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THE DESIGN OF THE OPTIMUM HULL FOR

A LARGE LONG-RANGE FLYING BOAT

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# NACA

## WASHINGTON

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### ADVANCE RESTRICTED REPORT

# THE DESIGN OF THE OPTIMUM HULL FOR A

# LARGE LONG-RANGE FLYING BOAT

By John B. Parkinson

## SUMMARY

Principles for designing the optimum hull for a large long-range flying boat are proposed to suit the requirements of minimum drag, seaworthiness, and ability to take off and land at all operational gross weights. The principles include the use of moderate gross-load coefficients, ample forebody lengths, and deep steps and the close adherence of the form to that of a streamline body of revolution with a moderate fineness ratio.

The validity of the design principles is illustrated by the results of tests in NACA tank No. 1 and in the NACA two-dimensional low-turbulence pressure tunnel of the form of the hull for a 400,000-pound transport flying boat. These results indicate that for large airplanes satisfactory hydrodynamic characteristics can be attained without an undue penalty in flight performance caused by the drag of the step and the chines.

The effect of size on the proportions and the take-off performance of long-range flying boats is shown for three hypothetical flying boats having gross weights of 120,000, 300,000, and 480,000 pounds and the same wing loading, power loading, and hull loading. When these loadings are held constant, the size of the hull relative to the wing and the take-off time and distance are decreased as the gross weight is increased.

The hull of the flying boat, aside from its inherent ability to take off and land at sea, provides an immediate solution for the landing-gear problem of large long-range airplanes.

## INTRODUCTION

The optimum hull for a long-range flying boat is one that performs the functions of a fuselage, flotation gear, and landing gear with the minimum of weight and drag. The ideal hull would be a streamline body of revolution with its maximum radius determined by the space for useful load and its fineness ratio determined by the length from the center of gravity to the tail surfaces.

Practicable hulls depart from the ideal in order to meet the following additional requirements that must be approximately satisfied if the flying boat is to be a self-sufficient and reliable unit of transportation:

(1) Seaworthiness in sheltered waters and moderate open-sea conditions. By seaworthiness is meant the ability to operate successfully as a surface boat without undue damage or danger from wind, waves, and spray.

(2) Ability to take off and land on the water at all operational gross weights. This requirement includes (a) water resistance low enough for reasonable take-off time and distance and (b) adequate hydrodynamic stability and control in pitch, yaw, and roll.

The best all-round compromise among aerodynamic, hydrodynamic, and structural requirements devised so far is the widely used V-bottom planing-type hull consisting of a forebody planing surface with the angle of dead rise increased at the bow to give sharp water lines, a step slightly aft of the center of gravity, and a pointed afterbody planing surface set at an upward angle with reference to the forebody. Such a hull blends with the airplane design in much the same way as a landplane fuselage except that a high location of the wing and a single vertical tail are desirable for clearance from spray. The V-bottom permits a reasonable weight of structure. The hull trims naturally at low water speeds for acceptable maximum (hump) resistance with the power loadings normally required in flight and for the minimum spray from the forebody. At planing speeds it is controllable in trim and can be pulled up for take-off. Its stability is such that it can be maneuvered and operated by the usual flight controls.

The adaptation of the type of hull described to various seaplane designs and research on its proportions and shape have been the principal activities of the seaplane towing tanks. The results of this work, together with extensive full-scale experience, enable the design of a large long-range seaplane to be approached with reasonable assurance that the design of a satisfactory hull can be accomplished with a reasonable amount of tank testing in addition to the usual wind-tunnel testing.

In this report, certain principles for the design of hulls for large long-range flying boats based on the accumulated experience of the NACA tanks are proposed. Their validity as applied to large airplanes is established by the results of an investigation of the hull of a 400,000-pound cargo flying boat, incorporating the principles and tested at the NACA laboratory at Langley Field, Va. Preliminary designs of three similar flying boats with the same form of hull are presented to illustrate the possibilities of water-based airplanes in the range of gross weights from 100,000 to 500,000 pounds and to indicate the effect of gross weight in this range on the relative size of hull to wing and on take-off performance.

DESIGN PRINCIPLES

The final form of a flying-boat hull is obtained from a succession of three-view outline drawings of the airplane, in which proportions and shape are adjusted until all the requirements are met in as satisfactory a manner as possible. This process entails a number of compromises and demands on the part of the designer, familiarity with all the aerodynamic, structural, and hydrodynamic principles involved, plus a sixth sense of what looks right. The detail design of the hull cannot be undertaken until the three views demonstrate that its shape and proportions blend harmoniously with the other components and the over-all design of the airplane.

## Proportions

Aside from the fundamental requirements of cubic capacity and minimum drag, the proportions of the hull are largely dependent on the maximum gross weight,.which determines the buoyancy and size of the planing surfaces required.  A sound and not over-optimistic estimate of the gross weight is the most important contribution to a successful hull design.  An overloaded hull will surely have inferior seaworthiness and hydrodynamic characteristics that will limit the pay load carried in everyday service or will result in excessive maintenance and repair.  It is well to recognize this principle at the start by basing the hull proportions on a weight in excess of the first assumption in order to allow for the inevitable increases during the progress of the detail design.

Beam.- The beam may be selected by use of the expression

$$c_{\Delta_0} = \frac{\Delta_0}{wb^3} \tag{1}$$

where

$c_{\Delta_0}$      gross-load coefficient

$\Delta_0$      gross load, pounds

w      specific weight of sea water (64 lb/cu ft)

b      maximum beam over chines, feet

Values of $c_{\Delta_0}$ vary widely in practice.  Earlier flying boats averaged about 0.35 but there has been a continual trend toward higher beam loadings in an attempt to reduce frontal area.  Present-day Naval patrol bombers average about 0.9 to 1.0, which perhaps is too high for general-purpose cargo or passenger airplanes.  Extensive experience with tank models and available information on full-size operation indicate that best over-all results are obtained with more moderate values of $c_{\Delta_0}$ ranging from 0.5 to 0.3, depending on the degree of conservatism desired.

As far as low-speed spray and general seaworthiness
are concerned, the permissible values of $C_{\Delta_0}$ are asso-
ciated with length-beam ratio because the detrimental
effects of a small beam can be to some extent compensated
for by increasing the length. How far this principle can
be carried is a subject for further research and, in the
meantime, satisfactory results are more certain with the
more moderate beam loadings. The acceptance of this
principle will avoid some of the practical difficulties
encountered with heavily loaded hulls and the extensive
towing-basin tests required to make them tolerable for a
new design.

Length.- The over-all length is made up approximately
of the length of forebody plus the required distance from
the center of gravity to the tail surfaces. The length
of forebody is based on the seaworthiness required for
the intended service.

It is shown in reference 1 that the length-beam
ratios of the forebody for various flying boats in service
are related by the expression

$$C_{\Delta_0} = k\left(\frac{L_f}{b}\right)^2 \tag{2}$$

where $L_f$ is the length in feet of the forebody from
bow to step and $k$ is a coefficient ranging from 0.0525
for boats with very light spray to 0.0975 for boats with
excessive spray. Satisfactory seaworthiness and low-speed
spray characteristics may be obtained for flying boats
with the values of $C_{\Delta_0}$ proposed previously and a design
value of $k$ of 0.0675 or less.

The optimum length of the afterbody from step to
sternpost is also a subject for further research,
particularly in regard to dynamic stability and landing
characteristics. It is influenced primarily, however,
by the buoyancy required aft of the center of gravity
for acceptable trims at rest and the dynamic lift required
at the hump speed for acceptable hump trims and hump
resistance. Above the hump speed, the afterbody serves
no useful purpose with regard to stability or resistance
except as a fairing for the forebody in flight. For
hulls with normal proportions, afterbody lengths

from 2.3 to 2.7 beams have proved satisfactory and an
average value of 2.5 may be assumed in advance of
towing-basin tests of the specific design.

Depth.- The depth of the hull is as important a
dimension as the beam, as far as frontal area, surface
area, and drag are concerned. When the wing root is in
the hull, as is usually the case, the depth of hull is
greater than that of the equivalent fuselage for a land-
plane in order to provide spray clearance for the
propellers and aerodynamic surfaces. The increment in
depth required may be kept to a minimum by the use of
moderate hull loadings because the height of the spray
is a function of the bottom pressures. The spray
normally strikes the flaps and horizontal tail, however,
at speeds at which the bow is out of the water and the
length of forebody has relatively little influence on
the spray; hence this spray is a function of beam
loading alone rather than the length-beam ratio.

There is no particular advantage in the use of very
narrow beams to reduce frontal area if the hull must be
made correspondingly deeper to obtain spray clearances.
The optimum ratio of beam to height has not been
determined. The best rule is to adhere to the moderate
hull loadings proposed and make the depth compatible
with the general design.

Depth of step.- It is a natural tendency to use as
small a depth of step as possible in order to keep the
discontinuity in form and structure as well as the hump
resistance at a minimum. If the step is too shallow,
however, the water resistance at high speeds is inordi-
nately high and the hull becomes violently unstable near
the take-off and landing speeds. The instability results
in jump take-offs and skipping below flying speed, which
are extremely hazardous and may even be catastrophic.
The choice of the depth of step therefore demands the
utmost consideration.

The minimum depth of step to avoid the hydrodynamic
instability may be determined experimentally by tank
tests of a dynamically similar model of the airplane.
It is shown in reference 2 that, with wing loadings of
from 35 to 45 pounds per square foot, depths of 5 percent
of the beam are inadequate for stable high-attitude
landings. The acceptance, at the beginning of the designs,

of a depth at the keel from 8 to 12 percent of the beam
will avoid most of the operational difficulties associated
with hydrodynamic instability at high water speeds.

Angle between forebody and afterbody keels.- The
relatively large angle between the keels forward and aft
of the step constitutes a conspicuous difference between
planing boats and seaplane hulls.  Its principal purpose
on the seaplane hull is to provide clearance at high water
speeds in order that the airplane may take off and land
at high lift coefficients.  If the angle between the
keels is too low, the trim at low speeds before the hump
speed is too low and the resistance is higher than at the
true hump, whereas the resistance at high planing speeds
is too high because of the frictional resistance of the
wetted afterbody.  If the angle of afterbody keel is too
high, the trims at rest and at the hump speed are unduly
high.  The best compromise appears to be $6^\circ$ or $7^\circ$.

Relative location of wing and hull.- The best fore-
and-aft location of the wing with respect to the step of
the hull is that where the stable range of positions of
the center of gravity for flight corresponds as far as
possible to the stable range for take-offs and landings.
The location of the hydrodynamic stable range depends on
the relative position of center of gravity and step.  The
determination of this range is one of the main purposes
of tank tests of a dynamic model of a proposed design.
In the model tests, all the important trimming moments,
including those due to thrust and slipstream, must be
simulated in order to predict accurately the stable
positions of the center of gravity of the full-size
airplane.  If the hydrodynamic stable range is too far
aft with respect to the aerodynamic range, the hull
may be moved forward or, as is more convenient in later
stages of the design, the step alone may be moved forward,
and vice versa.  When the location of the step itself is
changed, care must be taken to maintain the proper depth
of step by vertical displacement of the forebody or after-
body.

In advance of the specific model tests, the step
may be approximately located on a line that extends
vertically through the estimated mean position of the
center of gravity when the airplane is in the stall
attitude.  In the case of a step having a plan form
other than transverse, its effective longitudinal
position may be taken as that of the centroid or center
of gravity of the plan-form area of the step (refer-
ence 3).

