TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 194

A METHOD OF DETERMINING THE DIMENSIONS AND HORSEPOWER

OF AN AIRSHIP FOR ANY GIVEN PERFORMANCE.

By C. P. Burgess,
Bureau of Aeronautics, U.S.N.

May, 1924.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL NOTE NO. 194.

A METHOD OF DETERMINING THE DIMENSIONS AND HORSEPOWER

OF AN AIRSHIP FOR ANY GIVEN PERFORMANCE.

By C. P. Burgess.

Summary

A simple and easily applied method of calculating the dimen-
sions and horsepower necessary for an airship to have any given
performance is described and illustrated by examples. The method
includes means for estimating the changes in performance or in
size when modifications or new features are introduced into a
design, involving increase or saving in weights, or changes in
resistance or propulsive efficiency.

The preliminary estimate of the size of an airship to per-
form any desired duty, such as carrying a given military or
commercial load at some given speed and endurance, is based upon
two principal sets of data. One set is the proportions of total
weight taken by various items, and the other set is the relation
between horsepower, speed, and air displacement. The conven-
tional methods of stating such data are not very satisfactory,
and new methods are developed for the purpose of this report.

Introduction

It is customary to express the weight items as percentages of the gross lift; but this practice has the two serious objections that the gross lift varies with the kind and purity of the gas used for inflation even when standard atmospheric conditions prevail, and the magnitude of the aerodynamic forces and the resistance depend not upon the gross lift, but upon the total air displacement of the hull. It is therefore proposed to express the weights as percentages of the air displacement, and to use a standard conversion factor or relation between air displacement by weight and by volume. This standard factor is that one cubic foot of air weighs .07635 lb. at sea level, with a temperature of 50°F, and a barometric pressure of 29.92" of mercury. The weights to be considered in the design estimate will then include the item "air and gas."

The relation between horsepower, speed and size may be expressed in the form:

$$HP = \frac{V^3 \ D^{2/3}}{C}$$

Where   HP = horsepower,

V = speed,

D = air displacement,

C = a constant determined by
data on previous ships.

When C is the Admiralty constant, V is expressed in

knots and D in long tons. The magnitude of the constant is a function of the density of the air, and its dimensions are rather awkward and not in line with other aerodynamic calculations. It is proposed to substitute for the Admiralty constant the expression:

$$HP = \frac{V^3 \, \rho \, (vol)^{2/3}}{K}$$

where V = speed in ft./sec.,

              ρ = density of the air in slugs,

     vol = air volume or displacement in ft.^{3}

        K is a constant which may be expected to lie between 30,000 and 35,000 in a modern rigid airship, and to be about 20,000 to 25,000 in small nonrigids of less than 200,000 ft^3 volume.

Since D, the standard air displacement in pounds, equals .07635 times the volume in ft.^{3}, $(vol)^{2/3} = 5.55 \, D^{2/3}$, and

$$HP = \frac{5.55 \, V^3 \, \rho \, D^{2/3}}{K}$$

Procedure in Finding the Size and Horsepower for an Airship
to Carry a Given Load with a Given Speed and Endurance.

The total displacement is divided into items as follows: (1) air and gas, (2) fixed weights exclusive of power plane, power cars, and fuel system, (3) crew, stores, and ballast, (4) power plant and cars, fuel system and fuel, (5) specified military or commercial load. Items (1), (2) and (3) are ex-

pressed directly as fractions of D, based on data from existing ships with such corrections as seem reasonable to allow for novel features. Item (4) is expressed in terms of the horsepower, and hence of $D^{2/3}$, and items (4) and (5) together take that fraction of D remaining over from items (1) to (3), inclusive.

Problem 1. Find the volume and horsepower of a rigid airship to carry a military load of 15,000 lb. at 60 knots (101.3 ft./sec.) for 60 hours, 85% of the total volume being filled with helium lifting .064 lb./ft.^{3} (94% pure), in the standard atmosphere.

