NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

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PRACTICAL POSSIBILITIES OF HIGH-ALTITUDE FLIGHT WITH EXHAUST-GAS TURBINES IN CONNECTION WITH SPARK IGNITION ENGINES
COMPARATIVE THERMODYNAMIC AND FLIGHT MECHANICAL INVESTIGATIONS

By A. Weise

Translation
"Praktische Möglichkeiten des Höhenfluges mit
Abgasturbinen an Zündermotoren
Vergleichende thermodynamische und flugmechanische Untersuchungen"
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SUMMARY

As a means of preparing for high-altitude flight with spark-ignition engines in conjunction with exhaust-gas turbosuperchargers, various methods of modifying the exhaust-gas temperatures, which are initially higher than a turbine can withstand, are mathematically compared. The thermodynamic results first obtained are then examined with respect to the effect on flight speed, climbing speed, ceiling, economy, and cruising range. The results are so presented in a generalized form that they may be applied to every appropriate type of aircraft design and a comparison with the supercharged engine without exhaust-gas turbine can be made.

I. INTRODUCTION

If sufficient power output from an aircraft engine is to be maintained at very high altitudes in spite of the reduction in air density, the air for combustion must be precompressed in a supercharger. Even below stratospheric altitudes that are foreseen for the long-distance flying of the future, the portion of engine output consumed by the supercharger is considerable. In order to balance this loss, it is desirable to use the energy that is still

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available in the exhaust gas at the end of the power stroke due to the excess pressure and temperature of the gas by continuing its expansion in an exhaust-gas turbine.

The fundamental theoretical relations involved in the operation of high-altitude engines with superchargers and exhaust-gas turbines have been fully expounded by Hansen (references 1 and 2). By methods of computation that he devised, Hansen derived the useful work outputs, fuel-consumption indices, specific weights, and cooling surfaces for numerous examples of high-altitude engines. In achieving a simple and clear picture of what was technically possible, many practical limitations and secondary influences were not considered. These factors must be taken into account, however, before an experimental unit can actually be constructed.

One of the problems arising in this connection is dealt with in this report. It concerns the control of the high exhaust-gas temperature in the operation of exhaust-gas turbines in connection with spark-ignition engines. The exhaust gas, the temperature of which is between 750° and 1050° C, cannot be fed directly into a turbine because the materials in the turbine will not withstand a temperature of more than 600° C for continuous operation. As a means of circumventing this difficulty certain cooling systems have been proposed, which are compared in this report with respect to technical practicability, economy, and effect on flight speed, climbing speed, ceiling, and flight range of aircraft.

The influence of excess scavinging and combustion air upon the economy of the Diesel-engine system must be studied. This part of the problem has been covered in reference 3; therefore, the present report has to deal only with cooling systems for exhaust-gas turbines operating in conjunction with spark-ignition engines. The primary classification of the cooling systems is based on whether the exhaust gas itself or the mechanical parts endangered by exposure to it are cooled.

II. COOLING OF EXHAUST GAS

The manner of operation of the two systems for cooling the exhaust gases that merit consideration, mixture cooling and surface cooling, will now be described.

1. Description of Systems

A. Description of mixture-cooling system. - In the mixture-cooling system, before the exhaust gas enters the turbine, it is mixed with compressed air supplied from the regular supercharger compressor. In addition, the cylinders of the four-cycle spark-ignition engine may be scavenged with compressed air in order to increase the charge by removing all traces of combustion gases and thereby increasing the power output. The thermal and mechanical demand on the engine, in that case, is increased just as in the case of increasing the suction pressure. The scavenging air, which obviously cannot pass through the carburetor, may be suitably controlled by means of a rotary slide valve in the induction pipe.

Figure 1 shows a flow plan for the mixture-cooling system in combination with cylinder scavenging.

Elimination of the rotary slide valve is made possible by adopting the gasoline spray injection system now being tested; with this system the loss of fresh mixture into the exhaust duct can be easily prevented by suitable timing of the beginning of the injection.

When the system just described is used, the supercharger and the turbine must be built for a greater flow than would be required for the engine alone. On the one hand, additional work must be expended in the supercharger to provide the mixed air; but on the other hand, this air mixed with the exhaust gas performs additional work in the turbine.

B. Description of surface-cooling system. - In surface cooling the temperature of the exhaust gas is reduced by heat exchange with the atmosphere. For this purpose the gas is led from the engine through a heat exchanger, the outer surface of which is exposed to the flight stream. The combustion space may also be scavenged with this system. The supercharger and turbine may be of a size to supply the requirements of only the engine.

The flow plan in figure 1 will apply to surface cooling with scavenging if the mixture-air supply line is removed and the mixing nozzle is replaced by the exhaust-gas cooler.

With either system the engine does not operate with free exhaust. A loss of power is caused by the stagnation of the gases in the exhaust duct, mixing nozzle, or exhaust-gas cooler.

C. Comparison of system without turbine. - The gain due to the exhaust-gas turbine was readily made apparent by computing comparable values for the engine with the supercharger alone, that is, without a turbine.

2. Thermodynamic Computations

A. Method of computation. - The computations are based on the work by Hansen (references 1 and 2). The methods of computation developed therein have been suitably modified where necessary in accordance with the new problems. Only as much explanation of the method of computation will be given as will enable them to be verified with the aid of Hansen's exposition and of generally familiar thermodynamic methods of computation. The assumptions and the conditions will be fully specified.

(a) Engine work

The two systems will be compared as applied to a BMW-VI four-cycle aircraft engine with a compression ratio $\epsilon = 6.0$; in both cases the combustion space will be scavenged. For the variation of air pressure and temperature with altitude, the values of the CINA (international standard atmosphere) will be used. Hansen's formulas have been adapted for the decrease of oxygen content of the air in the stratosphere. In certain cases, calculations for an altitude of 20 kilometers were made with the assumption of unchanged oxygen content for comparison. These comparison points have been indicated on the graphs by asterisks and arrows.

The final supercharger compression is taken as 1.16 standard atmospheres, the pressure in the compression chamber before and after the scavenging as 1.10 standard atmospheres, and the pressure in the exhaust-gas receiver as well as that in the cylinder, at the end of induction as 1.033 standard atmospheres. These values take account of all required pressure drops and allow for a small additional loading of the engine as compared with operation without a supercharger. Avoidance of excessively large cooling surfaces is made possible by considering the recooled air supplied from the supercharger as having a temperature of 60° C at all altitudes. Near sea level the temperature of the induction air could be lower in reality. This fact is disregarded as the influence is small and we are concerned with high-altitude flight. The effectiveness of cylinder scavenging is assumed to be such that $\nu = 0.25$ of the residual combustion gases present in the compression chamber at the end of the exhaust stroke will remain there. The excess-air factor is $z_l = 1.1$.

The quadratic equation given by Hansen in reference 1 (p. 8, formula 3) is applicable in the case of combustion-chamber scavenging also, provided that $1/\epsilon$ is entirely replaced by ν/ϵ.

(b) Supercharger work

The supercharger work was also computed on the basis of the pressures given under (a). The large pressure ratio per stage chosen by Hansen, namely 2.2, has been retained. The intercooling between the individual stages was limited to a minimum temperature of 60° C. The supercharger-work quantities were computed for adiabatic efficiencies of 0.5, 0.6, and 0.7. According to measurements now available (reference 3), the efficiencies of one- and two-stage superchargers vary between approximately 0.5 and 0.6. In the case of multistage superchargers for high-altitude flight, the pressure drop in the intercoolers also must be allowed for, thus reducing the over-all efficiency. Until further progress in supercharger construction is an accomplished fact, an efficiency of not more than 0.5 and 0.6 can probably be expected.

(c) Turbine work

The turbine work was computed for stagnation conditions in the exhaust according to Hansen (reference 2) and on the basis of an unvarying receiver pressure of 1.033 standard atmospheres. The temperature of the exhaust gas or of the mixture of exhaust gas and air was fixed at 600° C. The cooling of the exhaust gas due to expansion in the nozzle does not substantially reduce the thermal load on the leading edge of the blades because, according to Ackeret (reference 4, p. 306), the temperature of the boundary layer at the surfaces is approximately that prevailing before the expansion. Only the participation of radiation from the gas in the transfer of heat to the blade becomes smaller.

In computing the consumption of mixture air in mixture cooling, the calculation was based on the use of cooled compressed air. If uncooled air were used, only a somewhat lighter and smaller air aftercooler would be obtained for the last stage of the supercharger and against this gain the auxiliary mechanical units (supercharger and turbine) would have to be substantially heavier on account of the greater quantity of mixture air required; therefore, the mixture of cooled air should be more advantageous.

In the computation of the efficiency of the turbine, which is based on steam-turbine theory, the deduction of 10 percent made by Hansen (reference 2) for the shock and heat losses associated with free exhaust was not made. The reduction of power output due to clearance loss and bearing friction was estimated at 4 percent. Furthermore, the efficiency computed for an altitude of 20 kilometers was not used for all altitudes as it was in Hansen's work; instead, the higher efficiencies calculated for lower altitudes were used. The turbine efficiencies at the shaft η_T calculated from the available adiabatic heat drop are shown in figure 2; these efficiencies, in both mixture cooling and surface cooling, are attainable up to an altitude of 15 kilometers with one simple impeller at a peripheral speed of not more than 300 meters per second and above 15 kilometers with two counterrotating impellers having peripheral speeds of 300 and 200 meters per second.

For the computation of the heat drops and the mixing processes, an i-s diagram was used for air and for a normal exhaust gas (resulting from a fuel mixture of 1/3 BV-benzol and 2/3 medium gasoline burned with an excess air factor of 1.1 and 0.21 oxygen content of the air). This diagram was computed by using the average specific heats given by Mollier (reference 5).

(d) Specific weights of structural units

The specific weights of the engine units, which were computed in accordance with the reasoning set forth by Hansen (reference 2), were divided by the specific weight of the engine at sea level g_{Mo}. Unfortunately, sufficient experimental data are unavailable as to the ratio of the specific weight of the supercharger and the turbine to that of the engine itself. Therefore, this ratio x was treated as uniform and by considering its limits $x = 0$ and $x = 1$ all possible cases were included. In practice, x should lie between 0.4 and 0.6.

(e) Specific weights and surface areas of cooling units

As in Hansen's work (reference 2), the specific weight of the engine cooler at sea level was set at 0.10 to 0.135 of the specific weight of the engine at sea level, an assumption that may be correlated with recent estimates by Fuchs, Hopf, Seewald (reference 6), if engines of very light construction are disregarded. The weight of a gas cooler was assumed to be half as great for a given surface area as that of a water cooler. The weight of the cooler plays only an unimportant part in the final result.

The case is different with the cooling surfaces, which substantially affect the total resistance of the aircraft and must therefore be more accurately computed.

In accordance with the procedure followed throughout this report, only ratios were computed at first; namely, all heat-exchanging surfaces were based on the cooling surface of the engine cooler at sea level; for this purpose a wall temperature in the engine cooler of 75° C was assumed.

For the rest of the ratios, many assumptions and methods of calculation having to do with heat transfer have been modified as compared to Hansen's procedures (reference 2), while maintaining the same form of the law of heat transfer (reference 7) (dependent upon velocity, pressure, and temperature).

The average wall temperatures of the gas coolers were not estimated but calculated. In this connection the flow velocity of the supercharger air and the exhaust gas was considered as not varying with altitude, namely, as equal to only one-half the flight speed at sea level. Even so the pressure loss in the coolers will be quite large.

The form factor for heat transfer was taken as 2.3 greater for the outside (corresponding to four rows of tubes normal to the air stream) than for the inside (corresponding to the inner wall of one tube (reference 8)).

Particular difficulty was encountered in deciding upon a formula for the dependence of flight speed on altitude. Hansen based his calculations upon unchanging impact pressure, that is, upon an increase of flight speed inversely proportional to the square root of the air density. This pronounced increase of speed results in small cooling surfaces but can be attained only under conditions that yield no satisfactory basis for comparisons. That is, flight at sea level can be significantly compared with high-altitude flight only if the proportion of power-plant weight to total aircraft weight is taken as the same in each case and if, in addition, it is postulated that the power-plant loading coefficient remains the same at various altitudes. Unchanging impact pressure requires a substantial increase of the thrust power; a fact that cannot be correlated with the requirements just mentioned. If the increase in flight speed with altitudes was taken as inversely proportional only to the cube root of the air density, the increase would be approximately equivalent to constant flight power. Even this increase cannot be attained in practice under these requirements, because the specific weight of high-altitude power plants generally increases with altitude.

Nevertheless, a certain increase in flight speed with altitude may be expected. The exact formula of the increase becomes apparent only as the final result of all computations; it will not be the same for all aircraft. The exact values for the cooling surfaces can therefore be found only by a process of gradual approximation, taking into account certain numerical values pertaining to the aircraft structure. The resulting increase in difficulty of the problem is prohibitive for this investigation. Consequently, the calculations were based throughout on an increase of speed corresponding to the reciprocal of the cube root of the air density, whereby the cooling surfaces computed are too small. The magnitude of the errors will be computed at the end.

B. Results of mixture cooling. - The discussion of the results will be based on reference to the figures, in which the results are plotted as functions of the altitude. In calculations of the effect of altitude, it is assumed that at each point the auxiliary mechanical units and the coolers are of the proper sizes for the outputs required at the respective altitudes. Therefore, the diagrams do not represent the behavior of the same power plant at various altitudes.

Figure 3. Mechanical work of engine, supercharger, and turbine in meter kilograms per liter of displacement and per working cycle. If the supercharger efficiency is 0.5, the work input of the supercharger can no longer be met by the turbine even at an altitude of a few kilometers. The same condition applies in the stratosphere for a supercharger efficiency of 0.6 or less.

For comparison there is plotted as a dashed line the engine work output for operation without scavenging and slight supercharging. At sea level the work output is increased 14.5 percent by scavenging and supercharging.

Figure 4. Useful work of the whole installation, that is, the sum of engine and turbine work output minus supercharger work input. For the supercharger efficiencies attainable in practice, the useful work, especially in the stratosphere, decreases much more rapidly than in the installation calculated by Hansen without consideration of necessary cooling. Even the assumption of unaltered oxygen content of the air does not change this very much.

Figure 5. Relative increase of the scavinging-air quantity and exhaust-gas quantity due to the mixture process. At sea level the supercharger and turbine must be built for almost double the flow of scavenging air and exhaust gas. In the stratosphere the consumption of cooling air is less, in accordance with the decreasing oxygen content.

The exhaust-gas quantity increases relatively less than the quantity of air required to be compressed because the exhaust-gas quantity in itself and its relative value compared with the air quantity are greater by the amount of the fuel quantity.

Figure 6. Specific fuel consumption based on the effective output of the whole installation for supercharger efficiencies of 0.5 and 0.6. (The result for surface cooling is also plotted in this diagram for comparison.) Corresponding to the decreasing useful power output, the specific fuel consumption becomes substantially greater in the stratosphere. Thus an influence damaging to the economy of high-altitude flight is shown here.

Figures 7 and 8. These diagrams, from Hansen, give a picture of the increase of the specific weight of the mechanical and cooling installations with altitude. Figure 7 gives the increase for a supercharger efficiency of 0.6 and figure 8 for 0.5. The specific weights are based on the specific weight of the engine with a normal water cooler at sea level. The specific weight of the mechanical installation (engine, turbine, and supercharger) is plotted upward from the abscissa axis and the specific weight of the additional cooling installation for high-altitude flight is plotted downward from the axis, therefore the sum of the two may be gaged by the distance between the curves.

The definition of x has already been given (p. 6). The values $x = 0$ and $x = 1$ cover the extreme possible limits. The probable range in practice is shown as shaded. In the case of engines of lighter construction than the BMW-VI model, the additional cooling installation required for high-altitude flight may be relatively heavier.

For a supercharger efficiency of 0.5, already at an altitude of approximately 11 kilometers, the total weight of the power plant will be double and at about 15 kilometers three times its weight at sea level for the same power output.

Figure 9. Relative cooling-surface magnitudes, based on values at sea level, subdivided into the surface required for the engine cooler and that required for the supercharger intercoolers, are superimposed in order that the total surface may be read.

Note the initial decrease and subsequent increase of the cooling surface for the engine cooler, which at great altitudes is exceeded by the surface of the air coolers. Changing of the supercharger efficiency from 0.6 to 0.5 only slightly increases the total surface.

C. Results for surface cooling.

Figures 10 to 14. These figures show, in the same manner as for mixture cooling, the component work quantities, the useful work of the mechanical installation, the specific weights, and the surface areas for various supercharger efficiencies.

Figure 10. The work done in the turbine and the supercharger becomes considerably smaller because the absence of mixture air results in a reduced flow quantity passing through those units.

Figure 11. This figure shows the useful work corresponding to various supercharger efficiencies and should be compared with figure 4.

In the region in which figure 3 showed the turbine work to be greater than that of the compressor, the useful work is somewhat less in the case of surface cooling; elsewhere it is increased, particularly so at low supercharger efficiency.

This fact is explained by the following relations: In both mixture and surface cooling the heat content of the gas in the receiver is the same (except for the very small difference due to the variance in composition) and therefore the turbine work obtainable per unit weight of gas is equal. The gas quantity, however, is greater in the case of mixture cooling and hence the total turbine work is also greater (compare figs. 3 and 10). If this air quantity, which does additional work in the turbine, is to be obtained, additional work of compression must be expended in the supercharger. The ratio of these work quantities is given in close approximation by the ratio of l_T to l_V (fig. 3), as here also it is approximately the same gas quantities that must be compressed and work under the same conditions as the additional air quantity. (Only the quantity of fuel, transformed into gas by the combustion and entering the turbine as an additional gas quantity, causes a very small difference, which may be ignored in this discussion for the sake of simplicity.) If l_V is greater than l_T when there is no mixture, an amount of work equal to the difference $l_V - l_T$ may be saved. As the mixed quantity of air is, according to figure 5, quite considerable, some important differences result. At the supercharger efficiencies that can be expected in practice, surface cooling proves to be clearly superior even below stratospheric levels; at an altitude of 16 kilometers it yields 27 percent more output for a given engine displacement and speed at 50 percent supercharger efficiency. This advantage is strikingly expressed in the specific fuel consumption, which has already been shown in figure 6 in connection with mixture cooling.

Figures 12 and 13. The superiority of surface cooling in respect to useful output is also shown in the corresponding specific weights; even the additional exhaust-gas cooler makes no difference in this respect.

Figure 14. The representation of the cooling surfaces proves that the size of the exhaust-gas cooler makes itself felt only near sea level, that is, in a region not very important in practice. At higher altitudes the saving due to the smaller compressed-air cooler is so large that the total cooling surface is actually smaller than in the case of mixture cooling.

Figure 15. This figure permits a comparison of the total surfaces for mixture and for surface cooling at a supercharger efficiency of 0.5. In addition, the cooling-surface requirements for operation without turbine, that is, with engine and supercharger alone, are plotted here.

Figure 16. In order to determine whether an exhaust-gas cooler is operable, the highest wall temperatures expected had to be calculated.

The figure shows how the wall temperature at the exhaust-gas inlet side of the cooler varies between the exhaust-gas temperature and that of the outside air. Even at the highest flying altitudes the wall temperature lies far below the permissible limit. If the size of the cooler were decreased it would be necessary in redesigning to try to improve heat transfer on the inside; at the same time, of course, the heat transfer on the outside cannot be allowed to become less efficient.

An important consideration in this regard is the pressure loss in the exhaust-gas cooler because it involves a loss of work in the turbine. The advantage of a lighter cooler having less air resistance must therefore be weighed against the disadvantage of loss of turbine output.

Figure 17. The effect of pressure loss in the exhaust-gas cooler on the turbine output is illustrated by plotting the turbine work obtainable per kilogram of exhaust gas with surface cooling for two different receiver pressures, namely 1.033 and 0.8 standard atmospheres. As the pressure loss in the exhaust-gas cooler may be considered as not varying with altitude, it becomes evident that the loss of work even with high resistance of the exhaust-gas cooler becomes relatively small at high altitudes. The loss is easily understood because the work obtainable is dependent on the pressure

ratio and not the pressure drop. The loss is even smaller if calculated by comparison with the turbine work in the case of mixture cooling (shown as a dashed line) because the mixture cooling is a little lower in spite of equal exhaust-gas temperature due to the different composition of the gas.