## Shape

When the over-all proportions and the dimensions of
the planing surfaces are decided upon, the minimum drag
may be obtained if the lines of the hull conform with
the following general principles that are self-evident
but are sometimes overlooked in practice:

(1) The departures from a streamline body should
be kept at the minimum consistent with the desired
hydrodynamic characteristics

(2) Although the actual cross sections must depart
from the ideal, the curve of section areas should follow
that of the streamline body as closely as possible

(3) The chines should be disposed along the probable
flow lines around the body as far as possible, particularly
at the bow

(4) The actual shape of the hull at every point
should be smooth and fair in three dimensions except
for the necessary discontinuities at the chines and
step

For gross-load coefficients less than 0.3, a stream-
line body of revolution with a moderate fineness ratio
may be readily adapted as the basic form to follow for
the hull lines. The probable flow lines about such a
body are roughly apparent and will not be influenced
greatly by the addition of the V-bottom planing surfaces.
The elevated position of the stern, which is desirable
for practicable hulls, may be obtained with the minimum
of penalty in drag by smoothly warping the axis of
revolution. When the height of hull is greatly different
from the breadth, an elliptical cross section provides
the closest approximation to the circular section of the
body of revolution.

The curve of section areas provides an additional
guide for the proper fairing of the lines. The fairing
for a shape as complex as a flying-boat hull is best
accomplished by the methods used by naval architects in
obtaining the smooth and pleasing contours of the form
of a ship. The desired form should be so well defined
by offsets and measurements that little freedom remains
in the full-size lofting of the lines.

Below the chines, the shape must conform to that found by experience to have suitable hydrodynamic characteristics but otherwise should be smooth and fair for the minimum of interference to the flow of water or air and for ease of construction. Angles of dead rise, exclusive of chine flare, of approximately 20° to 22.5° have been found to be generally acceptable in full-size operation for normal take-offs and landings.

A fundamental principle in the fairing of the forebody bottom apparently is to maintain a cylindrical form of the forebody planing surface as far forward of the step as proper fairing of the lines at the bow will allow. A rough rule is that the buttocks should be straight and parallel for at least 1.5 beams forward of the step in order to obtain satisfactory spray, resistance, and stability characteristics. If the buttocks remain straight too far forward, however, they will become too convex at the bow and the cleanness of running at taxying speeds will be impaired. Part of the improvement in spray characteristics that results from lengthening the forebody can usually be attributed to the finer water lines and improved fairing made feasible by the greater length.

A detailed exposition of the shape below the chines is beyond the scope of this report. Information regarding most of the important parameters of form may be found in the various reports of fundamental researches in the NACA tanks. (See bibliography.)

The form below the chines finally adopted should always be investigated in the towing tank before the structural design of the hull is begun. During the tank tests, small modifications in shape are sometimes found that offer the possibility of large improvement in the hydrodynamic characteristics but, if the design is too far advanced, these modifications are difficult to incorporate in the full-size hull.

TYPICAL APPLICATION OF DESIGN

PRINCIPLES AND RESULTS

There is no optimum form of hull for all flying boats just as there is no optimum form of fuselage, wing section,

or propeller for all airplanes.  The hull in every case
must be tailored to fit the design by use of the broad
principles outlined and by the results of wind-tunnel and
tank tests of the most promising preliminary form.
Adoption of the more conservative principles at the
inception, however, will result in a large reduction in
the experimental work.

## NACA Model 84-FF

NACA model 84-FF is one of an extensive series of
hulls designed and investigated by the NACA for the
purpose of developing forms that would combine low air
drag with good hydrodynamic qualities.  This investigation
is described in reference 4.  The lines and proportions
of model 84-FF are shown in figure 1.  They are based on
a streamline body of revolution having the maximum
radius at 30 percent of the length and a fineness ratio
of 7.22.  Clearance at the bow and stern are obtained by
warping upward the axis of revolution forward and aft of
the maximum radius.  The lines of the forebody are exterior
to the basic form and are such that the height is 6 per-
cent greater than the beam.  The depth of step and
length of afterbody, however, are small as compared with
those in current use, and the length from step to tail
is too short for present-day airplanes.

According to equation (2), a value of $k$ of 0.0675
gives a maximum practical value of $C_{\Delta_0}$ (equation (1))
of 0.67 for the length-beam ratio of the forebody used.
The results of the tank tests reported in reference 4
indicate that the resistance and spray characteristics
at this gross-load coefficient are satisfactory.  In the
light of more recent experience, however, the depth of
step and length of afterbody are questionable with respect
to the buoyancy needed aft and to the hydrodynamic sta-
bility.

Aerodynamic tests in the NACA 8-foot high-speed
tunnel (reference 4) indicate that model 84-F (84-FF
without the chine flare) has a minimum drag coefficient
of 0.098 based on frontal area with transition fixed at
5 percent of the length at a Reynolds number of $20.5 \times 10^6$.
This coefficient is only 18 percent greater than that of
the streamline body of revolution from which the hull
was derived and demonstrates the validity of the

principles on which the form was based.  The increase in
drag caused by the chine flare was not determined in
these tests but can be assumed to be small.

## NACA Model 155

The form of the hull of the 400,000-pound cargo
airplane (NACA model 155), adapted from that of model
84-FF, is shown in figure 2 and illustrates the devia-
tions from the standard form thought necessary or desir-
able for this specific design.  The maximum width was
determined by the cargo requirements and is somewhat
greater than the beam over the chines.  The maximum
gross-load coefficient is 0.65, which is based on a
load well in excess of the normal gross weight that was
assumed at the time of the preliminary design.  This
beam loading, together with an increased forebody
length-beam ratio, gives a value of k of only 0.0552,
which assures a reserve of seaworthiness compatible with
the general conservatism of the design and the require-
ments of the intended service as a long-range cargo
carrier.

The depth of step is 9 percent of the beam in accord
with recent experience with skipping and the length of
afterbody is increased for additional buoyancy aft of the
center of gravity.  The length of tail extension is such
that the predetermined tail arm is attained and the form
aft of the sternpost is carefully faired in an attempt
to reduce the drag of the afterbody.

Preliminary tests of a $\frac{1}{40}$-size model in NACA tank
No. 1 indicated that, when the afterbody was immersed at
high water speeds, the flow did not clear the tail
extension.  A small chine flare similar to that of
model 84-FF, however, proved to be all that was required
to make the lines satisfactory in this respect.

Wind-tunnel tests.- Following the preliminary tank
tests, the aerodynamic drag of the same model in combina-
tion with a proposed NACA low-drag wing was extensively
investigated in the NACA two-dimensional low-turbulence
pressure tunnel.  The significant results of the wind-
tunnel tests are shown in figure 3, in which

$$c_{D_A} = \frac{D_c - D_w}{qA}$$

where

$C_{D_A}$        frontal-area drag coefficient

$D_c$        drag of surveyed portion of wing-hull combination

$D_w$        drag of surveyed portion of wing alone

A        maximum cross-sectional area of hull

q        dynamic pressure

The model was tested in the smooth condition and with transition fixed by artificial roughness at a point 5 percent of the length of the hull from the bow. As in the aerodynamic tests of reference 4, drag coefficients with fixed transition are considered more nearly representative of actual full-size values than the drag coefficients of the smooth model.

With fixed transition, the minimum drag coefficient of the hull is 0.0795 as compared with 0.0983 for model 84-F at approximately the same Reynolds number. In comparing these values, the differences in the test procedures and conditions should be considered as well as the differences in form.

For the smooth condition, the minimum drag coefficient is 87 percent of the minimum drag coefficient with transition fixed at 5 percent of the length. This result indicates that laminar flow can persist over a considerable portion of the forebody aft of the 5-percent point and that the chines at the bow are favorably disposed with respect to the flow.

A fairing aft of the very deep step, having a length 14 times the depth of step, reduces the minimum drag coefficient 13 percent in the smooth condition. If the same increment is applied to the minimum drag coefficient with fixed transition, shown by the short-dash curve of figure 3, the corresponding reduction is 11 percent. These percentages are indicative of the proportion of the total drag of the hull attributable to the deep step.

The merit of the form is best judged by comparing its drag with the drag of a flat plate having the same surface area. This comparison is made in figure 3 by including

the numerical value of the coefficient of skin friction
with fully turbulent boundary layer at the test Reynolds
number multiplied by the ratio of the surface area of the
model to its frontal area. The resulting coefficient is
70 percent of the minimum drag coefficient of the hull
with fixed transition and is 79 percent of the estimated
minimum drag coefficient with fixed transition and the
step faired. The form drag of the hull, including the
drag of the chines, may therefore be estimated to be of
the order of only 21 percent of the total drag.

Tank tests.- Following the tests of the $\frac{1}{40}$- size model
of the hull, the hydrodynamic characteristics of a $\frac{1}{16}$-size
dynamic model of the airplane, equipped with scale powered
propellers that developed 70 percent of the scale thrust,
were investigated. These tests showed the design to
have excellent take-off and landing stability, comparative
freedom from porpoising at the desired positions of the
center of gravity, and full clearance of propellers,
flaps, and tail surfaces from objectionable spray during
take-offs at the full-load gross weight. The only
further modification found necessary was the usual adjust-
ment of the location of the step to obtain freedom from
porpoising at the forward positions of the center of
gravity required by the cargo loading schedules.

The limits of stability for the final form are shown
in figure 4. The power-off trim track with the center
of gravity at 26 percent of the mean aerodynamic chord
and neutral elevator is well clear of the lower trim
limit. The porpoising at high trims and high speeds is
very mild, as evidenced by the small spread between the
two branches of the upper trim limit.

The stable range of positions of the center of
gravity is defined conservatively by assuming the elevators
neutral at the forward limits and 15° up at the after
limits. During operation with positions of the center of
gravity close to these limits or in the event of a power
failure on take-off, serious porpoising may be averted by
moving the elevator up when near the forward limits or
down when near the after limits. The range shown in
figure 4 is ample for the various cargo loadings assumed
in the design.

The stable range of positions of the center of
gravity, power on, at a gross-load coefficient of 0.65 is

from 24 to 36 percent of the mean aerodynamic chord, and
the center of the range for normal operation is at
30 percent of the mean aerodynamic chord.  With the center
of gravity at 30 percent of the mean aerodynamic chord,
a line through the center of gravity and the step is
inclined at an angle of 15.3° from a perpendicular to the
base line as compared with an angle of trim for a full-
stall landing of approximately 14°.

## NACA Model 180

The lines of NACA model 180 (fig. 5) illustrate the
use of an elliptical streamline body as the basic form
for a hull and the essential differences in proportions
among various applications of the same design principles.
The design gross-load coefficient is 0.76 and the length
of forebody to the centroid of the step is such as to give
a value of the coefficient  k  of 0.0657.

The incorporation of the V-step in the lines is in
accordance with results of reference 5 showing that the
mean depth of such a step can be less than the equivalent
transverse step for similar landing stability.  It is
not yet established that the drag due to the V-step is
appreciably less but the inherently smaller frontal area
is an indication of a slight over-all advantage over the
transverse step.

## THREE PRELIMINARY DESIGNS FOR

## LARGE TRANSPORT FLYING BOATS

The immediate possibilities and broad technical
aspects of large airplanes for overseas air routes are
illustrated by the preliminary designs of three flying
boats having gross weights of 120,000, 300,000, and
430,000 pounds.  These gross weights are chosen
arbitrarily to provide the same power loading with the
P. & W. R-2800 engine, the P. & W. R-4360, and an
eventual more powerful version of the R-4360 in combina-
tions of four, six, and eight, respectively.  There are
thus represented a four-engine airplane within the scope
of present practice, a six-engine airplane that is the
next logical development in multiengine transports, and
an eight-engine airplane that will follow naturally if

the intermediate size proves satisfactory in all respects.
The three airplanes are appropriately designated by the
names of three ocean birds, Shearwater, Gannet, and
Albatross.

## Three-View Drawings

In order to maintain comparable physical dimensions
and performance for the three sizes, the wing loadings
and hull loadings are made the same, along with the power
loadings. The arbitrary values chosen for these loadings
and the other design assumptions held constant for all
the gross weights are given in table I. The resulting
data and dimensions for the three airplanes are given in
table II. The corresponding three-view drawings are
shown in figures 6, 7, and 8 and a comparison of the plan
views to the same scale is shown in figure 9. A per-
spective drawing of the intermediate size, illustrating
the anticipated trend for six-engine transports, is
given in figure 10.

