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INTERCOOLER COOLING-AIR WEIGHT FLOW AND PRESSURE DROP FOR MINIMUM POWER LOSS

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ADVANCE RESTRICTED REPORT

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SUMMARY

An analysis has been made of the power losses in airplane flight of cross-flow plate and tubular intercoolers to determine the cooling-air weight flow and pressure drop that give minimum total power loss for any given cooling effectiveness. The power losses considered in this analysis are those due to (1) the extra drag imposed on the airplane by the weight of the intercooler, its duct, and its supports and (2) the drag sustained by the cooling air in flowing through the intercooler and its duct. The investigation covers a range of flight conditions of altitude, airspeed, lift-drag ratio, supercharger-pressure ratio, and adiabatic efficiency.

The analysis reveals the following facts concerning the cooling-air operating conditions of intercoolers:

(1) The optimum cooling-to-charge-air weight-flow ratio, that is, the flow ratio that gives minimum total power loss, is only slightly dependent on the airplane flight conditions and the charge-air pressure drop and is mainly a function of the intercooler cooling effectiveness and cooling-air pressure drop.

(2) When the cooling-to-charge-air weight-flow ratio is varied to maintain its optimum value, the cooling-air pressure drop is optimum between 1 and 3 inches of water; the variation within this range depends on flight conditions, charge-air pressure drop, and type of intercooler (plate, charge-across-tube, or charge-through-tube). Within this range of pressure drop the change in total power loss from the minimum value is slight.

The optimum values of cooling-air pressure drop and weight-flow ratio are tabulated. Curves are presented to illustrate the results of the analysis. Included are curves that give the variation in intercooler volume and the sacrifice in thrust power incurred by a departure of intercooler operation from the optimum values of cooling-air pressure drop and weight-flow ratio.

INTRODUCTION

In the design of intercoolers, if the power required to force air through the passages were the only consideration, a large, heavy intercooler would minimize the power cost. In aircraft added weight increases the airplane drag losses, and it is therefore necessary that an intercooler be designed to effect a compromise between the intercooler cooling-air losses and the losses due to the intercooler weight. In making this compromise the designer can vary either the intercooler core structure or certain intercooler operating conditions. Although variation in core-structure dimensions is quite important in permitting changes in external dimensions for fitting an intercooler into the available space (references 1 and 2), it is of less importance in minimizing the power losses. The designer has much more control over the power losses through variation of such intercooler operating conditions as cooling-air weight flow and pressure drop. Changes in cooling-air weight flow and pressure drop are also accompanied by changes in external dimensions of the intercooler for a given core structure.

The power losses due to the cooling-air flow and the intercooler weight can be expressed in terms of operating conditions, which fall into two classes: (1) intercooler operating conditions and (2) flight conditions. Class (1) consists of the cooling effectiveness and the weight flows and the pressure drops of the charge and the cooling air. Class (2) consists of altitude, airspeed, lift-drag ratio, supercharger efficiency, and pressure ratio. For the designer the flight-condition group is usually fixed. Of the intercooler operating conditions, the cooling effectiveness and the charge-air weight flow are usually predetermined; the designer is therefore free to choose, within limits, the cooling-air weight flow and pressure drop.

In this analysis the cooling-to-charge-air weight-flow ratio and pressure drop that give minimum total power loss have been determined for various conditions of flight and for various cooling requirements. The selection of an intercooler for a specific installation is, however, also a compromise between intercooler dimensions and intercooler total power loss. The designer is, in most cases, limited in the choice of the intercooler operating conditions by the space available in the airplane for the intercooler. Considerations of the charge-air and the cooling-air ducting also enter and complicate the entire picture. Thus, a design for minimum total power loss may, for a given installation, be prohibitive on the basis of installations in the airplane in spite of the variety of shapes and sizes of intercoolers made possible by changing the intercooler core-structure dimensions. Charts are presented that give the magnitude of power sacrifice and the change in intercooler volume resulting from a departure from the optimum conditions.

The optimum charge-air pressure drop has not been included in the analysis because the attendant power losses depend to a large degree on the specific engine installation.

PROCEDURE

The cooling-air and transportation power losses. - The equation for the cooling-air drag power loss of an intercooler is derived in the appendix (equations (1) through (11)) from a consideration of the momentum change of the cooling air as it flows through the intercooler and duct. The effect of the addition of heat to the cooling air in the intercooler is included in the derivation. This effect causes a slight reduction of the cooling-air drag loss and, for low values of cooling-to-charge air weight-flow ratio M_1/M_2 and the cooling-air pressure drop Δp_1, may even result in a thrust rather than a drag.

The increase in airplane drag resulting from the weight increase due to the addition of an intercooler is calculated as the drag of the additional airplane wing area required to keep the wing loading, and thus the take-off and landing speeds, constant. This additional power loss is given by equations (12) and (13) of the appendix.

Since the two intercooler power losses vary in opposite directions with variation of M_1/M_2 or Δp_1, it is expected that for certain values of these two operating variables the sum of the two power losses is minimum. These optimum values of M_1/M_2 and Δp_1, denoted herein as $(M_1/M_2)_{opt}$ and $(\Delta p_1)_{opt}$, are determined by the procedure outlined in the appendix.

The parameter $(L/D)_{eq}$. - In this analysis it is convenient to make use of a parameter $(L/D)_{eq}$ relating the intercooler transportation costs to the heat-transfer surface area. This parameter is defined as

$$(L/D)_{eq} = \frac{L/D}{\left(\frac{\rho_m}{173}\right)\left(\frac{12t}{0.01}\right)\left(\frac{K_W}{1.2}\right)\left(\frac{y}{2}\right)\left(\frac{S}{S_o}\right)}$$

It should be noted that the parameter $(L/D)_{eq}$ includes the following variables in addition to the airplane wing lift-drag ratio L/D:

(a) Density of the material of which the intercooler is constructed ρ_m

(b) Plate or tube-wall thickness t

(c) Ratio of weight of intercooler to weight of intercooler plates or tubes R_W

(d) Ratio of increase in airplane weight caused by the intercooler to the weight of the intercooler y

(e) Ratio of the heat-transfer surface area of the intercooler S to the surface area of a reference intercooler S_0

The significance of the parameter $(L/D)_{eq}$ is given in more detail in the appendix.

The reference intercooler. - The relation between the heat-transfer surface area and the operating conditions and core structure is obtained from reference 1 for the plate intercooler and from reference 2 for the tubular intercooler. In references 1 and 2 the relation for each type of intercooler is first given for a reference intercooler, which is defined as one having a reference core structure. The variation in heat-transfer area with core structure for constant operating conditions is then given. This variation of heat-transfer area with core structure is the S/S_0 term included in the $(L/D)_{eq}$ parameter. The transportation loss is then, as shown in the appendix, a function only of $(L/D)_{eq}$, airplane velocity, and heat-transfer surface area of the reference intercooler.

The optimum M_1/M_2 and Δp_1. - The optimum values of M_1/M_2 and the related optimum values of Δp_1 were determined graphically for extreme conditions of intercooler operation and airplane performance. The range of conditions covered in the graphical investigation is:

Intercooler operating conditions:

Charge-air sea-level pressure drop (σ is air density relative to standard atmosphere and Δp_f is skin-friction pressure drop of air across intercooler) $\sigma_{2_{av}} \Delta p_{f_2}$, inches of water	2-12
Cooling effectiveness η, percent	30-85

Airplane flight conditions:

Altitude, feet	20,000-50,000
Dynamic pressure in flight q, inches of water	.1215-25
$(L/D)_{eq}$	5-20
Supercharger pressure ratio r	1-3
Compressor efficiency η_{ad}, percent	65-100

The duct efficiency was assumed constant at 90 percent.

Although the analysis was made for a range of $(L/D)_{eq}$ from 5 to 20, values above this range may be encountered in special cases because of the numerous variables included in the parameter. It can be stated that the results of the analysis presented herein also apply for values of $(L/D)_{eq}$ up to infinity, because when $(L/D)_{eq}$ is infinite, the total power loss is equal to only the loss due to the cooling-air drag; plots of cooling-air power loss against Δp_1 for optimum M_1/M_2 show optimum values of Δp_1 and M_1/M_2 that are in substantial agreement with values given for the range of $(L/D)_{eq}$ considered in this report.

RESULTS AND DISCUSSION

The results of the analysis outlined in the appendix may be simply represented for the foregoing practical range of conditions as

$$\left(\frac{M_1}{M_2}\right)_{opt} = \frac{be^{3.06\eta}}{\Delta p_1^{\,m}}$$

$$(\Delta p_1)_{opt} = 1 \text{ to } 3 \text{ inches of water}$$

where b and m are constant, the values of which depend on the airplane flight and intercooler operating conditions. Since b and m do not vary critically over the range of conditions investigated in this report and since small changes in M_1/M_2 away from the optimum have very little effect on the total-power loss, the factor b and exponent m may, for general design purposes, be assigned constant average values. These average values were determined as approximately $b = 0.49$ and $m = 0.36$ and will give M_1/M_2 values suitable for intercooler design on the basis of minimum power loss.

Thus, when the system is operating at the optimum cooling-air pressure drop (from 1 to 3 in. water), the optimum ratio of cooling-air to charge-air weight flow is given from the foregoing equation roughly as follows:

η (percent) ↓ \ Δp_1, in. water →	$(M_1/M_2)_{opt}$ 1	2	3
30	1.2	1.0	0.8
40	1.7	1.3	1.1
50	2.3	1.8	1.5
60	3.1	2.4	2.1
70	4.2	3.2	2.8
80	5.7	4.4	3.8

For any value of η within the range given in the table, a value of Δp_1 from 1 to 3 inches of water can be chosen without changing the power loss an appreciable amount. There is a slight trend in favor of the lower values of Δp_1 at high altitudes.

As previously emphasized, the space available in the airplane for the installation of the intercooler and its ducts is a consideration of primary importance in the selection of the cooling-air operating conditions. This consideration may make it necessary to deviate from the optimum cooling-air conditions. It is of interest to know how the dimensions of an intercooler change with variation in cooling-air conditions from their optimum values. This information may be obtained from references 1 and 2. A table based on the design information given in reference 1 has been prepared for the plate intercooler to illustrate the dimensional trends involved. For this table the plate intercooler is assumed to have 0.010-inch plates spaced 1/16 inch for the cooling-air flow passages and 1/32 inch for the charge flow passages. The intercooler is assumed to operate at a cooling effectiveness of 50 percent with a charge-air pressure drop of about 8 inches of water. The dimensions of this intercooler for various cooling-air operating conditions are given in table 1.

TABLE 1. - EFFECT ON INTERCOOLER DIMENSIONS OF CHANGING COOLING-AIR OPERATING CONDITIONS

Δp_1 (in. water)	M_1/M_2	Cooling-air flow length (in.)	Charge-air flow length (in.)	No-flow length (in. per lb/sec charge-air flow)	Core volume (cu in. per lb/sec charge-air flow)
2(opt.)	1.8(opt.)	5.0	7.0	17.1	600
	2.5	3.5	6.2	22.4	490
6	1.2(opt.)	9.9	7.3	8.8	640
	2.5	4.4	5.3	16.7	390
10	1.0(opt.)	13.4	7.3	6.5	640
	2.5	5.0	4.9	14.2	350

Table 1 shows that for a given core structure and conditions of constant charge-air pressure drop and cooling effectiveness an increase in M_1/M_2 from the optimum value for a given value of Δp_1 results in a reduction in intercooler volume, a reduction in cooling-air flow length, and an increase in the no-flow dimension. It is shown later in the report (fig. 3(a) and discussion on page 10) that for any value of Δp_1 an appreciable change in M_1/M_2 from the values listed as optimum is permissible and will give only a small increase in power loss. Choice of the higher values of Δp_1 for a given cooling-air weight flow leads to intercoolers having larger cooling-air flow lengths and smaller no-flow dimensions than for the optimum value of Δp_1.

It is apparent from the values in table 1 that intercoolers operating under the optimum cooling-air conditions given in this report are characterized by long no-flow lengths and short cooling-air lengths. The intercooler that would best meet these optimum cooling-air requirements is thus of a shape suitable for wing installation or of the annular shape with the periphery as the no-flow length and the radial thickness as the charge-air flow length. Intercoolers approaching a cubical shape will necessarily operate with a cooling-air pressure drop that is greater than necessary to obtain a given amount of cooling at minimum cost. Such coolers may, however, be more convenient to install in some cases.

The analysis of this report is based on computations from basic heat-transfer data on flat plates and banks of tubes. These same elements are used on commercial intercoolers. The data on commercial intercoolers cover only a limited range of sizes, and a comprehensive analysis to determine the optimum cooling-air operating conditions was not possible. The few checks that could be made indicated agreement with the optimum values for cooling-air pressure drop and weight flow given by this report.

Figure 1 gives the variation in total power loss with cooling-air pressure drop for a value of $\sigma_{2_{av}} \Delta p_{f_2}$ of 6 inches of water, typical values of $(L/D)_{eq}$ and airplane climbing speed, and extreme values of intercooler cooling effectiveness and operation altitude. In this figure M_1/M_2 was kept optimum throughout, that is, M_1/M_2 varied in such a manner that for any set of conditions, including Δp_1, the total power loss was a minimum. The optimum value of Δp_1 is shown by the curves to vary between 1.2 and 1.5 inches of water. Of particular interest is the flatness of the power-loss curves in the neighborhood of the optimum Δp_1.

In figure 2 is shown, for optimum M_1/M_2, the effect of $(L/D)_{eq}$ and airplane speed on the optimum Δp_1 at 50,000 feet altitude and 85 percent intercooler cooling effectiveness. It is seen that $(\Delta p_1)_{opt}$ lies between 1 and 3 inches of water and that little power is sacrificed for the conditions shown in the figure by operating the intercooler at an average cooling-air pressure drop of 2 inches of water. Plots similar to those of figures 1 and 2 made for numerous airplane flight and intercooler operating conditions show that, for the range of conditions investigated in this report, very little sacrifice in power is sustained at 2 inches of water cooling-air pressure drop.

The analysis outlined in the appendix for the plate intercooler also applies for the tubular intercooler provided the proper value of $(L/D)_{eq}$ is used. For a given set of intercooler operating conditions the heat-transfer areas for the tubular intercooler and plate intercooler are sufficiently near equality (references 1 and 2) that the range of values of $(L/D)_{eq}$ covered by the curves of this report includes the range of interest for both types of intercoolers. Thus the optimum values of Δp_1 and M_1/M_2 obtained from these curves should apply for both types of intercooler.

Figures are presented to assist the designer in choosing the intercooler cooling-air design conditions (Δp_1 and M_1/M_2) best suited to his particular purpose from considerations of volume as well as power loss. These figures relate the intercooler total power loss to the volume of the reference intercooler for a wide range of flight and intercooler operations. Curves giving the variation in intercooler volume due to change in core structure from the reference structure are given in references 1 and 2. As pointed out previously, the effect of change in core structure on the power loss is included in the $(L/D)_{eq}$ parameter through the ratio S/S_o, which is also plotted in references 1 and 2 against core-structure dimensions.

Figures 3 to 6 are direct plots of reference intercooler volume against total power loss for the following operating variables:

Altitude, feet: 20,000; 30,000; 40,000; and 50,000

Dynamic pressure in flight q, inches of water: 12.5 and 25

Cooling-air pressure drop Δp_1, inches of water: 2, 6, and 10

Cooling effectiveness η, with corresponding values of M_1/M_2, percent:

η = 40 percent for M_1/M_2 = 0.6, 0.75, 1, 1.5, and 2

η = 60 percent for M_1/M_2 = 1.25, 1.5, 2, 3, and 5

η = 80 percent for M_1/M_2 = 2.5, 3, 4, and 6

These plots are drawn for $(L/D)_{eq} = 10$ and for $\sigma_{2_{av}}\ \Delta p_{f_2} = 6$ inches of water. Included in these plots is the relation between the reference intercooler volume and the transportation power loss expressed simply by the dashed straight line. For a given type of intercooler this relation is dependent only on altitude, on q, and on $(L/D)_{eq}$. Figures 3 and 4 apply for the plate intercooler, and figures 5 and 6 apply for the charge-through-tube intercooler.

Plots of the relationship of total power loss and volume for the tubular intercoolers are identical in trend to figures 3 and 4 for the plate intercooler; the only difference is in the absolute values.

Attempts were therefore made to present the relations for the tubular intercoolers in terms of correction factors for adjusting the total power loss and volume values obtained from figures 3 and 4. For the charge-through-tube intercooler these corrections proved too complicated and involved to present; the relations for the charge-through-tube intercooler are therefore given directly in figures 5 and 6.

