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AIRPLANE FLIGHT IN THE STRATOSPHERE*

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The stratospheric ascension of Professor Piccard and the recent attempts in various countries to reach the stratosphere with airplanes have attracted the attention of technicists to the problems of high-altitude flight.

Although these first attempts were chiefly for scientific purposes, airplanes capable of flight in the stratosphere would have inestimable advantages from both military and commercial viewpoints. From the military viewpoint they would have almost absolute invulnerability. For commercial purposes they could attain very high speeds without increasing the specific fuel consumption.

We will illustrate the latter point. From the fundamental equations of uniform level flight

$$Q = \rho \, C_p \, S \, V^2 \qquad (1)$$

$$\Pi = \rho \, C_r \, S \, V^3 \qquad (2)$$

in which Q is the weight of the airplane (kg), Π the necessary power (kgm/s), ρ the air density (kg s²/m⁴), S the wing area (m²), V the translational speed (m/s), and C_p and C_r the respective absolute coefficients of lift and drag, we readily obtain

$$V = \sqrt{\frac{Q}{\rho \, C_p \, S}} \qquad (3)$$

$$\Pi = Q \frac{C_r}{C_p} V \qquad (4)$$

It follows from equation (3) that variations in speed can be effected by two means, either by varying the density ρ through changes in the flight altitude, or by varying

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*"Velivoli e Motori d'Alta Quota." Aeronautica, December, 1931, pp. 823-827.

the lift coefficient C_p through changes in the attitude of the airplane. In the former case, with constant C_p and C_r, the power absorbed always varies in proportion to the speed, since the head resistance remains constant. In the latter case, on the contrary, C_p and C_r vary, and the power absorbed varies correspondingly.

If we assume the attitude of maximum efficiency at which the ratio C_p/C_r is minimum and therefore the head resistance is minimum, we know that, for every increase in speed, there is an accompanying increase in power, which is much less when the increase in speed is obtained by changing the altitude, than when it is obtained by changing the attitude of the airplane.

For example, let us assume that the airplane polar is as plotted in Figure 1, and that the wing loading is 50 kg/m² (10.24 lb./sq.ft.). Equations (3) and (4) then become

$$V = \sqrt{\frac{50}{\rho \; C_p}}$$

$$\frac{\Pi}{Q} = \frac{C_r}{C_p} V$$

If we express the speed in km/h and the specific power Π/Q in hp/ton (metric) and also introduce the relative density

$$\delta = \frac{\rho}{\rho_o} = \frac{\rho}{0.125} = 8 \; \rho$$

we obtain

$$V = \frac{72}{\sqrt{\delta \; C_p}} \qquad (5)$$

$$\frac{\Pi}{Q} = 266.67 \; \frac{C_r}{C_p \sqrt{\delta \; C_p}} \qquad (6)$$

In Figure 2 the continuous line is the curve for the specific power at sea level plotted against the translational speed, while the straight dash line represents the specific power required for uniform level flight at constant attitude of maximum efficiency, but at various altitudes.

On this line are dots and numbers indicating the various altitudes (km). It is seen that for 200 km/h (124 mi./hr.) the power required at an altitude of 10,000 m (32,808 ft.) is only about half that required at sea level, and that the variation increases as the speed decreases. Similarly, with the specific power of 100 hp/ton, a speed of 200 km/h was obtained at sea level and about 390 km/h (242 mi./hr.) at 19,000 m (62,335 ft.). Hence, if it is assumed that the fuel consumption is proportional to the power, independently of the altitude, the fuel consumption per kilometer in both these cases is only about half what it would be at sea level.

In practice, the results are not quite so favorable. The problem would be solved, if we had a propeller capable of exerting a uniform tractive force, independently of the altitude and speed, according to the "superaviation" introduced by Professor Crocco. In such a case there would have been no altitude nor speed limits, at least in the field of subacoustic velocities.

There is no immediate prospect, however, of obtaining such a propeller, mainly because we do not yet have sufficiently powerful explosives. Explosives are necessary because they alone can furnish sufficient power at such high altitudes, where the air is too rarefied to support combustion and where it is not possible, due to the excessive weight of the containers, to carry the necessary oxygen, even in the liquid form.