The three-view drawings show  how the low-drag
hull fits in with the other components of the structure
and also the influence of the design assumptions on the
proportions. The proportions of wing, hull, and tail
surfaces change with the size because the dimensions of
the wing with constant wing loading vary as the square
root of the ratio of the gross weights; whereas the hull
dimensions with constant gross-load coefficient vary as
the cube root of the ratio of the gross weights. Inasmuch
as the tail moment arms vary with the dimensions of the
hull, the tail areas become a larger percentage of the
wing area as the gross weight is increased. The sizes
of the hulls and tail surfaces - relative to the wing -
that follow from these dimensional relations are compared
in figure 11.

There are, of course, innumerable variations of
loadings and dimensions possible for any of the air-
planes, depending on factors not taken into account in
the present analysis and on the individual preferences
of the designer. It appears that, as the size is
increased, the hull of a flying boat can become rela-
tively smaller and retain ample proportions for sea-
worthiness. The drag therefore becomes of less and
less consequence in relation to the drag of the wing.

· The length of the tail extension can probably be changed
somewhat to vary the actual tail area required without
sensibly affecting the drag of the hull.

The absolute clearances of the wing and propellers
above the load water line increase with the size of the
airplanes. ˙ The clearance of the bottom of the wing in
proportion to the hull dimensions is slightly less as the
size increases; the clearance of the propeller tips in
proportion to the propeller diameter becomes greater as
the size and number of engines are increased.

## Take-Off Performance

· The power loading of the three designs, primarily
determined by the engines available and the long-range
performance required, is relatively high for take-off;
therefore, the question remains as to whether the water
resistance of the low-drag hulls will limit their func-
tion as a landing gear. The approximate take-off
performance and trend with size may be calculated from
the data for model 84-EF-3 (reference 4).

Procedure.- Take-off calculations were made by using
the data of reference 4 and the assumed values of aero-
dynamic lift and drag coefficient plotted in figure 12.
The thrust was estimated from the data of reference 6 and
gear ratios for the four-blade propellers were assumed to
give the same thrust per, horsepower with the three sizes
of propeller. The hulls were assumed to be free to trim
up to a speed beyond the hump at which the trim dropped
to $5°$, the trim being held at this value for the remainder
of the take-off. The take-off speed at $5°$ trim ($9°$ angle
of attack of the wing) is approximately 96 miles per hour.

Results.- The curves of the computed values of air
drag, total resistance, and thrust, along with the
graphical determination of the take-off time and dis-
tance, are shown in figures 13 to 15. The curves indi-
cate that, for large low-drag flying boats such as those
under consideration, the critical point in the take-off
is at the hump speed rather than near take-off speed and
that the assumed power plants are sufficient to provide
reasonable take-off times and distances for such large
airplanes. The pertinent hydrodynamic data at the hump
speed from the calculations are

| | Shearwater | Gannet | Albatross |
|---|---|---|---|
| Trim, degrees . . . . . . . . . . . . | 10.7 | 10.3 | 10.1 |
| Load on water, pounds . . . . . . . | 101,000 | 236,000 | 360,500 |
| Ratio load on water to gross weight . . . . . . . . . . . | 0.842 | 0.786 | 0.752 |
| Water resistance, pounds . . . | 23,000 | 52,400 | 79,000 |
| Ratio load on water to water resistance . . . . . . . . | 4.38 | 4.50 | 4.64 |

The total resistance shown is conservative, because the trims at the hump speed and at take-off are higher than best trim and the resistances are uncorrected for the decrease in the coefficient of skin friction with increase in Reynolds number (reference 7). The estimated times and distances become less as the size of the airplane is increased, an indication that there is no reason to expect an unforeseen take-off problem for the larger flying boats.

With constant wing and power loadings, the favorable effect of size on the take-off performance is mainly a Froude number effect; in other words, the larger hulls operate at relatively lower speeds with respect to their dimensions. This favorable effect is brought out clearly in figure 16, in which the forces involved are reduced to nondimensional form by dividing them by the gross weight. As the size is increased the hump speed becomes higher. As a result, the load on the water is lower, the load-resistance ratio is higher, and the acceleration through the critical region is greater. The larger airplanes also take off at lower Froude numbers, and their high-speed resistances are relatively lower because they do not reach the Froude number at which the frictional resistance of the afterbody becomes predominant.

## CONCLUDING REMARKS

The results of the investigations described indicate the practicability of the present form of flying-boat hull up to a gross weight of 500,000 pounds and support the validity of the design principles proposed. As the gross weight is increased, the volume of the hull becomes relatively less, so that the benefits of moderate hull loadings can be attained without undue penalty in weight and drag. The increment in drag caused by an adequately

deep step is smaller than is the probable increment caused
by unavoidable roughness on the full-size airplane.  Close
adherence to the form of a streamline body and a favorable
disposition of the chines with respect to the flow result
in drag coefficients largely attributable to the skin
friction.  Radical departures from the form for minimum
drag, or forms having excessive surface area, will not
in general be desirable for high-performance airplanes
regardless of their hydrodynamic advantages.

Landing gears for landplanes have become relatively
heavier and ground pressures with conventional arrangements
have become higher as the gross weight has increased.
The gears for gross weights above 140,000 pounds have not
yet made their appearance but will probably take the form
of multiple wheels or caterpillar treads to reduce the
concentration of stresses in the airplanes and runways.
The hull of the flying boat, aside from its inherent
ability to take off and land at sea, provides an immediate
solution for the landing-gear problem of large long-range
airplanes.


Langley Memorial Aeronautical Laboratory
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TABLE I.- LOADINGS AND DESIGN ASSUMPTIONS HELD CONSTANT

FOR THE THREE PRELIMINARY DESIGNS

Power plants - radial air cooled:

    Power loading, take-off, lb/hp . . . . . . . . . 16.67
    Power loading, cruising, lb/hp . . . . . . . . 27.75
    Fuel consumption, lb/hp-hr . . . . . . . . . . . 0.45

Propellers - constant speed:

    Number of blades . . . . . . . . . . . . . . . . Four
    Tip speed, take-off, fps . . . . . . . . . . . . 1050

Wing - NACA low-drag section:

    Wing loading, full-load
      gross weight, lb/sq ft . . . . . . . . . . . 42.0
    Aspect ratio . . . . . . . . . . . . . . . . . . 8.95
    Taper ratio . . . . . . . . . . . . . . . . . 2.575:1

Horizontal tail - NACA low-drag section:

    Volume/(Wing area × M.A.C.) . . . . . . . . . 0.500
    Aspect ratio . . . . . . . . . . . . . . . . . 3.9
    Taper ratio . . . . . . . . . . . . . . . . . 2.46:1
    Center of pressure, percent root chord . . . . . . 25

Vertical tail - NACA low-drag section:

    Volume/(Wing area × Span) . . . . . . . . . . 0.033
    Aspect ratio . . . . . . . . . . . . . . . . . 1.48
    Taper ratio . . . . . . . . . . . . . . . . . 2.09:1
    Center of pressure, percent root chord . . . . . . 25

Hull:

    Gross-load coefficient . . . . . . . . . . . . . 0.704
    Coefficient k . . . . . . . . . . . . . . . . 0.0598
    Ratio of length to maximum beam . . . . . . . . 8.64
    Ratio of depth to maximum beam . . . . . . . . . 1.25
    Ratio of cargo space to
      gross weight, cu ft/lb . . . . . . . . . . 0.0459

Center-of-gravity position:

    Mean position, percent M.A.C. . . . . . . . . . . 30
    Forward of step, percent maximum beam . . . . 20.85
    Above keel, percent maximum beam . . . . . . . 83.33

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### TABLE II.- DATA AND DIMENSIONS FOR THE
### THREE PRELIMINARY DESIGNS

|  | Shearwater | Gannet | Albatross |
|---|---|---|---|
| Full-load gross weight, lb . . . | 120,000 | 300,000 | 480,000 |
| **Power plant:** | | | |
| Number of engines . . . . . . . | Four | Six | Eight |
| Horsepower, per engine . . . . | 1800 | 3000 | 3600 |
| Horsepower, take-off . . . . . | 7200 | 18,000 | 28,800 |
| Horsepower, cruising, at altitude of 10,000 ft . . . | 4320 | 10,800 | 17,300 |
| **Propellers:** | | | |
| Diameter, ft . . . . . . . . . | 15.2 | 18.0 | 19.0 |
| Activity factor per blade . . . . | 67 | 123 | 115 |
| **Wing:** | | | |
| Area, sq ft . . . . . . . . . . . | 2857 | 7143 | 11,430 |
| Span, ft . . . . . . . . . . . . | 160 | 253 | 320 |
| M.A.C., ft . . . . . . . . . . . | 19.1 | 30.2 | 38.2 |
| **Hull:** | | | |
| Length, ft . . . . . . . . . . | 130.8 | 177.2 | 207.5 |
| Maximum beam, ft . . . . . . . | 15.1 | 20.5 | 24.0 |
| Beam over chines, ft . . . . . | 13.9 | 18.8 | 22.0 |
| Depth, ft . . . . . . . . . . . | 18.9 | 25.6 | 30.0 |
| Space for cargo, cu ft . . . . | 5500 | 13,700 | 22,000 |
| **Center of gravity:** | | | |
| Distance forward of step, ft . | 3.15 | 4.27 | 5.00 |
| Height above keel, ft . . . . . | 12.6 | 17.1 | 20.0 |
| **Tail surfaces:** | | | |
| Vertical area, sq ft . . . . . . | 200 | 600 | 1100 |
| Horizontal area, sq ft . . . . . | 360 | 1100 | 2000 |
| Tail moment arm, ft . . . . . . | 76 | 98 | 109 |

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Fig. 1
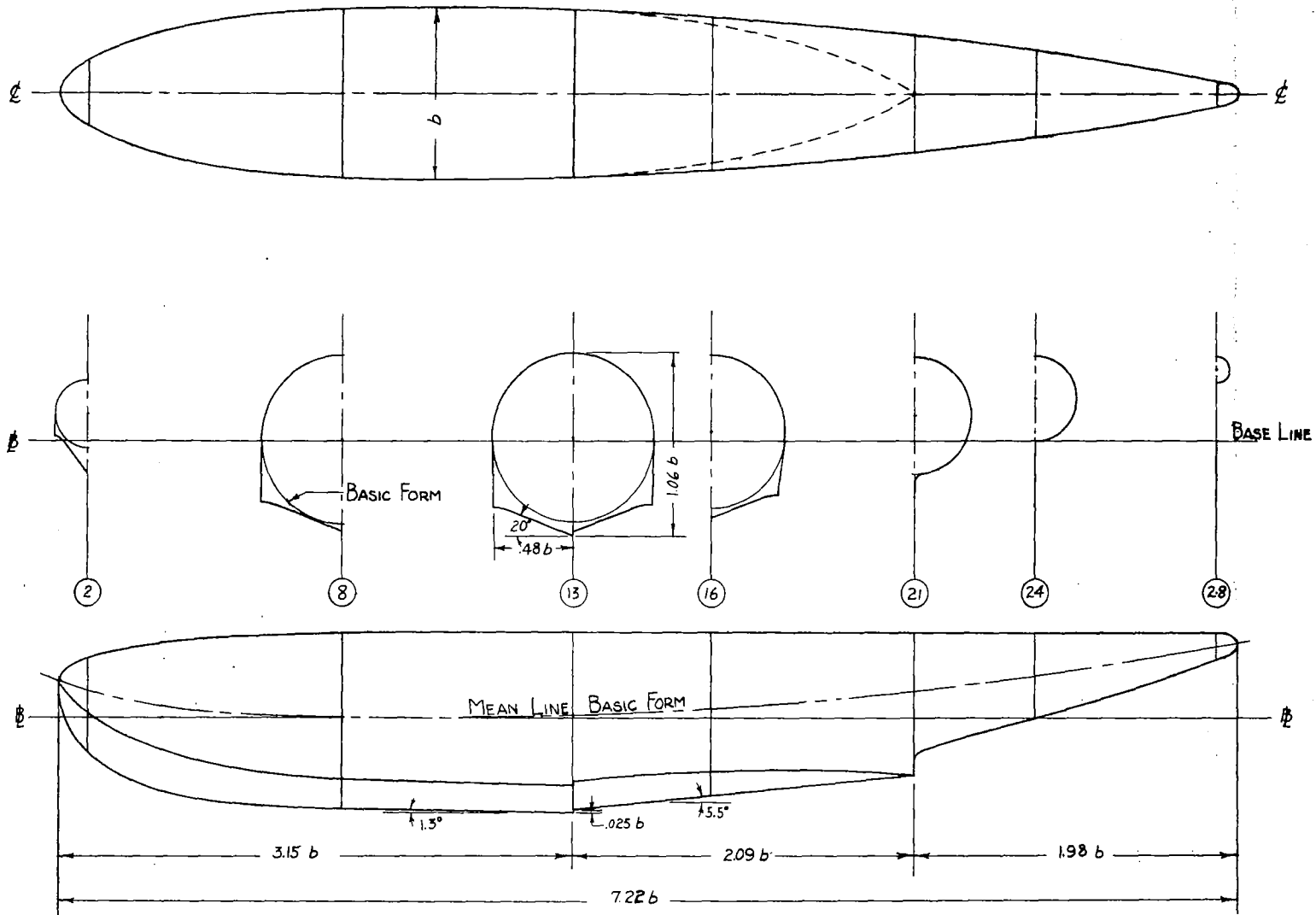