The corrections for the charge-across-tube intercooler were found convenient to present and relatively simple to apply; these corrections are accordingly given in the form of figure 7. The ratio of the volume or transportation power loss of the charge-across-tube intercooler to that of the plate intercooler is given in figure 7 as a function of altitude and cooling effectiveness for constant operating conditions and for $(L/D)_{eq} = 10$ and $\sigma_{2_{av}} \Delta p_{f_2} = 6$ inches of water. The procedure for using figure 7 in conjunction with figures 3 or 4 is summarized as follows:

1. The volume correction is directly applicable from figure 7.

2. Figures 3 or 4 can be used to find P_T/M_2, P_W/M_2, and therefore P_c/M_2, for the plate intercooler.

3. The value of P_W/M_2 can be corrected from figure 7 in the same manner as the volume.

4. For given flight and intercooler operating conditions, the cooling-air power loss P_c/M_2 is the same for the three types of intercooler. Thus the corrected value of P_W/M_2 can be added to the unchanged value of P_c/M_2 to give P_T/M_2 for the charge-across-tube intercooler.

It must be remembered that figures 3 to 7 apply only for $(L/D)_{eq} = 10$ and $\sigma_{2_{av}} \Delta p_{f_2} = 6$ inches of water. Further corrections for variation in $(L/D)_{eq}$ and $\sigma_{2_{av}} \Delta p_{f_2}$ are given in figures 8, 9, and 10. The detailed use of these figures will be illustrated in a later section.

The total power-loss-volume plots show that on the basis of power loss $(M_1/M_2)_{opt}$ is not a very definite value. For example, in figure 3(a), when $\Delta p_1 = 2$ inches of water and $\eta = 80$ percent, little change in total power loss occurs as M_1/M_2 is varied over the entire range shown. The intercooler volume is, however, very sensitive to change in M_1/M_2 below the optimum value because the volume increases rapidly and the power loss also increases, although to a lesser degree. On the other hand, M_1/M_2 may be increased quite appreciably from the optimum value with considerable reduction in intercooler volume and with only a slight loss in power. These plots also show that an increase in Δp_1 from the optimum average value of 2 inches of water at a given value of M_1/M_2 causes a decrease in volume at a sacrifice in power. If as Δp_1 is increased the value of M_1/M_2 is kept optimum, the volume changes only slightly at an expense in power. The various plots indicate the magnitude of these changes for the variety of design conditions presented.

The plots of total power loss against volume do not include values of Δp_1 below 2 inches of water. This presentation is considered unnecessary because of the rapid rise in total power loss somewhat below this value and also because of the confusion that would result in the figures. Furthermore, it is considered that the practical range of Δp_1 lies above 2 inches of water.

It is of interest to compare the curves of total power loss against volume for values of q of 12.5 and 25 inches of water in figures 3 to 6. The principal effect of increasing q (or airspeed) is an increase in total power loss at low values of Δp_1. This effect is the result of the relative magnitudes of the decrease in cooling-air-drag loss and of the increase in transportation power loss accompanying the increase in airspeed. The cooling-air-drag decrease is caused by the increased utilization of ram for thrust at the higher airspeed, that is, by the increased Meredith effect.

A value of q of 12.5 inches of water represents a good value for present-day speed of best climb; a q of 25 inches of water is typical of the high-speed condition. The analysis covering the range of q from 12.5 to 25 inches of water shows the optimum values of M_1/M_2 and Δp_1 to be independent of q.

Figure 9 shows that the total power loss decreases as the charge-air pressure drop increases. This effect does not mean, however, that high values of charge-air pressure drops are desirable because no account has been taken of the supercharger work required to force the charge air through the intercooler nor of the effect of charge-air pressure drop on manifold pressure. This report is confined to a study of optimum cooling-air design conditions, which for all practical purposes are independent of $\sigma_{2_{av}} \Delta p_{f_2}$ over the range covered in this report.

ILLUSTRATION OF THE USE OF THE FIGURES

Let it be required to find the volume of and the total-power loss sustained by a charge-across-tube intercooler having a reference core structure (reference intercooler of reference 2) and designed to operate at the optimum cooling-air conditions. The flight and the other intercooler operating conditions are:

(1) Cooling effectiveness η, percent 80
(2) Charge-air friction loss in intercooler passages $\sigma_{2_{av}}\ \Delta p_{f_2}$, inches of water 10
(3) $(L/D)_{eq}$ 14
(4) Altitude, feet 50,000
(5) Dynamic pressure in flight q, inches of water 12.5

The outline of the procedure used in this problem is as follows:

(a) Figure 3(d) gives the optimum cooling-air design conditions and the volume, total power loss, and transportation power loss for the reference plate intercooler when $(L/D)_{eq} = 10$ and $\sigma_{2_{av}}\ \Delta p_{f_2} = 6$ inches of water.

(b) Figure 7 gives the volume and power-loss corrections applied to the values obtained for the plate intercooler to give the values for the charge-across-tube intercooler.

(c) From figure 8 the total power loss is adjusted to apply for $(L/D)_{eq} = 14$. The volume is independent of $(L/D)_{eq}$.

(d) From figure 9 the total power loss is adjusted to apply for $\sigma_{2_{av}}\ \Delta p_{f_2} = 10$ inches of water.

(e) From figure 10 the volume is adjusted to apply for $\sigma_{2_{av}}\ \Delta p_{f_2} = 10$ inches of water.

The solution of the problem according to the foregoing outline follows.

(6) From figure 3(d) and item (1):

$$\left(\frac{M_1}{M_2}\right)_{opt} = 4$$

$$(\Delta p_1)_{opt} = 2 \text{ inches of water}$$

(7) Also, from figure 3(d), for the plate intercooler

$$v_c/M_2 = 15,700 \text{ cu in./(lb/sec)}$$

$$P_T/M_2 = 21.5 \text{ hp/(lb/sec)}$$

$$P_W/M_2 = 15.2 \text{ hp/(lb/sec)}$$

(8) Therefore, from item (7)

$$P_c/M_2 = 21.5 - 15.2 = 6.3 \text{ hp/(lb/sec)}$$

(9) From figure 7 and items (1) and (4) to correct item (7) to apply for the charge-across-tube intercooler:

$$v_o/M_2 = 0.468 \times 15,700 = 7340 \text{ cu in./(lb/sec)}$$

$$P_W/M_2 = 0.684 \times 15.2 = 10.4 \text{ hp/(lb/sec)}$$

(10) From items (8) and (9), since P_c/M_2 is independent of the type of intercooler for given flight and intercooler operating conditions

$$P_T/M_2 = 6.3 + 10.4 = 16.7 \text{ hp/(lb/sec)}$$

(11) From figure 8 and item (9) the total power loss for $(L/D)_{eq} = 14$ is

$$P_T/M_2 = 16.7 - 3 = 13.7 \text{ hp/(lb/sec)}$$

(12) From figure 9(a) and item (11) for $\sigma_{2_{av}} \Delta p_{f_2}$ = 10 inches of water

$$P_T/M_2 = 13.7 - 0.4 = 13.3 \text{ hp/(lb/sec)}$$

(13) From figure 10 and item (9) for $\sigma_{2_{av}} \Delta p_{f_2}$ = 10 inches of water

$$v_o/M_2 = 0.97 \times 7340 = 7120 \text{ cu in./(lb/sec)}$$

Items (12) and (13) are the final corrected values of total power loss and volume required in the problem.

It is noted that the values given for v_c apply for the reference core structures. For a given set of intercooler operating conditions the effect of core structure on intercooler volume may be obtained from references 1 and 2.

CONCLUSIONS

In connection with the selection of an intercooler of minimum net drag, the following conclusions are drawn concerning the optimum cooling conditions:

1. The optimum ratio of cooling-air weight flow to charge-air-weight flow, that is, the ratio that gives minimum intercooler total-power loss, is practically independent of the airplane flight conditions and the intercooler charge-air pressure drop. For all practical purposes the optimum weight-flow ratio is a simple function of the cooling effectiveness and the cooling-air pressure drop.

2. When the cooling-air weight flow is maintained at its optimum value, the cooling-air pressure drop becomes optimum between 1 and 3 inches of water regardless of the cooling effectiveness, flight conditions, and charge-air pressure drop. Within this range of cooling-air pressure drop there is only a slight change in total-power loss from the minimum value.

3. For operation in the optimum range of cooling-air pressure drop, the optimum ratio of cooling-air weight flow to charge-air weight flow becomes a function only of cooling effectiveness.

4. For optimum cooling-air weight flow, a value of Δp_1 from 1 to 3 inches of water can be chosen without changing the net intercooler power loss an appreciable amount. There is a slight trend in favor of the lower values of Δp_1 at high altitudes. Choice of higher values of Δp_1 leads to intercoolers having larger cooling-air flow lengths and smaller no-flow dimensions than for the lower values of Δp_1. Such coolers may be more convenient to install in some cases.

5. For a given value of cooling-air pressure drop, an appreciable variation of cooling-air weight flow (within limits discussed in the report) from the optimum values will cause little change in the net intercooler power loss. An increase in cooling-air weight flow above the optimum will require an increase in the no-flow intercooler dimension, a decrease in the cooling-air flow dimension, and a decrease in intercooler volume. A reduction in cooling-air weight flow from the optimum value will reverse these trends.

6. The optimum values of cooling-air weight flow and pressure drop given herein are, within practical limits, unaffected by (1) plate or tube-wall thickness, (2) density of intercooler material,

and (3) weight of accessory material required in installation. These optimum values apply equally well for the plate and tubular intercoolers.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio. February 25, 1944.

APPENDIX

SYMBOLS

a	ratio of cooling-air skin-friction pressure drop to total cooling-air pressure drop, $\Delta p_{f_1}/\Delta p_1$
A_r	over-all effective heat-transfer area, sq ft
c_p	specific heat of air at constant pressure (0.24 Btu/(lb)(°F))
e	base of natural logarithms
g	acceleration of gravity, ft/(sec)^2
L/D	airplane wing lift-drag ratio

$(L/D)_{eq}$	lift-drag ratio equivalent $\left[\dfrac{L/D}{\left(\dfrac{\rho_m}{173}\right)\left(\dfrac{12t}{0.01}\right)\left(\dfrac{R_W}{1.2}\right)\left(\dfrac{y}{2}\right)\left(\dfrac{S}{S_o}\right)}\right]$
M	rate of air-weight flow, lb/sec
p	air pressure, in. water
Δp	total pressure drop of air across intercooler, in. water
Δp_f	skin-friction pressure drop of air in intercooler, in. water
P_c	cooling-air drag power loss, hp
P_T	total power loss due to cooling-air drag and intercooler weight $(P_c + P_W)$, hp
P_W	power required to transport intercooler and its accessories, hp
q	free-stream dynamic pressure, in. water
r	supercharger-pressure ratio
R_W	ratio of weight of intercooler to weight of intercooler plates or tubes
S	heat-transfer surface area of intercooler, sq ft
t	plate thickness of plate intercooler or tube-wall thickness of tubular intercooler, ft
T	air temperature, °F absolute
U	over-all heat-transfer coefficient based on A_r, Btu/(sec)(sq ft)(°F)
v	intercooler volume, cu ft (or cu in. where designated)
V	airplane velocity, fps
W	intercooler weight, lb
y	ratio of increase in airplane weight caused by addition of an intercooler to weight of intercooler
γ	exponent of adiabatic compression

η intercooler cooling effectiveness

η_{ad} supercharger adiabatic efficiency

η_d intercooler duct efficiency

θ weight flow-pressure drop ratio $\left(\frac{M_1 \ \sigma_{1_{av}} \ \Delta p_{f_1}}{M_2 \ \sigma_{2_{av}} \ \Delta p_{f_2}}\right)$

ρ air density, lb/cu ft

ρ_m density of plate or tube-wall material, lb/cu ft

σ density of air relative to standard atmosphere

Subscripts:

a free-air-stream conditions

av average conditions in intercooler

e conditions at duct exit

en conditions at intercooler entrance

ex conditions at intercooler exit

opt optimum on basis of total power loss

s supercharger

o reference intercooler conditions where the reference intercooler is defined in references 1 and 2

1 cooling air

2 charge air

Analysis

The application of Bernoulli's incompressible-flow equation to the cooling-air flow ahead of the intercooler (fig. 11) gives,

$$p_{en} - p_a = \frac{1}{10.4g} \eta_d \rho_a \left(V_a^2 - V_{en}^2\right) \qquad (1)$$

Also, when Bernoulli's equation is applied to the cooling-air flow behind the intercooler

$$p_{ex} - p_a = \frac{1}{10.4g}\rho_{ex}\left(V_e^2 - V_{ex}^2\right) \qquad (2)$$

From equation (2) the duct-exit velocity may be explicitly given as

$$V_e^2 = \frac{10.4g}{\rho_{ex}}(p_{ex} - p_a) + V_{ex}^2 \qquad (3)$$

The pressure drop across the intercooler may be expressed as

$$\Delta p_1 = (p_{en} - p_a) - (p_{ex} - p_a) \qquad (4)$$

When equations (1) and (4) are substituted in equation (3) and when the resulting equation is rearranged

$$V_e = \sqrt{\frac{\eta_d\rho_a}{\rho_{ex}} V_a^2 \left[1 - \left(\frac{V_{en}}{V_a}\right)^2\right]\left[1 - \frac{\Delta p_1}{p_{en} - p_a} + \frac{\rho_{ex}V_{ex}^2}{\eta_d\rho_a\left(V_a^2 - V_{en}^2\right)}\right]} \qquad (5)$$

The cooling-air velocity near the entrance and exit faces of the intercooler is usually a very small fraction of the free-stream velocity. Thus, equation (5) may be written with negligible error as

$$V_e = V_a\sqrt{\eta_d\frac{\rho_a}{\rho_{ex}}\left(1 - \frac{\Delta p_1}{p_{en} - p_a}\right)} \qquad (6)$$

When the general gas law is introduced

$$\frac{\rho_a}{\rho_{ex}} = \frac{1 + \frac{\Delta T_1}{T_a}}{1 - \frac{\Delta p_1}{p_a}} \qquad (7)$$

The cooling-air drag power loss arising from the momentum change of the cooling air flowing through the duct is

$$\frac{P_c}{M_2} = \frac{M_1}{M_2}\frac{V_a}{550g}(V_a - V_e) \tag{8}$$

When equations (6) and (7) are substituted in equation (8)

$$\frac{P_c}{M_2} = \frac{M_1}{M_2}\frac{V_a^2}{550g}\left[1 - \sqrt{\eta_d\left(1 + \frac{\Delta T_1}{T_a}\right)\left(\frac{1 - \frac{\Delta p_1}{\eta_d q}}{1 - \frac{\Delta p_1}{p_a}}\right)}\right] \tag{9}$$

The ratio $\Delta T_1/T_a$ in equation (9) may be given in terms of intercooler and supercharger characteristics by the use of the heat-balance equation for the charge and cooling air. Thus,

$$\frac{\Delta T_1}{T_a} = \frac{\eta}{M_1/M_2}\frac{\Delta T_s}{T_a} \tag{10}$$

where from supercharger performance relations

$$\frac{\Delta T_s}{T_a} = \frac{r^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{ad}} \tag{11}$$

Transportation power loss. - The power required to transport the additional airplane weight due to the installation of an intercooler is determined on the basis of constant wing loading and thus constant take-off and landing speeds. The transportation power loss is, then, the drag of the additional wing area required to keep constant wing loading. This drag power is

$$\frac{P_W}{M_2} = \frac{V_a}{550\ L/D}\frac{yW}{M_2} \tag{12}$$

The relation between the intercooler heat-transfer surface area and the intercooler weight can be expressed as

$$\frac{W}{M_2} = \rho_m t R_W \frac{S}{M_2} \tag{13}$$

The foregoing equations are general and hold for both the plate and tubular intercoolers. The following equations will deal specifically with the plate intercooler, although the same general procedure may also be employed with the charge-across-tube and the charge-through-tube intercoolers.

From equations (12) and (25) of reference 1 the heat-transfer surface area and the operating conditions and core-structure dimensions of the plate intercooler are related by

$$\frac{S}{M_2} = 69.4 \left(\frac{UA_r}{M_2 c_p}\right)^{7/5} \frac{\left(\theta^{-2/7} + 1\right)^{7/5}}{\left(\sigma_{2_{av}} \Delta p_{f_2}\right)^{2/5}} \frac{S}{S_o} \tag{14}$$

where S/S_o is a function of the core-structure dimensions and is given in reference 1 by equation (25) and figure 2.

