Hennigsdorf; and the Siemens Schuckert Werke in Siemenstadt, are discussed, as are also the airscrews with fixed pitch, airscrews with variable pitch, by Prof. Reissner, and closing with a consideration of the technical aviation problems, plans, and prospects.

Translated by the Office of Naval Intelligence, Navy Department.
Checked by L. M. Griffith, N.A.C.A.

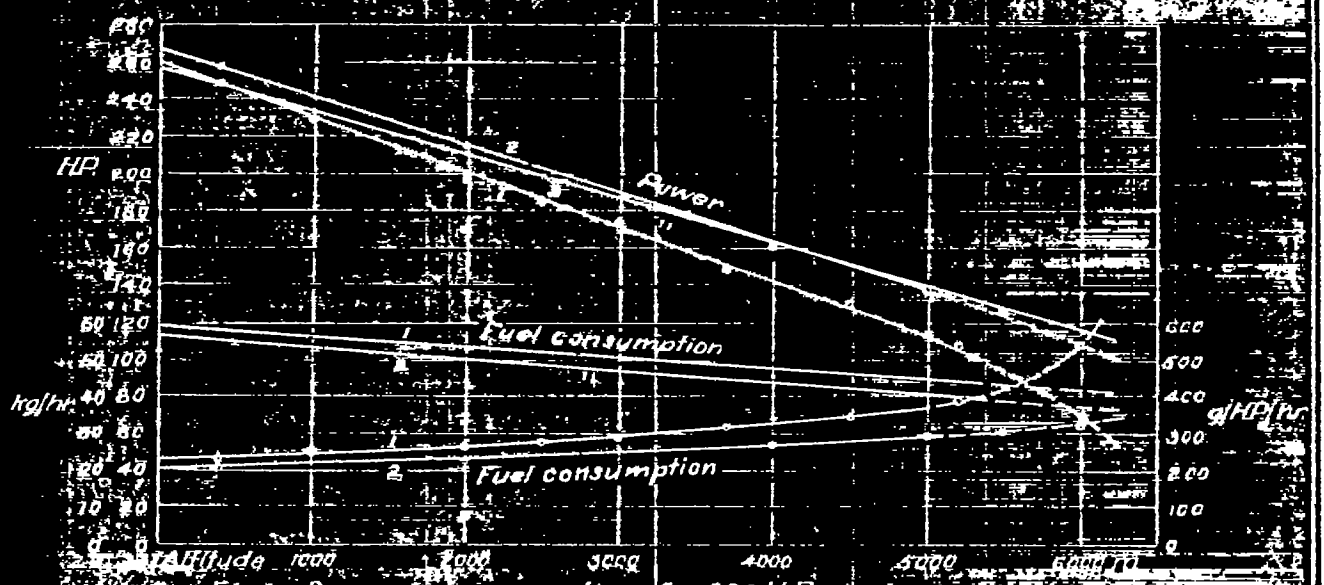


Fig. 1 Power and consumption of a 260 H.P. airplane engine at 1450 R.P.M. with increasing altitude.
The upper consumption curves represent kg/hr; the lower curves the rate per HP/hr in grams.

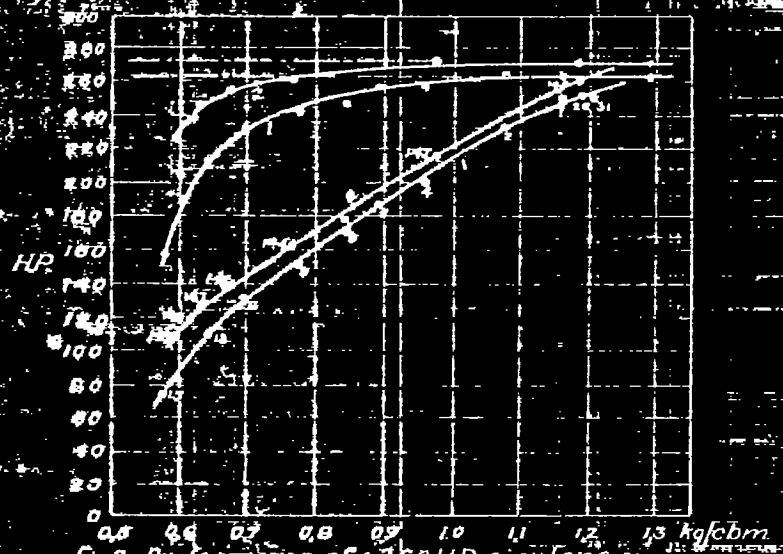


Fig 2 Preformance of a 260 H.P. airplane engine at 1450 R.P.M. relative to the air density.

Fig. 1 and 2

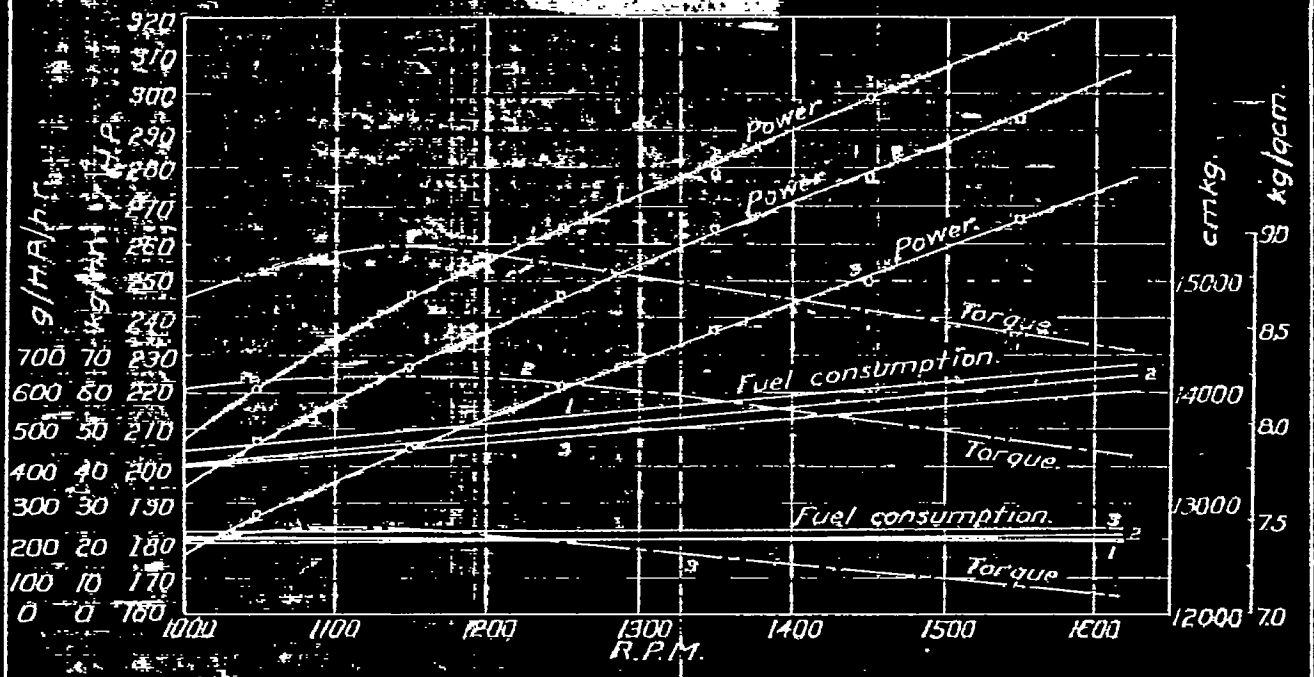
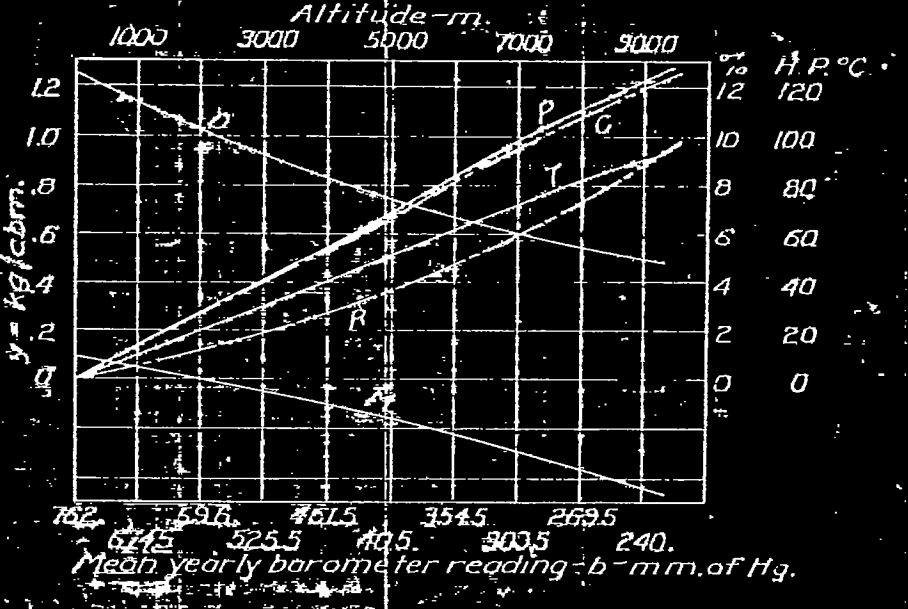