Explosion engines are not suitable for stratospheric flight, because their power is closely related to the density of the air. The indicated power of such engines is in fact proportional to the weight of the air drawn in per unit of time, but, since this air must be accumulated at a constant volume during each cycle, the indicated power is itself proportional to the density of the air. On the other hand, the mechanical losses, at least for a considerable fraction, may be considered independently of the indicated power. For this reason the effective power of an ordinary explosion engine decreases, with increasing altitude, still more rapidly than the atmospheric density. Hence there is an altitude, about 20,000 m (65,615 ft.), at which the effective power of ordinary explosion engines becomes zero, because the indicated power barely offsets the mechanical losses.

Not much better results are obtained with so-called high-altitude engines, whether supercharged, superdimensioned, or provided with compressors, all of which furnish at sea level what is commonly termed "equivalent or ideal power," but which, due to the weakness of their parts and to the self-ignitions which occur, cannot be used beyond a certain value of the torque, which, however, is maintained up to a certain altitude. Above the range of this "ideal power," however, the variation in the power with the altitude almost equals that of ordinary engines. The altitude at which the power becomes zero is also approximately the same.

In order to avoid these difficulties, various theoretical solutions are proposed, including the variation during flight, in proportion to the decrease in the density of the air, either of the compression ratio of the engine or even of the transmission ratio between the engine and the compressor. The first solution, however, presents excessive mechanical difficulties, aside from the fact that there would always be a practical limit in the reduction of the volume of the combustion chamber. The second solution, which would require, among other things, a change in speed between the engine and the compressor, would also not give very satisfactory results, either because the peripheral velocity of the propeller cannot exceed a certain value, or because the efficiency of the compressor is always low, and there would accordingly be an altitude at which all the power supplied by the engine would be absorbed by the compressor.

A third solution, and perhaps the best from the theoretical viewpoint, is that of the turbocompressor, which comprises a turbine driven by the exhaust gases and convected with a centrifugal compressor. The higher pressure of the exhaust gases, as compared with that of the atmosphere, is thus utilized, with the result that the angular velocity and the power supplied to the compressor increase with the altitude, while the power furnished by the engine remains constant. Nevertheless this system is not recommended by the experience of recent years, especially for the excessive peripheral velocities necessarily attained by the turbine and for the high temperatures reached by the turbine vanes.

Due to the above-mentioned considerations, Colonel Italo Raffaelli, in an interesting article in the September (1931) number of Rivista Aeronautica, advocated the adoption of steam engines for airplanes designed to fly at very high altitudes. The functioning of steam engines is, in fact, quite different from that of explosion engines. The power furnished by the latter is, indeed, also affected by the weight of the air inducted per unit of time, but, in order to keep this weight constant, it is not necessary to resort to compressors, since it suffices to increase, with the altitude, the opening of the air-inlet valve or the intake velocity, which latter is accomplished in part automatically by the effect of the greater translational speed of the airplane at high altitudes.

The power furnished by a steam engine can therefore be kept constant to any altitude, at least so long as there is enough oxygen in the atmosphere. The low temperatures existing at high altitudes, together with the high translational speed, would facilitate the condensation of the steam and thus appreciably increase the power and efficiency of the engine. It is known, moreover, that the first attempts to fly were made with steam engines, which were soon abandoned, however, because of their excessive weight and high specific fuel consumption.

With the progress in naval engineering, the steam engine has been greatly improved, although the problems of lightness and fuel consumption are not so important for ships. There are now, in fact, on some German torpedo boats, complete engines whose weight does not exceed 6 kg (13.2 lb.) per hp and whose fuel consumption is less than 260 grams (0.573 lb.) per horsepower-hour.

Their weight is still rather great in comparison with that of explosion engines, but it should not be difficult to reduce it to 4 kg (8.8 lb.) per hp, as predicted by Raffaelli in the article referred to. If the comparison with explosion engines is made at high altitudes, instead of at sea level, the steam engines have the advantage. Taking, as the basis of comparison, a weight of 0.8 kg (1.76 lb.) per hp for explosion engines, which is one-fifth of that predicted for steam engines, conditions would be equal at an altitude of about 11,000 m (36,090 ft.), at which height the power of explosion engines is only one-fifth of their power at sea level. At altitudes above 11,000 m (which have actually been attained), the advantage would be with the steam engines.