In reference 3 the cooling effectiveness of a cross-flow plate intercooler is given as approximately

$$\eta = 1 - e^{-\frac{M_1}{M_2}\left(1 - e^{-\frac{UA_r}{M_2 c_p}\frac{M_2}{M_1}}\right)} \tag{15}$$

The solution of equation (15) for $\frac{UA_r}{M_2 c_p}$ is

$$\frac{UA_r}{M_2 c_p} = -\frac{M_1}{M_2} \log_e \left[\frac{\log_e(1 - \eta)}{M_1/M_2} + 1\right] \tag{16}$$

For convenience, define

$$(L/D)_{eq} = \frac{L/D}{\left(\frac{\rho_m}{173}\right)\left(\frac{12t}{0.01}\right)\left(\frac{R_W}{1.2}\right)\left(\frac{y}{2}\right)\left(\frac{S}{S_o}\right)} \tag{17}$$

where ρ_m, t, R_W and y are given the reference numerical values of 173, 0.01, 1.2, and 2, respectively.

From equations (12), (13), (14), (16), and (17) the power required to transport the plate intercooler may be given in terms of the flight and intercooler operating conditions as

$$\frac{P_W}{M_2} = \frac{-24\ V_a}{550\ (L/D)_{eq}} \left\{\frac{M_1}{M_2} \log_e \left[\frac{\log_e (1 - \eta)}{M_1/M_2} + 1\right]\right\}^{7/5}$$

$$\left[\left(\frac{M_1}{M_2} a\ \sigma_{1_{av}}\ \Delta p_1\right)^{-2/7} + \left(\sigma_{2_{av}}\ \Delta p_{f_2}\right)^{-2/7}\right]^{7/5} \tag{18}$$

Solution for optimum M_1/M_2. - From equations (9), (10), (11), and (18) the total power loss can be expressed as a function of the flight and intercooler operating conditions by

$$\frac{P_T}{M_2} = K_1 \frac{M_1}{M_2}\left[1 - \sqrt{K_3\left(1 + K_2 \frac{\eta}{M_1/M_2}\right)}\right]$$

$$-K_4 \left(\frac{M_1}{M_2}\right)^{7/5}\left[\left(\frac{M_1}{M_2} a\sigma_{1_{av}}\ \Delta p_1\right)^{-2/7} + \left(\sigma_{2_{av}}\ \Delta p_{f_2}\right)^{-2/7}\right]^{7/5} (\log_e X)^{7/5} \tag{19}$$

where

$$K_1 = \frac{V_o^2}{550g} \qquad (20)$$

$$K_2 = \frac{r^{(\gamma-1)/\gamma} - 1}{\eta_{ad}} \qquad (21)$$

$$K_3 = \eta_d \left(\frac{1 - \frac{\Delta p_1}{\eta_d q}}{1 - \frac{\Delta p_1}{p_a}} \right) \qquad (22)$$

$$K_4 = \frac{24\ V_a}{550\ (L/D)_{eq}} \qquad (23)$$

$$X = \frac{\log_e(1-\eta)}{M_1/M_2} + 1 \qquad (24)$$

The optimum value of M_1/M_2 is evaluated by first letting

$$\partial\left(\frac{P_T}{M_2}\right) \Big/ \partial\left(\frac{M_1}{M_2}\right) = 0 \qquad (25)$$

and by then solving for M_1/M_2. The solution for M_1/M_2 in equation (25) has been obtained graphically for the following range of conditions:

η, percent	30-85
$\sigma_{2_{av}} \Delta p_{f_2}$, inches of water	2-12
Altitude, feet	20,000-50,000
q, inches of water	12-24
$(L/D)_{eq}$	5-20
r	1-3
η_{ad}, percent	65-100

The duct efficiency η_d was taken as 90 percent.

The results of the foregoing procedure can be given as

$$\left(\frac{M_1}{M_2}\right)_{opt} = \frac{be^{3.06\eta}}{\Delta p_1{}^m} \tag{26}$$

where

$$b = \phi_3\left(\frac{K_1}{K_4}, K_2, K_3, \frac{\eta}{M_1/M_2}, a\sigma_{1_{av}}\ \Delta p_1, \sigma_{2_{av}}\ \Delta p_{f_2}\right)$$

and

$$m = \phi_4\ (b)$$

Inasmuch as the terms b and m vary only slightly when minimum total power loss is designed for, they may for general intercooler design purposes be assumed constant at an average value for the range of flight and intercooler operating conditions covered in this report. Thus, $b = 0.49$ and $m = 0.36$, approximately.

Solution for optimum Δp_1. - If equation (26) is substituted in equation (19)

$$\frac{P_T}{M_2} = K_1\ \frac{be^{3.06\eta}}{\Delta p_1{}^m}\left[1 - \sqrt{K_3\left(1 + K_2\frac{\eta\Delta p_1{}^m}{be^{3.06\eta}}\right)}\right]$$

$$-K_4\left(\frac{be^{3.06\eta}}{\Delta p_1{}^m}\right)^{7/5}\left[\left(be^{3.06\eta}\ a\sigma_{1_{av}}\ \Delta p_1{}^{1-m}\right)^{-2/7} + \left(\sigma_{2_{av}}\ \Delta p_{f_2}\right)^{-2/7}\right]^{7/5}$$

$$\left\{\log_e\left[\frac{\log_e(1-\eta)\ \Delta p_1{}^m}{be^{3.06\eta}} + 1\right]\right\}^{7/5} \tag{27}$$

The optimum value of Δp_1 when M_1/M_2 is also optimum will be defined when

$$\partial\ (P_T/M_2)/\partial\ (\Delta p_1) = 0 \qquad (28)$$

In this differentiation the terms b and m were considered as independent of Δp_1. This assumption was investigated over the range of values of Δp_1 between 1 and 10 inches of water and was found to be substantially true.

Graphical solutions of equation (28) for $(\Delta p_1)_{opt}$ over the range of conditions investigated in this report show that $(\Delta p_1)_{opt}$ varies between 1 and 3 inches of water.

The approximations in the foregoing analysis have been made for the purpose of simplifying the mathematics involved. The optimum cooling-air weight flow and pressure-drop values obtained through the use of these approximations have been checked against the values obtained by a more laborious method as illustrated by figures 1 and 2. The errors introduced by these approximations were found to be small and unimportant.

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1. Pinkel, Benjamin, Reuter, J. George, and Valerino, Michael F.: The Cross-Flow Plate-Type Intercooler. NACA ACR, April 1942.

2. Reuter, J. George, and Valerino, Michael F.: An Analysis of the Effect of Core Structure and Performance on Volume and Shape of Cross-Flow Tubular Intercoolers. NACA ARR, Dec. 1942.

3. Reuter, J. George, and Valerino, Michael F.: Comparison of Intercooler Characteristics. NACA ARR Nov. 1942.

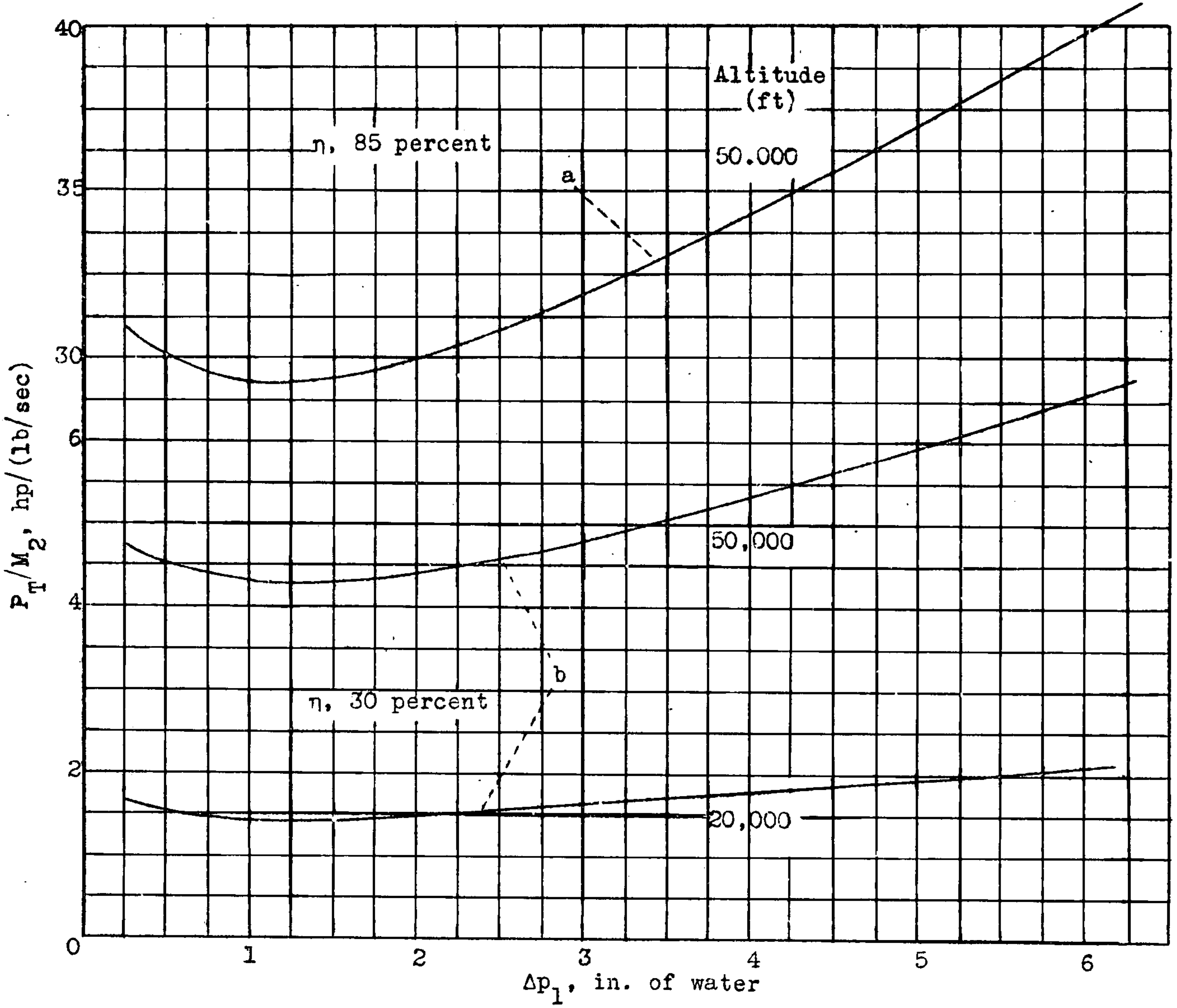


Figure 1.- Variation of plate intercooler total power loss with cooling-air pressure drop for optimum cooling-air flow. $(L/D)_{eq}$, 10; q, 12.5 inches of water; $\sigma_{2_{av}} \Delta p_{f_2}$, 6 inches of water.

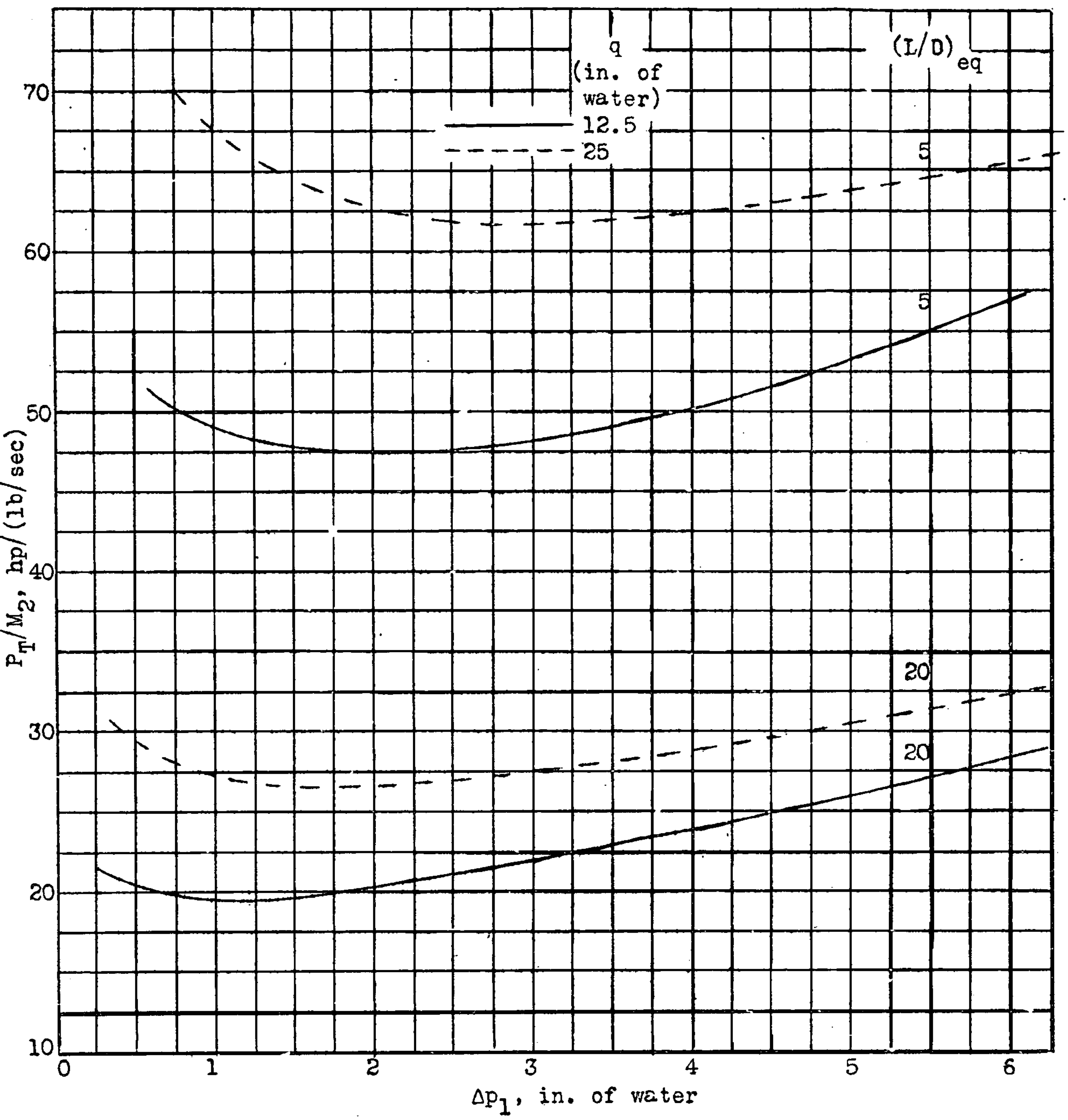
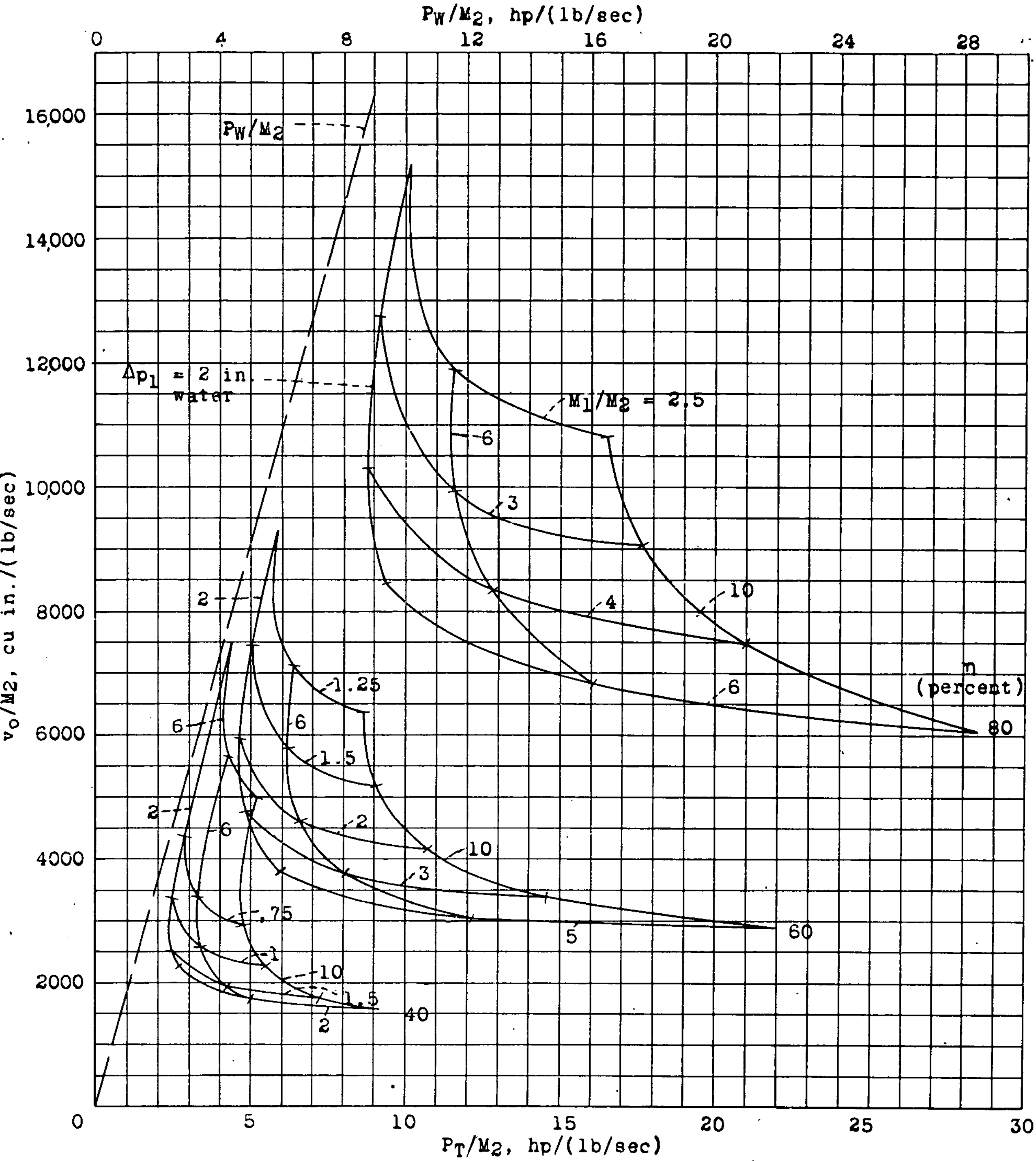