A conception of the loss of work due to exhaust-gas cooling in general may be obtained by a comparison with the curve for the adiabatic heat drop of the uncooled gases at a pressure of 1.033 standard atmospheres. The loss due to throttling the exhaust is still greater, although it sharply decreases with increasing altitude to which the loss due to the increased back pressure of the engine would have to be added. This value is also shown in the figure.

D. Results for supercharged engine without turbine. - Figures 18 to 20 show, in the usual manner, the most important comparative values for the engine with a supercharger alone.

Particularly striking is the substantially greater specific fuel consumption resulting from the loss of the turbine work.

E. General remarks and deductions concerning cooling systems.

(a) Thermodynamic comparison of two cooling systems

The following quantities are important in the comparative evaluation of the different systems: specific weight, specific fuel consumption, and cooling-surface requirements. In respect to specific weight and fuel consumption, surface cooling is more efficient at all altitudes; only the cooling-surface requirements that affect the over-all resistance of the aircraft are smaller in the troposphere for mixture cooling. For stratospheric flight, surface cooling is to be preferred in every case. The net effect of the smaller weight and larger cooling surfaces on flight characteristics in the troposphere can be made clear only by a flight-mechanical inquiry, which will be presented in section I, subsection 2.

After more thorough investigation into the thermodynamics of the two systems of operating exhaust-gas turbines, the following remarks can be made:

In both the systems under consideration work losses are incurred, as seen from figure 17, due to operating with throttled exhaust, that is, because a part of the work ability, which the exhaust gas still possesses at the end of its expansion in the cylinder, is destroyed by the irreversible exhaust process. If the exhaust gas is then cooled by irreversible heat exchange in the exhaust-gas cooler, it undergoes a further loss of work ability. This loss, also shown in figure 17, must be charged against the cooling process itself. In the case of mixture cooling, when compressed air is added to the exhaust gas an irreversible mixing process is initiated that must also, according to fundamental thermodynamic laws, involve work losses. These losses are smaller than in the case of surface cooling because a part of the heat content of the exhaust gas remains available in the warmed mixture air. The additional turbine work thus obtained does not suffice, however, to compress the additional air required at the turbine and supercharger efficiencies available in practice. There remains a deficit, which in the last analysis makes the process less desirable than surface cooling.

(b) Transfer of power between engines, turbine, and supercharger

The useful work of the whole high-altitude power plant may be defined as the algebraic sum of three individual outputs. The question is, how this theoretical calculation may be realized in practical technique.

In the exceptional cases, in which turbine work and supercharger work are equal, the simplest solution is the direct coupling of turbine and supercharger.

It is a different matter when surplus turbine work is to be made usable at the propeller or when more work must be put into the supercharger than the turbine can supply. A transfer of output between the engine and the turbosupercharger is then necessary. For flight at a given altitude, such a transfer of output may be mechanically accomplished without too much complication. However, if it is then desired to fly at a different altitude - and in practice it must be done - complicated transmission devices, for example fluid drives, cannot be avoided because of the speed changes of the individual units. Further discussion of this point will be found in the report by Hansen (reference 2).

The mechanical difficulties would presumably be less if, in the case of insufficient turbine power, the supercharger were split, that is, if the turbosupercharger were mechanically independent and an auxiliary compressor driven by the engine were used to supply the extra supercharging power.

As another means of avoiding the mechanical transfer of power between the engine and the supercharger group, the impact pressure on the turbine blading might be increased until it reached the point at which the turbine output would be just sufficient for the needs of the supercharger. If the pressure were increased, the engine output would decrease because of the higher back pressure and an appropriate investigation would be required to determine the effect of this arrangement upon the useful output.

One thing can be said now on this subject: As the turbine work is dependent upon the pressure ratio, a specified increase in receiver pressure will produce an increase in turbine work, which will be smaller in proportion as the pressure ratio, that is, the altitude, is greater. Thus the gain will unfortunately be lacking just when it is most desired. On the contrary, the loss of engine work is proportional to the pressure drop and is therefore independent of the altitude. It follows from this statement that the method of increasing the impact pressure presumably will not enable going very much farther into the application of direct coupling between supercharger and turbine.

3. Flight-Mechanical Deductions from Thermodynamic Results

A. General foreword. - Before definite judgement can be passed on the practical value of the systems under consideration, it must be determined how their thermodynamic qualities affect the flight characteristics insofar as these depend upon the power plant. These flight characteristics consist of flight speed, climbing speed, ceiling, cruising range, and index of economy.

In such problems the practice has been to select specific aircraft types of known flight-mechanical data and, starting from them, to calculate the changes in the flight characteristics. However, this procedure cannot be satisfactory in an investigation aiming at thoroughness and lucidity because the results would be accidental and even the use of a highly diversified selection of types would not give an insight into the exact way in which particular characteristics behave, that is, the results could not be generalized.

A contribution to a general solution was made by Schrenk (reference 9), who organized the flight-mechanical relations (references 10 and 11) discovered by him into a general diagram for high-altitude flight and applied this to Kamm's investigations (reference 12) of the high-altitude engine with exhaust-gas turbine. However, he limited his use of this method to the computation of the flight speed; for the determination of the cruising range he returned to the method of recalculating a specific aircraft type.

Schrenk took account of only the specific weight of the power plant and neglected the important influence of the size of the cooling surfaces.

Devoting a separate inquiry to the subject, this writer, upon the basis of the cited work by Schrenk, elaborated a method of computing all the previously mentioned flight characteristics from the thermodynamic values of the propulsion system, including therein the influence of the cooling surfaces. The flight-mechanical qualities of the aircraft enter into this representation only in the form of two dimensionless characteristic values.

The first of these is the power ratio α, defined as the ratio of N_0, the flight power delivered by the propeller thrust at sea level, to $N_{so\,\varepsilon}$, the soaring power [NACA Comment: Soaring power is equal to the minimum power required to maintain level powered flight. The term is used in the remainder of the paper with this meaning.] at sea level at the optimum gliding angle. For current aircraft this ratio is always greater than 1; the average value for commercial aircraft is approximately 2.5. The highest value reached today is perhaps $\alpha = 7$. The computations will cover values of α between 1 and 10.

The second characteristic value is the resistance ratio φ, defined as the ratio of the frontal resistance of the normal engine cooler (for flight at sea level) to the total frontal resistance of the aircraft and based on a power-ratio $\alpha = 1$. If $\alpha > 1$, the value determined for the frontal resistance of the cooler must be diminished by the ratio α in order to calculate φ.

Careful investigation shows that φ^*, a factor of φ, does not depend on α but, given equal technical excellence of cooler design, depends only on $v_{o\,\varepsilon}$, the gliding speed of the aircraft at optimum gliding angle. An aircraft that glides more slowly than another will, at a given power-ratio α, also fly more slowly in the same proportion. Consequently, the limiting values of the speed of the aircraft may be substituted for the limiting values of φ^* and it is found that the ratio of cooler resistance to total resistance is greater for high-speed aircraft than for low-speed aircraft. The limits $0.06 < \varphi^* < 0.24$ used for the subsequent computations correspond approximately to surface-loading limits of 45 and 110 kilograms per square meter; (it should be noted that strictly speaking it cannot be expressed in terms of surface-loading alone). The regions corresponding to these limits are shaded in the diagrams. Practically all military and commercial aircraft lie within this region. The more advantageous values apply always to the slower aircraft. The Baumuster Ju 52 design lies approximately in the middle of the region. In the comparative computations that follow, normal water cooling for the engine has been assumed throughout. No consideration has been given to the possibility of using the aircraft skin as a cooling surface without any additional frontal resistance worth mentioning. It is well known that only relatively small cooling-surface requirements can be met in that manner.

Besides the two principal characteristic values α and φ^*, there are two others which are not so important because they are only required when it is desired to convert the characteristic values σ for the climbing speed and λ for the economy or cruising range, which are in themselves very informative indices, into the actual climbing speed or cruising range. The value σ may be converted into the climbing speed by dividing it by the "soaring power loading" $\frac{G}{N_{so\epsilon}}$ (G = weight of the aircraft). For the computation of the actual cruising range, the ratio of the fuel weight to the total weight of the aircraft at take-off is required.

The fundamentals of the computing methods will be set forth in a special report. Only so much will be said here in that connection as is necessary for comprehension of the results.

B. Flight-mechanical evaluation of thermodynamic results. - The flight-mechanical evaluation extends to the specific weights, indices of fuel consumption, and surface areas previously computed for mixture cooling, surface cooling, and a supercharged engine without a turbine. In order to insure clarity in the representation, the evaluation will be made only for a supercharger adiabatic efficiency of 0.6 and for a specific weight ratio of x equal to 0.5. For surface cooling only the results at 50-percent supercharger efficiency are also shown. Thus for the same nominal power the specific weight of the supercharger and the turbine was taken as one-half as great as that of the engine proper. The estimation of x was not made too low because the weights of piping, gearings, couplings, controls, and instrumentation must be counted as part of the weight of the auxiliary mechanical units. If after the construction of such installations, values of x were found that differed markedly from the value used here, that would in no way alter the basic picture. In the case of a smaller value of x, which should, of course, then be used throughout, the different systems would become more nearly alike in their characteristics, although the nature of their differences from each other would remain the same, that is, the less advantageous system would remain so. At lower adiabatic supercharger efficiencies, all results would be less advantageous and the distance between them would increase.

The results of the evaluation will again be discussed with reference to the respective figures.

Figures 21 to 23. From the diagrams for the specific weight (figures 7, 8, 12, and 13), the reciprocal of the sum of mechanical-unit and cooler weights is derived as taken from the average values of the shaded regions. The curves g_o/g plotted therefrom give a picture of the decrease of available engine output as a function of altitude with the total power-plant weight remaining the same. These curves form the basis for the subsequent computations because computations are made on the assumption that as high-altitude flight is reached the proportion of power-plant weight to total aircraft weight does not change. In comparisons made on this basis the tacit assumption is made that the specific weight is independent of the size of the mechanical unit - an assumption that may be readily permitted for these comparisons.

The cooling surfaces previously computed are based on unchanged displacement of the engine. The displacement, however, diminishes in the ratio g_o/g. Thus the cooling surfaces are to be diminished in the same ratio. The resulting curves are also given in the figures. The curves show a maximum value for the cooling surface in the stratosphere, which lies above the sea-level value. At the altitude at which the useful work of the mechanical installation becomes zero, the cooling surfaces also must become infinitely small, because at that point with a given power-plant weight only an infinitely small output can be utilized in the aircraft. For an altitude chamber no additional weight was introduced. This weight would be deducted from the useful load.

Figures 24 to 27. These diagrams serve to compute the climbing speed and the ceiling. The values $\left(\frac{g_o}{g}\right)'$ plotted against altitude represent the effective flight power outputs that remain available after accounting for cooler resistance. These values take the form of pure ratios based on the flight power of an aircraft equipped with only the normal engine cooler and flying at sea level and power ratio $\alpha = 1$.

The $\left(\frac{g_o}{g}\right)'$ curves are plotted for various power ratios. It should be noted that even at sea level the available power is less than the power ratio. This difference in power expresses the fact that a large aircraft expends a part of its surplus power uselessly due to the relatively great cooling resistance. For each power ratio two curves are plotted, the upper referring to very low-speed and the lower to very high-speed aircraft. This method of plotting takes account of the limits of the ratio of cooling resistance to total resistance for the various types of aircraft.

The validity of the curves is limited by the structural dimensions of the aircraft only insofar as these serve to determine the characteristic values α and φ^*. Furthermore, along the course of a curve as it passes through various altitudes the ratio of power-plant weight to total aircraft weight and the ratio of aircraft weight to wing span must be assumed to remain constant. The actual magnitude of these values is unimportant in this connection.

In the diagram will also be found two auxiliary curves, the values of which increase with the altitude. The solid curve gives the minimum soaring power; thus the intersections with the other output curves indicate the ceilings. The distance between this curve and the other output curves measured in the ordinate direction is the previously mentioned comparative value σ for the climbing speed. Logically, at the ceiling altitude it becomes zero along with the actual climbing speed.

It must further be pointed out that it is not possible to find the climbing time in these diagrams by integrating the reciprocal of σ through the altitude of flight because at each altitude there is assumed a different power plant, each appropriately designed for the respective altitude. With the method of representation being used, there can be obtained from σ only the climbing speed, which the power plant designed for the altitude in question will impart to the aircraft when flying at precisely that altitude.

The dashed line that forms a curve similar to the ceiling curve determines by its intersections the altitudes at which flight at optimum gliding angle will take place. The subsequent computations show that the most economical flying altitude is a little less than this altitude.

The comparison of the climbing speeds for the different systems gives the same picture as the comparison of the ceilings in the following figures.

Figures 28 to 30. The ceilings determined from the foregoing diagrams are here plotted against the power ratio, separately for the limiting values of the resistance factor φ^*. The surface-cooling system is clearly more advantageous in every case. Less altitude can be attained with mixture cooling than with a supercharged engine without a turbine. Even with surface cooling the gain due to the exhaust-gas turbine is not very considerable. It is strikingly apparent that the increase of ceiling altitude with increasing power ratio proceeds at an ever diminishing rate. Thus, technical improvement constantly becomes more difficult.

Figure 31. This figure shows an example of how the curves in figures 24 to 26 were plotted in the Schrenk diagram for high-altitude flight for the purpose of deriving the flight speed. This diagram (reference 9) contains only relative values, which are independent of the flight-mechanical data of the aircraft. The abscissa is the ratio of flight speed v to the speed $v_{0\epsilon}$ along the flight path at optimum gliding angle at sea level; the ordinate is the corresponding power ratio $N/N_{s0\epsilon}$. In this grid there are two families of curves, one for equal flight altitudes and one of straight lines for equal gliding-angle ratios ϵ/ϵ_{min}. The line $\epsilon/\epsilon_{min} = 1$ constitutes the envelope curve for the altitude lines and its points of tangency with the lines divide them into two branches. The branch of each curve corresponding to smaller values of $v/v_{0\epsilon}$, that is, to large angles of incidence, terminates at the line $\epsilon/\epsilon_{min} = 1.16$ because the ceiling altitude is reached at that point. The examples plotted in the diagram (which are for the most advantageous system) show that with a given gliding speed the flight speed cannot be very markedly raised and reach a maximum limit.

Figures 32 and 33. Here are shown the maximum speeds computed with the aid of the Schrenk diagram based on the speed that the same aircraft would attain at sea level with the same total power-plant weight. The plotted speed ratios are not the same as those taken directly from the Schrenk diagram because in making comparisons under the assumptions just stated, it is necessary to take into account the fact that the gliding speed of the aircraft $v_{0\epsilon}$ is reduced by the additional cooling surface.

The resulting evaluation is the same as that based on the ceiling altitudes. The increase of speed is greatest in the case of surface cooling; for mixture cooling it is again less than without a turbine. The altitudes for maximum speed are lower than the altitude for optimum gliding angle.

Figures 34 and 35. Here again the maximum speeds are shown separately for high- and low-speed aircraft. The reference value is, in this case, the gliding speed of an aircraft flying at the optimum gliding angle at sea level with its normal water cooler and without a supercharger or turbine, that is, flying with a power ratio $\alpha = 1$. Thus the increase of speed of the sea-level aircraft produced by an increase in power ratio is also given for comparison. Even this value is different for high- and low-speed aircraft because of the different effect of the cooling-surface areas.

Here, too, it may be seen that the gain derived from flying at high altitude becomes markedly effective only at high power ratios. The supercharged engine without a turbine again proves superior to the installation with mixture cooling. The surface-cooling system appears rather less favorably here than previously; therefore at low power ratios it is not as efficient or even a little less efficient than the supercharged engine without a turbine. The reason surface cooling appeared more advantageous in figure 30 was that the calculations for sea level were based on an exhaust-gas cooler so as to obtain a smooth curve. Consequently, the reference value was made too small. For a decisive comparison the representations given in figures 31 and 32 must also be considered. It is then found that an aircraft of the type Ju 52 with a power ratio $\alpha = 2.5$ would gain 15 percent in speed by flying at high altitude with surface cooling, 12.5 percent with a supercharged engine without a turbine, and 7.5 percent with mixture cooling.

Figure 36. When the previous assumptions are checked as to the dependence of flight speed upon altitude, this function is plotted for two limiting cases. Also plotted are the velocity formulas for unchanging impact pressure and for unchanging flight power, by means of which the cooling surfaces were previously computed. As was to be expected, even this increase in speed has not been attained. As the flight altitude approaches the ceiling, the speed decreases so markedly that it may even become less than it was at sea level. Then, of course, the previously assigned cooling surfaces are inadequate by far or the previously computed ceiling will not quite be reached. For the maximum speed, the cooling surfaces in the two examples would have to be 17 and 33 percent greater. This increase means a reduction in both flight power and gliding speed by 4 and 7 percent and a corresponding decrease in the maximum speed. Mixture cooling is more disadvantageously affected by the enlargement of cooling surface, its results therefore becoming still less favorable in comparison to the other systems because in this case the speed departs most widely from the assumed value.

Emphasis should be placed on the fact that the velocity curve does not express the behavior of the same aircraft at various altitudes but that, while maintaining a constant ratio of power-plant weight to aircraft weight and of aircraft weight to wing span, the power plant is assumed to be redesigned for each altitude.

The possibility of actually flying slower at greater altitudes, that is, in air of much less density than at sea level, might appear incomprehensible. However, only at the large power ratios with which high-altitude flight is possible, is flight at sea level accomplished with very small lift coefficients; thus by increasing the angle of incidence the lift can still be markedly increased. Actually there is a limit to this increase, the reaching of which is not automatically noticeable when using the Schrenk assumptions concerning the idealized airfoil-polar diagram. A special check computation showed that within the range covered by this report the limits of what is flight mechanically possible are only reached at the highest power ratios by the fastest aircraft, and even then only if the aircraft are poorly designed aerodynamically. For practical evaluation it is unnecessary to discuss any further the limits of validity and accuracy of the flight-mechanical data employed here.

Figure 37. The altitudes at which the maximum speeds are attained are shown in this figure. The values for mixture cooling, which are not plotted, coincide approximately with those for the supercharged engine without a turbine.

Figure 38. As a measure of the economy of high-altitude flight in comparison with sea-level flight, the index $\lambda = \frac{v/v_o}{b_e/b_{eo}(g_o/g)}$, may be used because a given quantity of fuel will suffice for flight over a distance that will increase in direct proportion to the flight speed, in inverse proportion to the specific fuel consumption, and in inverse proportion to the engine output at the assumed constant engine weight. From the definition of λ, it follows that this index is at the same time a measure of the cruising range or, more precisely, a measure of the differential distance that can be flown with the consumption of an infinitely small quantity of fuel. The total cruising range is to be determined by integration; in this connection, account must be taken of the fact that as the fuel load diminishes the soaring power decreases, whence the power ratio increases if the power plant remains unchanged.

If the value λ is computed as a function of altitude, it is found that the optimum cruising ranges are attained at altitudes that are greater than the altitudes for maximum speed and somewhat less than those for flight at the best gliding angle.

The optimum values for λ found in figure 38 show that by the utilization of the exhaust-gas energy the economy can be considerably improved over that of flight without the turbine. Here also surface cooling is more efficient although not so markedly as in previous calculations. The gain in cruising range is not very great at those small power ratios, which are inevitable in long-distance flight because of the heavy fuel loading. However, because transoceanic flight, for example, is today precisely at the limit of possibility even a small gain may open up entirely new technical possibilities.