Since the hull is specified in the conditions of the problem to be 85% full of gas, the weight of the air in the hull is 15% D; and the weight of the gas is 85% D multiplied by the difference between the weights of air and gas per unit volume, and divided by the weight of air per unit volume. The total weight of air and gas is therefore given by

$$\text{Air and gas} = [.15 - .85 (.07635 - .064)/.07635] \times D$$
$$= .288 D.$$

From existing data, the fixed weights exclusive of power plants, power cars and fuel system equal .3D, and the crew, stores and ballast amount to .055 D.

There remains for power plant, fuel and military load
$$(1 - .288 - .30 - .055) D = .357 D.$$

Assuming the weight of the power plant and its cars to be 8 lb./HP and the weight of the fuel and fuel system to be 0.6 lb.

per horsepower hour, the total weight of power plant, fuel sys-
tem and fuel is $[3 + (.6 \times 60)]$ HP = 44 (HP). Combining this
with the military load,

$$15,000 + 44(\text{HP}) = .357 \, D \tag{1}$$

Suppose that from existing data on similar ships,

$K = 35,000,$

$$\text{HP} = \frac{5.55 \times (101.3)^3 \times .00237 \times D^{2/3}}{35,000}$$

$$\text{HP} = .39 \, D^{2/3} \tag{2}$$

Combining equations (1) and (2),

$$D - 48 \, D^{2/3} = 42,000 \tag{3}$$

The problem of the size required for a given performance
will always reduce to an equation of the form of (3), which may
be expressed generally:

$$D - AD^{2/3} = B.$$

The solution for any particular values of A and B may be ob-
tained from the charts (Fig. 1 or 2) by laying a straight edge
across these values of A and B on the scales at the left and
right hand sides of the chart.

In this problem, A = 48 and B = 42,000, and from the
chart, figure 1, D = 215,000 lb., and the air volume = 215,000/
.07635 = 2,820,000 ft.³

For convenience in calculating the horsepower, $D^{2/3}$ is
plotted against D in figure 3, although it is more accurate,
and usually more convenient, to obtain $D^{2/3}$ from a slide rule
or a table after finding D. In this case, $D^{2/3} = 3600$, and

$HP = .39 \times 3600 = 1410.$

Problem 2. Find the volume and horsepower of an airship to fulfill the same conditions as in Problem 1, except that the speed is to be 70 knots (118.2 ft./sec.) for 60 hours.

$$HP = \frac{5.55 \times (118.2)^3 \times .00237 \times D^{2/3}}{35,000}$$

$= .62\ D^{2/3}$, and by combining with equation (1),

$D - 76.5\ D^{2/3} = 42,000.$

From figure 1, $D = 570,000$ lb.

$D^{2/3} = 6900.$ Air volume $= 7,470,000$ ft.^{3}

$$HP = .62 \times 6900 = 4290.$$

This example shows the great cost of increasing the speed while maintaining the same hours of endurance at the higher speed. On the other hand, the speed could be quite easily increased to 70 knots, if the endurance remains 60 hours at 60 knots.

The horsepower at 60 knots is only 63% of that required for 70 knots, and the weight of power plant and fuel per horsepower is therefore $8 + (.63 \times .6 \times 60) = 30.7$ lb. The fundamental equations are therefore:

$15,000 + 30.7\ (HP) = .357\ D$

and $\quad HP = .62\ D^{2/3}$, whence

$D - 53.3\ D^{2/3} = 42,000$

$D = 260,000$ lb. $\quad D^{2/3} = 4080$

$HP = .62 \times 4080 = 2530$

Air volume $= 260,000/.07635 = 3,400,000$ ft.^{3}

The method may be used also to find the extent to which the size may be reduced by structural improvements, as follows:

Problem 3. Suppose that by an improved design, the structural weight can be reduced 10% in comparison with the conditions assumed in Problem 1. The fixed weights exclusive of power plant, power cars, and fuel system become .27 D, and assuming as in Problem 1 that 60 knots is required for 60 hours,

$$15,000 + 44 \, (HP) = .387 \, D$$

and $\qquad HP = .39 \, D^{2/3}$, whence

$$D - 44.4 \, D^{2/3} = 38,800$$

$$D = 180,000 \text{ lb.} \qquad D^{2/3} = 3200$$

Air volume $= 180,000/.07635 = 2,360,000 \text{ ft.}^3$

$$HP = .39 \times 3200 = 1250.$$

By comparison with the results of Problem 1, it is found that a 10% saving in fixed weights exclusive of power plant, permits a 16% reduction in volume and 11.3% in horsepower.