Figure 1.- Lines of NACA model 84-FF flying-boat hull.

OUTLINE OF WING FOR WIND-TUNNEL TESTS

.55b

1.32b

20°    20°

b/2

BASIC FORM

MEAN LINE    BASIC FORM

2°    .091b    5°

3.43 b

2.50b

3.50 b

9.43 b

Fig. 2
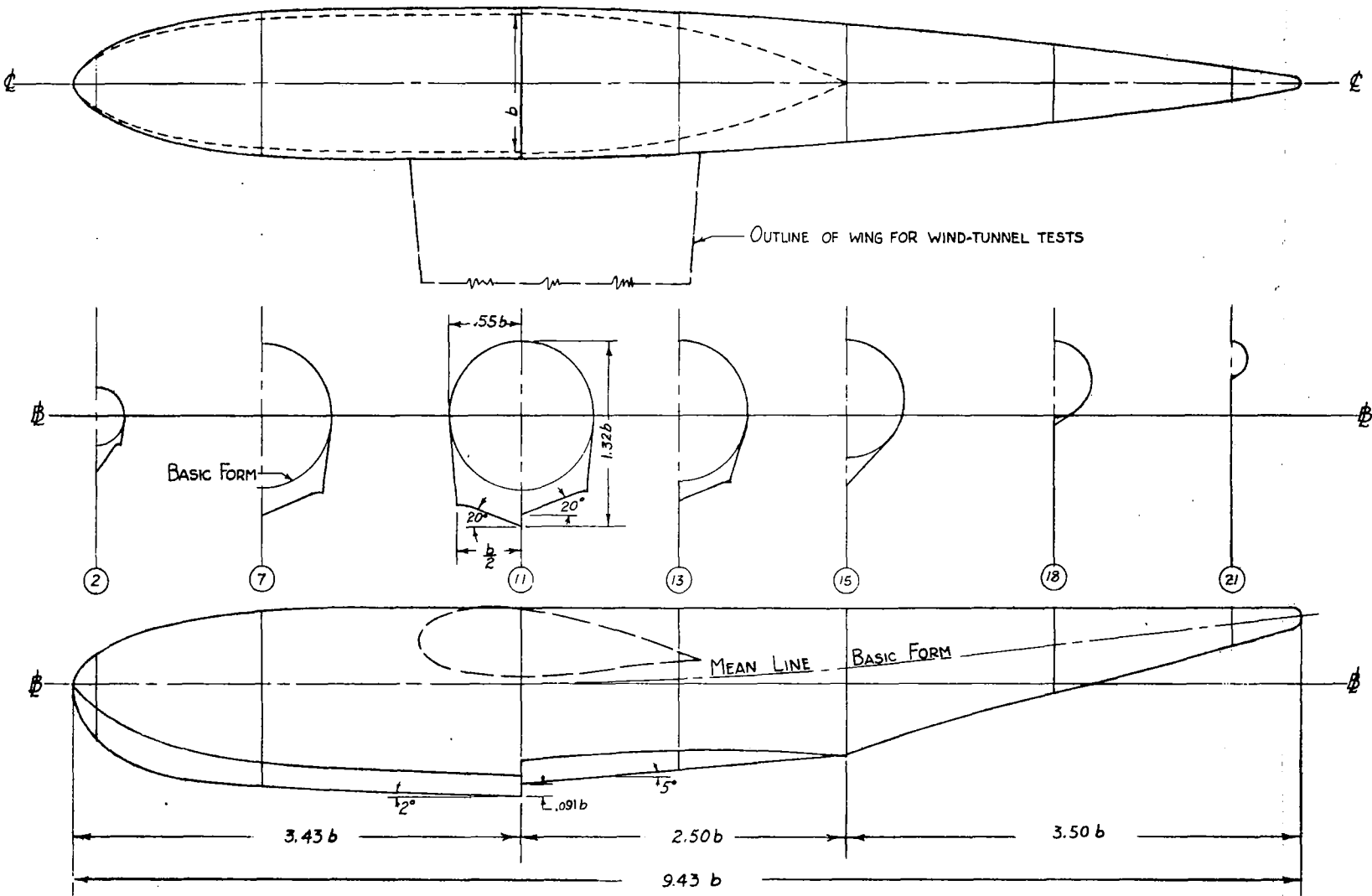
Figure 2.- Lines of NACA model 155 flying-boat hull.
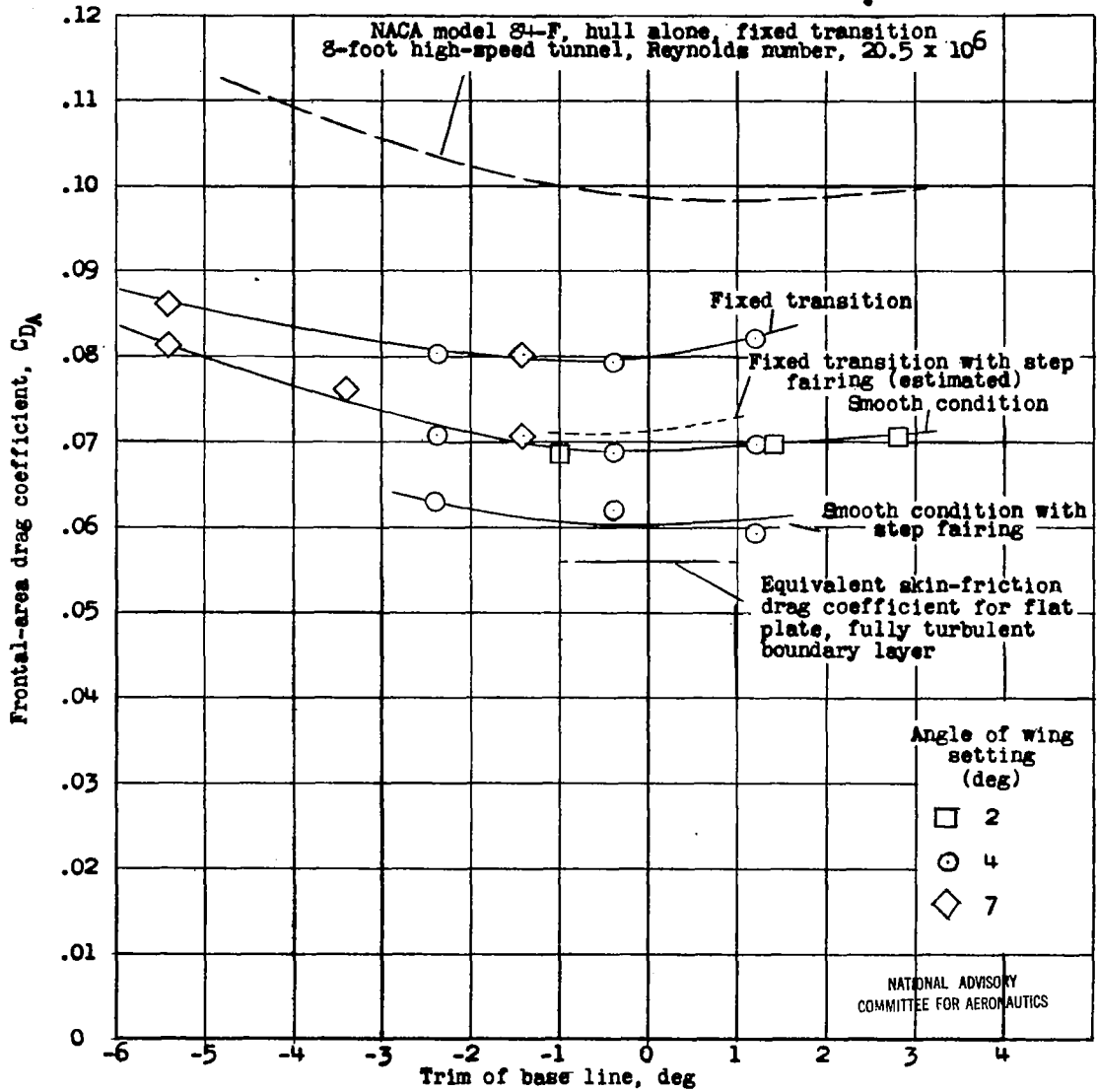
Figure 3.— Frontal-area drag coefficients of NACA model 155 flying-boat hull as determined in the NACA two-dimensional low-turbulence pressure tunnel. Reynolds number, 22.5 x 10⁶.
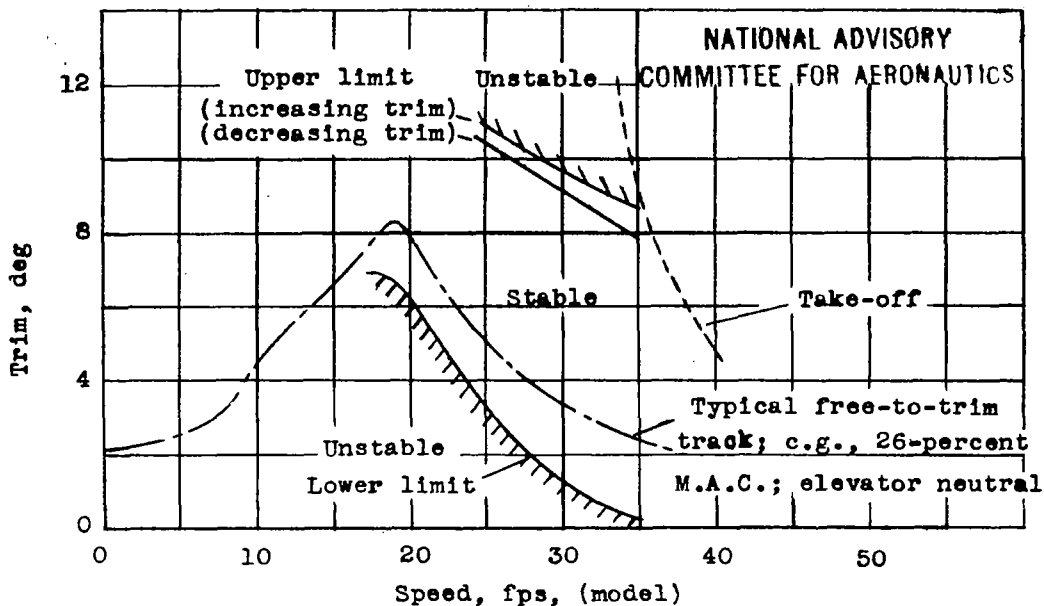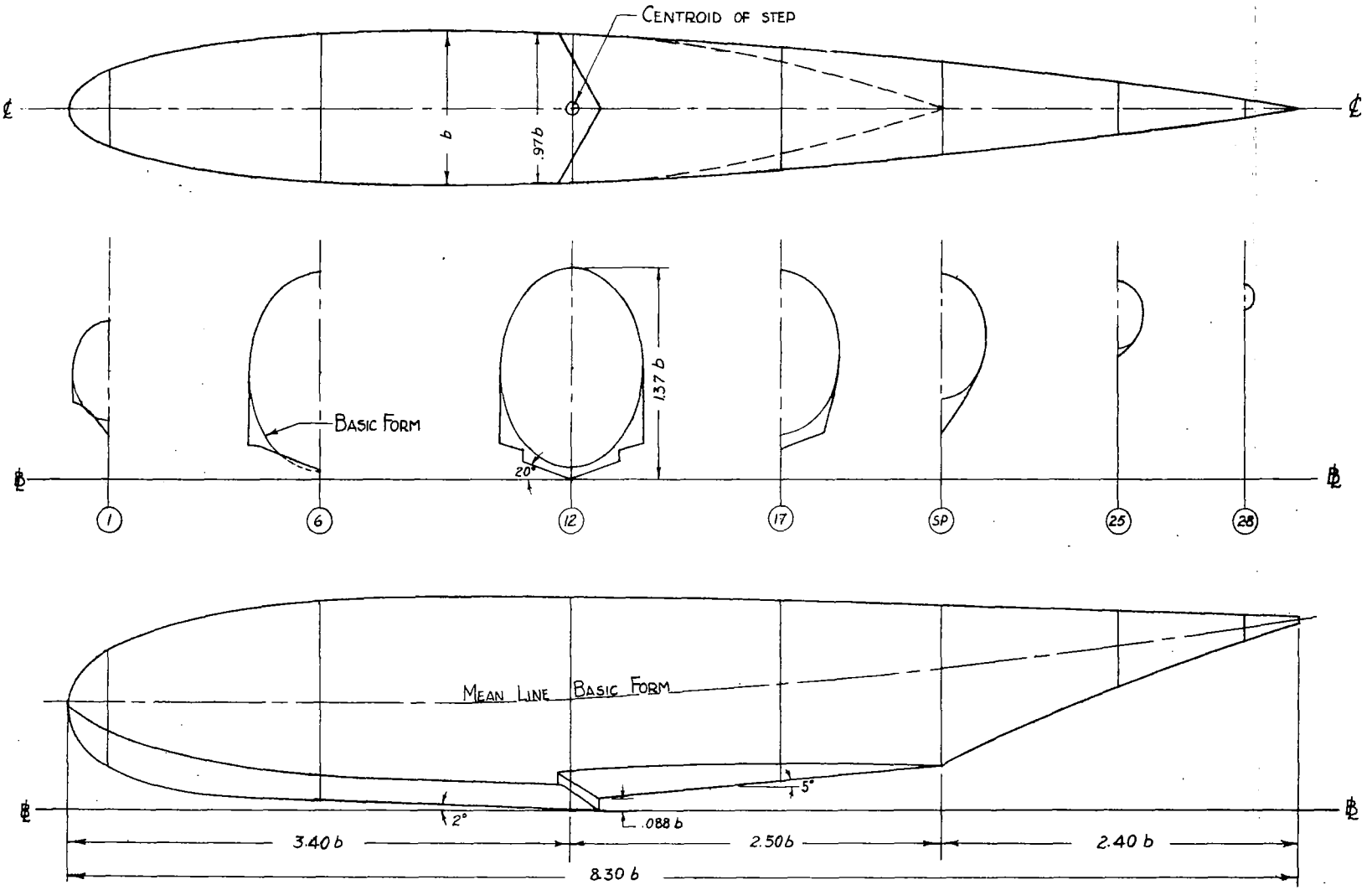
(a) Trim limits of stability without power. $C_{\Delta_0}$ = 0.66.
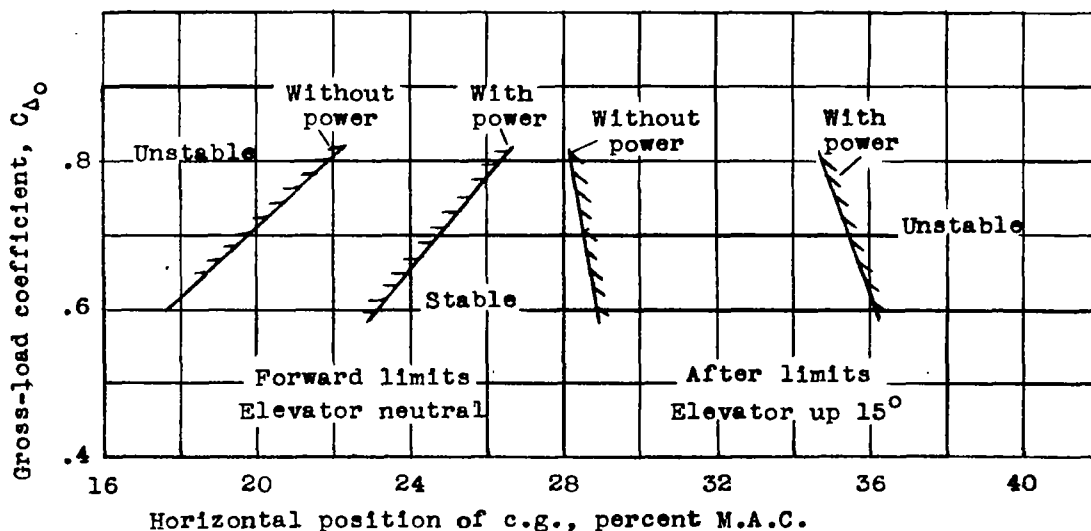
(b) Center-of-gravity limits of stability.