Fig. 3. Power, torque (also mean working pressure in a different unit of measure) and consumption of a 260 H.P. airplane engine for three different charging pressures and temperatures before the carburetor with increasing number of revolutions. (Upper consumptions curves are for kg/hr., lower for g/H.P./hr.)



D = Air density
P = Power required for adiabatic compression of 1 kg/sec.
C = Compression power = engine power X 100.
T = Rise in temperature Δt with adiabatic compression.
R = Compression ratio = $b_0 \div b$
M = Mean yearly temperature t_m

Fig. 4. Power consumption of the supercharger.

Figs. 3 and 4

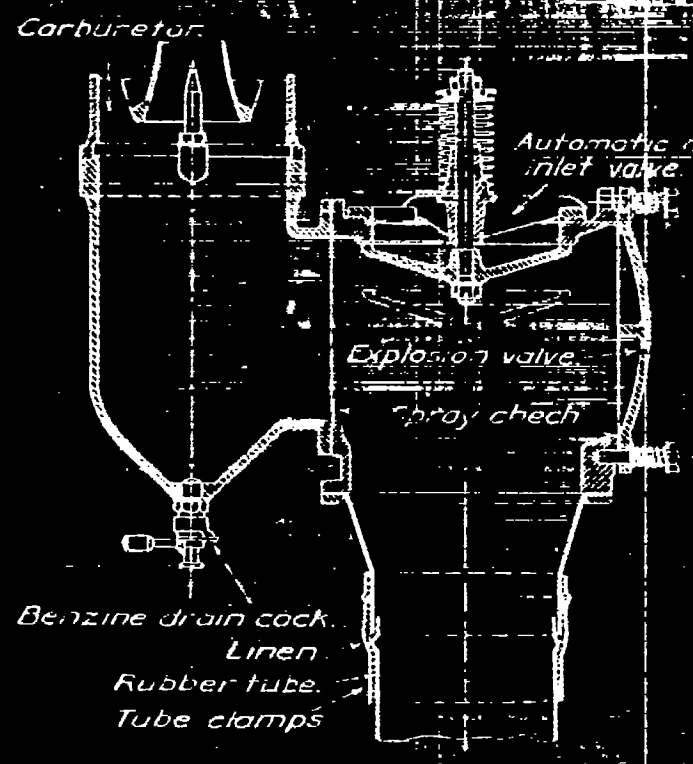


Fig. 5. Compressed air relief valve for a 260 H.P. airplane engine.

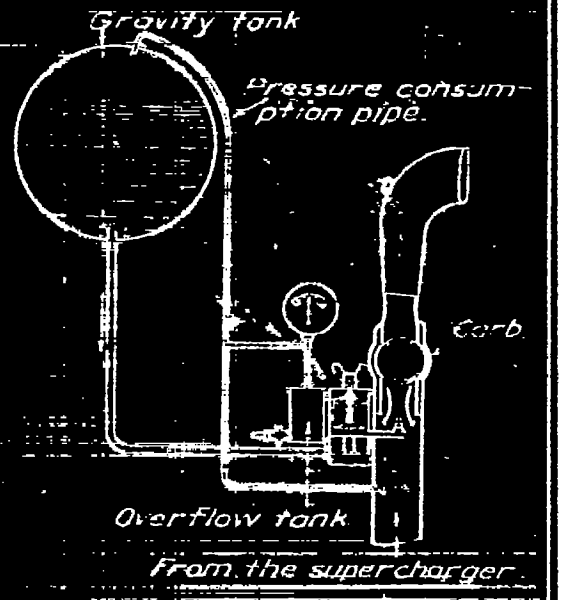


Fig 7 Fuel system with gravity tank.

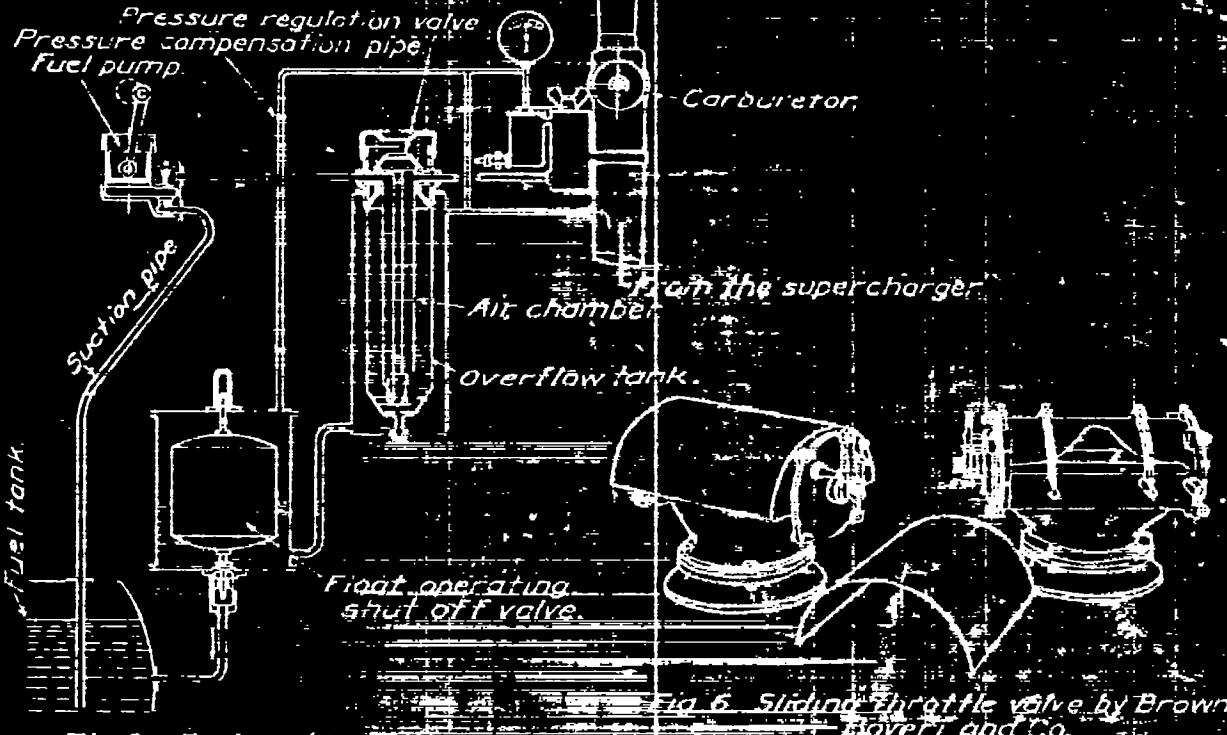


Fig. 8 Fuel system with pump

Fig. 6 Sliding throttle valve by Brown, Lavery and Co.