In evaluation of the economy of high-altitude flight on the basis of the λ_{max} values it must not be overlooked that λ is based on the sea-level value at the same power ratio. Flight at sea level becomes less and less economical as α increases because the speed increases more slowly than the flight power, as shown in figures 31 and 32. Information would be obtained by comparing high-altitude flight at power ratios greater than 1, which is, of course, more economical than sea-level flight at the same power ratios, with the most economical sea-level flight, namely that obtained at $\alpha = 1$. For this purpose there is plotted in figure 39 the curve that λ_{max} would have to follow if the economy, based on sea-level flight with $\alpha = 1$, were to remain the same. It is seen that with a supercharger efficiency of 0.6, sea-level economy is only possible up to a maximum power ratio of 2.5. Above that point high-altitude flight becomes in every case less economical. The relations take an even more unfavorable form with respect to cruising range because with increasing power ratio the high power-plant weight will make it necessary to decrease the fuel load if the pay load is to remain the same. If this change is disregarded, the following can be taken as an example for a long-distance aircraft with a power ratio of 2 and optimum propulsive system (surface cooling and $\eta_V = 0.6$): This aircraft could fly at an altitude of 8 kilometers about 34 percent farther and 10 percent faster than an aircraft with the same power ratio at sea level. If it is compared with an aircraft flying at sea level with a power ratio $\alpha = 1$, which could thus climb only very little higher, about the same cruising radius and a 58-percent increase in speed are obtained.

As long as a long-distance aircraft that is loaded nearly to the limit of its lifting capacity is being considered, high-altitude flight can offer a gain in speed; but only small power ratios can be permitted if the mileage that can be flown with a given quantity of fuel is not reduced. The methods of comparison hitherto in use are applicable to long-distance aircraft only before the fuel supply has been perceptibly reduced, because the power ratio increases as the weight of fuel decreases. Consequently, during a long-distance flight, $\alpha = 1$ can in no case remain true for the whole distance. Therefore the over-all cruising range can be increased by flying at higher altitudes as the distance traveled increases. A heavily laden transoceanic aircraft, for example, should fly best near sea level at first and with decreasing fuel load gradually ascend, whereupon the exhaust-gas turbine and the supercharger would be brought into operation. The determination of optimum flight path will be shown in the forthcoming flight-mechanical study previously mentioned.

Figure 39. Some further data for surface cooling at 50-percent supercharger efficiency are presented in figure 39 to complete the picture.

III. Cooling of Structural Parts

In the cooling of the exhaust gas, it is found that work losses occurred first because of the necessary reduction of the exhaust-gas temperature and second because of the operation necessarily involved in throttling the exhaust flow. The losses were so large that the advantage of high-altitude flight and use of the turbine remained small.

If the method of cooling not the exhaust gas but the structural parts exposed to the hot gas is adopted, after overcoming the fundamental constructional difficulties, use could be made of the free exhaust method of operation from which a considerable gain in output would result, especially at moderate altitudes. How great the work losses due to the cooling would be in the cooling of parts is a question that can only be answered if it is possible to compute the quantities of heat transferred to the nozzles and blades. Unfortunately that is not possible today as nothing is known of the laws governing heat transfer at velocities in the order of 1000 meters per second. For this reason the problem of cooling of structural parts cannot be exactly treated today. Only some general considerations may be set forth, which are based on the assumption that even at these high flow velocities the heat transfer improves with increasing velocity and increasing temperature differences.

If with the aim of cooling the wheel it is desired to enclose only a part of the turbine rotor, the unenclosed part can, as has already been suggested (reference 2), be exposed to the flight stream. As the temperature difference between the blade surface and the flight stream (approx. 600° C) is not much greater than the temperature difference between blade surface and exhaust gas (approx. 400° C) and the heat transfer at the relatively low velocity of the flight stream is poorer than at the high exhaust-gas velocity, apparently the wheel can be enclosed only to a very small degree. This slight enclosure causes an increase in constructional difficulties, the turbine becomes very heavy, large windage losses make their appearance, and the additional flight resistance attributable to cooling would no doubt become very large. As a means of partly circumventing this difficulty, a part of the wheel might be supplied with precompressed air, which could do work in the turbine. If, for this purpose, air that is no more highly compressed than that supplied by the normal supercharger is used, its outflow velocity from the nozzles is much less than the exhaust-gas velocity because of the lower temperature. Consequently, on the one hand, the impact loss in connection with the performance of work in the turbine becomes greater and, on the other hand, it is necessary in order to obtain enough cooling effect, to extend greatly the sector of the wheel supplied with air, whereupon the turbine will consume a great deal of air. As a result, the same disadvantages appear that make the mixture-cooling system undesirable. Perhaps an improvement could be achieved by the use of an auxiliary compressor to bring the cooling air to such a pressure that its flow velocity would be of the same order of magnitude as that of the exhaust gas.

Thus there are a whole series of arguments against the utility of partial exposure of the rotor to the working fluid. Obviously, nothing final can be said without carrying out computations.

The blades can also be cooled internally with air. The cooling surface available for this purpose is of the same order of magnitude as that of the heat-absorbing surfaces on the exhaust-gas side. In accordance with what has been said in the previous paragraphs, the velocity of the cooling air must also approach that of the exhaust gas; that is, it must be very great. Because of this necessity it is already apparent that a negligibly small quantity of cooling air cannot be used even if the cooling-channel cross section is made much smaller than the blade cross section. The forcing of the cooling air through narrow channels at high velocity would require the expenditure of a considerable amount of work in the compressor.

Whether internal-fluid cooling or evaporation cooling of the blade would enable the removal of large enough quantities of heat cannot be decided as long as nothing is known concerning the magnitude of these quantities. Such a cooling system would necessitate the use of a recooler or condenser. These accessories would again cause additional flight resistance and a corresponding loss of power.

It is not impossible that the operation of spark-ignition engines with an exhaust-gas turbine using cooling of mechanical parts might give better results for high-altitude flight than can be expected with the exhaust-gas cooling system. As an aid in answering this question definitely, experiments on heat transfer under exhaust-gas-turbine conditions are very urgently desired.

IV. SUMMARY

The difficulty in the operation of spark-ignition engines with exhaust-gas turbines lies in the high exhaust-gas temperatures, which cannot be withstood without special cooling arrangements. As a step in preparation for the construction of high-altitude engines with exhaust-gas-turbine superchargers, an investigation is made of the possible cooling methods.

For the present the cooling of mechanical parts cannot be exactly computated because the laws of heat transfer at the high gas velocities in question are not known.

Therefore, the quantitatively treated section is confined to two systems for which an adequate theoretical foundation is available. The first of these is mixture cooling, in which the exhaust gas is cooled by the mixture of air, the compression of the air constituting an added function of the supercharger. The second system is surface cooling, in which the exhaust gas is sent through a surface cooler exposed to the flight stream before entering the turbine. The behavior of the supercharged engine without a turbine is also presented for comparison.

All assumptions concerning efficiencies of superchargers, engine, and turbine are based as far as possible, upon experimental measurements and deductions from experimental measurements. In this connection values were always used the practical attainment of which at the present time seems assured. The oxygen content of the atmosphere was assumed to decrease in accordance with the diffusion balance. The principal uncertainty is encountered in the assumption of the specific weight of the supercharger and the turbine.

The results of the thermodynamic computations are embodied in the figures for work per unit of displacement, the indices of fuel consumption, the specific weights, and the cooling-surface areas. Great work losses, as compared to theoretical possibilities, are encountered because of the necessity of throttling the flow of gas and of reducing the temperature of the gas. Consequently, the output obtainable per kilogram of power-plant weight decreases markedly and quite uniformly with increasing altitude. With surface cooling the output is reduced by half at 17 kilometers with mixture cooling at 11 kilometers, and in the case of a supercharged engine without a turbine at 13.5 kilometers. The cooling-surface requirements per kilogram of engine weight increase with altitude by not more than 60 percent and then decrease again at still higher altitudes. For a given engine, surface cooling requires greater cooling surfaces in the troposphere than mixture cooling. In the stratosphere, surface cooling is superior to mixture cooling in respect both to weight and cooling surfaces.

The utility of the different systems can be definitely compared only in the light of the flight-mechanical investigation that follows. In accordance with a method originated by this writer and concerning which a separate report will be made, it is possible to compare flight speed, climbing speed, ceiling, economy, and cruising range without being limited to specific aircraft types. The behavior of any type of aircraft within the scope of our inquiry can be derived from two characteristic values of the aircraft design.

The flight-mechanical evaluation gives the following general picture: Flight speed, climbing speed, and ceiling cannot be very considerably improved by using the surface-cooling system as compared with operation without a turbine. The mixture-cooling system actually works somewhat less efficiently than the supercharged motor without a turbine. With surface cooling and the exertion of every effort the attainment of a ceiling of 17 kilometers should be possible. The speed of a transport aircraft could be increased only about 15 percent by means of high-altitude flight.

With regard to cruising range and economy, on the other hand, high-altitude flight using the exhaust-gas turbine possesses noteworthy advantages. At small power ratios, surface cooling and mixture cooling are of equal value in this respect but at large power ratios surface cooling is again more efficient. At small power ratios, a given cruising range is obtained at higher speed with surface cooling than with mixture cooling. Unfortunately it is precisely in the case of long-distance flight that the gain in cruising range remains small. Nevertheless, it is approximately

30 percent; therefore, many flights that are now barely possible could be accomplished with greater safety.

The advantages of high-altitude flight are especially noteworthy in the case of high power ratios toward which development is at present directed.

For future practical work the following conclusions must be drawn from the calculations and generalizations:

1. For the time being only the surface-cooling system need be considered for construction and testing. Only if we succeed in raising the efficiencies of the supercharger and turbine well above the values assumed in this report may the picture in regard to mixture cooling change for the better — and then probably only in the troposphere.

2. The very necessary comparison with systems in which the mechanical parts are cooled require that the laws of heat transfer applying to the flow of hot gases through blade channels be clarified.

Translation by Edward S. Shafer,
National Advisory Committee
for Aeronautics.

REFERENCES

1. Hansen, A.: Thermodynamische Rechnungsgrundlagen der Verbrennungskraftmaschinen und ihre Anwendung auf den Höhenflugmotor. Forschung auf dem Gebiete des Ingenieurwesens, Ausg. B, Bd, 2, Heft 344, May 1931.

2. Hansen, A.: Der Höhenflugmotor, seine thermodynamischen Grundlagen und seine Entwicklungsmöglichkeiten. Urschrift, 1929.

3. Schmidt-Kühl: Die Aussichten der Abgasturbinenaufladung für Dieselflugmotoren. 1. Teilbericht. Theoretische Untersuchungen. DVL-Forschungsbericht FB 327.

4. Ackeret, J.: Gasdynamik. Bd. VII, Kap. 5 of Handbuch d. Phys., H. Geiger and K. Scheel, ed., Julius Springer (Berlin), 1927, pp. 289-342. (British R.T.P. Trans. No. 2119, Ministry Aircraft Prod.)

5. Mollier: Wärme. Bd. I of "Hütte", Des Ingenieurs Taschenbuch, Abschn. 4, 26th aufl., Akademischen verein Hütte, E. V. (Berlin), 1931, p. 515.

6. Fuchs, Hopf, Seewald: Aerodynamik. Bd. I of Aerodynamik, 2d aufl., Berlin, 1934, p. 63.

7. Anon.: Bd. I of "Hütte", Des Ingenieurs Taschenbuch, 25th aufl., Akademischen verein Hütte, E. V. (Berlin), 1925, p. 452.

8. Anon.: Wärme. Bd. I of "Hütte", Des Ingenieurs Taschenbuch, Abschn. 4, 26th aufl., Akademischen verein Hütte, E. V. (Berlin), 1931, pp. 498-499.

9. Schrenk, Martin: Jahrb. d. wissenschaftlichen Gesellschaft f. Luftfahrt, 1927, p. 129.

10. Schrenk, Martin: Zur Berechnung der Flugleistungen ohne Zuhilfenahme der Polare. Z.F.M., Jahrg. 18, Heft 7, April 14, 1927, pp. 158-167. (NACA TM No. 456, 1928.)

11. Schrenk, Martin: Einige weitere flugmechanische Beziehungen ohne Zuhilfenahme der Polare. Z.F.M., Jahrg. 18, Heft 17, Sept. 14, 1927, pp. 399-405. (NACA TM No. 457, 1928.)

12. Kamm, W.: Jahrb. d. wissenschaftlichen Gesellschaft f. Luftfahrt, 1927, pp. 116-132. [Recent Problems in the Development of Aircraft Engines with Especial Reference to High Altitude Engines.]

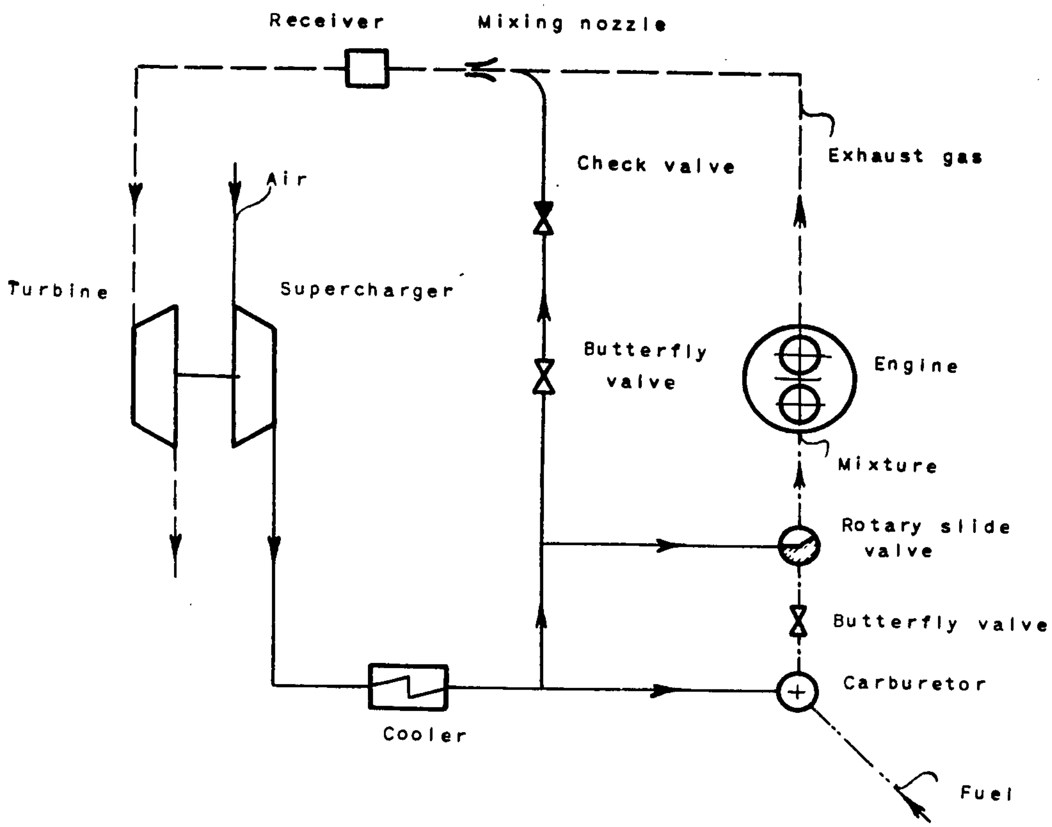


Figure 1. - Flow plan for mixture-cooling system. Compressed air is mixed with exhaust gas by means of a butterfly valve and a check valve. In the case of surface cooling, the mixing nozzle is replaced by an exhaust-gas cooler and the air duct is omitted.

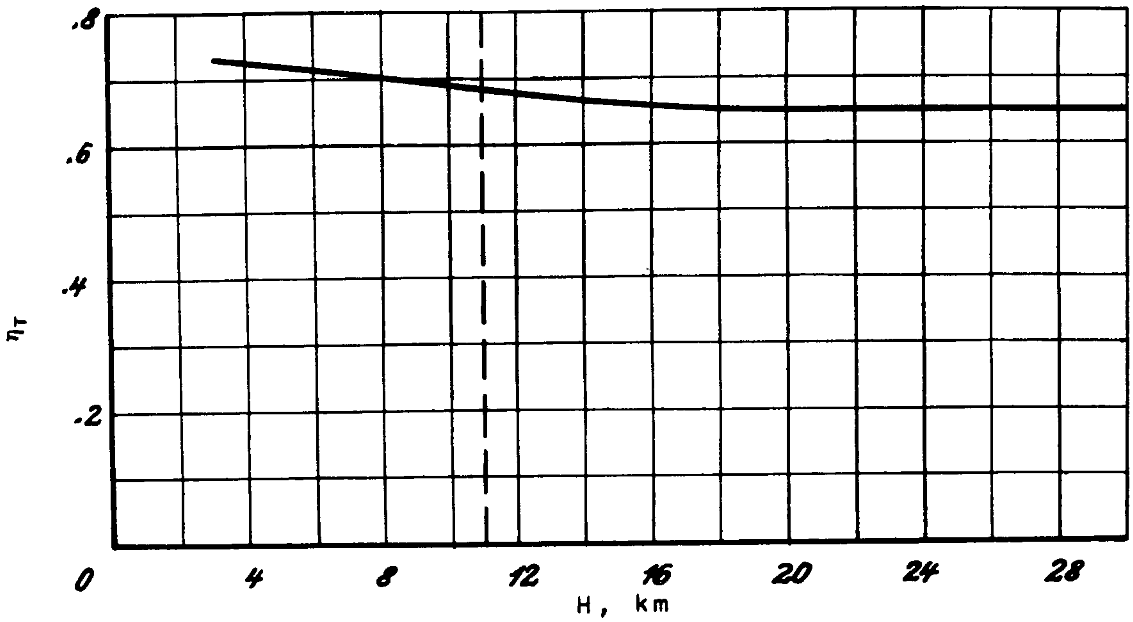


Figure 2. - Turbine efficiency as function of flight altitude.

η_T adiabatic turbine efficiency

H flight altitude, km

These efficiencies are attainable up to about 15 kilometers with one impeller (u = 300 m/sec) and above that altitude with two counter rotating impellers (u_1 = 300 m/sec; u_2 = 200 m/sec).