As regards the fuel consumption of 0.26 kg (0.573 lb.) per horsepower-hour, this is only a little more than that of ordinary explosion engines at sea level and is considerably less than that of the latter at high altitudes.

As regards the engine, we think the predicted weight is susceptible of reduction. Colonel Raffaelli, in the article referred to, predicts the use of superheated steam at pressures of 50 to 100 atmospheres. It might be better to attain the critical temperature of water, 374°C (705.2°F.), which corresponds to a pressure of 225 kg/cm² (3200 lb./sq.in.). At this temperature, water passes from the liquid to the gaseous state without change of volume and without the formation of bubbles, thus obviating the need of a receptacle for the steam. The boiler could therefore be reduced to a simple coil, to which the water could be supplied under pressure by a pump, with great advantages as regards bulk and weight and the smaller quantity of water in the boiler.

Moreover, the specific heat of saturated steam is minimum at the critical pressure, whence also for this reason, with equality of hourly production of steam, the dimensions of the boiler can be reduced to the minimum. The low heat content does not involve a greater consumption of steam than at normal pressures, due to the fact that in starting with the critical conditions, the specific heat of 0.5 is reached almost at the beginning of the expansion and this specific heat is held almost constant at any final expansion pressure. Since, in starting, instead, from saturated steam under any other pressure, or, still worse, in starting from superheated steam, the final specific heat would always be above 0.5, this fact simultaneously leads to the best utilization of the thermal energy of steam and to the reduction to the minimum of the residual heat absorbed in the condenser. Hence the dimensions and weight of the condenser are also reduced to the minimum.

A few figures may make this clearer. The total heat of vaporization of water at 225 kg/cm² (3200 lb./sq.in.) and 374°C (705.2°F.) is 501 calories. We assume, for reasons which will become apparent, that the condenser contains a 50% vacuum, or a pressure of 0.5 kg/cm² (7.11 lb./sq.in.) at a temperature of 81°C (177.8°F.). Considering that the specific heat at the turbine outlet is 0.5, the final thermal content is 356 calories. The quantity of heat corresponding to the pressure increase is therefore 145 calories per kilogram of steam, equivalent to 0.229 horsepower-hour. Assuming a total turbine efficiency of 80%, which can at least be obtained at high powers, the steam consumption is 5.46 kg (12.04 lb.) per horsepower-hour, developed by the turbine.

It is necessary, however, to take account of the energy absorbed by the pump, which must draw the water from the condenser at a pressure of 0.5 kg/cm² (12.04 lb./sq.in.) and force it into the boiler at a pressure of 225 kg/cm² (3200 lb./sq.in.). By a simple calculation, taking account of the efficiency, it is found that the pump absorbs about 5% of the power furnished by the turbine. Taking this into account, the consumption of steam amounts to 5.75 kg (12.68 lb.) per horsepower-hour.

As regards the boiler, since the intake temperature of the water may be assumed to be that of the condenser, or 81°C (177.8°F.), which corresponds to a thermal content of 81 calories, it should impart to the fluid, for every horsepower-hour, a quantity of heat equal to

$$5.75\ (501-81) = 2415 \text{ calories.}$$

The "Manuale dell'Ingegnere" of Colombo (1929 edition) describes the Benson serpentine boiler which generates steam at the critical pressure with an efficiency of 90%. We will therefore assume that, in the special case under consideration, it is possible to attain an efficiency of 85%. In this case the heat produced per horsepower-hour amounts to 2850 calories. If, therefore, naphtha with a calorific value of 10,500 calories is used, the fuel consumption with such an engine will be about 0.271 kg (0.597 lb.) per horsepower-hour, a little greater than that previously indicated, but still satisfactory, especially on account of the smaller weight of the engine in question.

Lastly, let us consider the condenser. In present-day stationary plants, the normal vacuum is 95%. We have assumed, however, a vacuum of only 50% because, in the case under consideration, it is more convenient not to reduce the pressure and temperature too much, so as not to be obliged to adopt very thick walls and excessive radiating surfaces. This does not prohibit us, however, from reducing the pressure and temperature inside the condenser, when they are reduced externally with increasing altitude.

