ARR March 1943

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED
March 1943 as
Advance Restricted Report

THE EFFECT OF ALTITUDE ON COOLING

By Maurice J. Brevoort, Upshur T. Joyner, and George P. Wood

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

WASHINGTON

L - 386

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

THE EFFECT OF ALTITUDE ON COOLING

L-386

By Maurice J. Brevoort, Upshur T. Joyner, and George P. Wood

INTRODUCTION

The question of whether the liquid-cooled or air-cooled engine is the better for use in airplanes has always been a lively subject for discussion. The discussion has alternately favored each means of cooling and, at the present time, many people believe that high-altitude operation, at 40,000 feet and above, favors the liquid-cooled engine and that the cooling of an air-cooled engine becomes impossible at some high altitude.

The purpose of this report is to set down the variables that control the cooling of both engines and then to show by illustrations how either engine may be cooled at any desired altitude.

A practical and impartial discussion of this problem should be of assistance in evaluating the relative merits of both types of engine and should serve as a guide to assist in planning for the procurement of engines for future airplanes.

A great deal of the confusion regarding the relative merits of different types of engine for high-altitude operation arises from the fact that an engine with its cooling system (radiators or fins) may be designed for one altitude and then operated at a higher altitude. As long as the operating altitude is below [illegible]0,000 feet, only a small amount of trouble is encountered because compensating effects make the cooling problem less severe than at higher altitudes. At high altitude, the cooling problem becomes insurmountable unless the cooling arrangements are designed for high altitude. This fact means either an increase in cooling-air flow or an increase in surface area for cooling as the altitude increases.

In general, the cooling problem is solved most satisfactorily by increasing the cooling surface as the altitude increases. A liquid-cooled engine requires an increase in radiator size and an air-cooled engine requires increased finning with altitude.

Two illustrative examples are considered herein, one for a modern air-cooled engine and the other for a liquid-cooled engine developing the same power. The cooling characteristics of engines are known for certain low altitudes from test-stand and flight-operation data. It is a simple matter to compute the surface or air flow that is required to give the same cooling for either engine at any other altitude.

An appendix is presented that gives the method and the basis of the analysis.

AIR-COOLED ENGINE

Figure 1 is a chart in which the ratio of pressure drop required for cooling to pressure drop available for cooling is plotted against altitude for the high-speed flight condition. The method of calculation is shown in

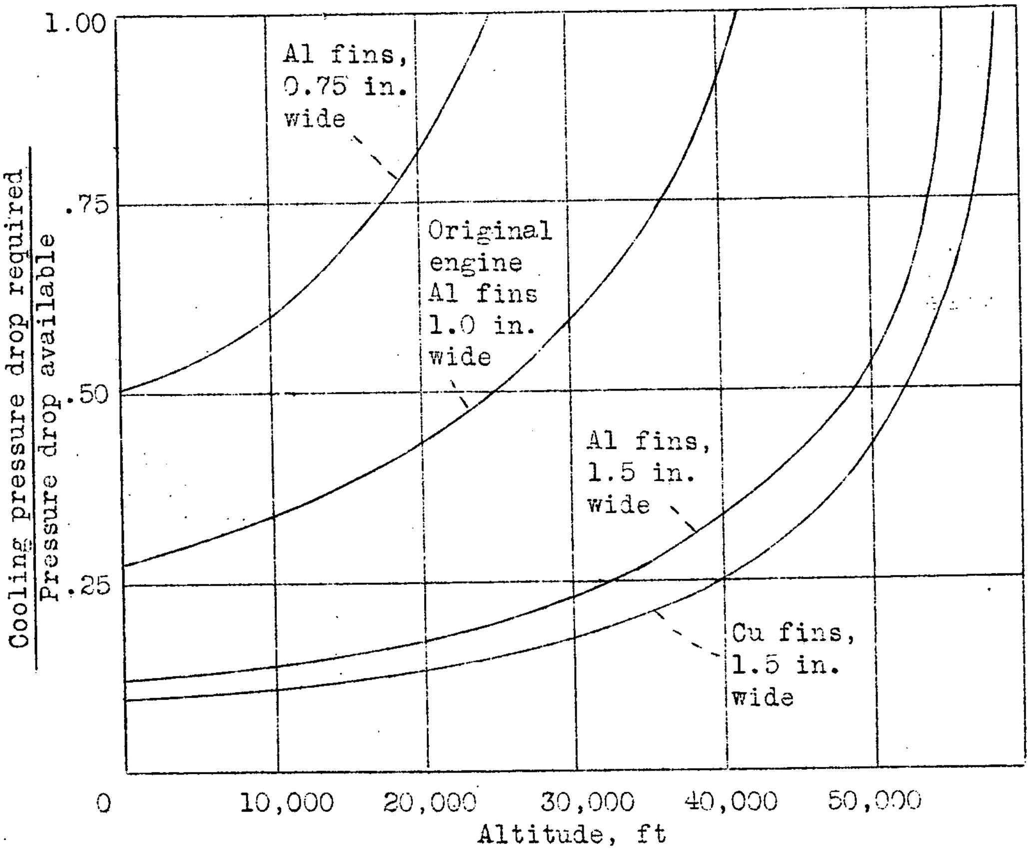

Figure 1.- The effect of altitude on the ratio of cooling pressure drop required to pressure drop available in the high-speed condition for the original air-cooled engine and for three hypothetical fin arrangements.

the appendix. The curve for the original engine shows that it will cool at rated power up to an altitude of about 42,000 feet.

The original engine had aluminum fins 1.0 inch wide. Curves for aluminum and copper fins 1.5 inches wide are also shown. The wider aluminum and the copper fins would allow the engine to cool at 55,000 and at 59,000 feet, respectively. A fourth curve is presented to show the relative effect of fins 0.75 inch wide, which represent older engines or engines of lower power rating.

The effect of altitude on the ratio of cooling required to cooling available with cowling flaps for the original engine and for the engine with copper fins 1.5 inches wide in the climb condition is shown in figure 2.

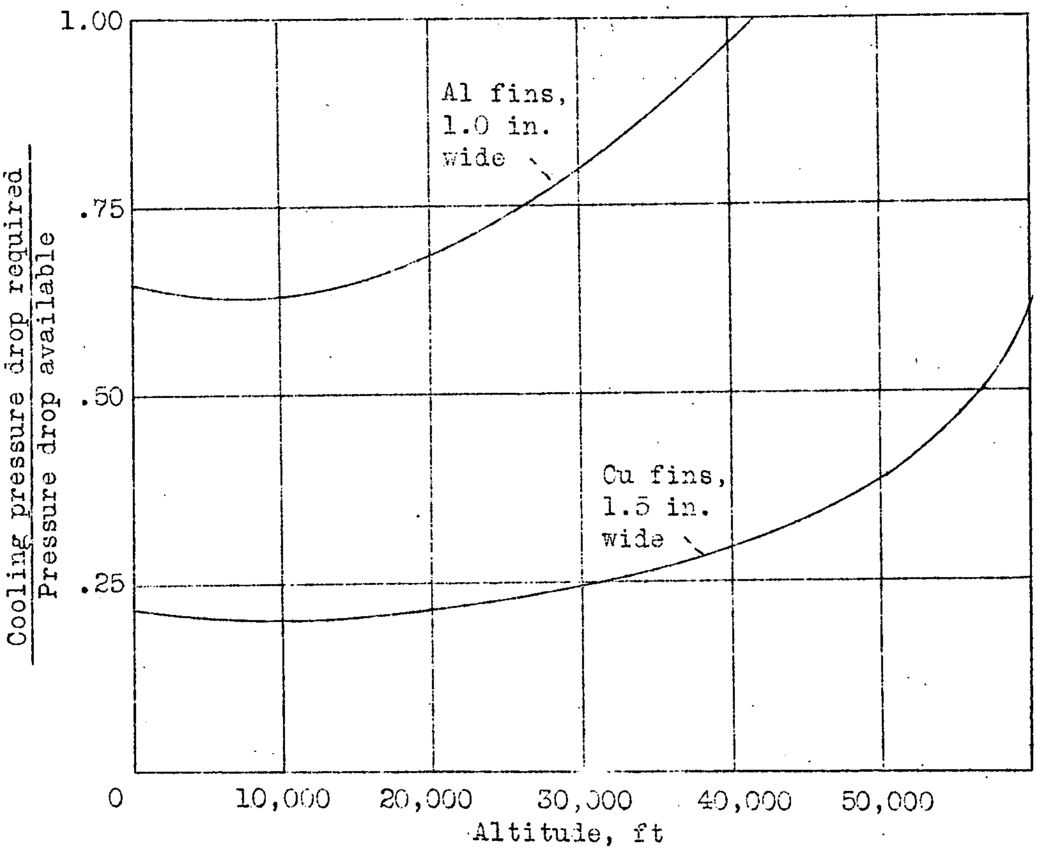

Figure 2.- The effect of altitude on the ratio of cooling required to cooling available in the climb condition for original engine using 1.0-inch aluminum fins and for the same engine using 1.5-inch copper fins.

It is interesting to note that in climb the original engine is able to cool at 41,000 feet. The 1.5-inch copper fins give a limiting altitude above 60,000 feet.

The power required for pumping cooling air in the high-speed flight condition for the four fin widths over the same altitude range is given in figure 3 as percent of engine power. The power required for pumping is the power associated with the increase in drag of an airplane when the cooling air flows through a conventional cowling or scoop.

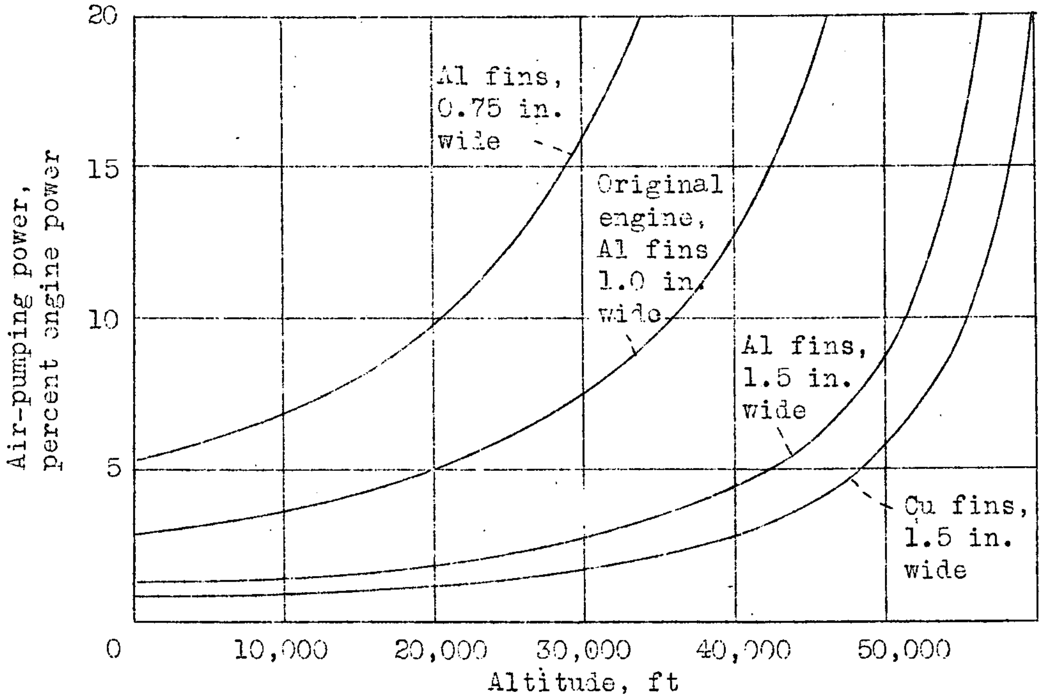

Figure 3.- The effect of altitude on the percent of engine power required to pump cooling air for the fin arrangements and the operating condition employed for figure 1.

Figure 4 shows as percent of engine power the power required to carry the weight of the fins in the high-speed flight condition. The power required to carry the best fins is surprisingly low when the relative cooling performance is considered.

The jet power due to the heat added to the cooling air, which is shown in figure 5, is an illustration of the well-known Meredith effect.

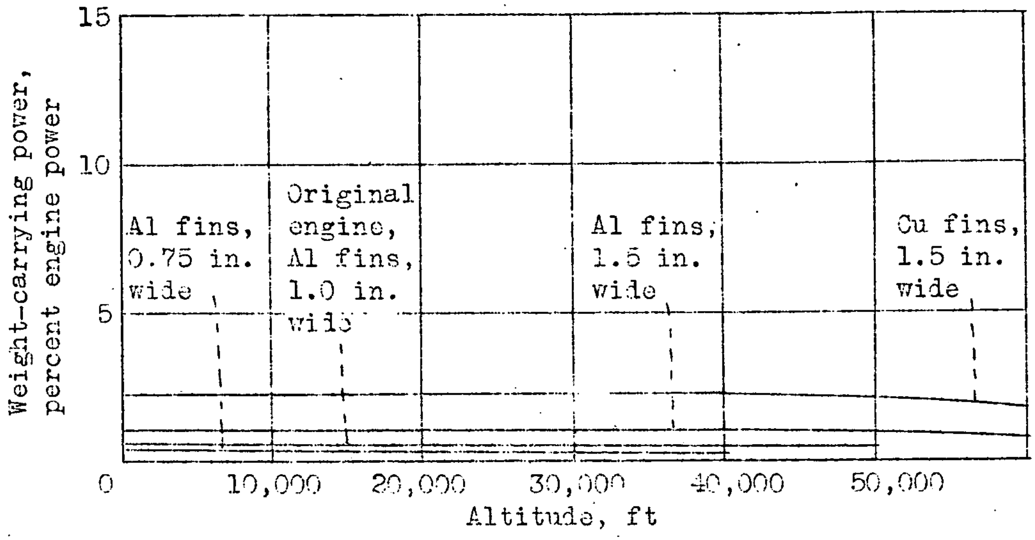

Figure 4.- Effect of altitude on the power to carry the fins in percent of engine power for the four fin arrangements.

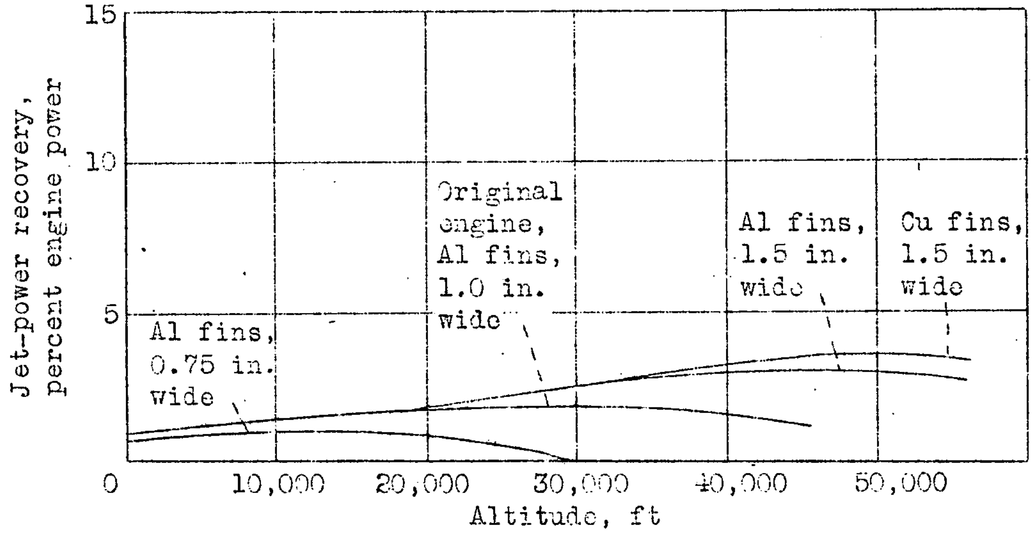

Figure 5.- Variation of jet-power recovery in percent of engine power for the four fin arrangements. High-speed flight condition.