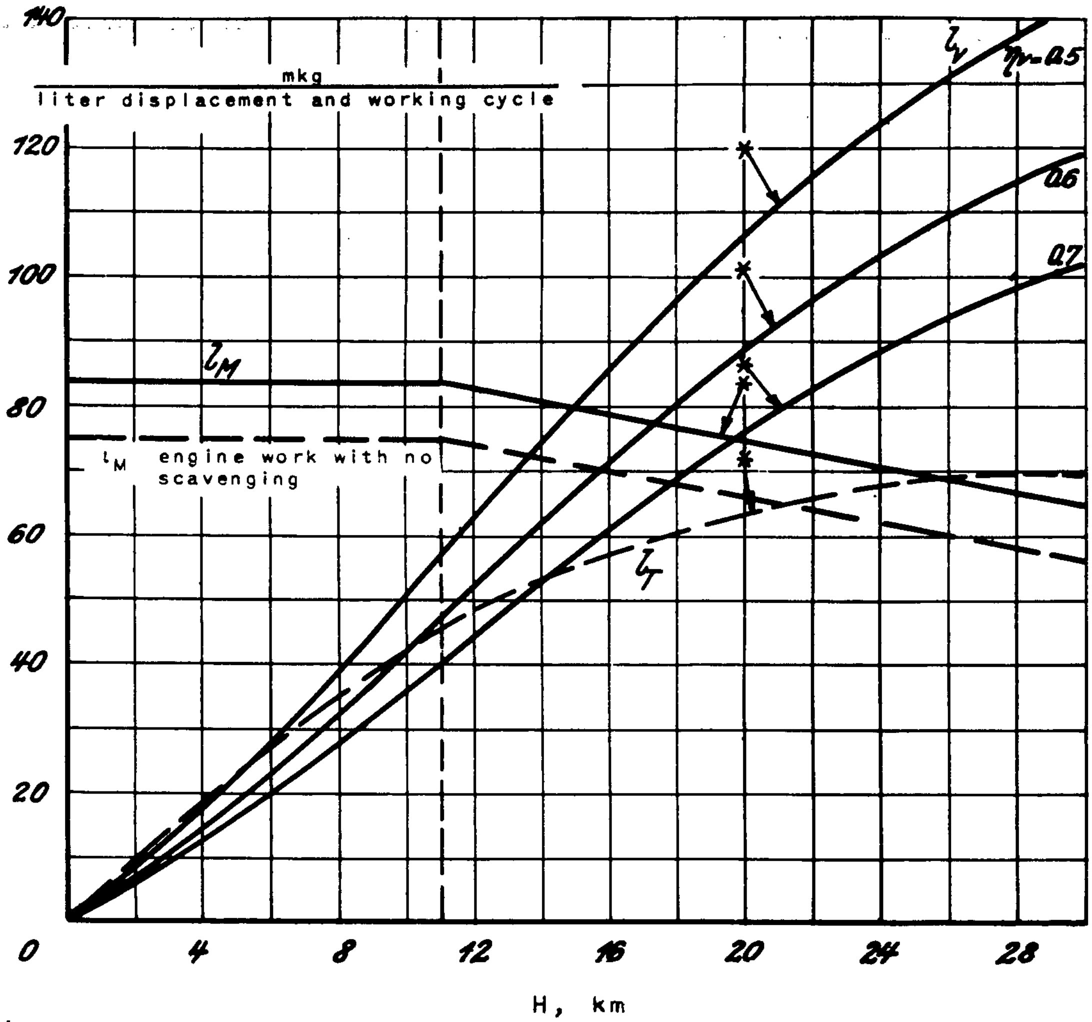


Figure 3. - Component work quantities in mixture cooling.

l_M engine work

l_V supercharger work

l_T turbine work

η_V adiabatic supercharger efficiency

All work quantities expressed as meter kilograms per liter displacement and per working cycle

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere

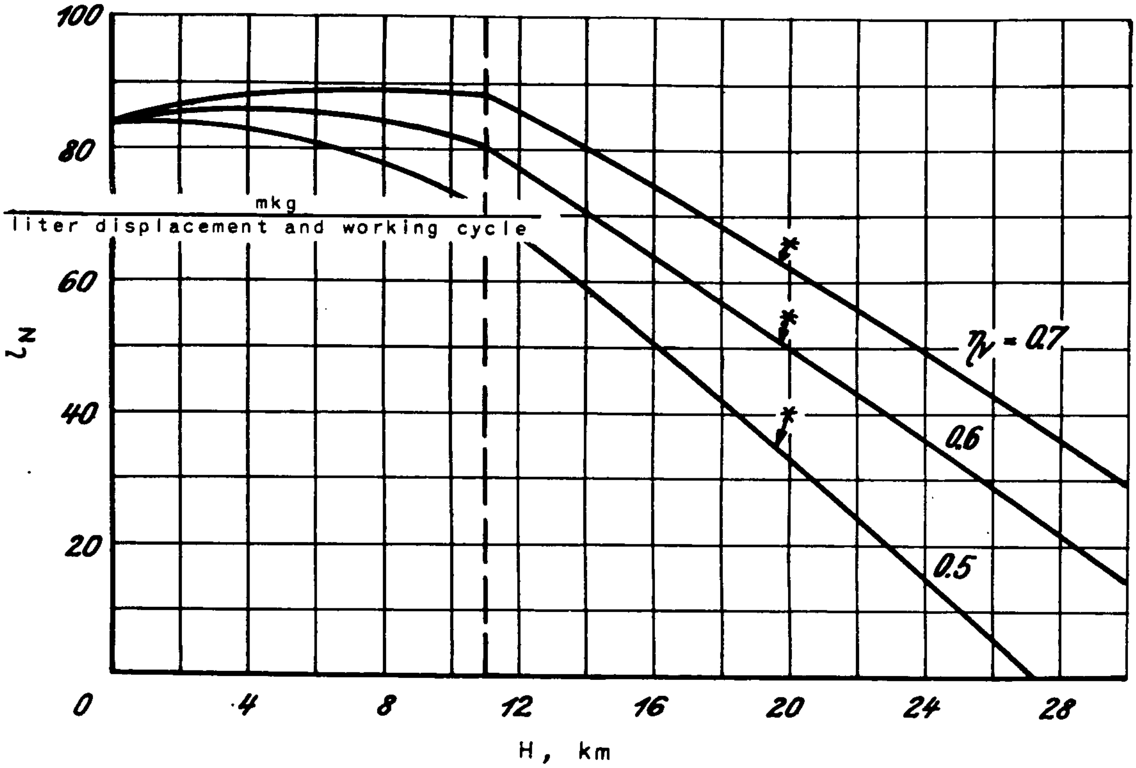


Figure 4. - Useful work in mixture cooling.

l_N useful work in meter kilograms per liter of displacement and per work cycle

η_V adiabatic supercharger efficiency

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere

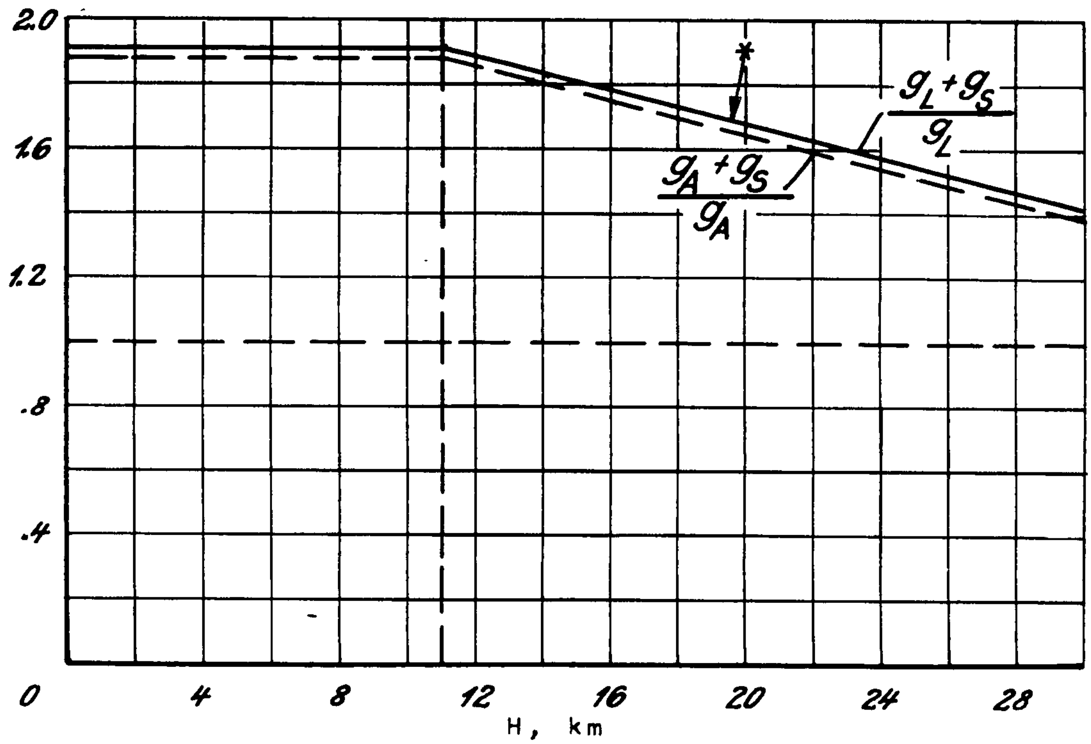


Figure 5. - Increase in quantities of air and exhaust gas due to mixture cooling.

g_L air quantity without mixture air

g_S mixture air quantity

g_A exhaust-gas quantity without mixture air

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere

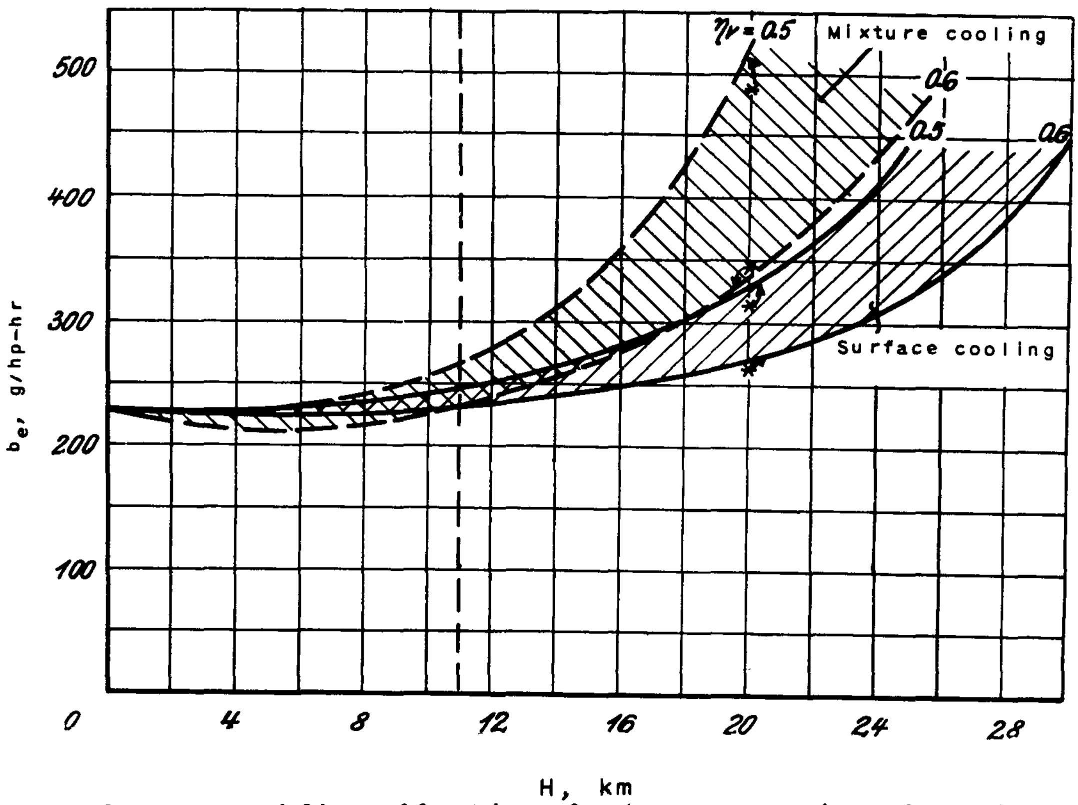


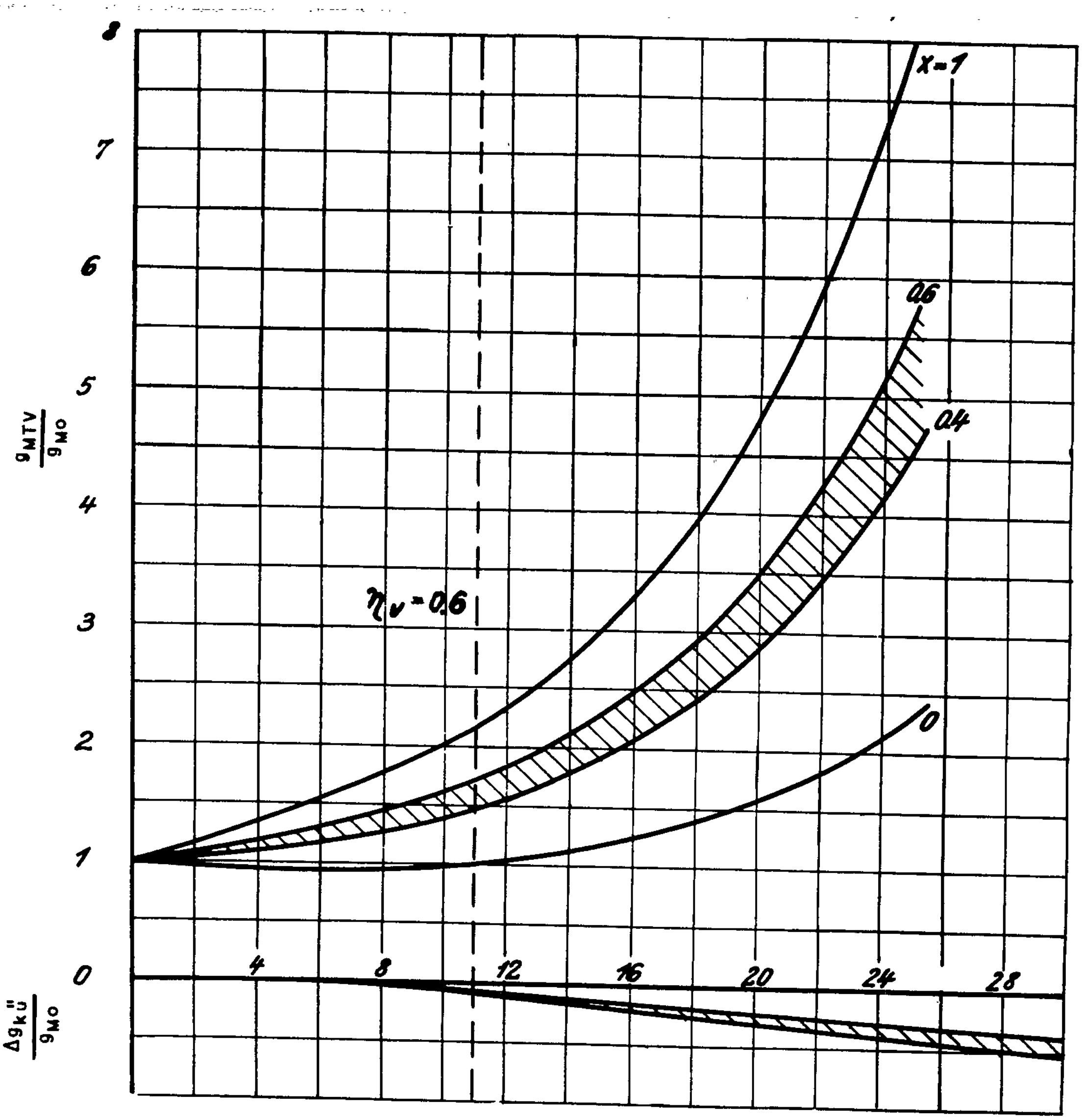
Figure 6. - Specific effective fuel consumption for mixture cooling and surface cooling.

b_e specific effective fuel consumption, g/hp-hr

η_V adiabatic supercharger efficiency

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere



H, km

Figure 7. - Specific weights of mechanical and cooling installations with mixture cooling; η_v = 0.6. (For explanation of symbols, see fig. 8.)

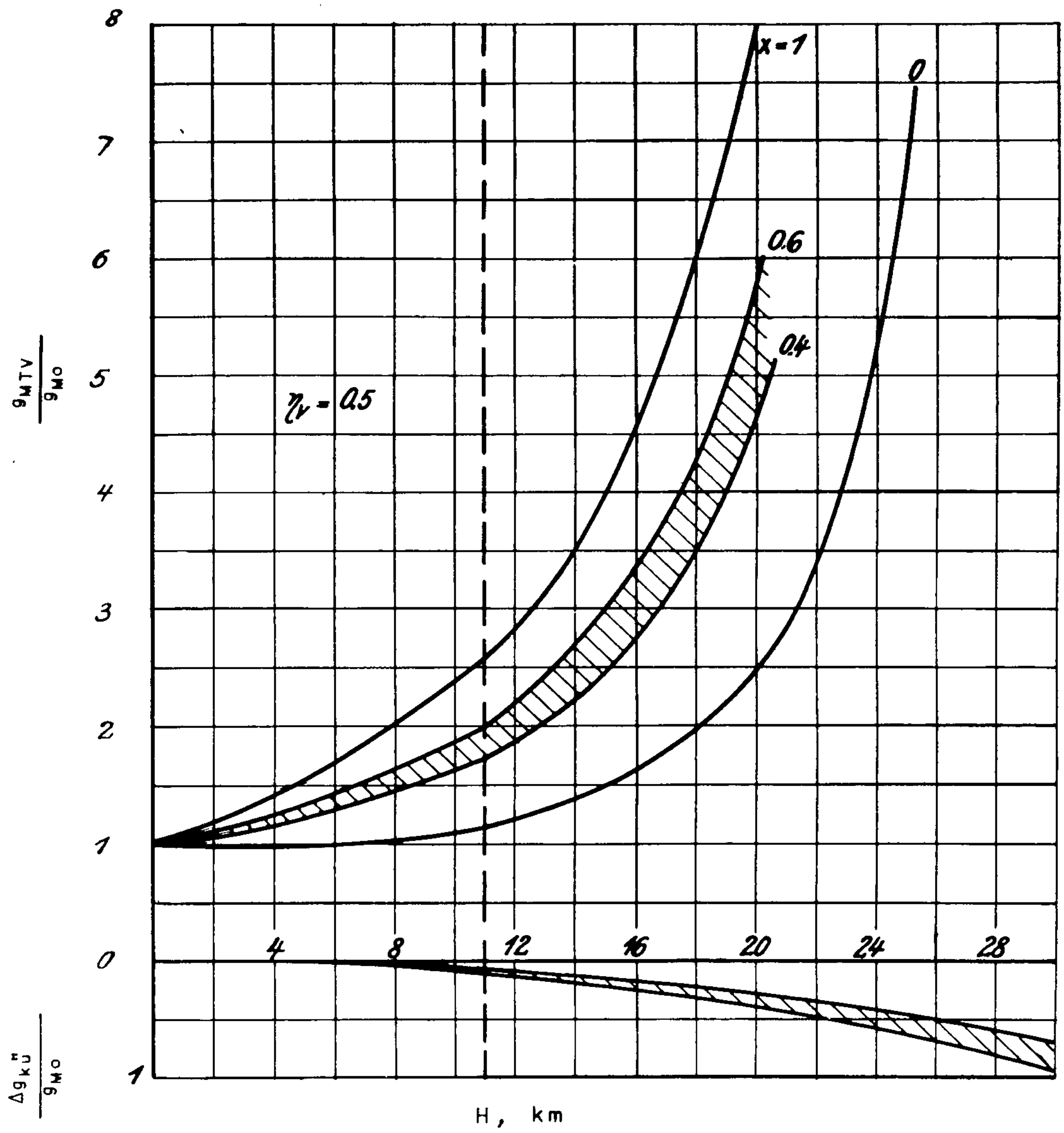


Figure 8. - Specific weights of mechanical and cooling installation with mixture cooling; η_V = 0.5.

g_{MTV} specific weight of whole mechanical installation (engine, turbine, and supercharger)

g_{Mo} specific weight of engine with cooler at sea level

$\Delta g_{k\ddot{u}}''$ additional specific weight of cooler unit for high-altitude flight

H flight altitude, km

η_V adiabatic supercharger efficiency

x ratio of specific weight of supercharger and turbine to specific weight of engine

The values to be considered for practical purposes lie in shaded region.