A 10% improvement in the resistance coefficient may also be tested in a similar manner. Repeating the conditions of Problem 1, let K be increased by 10% from 35,000 to 38,500. Then

$$HP = .355 \, D^{2/3}$$

$$D - 43.75 \, D^{2/3} = 42,000$$

$$D = 185,000 \text{ lb.} \qquad D^{2/3} = 3250$$

Air volume $= 185,000/.07635 = 2,420,000 \text{ ft.}^3$

$$HP = .355 \times 3250 = 1150.$$

If it is required to operate at a high altitude, the conver-

sion factor, air volume = $D/.07635$, still holds, but in esti-
mating the weights, the allowance made for air and gas must be
increased, as in the next problem.

Problem 4. Determine the volume of a nonrigid airship to
carry a military load 1000 lb. at 4000 ft. altitude at 50 knots
(84.5 ft./sec.) for 10 hours. Ship to be inflated with hydrogen
which has a lift of .068 lb./ft.^{3} in the standard atmosphere at
sea level. Starting a flight at 4000 ft. fully inflated, corre-
sponds to 88.8% inflation at sea level; the weight of air and gas
at sea level is therefore

$$[.112 + .888 (.07635 - .068)/.07635] \ D = .209 \ D$$

It may seem cumbersome to calculate the weight of air and
gas in this manner instead of correcting D for the altitude,
but it should be remembered that since the structural weights
are to be taken as fractions of D, it is important that D
should be taken as a constant fraction of the air volume.

From data on previous ships, the fixed weights exclusive of
power plant and fuel system equal .4D, and crew, stores, and
ballast amount to .1D. There remains for the power plant, fuel
and military load $(1 - .209 - ,4 - .1) \ D = .291 \ D$. Taking the
weight of the power plant as 6 lb./HP, and the weight of the fuel,
oil, and containers as 0.6 lb./HP.H, the total weight of power
plant, fuel, and fuel system is $[6 + (10 \times .6)] \ HP = 12 \ (HP)$,
and the equation is obtained:

$$1000 + 12 \ (HP) = .291 \ D.$$

From existing data, $K = 22,000$, and at 4000 ft. altitude,

$\rho = .888 \times .00237 = .0021$ slugs, therefore,

$$HP = \frac{5.55 \times (84.5)^3 \times .0021 \times D^{2/3}}{22,000}$$

$$= .32 \; D^{2/3}$$

Combining these equations as before,

$$D - 13.2 \; D^{2/3} = 3340$$

From figure 2, $D = 9100$ lb. $D^{2/3} = 435$

Air volume $= 9100/.07635 = 119,000$ ft.^{3}

$HP = .32 \times 435 = 139$.

The method may also be used to find the military or commercial load which can be carried by an airship of given size at a given speed and endurance, as follows:

Problem 5.   Find the commercial load which can be carried by a rigid airship of 5,000,000 ft.^{3} air volume, at 4000 ft. altitude, inflated with helium lifting .064 lb./ft.^{3} in standard atmosphere at sea level, and having a speed of 70 knots and an endurance of 24 hours. Given $K = 35,000$, and fixed weights exclusive of power plant $= .3$ D crew, stores and ballast $= .05$ D. Power plant $= 8$ lb./HP, fuel $= 0.6$ lb./HP.H, whence total weight of power plant and fuel $= [8 + (.6 \times 24)]$ HP $= 22.4$ HP
$D = .07635 \times 5,000,000 = 382,000$ lb.

Assuming that when fully inflated the gas cells occupy 95% of the air volume, the volume of gas when 88.8% inflated at sea level (to allow for 4000 ft. altitude) is $.95 \times .888 = .844$

times the air volume, and the weight of the air and gas is

[.156 + .344 (.07635 - .064)/.07635] × D = .293 D

$$HP = \frac{(118.2)^3 \times .0021 \times (5,000,000)^{2/3}}{35,000}$$

= 2900

The total weight of the power plant, power cars, fuel and fuel system is 22.4 × 2900 = 65,000 lb. The weight available for commercial load is

382,000 (1 - .293 - .3—.05) - 65,000 = 71,500 lb.