The net power required to cool the air-cooled engine in the high-speed flight condition is given in figure 6. This power includes the power to pump the cooling air over the engine and the power to carry the fins and credits the

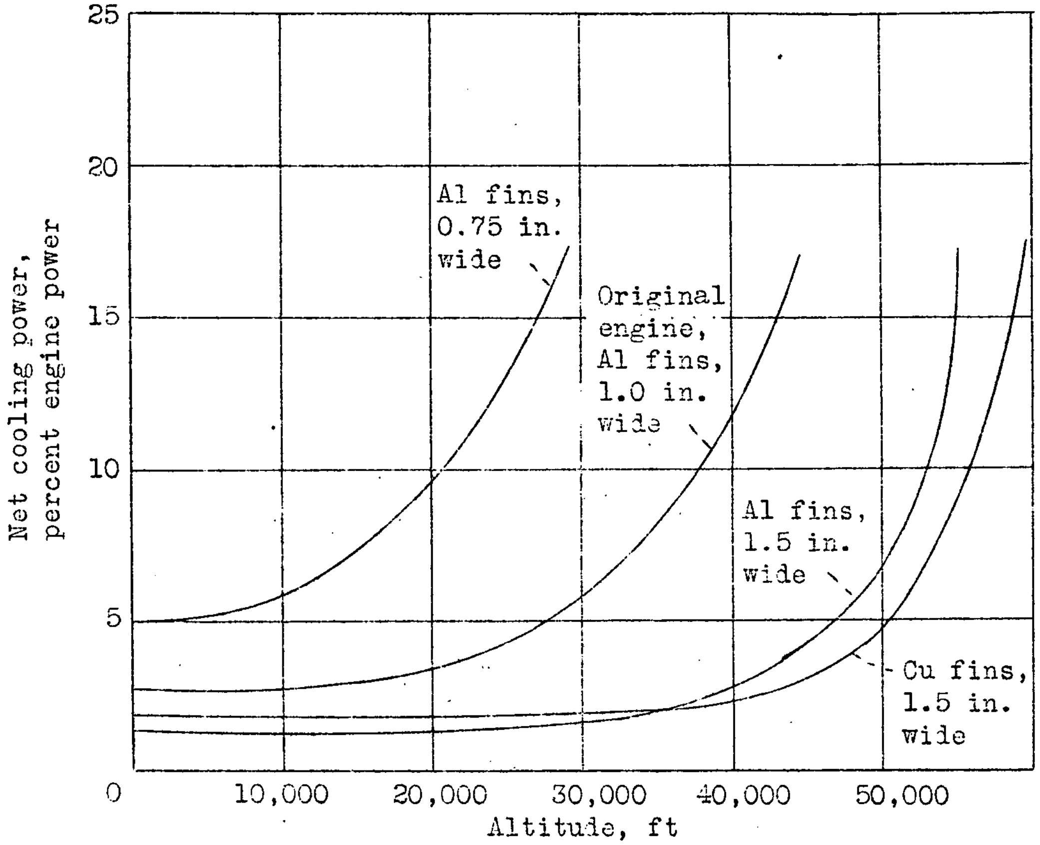

Figure 6.- Net cooling power in percent of engine power for an air-cooled engine as affected by altitude. High-speed flight condition.

system with the thrust power obtained from heating the cooling air. Figure 6 is interesting as a demonstration of the effectiveness of increased surface area in reducing the power for cooling, especially at high altitude.

LIQUID-COOLED ENGINE

Two cases are considered for the liquid-cooled engine: (1) with the coolant at atmospheric pressure at all altitudes (solid lines on figs. 7 to 11) and (2) with the coolant maintained at sea-level pressure at all altitudes (dashed lines on figs. 7 to 11).

Whenever a liquid-cooled engine tends to overheat at some particular altitude because of insufficient cooling and whenever the additional pressure drop needed to increase the cooling with the existing radiator installation is not available, the need for additional cooling can be satisfied by the substitution of a radiator of sufficiently larger cooling surface (larger volume). The variation of required optimum radiator volume with altitude for a liquid-cooled engine is shown in figure 7.

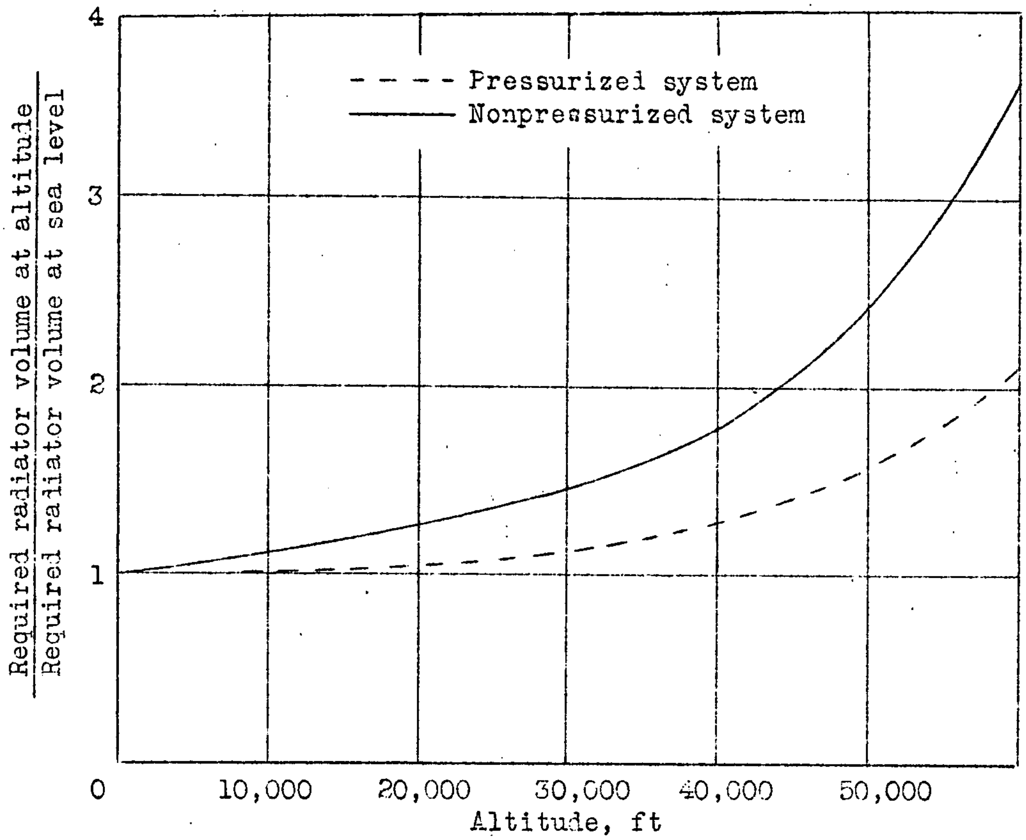

Figure 7.- Variation of required optimum radiator volume with altitude. Liquid-cooled engine; high-speed flight condition.

It can be clearly seen from figure 7 that the maximum altitude at which a liquid-cooled engine can be cooled is definitely fixed by the size of the radiator just as the limiting altitude of an air-cooled engine is fixed by its fins.

In order to illustrate the effect of altitude on the cooling performance of a liquid-cooled engine, a liquid-cooled engine of the same power as the air-cooled engine used and the same airplane have been assumed.

The variation with altitude of the ratio of the cooling pressure drop required to the pressure drop available for a liquid-cooled engine is given in figure 8. It can be seen from this figure that the original radiator installation, which was designed to be optimum at an altitude of 20,000 feet, becomes insufficient for cooling at an altitude of 49,000 feet. Two other radiator installations with greater cooling surface (volume) designed to be optimum at altitudes of 40,000 feet and 60,000 feet are also shown. Both of these installations will cool the engine at a higher altitude than the original installation.

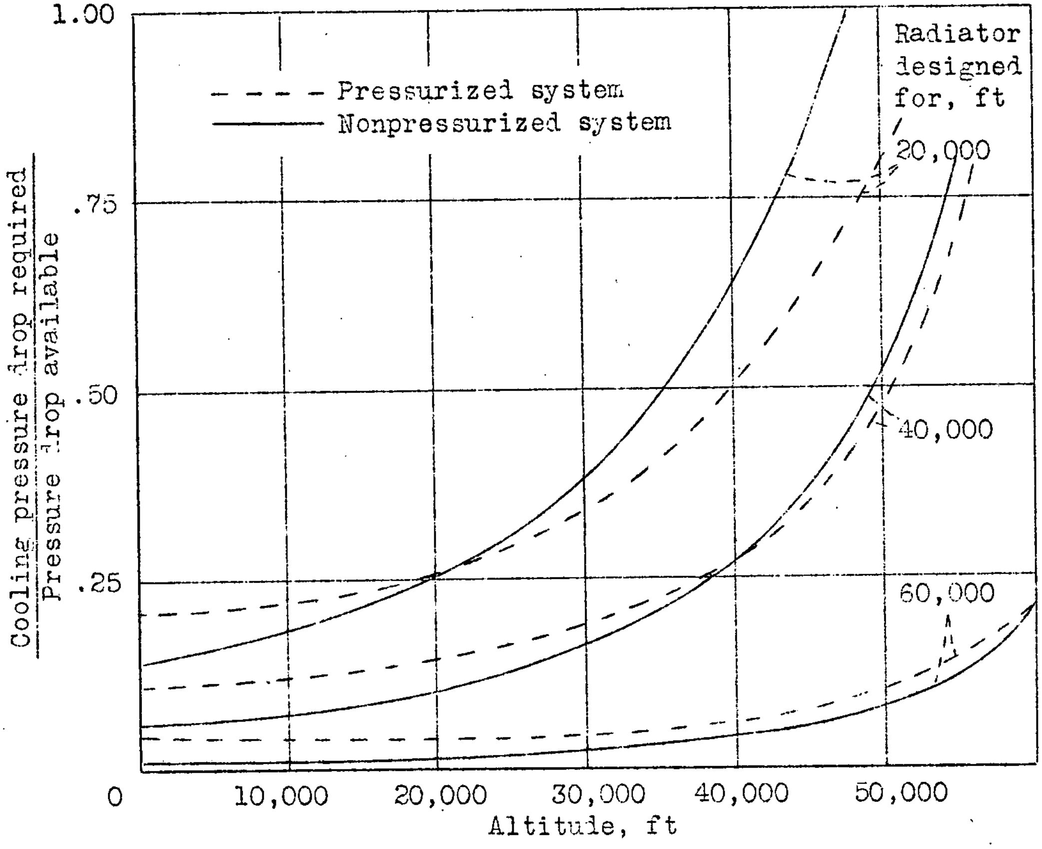

Figure 8.- The effect of altitude on the ratio of cooling pressure drop required to pressure drop available for the liquid-cooled engine. High-speed flight condition.

The power required to cool the engine in the high-speed flight condition is shown in figures 9 to 11. Figure 9 shows the air-pumping power plus the weight power, figure 10 shows the power recovered in the radiator exit jet as a result of heating the cooling air, and figure 11 shows the net cooling power.

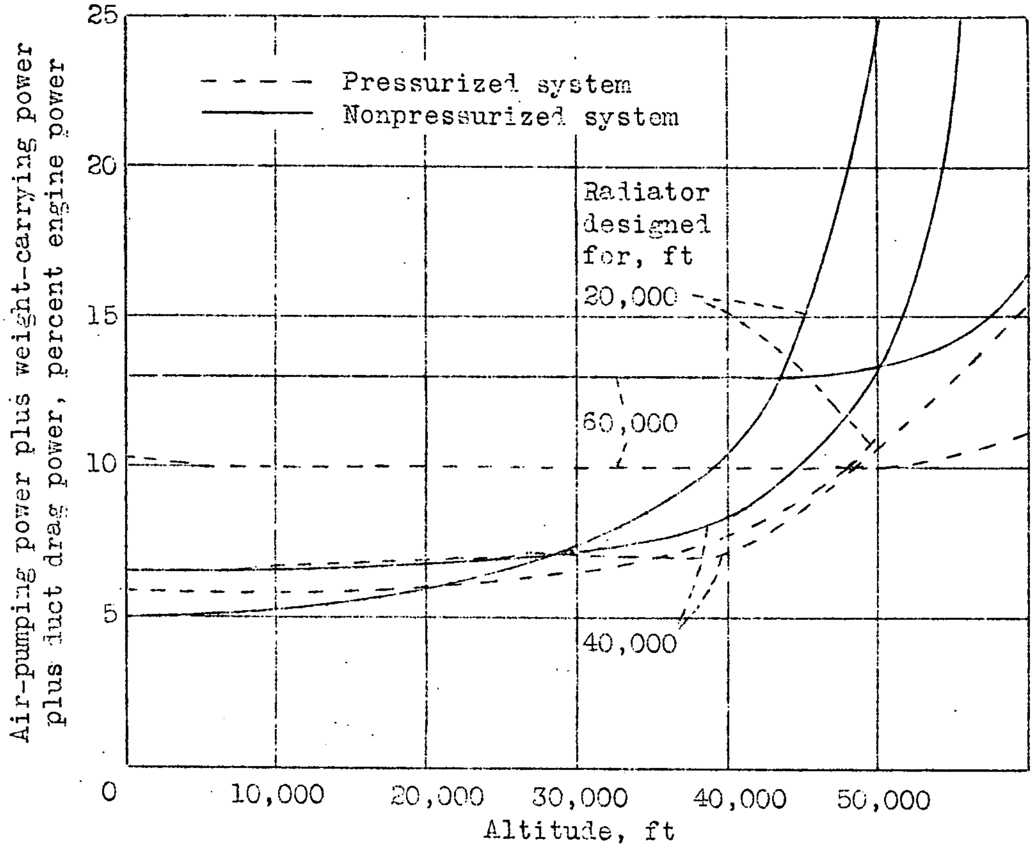

Figure 9.- The effect of altitude on the sum of air-pumping power, the power to carry the weight of coolant and radiator, and the power consumed by duct drag for the liquid-cooled engine. High-speed flight condition.