Under the given conditions the mean temperature is about 10°C (18°F.) higher than in the radiators of ordinary explosion engines. Taking into account, therefore, the lower coefficient of external heat transmission of the steam, as compared with water, and the greater thickness of the walls of the condenser in comparison with the radiator walls, it may be assumed that the heat dispersed per unit of time and surface area is approximately the same in both cases. The comparison between the two surface areas is therefore made on the basis of the quantity of heat to be dispersed. In the case of the condenser and on the basis of the above-mentioned data, we have

$$5.75 (356-81) = 1580 \text{ calories}$$

for every horsepower-hour while, in the case of the radiators, we have only about 500 calories. Hence, with equality of power, the surface area of the condenser of a steam engine must be about three times as great as that of the radiator of an explosion engine. The ratio between the weights may be assumed to be about four. These values are rather large, but not prohibitive.

As regards the complete engine, it may be assumed that the attainment of the critical pressure and the relatively high pressure in the condenser enable a saving of 25% in weight as compared with the weight of the superheated steam engine at a relatively low pressure and that, therefore, the total weight may be reduced, without excessive difficulty, to 3 kg (6.6 lb.) per horsepower.

Disregarding the interesting disposition of the various parts of the steam engine proposed by Colonel Raffaelli, we agree with him that great improvement in high-altitude flight is possible by using steam engines.

Of course this is not the complete solution of the problem, which can be obtained only through jet propulsion. Even with steam engines, it is possible to keep the power constant, or increase it slightly with increase in altitude, but it is certainly not possible to keep the traction constant, or to increase the power in proportion to the velocity. By adopting steam engines, we will therefore have an airplane ceiling. Moreover, in order to keep the power constant at any altitude, it is necessary to use variable-pitch propellers.

We now see what results can be obtained with an engine having the above-mentioned characteristics, namely, a weight of 3 kg/hp (6.6 lb./hp) and a fuel consumption of 0.27 kg (0.595 lb.) per horsepower-hour. Referring to the hypothetical engine, with the principle of which we are now occupied, we assume the installation of a specific power of 80 hp/ton (1000 kg or 2205 lb.), with which the weight of the engine would increase to about one-fourth the total weight of the airplane. Assuming that the propeller has an efficiency of 75%, the disposable power becomes 60 hp/ton, with which it is possible to acquire a speed of over 230 km (143 miles) per hour at an altitude of over 12,000 m (39,370 ft.). (Fig. 2.) The fuel consumption per ton-kilometer is then

$$80 \times 0.27 \div 230 = 0.094 \text{ kg } (0.207 \text{ lb.}).$$

In order to obtain the same speed at sea level, 152 hp/ton would be necessary; and assuming a propeller efficiency of 80%, 190 hp/ton would be required. With a specific fuel consumption of 0.23 kg (0.507 lb.) per horsepower-hour, the consumption per ton-kilometer would be

$$190 \times 0.23 \div 230 = 0.19 \text{ kg } (0.42 \text{ lb.}),$$

or about double the preceding.

In the latter case, however, the weight of the engine, which is assumed to be of the explosion type, amounts to about 15% of the weight of the airplane, or about 10% less than in the preceding case. This difference corresponds, in the first airplane, to a difference of about 1000 km (621 mi.) in flight range.

If, therefore, both airplanes have a flight range of 1000 km (621 mi.) they can carry the same commercial load, the first one having a fuel consumption of one-half as much as the second. For longer flight ranges, the former can carry a commercial load even greater than that of the latter and therefore the economic benefit is increased. For shorter flight ranges, however, the benefit is diminished. The lower cost of naphtha, as compared with the cost of gasoline, should also be taken into account.

With the same specific power, the only way to increase the speed is to increase the efficiency of the airplane. Aside from increasing the efficiency, it is necessary to reduce the weight of the engine, in order to reduce the ratio of the specific fuel consumption to the commercial load. Nothing can be accomplished in this direction by reducing the wing loading. In fact, with equal efficiency, as follows from equation (2), the necessary specific power is kept proportional to the speed alone and therefore remains constant for the same efficiency and speed, whatever the wing loading may be. Any reduction in the latter increases the flight altitude, which is the variable factor.

It can indeed be observed that, with a reduction in the wing loading and consequent increase in the wing area, the structural drag diminishes and the efficiency increases. On the other hand, the weight of the airplane is increased, which, of course, reduces its carrying capacity. It is therefore necessary, from time to time, to determine the best wing loading.