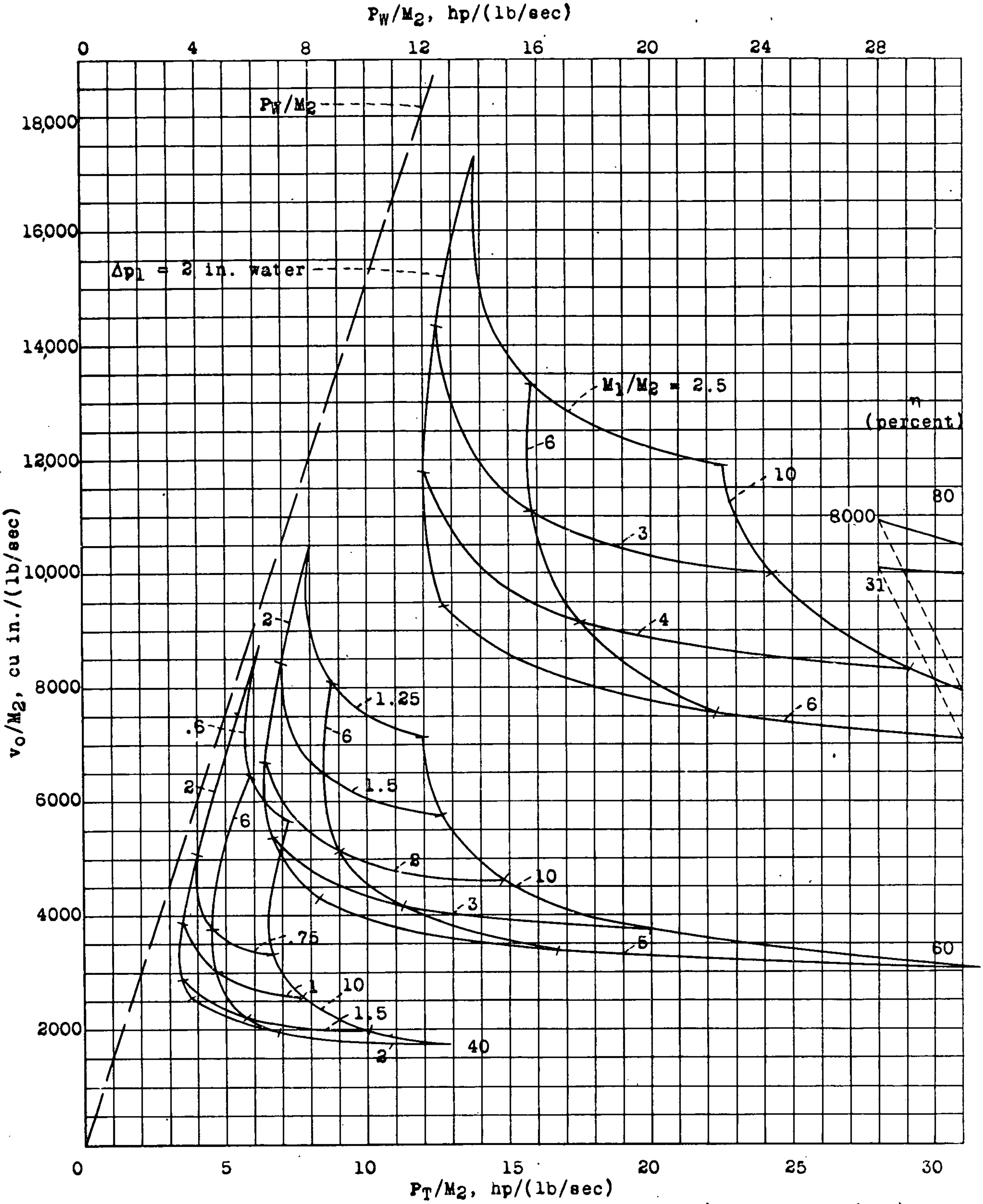
Figure 2.- Variation of plate intercooler total power loss with cooling-air pressure drop for optimum cooling air flow when $(L/D)_{eq}$ is 5 and 20, and q is 12.5 and 25 inches of water. Altitude, 50,000 ft; η, 85 percent.



(1 block = 10 divisions on 1/50" Engr. scale)

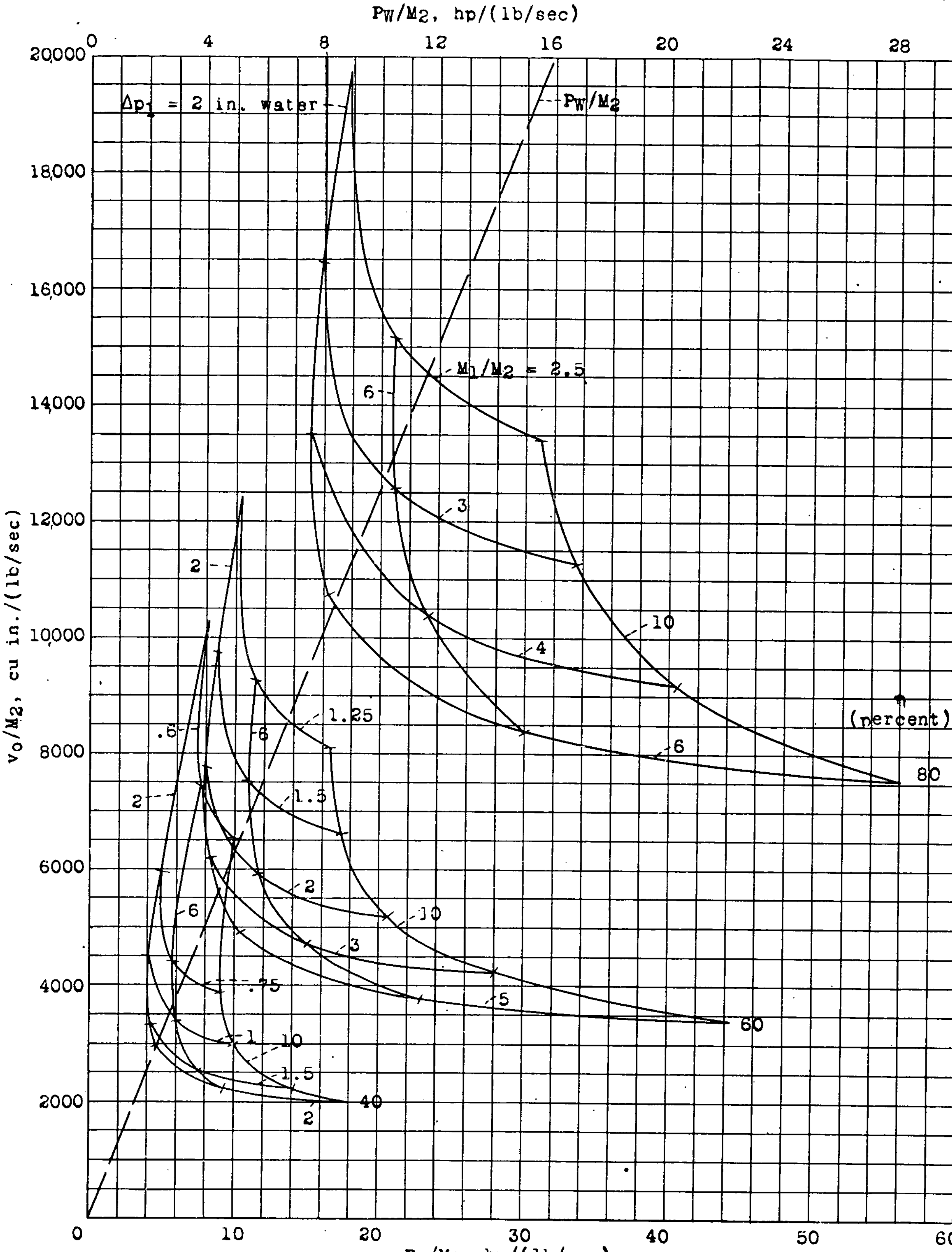
(a) 20,000 feet altitude.

Figure 3(a to d).- Relation between the volume and the total power loss of the plate intercooler when q is 12.5 inches of water. $(L/D)_{eq}$, 10; $\sigma_{2_{av}}\Delta p_{f_2}$, 6 inches of water.



(b) 30,000 feet altitude.

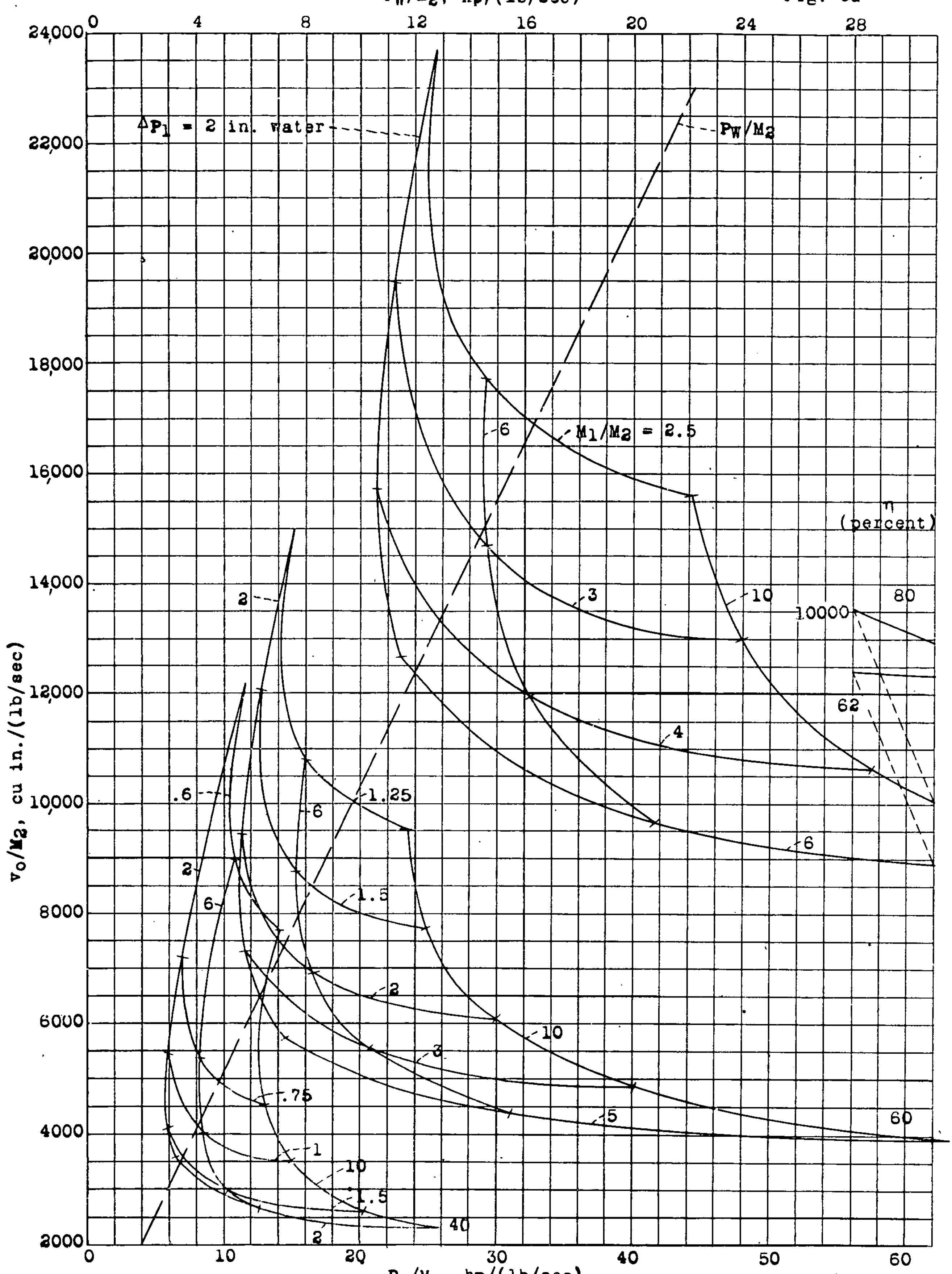
Figure 3.- Continued.



(c) 40,000 feet altitude.

(1 block = 10/50")

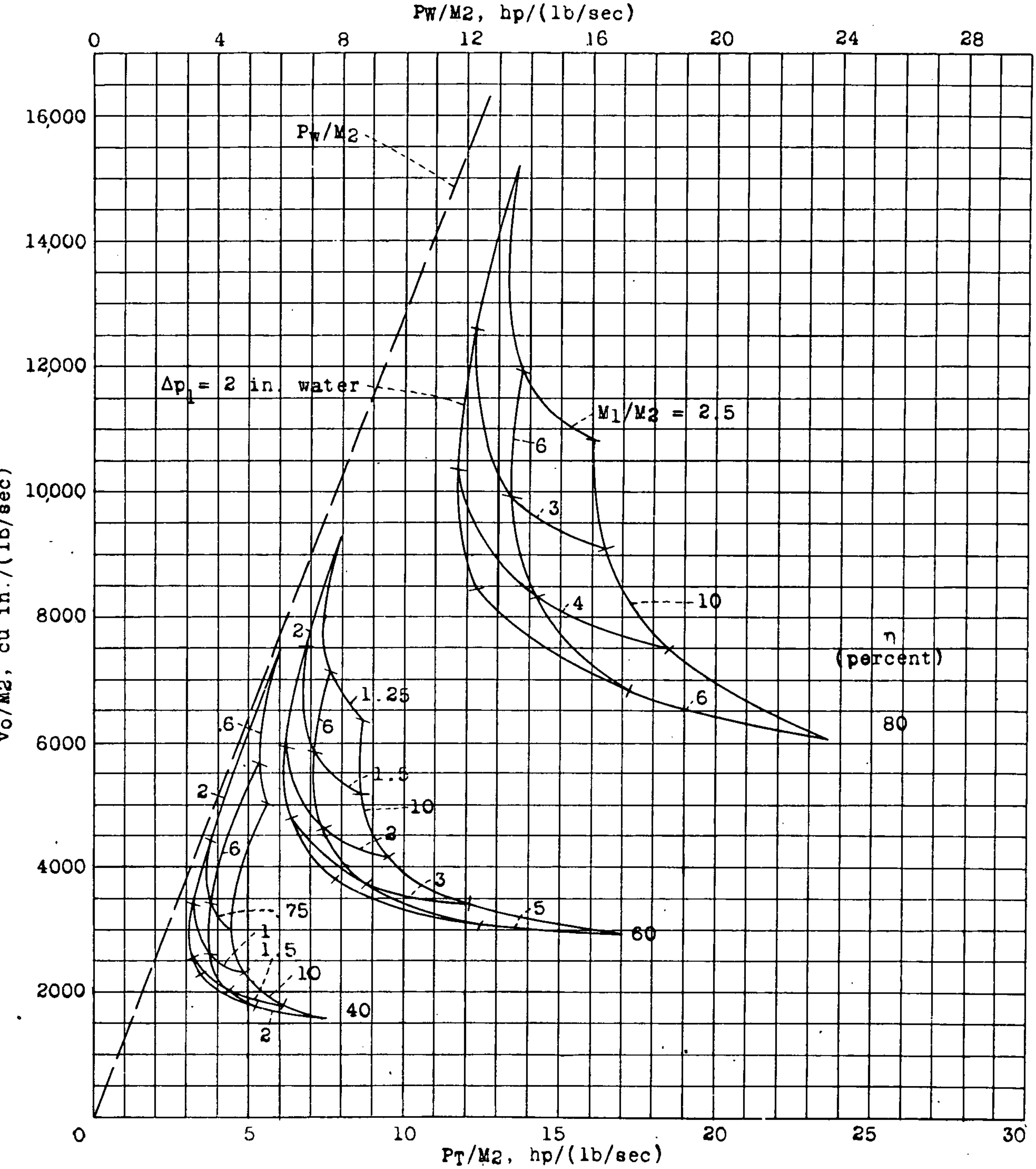
Figure 3.- Continued.