Figure 4.- Hydrodynamic stability characteristics of the 400,000-pound
    cargo airplane as determined from tests in NACA tank No. 1 of 1/16-
    size powered dynamic model. Flaps deflected 20°.

CENTROID OF STEP

BASIC FORM

MEAN LINE BASIC FORM

Fig. 5

Figure 5.- Lines of NACA model 180.

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0    10    20    30
FEET
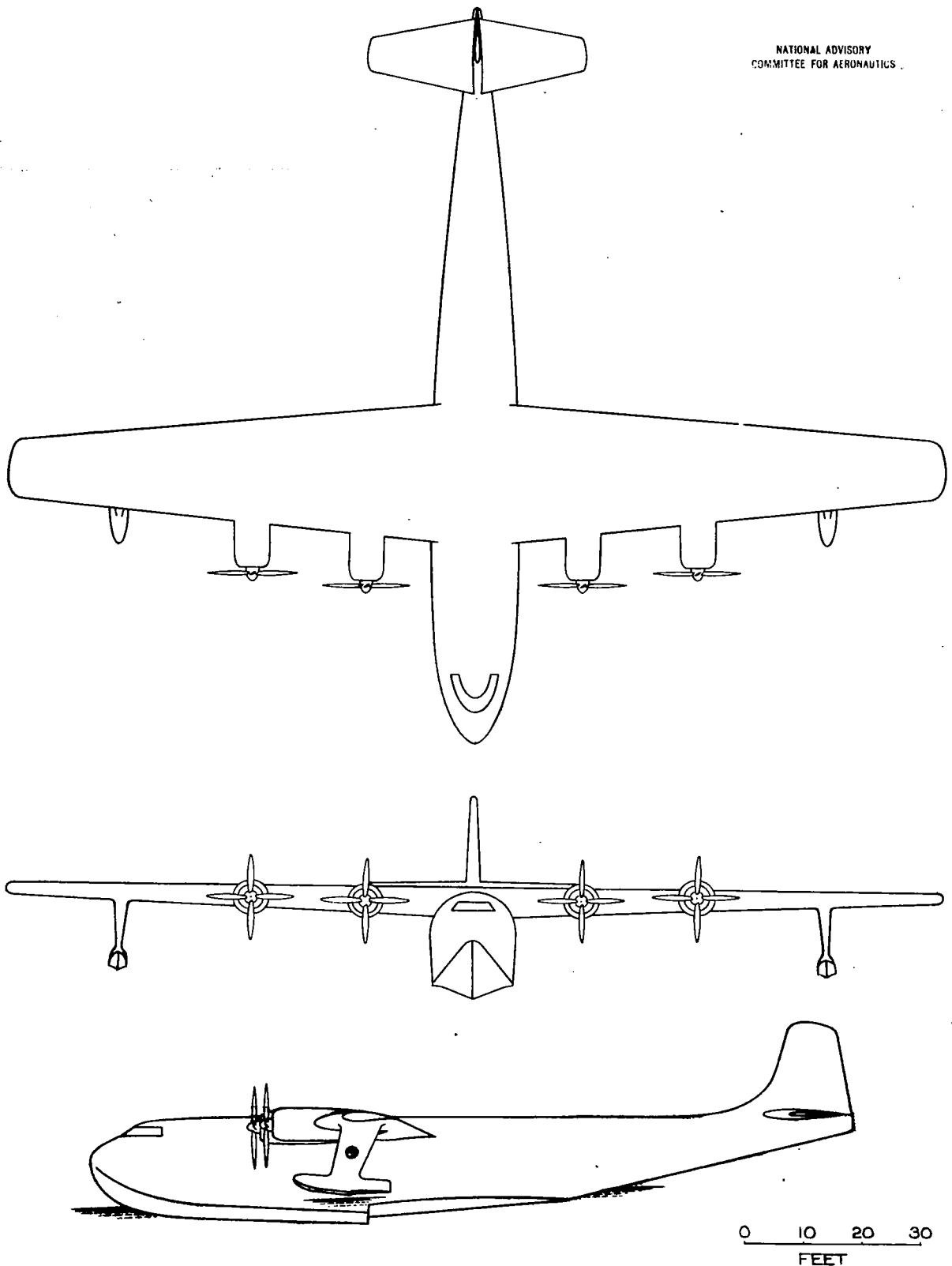
Figure 6.- Three-view drawing of Shearwater.  Gross weight,
120,000 pounds.