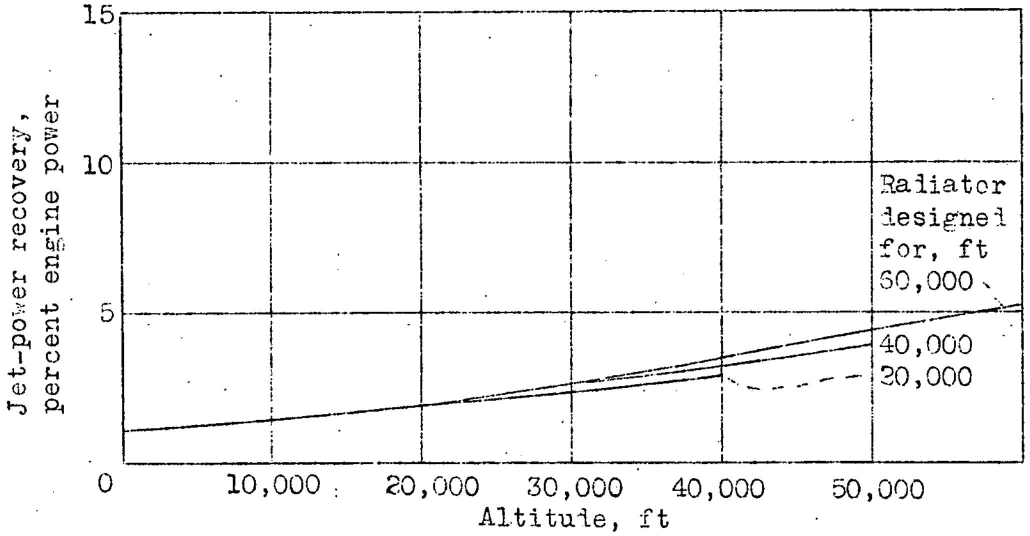

Figure 10.- Variation with altitude at the radiator exit of jet-power recovery for the liquid-cooled engine. High-speed flight condition.

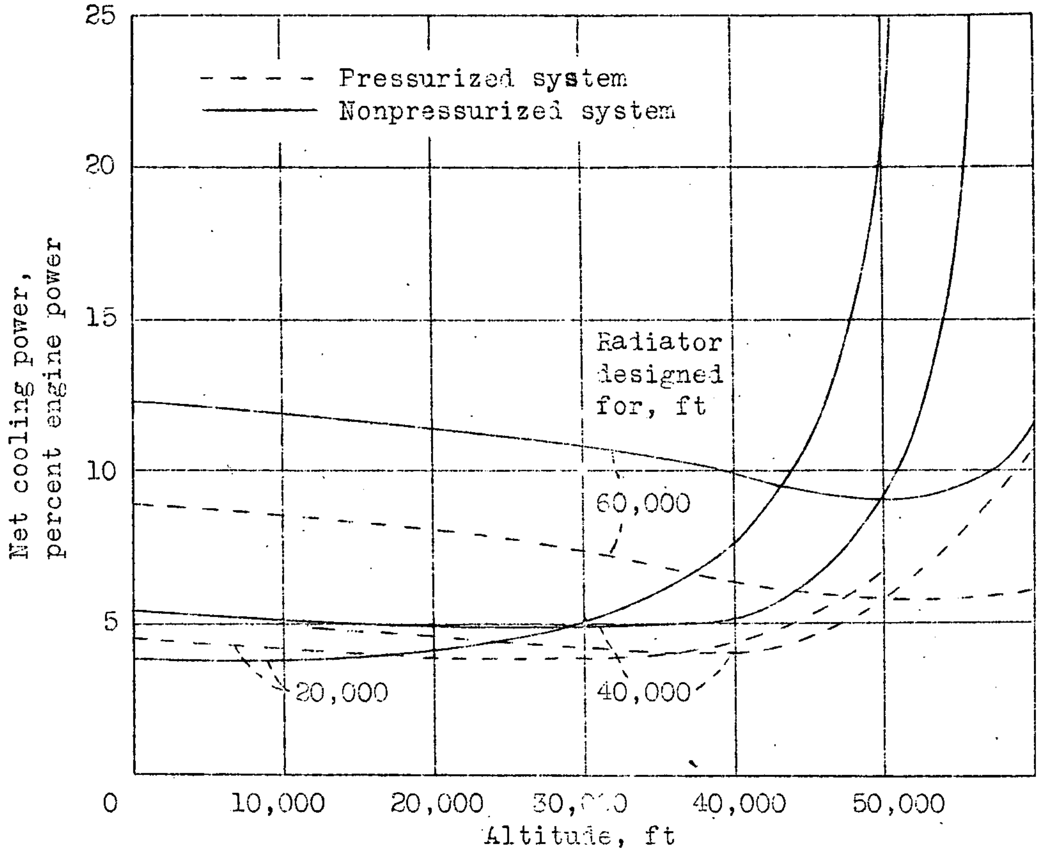

Figure 11.- Net cooling power in percent of engine power for a liquid-cooled engine. High-speed flight condition.

The solution to the high-altitude cooling problem for liquid-cooled engines shown here is simply the addition of more cooling surface. This solution is the same as that shown for the air-cooled engine and the same kind of results were obtained in both cases.

DISCUSSION

The problem of cooling at altitude has been illustrated for the liquid- and for the air-cooled engines. Neither engine is limited in altitude possibilities by cooling.

The present analysis has been confined to the single problem of cooling. There are numerous problems connected with supercharging, intercooling, carburetion, aerodynamics, etc. The cooling, taken by itself, appears to be relatively simpler than many of the other problems associated with high-altitude flight.

For instance, on a good installation at an altitude of 40,000 feet, the air-cooled engine with 1.5-inch aluminum fins uses less than 40 percent of the available pressure drop and requires less than 3 percent of the engine power for cooling. The liquid-cooled engine having a radiator designed for 40,000 feet altitude uses 27 percent of the available pressure drop and requires 5 percent of the engine power for cooling with the coolant at atmospheric pressure and uses 27 percent of the available pressure drop and requires 4 percent of the engine power for cooling for the pressurized case.

The important point to be gained from this illustration is not the difference between liquid-cooled and air-cooled engines but the more important fact that each requires only a very small power for cooling and each requires pressure drops which are easily developed.

When the problem is pursued further in the appendix, it will be noted that the cooling power computed here assumes that the power to pump the cooling air through the fins or the radiator tubes is accomplished at 100-percent pumping efficiency. The actual pumping efficiency should not be below 80 percent except in the case in which all the available pressure drop is needed for cooling. Even in this case the ideal efficiency should not fall below 50 percent. In most installations, however, there are avoidable increases in form or pressure drag due to the cooling installation that may reduce the apparent pumping efficiency to a fraction of the value obtainable on the best possible installation.

CONCLUSIONS

The foregoing analysis has shown that air-cooled and liquid-cooled engines can be cooled with a small fraction of the available pressure drop and with cooling powers of 2 to 5 percent of the engine power. The pressure drops and powers in both cases are materially below present-day installation values on operating airplanes. It thus develops that much greater gains can be made by improving either installation than can be attributed to the true differences between the two types of engine.

As a result of the analysis and the more complete computations presented in the appendix, if proper design of cooling surface (fins or radiator) is used, it can be concluded that:

1. Cooling is not the limiting factor in the design of high-altitude airplanes.

2. Cooling is not a valid reason for selecting either liquid- or air-cooled engines for high-altitude operation.

3. It is essential that the cooling system be designed for the operating altitude.

4. Disregard of conclusion 3 has been the major cause of the confusion concerning high-altitude cooling.

5. The solutions to the cooling problem given here involve no impractical or unattainable arrangements.

Conclusions pertaining to the air-cooled engine and to the liquid-cooled engine are given at the end of the sections Air-Cooled Engine and Liquid-Cooled Engine in appendix B.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

APPENDIX A

SYMBOLS

A	leak area around cylinders, radiator frontal area, square feet
c_p	specific heat of air at constant pressure, Btu per pound per °F
D	hydraulic diameter of air passage, feet
f	fin effectiveness
g	acceleration due to gravity, feet per second per second
h	local coefficient of heat transfer, Btu per square foot per second per °F
H	rate of heat transfer, Btu per second
k	thermal conductivity of air, Btu per square foot per second per °F per foot
k_m	thermal conductivity of metal, Btu per square foot per second per °F per foot
M	weight rate of flow, pounds per second
p	static pressure, pounds per square foot
Δp_f	friction pressure drop, pounds per square foot
r_b	radius from center of cylinder to root of fin, feet
R	gas constant
s	fin spacing, feet
S	area of cylinder walls, square feet
t	average fin thickness, feet
w	fin width, feet
T	absolute temperature of air
T_o	average engine temperature, °F
T_a	free-air temperature, °F
T_i	inlet temperature of air, °F

T_o	outlet temperature of air, $^{\circ}F$
ΔT	average temperature difference between engine and air, $^{\circ}F$
U	over-all heat-transfer coefficient from metal to air, Btu per square foot per second per $^{\circ}F$
V	speed of air, feet per second
V_i	speed of air in cooling-air passage entrance, feet per second
V_o	speed of air in cooling-air passage exit, feet per second
V_a	speed of airplane, feet per second
ρ	density of air, slugs per cubic foot
ρ_a	free-air density, slugs per cubic foot
ρ_i	inlet density of air, slugs per cubic foot
ρ_o	outlet density of air, slugs per cubic foot
q	dynamic pressure, pounds per square foot
q_a	dynamic pressure corresponding to V_a, pounds per square foot
q_i	inlet dynamic pressure, pounds per square foot
q_o	outlet dynamic pressure, pounds per square foot
μ	coefficient of viscosity of air, slugs per foot per second
W	weight of fins, pounds
Δp	pressure drop, pounds per square foot
Q	volume rate of flow, cubic feet per second
C_{D_d}	drag coefficient of duct
D_d	drag of duct, pounds
P_D	power required to overcome duct drag, horsepower
$a = \sqrt{\frac{2h}{k_m t}}$	
C_D/C_L	ratio of airplane drag coefficient to lift coefficient

APPENDIX B

METHODS AND ASSUMPTIONS USED IN COMPUTATIONS

INTRODUCTION

The purpose of the present analysis is to show how altitude enters the problem of cooling an engine. Both a liquid-cooled engine and an air-cooled engine are considered and it is assumed that manufacturing techniques and airplane design and performance are as good as, but no better than, the best present practice. The effect of altitude on the problem of engine cooling is the only altitude effect considered in this paper.

The whole analysis has been based on the assumption that the engine is operating at or below its critical altitude over the entire range of altitude considered. Under this condition the pressure and temperature at the carburetor inlet are maintained at some fixed value, regardless of altitude, and the oil temperature and the rate of flow are also constant. The engine is assumed to operate at any altitude exactly as it would at sea level, provided that the cylinder and the head-wall temperatures are maintained constant. The conditions assumed here are conditions that can be realized on a well-designed installation for a supercharged engine.

It is well to realize the importance of these conditions because many of the results obtained from this analysis appear to contradict experience. This contradiction is inevitable because almost all the experience with cooling at high altitude has been obtained on airplanes employing engines operating above their critical altitude or otherwise inadequately equipped for high-altitude operation.

For instance, calculations show that engine cooling on typical airplanes should increase in difficulty up to the critical altitude and decrease in difficulty as altitude increases above the critical altitude. Experience with actual airplanes operating above the critical altitude shows that overheating occurs at the higher altitudes.

This apparent divergence between experience and computed performance is not real, however, and is explained by the fact that the carburetor tends to lean the air-fuel mixture above the critical altitude. As the mixture becomes progressively leaner, more cooling is required. This illustration should make it clear that experiences with high-altitude cooling must be given very critical examination.

The problem of cooling at altitude has been analyzed along two lines: (1) to determine the required increase in Δp as the altitude increases and (2) to show the benefit of increased cooling surface in regard to pressure drop and power for cooling. The tendency in the past has been to maintain fins or radiators at the minimum size. Consequently, there has been an inevitable increase in the quantity of cooling air required that has resulted in increasing the required cooling-air pressure drop beyond the pressure drop available.

The present analysis applies to an actual air-cooled engine. The pressure drop required for cooling at sea level at rated power is the starting point for the analysis. One engine would have been as good as another for this analysis and the type of finning or the methods of manufacturing the fins are no part of this report. The effect on cooling of adding cooling surface is demonstrated here by computations.

Also in the liquid-cooled engines the processes connected with the transfer of heat from the engine to the coolant are not considered. The analysis is confined entirely to determining the radiator size required to cool using a representative coolant.

The air density and temperature decrease with altitude. The temperature of NACA standard air becomes constant at -67° F at 36,000 feet and Army air comes to the same temperature at 46,500 feet. (See fig. 12.)

The lower temperature of the cooling air at altitude tends to ease the cooling problem there, whereas the lower density tends to aggravate the problem. The density decrease with altitude results in a decreasing dynamic pressure and increasing speed. Figure 13 shows computed values of q_a and V_a for a typical high-speed airplane neglecting changes in drag due to compressibility. In obtaining the flight speed at each altitude, the curve of drag coefficient against lift coefficient for an existing late-model pursuit airplane was used. The effective thrust power was reduced at each altitude by the power required by an intercooler and oil cooler chosen for that altitude. Cylinder baffling was assumed the same for all sets of fin dimensions.

With the density, temperature, and speed varying with altitude in such a way that they have partly compensating effects and effects of varying magnitude, it is not generally possible to predict without analysis the exact effect of altitude on cooling.

Even though the airplane assumed here is a modern pursuit airplane of high performance, the conclusions reached are fairly general. Modern high-performance airplanes have reached such a high degree of refinement that conclusions reached on cooling for a pursuit airplane can be applied without great modification to other high-performance types.

AIR-COOLED ENGINE

The computation of cooling at altitude consists in calculating the mass flow of air required for cooling. The engine rated power is 1675 horsepower and the propeller efficiency is assumed to be 80 percent at all altitudes. The engine must dissipate 445 Btu per second at an average head temperature T_e of 410° F. The surface S for cooling is 15 square feet. The fin width w is 1.0 inch. The fin spacing s is 0.15 inch. The outside cylinder radius r_b is 3.6 inches. The thermal conductivity k_m of aluminum is 0.0345 Btu per second per square foot per $^{\circ}F$.

The mass flow of air required varies with the temperature difference available for cooling. This varying mass flow requires an increasing pressure drop with altitude which determines the limiting altitude at which the airplane may be operated under any flight condition.

Analysis

The present analysis is an extension of the problem as it was presented in reference 1. Certain formulas are taken from reference 1 and from other sources. These formulas are reproduced here for use in this computation.