(1 block = 10/50")

(d) 50,000 feet altitude.

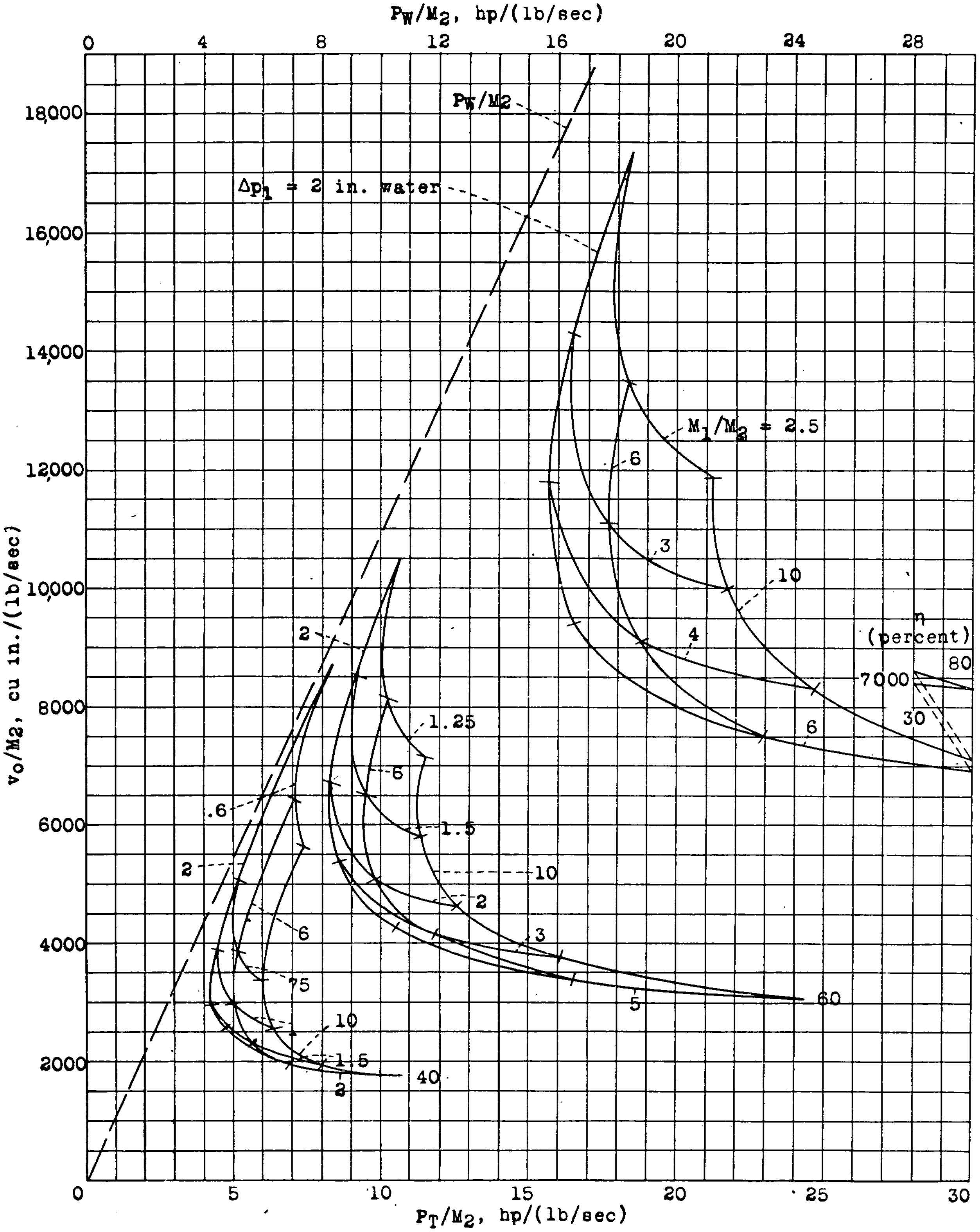
Figure 3.- Concluded.



(1 block = 10/50")

(a) 20,000 feet altitude.

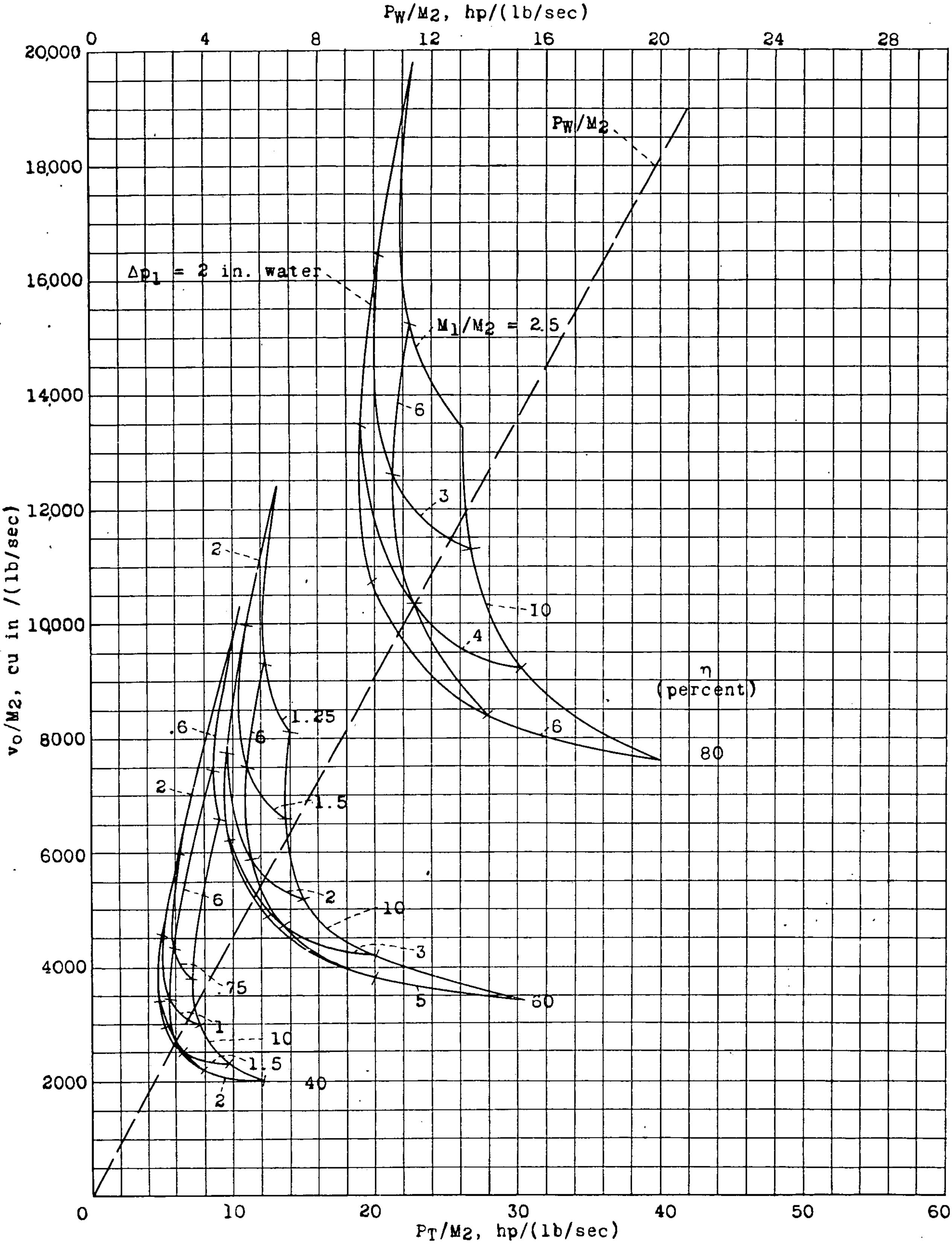
Figure 4(a to d).- Relation between the volume and the total power loss of the plate intercooler when q is 25 inches of water. $(L/D)_{eq}$, 10; and $\sigma_{2av}\Delta p_{f_2}$, 6 inches of water.



(1 block = 10/50")

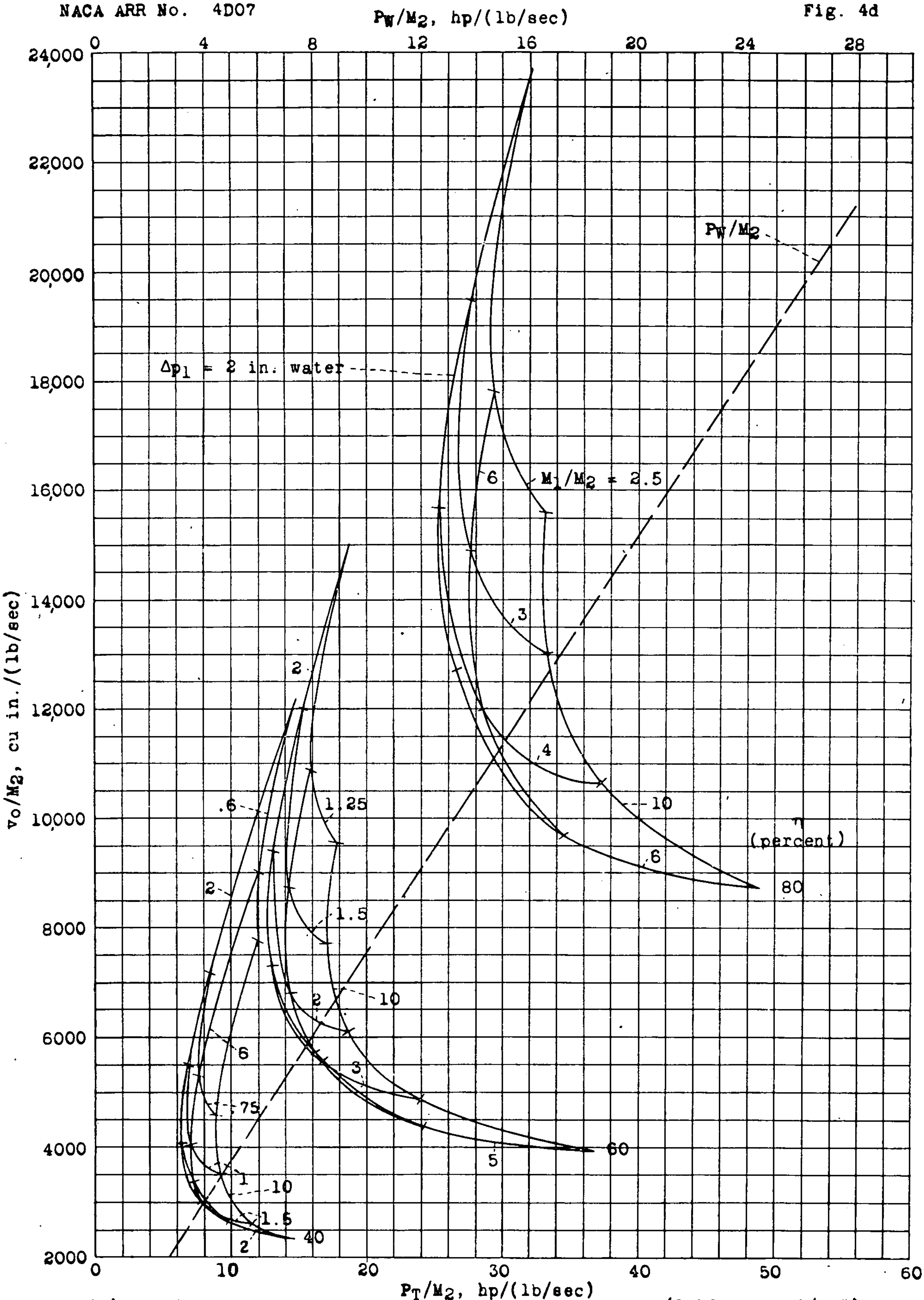
(b) 30,000 feet altitude.

Figure 4.- Continued.



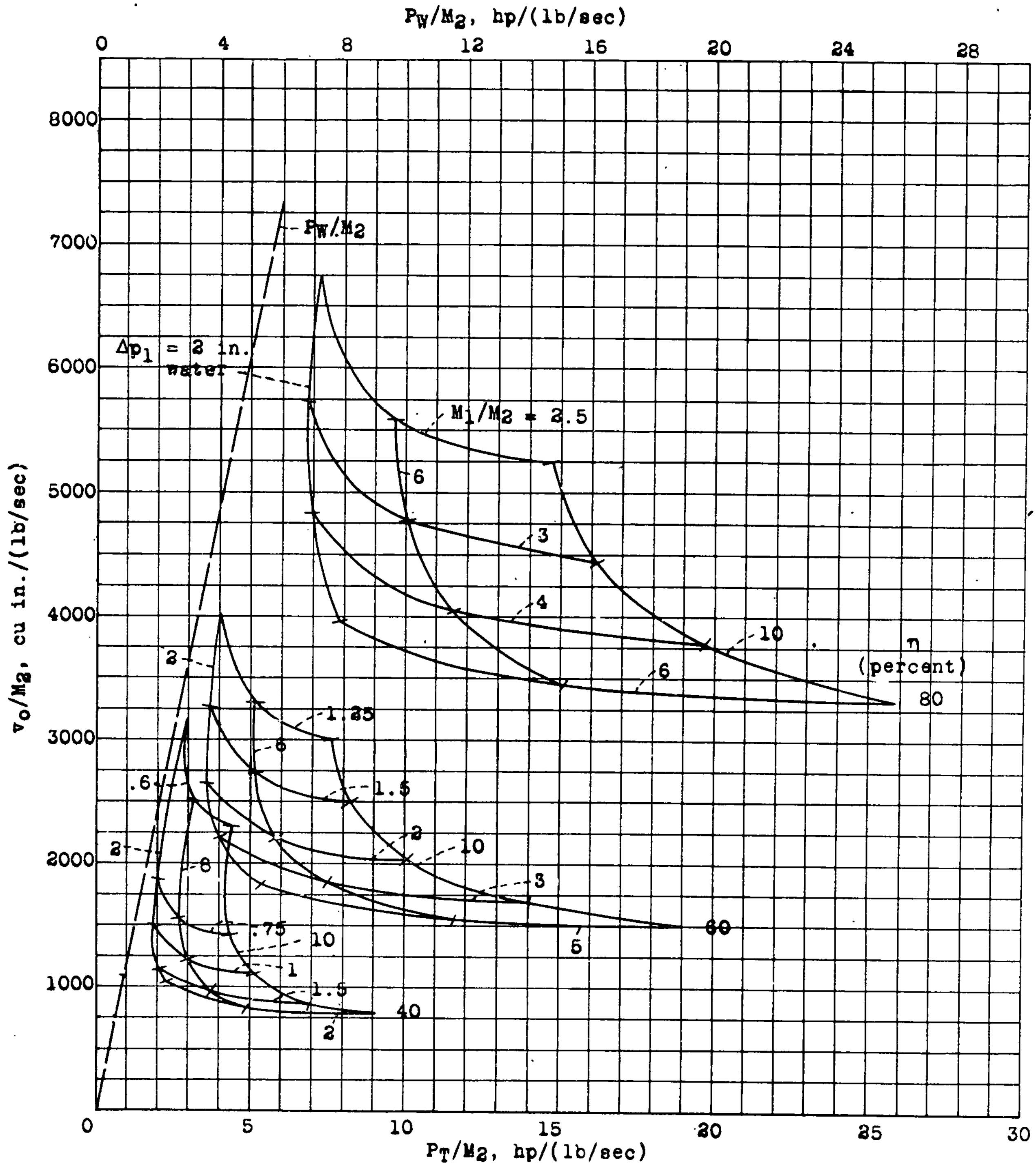
(c) 40,000 feet altitude. (1 block = 10/50")

Figure 4.- Continued.