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O   10  20  30  40  50
        FEET
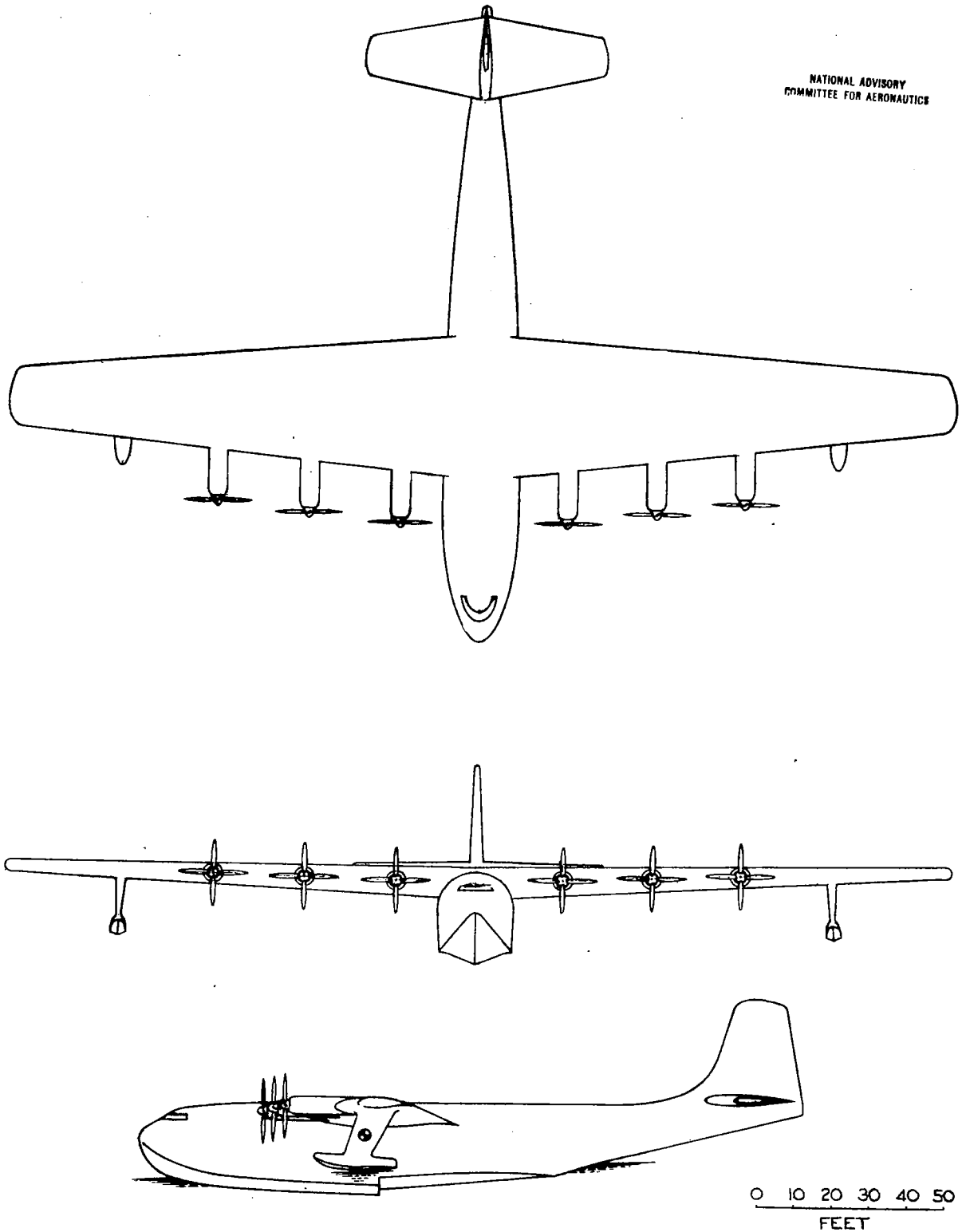
Figure 7.- Three-view drawing of Gannet.  Gross weight,
                300,000 pounds.

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0    20    40    60
FEET
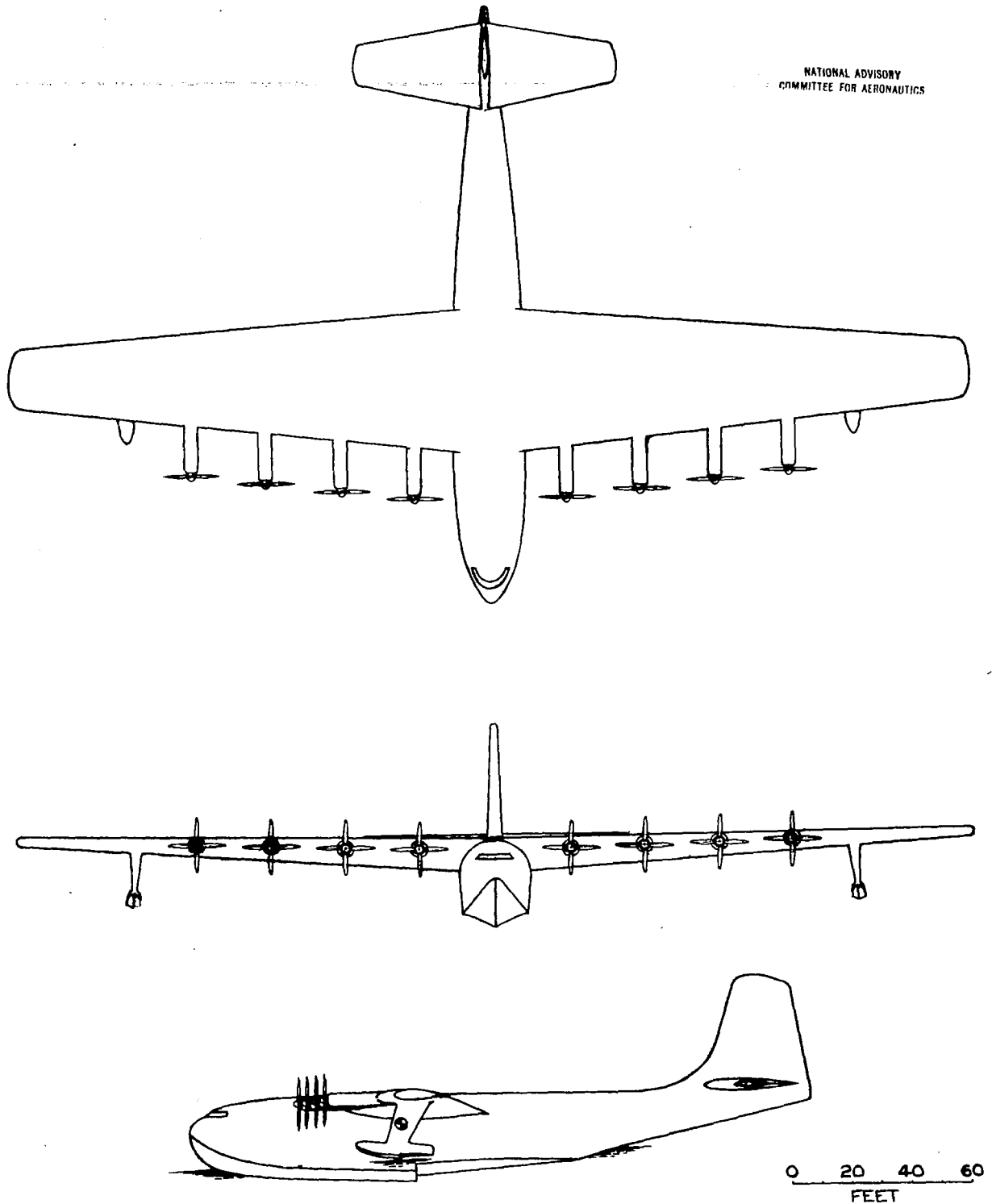
Figure 8.- Three-view drawing of Albatross.  Gross weight,
480,000 pounds.

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ALBATROSS

SHEARWATER

GANNET

0    20    40    60
FEET
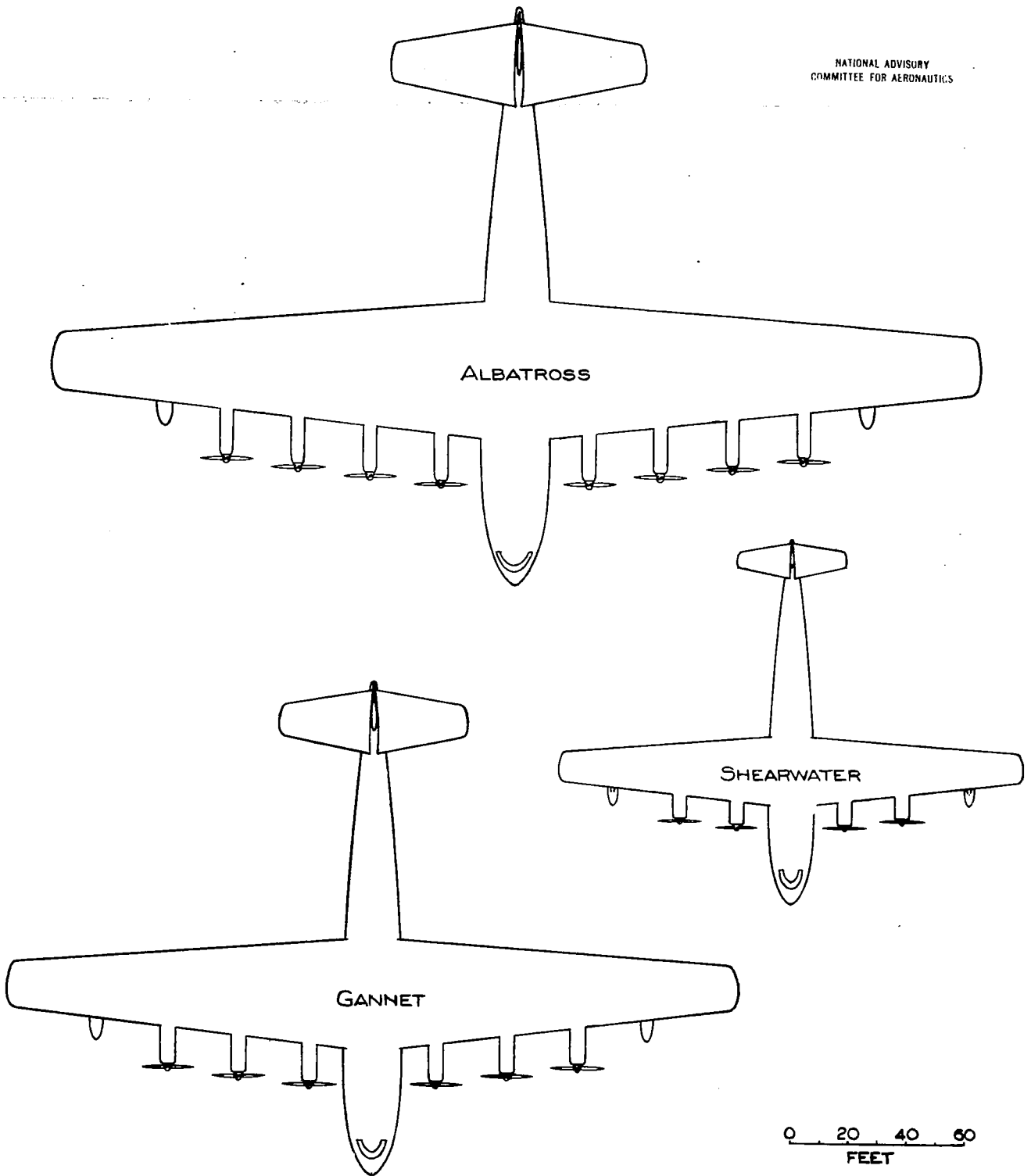
Figure 9.- Plan views of Shearwater, Gannet, and Albatross
to same scale.
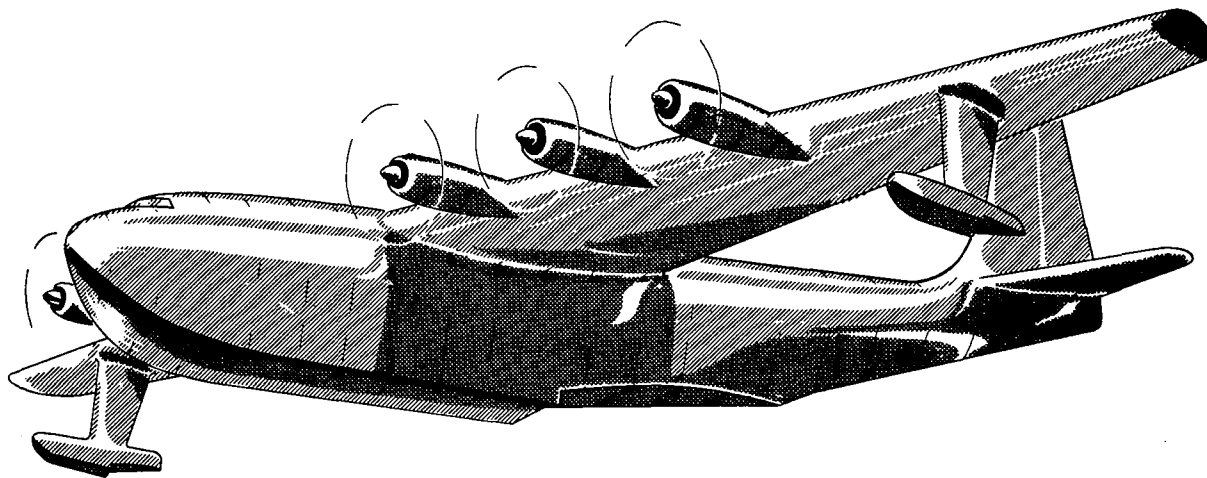
Figure 10.- Perspective drawing of Gannet.  Gross weight, 300,000 pounds.