We have presented the problem from the commercial viewpoint, concluding that the economical benefit from the use of steam engines increases with increase of flight range, while it may be absent or negative for short flights; also that the maximum speed and the specific consumption are only slightly affected by the wing loading.

Examination from military and scientific viewpoints leads to different conclusions. In fact, from these viewpoints, great importance attaches to the highest attainable altitude, which is greatly affected by the wing loading, while the amount of the useful load may sometimes be of secondary importance. Disregarding the propeller, which is supposed to be adapted to the flight conditions under consideration, the attitude corresponding to the maximum altitude is the one corresponding to the minimum power required for flight at sea level.

Returning to our hypothetical airplane, we find that the attitude in question, with a wing loading of 50 kg/cm^2 (711 lb./sq.in.), corresponds to a speed of 98 km (61 mi.) per hour and a specific power of 27 hp/ton. (Fig.2.) If this attitude is constantly maintained, the necessary specific power will be, as before, proportional to the speed, but independent of the attitude and of the wing loading. If, therefore, it is assumed that we have, in the case considered, 100 hp installed and 75 hp effective per metric ton, with the weight of the engine equal to about 0.3 of the total weight of the airplane, the maximum speed will be

$$98 \times 75 \div 27 = 272 \text{ km (169 miles) per hour.}$$

If we introduce into equation (1), on the other hand, $V = 272$ km/h $= 75.55$ m/s and $C_p = 0.55$, the latter being the coefficient of lift corresponding to the attitude of minimum power, then

$$Q = 3140 \; \rho \; S = 392.5 \; \delta \; S,$$

from which

$$\delta = 0.00255 \; Q/S.$$

Therefore the relative density of the atmosphere diminishes, or the highest attainable altitude increases, with the reduction in the wing loading. The obtainable results are as follows.

Wing loading, QS	50	40	30	28.25
Relative density, δ	0.128	0.102	0.0765	0.072
Altitude, m*	16,300	17,800	19,600	20,000

Theoretically, therefore, the maximum attainable altitude is not limited. Practically, however, the wing loading and, consequently, the altitude are limited by the weight of the airplane. It is known that, in the case under consideration, it is possible to reach an altitude of 20,000 m (65,617 ft.) with a wing loading of 28.25 kg/m² (5.79 lb./sq.ft.), which is not too low.

We will now mention the aerodynamic characteristics, which a high-altitude airplane should have. From equations (3) and (4), after eliminating V, we obtain

$$\frac{\Pi}{Q} = \sqrt{\frac{C_r^2}{C_p^3}} \sqrt{\frac{Q}{\rho \; S}}$$

In order to reach the maximum altitude with unimpaired power, it is therefore necessary, as already seen, to reduce to the minimum the wing loading Q/S and the coeffi-

*m X 3.28083 = ft.

cient of power

$$\eta = \sqrt{\frac{C_r^2}{C_p^3}}$$

As we have already seen, it is then important to have the maximum efficiency,

$$E' = C_p/C_r!$$

Hence the polar of a good high-altitude airplane must have a very small coefficient of power and a very great efficiency, and resemble, in this respect, the polars of long-distance airplanes. The polar in Figure 1 is almost ideal. It closely resembles, however, the polars of the most recent long-distance airplanes from which it was derived. As shown by the figure, the coefficient of power hardly reaches the value of 0.1 with a lift coefficient of 0.55. The efficiency, however, exceeds 14 for C_p = 0.45. One notes a rather high maximum lift coefficient and a small variation of the drag coefficient in terms of the lift, which indicates the adoption of a highly cambered and much elongated wing. The minimum coefficient of drag, however, is not lower than the normal, but this does not affect the particular use of airplanes not designed for high speeds at low altitudes.

In order to obtain the above-mentioned characteristics, it is therefore necessary, first of all, to have wings with a high lift coefficient, even though their profile drag is not very small. In the second place, it is necessary to have wings with a large aspect ratio. Lastly, the structural drag must be reduced to a minimum.