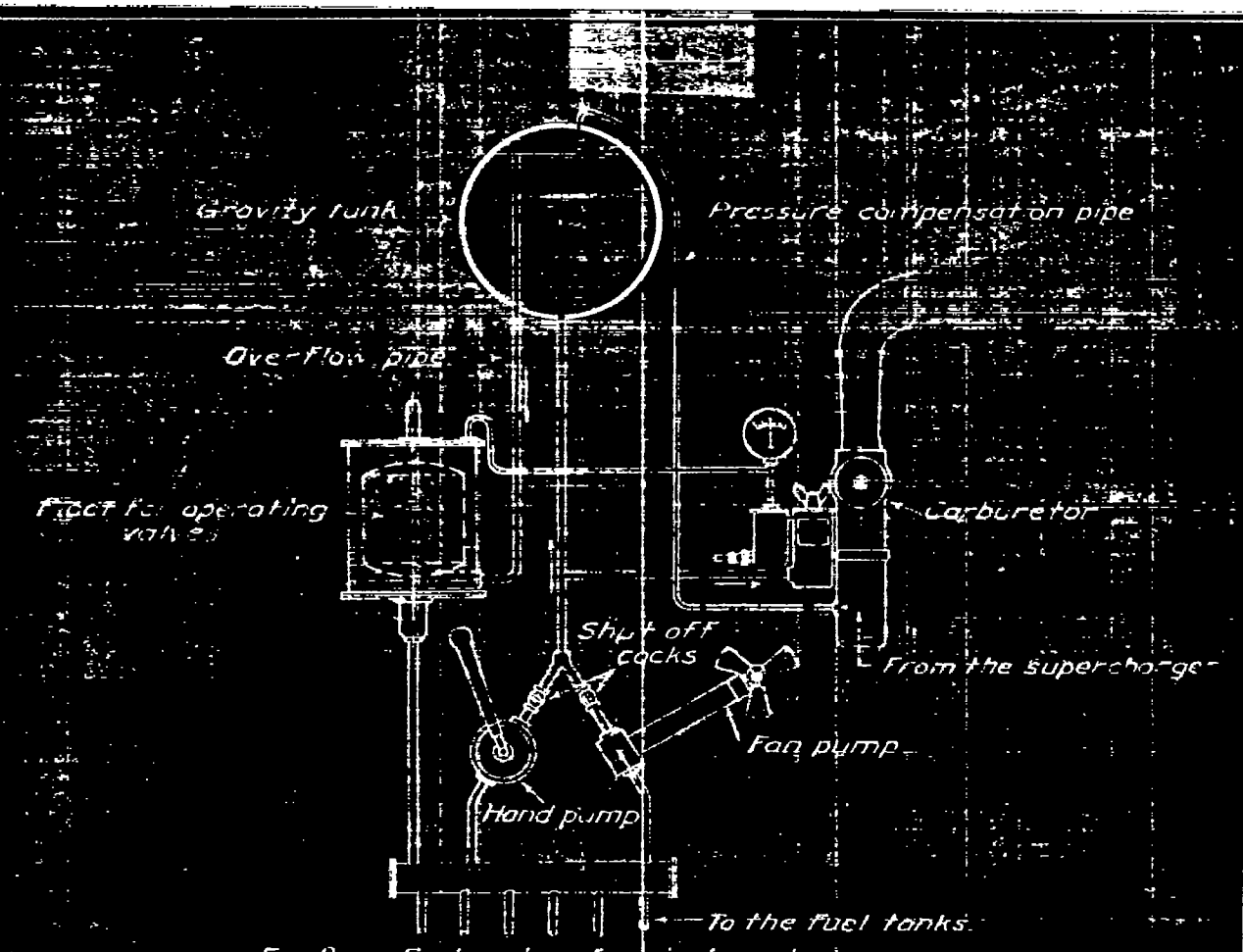


Fig. 9. Fuel system for giant airplanes.

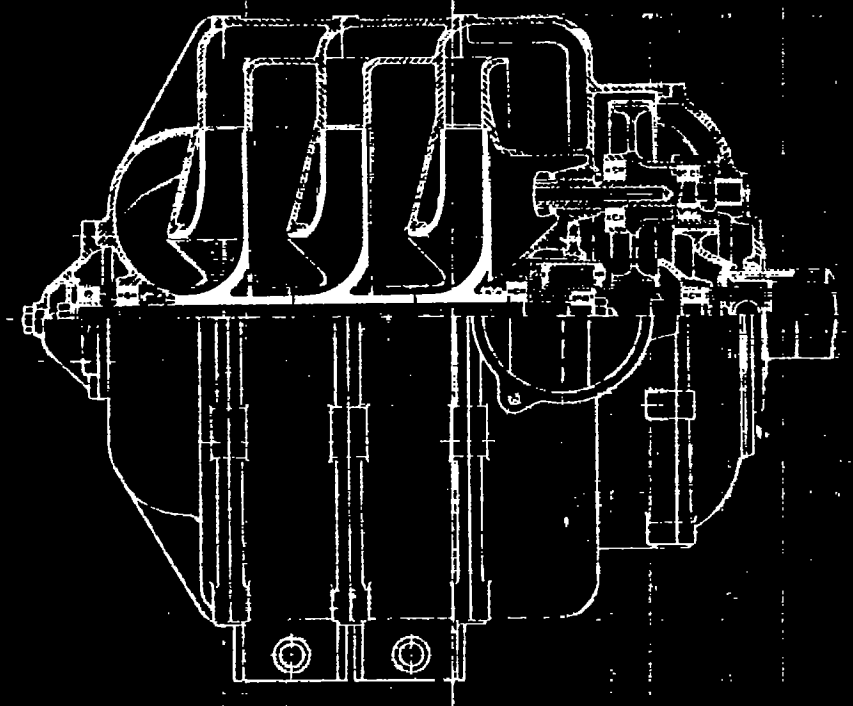
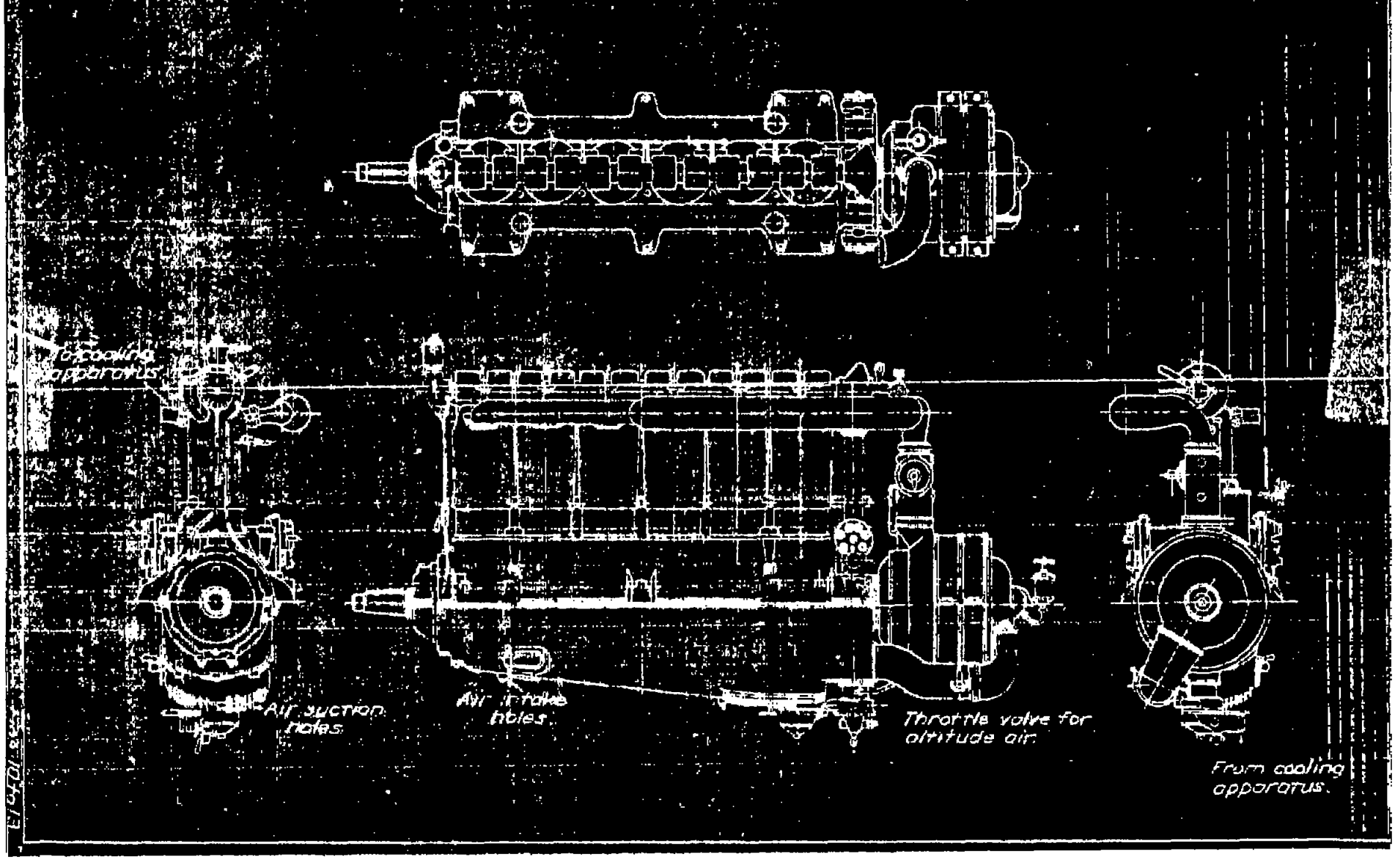