In order to find the mass flow that is necessary to effect the required rate of heat transfer at a given altitude and in order to find the corresponding values of air temperature and velocity at the entrance and at the exit to the baffles, equations (1) to (6) were solved simultaneously. Equation (1) is the heat-balance equation.

$$\frac{H}{M} = c_p(T_o - T_i) + \frac{V_o^2 - V_i^2}{(778)(2)g} \tag{1}$$

Equation (2) is the fundamental equation for heat transfer by forced convection.

$$H = S\ U\ \Delta T \tag{2}$$

Equation (3) is the equation of continuity.

$$\rho_i V_i = \rho_o V_o \tag{3}$$

Equation (4) states that the static-pressure drop between baffle entrance and exit is the sum of the momentum increase of the air and the friction pressure drop.

$$p_i - p_o = \rho V(V_o - V_i) + \Delta p_f \tag{4}$$

Equations (5) and (6) relate free-stream and entrance conditions.

$$T_i = T_a \left(\frac{\rho_i}{\rho_a}\right)^{\gamma - 1} \tag{5}$$

$$T_i = T_a + \frac{0.832}{10^4}(V_a^2 - V_i^2) \tag{6}$$

Entrance and exit conditions must be determined simultaneously, because they are mutually interdependent. For example, for a given altitude and airplane speed, T_i depends on the mass flow. The mass flow required for cooling depends, moreover, on ΔT. The quantity ΔT is the difference between the average engine temperature T_e and the arithmetic mean air temperature (cf. equation (7)). The weight rate of flow M is a function, therefore, of both inlet and outlet conditions.

Before a solution of equations (1) to (6) was made, substitution for certain of the quantities was made by means of the following relations:

$$\Delta T = T_e - \frac{1}{2}(T_i + T_o) \tag{7}$$

By definition,

$$M = gA\rho V \tag{8}$$

From reference 2,

$$U = \frac{h}{s + t} \left\{ \left(2w + \frac{w^2}{r_b} \right) \frac{\tanh aw}{aw} + s \right\} \tag{9}$$

From reference 3,

$$h = 0.2 \left(\frac{\mu}{D} \right)^{0.2} (\rho V)^{0.8} \tag{10}$$

if

$$\frac{k}{\mu} = 10 \tag{11}$$

From reference 4,

$$f = \frac{\tanh aw}{aw} \tag{12}$$

where

$$a = \sqrt{\frac{2h}{k_m t}} \tag{13}$$

And, from reference 1,

$$f \approx 1.07 - 0.3\ aw \tag{14}$$

The last equation for f, which is an approximation, is correct within 1 percent for $0.50 < f < 0.95$.

$$\Delta p_f = 0.3 \left(\frac{q_i + q_o}{2}\right) \tag{15}$$

From the general gas law,

$$p = R \rho T \tag{16}$$

Cooling in the original engine.- The known heat dissipation, fin dimensions, air temperature, and density variation with altitude are used with equations (1) to (16) to compute the variation of M, T_i, T_o, and Δp with altitude. The variation of these quantities with altitude is shown in figure 14. The properties of Army air were used in all calculations.

Figure 15 shows the breakdown of the pressure drop for cooling into its three components: (1) the useful frictional pressure drop, (2) the nonuseful momentum pressure drop, and (3) the nonuseful pressure drop at the exit. It should be remembered that pressure drop refers to a loss in total pressure. The friction pressure drop is given by equation (15), which is based on the experimental results described in reference 5. The momentum pressure drop is given by equation (4). The exit pressure loss is taken as $0.7q_o$ on the basis of the measurements described in reference 5.

The ratio of cooling pressure drop required to pressure drop available for cooling against altitude is shown in figure 16. For this analysis it is assumed that, in the high-speed condition, the pressure drop available is $0.75q_a$. This value is arbitrary and may be chosen in line with individual experience. Any other choice simply varies the limiting altitude.

Cooling with other fin arrangements.- The cooling for the original engine is illustrated in figures 14, 15, and 16. This engine is limited to an altitude of approximately 42,000 feet. If this altitude were to be exceeded by increase in pressure drop for cooling, some type of blower would be required and, because the pressure drop required rises so abruptly with altitude, the power for cooling would soon become excessive. It is obviously impracticable to obtain increased altitude by this means.

In the present section, an analysis will be made of the effect of adding surface to the cylinder by increased fin width. The following table shows the fin dimensions that will be used to illustrate the effect of adding surface area for cooling:

Fins	Fin material	Air properties	Flight condition	A (sq ft)	w (in.)	t (in.)
Original	Al	Army	High speed	2.2	1.0	0.060
Do---	--do--	--do--	Climb	2.2	1.0	.060
Wide Al	--do--	--do--	High speed	3.3	1.5	.052
Wide thin Cu	Cu	--do--	---do----	3.3	1.5	.035
Narrow Al	Al	--do--	---do----	1.65	.75	.060
Wide thin Cu	Cu	--do--	Climb	3.3	1.5	.035

The ratio of cooling pressure drop required to pressure drop available when the 1.5-inch aluminum fins are used is shown in figure 16. These fins are spaced at 0.15 inch, the same as the original fins, but the thickness is assumed to be 0.052 instead of 0.060 inch. This thickness is optimum for this width aluminum fin at 30,000 feet altitude.

Figure 17 shows the T_i, T_o, M, and Δp for this same fin arrangement. A comparison of figures 14 and 17 shows that the wider aluminum fins reduce the required pressure drop for cooling at 40,000 feet from 112 to 40 pounds per square foot. Consequently, the power for cooling is markedly lower for the wider fins.

When copper fins are used, the thickness may be reduced because of the high thermal conductivity of copper. The thickness was chosen as 0.035 inch. The optimum thickness is somewhat less, and a thinner fin is more desirable if it can be manufactured. The thin copper fins allow more fins to be added to an air-cooled engine with the same spacing.

The computed results for the copper fins are given in figures 16 and 18. A comparison of figures 14, 17, and 18 shows a further reduction of the required pressure drop to 30 pounds per square foot at 40,000 feet. The pressure drop required at 55,000 feet is 59 pounds per square foot, a value that is easily obtained. The value of M over the whole range as well as the value of Δp is reduced with the result that the power for cooling is further reduced.

Power for cooling.- The power for cooling is the algebraic sum of the power to pump the cooling air through the fins and the power to carry the fins and the thrust from the heated air at the exit.

The pumping power is given by ΔpQ.

The carrying power is given by $\frac{C_D}{C_L} WV_a$ where W is the weight of the fins.

The pumping power for the various fin arrangements considered is shown in figure 19. The thrust power from the heat is computed according to the analysis presented in reference 6 and this power is negative with respect to the other components of the cooling power. The thrust power at the exit due to the heat added to the cooling air is shown in figure 20 for the various fin arrangements. Figure 21 shows the power required to carry the fins in the high-speed condition. When it is seen how small this power actually is, the short-sightedness of trying to reduce engine weight by limiting fin area becomes apparent.

This point is further illustrated in figure 22, in which the net power, that is, the combination of power shown in figures 19 to 21, is given. The original engine requires 200 horsepower at 40,000 feet, whereas the wide aluminum or the copper fins require only 40 to 50 horsepower. The wide fins are nearly optimum for 40,000 feet when the power for cooling is the determining factor.

Cooling in climb.- Figure 23 gives the variation with altitude of the ratio of cooling pressure drop required to the pressure drop available for the original fins and for the 1.5-inch copper fins in climb. It was assumed that exit flaps would be used in the climb and that the total pressure drop available would be 1.2 times the flight dynamic pressure.

It can be seen by comparing figures 23 and 16 that the maximum altitude at which the engine will cool in climb is about the same as the maximum altitude at which it will cool in high-speed flight.

Fin effectiveness.- The variation with altitude of the ratio of the over-all heat-transfer coefficient for the finned cylinder to that for a plain cylinder with the same surface heat-transfer coefficient assumed in both cases is shown in figure 24. The over-all heat-transfer coefficient for the finned cylinder was calculated from the equation given earlier in the analysis. If the engine cylinder wall and cooling-air temperatures are the same in the two cases, this ratio is also the ratio of the heat dissipated by the finned cylinder to the heat dissipated by a plain cylinder. Hence, the ratio may be considered as a factor of cooling effectiveness.

Relation between sea-level pressure drop and limiting altitude.- The effect of the pressure drop required at sea level for cooling on the limiting altitude for cooling is shown in figure 25. This figure like most of the figures in this report is simply illustrative. A similar curve could be drawn for oil coolers, radiators, or intercoolers. The figure illustrates the fundamental fact that, if any piece of heat-transfer equipment is installed on an aircraft and cooled by a pressure drop which is related to the dynamic pressure of the airplane, the limiting altitude at which the apparatus cools is an inverse function of the pressure drop required at sea level.

Concluding Remarks

It must be apparent from the illustrative examples presented for the air-cooled engine that large surface area for cooling is the only practicable solution to the cooling problem at altitude.

The illustration was confined to wider fins for simplicity. The cooling can be materially increased by using smaller fin spacing. This change would require changes in baffling and arrangements to carry the air to the engine cylinder.

The illustration given herein is thus in no way exhaustive of the possibilities of improving cooling but shows what may be accomplished by simple practicable changes in fin design.

LIQUID-COOLED ENGINE

The calculations required to determine the effect of altitude on the cooling performance of a liquid-cooled engine are made fairly simply by use of the radiator design chart developed in reference 7.

For purposes of comparison with the preceding air-cooled engine-cooling analysis, the liquid-cooled engine is assumed to dissipate the same quantity of heat and to develop the same brake horsepower as the air-cooled engine and to be installed in an airplane with the same flight characteristics.

Computations are made for two cases. In one case, it is assumed that the coolant (97 percent ethylene glycol) is contained in a closed system and that at all altitudes its temperature is 290° F, which is 52° F below its boiling point at sea-level pressure.

In the calculations for the second case, it is assumed that the coolant (97 percent ethylene glycol) is subjected to free-stream atmospheric pressure at all altitudes and that the temperature of the coolant is maintained at 52° F below its boiling point at the prevailing free-stream atmospheric pressure. The temperature of the coolant as a function of altitude is shown in figure 26.

It is further assumed that in both cases the radiator is enclosed in a duct, such as described in reference 8, and that the cross-sectional area of the duct at the radiator is two-thirds of the frontal area of the radiator; that is, one-third of the radiator will be contained within the regular fuselage lines. The drag coefficient of the duct is given in reference 8 as $C_{D_d} = 0.06$, based on frontal area, and the drag of the duct D_d is, therefore,

$$D_d = \frac{2C_{D_d} A q_a}{3} \qquad (17)$$

and the horsepower P_D required to overcome the duct drag is

$$P_D = \frac{2C_{D_d} A q_a}{3} \frac{V_a}{550} \qquad (18)$$

In order to obtain the minimum power combination of radiator and duct at any flight condition, it is necessary to choose several radiators designed to operate at different pressure drops and then, by means of the radiator design chart of reference 7 and equation (18) of the present paper, calculate the total power of each combination and so to obtain the optimum design.

Analysis

The variation with altitude of required optimum radiator volume and of optimum open radiator frontal area, which equals two-thirds of total frontal area, is shown in figure 26. These curves were calculated directly from the radiator design chart.

The effect of altitude on the cooling performance of three radiator-duct installations is considered. One installation was designed to be optimum for the high-speed flight conditions at an altitude of 20,000 feet, one at 40,000 feet, and the third at 60,000 feet.

The variation with altitude of the sum of the air-pumping power, the power required to carry the weight, and the power required to overcome the drag of the duct is shown in figure 28 for the three installations considered; and figures 29 and 30 show the effect of altitude on the required pressure drop and on the volume rate of cooling-air flow, respectively.

If it is assumed that three-fourths of the main air-stream dynamic pressure can be utilized for pumping air through the radiator, the maximum altitude at which the radiator will cool satisfactorily is the altitude at which $\Delta p = 0.75q_a$, $\frac{\Delta p}{0.75q_a} = 1$. The limiting altitudes as well as the variation with altitude of the ratio of cooling pressure drop required to pressure drop available $\frac{\Delta p}{0.75q_a}$ for the three installations is shown in figure 31.

Meredith (reference 6) showed that it is possible to convert a part of the heat dissipated by the radiator into useful work or thrust at the radiator exit jet. This jet-power recovery has been calculated for the installations considered and is shown as a function of altitude in figure 32.

The net power requirement of the radiator installation is the difference between the gross power consumed by the installation (fig. 28) and the power recovered from the exit jet (fig. 32). This net power is shown in figure 33.

In figure 34, the power associated with the scoop drag has been subtracted from the net power using pressurized coolant as given in figure 33. The resulting power-consumption curves are representative of a case in which no scoop is used and the radiator is installed completely within the airplane lines in such a manner that there is no additional drag due to cooling-air entrance and exit. This case is obviously the ideal and will not be completely realized in practice. The actual performance of a liquid-cooled installation will be somewhere between the curves of figures 33 and 34 for the pressurized coolant.

By a comparison of figures 22 and 34, it can be concluded that a well-designed engine installation, either liquid- or air-cooled, should not consume more than about 2 or $2\frac{1}{2}$ percent of the engine brake horsepower.

Concluding Remarks

The comparison of the two cases for liquid cooling demonstrates the marked advantage of pressurized cooling and idealized submergence of the radiator within the airplane. The actual useful power for cooling will fall somewhere between the two cases considered.

It is impossible to avoid a comparison between the air-cooled and liquid-cooled engines in regard to cooling at altitude. Comparisons might be made according to weight, volume, power to cool, quantity of cooling air, etc. When such comparisons are made, each engine would show certain advantages.

It is generally recognized that each type of engine has characteristics which are desirable and which make it favorable for certain jobs and certain installations.

The impartial analysis of the cooling problem at altitude presented herein shows nothing that may be taken as demonstrating a marked advantage of one engine type over the other.

L-386

REFERENCES

1. Brevoort, M. J., and Joyner, U. T.: The Problem of Cooling an Air-Cooled Cylinder on an Aircraft Engine. Rep. No. 719, NACA, 1941.

2. Biermann, Arnold E., and Pinkel, Benjamin: Heat Transfer from Finned Metal Cylinders in an Air Stream. Rep. No. 488, NACA, 1934.

3. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co., Inc., 1933.

4. Harper, D. R., 3d, and Brown, W. B.: Mathematical Equations for Heat Conduction in the Fins of Air-Cooled Engines. Rep. No. 158, NACA, 1923.

5. Brevoort, Maurice J.: Energy Loss, Velocity Distribution, and Temperature Distribution for a Baffled Cylinder Model. T.N. No. 620, NACA, 1937.

6. Meredith, F. W.: Note on the Cooling of Aircraft Engines with Special Reference to Ethylene Glycol Radiators Enclosed in Ducts. R. & M. No. 1683, British A.R.C., 1936.