Before finishing this brief survey of the problems encountered in high-altitude flight, we will call attention to the problem of hermetically sealing the cabin. Above a certain altitude, it is no longer sufficient to resort to oxygen inhalers and electrically heated garments, but it is necessary to create for the pilot and passengers a habitation, in which the conditions of pressure and temperature, if not the same as at sea level, shall at least be those of an altitude at which one can live without discomfort. Such was the case of Piccard in his stratospheric balloon.

The German firm of Junkers, which has recently constructed an airplane with which it is hoped to reach an altitude of 20,000 m (65,617 ft.), has encountered serious difficulties in obtaining the impermeability of the cabin. After long experimentation, it has been compelled to adopt double windows and doors with special glass 1 cm (0.39 in.) thick with an intervening space of 7 cm (2.76 in.). The seriousness of this last problem resides in the fact that the accidental breaking of a window would entail the almost instantaneous death of the pilot and passengers through embolism of the brain and heart.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

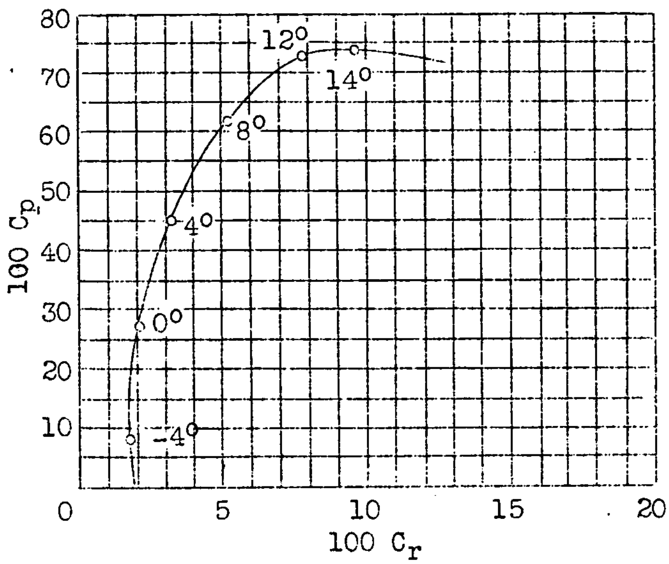

Fig.1 Lift coefficient of airplane plotted against drag coefficient.

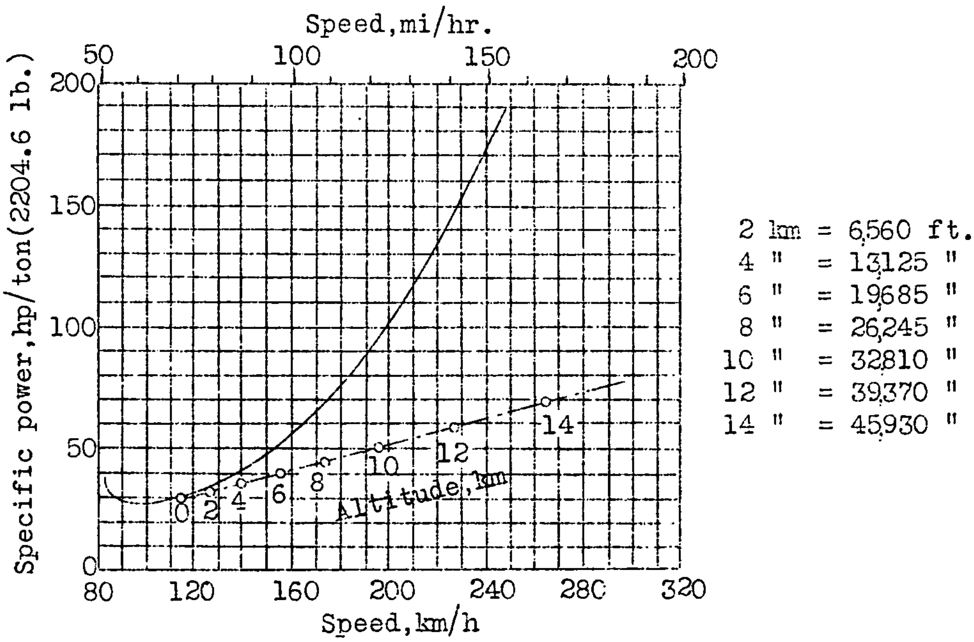

Fig.2 Specific power in hp/metric ton plotted against speed.