Fig. 10

GANNET,   300,000 LB

SHEARWATER, 120,000 LB

ALBATROSS,   480,000 LB
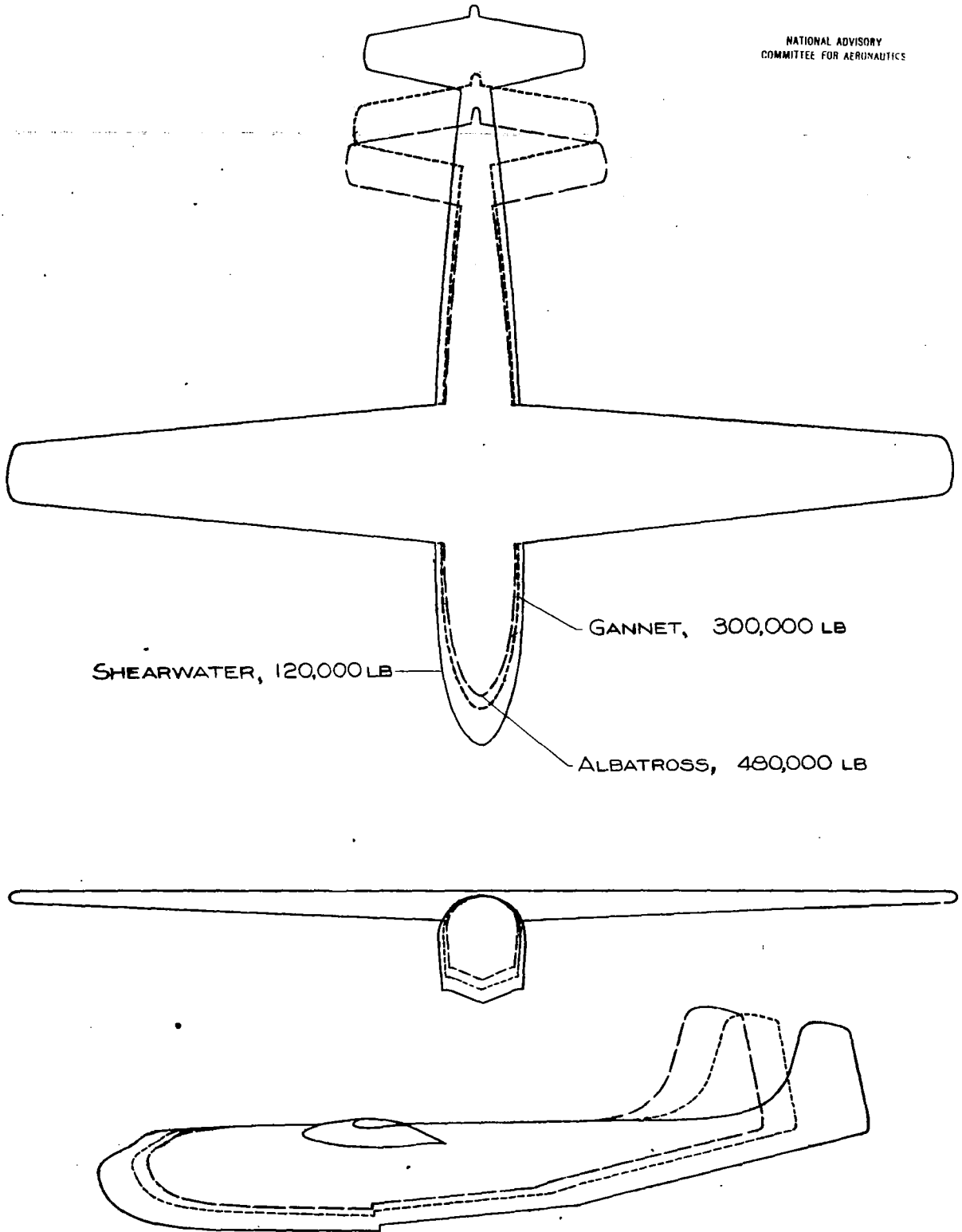
Figure 11.- Effect of gross weight on size of hull relative
   to wing with constant wing loading and hull load coefficient.
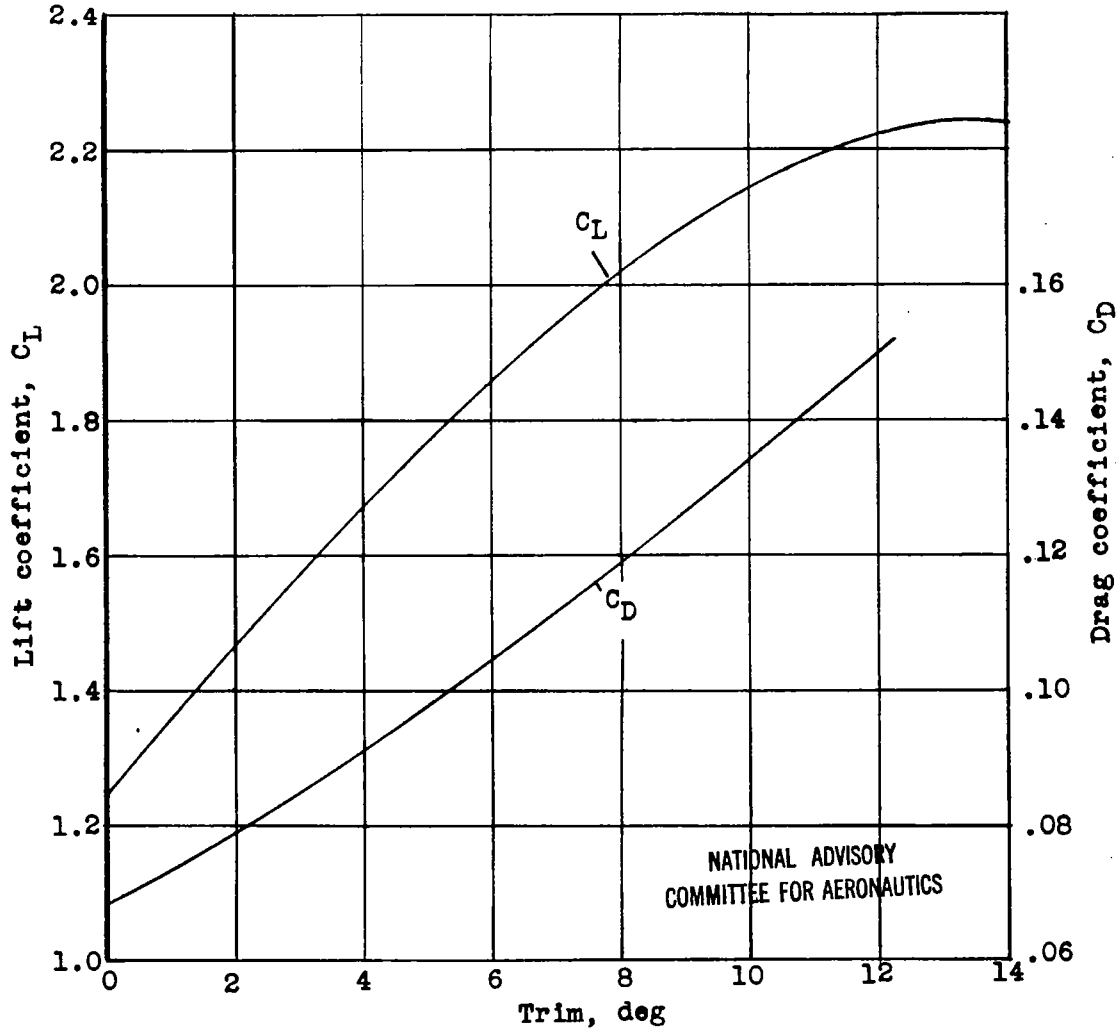
Figure 12.- Assumed lift and drag coefficients for take-off calculations. Angle of wing setting with respect to trim base line, 4°.