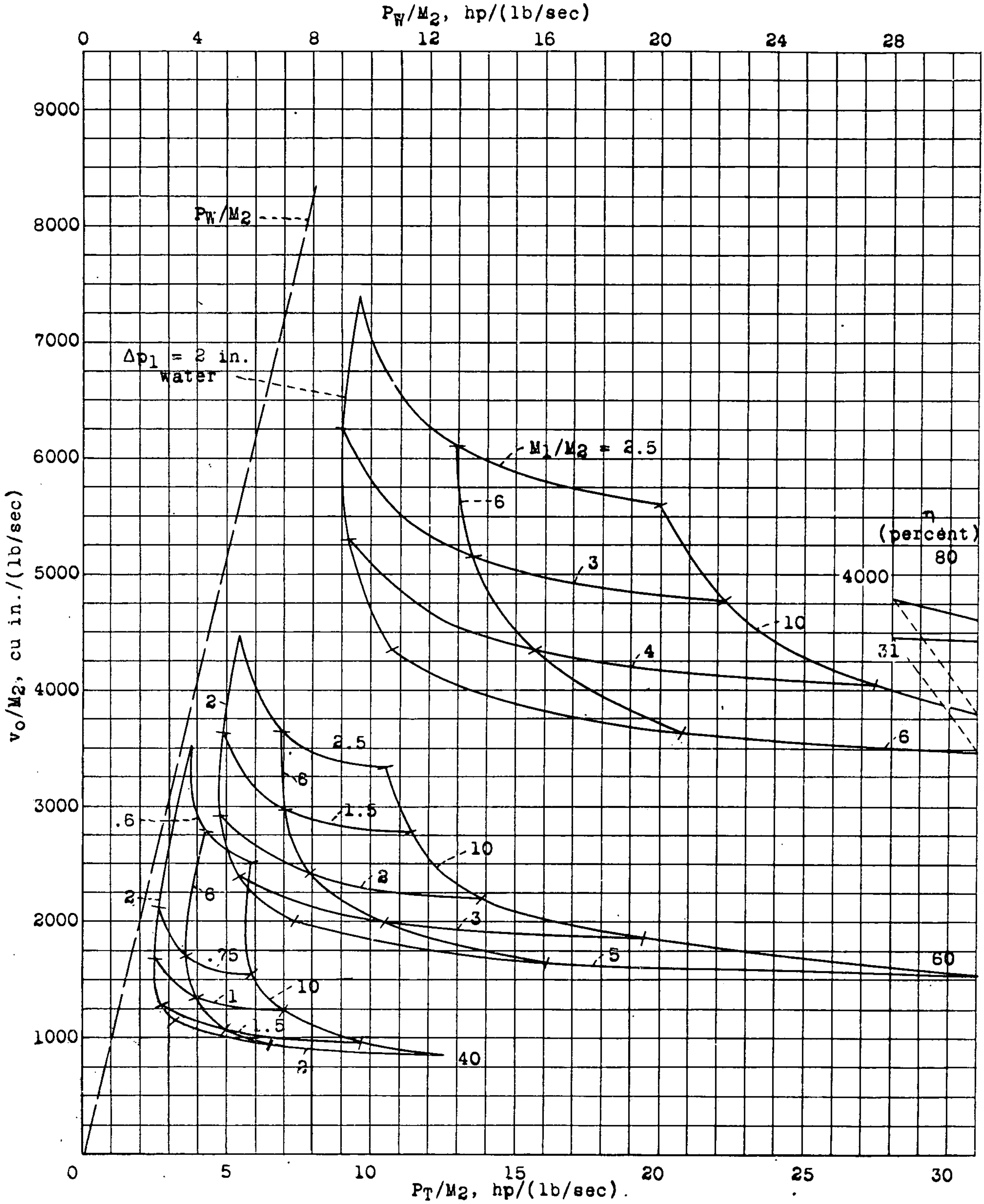
(d) 50,000 feet altitude. (1 block = 10/50")

Figure 4.- Concluded.



(a) 20,000 feet altitude. (1 block = 10/50")

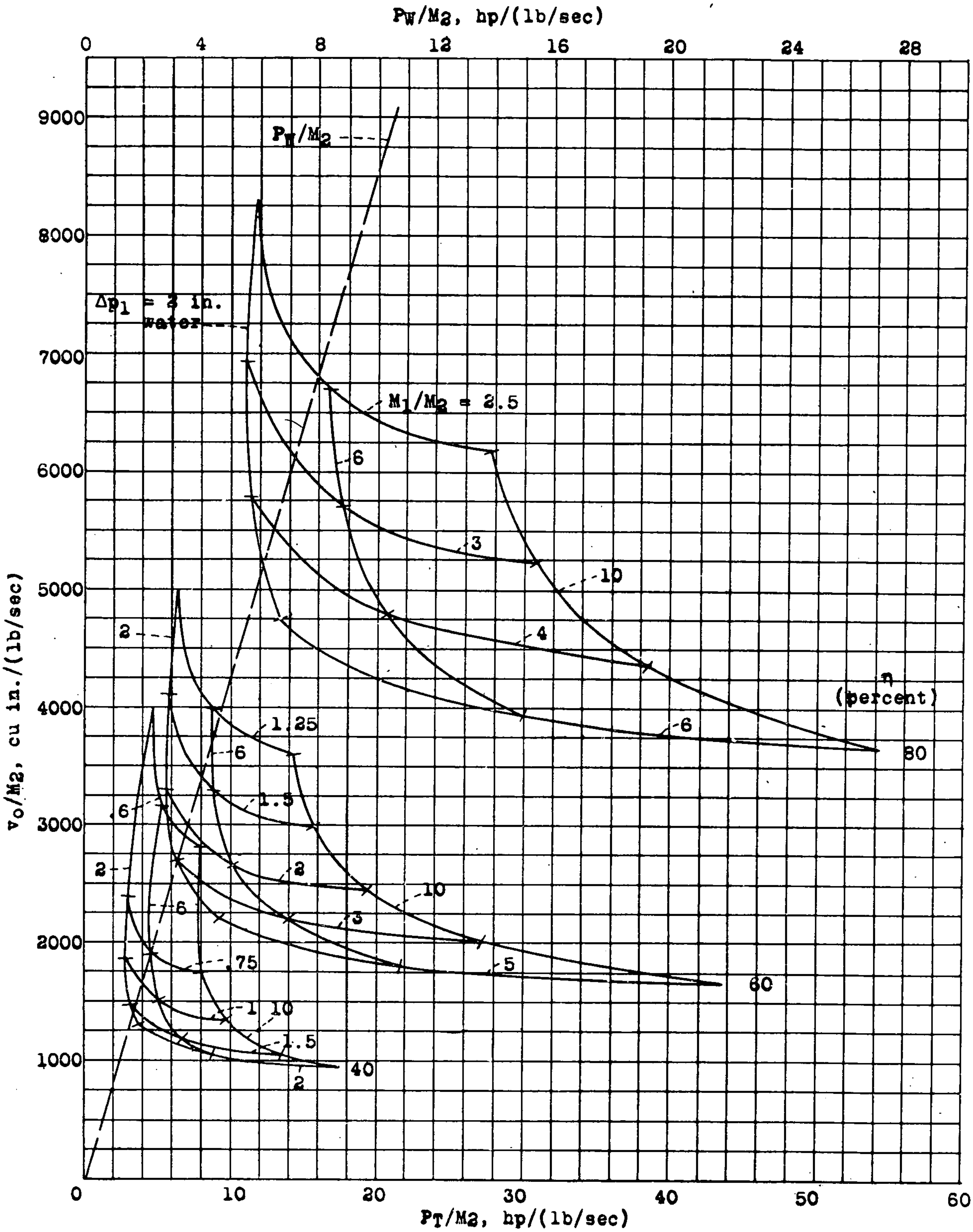
Figure 5(a to d).- Relation between the volume and the total power loss of the charge-through-tube intercooler when q is 12.5 inches of water. $(L/D)_{eq}$, 10; and $\sigma_{2_{av}} \Delta p_{f\,2}$, 6 inches of water.



(b) 30,000 feet altitude.

(1 block = 10/50")

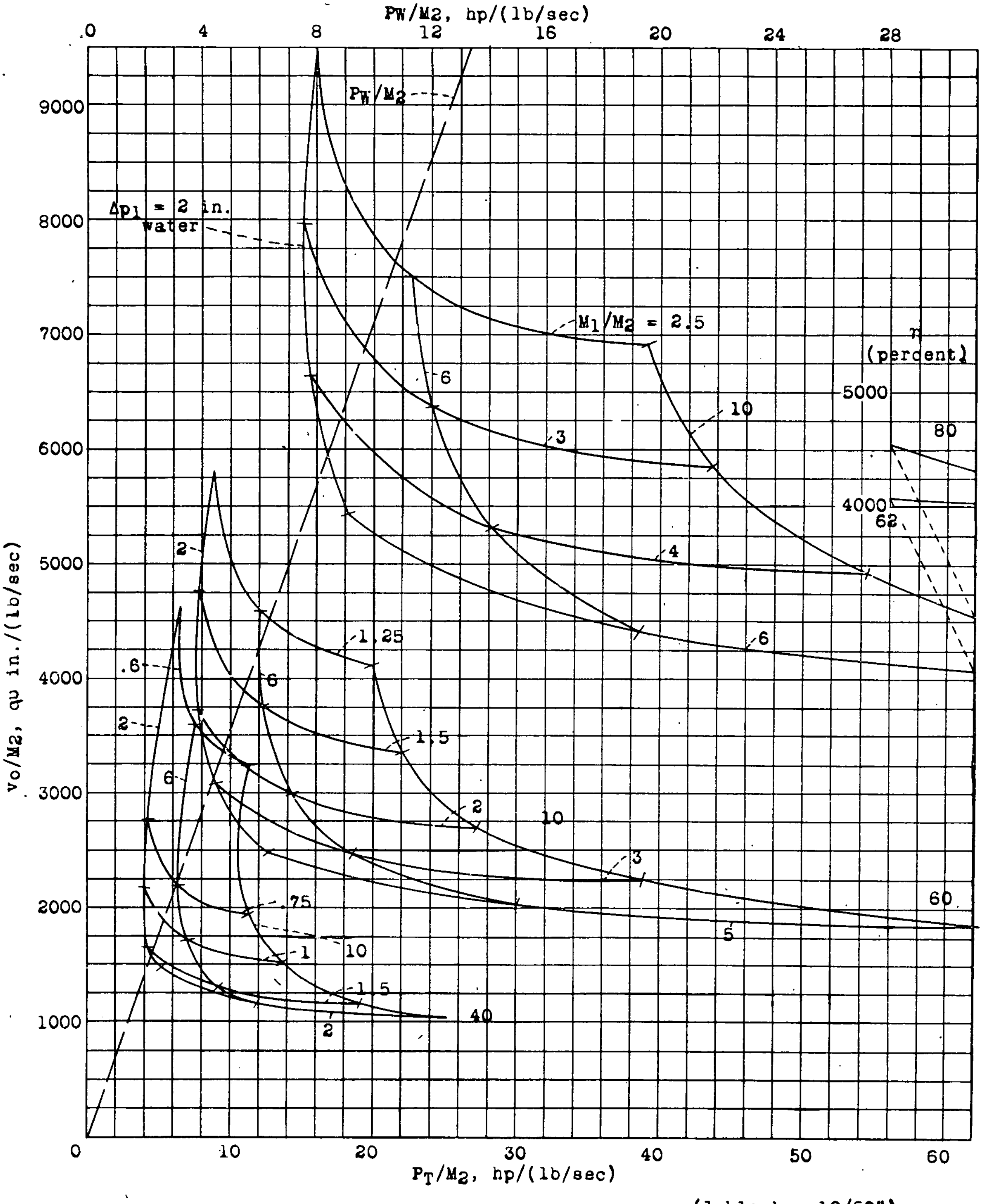
Figure 5.- Continued.



(c) 40,000 feet altitude.

(1 block = 10/50")

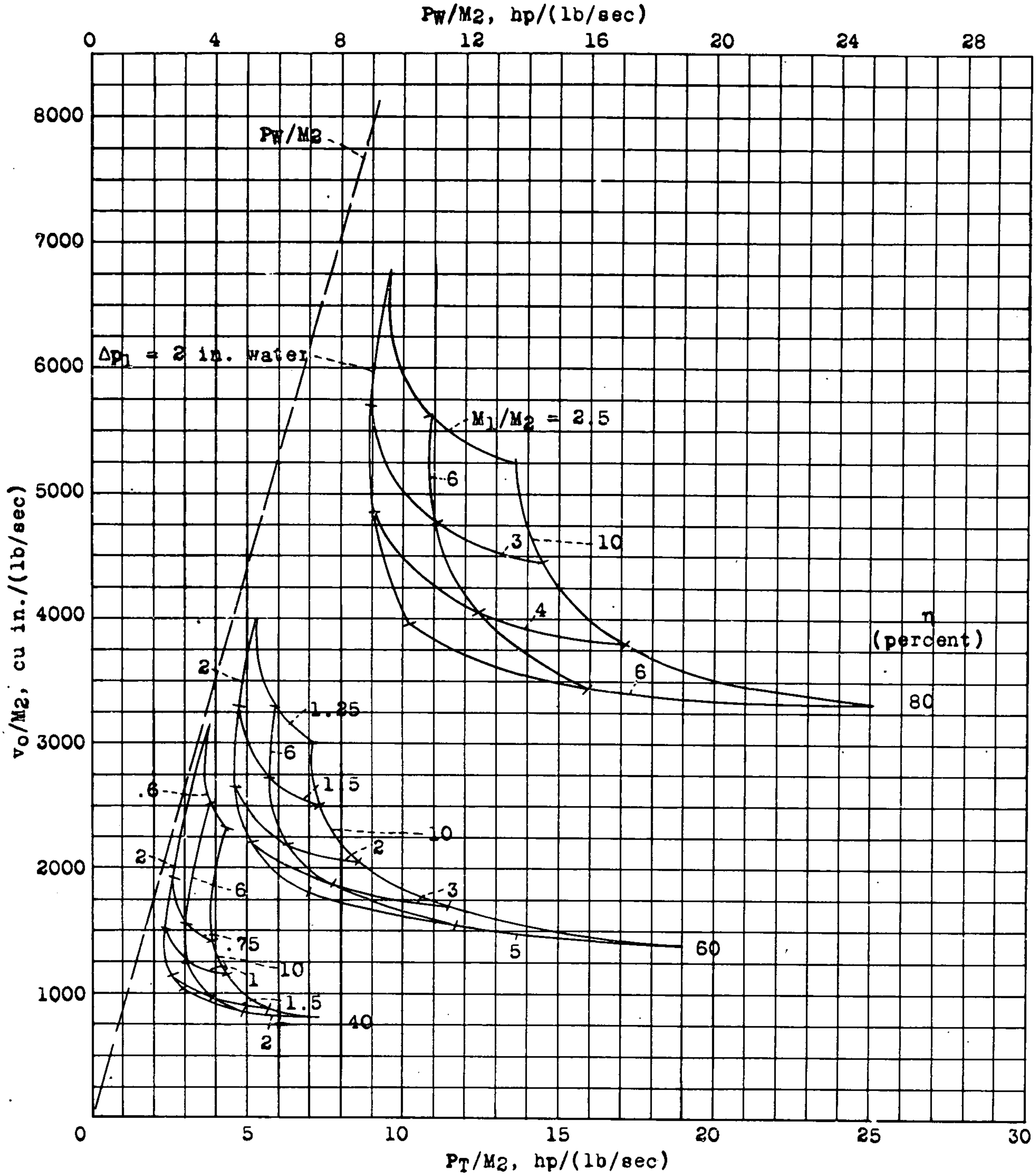
Figure 5.- Continued.



(1 block = 10/50")

(d) 50,000 feet altitude.