Fig. 14. Schwade supercharger.

Figs. 9 and 14

Figs. 10 to 13. The Otto, Schwade & Co. supercharger connected to 260 H.P. airplane engine.



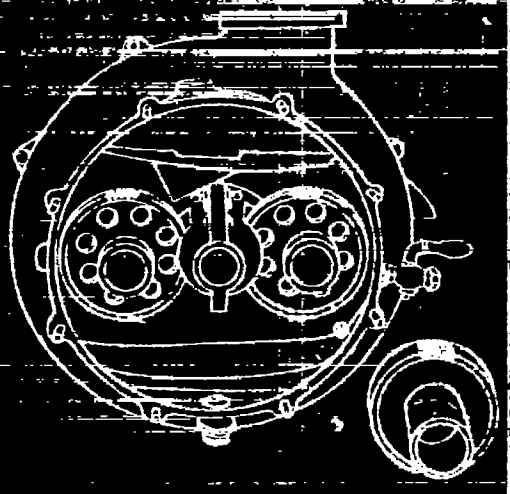


Fig. 15 Drive gear for the Schwade supercharger.

Fig. 16 The diffusor.

Fig 19 Parts of the slip coupling.

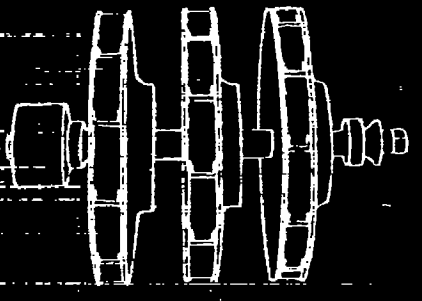


Fig. 17. Impellers.

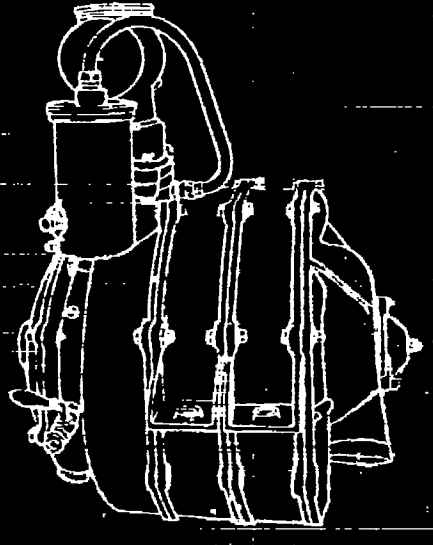


Fig 20 Schwade supercharger with carburetor mounted on top.

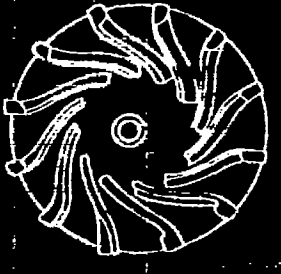


Fig 18. Impeller with one side removed.

Figs. 15, 16, 17, 18, 19, 20.

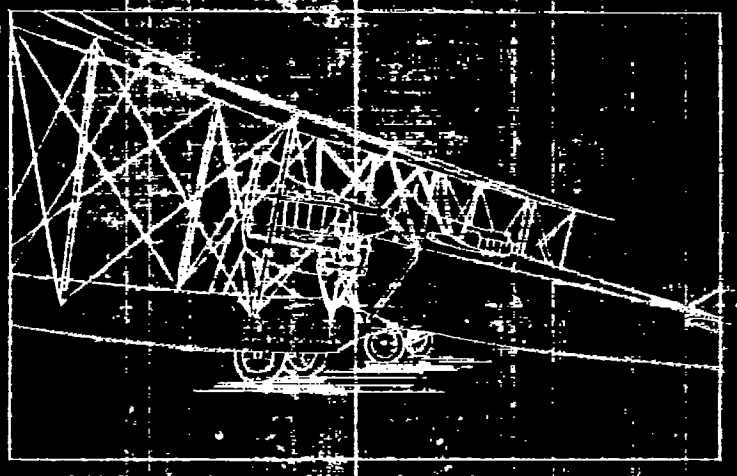
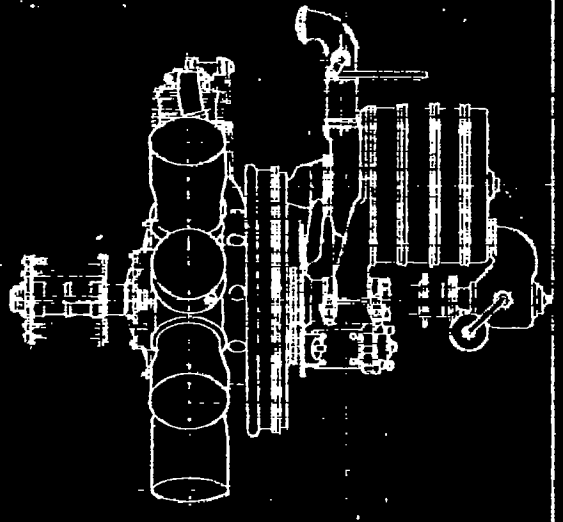
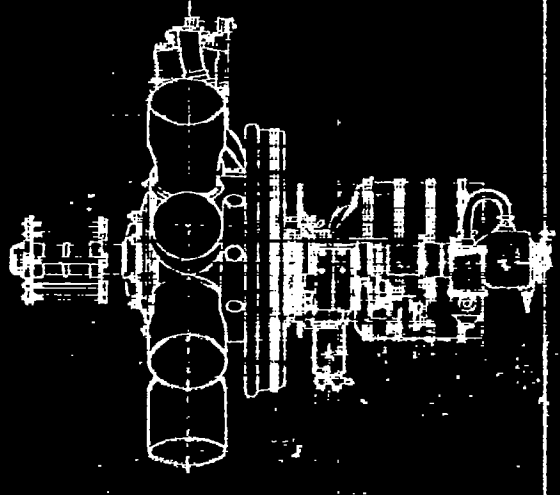
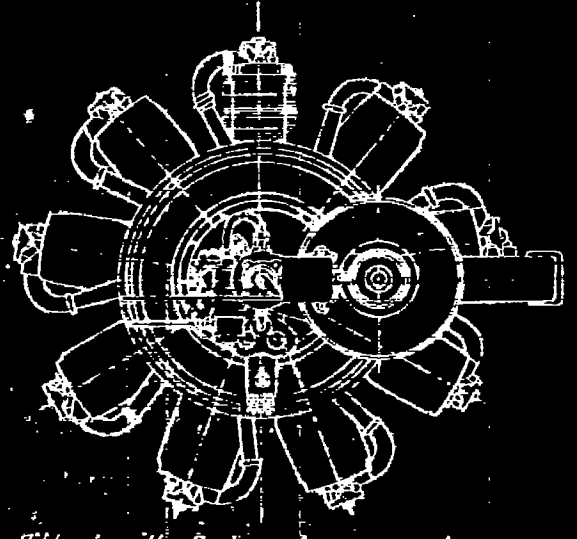