7. Brevoort, M. J.: Radiator Design. NACA A.C.R., July 1941.

8. Naiman, Irven, and Hill, Paul R.: The Effect of External Shape upon the Drag of a Scoop. NACA A.C.R., July 1941.

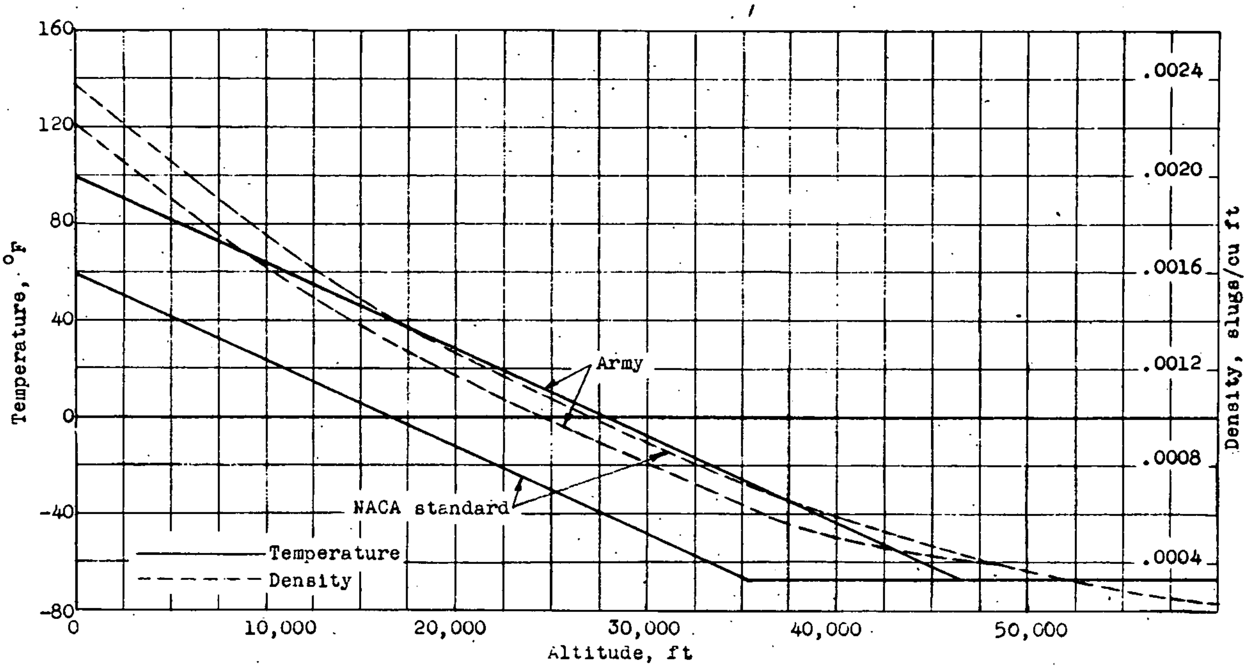

Figure 12.- Variation of temperature and density with altitude for NACA standard air and Army air.

(1 block = 10 divisions = 10/40 Engr. scale)

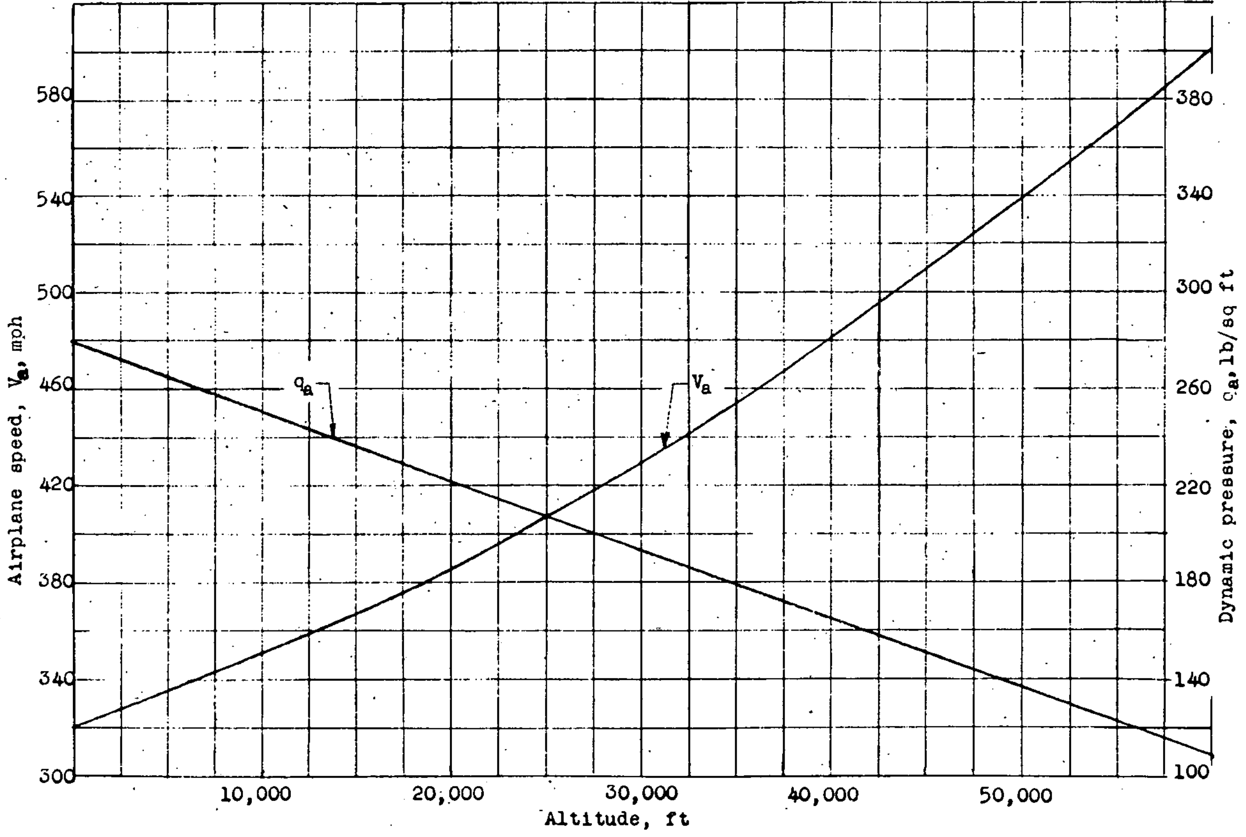

Figure 13.- Variation of speed and dynamic pressure with altitude for a modern pursuit-type airplane.

L-386

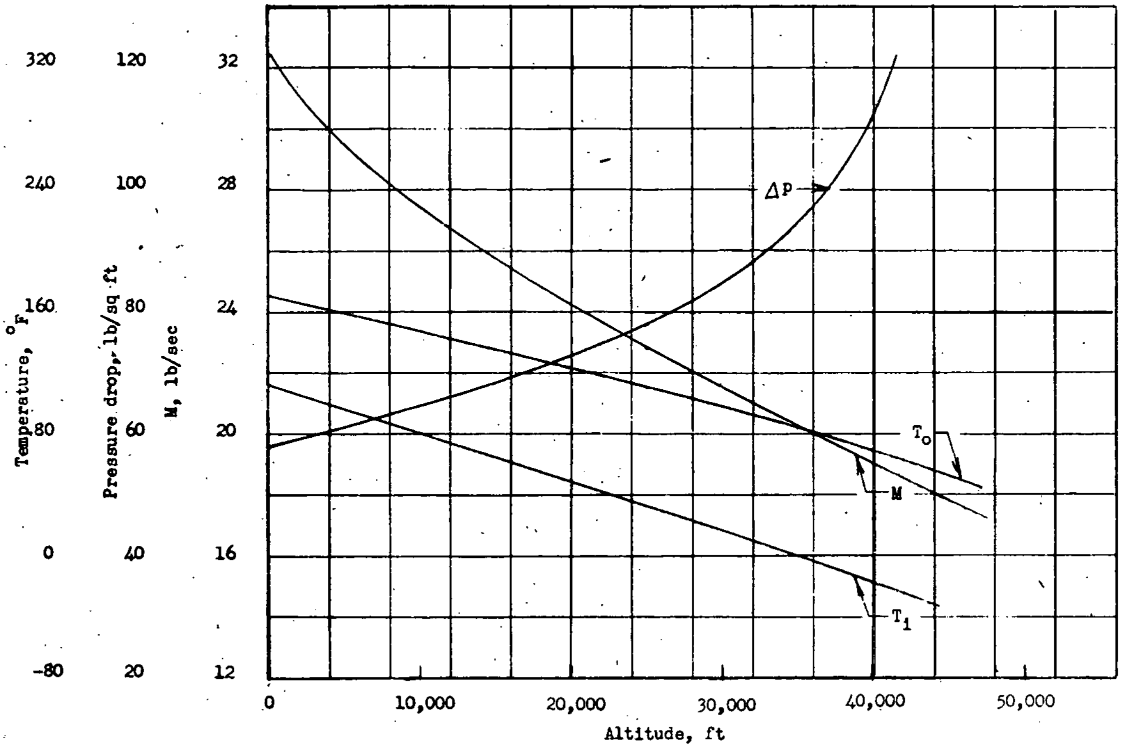

Figure 14.- Variation with altitude of M, T_i, T_o, and Δp for the original fins in high-speed flight. Army air.

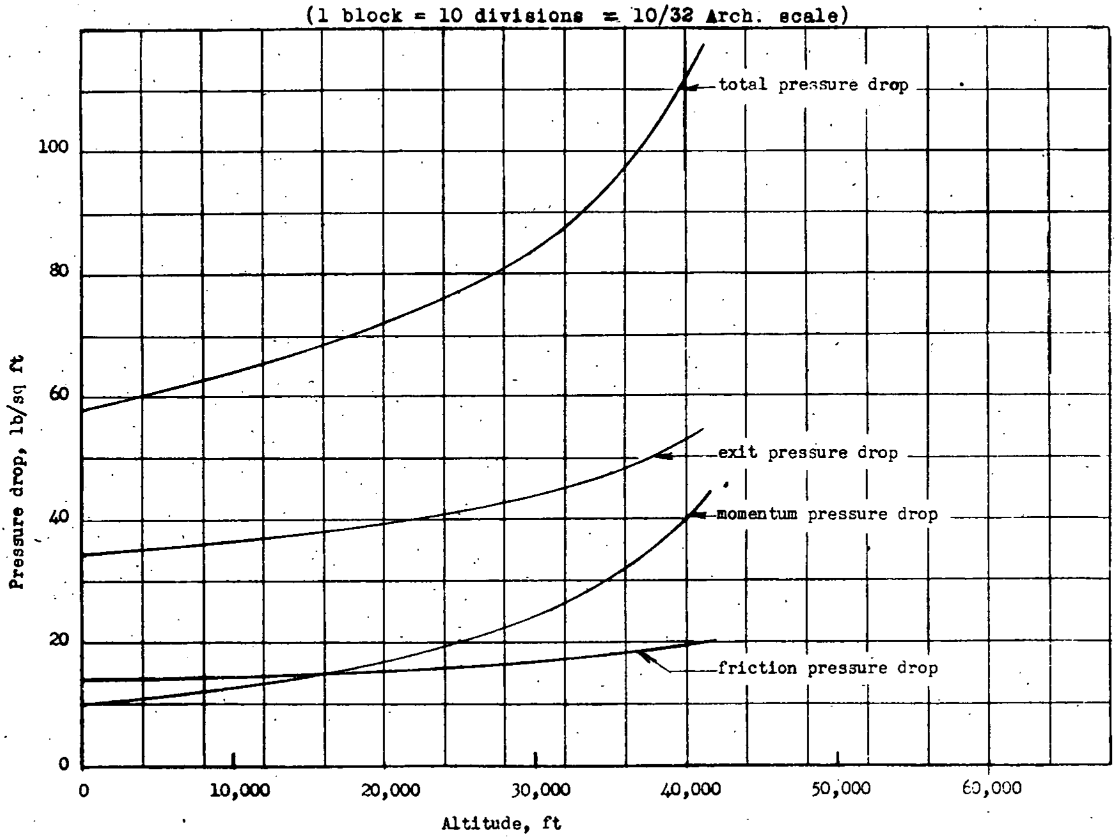

Figure 15.- Variation with altitude of friction pressure drop, momentum pressure drop, exit pressure drop and total pressure drop for the original fins in high-speed flight. Army air.

L-386

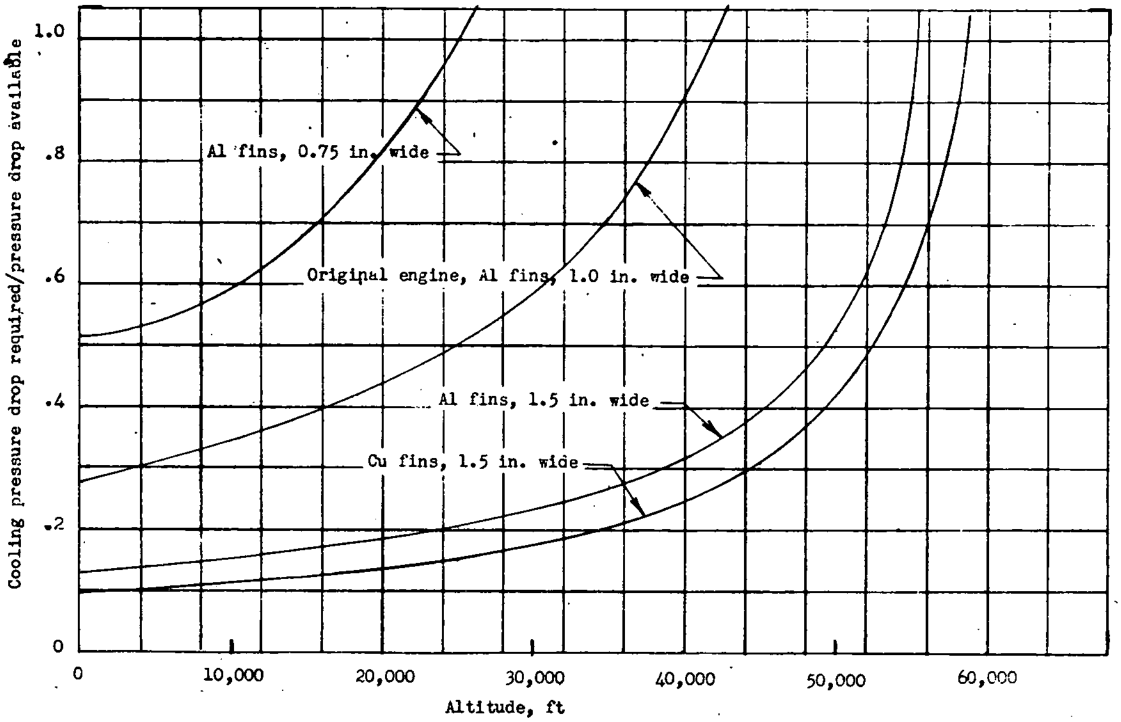

Figure 16.- Variation with altitude of the ratio of cooling pressure drop required to pressure drop available in high-speed flight for the original fins and for three alternative fin arrangements. Army air.