Choice of Dimensions for any Desired Air Volume.

Wind tunnel experiments indicate that the least resistance for a given volume is obtained with a length/diameter diameter ratio of a little less than 5, but with ratios from 4 to 6 there is very little change in efficiency. For nonrigid airships these ratios are very suitable, and the prismatic or cylindric coefficient, i.e., the ratio of the actual air volume to the volume of a prism having the largest cross-section airship, varies from 0.60 to 0.66, approximately.

The volume of an airship of circular cross-section = $2 k r \pi R^3$,

> where R = the radius of the largest cross-section.
>
> k = the prismatic coefficient,
>
> r = the length/diameter ratio.

The dimensions may be calculated by application of this

formula, assuming arbitrary values of k and r.

Example: Find the length and diameter of a nonrigid airship
of 200,000 ft.^{3} , volume assuming k = .62,   and r = 4.8.

$$R^3 = \frac{200,000}{2 \times .62 \times 4.8 \times \pi} = 10,700 \text{ ft.}^3$$

R = 22 ft.

Diameter = 2 R = 44.0 ft.

Length = 9.6 R = 211.5 ft.

In a rigid airship, it is usually desirable to increase the
length beyond five diameters in order to space the cars properly,
and to facilitate handling upon the ground, and to prevent ex-
cessive weight of the gas cells and transverse frames. Sometimes
shed accommodations also influence or dictate the choice of length
and diameter. When for practical reasons it is desired to have
more than five diameters to length, the designer has the choice
of inserting some parallel middle body, or retaining a continu-
ously curved form by increasing the station spacing. To determine
the relative merits of these two possibilities, two interesting
series of tests were carried out in the wind tunnel of the Bureau
of Construction and Repair at the Navy Yard, Washington, D. C.
In the first series of tests various lengths of parallel middle
body were inserted between the bow and stern of a model of the
C class nonrigid airship. The results are fully described in the
National Advisory Committee for Aeronautics Report No. 138, en-
titled "The Drag of C Class Airship Hull with Varying Length of

Cylindric Midships." The tests showed that a length of parallel
middle body up to one diameter made practically no change in the
resistance coefficient; and three diameters of parallel middle
body increased the resistance coefficient by only 7.6%.

The other series of tests was on models of the C class air-
ship with various spacing of the ordinates, giving lengths of
from 2 to 10 diameter, without parallel middle body. The results
of this series of tests have not been published, but it was found
that increasing the length/diameter ratio from the 4.6 of the C
class to 8.0 resulted in an increase of 13.2% in the resistance
coefficient. The curve of the resistance coefficient was found
to pass through a minimum value with a fineness or length/diameter
ratio of about 4.3, or very close to what was actually used in
the C class.

Comparison of the results of these two sets of tests indi-
cate that when it is desired to increase the fineness ratio be-
yond about 4.5, the additional length should be obtained by in-
serting parallel middle body rather than by increasing the spacing
of the ordinates.

It is obvious that the practical merits of the problem, aside
from purely aerodynamic considerations, are also very much in
favor of parallel middle body; the construction will be simpler
and less expensive and the overall dimensions of the ship with a
given volume and fineness ratio will be less.

The air volume of an airship hull with parallel middle body

equals $2 \pi R^2 (kr_1 + r_2)$ where R is the radius of the maximum cross-section, k is the prismatic coefficient of the tapered fore and after bodies taken together, r_1 is their combined length/diameter ratio, and r_2 is the corresponding ratio for the parallel middle body. It follows that

$$R^3 = \frac{\text{volume}}{2 \pi (kr_1 + r_2)}$$

From this equation the dimensions required for any given volume and characteristics of bow and stern and proportion of parallel middle body may be determined.

Example: Find the length and diameter of a rigid airship of 5,000,000 ft.^{3} air volume, in which the tapered bow and stern have a length of 4.6 diameter and a prismatic coefficient of 0.60, and the parallel middle body is three diameters long.

$$R^3 = \frac{5,000,000}{2 \pi [(.6 \times 4.6) + 3.0]}$$

$$= 138,000$$

$$R = 51.6$$

Length = $15.2 \times 51.6 = 785$ ft.