Fig. 21. A.E.G. airplane with Schwade supercharger installed.







Figs. 22. to 24. Revolving cylinder engine fitted with Schwade supercharger.

Figs. 21, 22, 23 and 24.

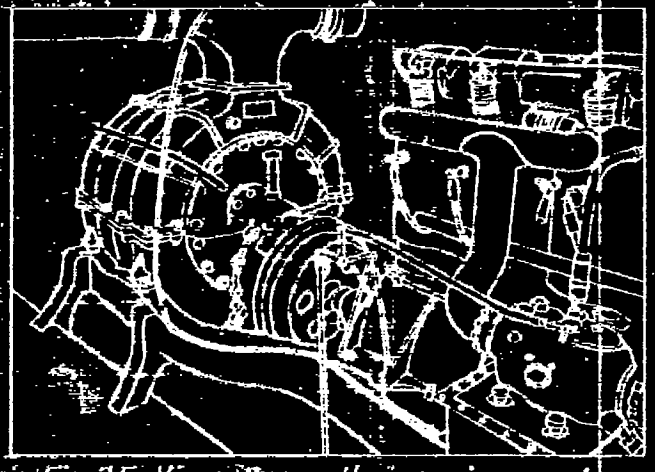


Fig. 25. View from the engine end.

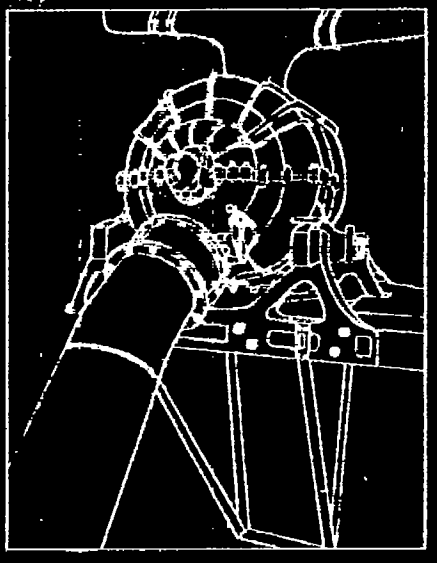


Fig. 26. View from the suction end

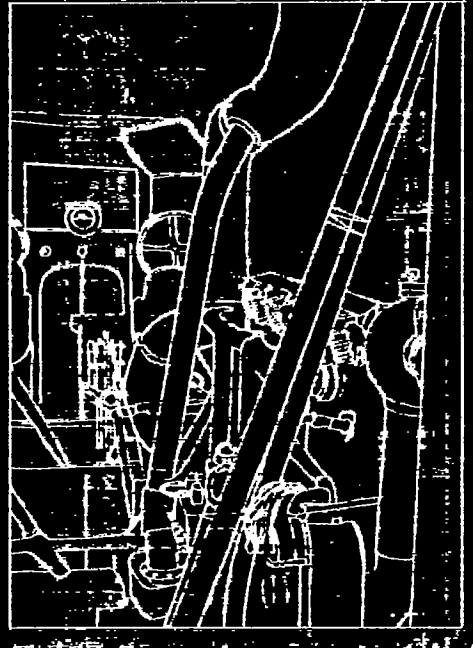


Fig. 27. Supercharger plant in the center gondola of a stacken giant airplane.

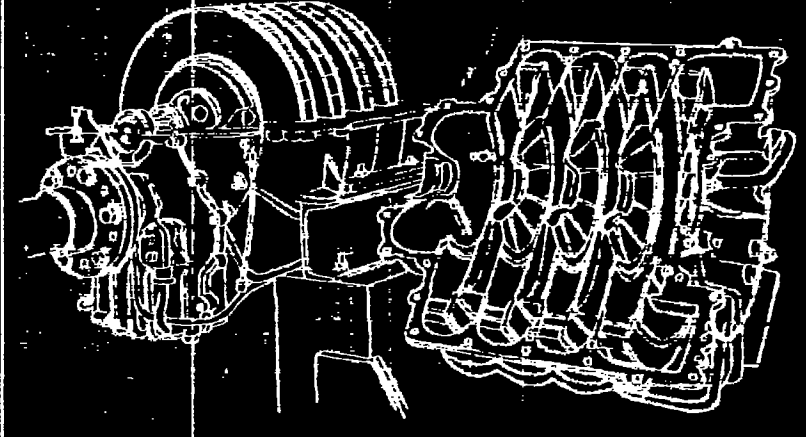


Fig. 28. Brown, Boveri and Co. supercharger for a 1200 H.P. engine plant.

Figs. 25, 26, 27 and 28.