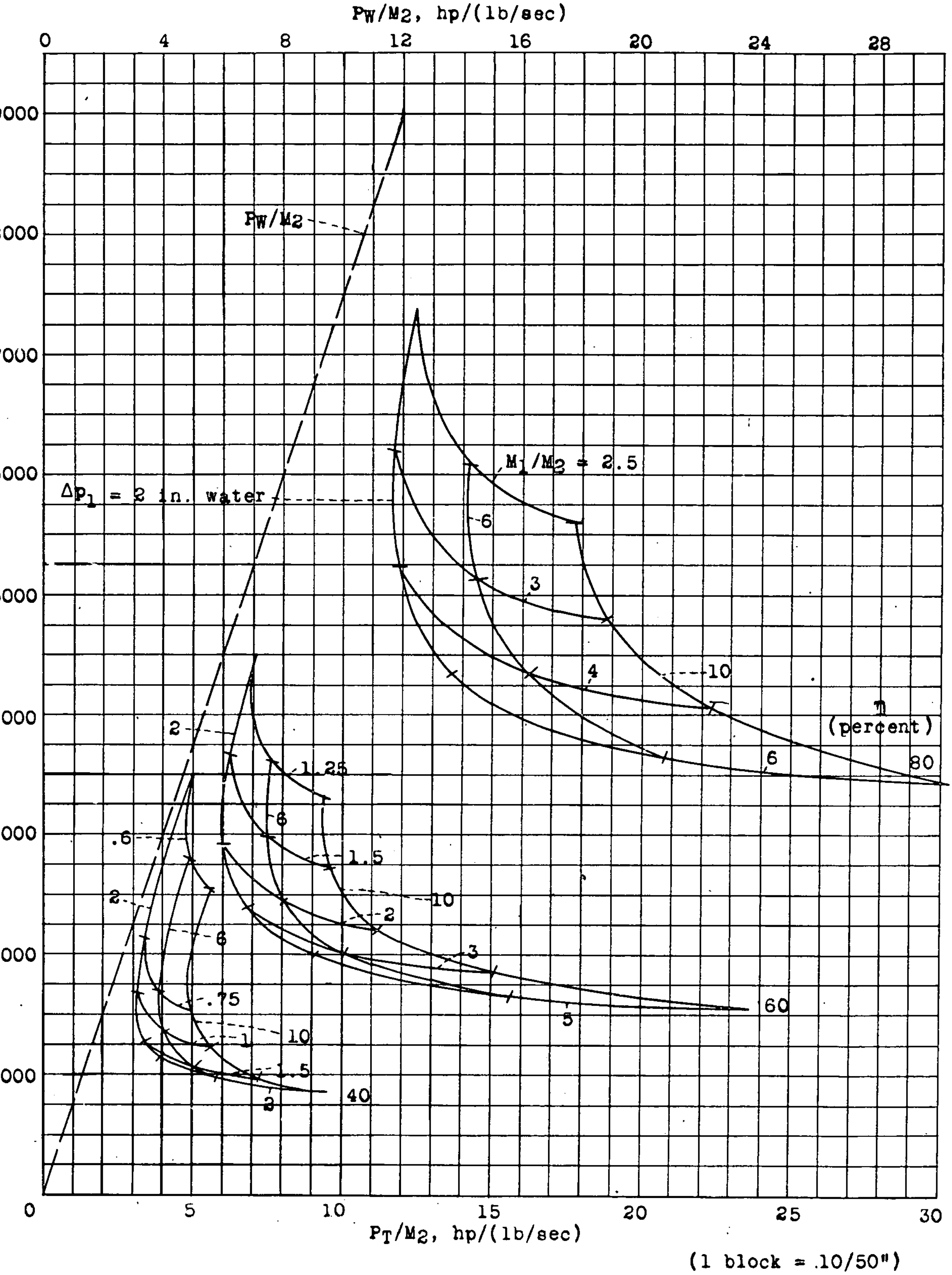
Figure 5.- Concluded.



(1 block = 10/50")

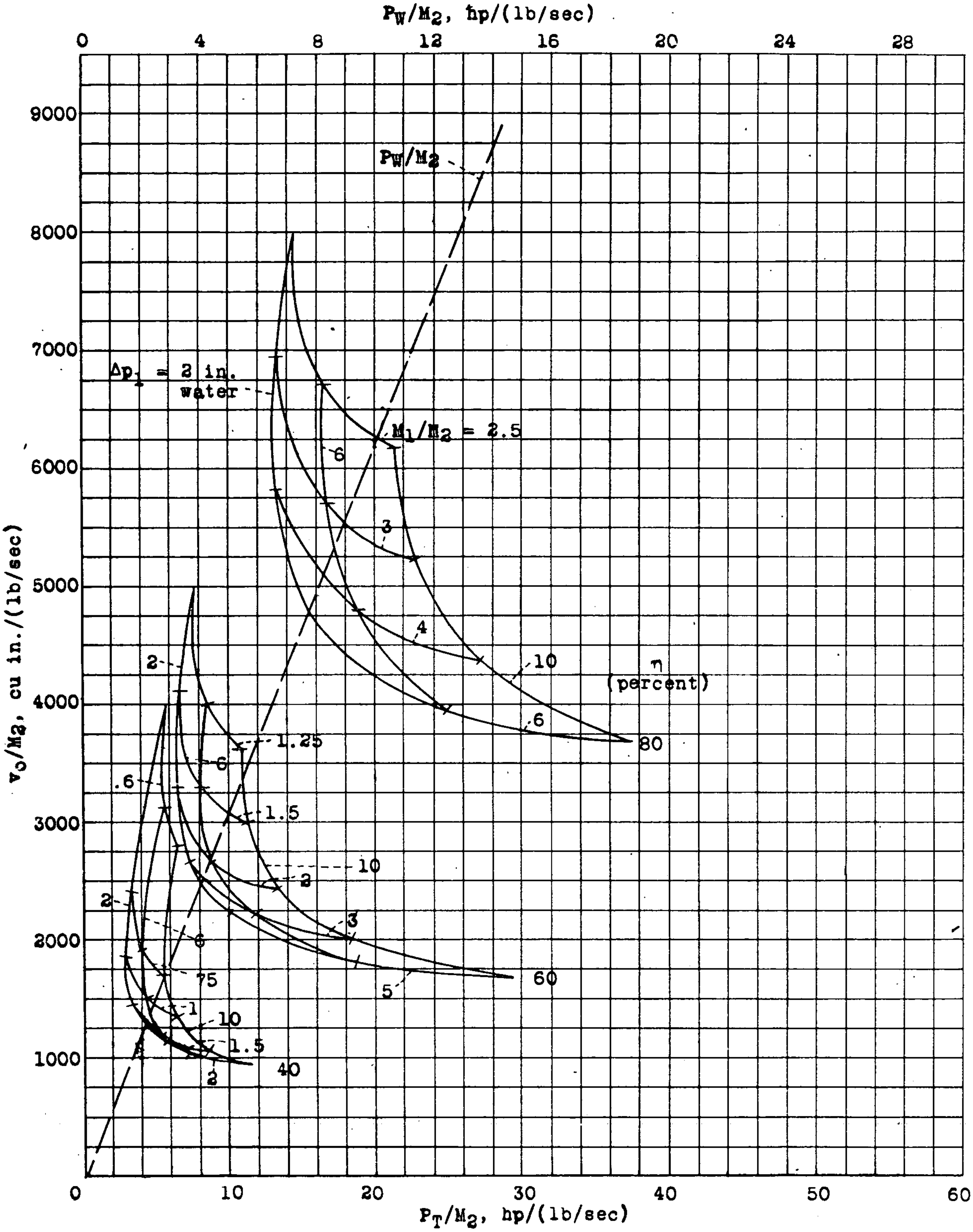
(a) 20,000 feet altitude.

Figure 6(a to d).- Relation between the volume and the total power loss of the charge-through-tube intercooler when q is 25 inches of water. $(L/D)_{eq}$, 10; and $\sigma_{2_{av}}\Delta p_{f_2}$, 6 inches of water.



(b) 30,000 feet altitude.

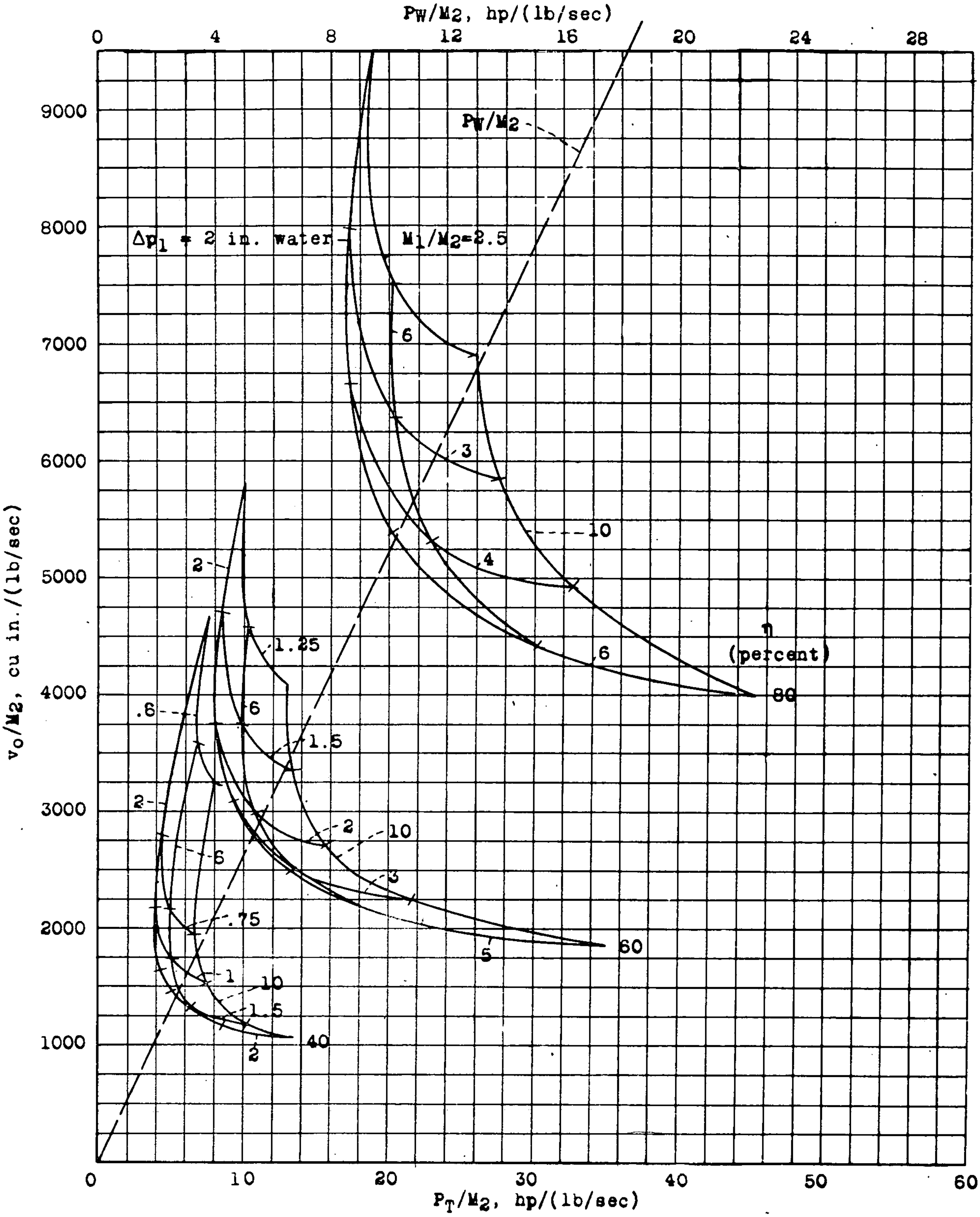
Figure 6.- Continued.



(1 block = 10/50")

(c) 40,000 feet altitude.

Figure 6.- Continued.



(1 block = .10/50")

(d) 50,000 feet altitude.

Figure 6.- Concluded.

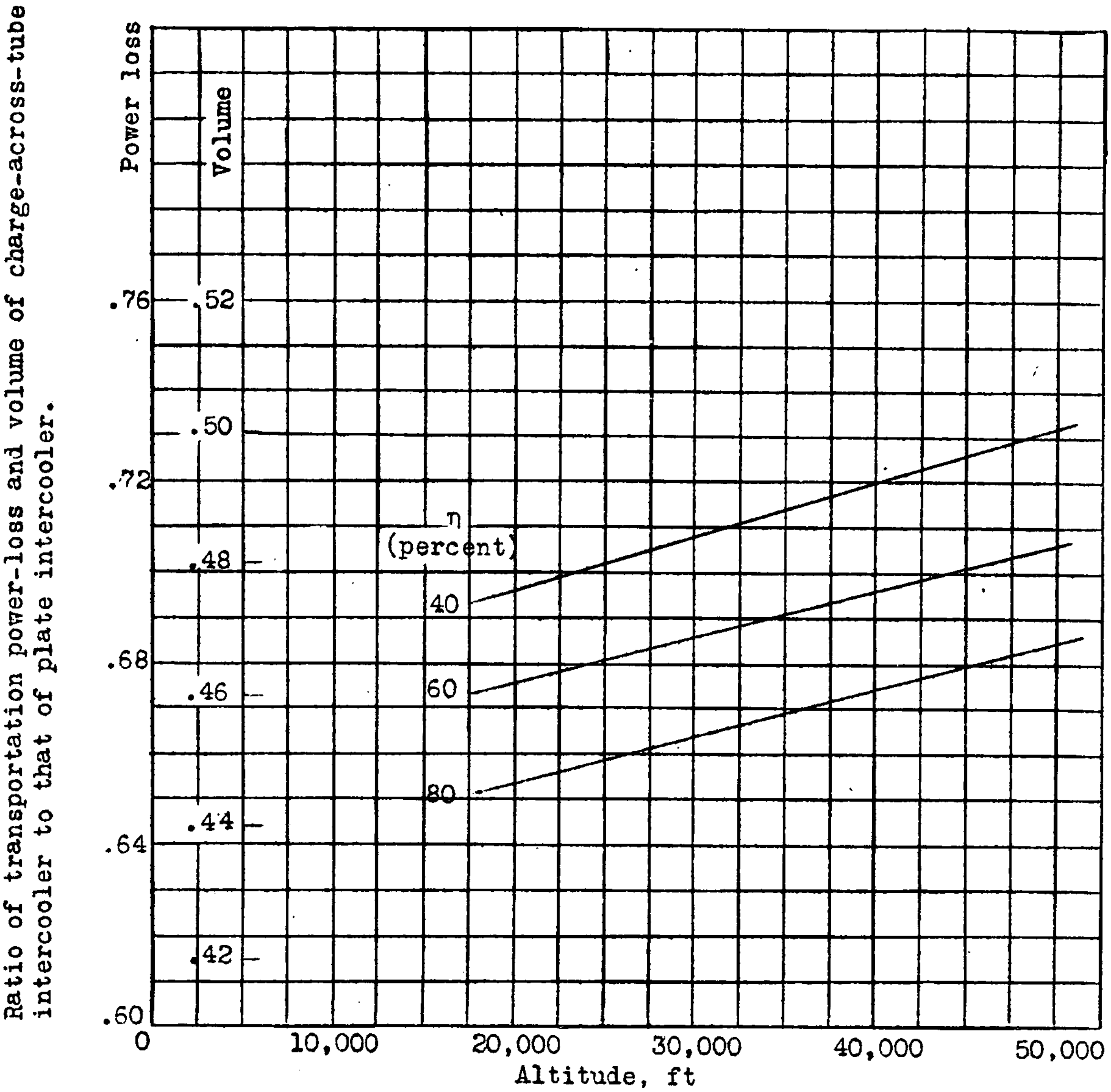


Figure 7.- Volume and transportation power loss corrections for charge-across-tube intercooler. $(L/D)_{eq}$, 10; $\sigma_{2_{av}} \Delta p_{f_2}$, 6 inches of water.

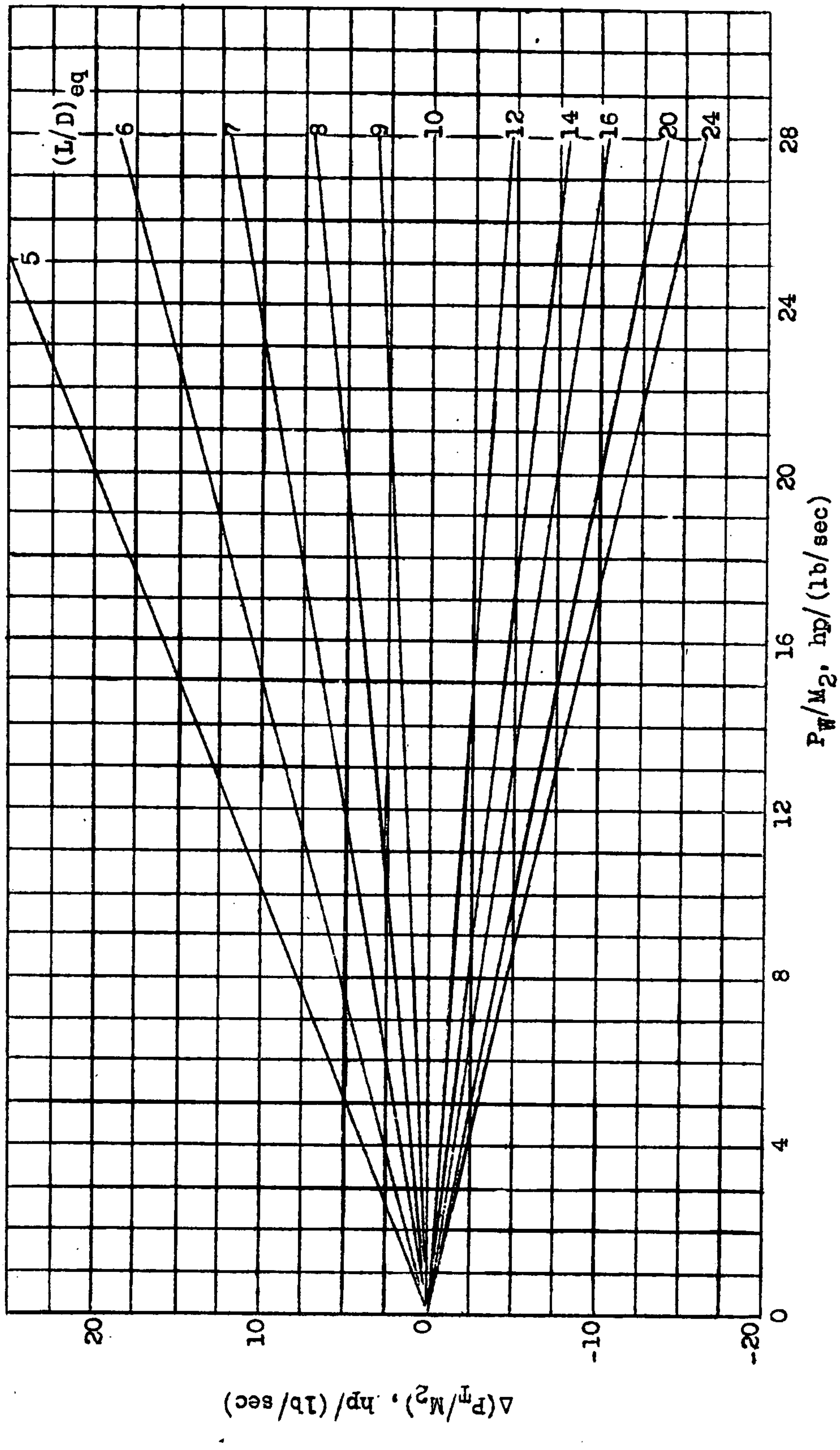


Figure 8.- Variation of intercooler total power loss with $(L/D)_{eq}$.