(1 block = 10/32")

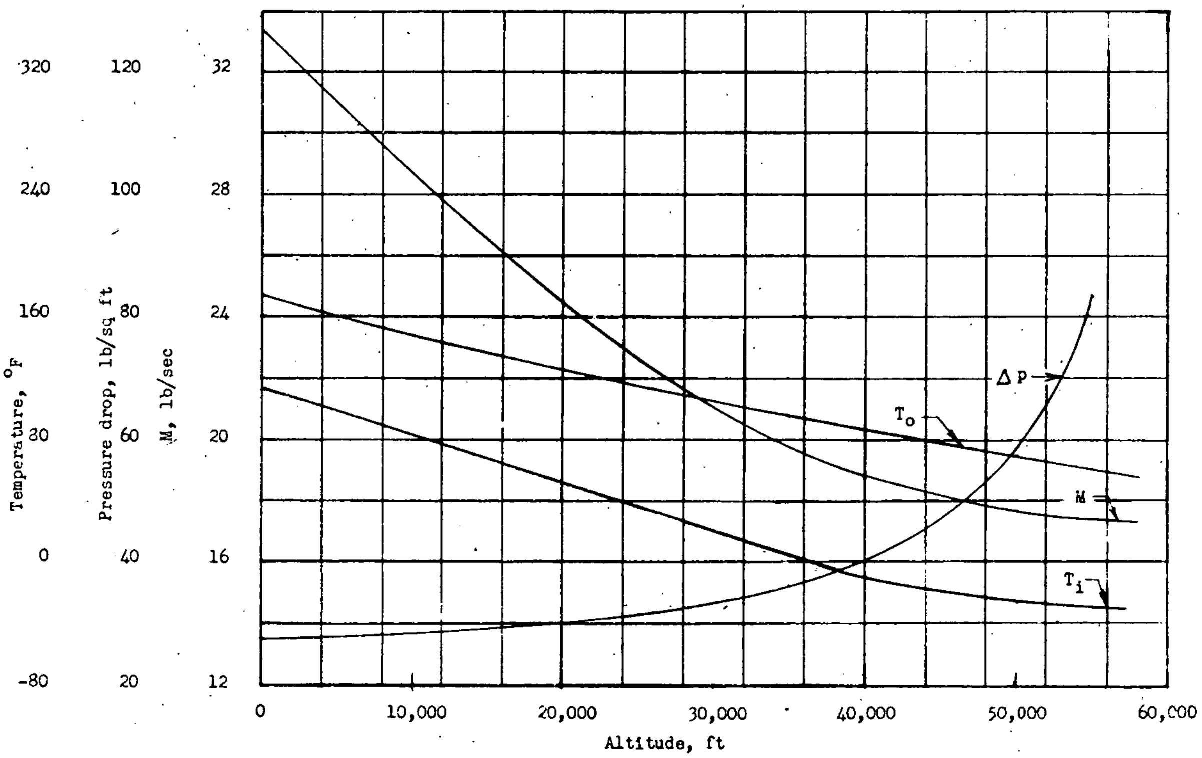

Figure 17.- Variation with altitude of M, T_i, T_o, and Δp for the 1.5-inch aluminum fins in high-speed flight. Army air.

L-386

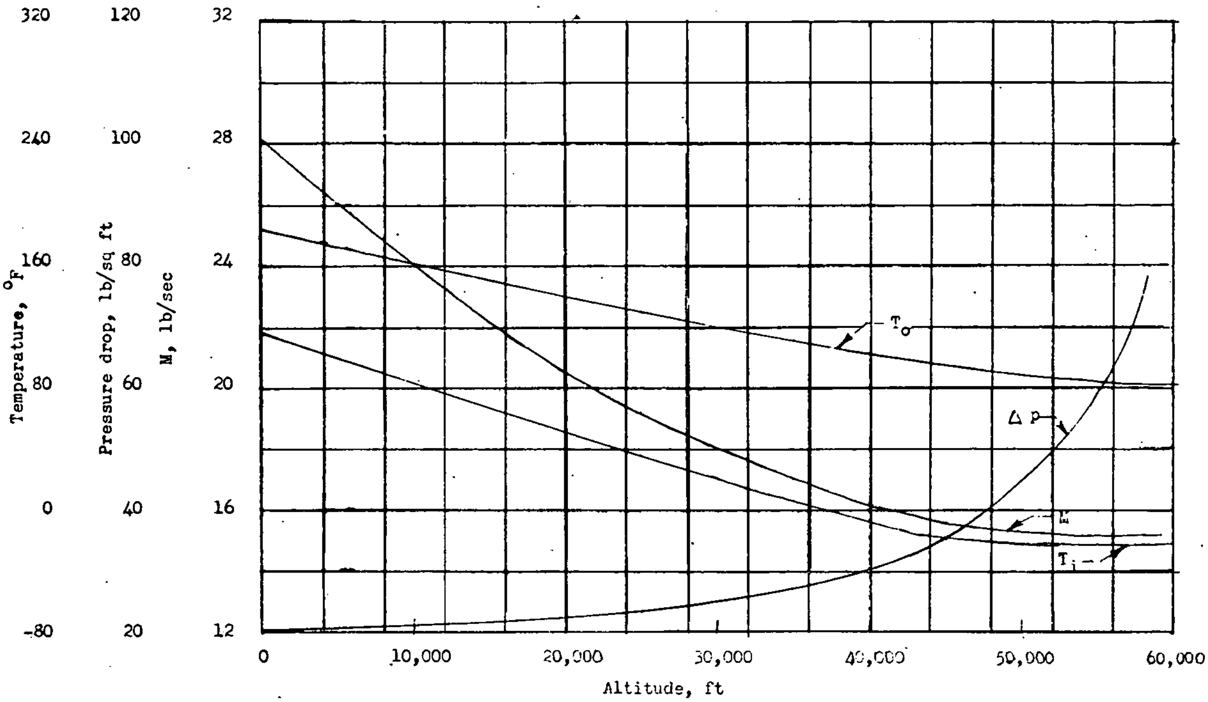

Figure 18.-Variation with altitude of M, T_i, T_o, and Δp for the 1.5-inch copper fins in high-speed flight. Army air.

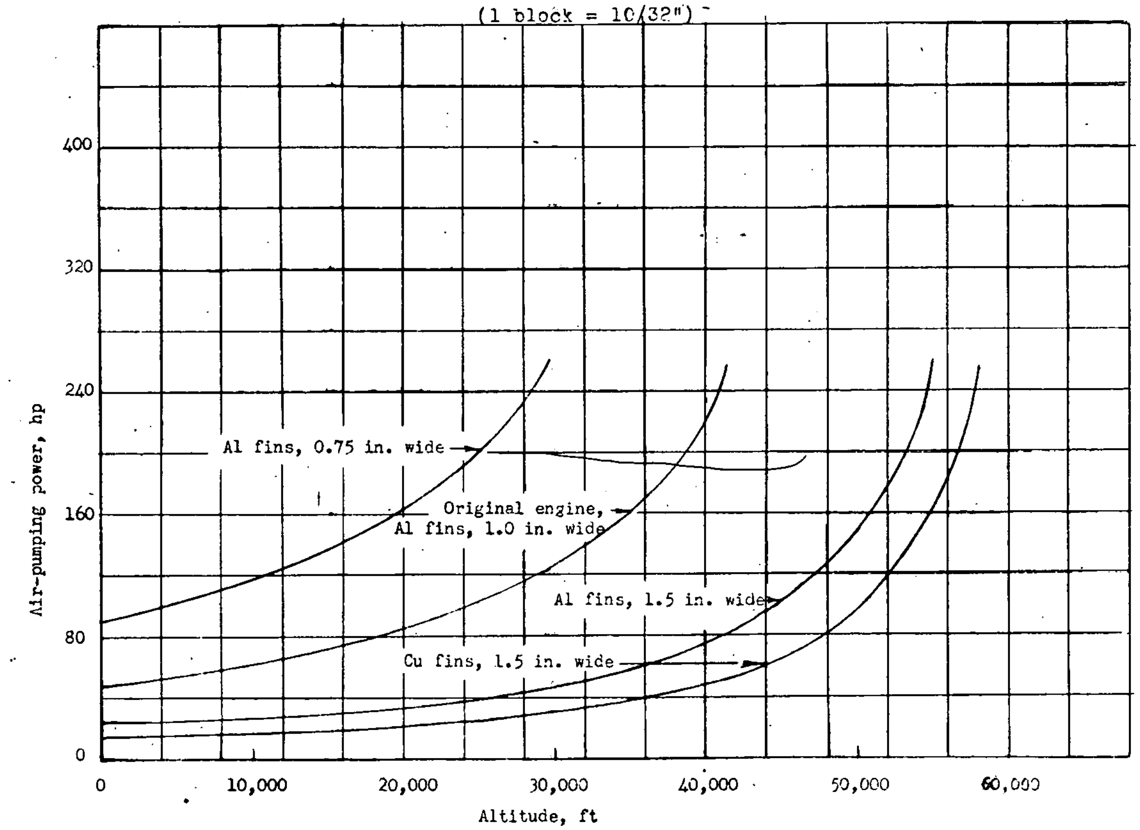

Figure 19.- Variation with altitude of air-pumping power in high-speed flight for the four fin arrangements considered. Army air.

L-396

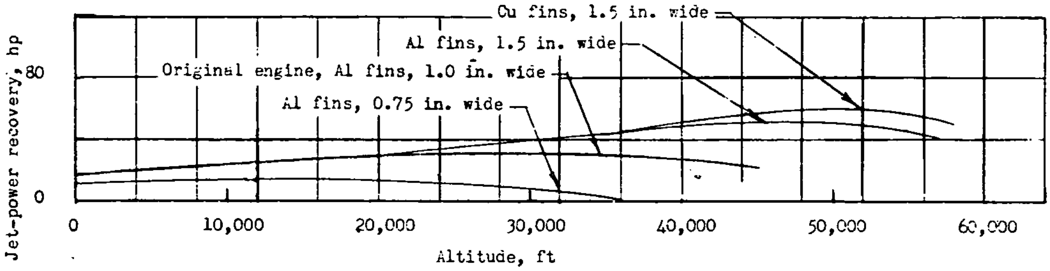

Figure 20.- Variation with altitude of jet-power recovery in high-speed flight for the four fin arrangements considered. Army air.

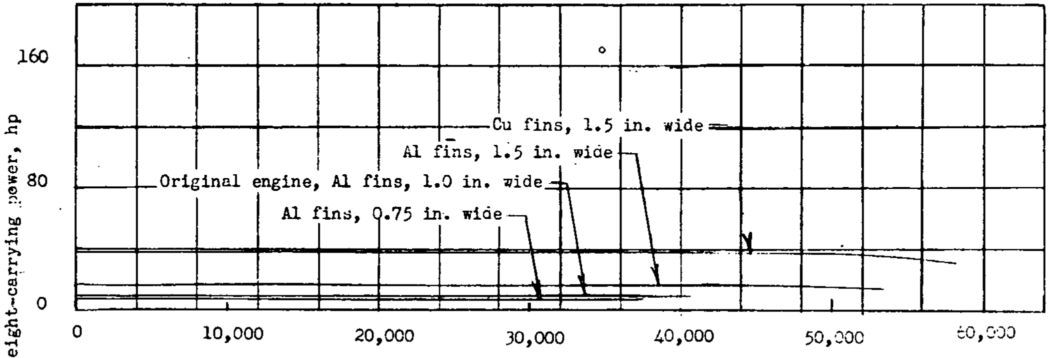

Figure 21.- Variation with altitude of weight-carrying power in high-speed flight for the four fin arrangements considered. Army air.

(1 block = 10/32")

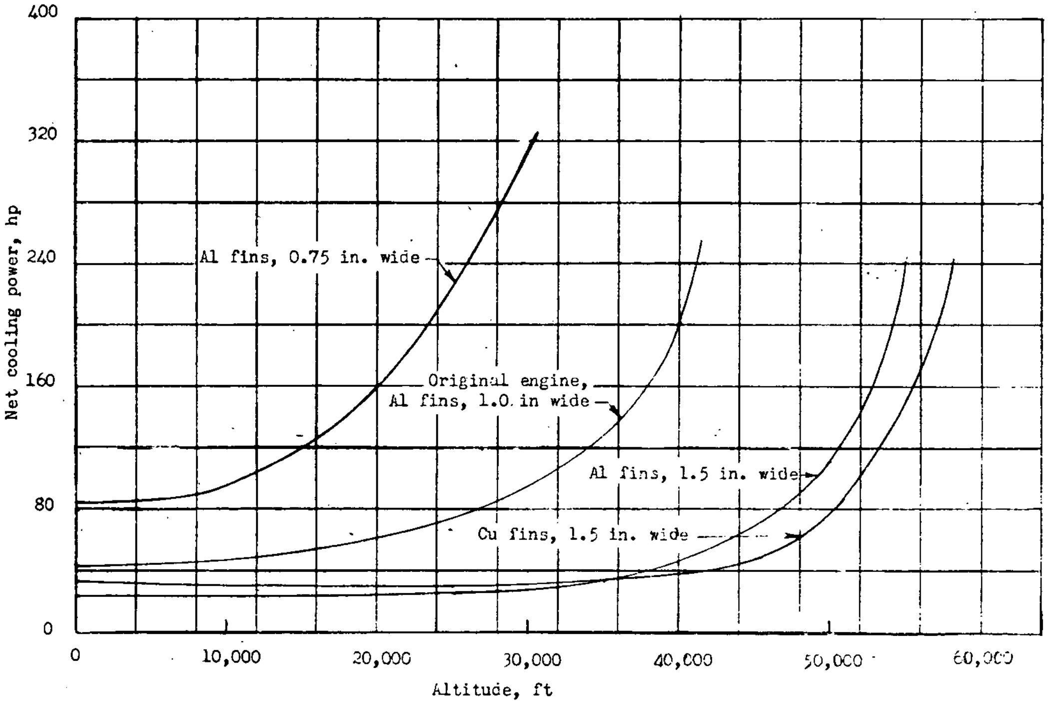

Figure 22.- Variation with altitude of net cooling power in high-speed flight for the four fin arrangements considered. Army air.

L-386

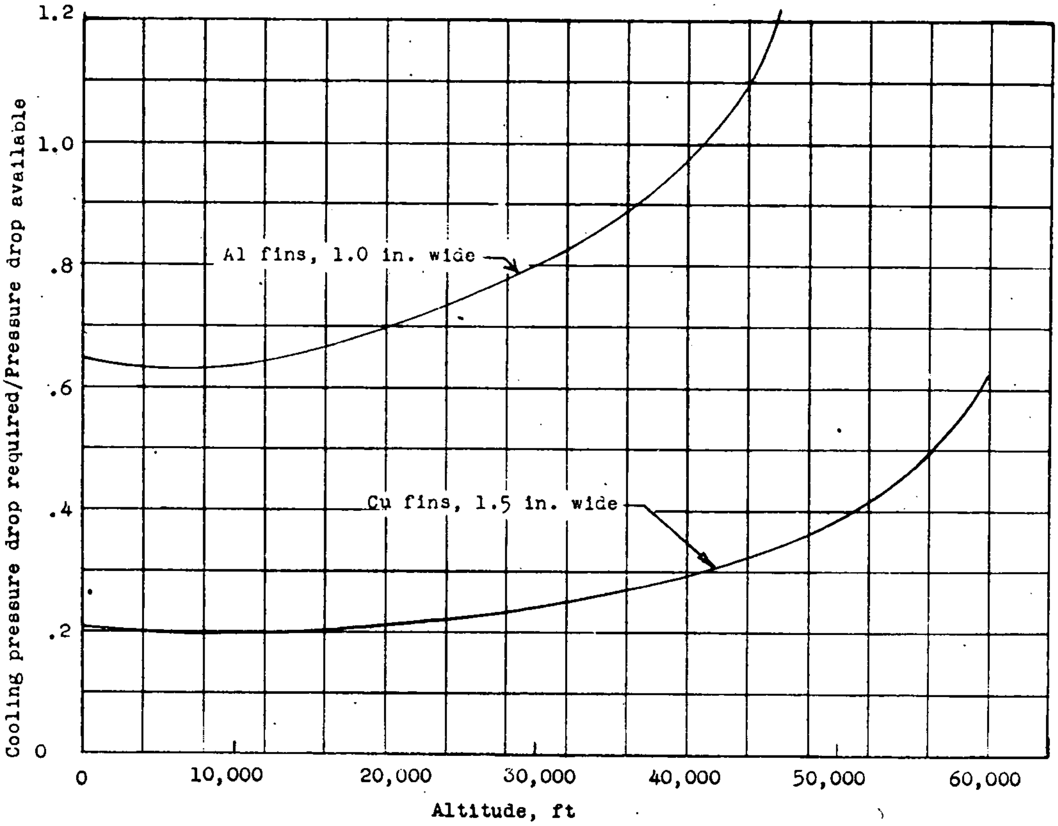

Figure 23.- Variation with altitude of the ratio of cooling pressure drop required to pressure drop available in climb for the original fins and the copper fins. Army air.