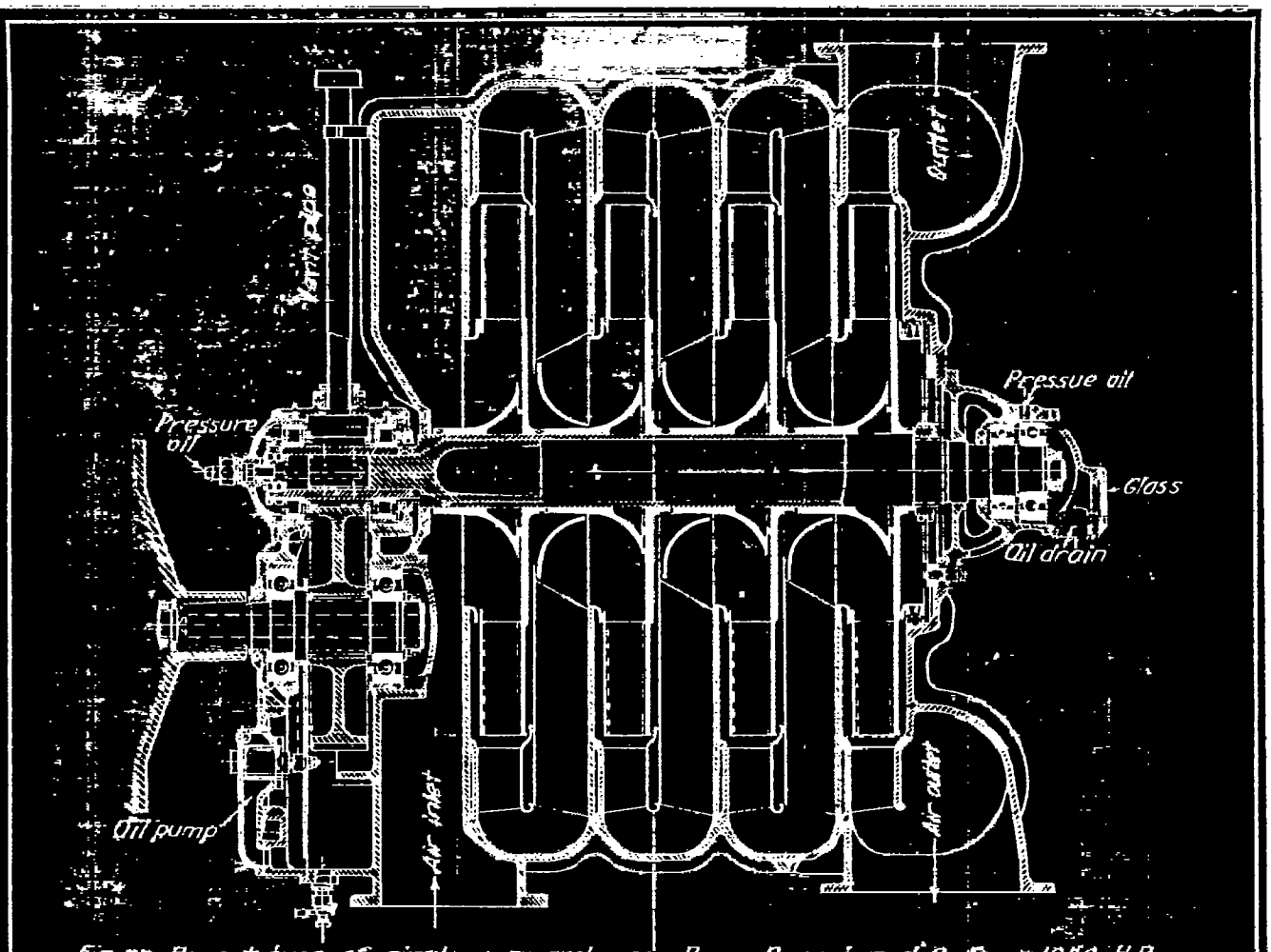


Fig. 29 Recent type of airplane supercharger, Brown, Boveri and Co., for a 1200 H.P. engine plant.

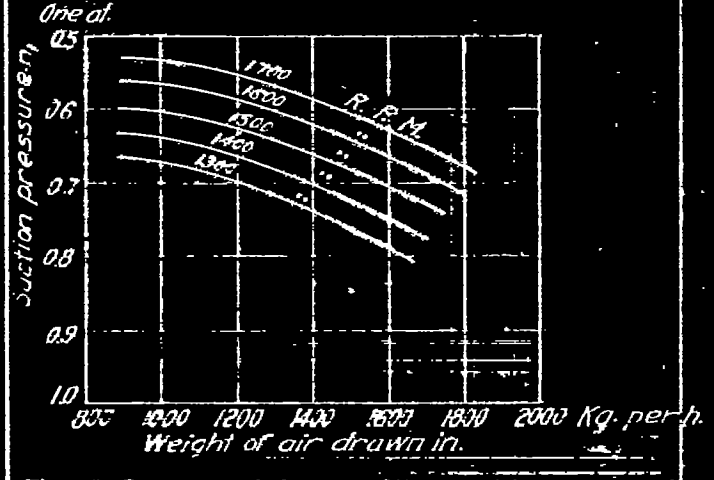
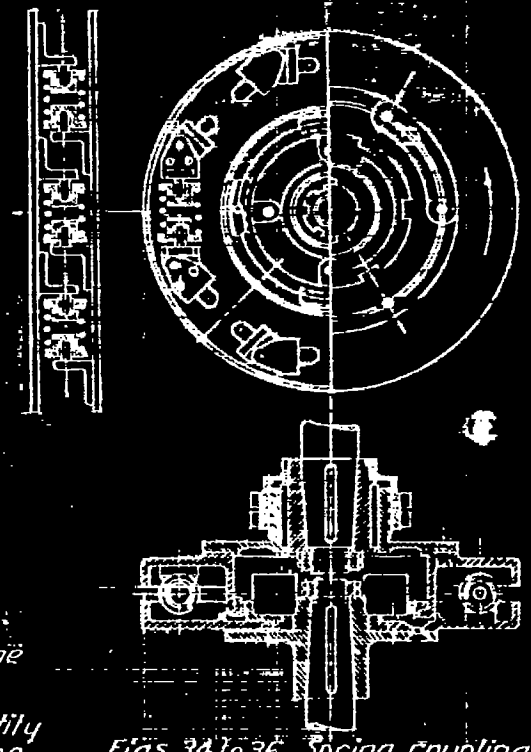


Fig. 33. Curves giving performance of the airplane supercharger, Brown, Boveri and Co., shown in Figs. 30 to 32.
Suction pressure p_1 in relation to the quantity of air delivered for various R.P.M. of the engine, with a constant final pressure p_2 = one atmosphere and constant suction temperature t_1 = [illegible] °C.



Figs. 34 to 36. Spring coupling for the airplane supercharger shown in Figs. 30 to 32 by Brown Boveri and Co.