Diameter = $2 \times 51.6 = 103.2$ ft.

Conclusions

The foregoing method of calculating the size and horsepower required for an airship of any specified performance depends on existing data, and as this data becomes more complete, the method will become increasingly accurate and flexible; that is, more applicable to new and unusual types of airships.

One of the principal uses to which the method can be applied is to show the variation in size necessary when varying some one factor of the performance requirements, keeping the other factors constant.
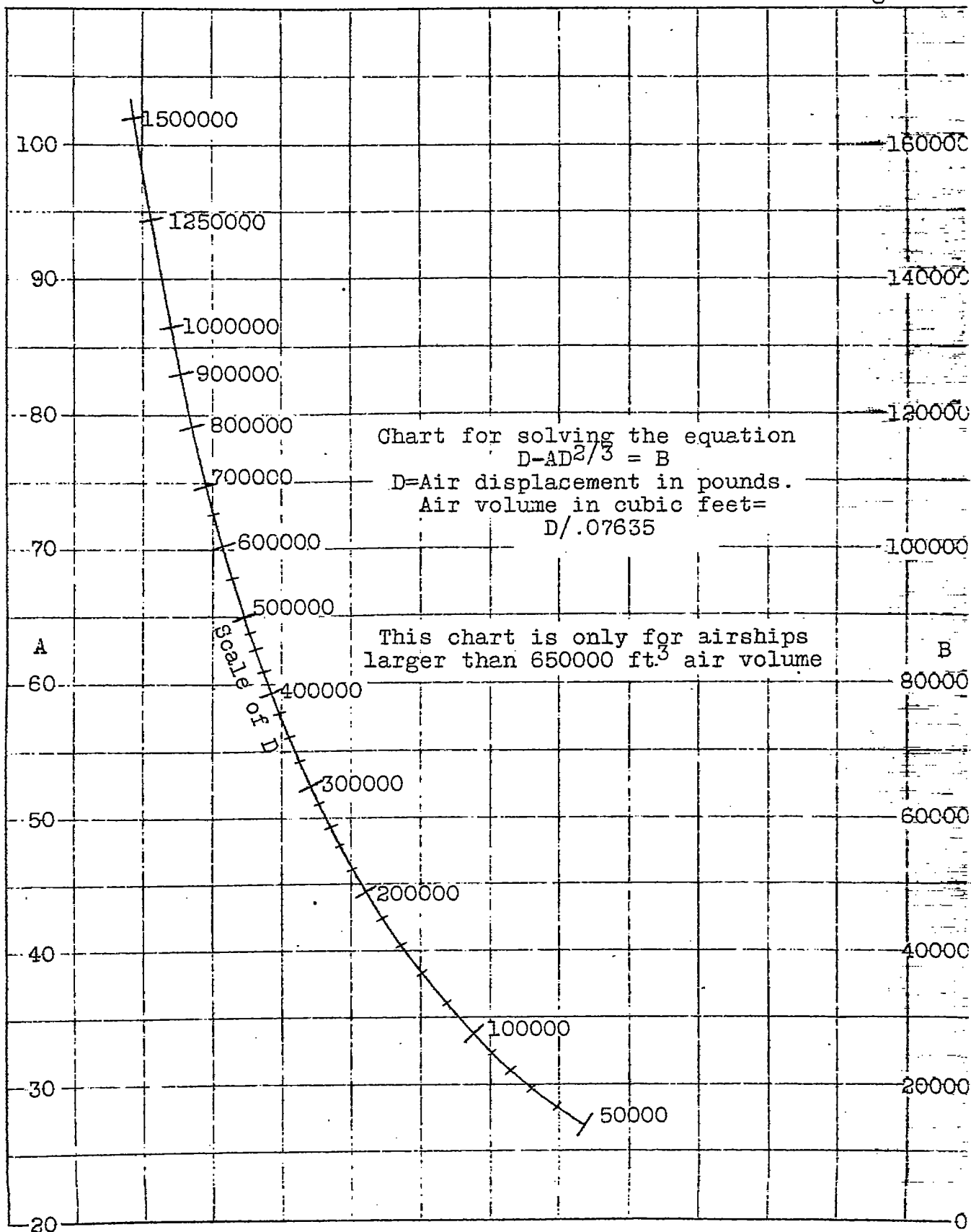
Chart for solving the equation
$$D-AD^{2/3} = B$$
D=Air displacement in pounds.
Air volume in cubic feet=
D/.07635