(1 block = 10/32")

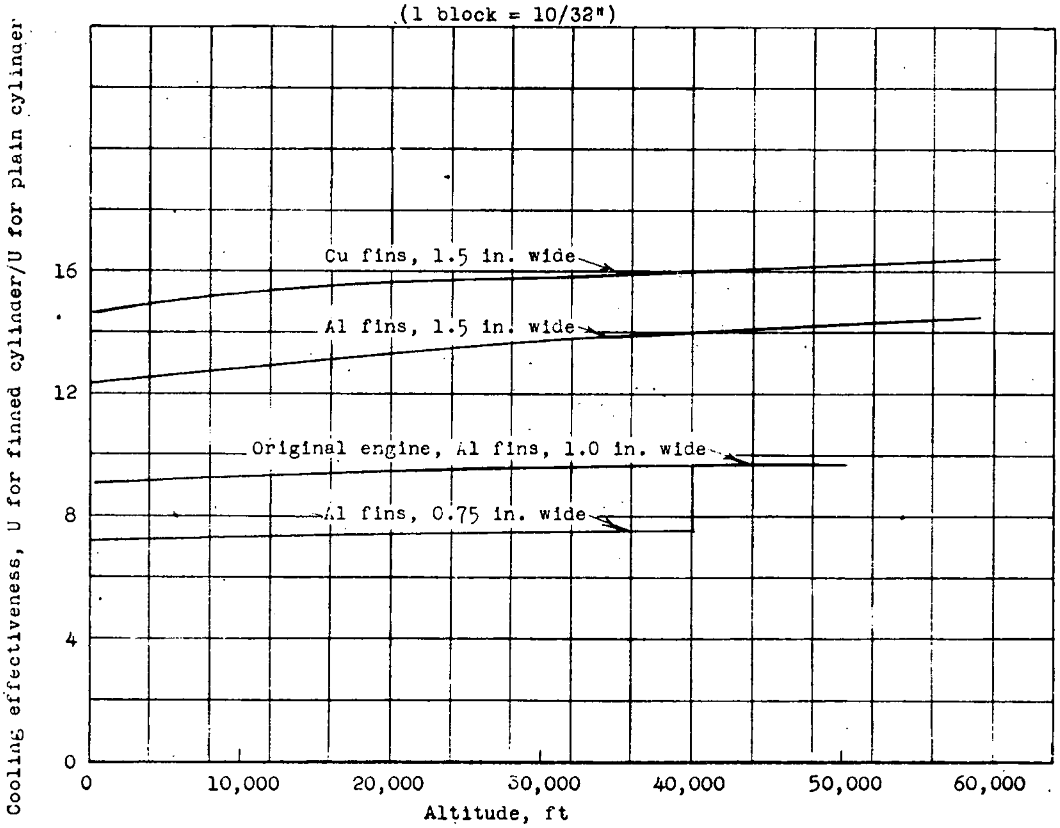

Figure 24.- Variation with altitude of cooling effectiveness in high-speed flight for the four fin arrangements considered. Army air.

L-386

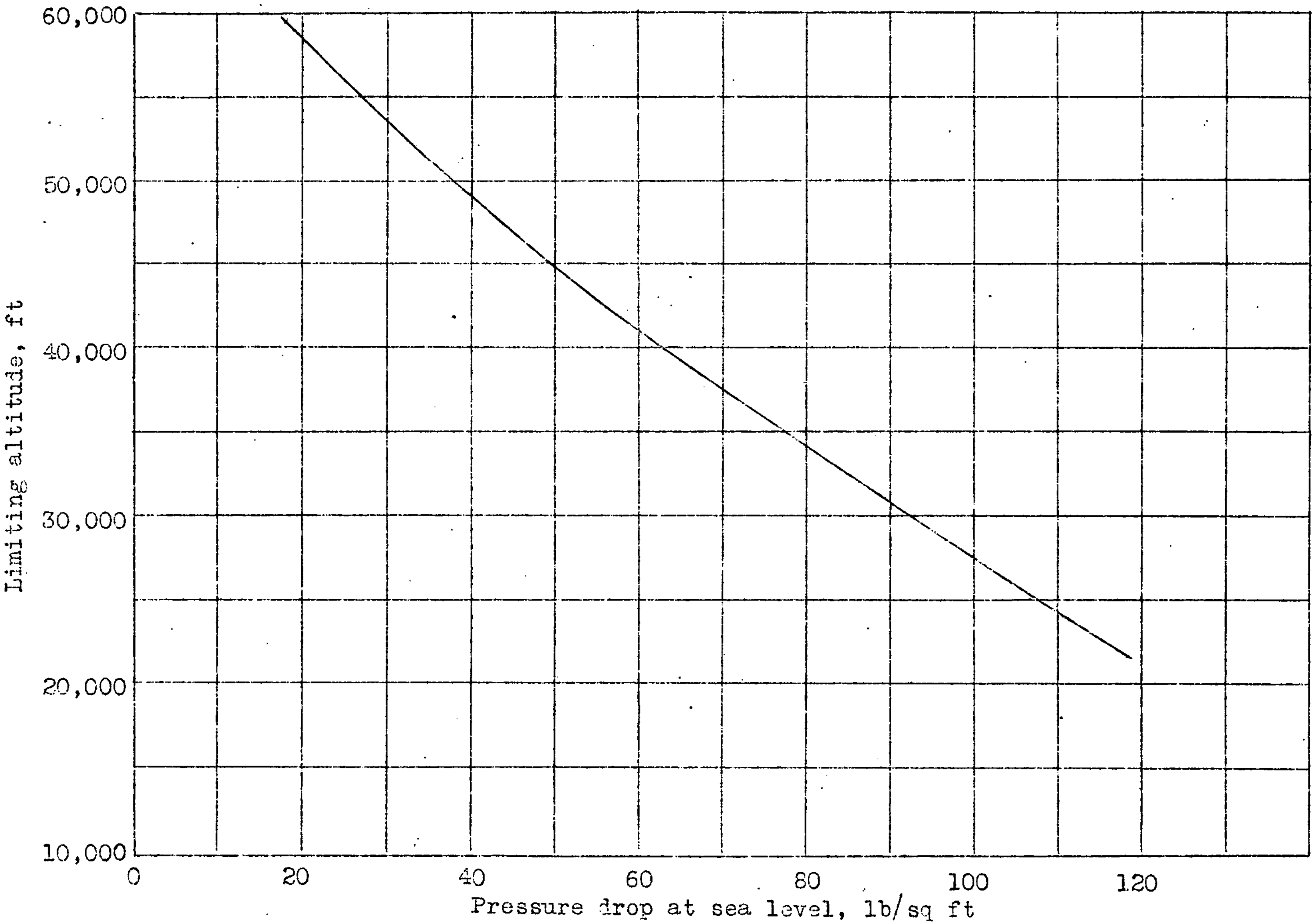

Figure 25.- Variation of limiting altitude with pressure drop required at sea level by air-cooled engine in pursuit airplane.

L-387

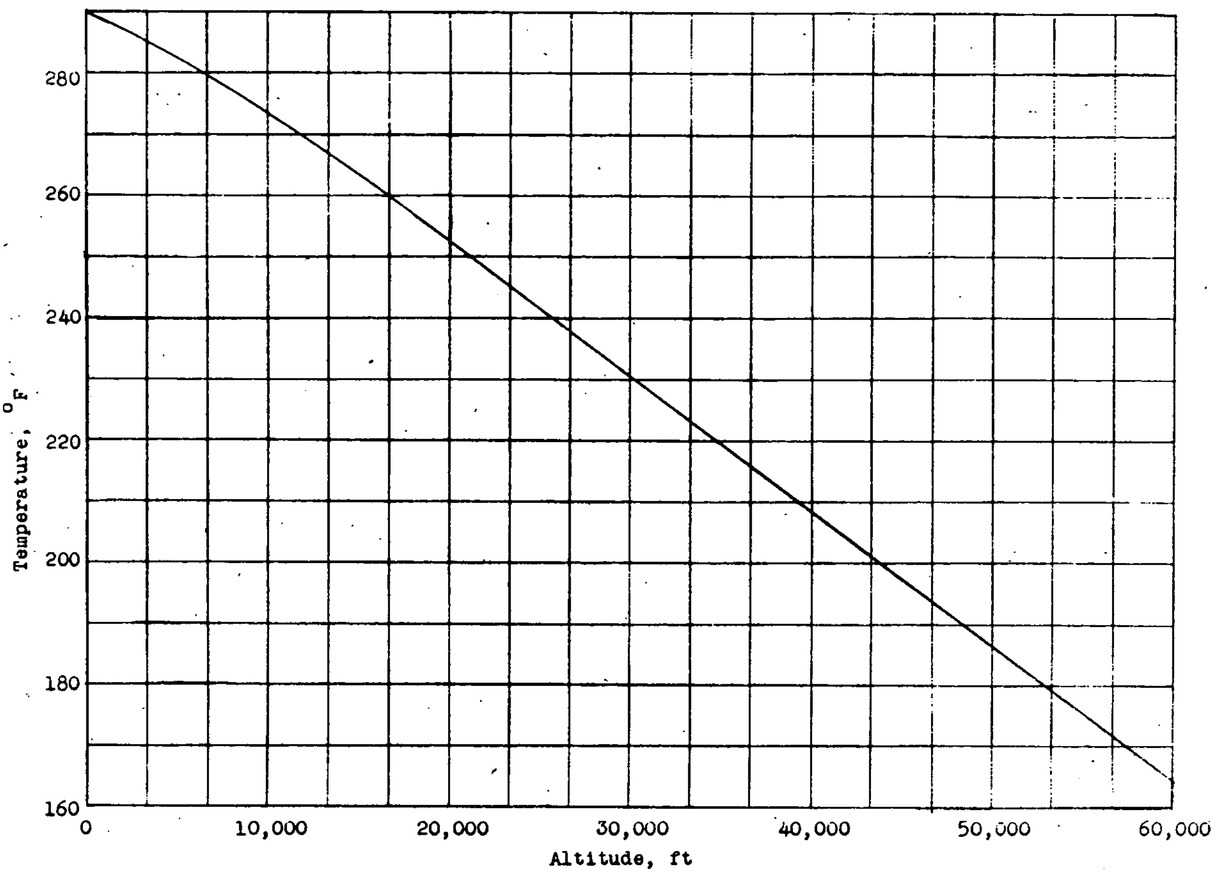

Figure 26.- Variation with altitude of temperature of 97 percent ethylene glycol. Temperature obtained by subtracting 52° F from boiling point at each altitude.

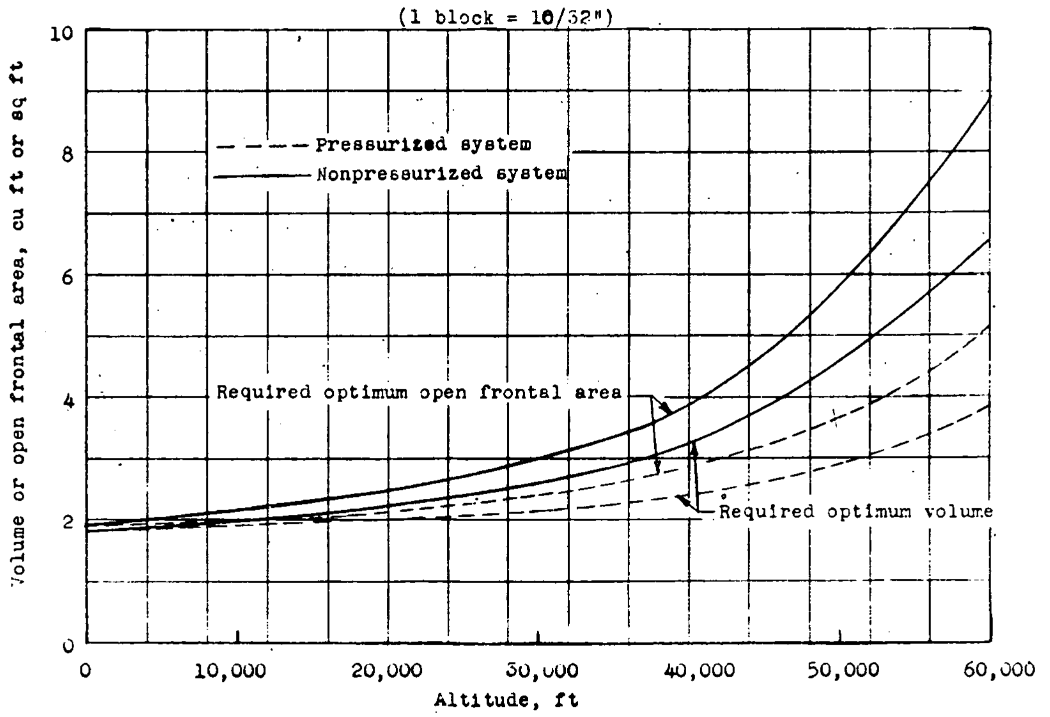

Figure 27.- Variation with altitude of required optimum radiator volume and open frontal area, which equals two-thirds of total frontal area. Army air.