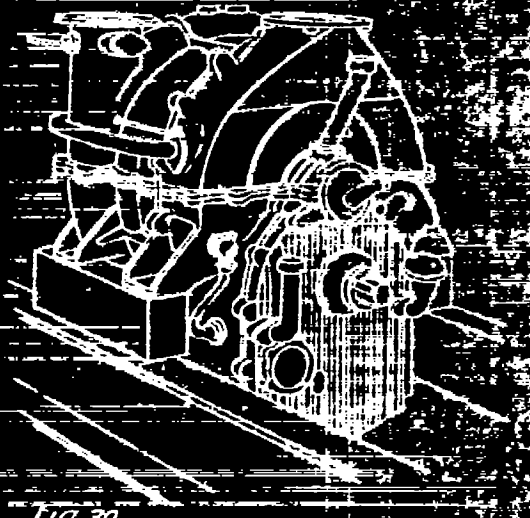


Fig. 30

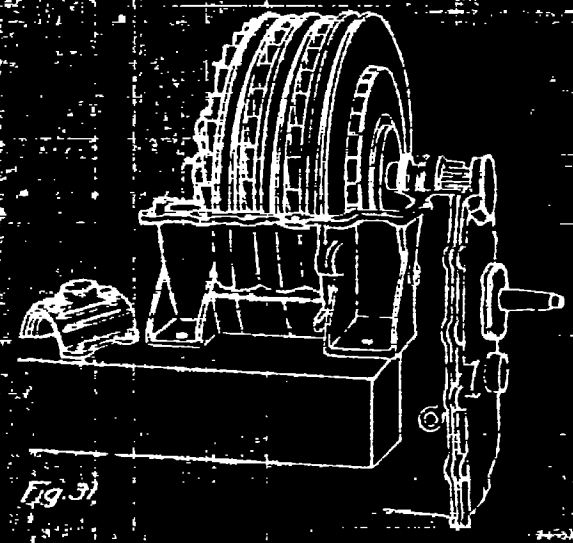


Fig. 31

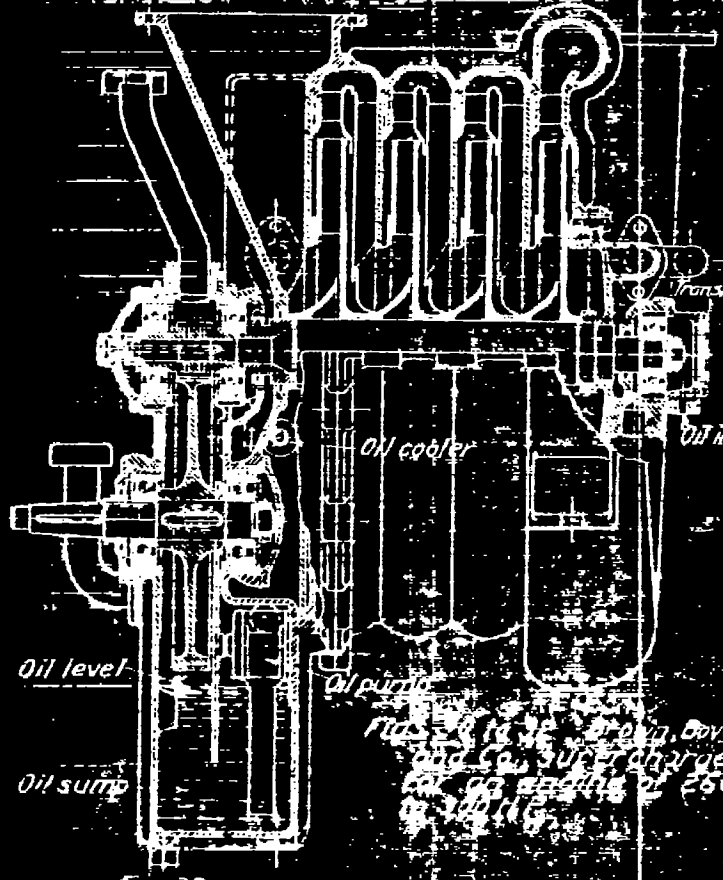


Fig. 32

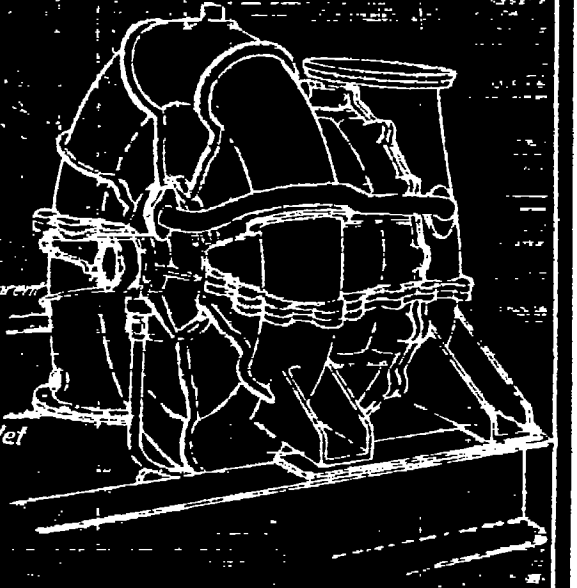
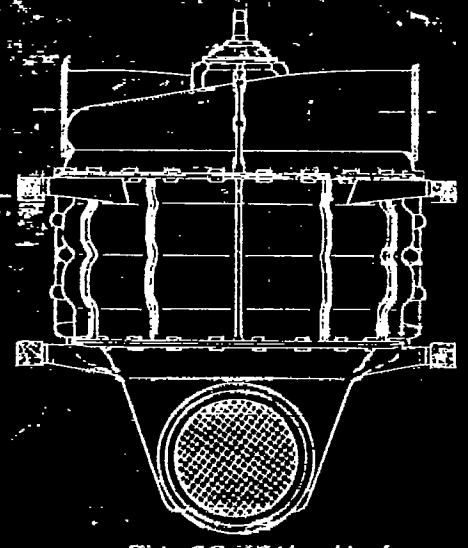
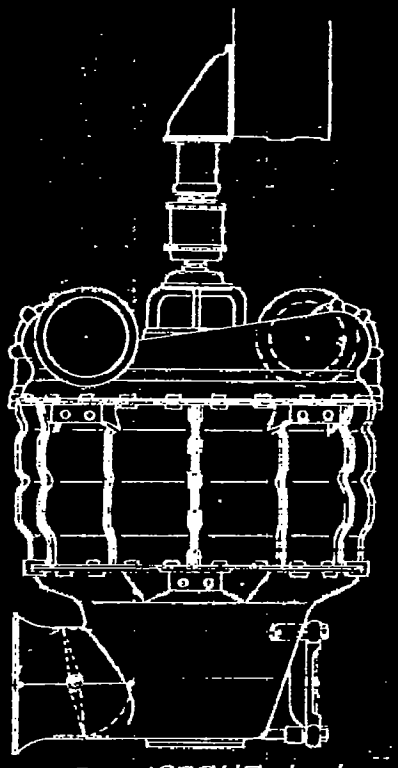


Fig. 37 Supercharger for a 350 H.P. airplane engine with suction connection directed downward.

Figs. 30 to 32 and 37





Figs. 39, 40 Vertical supercharger for a 1000 HP plant

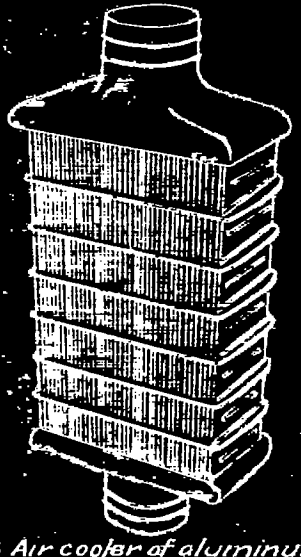


Fig. 38 Air cooler of aluminum.