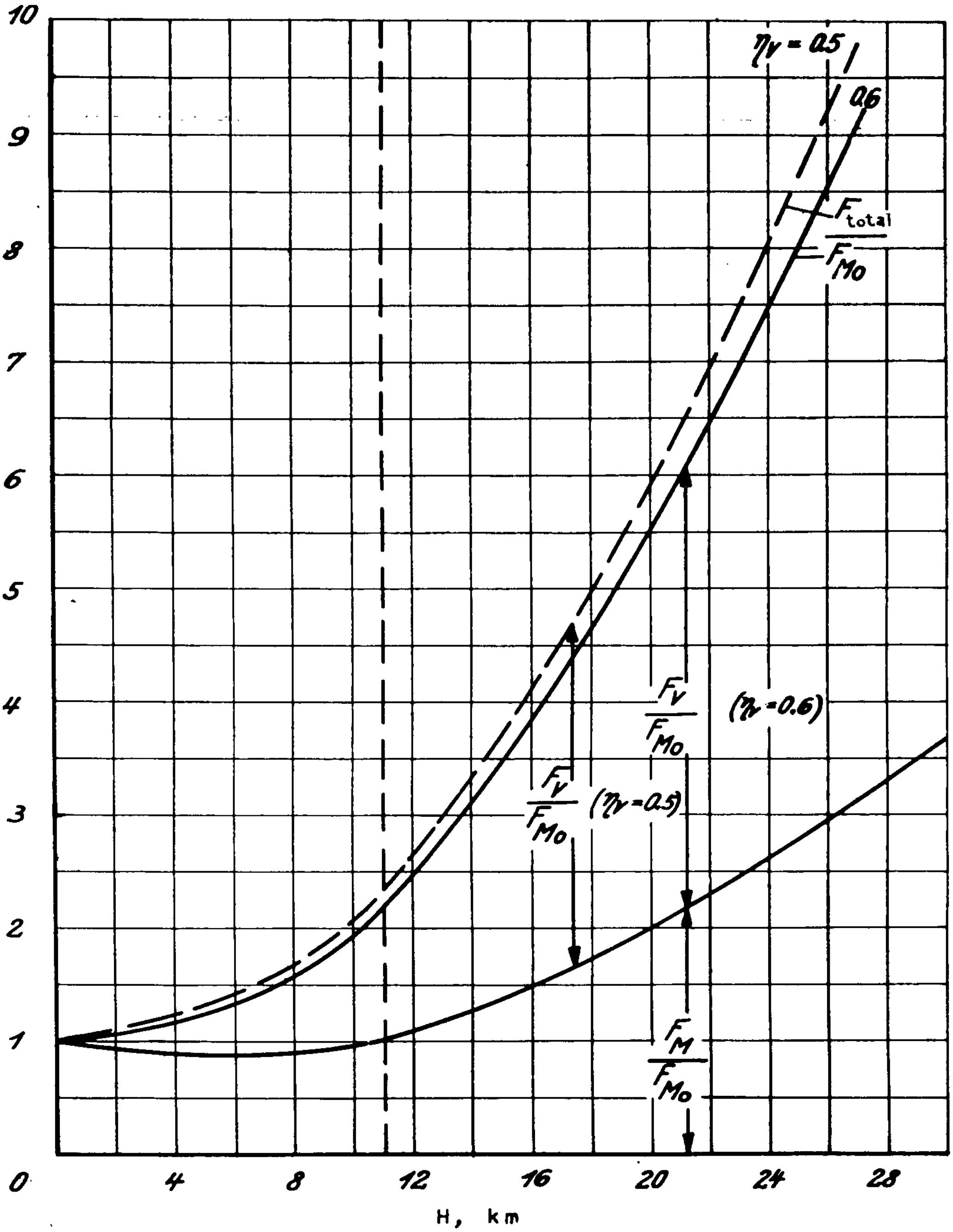


Figure 9. - Cooling-surface requirements for mixture cooling.

F_{Mo} cooling surface of normal water cooler for engine at sea level

F_M cooling surface of engine water cooler at various altitudes

F_V cooling surface of air coolers for supercharger

$F_{total} = F_M + F_V$

η_V adiabatic supercharger efficiency

H flight altitude, km

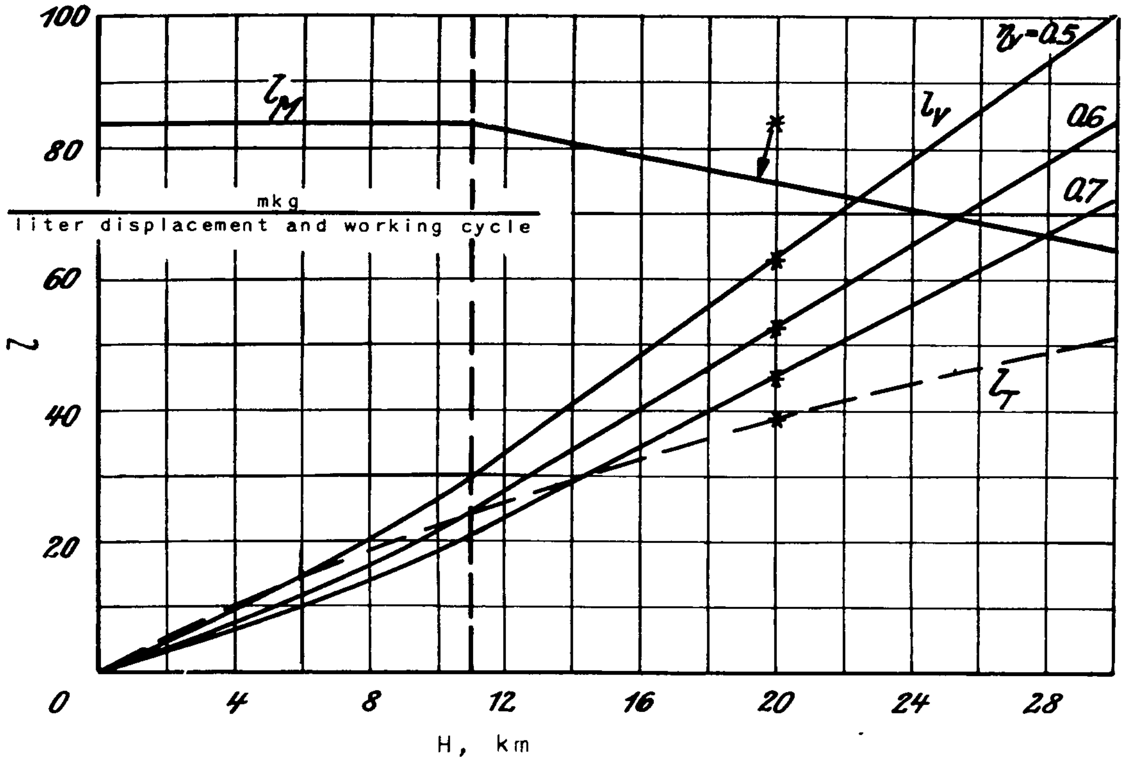


Figure 10. – Component work quantities in surface cooling.

l_M engine work

l_V supercharger work

l_T turbine work

η_V adiabatic supercharger efficiency

All work quantities expressed as meter kilograms per liter displacement and per working cycle

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere

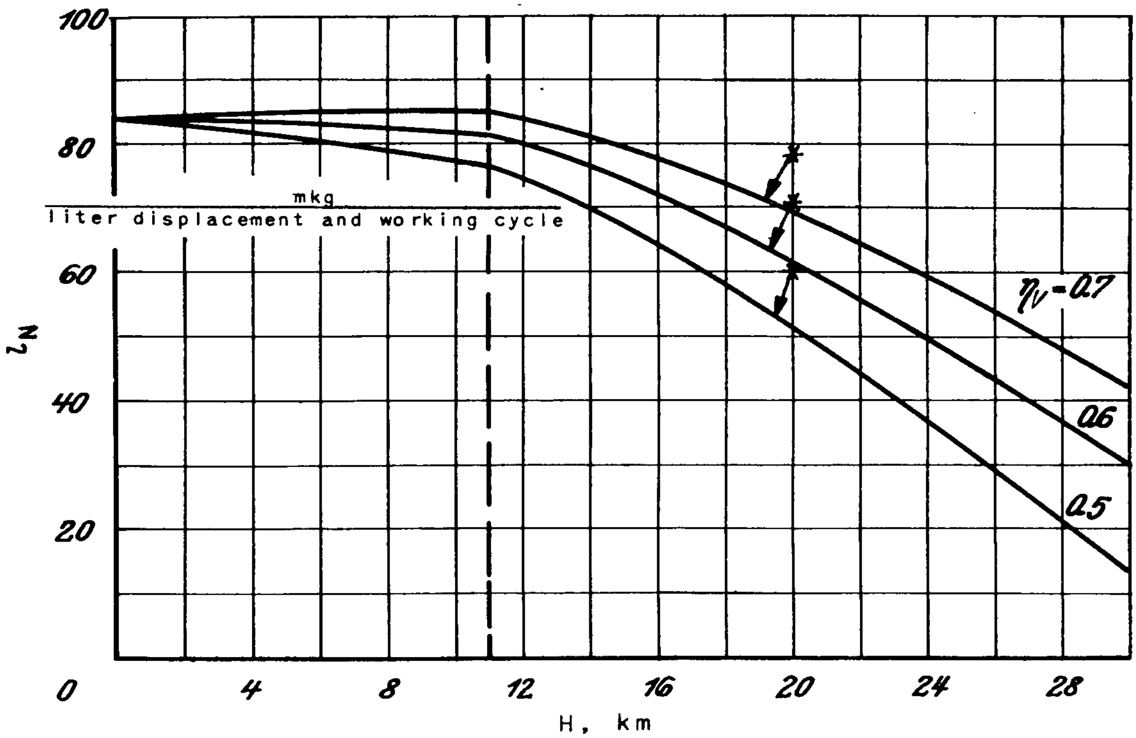


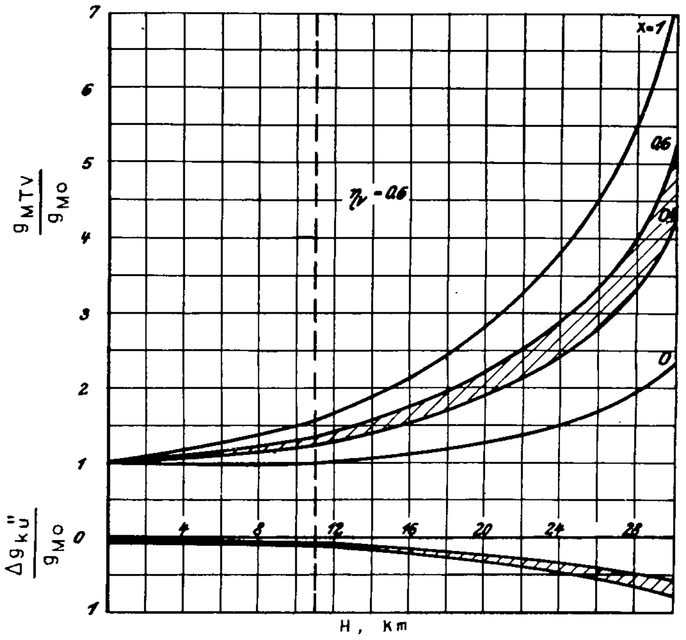
Figure 11. - Useful work in surface cooling.

l_N useful work in meter kilograms per liter of displacement and per working cycle

η_V adiabatic supercharger efficiency

H flight altitude, km

* value at altitude of 20 kilometers for unchanged oxygen content of atmosphere



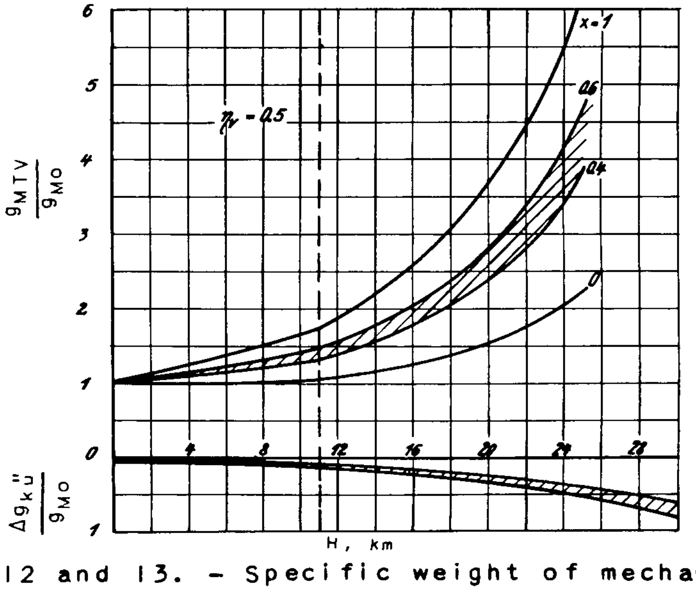


Figure 12 and 13. - Specific weight of mechanical and cooling units in surface cooling.

g_{MTV} specific weight of whole mechanical installation (engine, turbine, and supercharger)

g_{Mo} specific weight of engine with cooler at sea level

$\Delta g_{k\ddot{u}}''$ additional specific weight of cooler unit for high-altitude flight

H flight altitude, km

x ratio of specific weight of supercharger and turbine to specific weight of engine

η_V adiabatic supercharger efficiency

Values to be considered for practical purposes lie in shaded region.

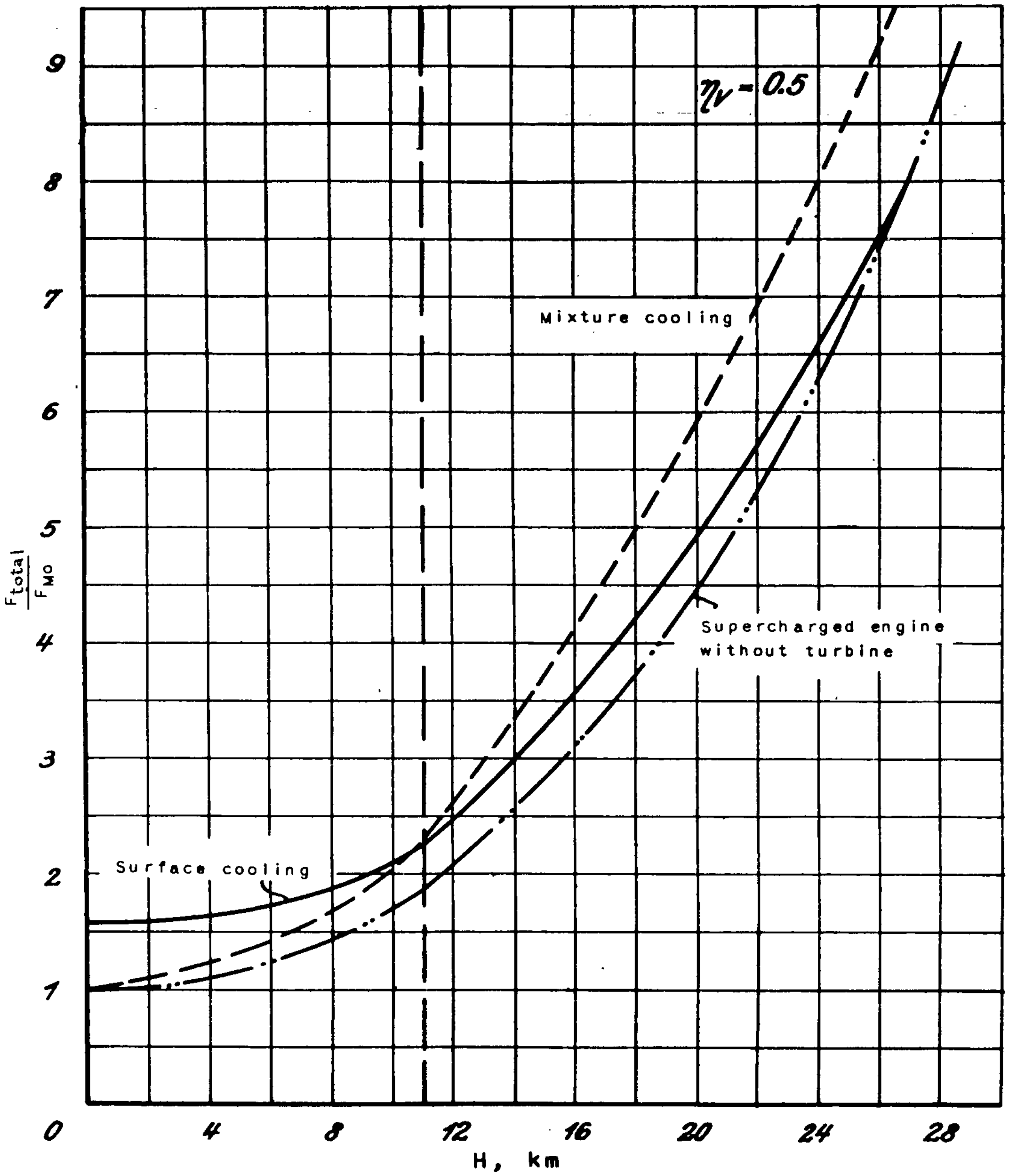


Figure 14. - Cooling-surface requirements for surface cooling.

F_{Mo} cooling surface of normal water cooler for engine at sea level

F_M cooling surface of engine water cooler at various altitudes

F_V cooling surface of air coolers for supercharger

F_K cooling surface of exhaust-gas cooler

$F_{total} = F_M + F_V + F_K$

η_V adiabatic supercharger efficiency

H flight altitude, km

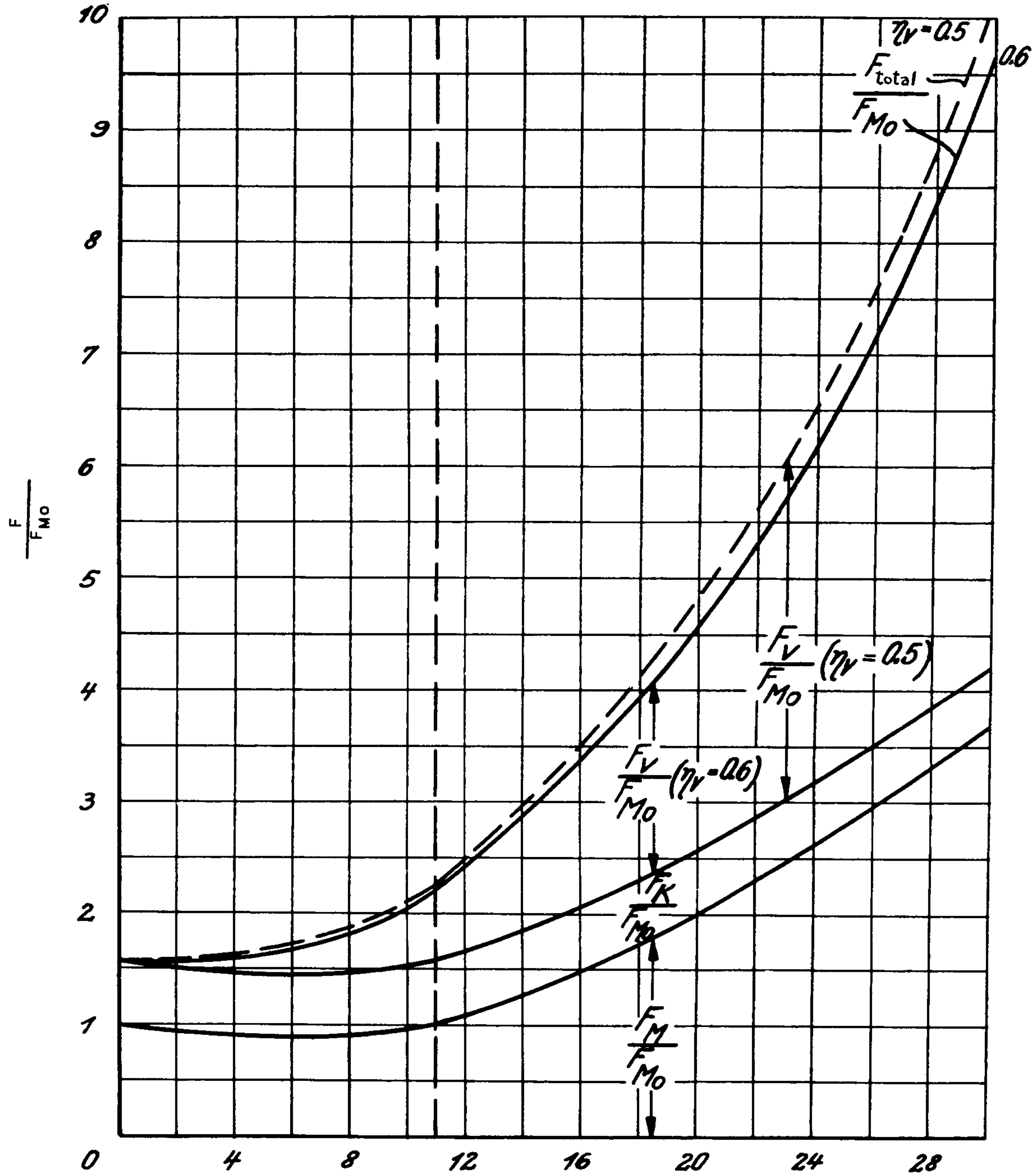


Figure 15. - Composition of total cooling surface for mixture cooling, surface cooling, and supercharged engine without turbine.