Fig. 12
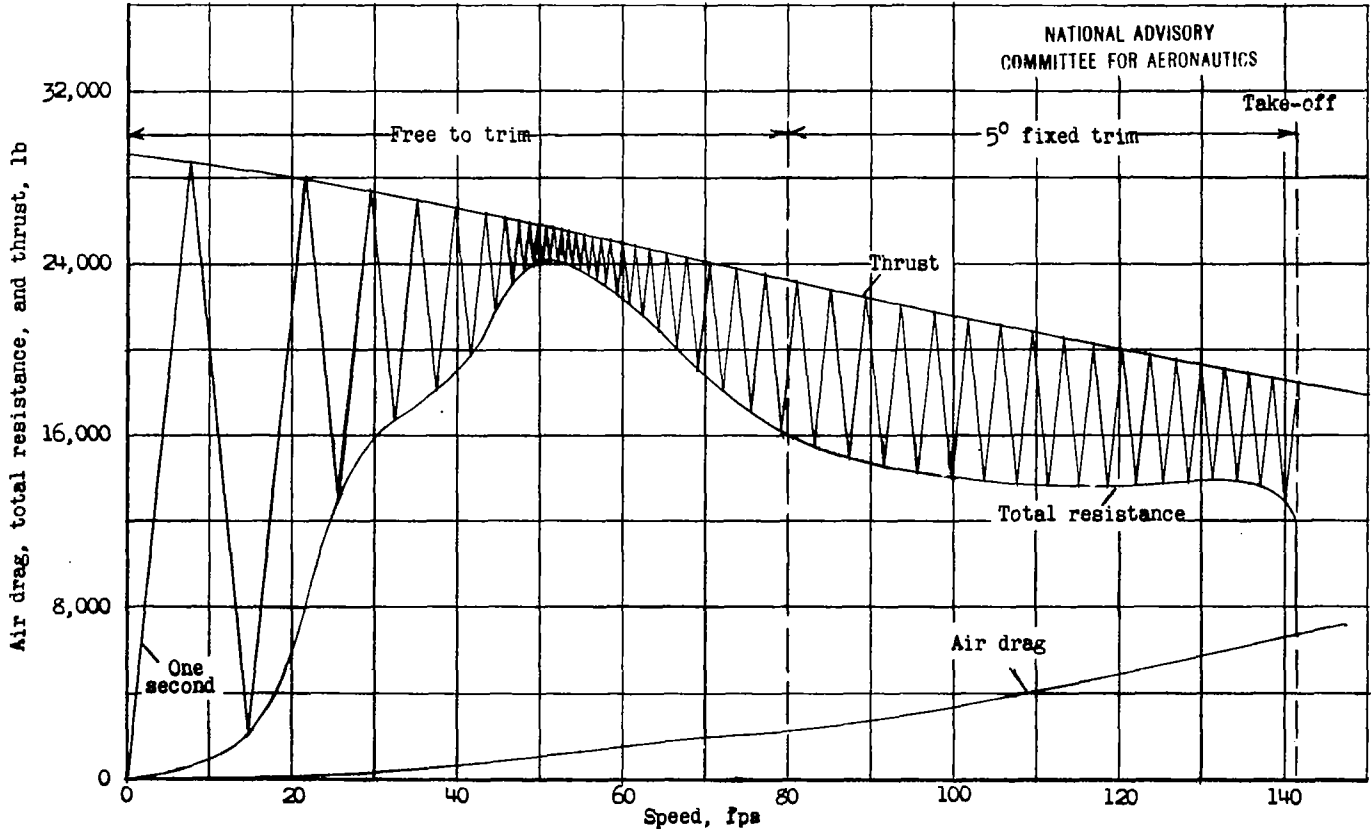
Figure 13.- Take-off performance of Shearwater.   Gross weight, 120,000 pounds; take-off time, 89 seconds; take-off distance, 6820 feet.
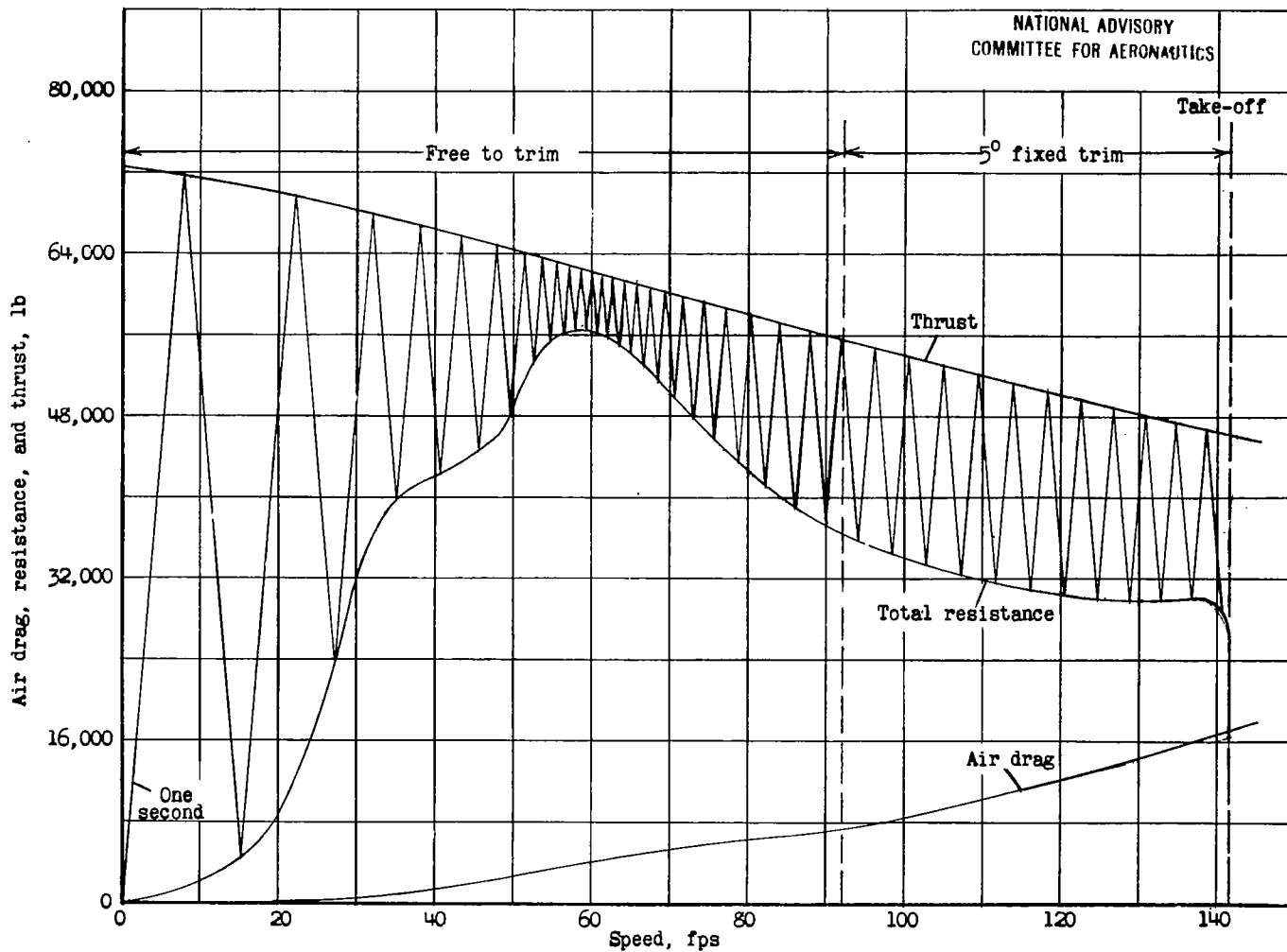
Fig. 13

Figure 14.- Take-off performance of Gannet.    Gross weight, 300,000 pounds; take-off time, 72 seconds; take-off distance, 5770 feet.
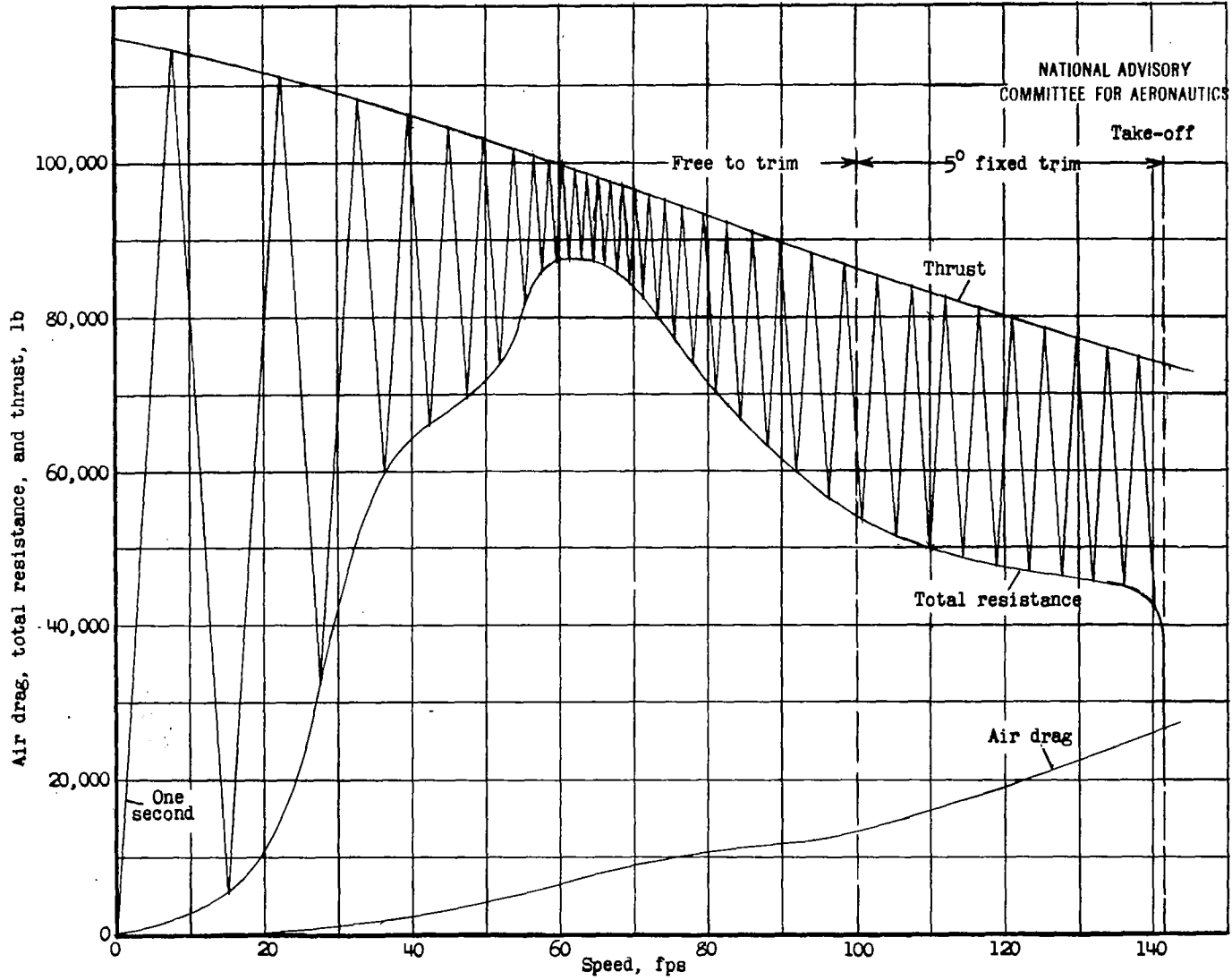
Fig. 14

Figure 15.- Take-off performance of Albatross.    Gross weight, 480,000 pounds; take-off time, 68 seconds; take-off distance, 5540 feet.
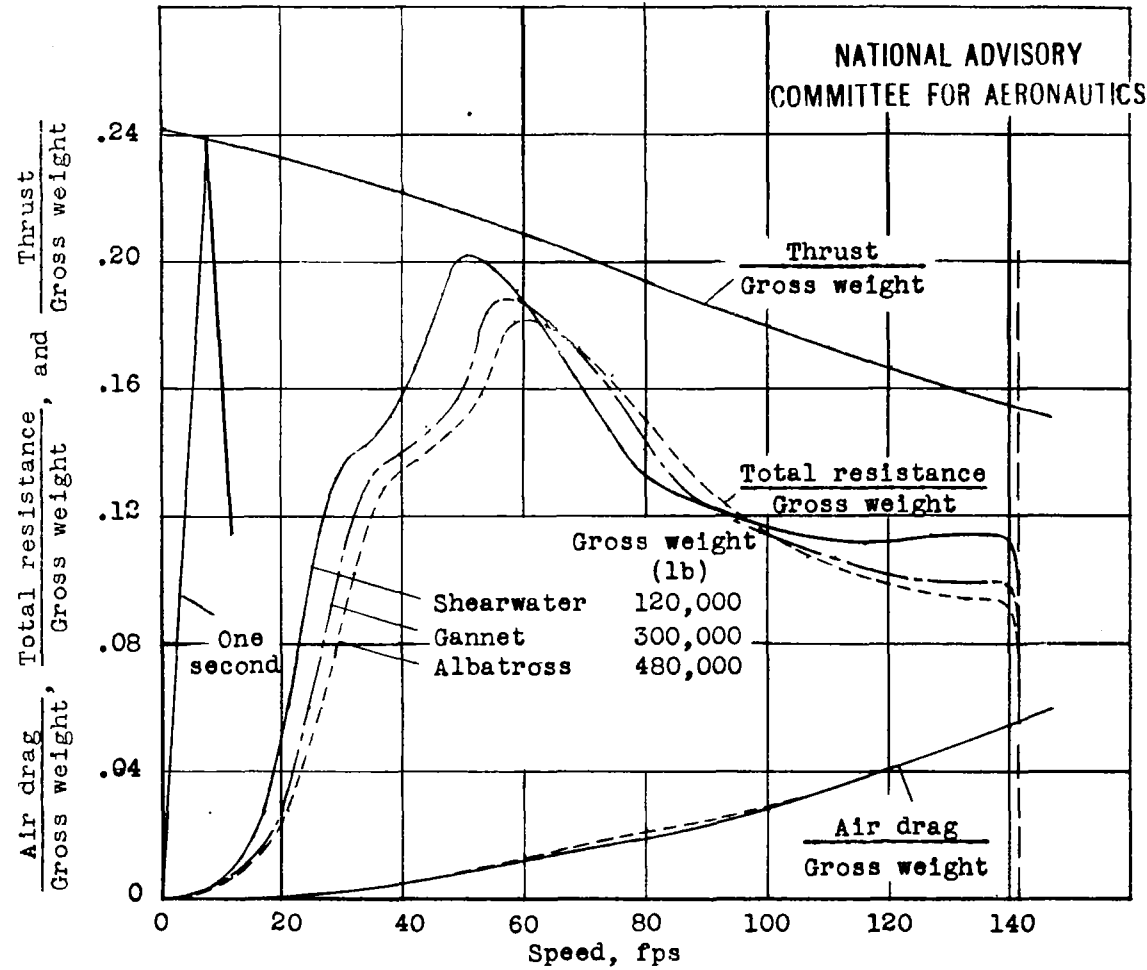
Fig. 15

Figure 16.- Comparison of air drag, total resistance, and thrust divided by gross weight for the various sizes of airplane.

Fig. 16