L-318

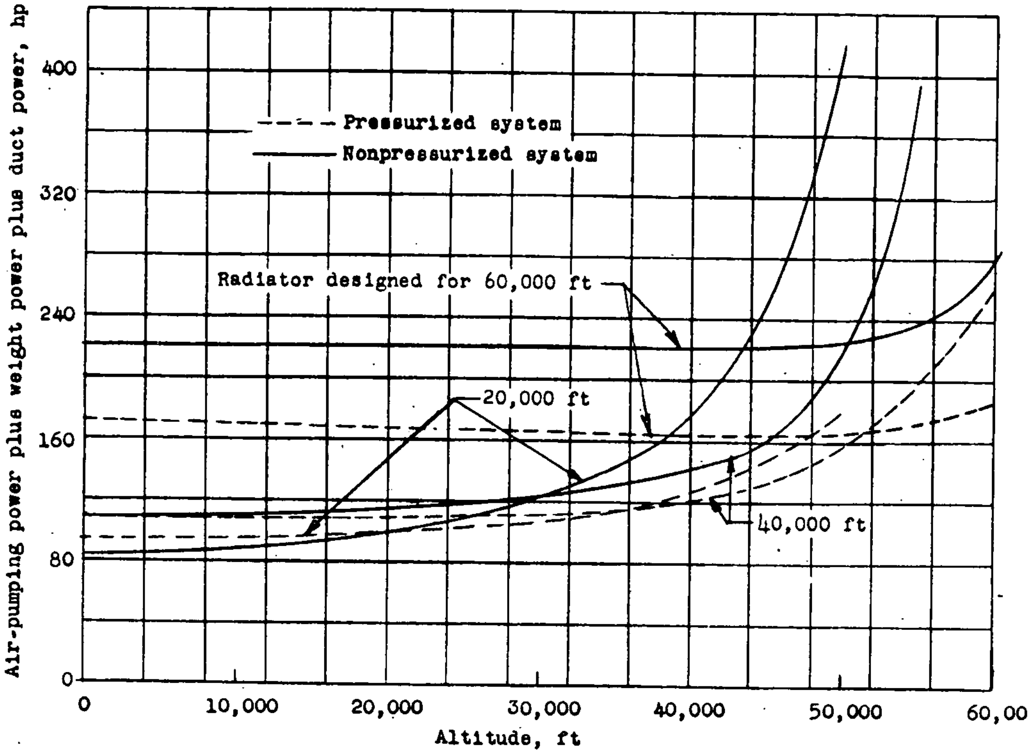

Figure 28.- Variation with altitude of the sum of the air-pumping power, the weight-carrying power, and the power associated with the duct drag for the three radiator installations considered. High-speed condition. Army air.

(1 block = 10/32")

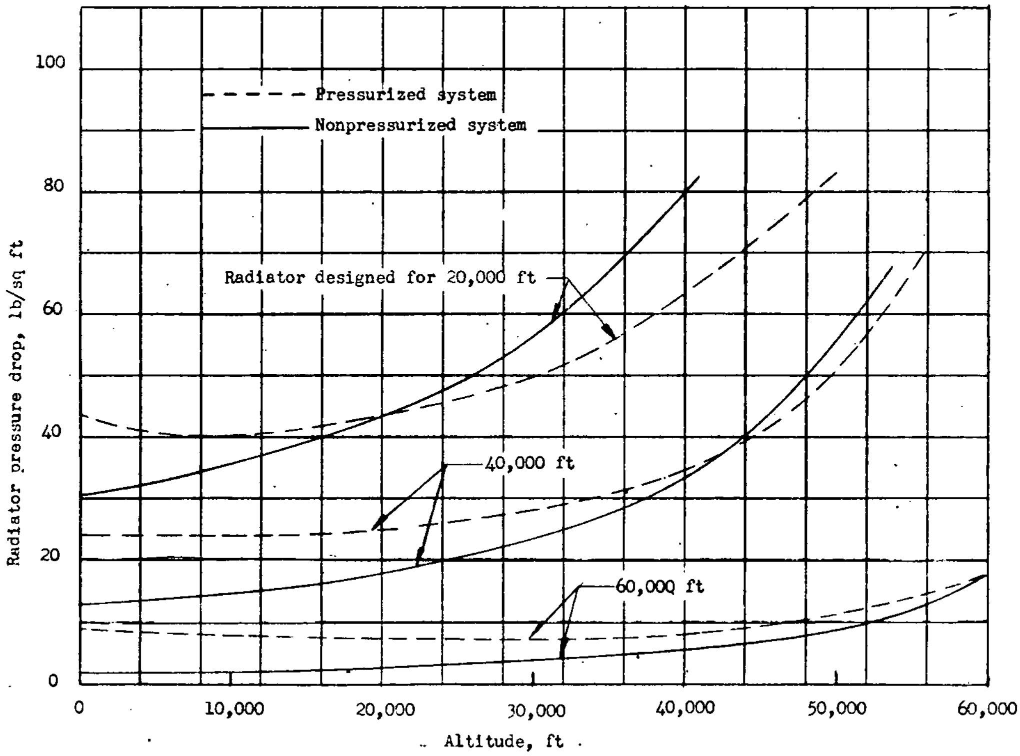

Figure 29.- Variation with altitude of pressure drop through radiators of optimum design for 20,000, 40,000, and 60,000 feet. Army air.

L-386

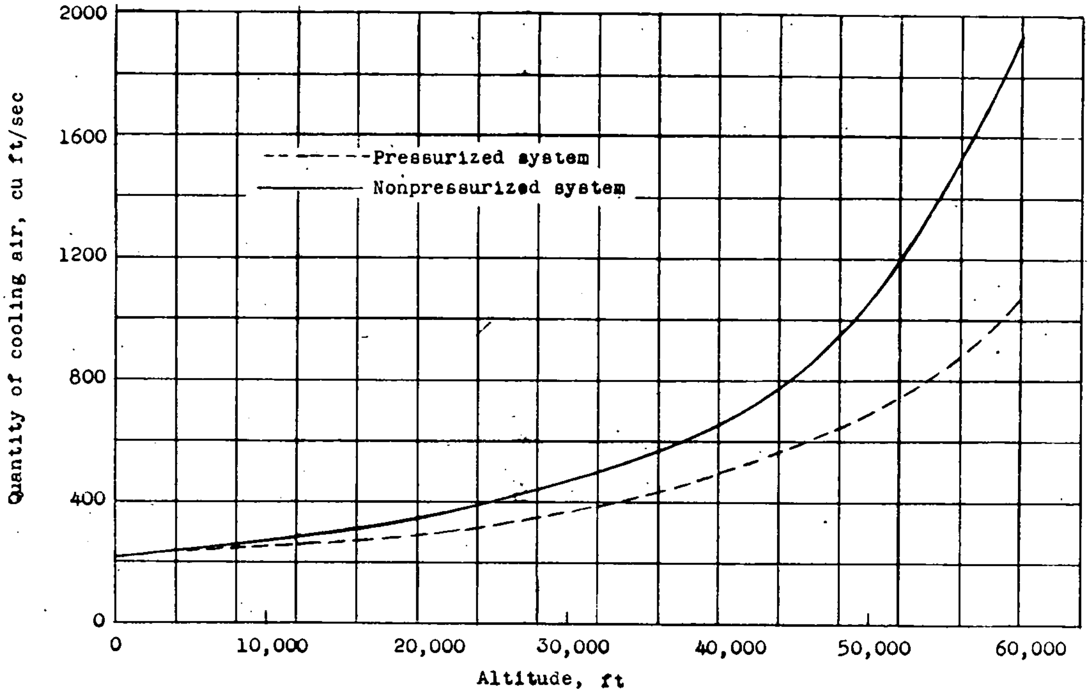

Figure 30.- Variation with altitude of the required quantity of cooling air for a liquid-cooled engine. Army air.

(1 block = 10/32")

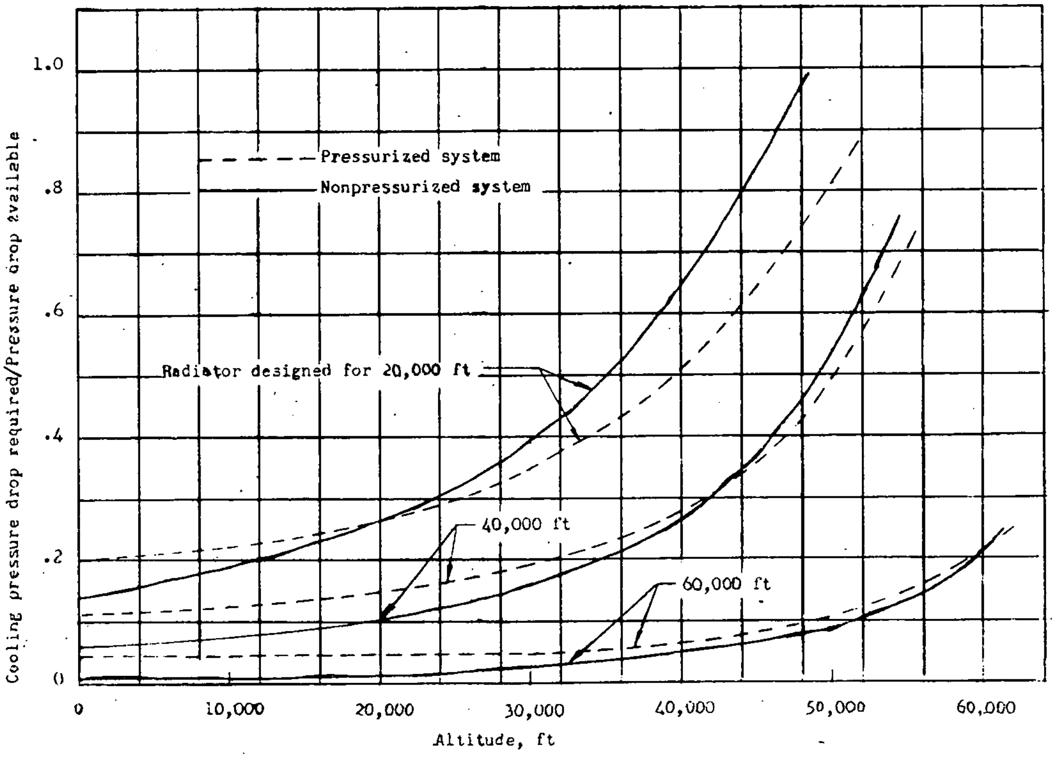

Figure 31.- Variation with altitude of the ratio of cooling pressure drop required to pressure drop available for the three radiator designs considered. Army air.

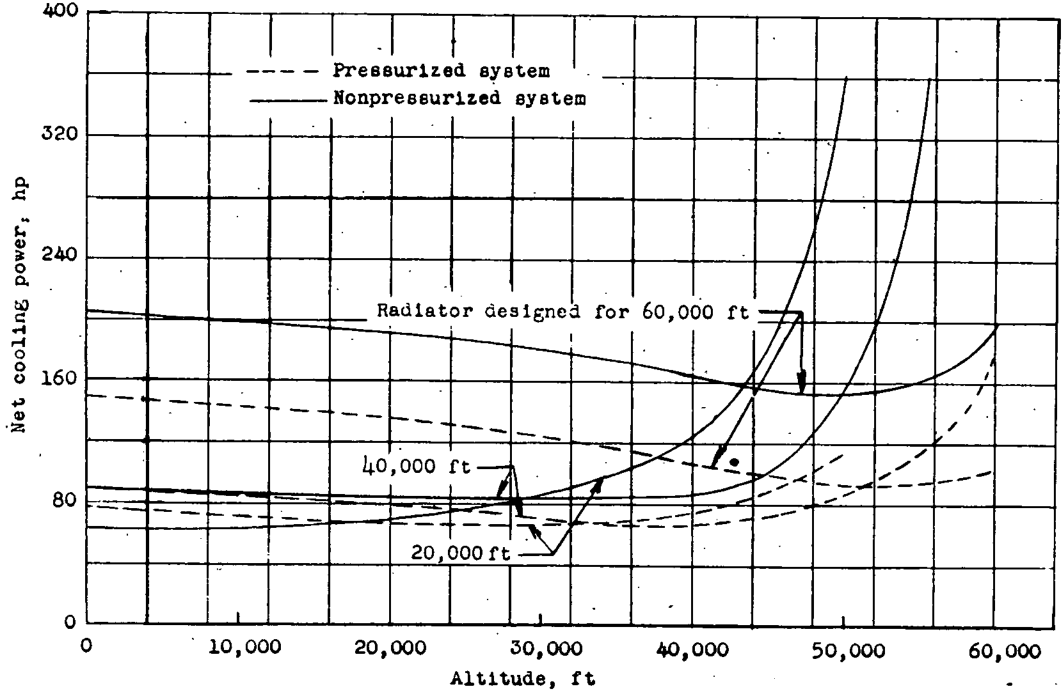

Figure 33.- Variation with altitude of the net cooling power for the three radiator installations considered. High-speed condition; Army air.

(1 block = 10/32")

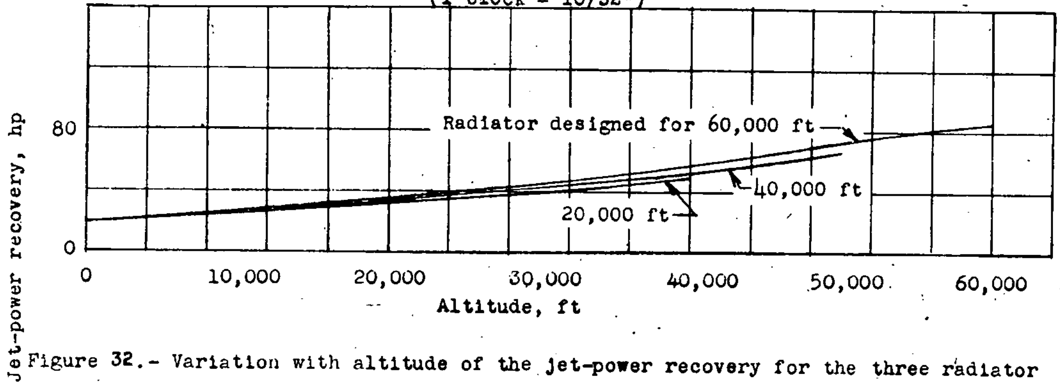

Figure 32.- Variation with altitude of the jet-power recovery for the three radiator installations considered. High-speed condition; Army air; pressurized and nonpressurized systems.

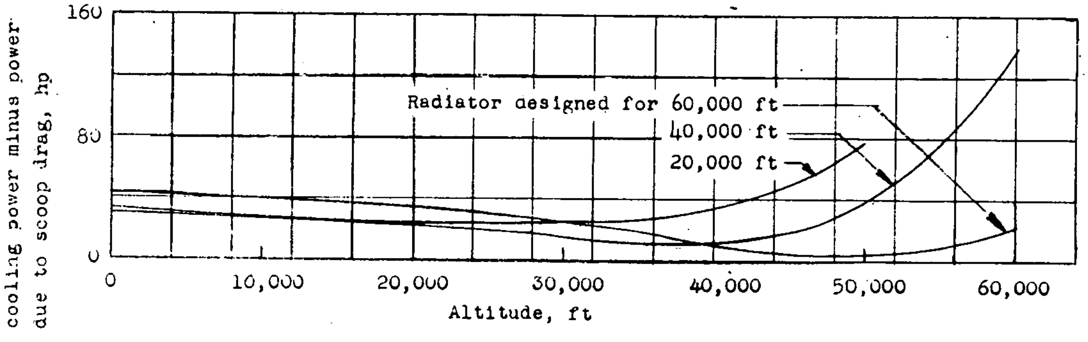

Figure 34.- Variation with altitude of the net cooling power minus power due to scoop drag for the three radiator installations considered. High-speed condition; Army air; pressurized system.