F_{total} sum of all cooling surfaces

F_{Mo} cooling surface of normal water cooler for engine at sea level

η_V adiabatic supercharger efficiency

H flight altitude, km

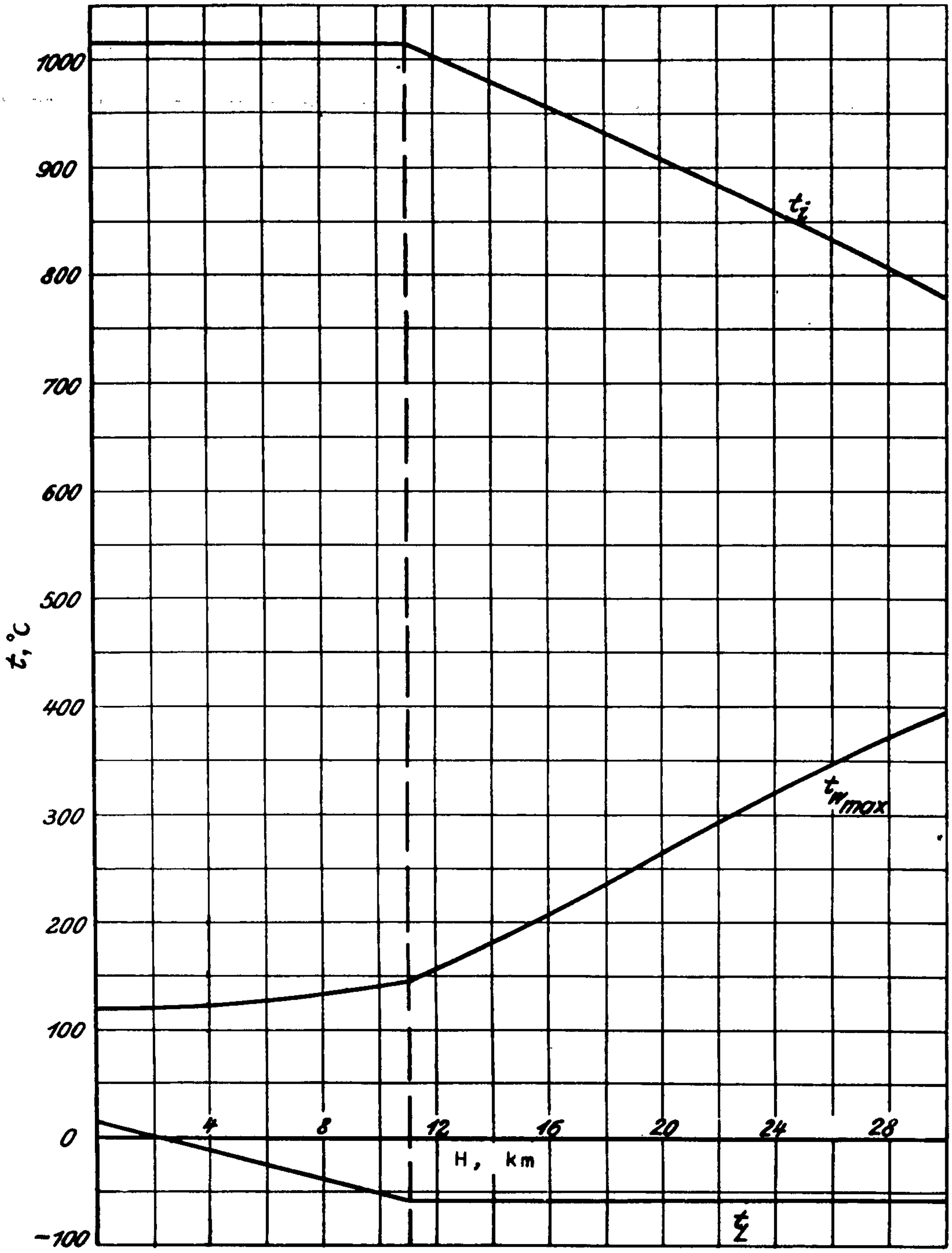


Figure 16. - Temperatures in exhaust-gas cooler.

t_i maximum exhaust-gas temperature, °C

$t_{w_{max}}$ maximum wall temperature, °C

t_L temperature of outside air, °C

H flight altitude, km

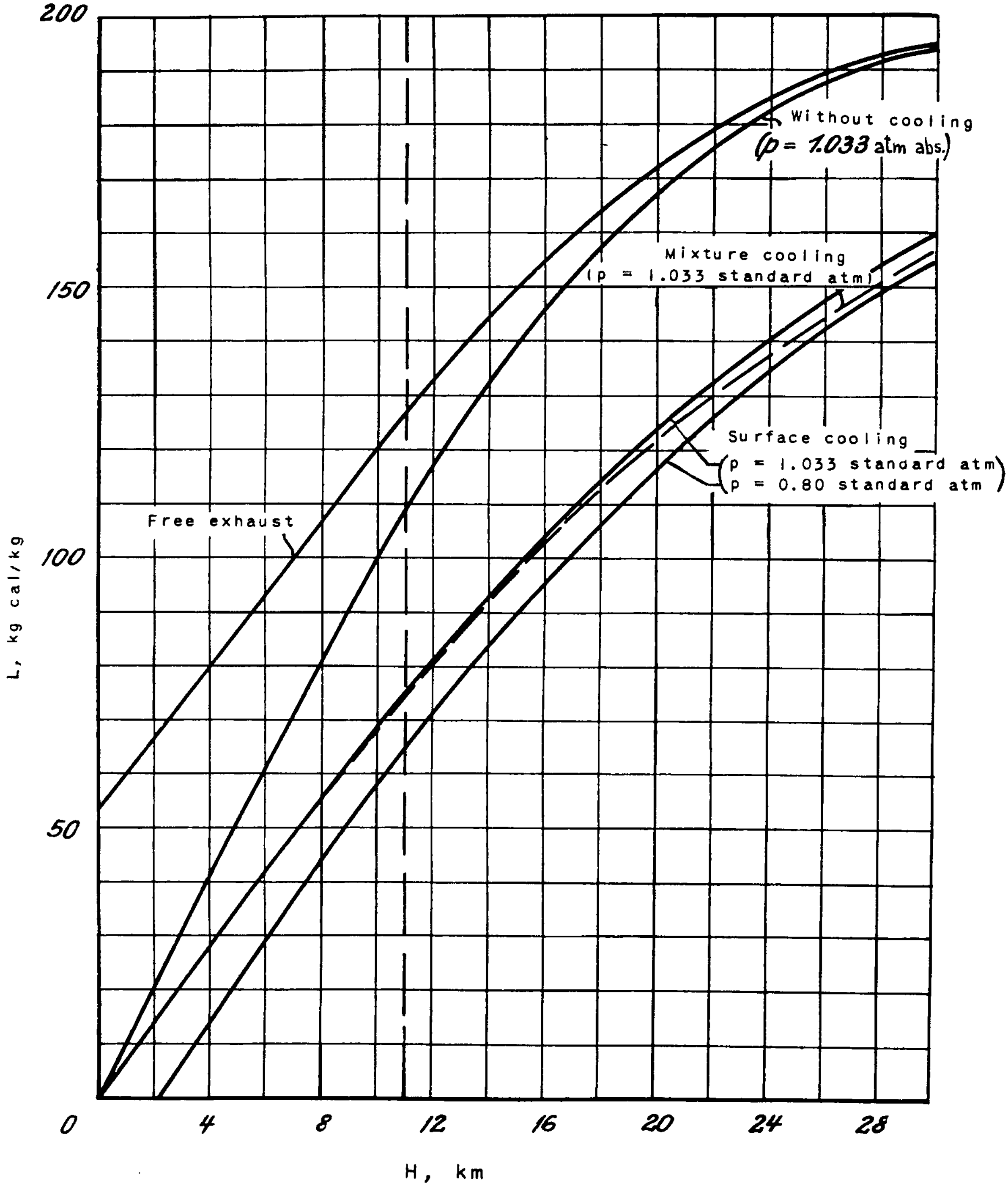


Figure 17. - Turbine work per kilogram of exhaust gas.

L turbine work, kg cal/kg

η_V adiabatic supercharger efficiency

p receiver pressure, standard atmospheres

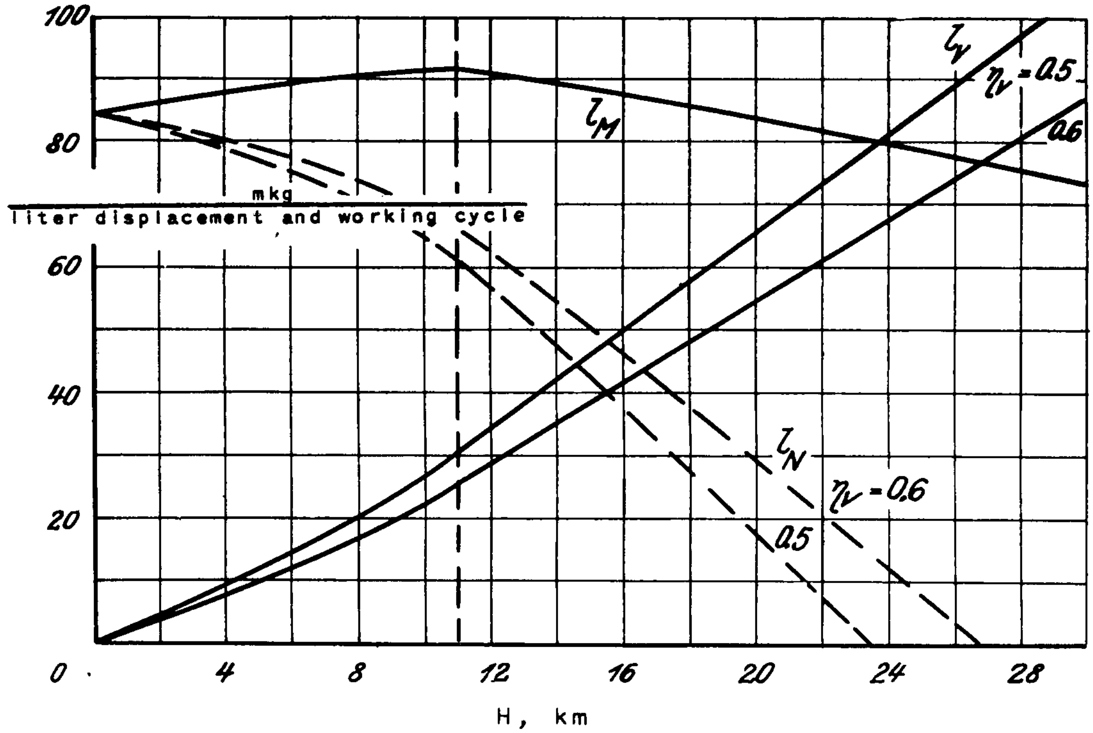


Figure 18. - Component work quantities and useful work in supercharged engine without turbine.

l_M engine work

l_V supercharger work

l_T turbine work

l_N useful work in meter kilograms per liter of displacement and per cycle

H flight altitude, km

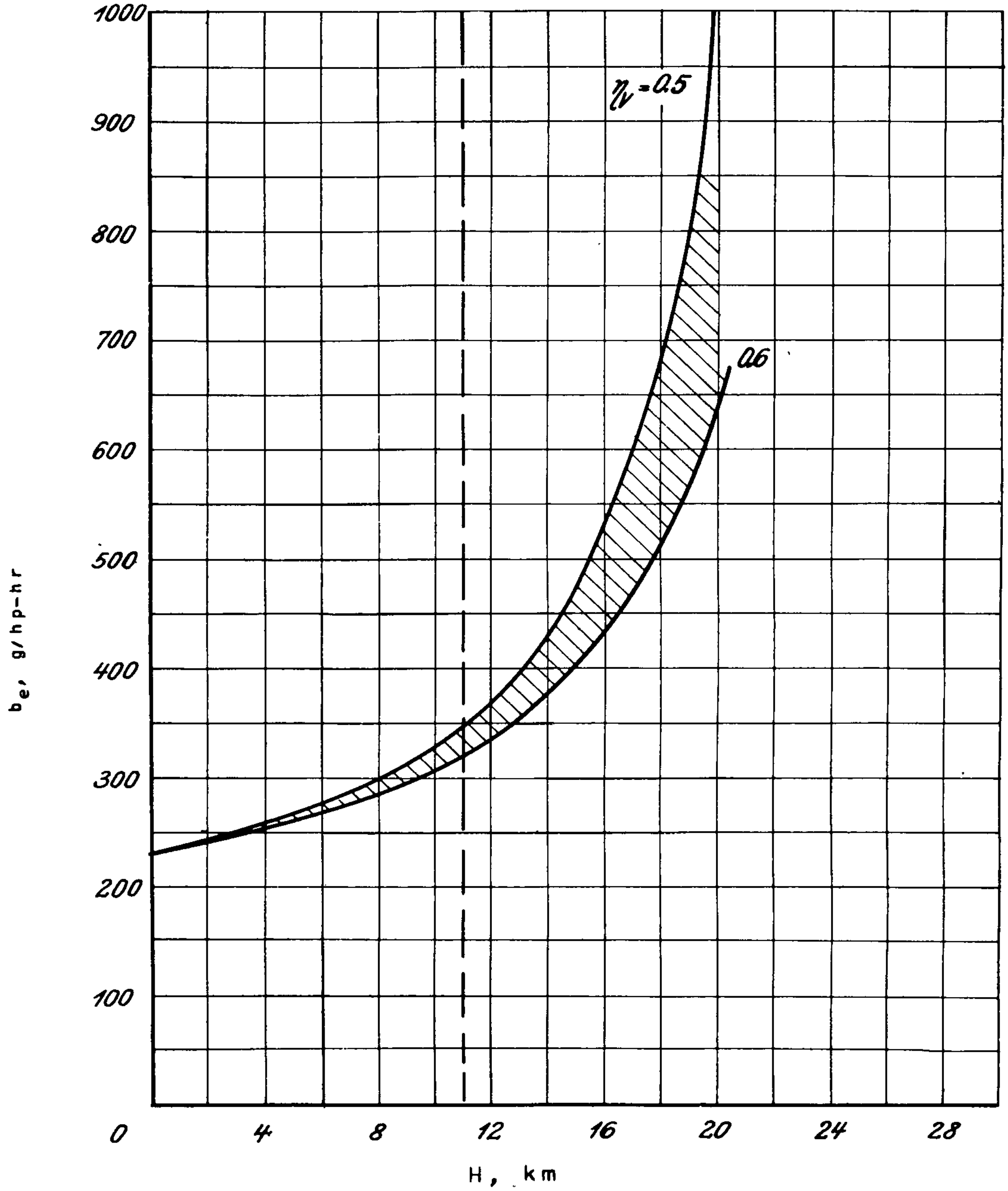


Figure 19. - Specific effective fuel consumption for supercharged engine without turbine.

b_e specific effective fuel consumption, g/hp-hr

η_V adiabatic supercharger efficiency

H flight altitude, km

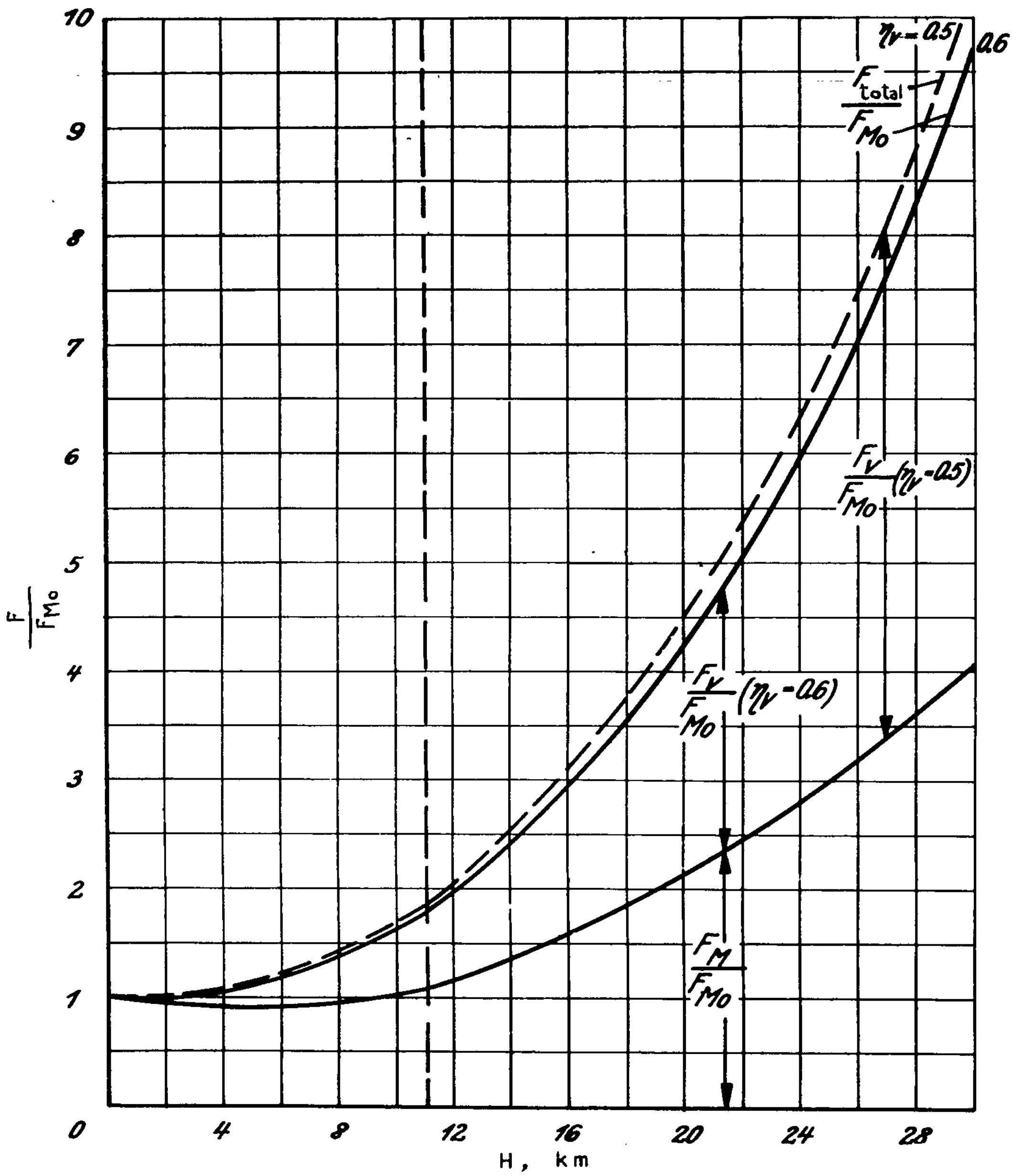


Figure 20. - Cooling-surface requirements for supercharged engine without turbine.