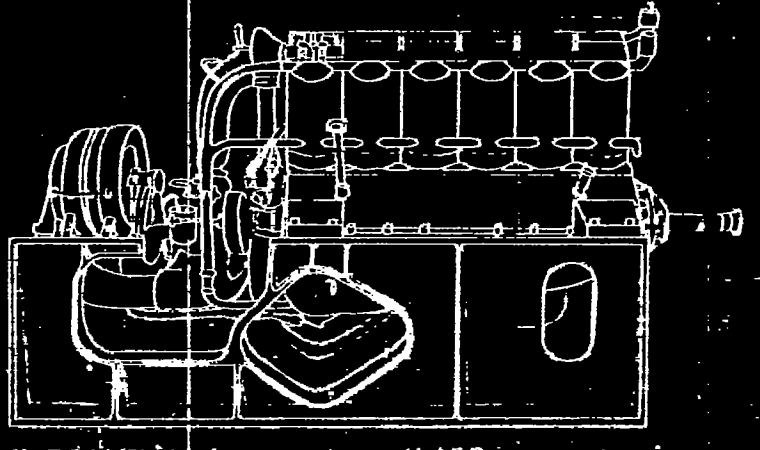


Fig. 41 260 HP airplane engine with AEG supercharger

Figs. 38 39 40

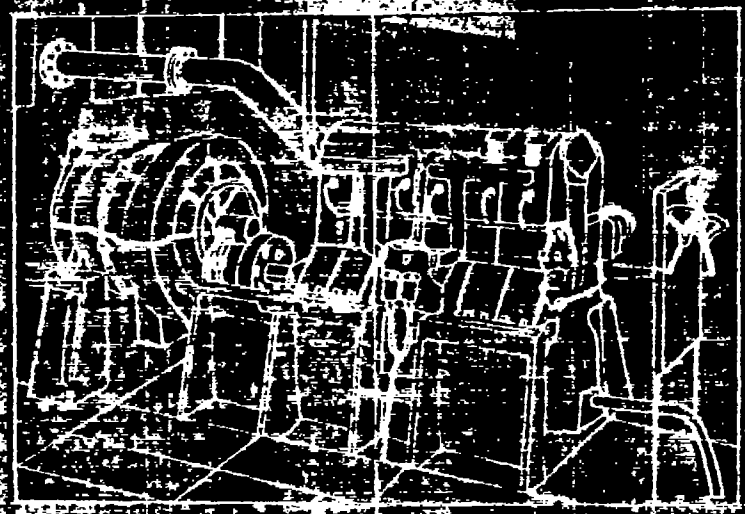


Fig 42 ALC supercharger with special driving engine for giant airplanes

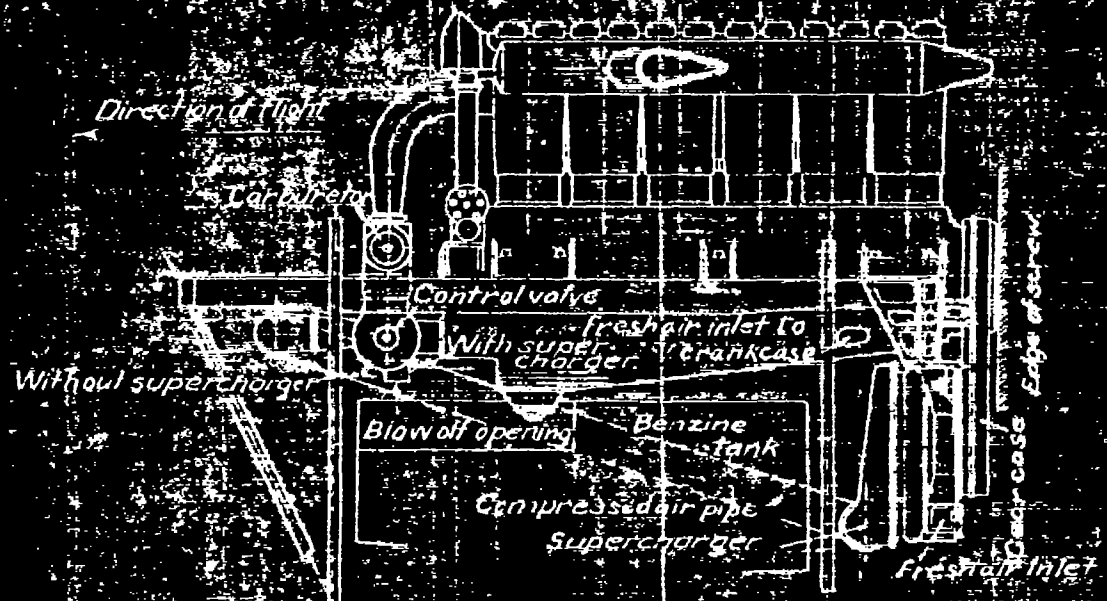


Fig 43 260 HP airplane engine fitted with Siemens Schuckert supercharger and control valve

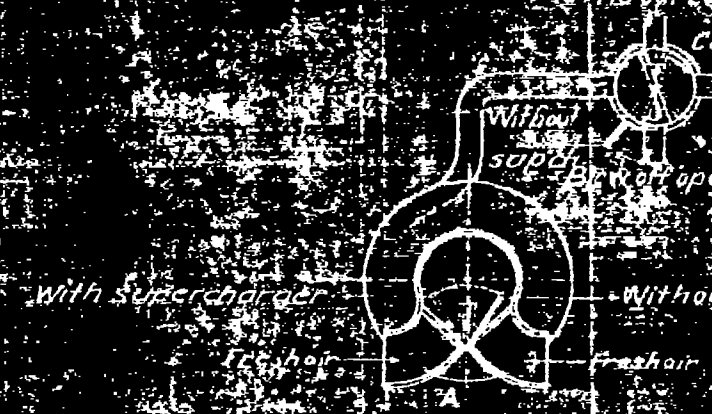


Fig 44 Arrangement of the control valve for the Siemens Schuckert Works supercharger

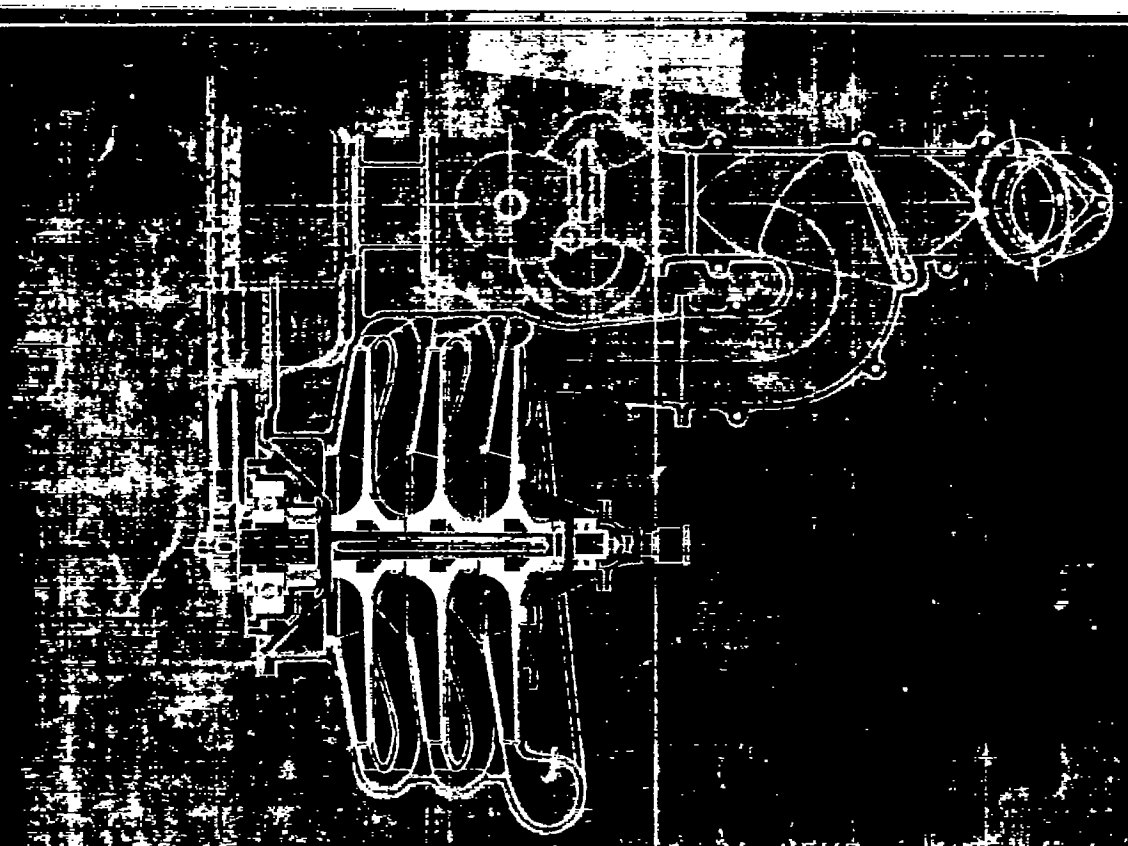


Fig 45 Three stage supercharger for the 115 HP revolving cylinder engine of the Siemens Schuckert Works.

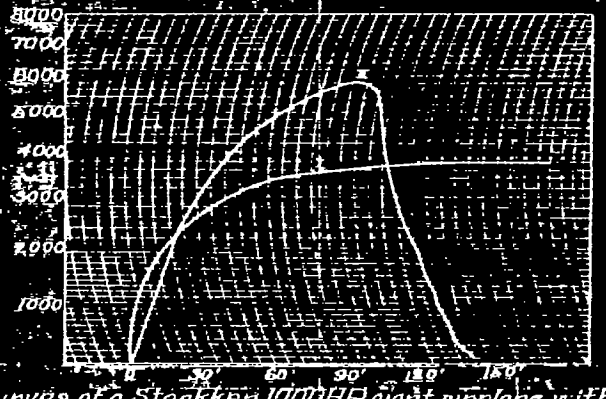


Fig 46 Barograph curves of a Staakken 1000 HP giant airplane with and without supercharger.
I. Average climbing curve without supercharger
II. Climbing curve with supercharger and compromise screw

Fig 47 Barograph curves of an AEG-C airplane with and without supercharger

Figs 45, 46 and 47