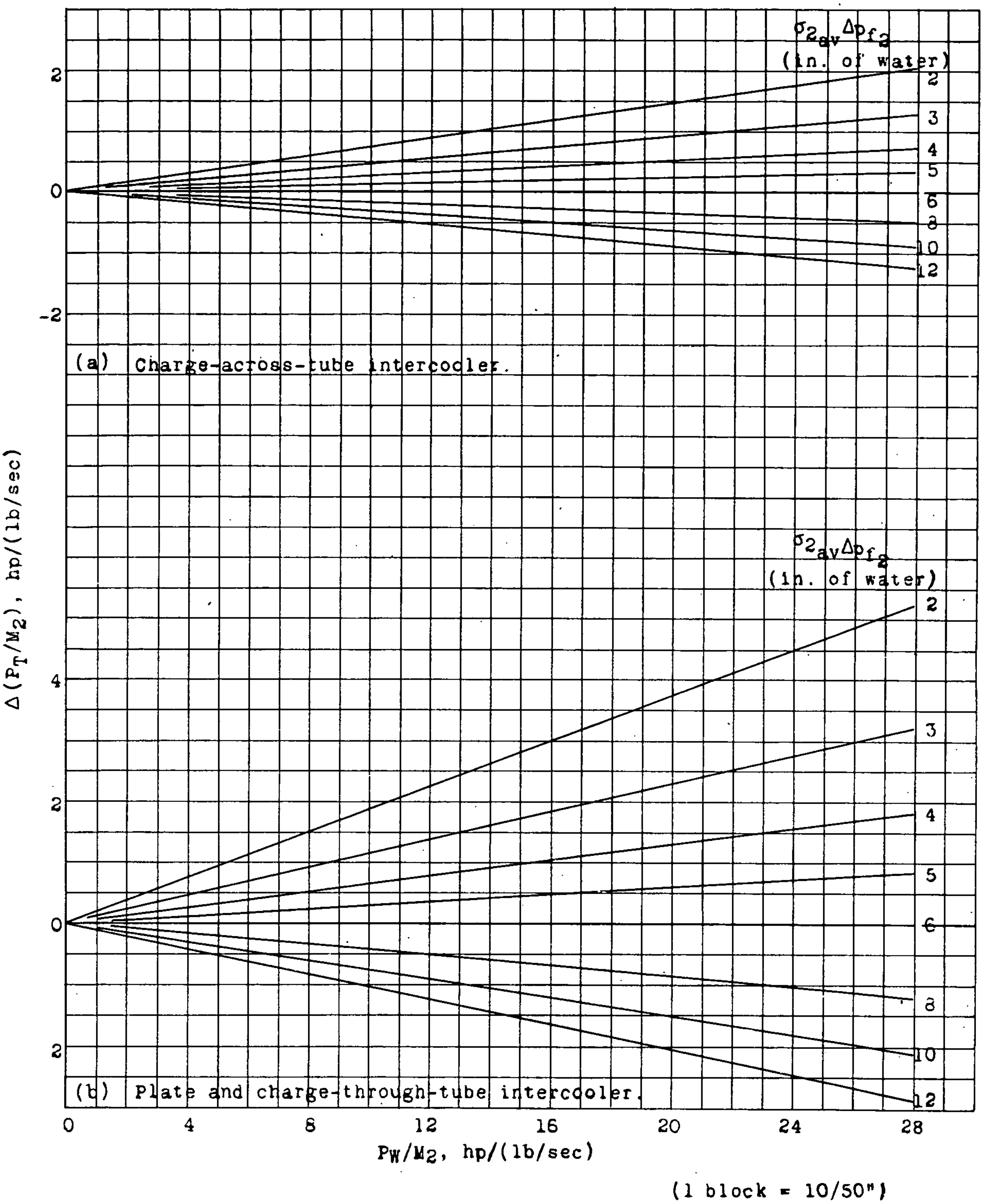


Figure 9.- Corrections to intercooler total power loss for variation in charge-air pressure drop.

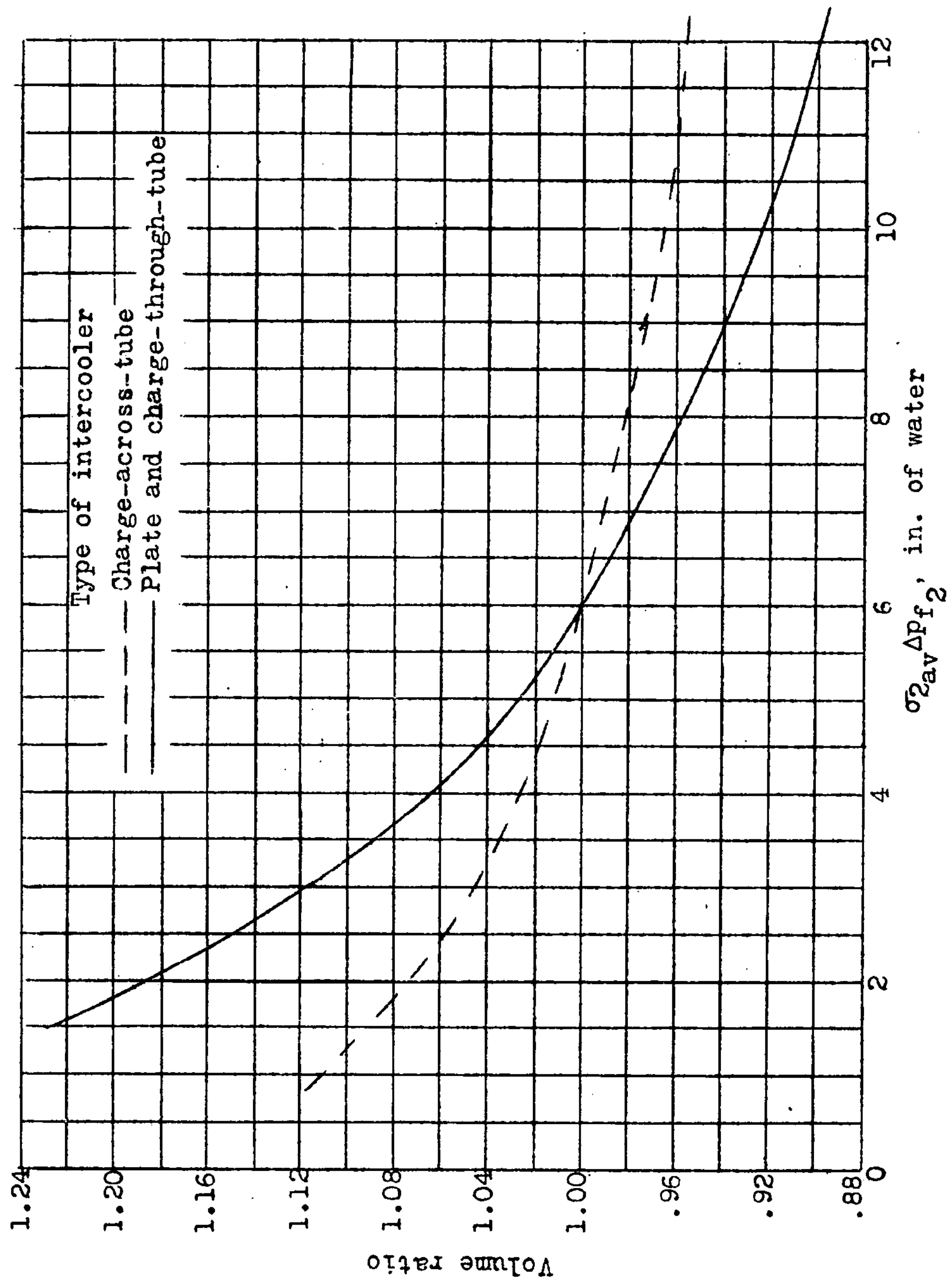


Figure 10.- Variation of intercooler volume with charge-air pressure drop.

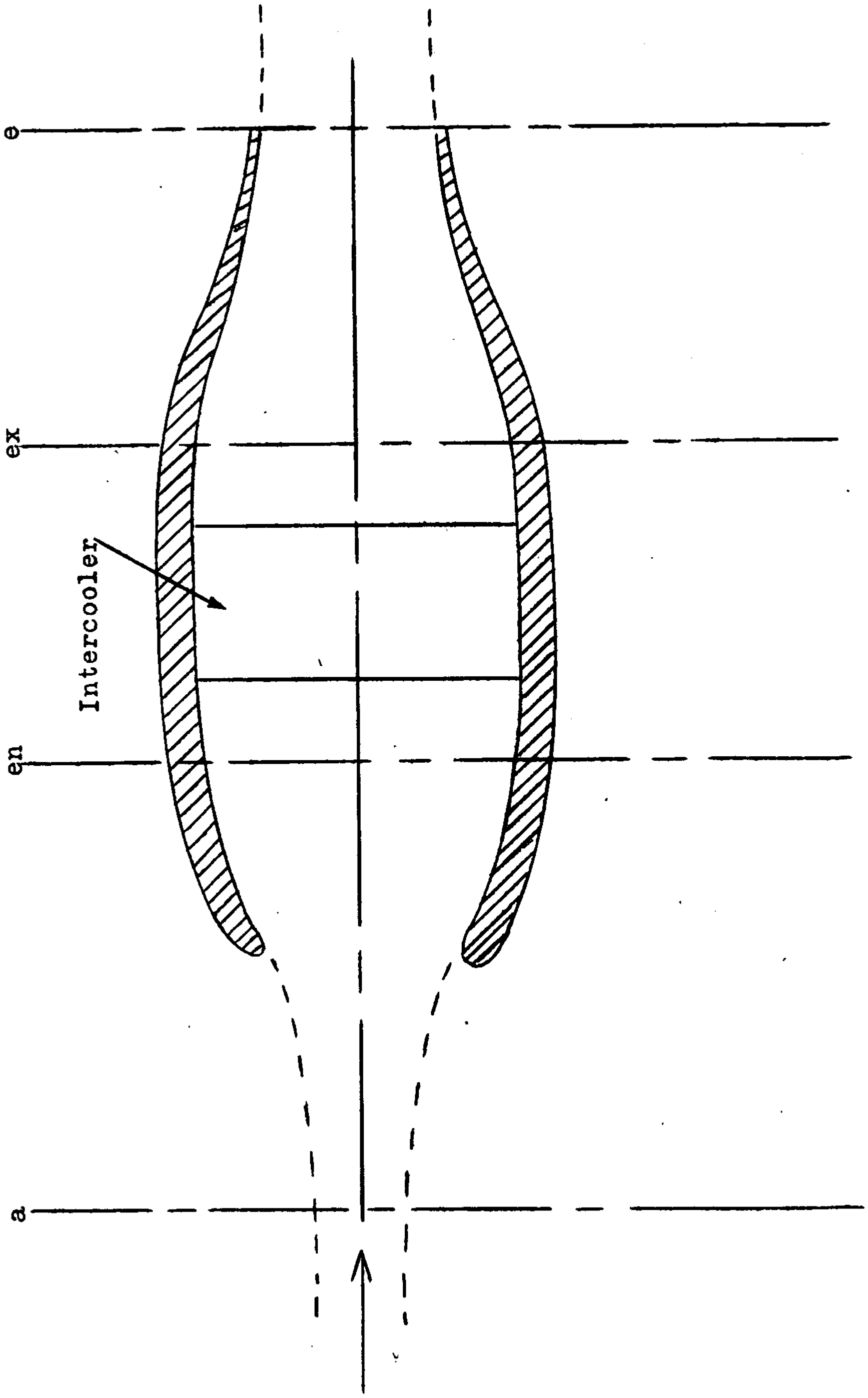


Figure 11.- Heat exchanger duct system.

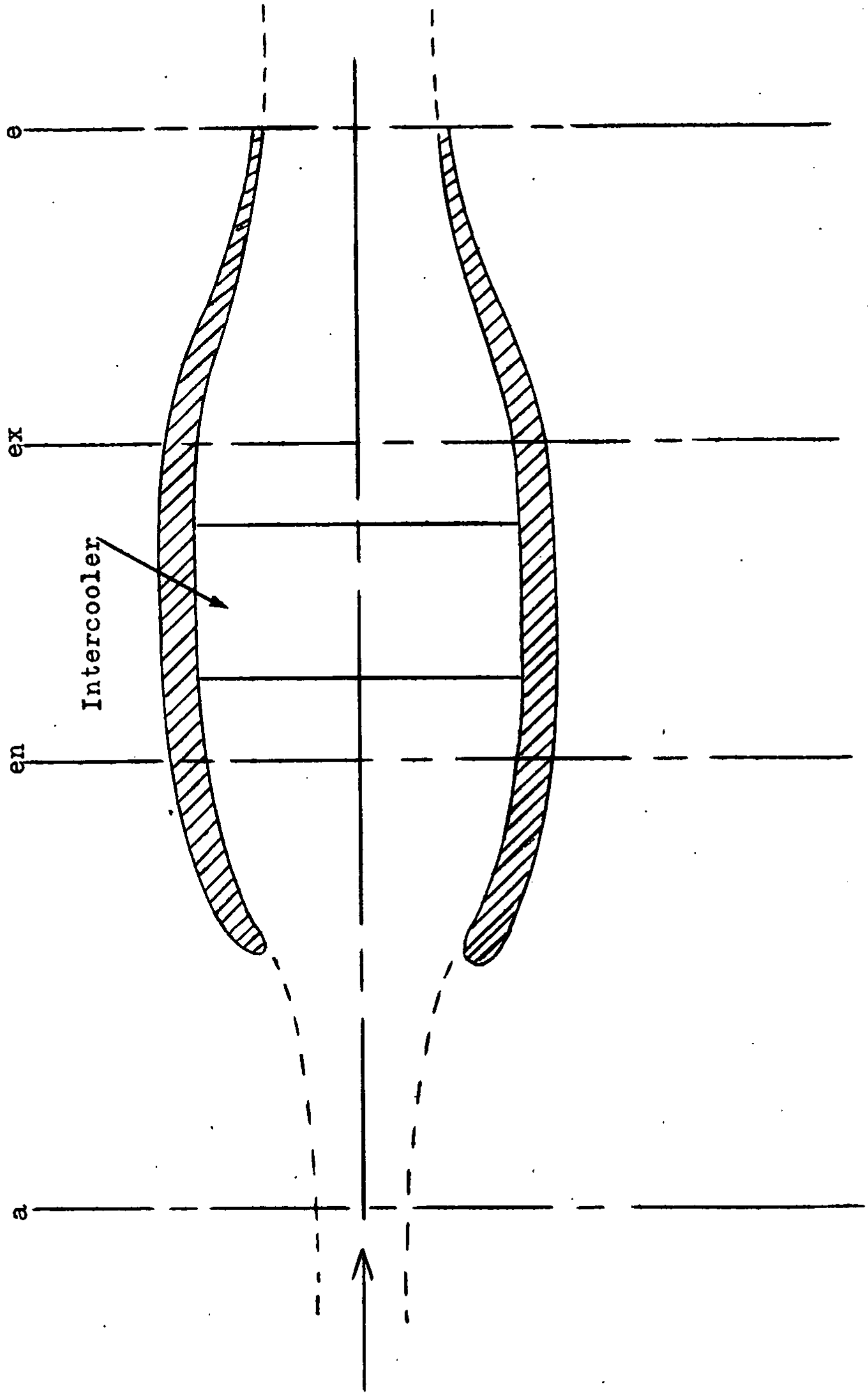


Figure 11.- Heat exchanger duct system.