F_{Mo} cooling surface of normal water cooler for engine at sea level

F_M cooling surface of engine water cooler at various altitudes

F_V cooling surface of air coolers for supercharger

$F_{total} = F_M + F_V$

η_V adiabatic supercharger efficiency

H flight altitude, km

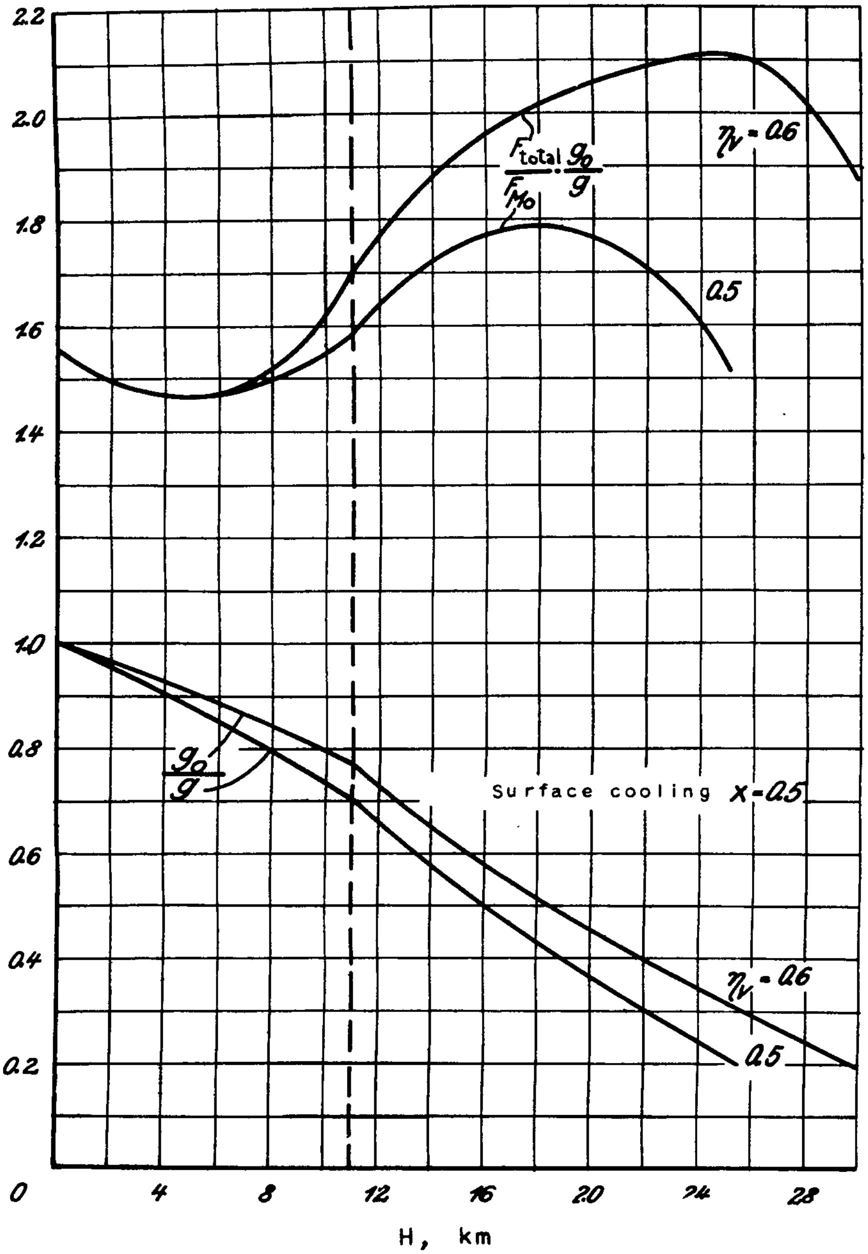
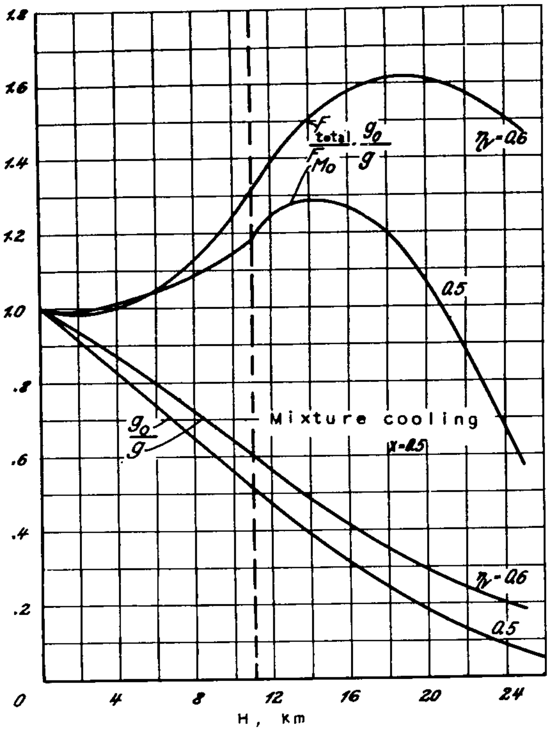
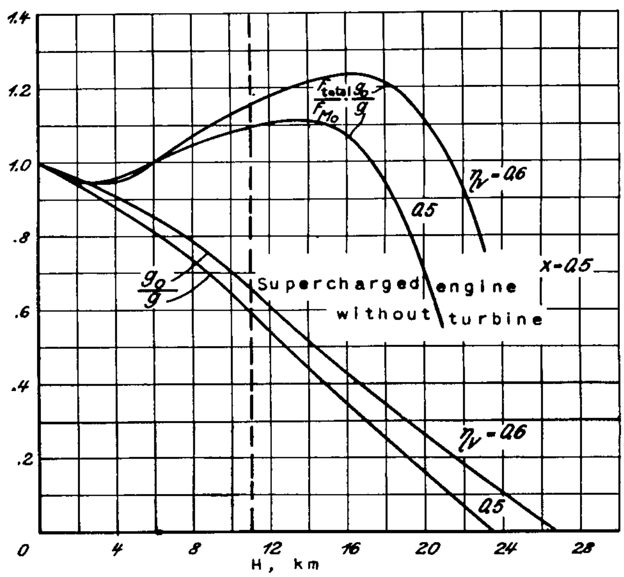


Figure 21. - Relative output for different systems.

- g specific weight of entire power plant (mechanical units and coolers)
- g_o value of g at sea level
- η_V adiabatic supercharger efficiency
- x ratio of specific weight of supercharger and turbine to specific weight of engine
- H flight altitude, km





Figures 22 and 23. - Relative output for different systems.

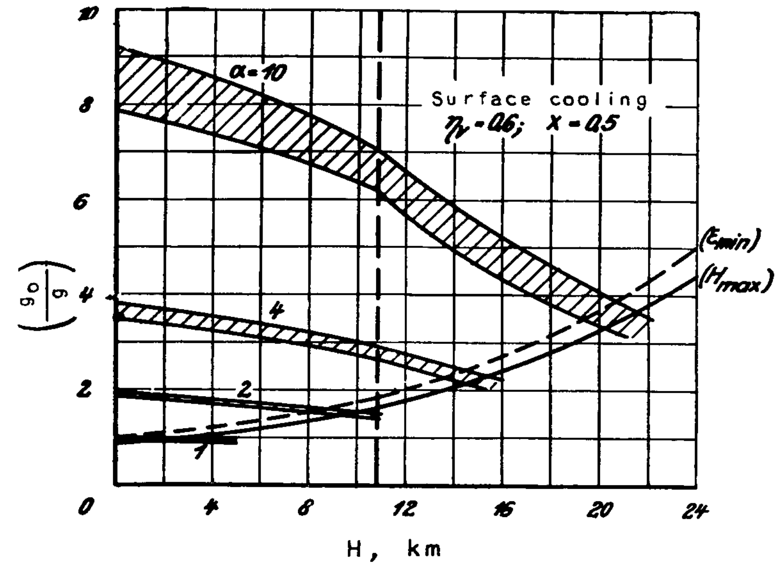
g specific weight of entire power plant (mechanical units and coolers)

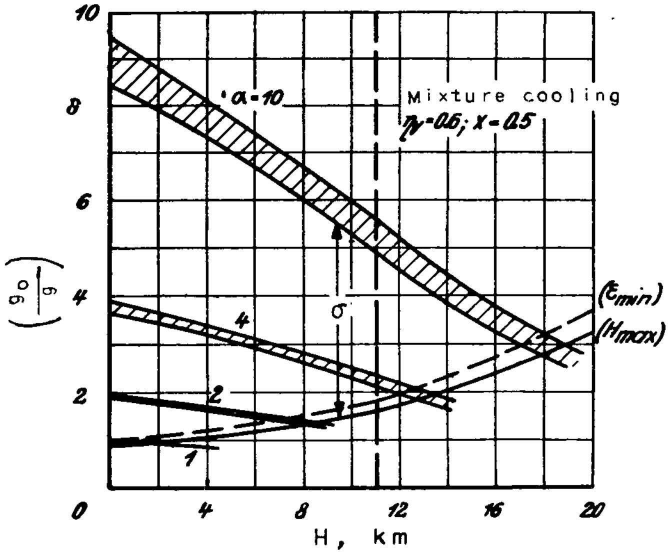
g_o value of g at sea level

η_V adiabatic supercharger efficiency

x ratio of specific weight of supercharger and turbine to specific weight of engine

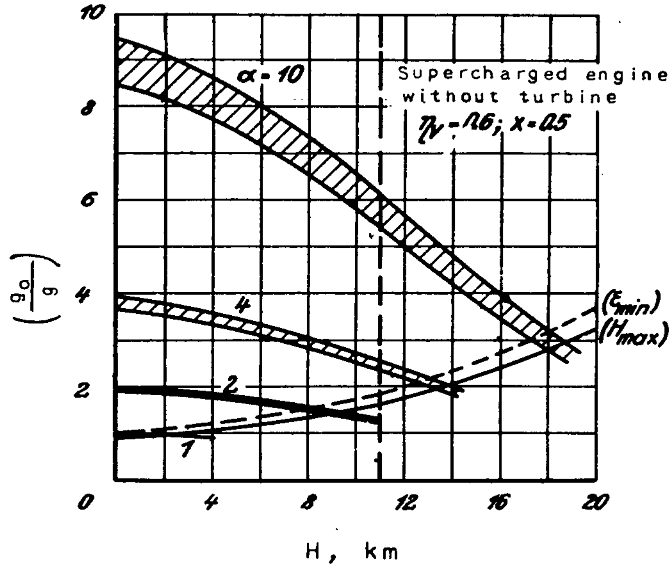
H flight altitude, km

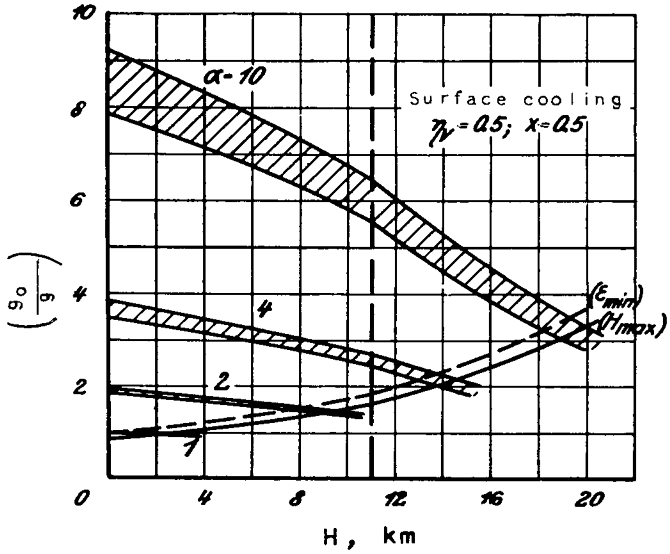




Figures 24 and 25. - Corrected specific output for different systems.

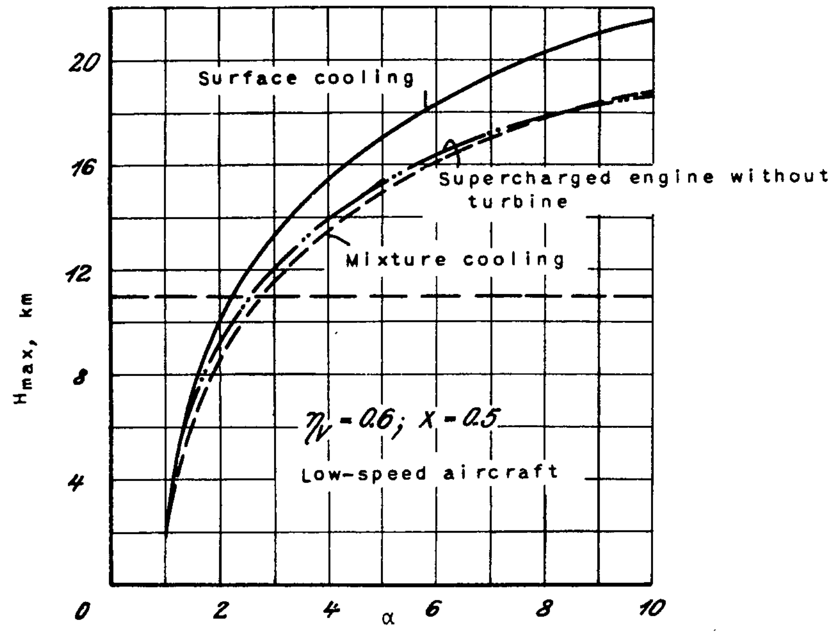
η_V	adiabatic supercharger efficiency
x	ratio of specific weight of supercharger and turbine to specific weight of engine
α	power ratio of aircraft
σ	index of climbing speed
ε_{min}	optimum gliding angle
H_{max}	ceiling altitude, km
H	flight altitude, km
	Upper boundary of shaded area: very low-speed aircraft
	Lower boundary of shaded area; very high-speed aircraft

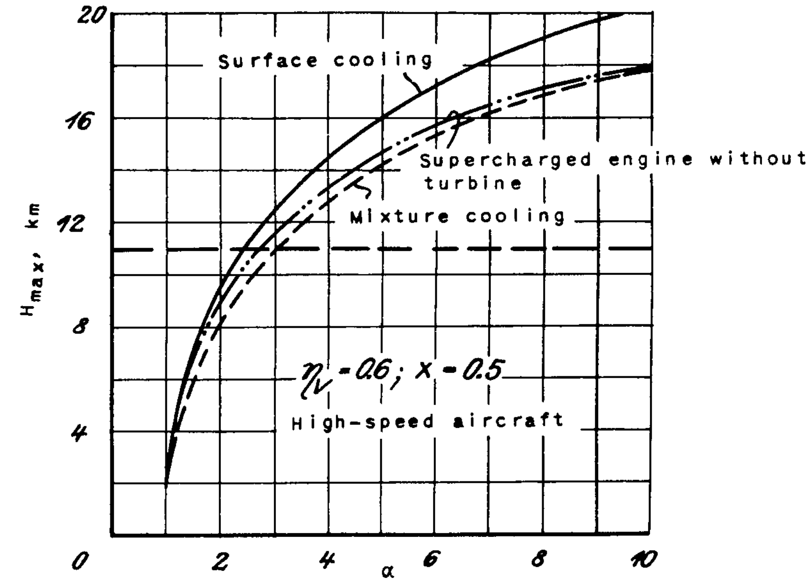




Figures 26 and 27. - Corrected specific output for different systems.

η_V	adiabatic supercharger efficiency
x	ratio of specific weight of supercharger and turbine to specific weight of engine
α	power ratio of aircraft
σ	index of climbing speed
ε_{min}	optimum gliding angle
H_{max}	ceiling altitude, km
H	flight altitude, km
	Upper boundary of shaded areas; very low-speed aircraft
	Lower boundary of shaded areas; very high-speed aircraft





Figures 28 and 29. - Ceilings for different systems.

H_{max} ceiling altitude, km

α power ratio of aircraft

η_V adiabatic supercharger efficiency

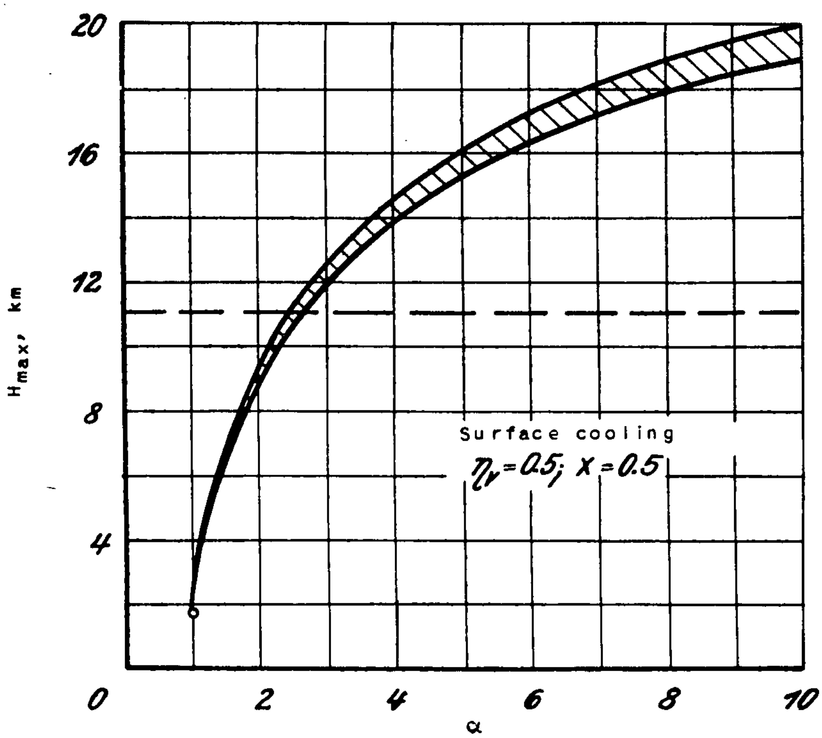


Figure 30. - Ceilings for different systems.