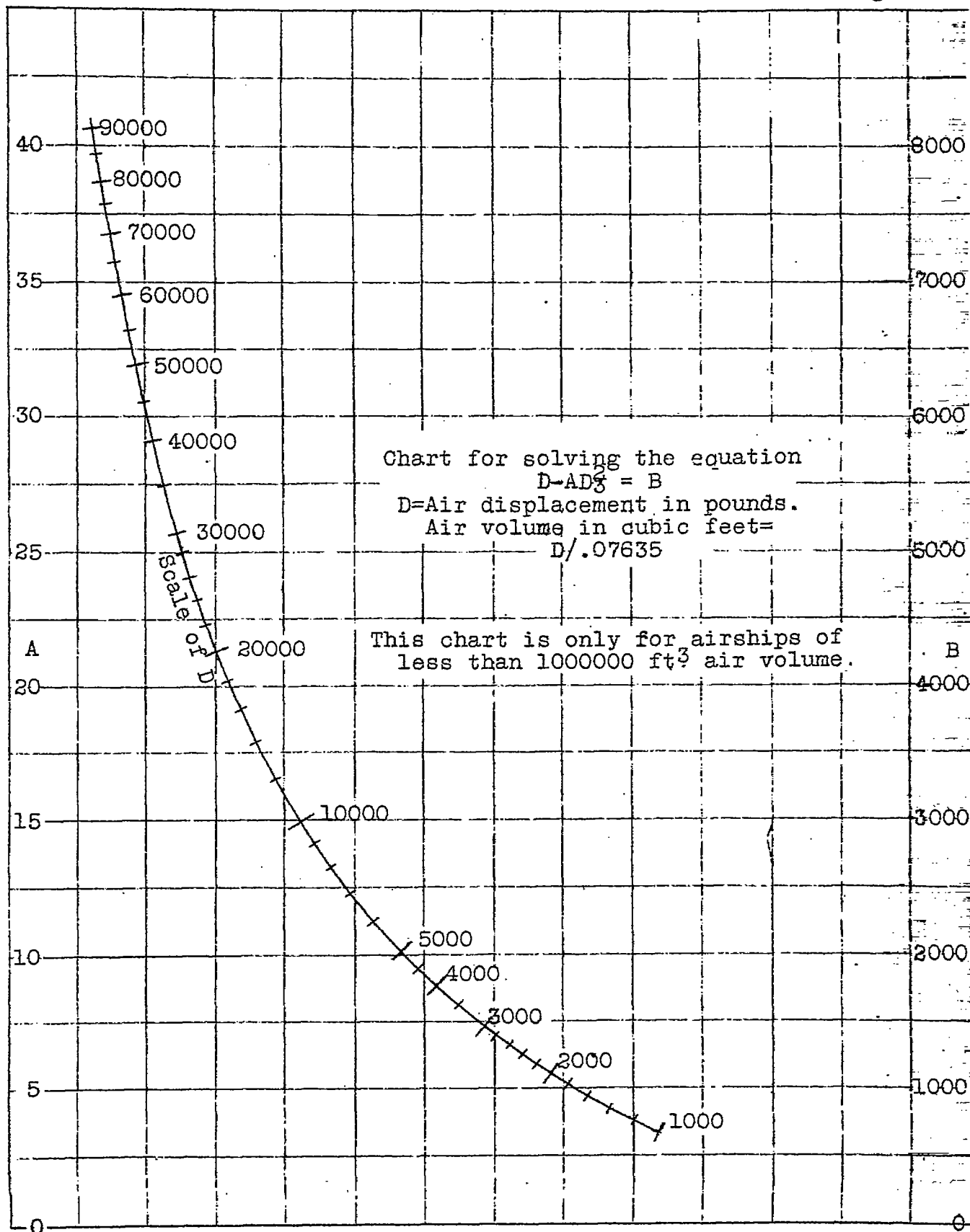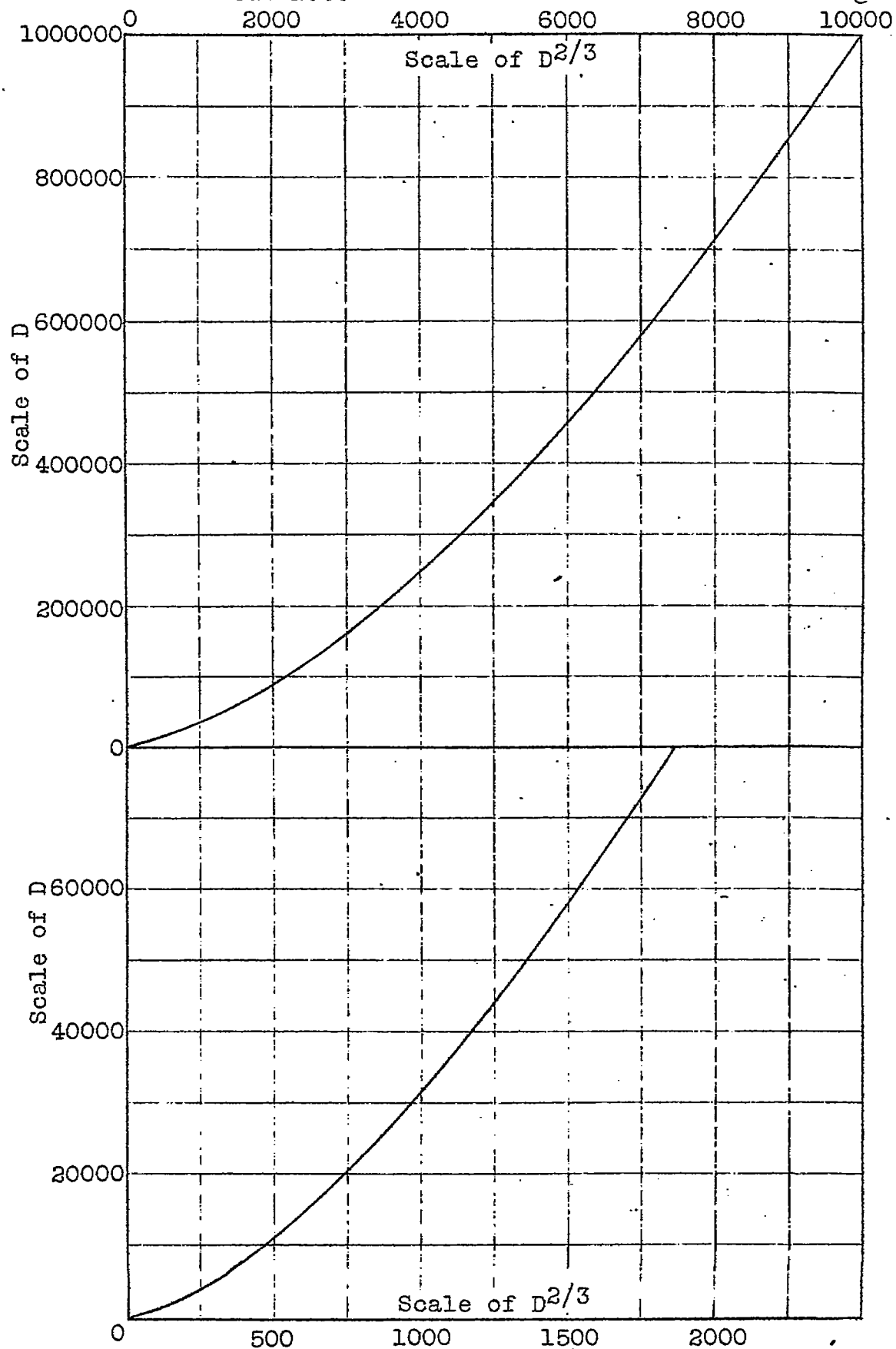This chart is only for airships
larger than 650000 ft.³ air volume

Fig.1

Fig.2

Fig.3　Chart for finding $D^{2/3}$ when D is known.