H_{max} ceiling altitude, km

α power ratio of aircraft

η_V adiabatic supercharger efficiency

Upper boundary of shaded area; very low-speed aircraft

Lower boundary of shaded area; very high-speed aircraft

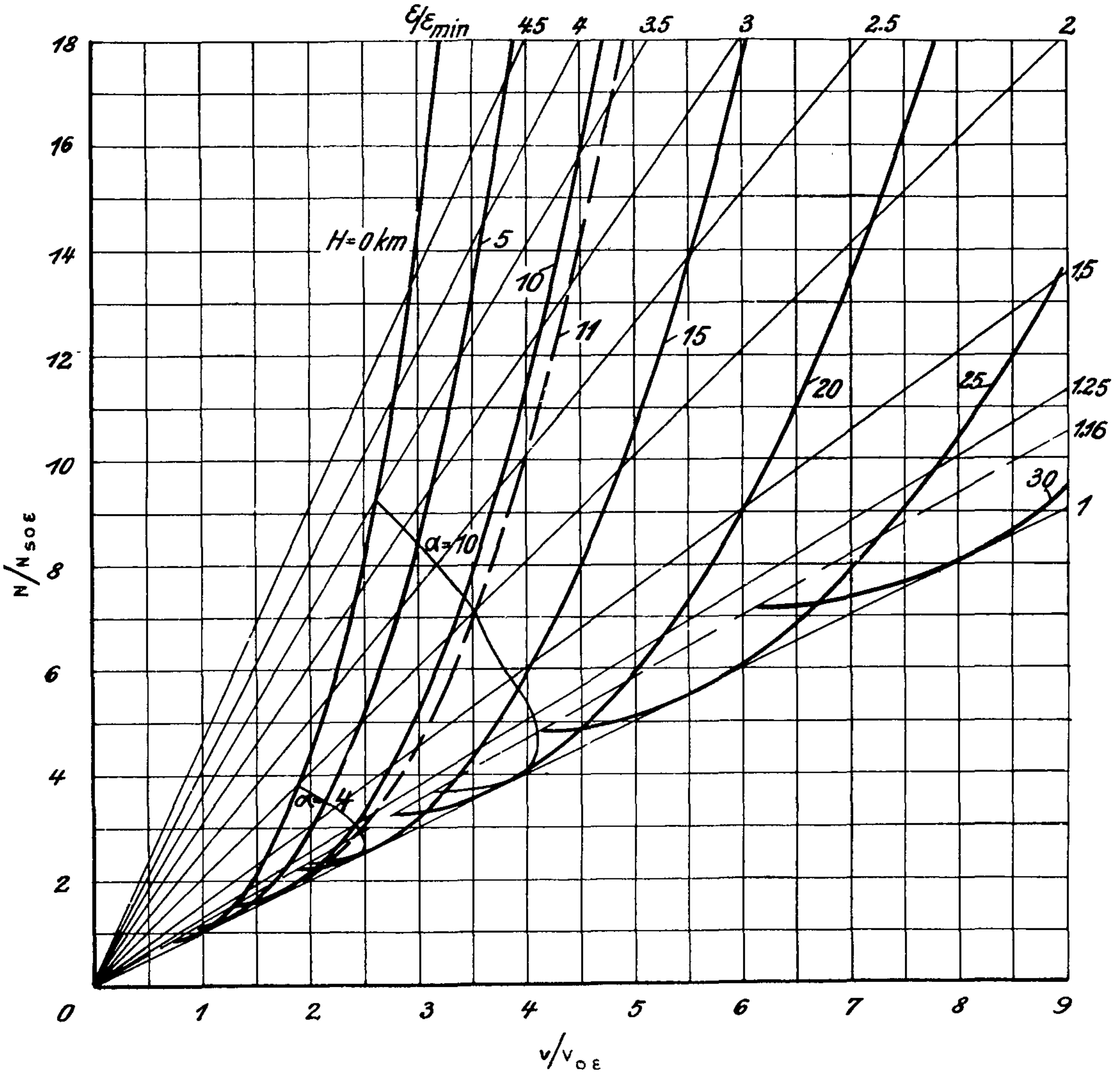
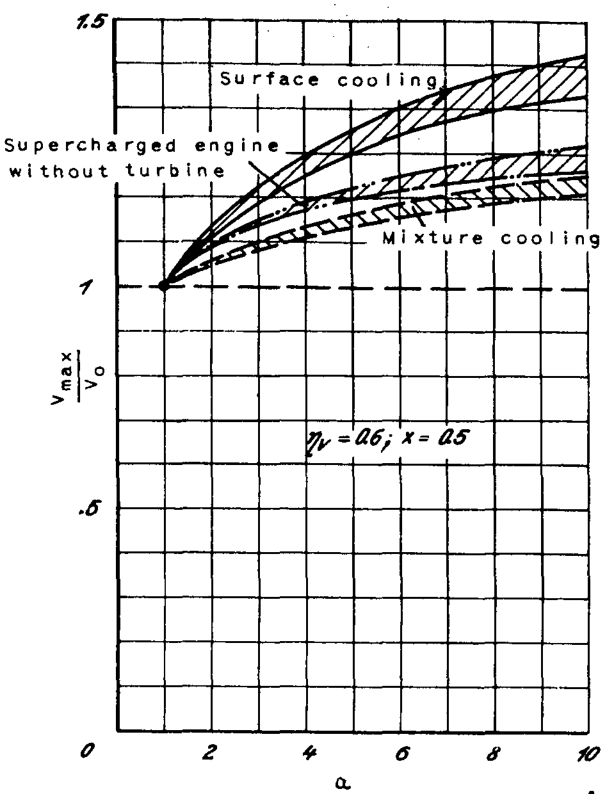
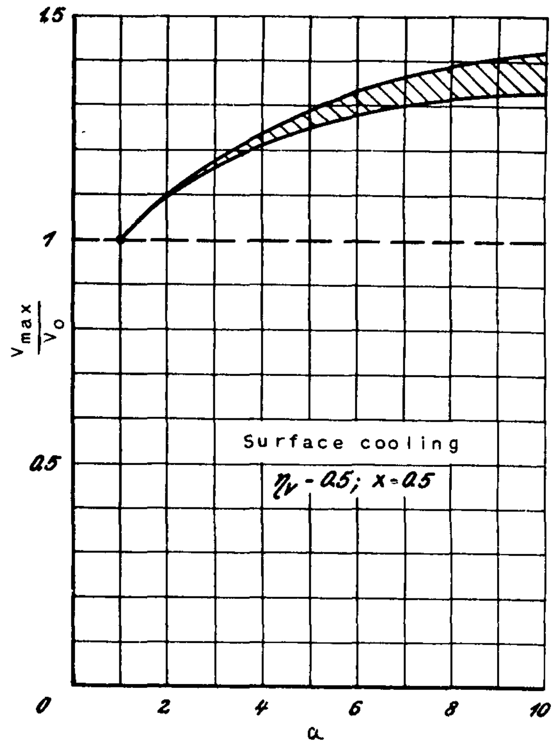


Figure 31. - Schrenk diagram for high-altitude flight.

v	flight speed
N	flight power
$v_{o\varepsilon}$	flight speed at optimum gliding angle at sea level
$N_{so\varepsilon}$	soaring power at optimum gliding angle at sea level
ε	gliding ratio
ε_{min}	optimum gliding ratio
H	flight altitude, km





Figures 32 and 33. - Ratio of maximum speed to speed at sea level with same power ratio.

v_{max} maximum speed

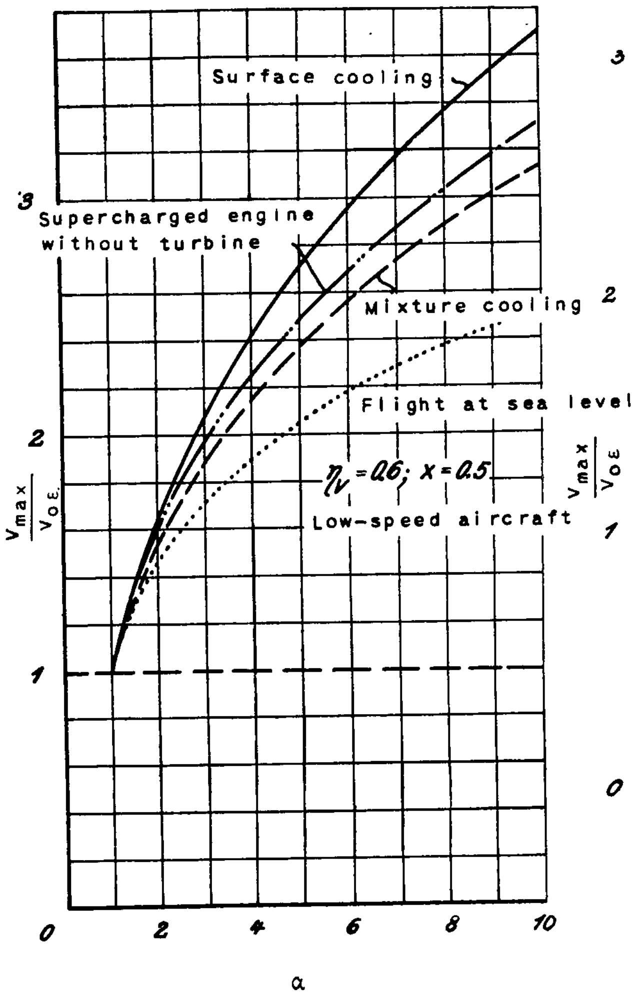
v_o speed at sea level

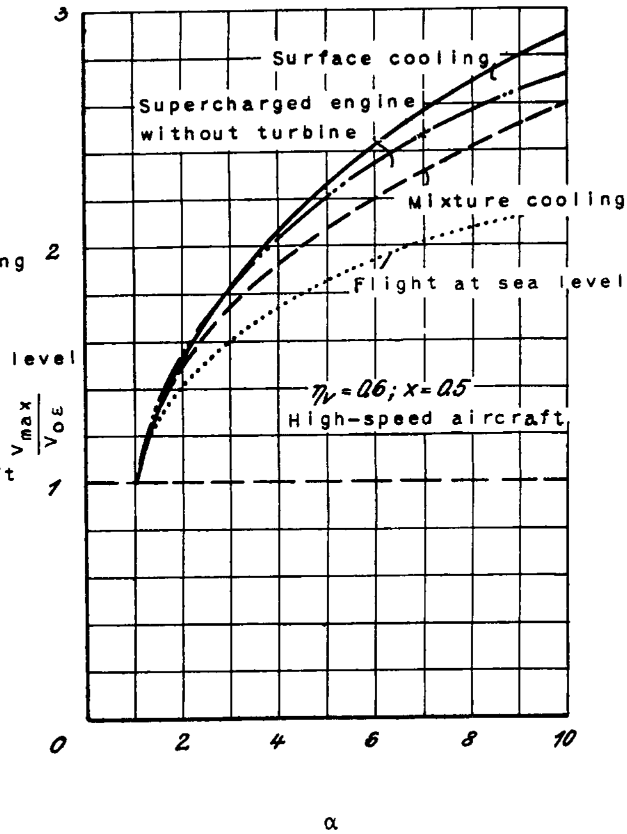
α power ratio of aircraft

η_v adiabatic supercharger efficiency

Upper boundary of shaded area; very low-speed aircraft

Lower boundary of shaded area; very high-speed aircraft





Figures 34 and 35. - Ratio of maximum speed to gliding speed at optimum gliding angle and sea level.

v_{max} maximum speed

$v_{o\varepsilon}$ gliding speed at optimum gliding angle and sea level

α power ratio

η_V adiabatic supercharger efficiency

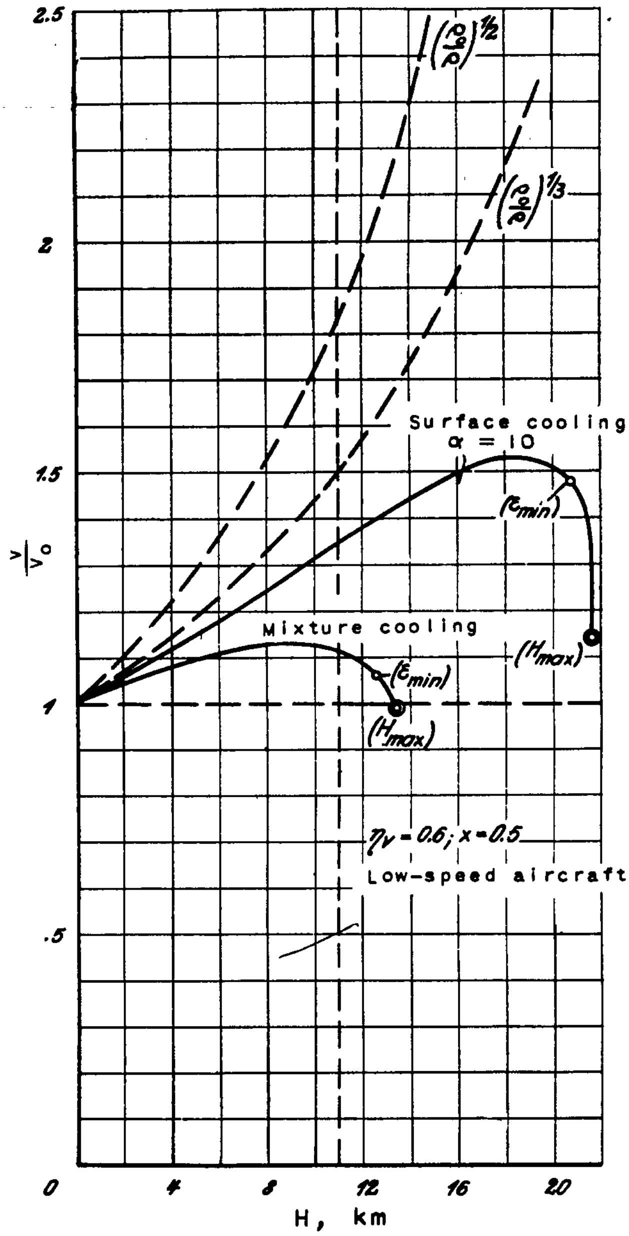


Figure 36. - Variation of speed with flight altitude.

v	speed along flight path
v_o	flight speed at sea level
ρ	air density
ρ_o	air density at sea level
α	power ratio
ε_{min}	optimum gliding angle
η_v	adiabatic supercharger efficiency
H	flight altitude, km
H_{max}	ceiling altitude

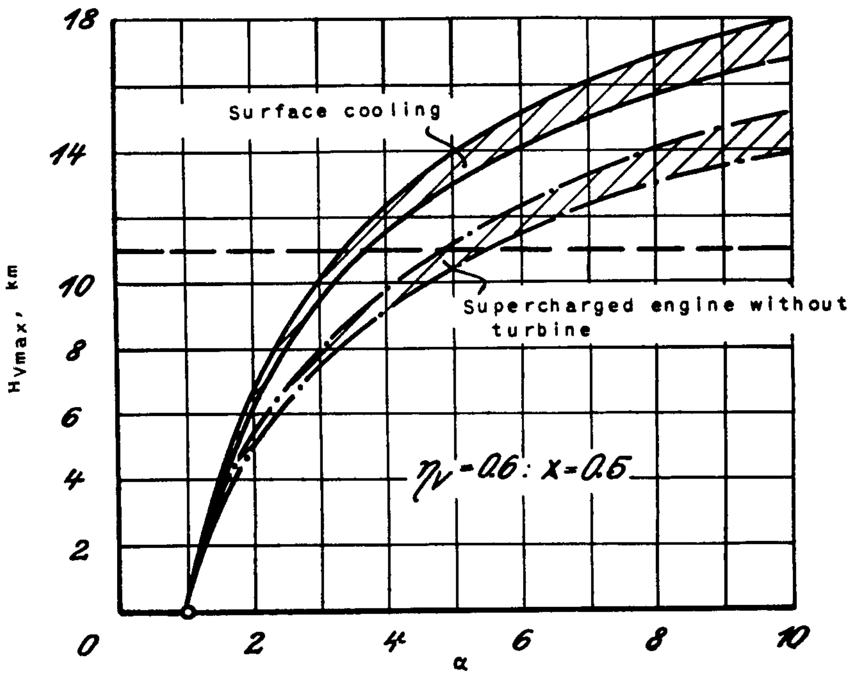


Figure 37. - Altitude for maximum speed.

H_{vmax} altitude at which maximum speed is attained, km

α power ratio

η_V adiabatic supercharger efficiency

x ratio of specific weight of supercharger and turbine to specific weight of engine

Upper boundary of shaded area; very low-speed aircraft

Lower boundary of shaded area; very high-speed aircraft

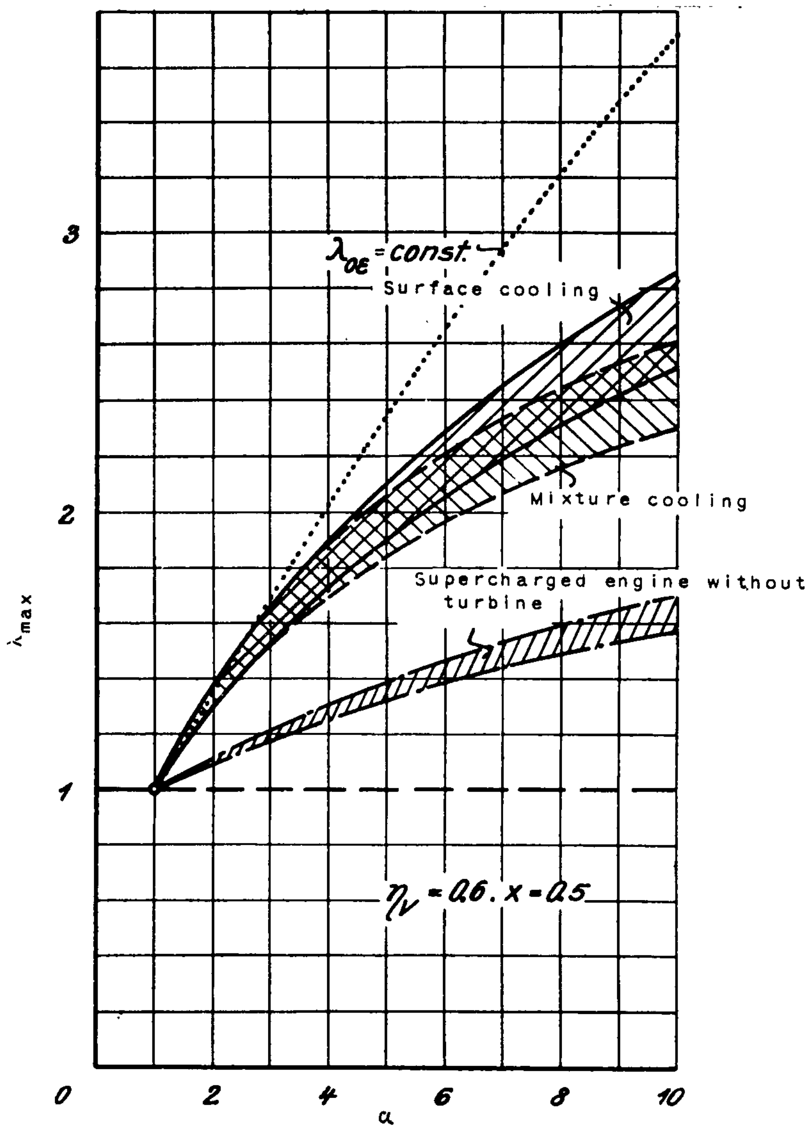


Figure 38. - Optimum index of economy.

λ_{max} optimum index of economy

$\lambda_{o\varepsilon}$ constant line along which values of λ_{max} would have to fall if economy were to remain same as for aircraft with $\alpha = 1$.

Upper boundary of shaded areas; very low-speed aircraft

Lower boundary of shaded areas; very high-speed aircraft

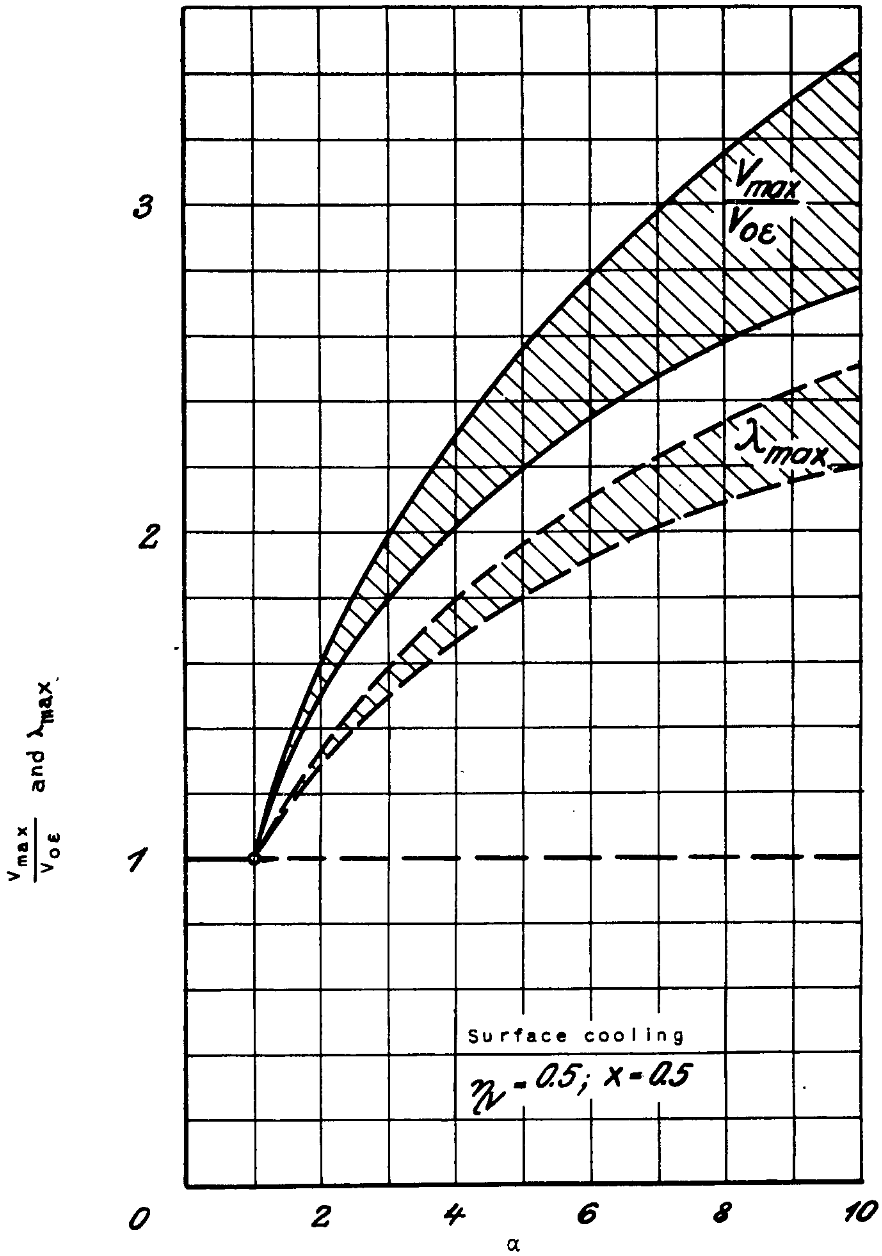


Figure 39. - Symbols and interpretation as in figures 34, 35, and 38.