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## INVESTIGATION OF MEANS FOR EXTENDING THE RANGE OF SEVERAL BOMBERS TO 6000 MILES

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MEMORANDUM REPORT

for the

Army Air Forces, Materiel Command

# INVESTIGATION OF MEANS FOR EXTENDING THE RANGE OF SEVERAL BOMBERS TO 6000 MILES

By H. S. Riber and S. M. Harmon

## INTRODUCTION

At the request of the Army Air Forces, an investigation has been made of means to increase to 6000 miles the ranges of the B-17E, B-24D, B-26C, and B-25A bombardment airplanes. Tank-wing trailers (figs. 1, 2, 3, and 4) and tank gliders (figs. 5 and 6) were judged most practicable, and calculations were made for each bomber to determine the loading and dimensions of a suitable trailer and a glider or pair of gliders to obtain the specified range with military load. The average cruising speed and the take-off distance to clear a 50-foot obstacle were also calculated.

The choice of trailers and gliders was made after a consideration of all of the following devices:

(1) Additional fuel carried internally in flexible tanks stuffed into the wings and in the fuselage

(2) Streamlined tanks mounted on or under the fuselage

(3) Streamlined tanks mounted under the wings

(4) Biplane wing tanks mounted on the fuselage

(5) Tank-wing trailers (figs. 1 through 4)

(6) Fuel-carrying glider or gliders with tanks in their wings or fuselage (The tanks are in the wings in figs. 5 and 6.)

Method (1) drops from consideration because sufficient fuel cannot be so carried in any of the subject airplanes. It suffers also from the difficulty, shared with methods (2), (3), and (4), of overloading the landing gear on the ground. Method (2), in addition, overloads the wings in the air. Method (3), provided several tanks are used under each wing, might be contrived to work without overloading the wings in the air because the load is distributed along the wings. Method (4) avoids overloading the wings in the air since the biplane wing tank is self-supporting. As has been previously mentioned, however, methods (3) and (4) both overload the landing gear on the ground unless the fuel is added by aerial refueling.

The last-mentioned expedient is not impracticable. It is, however, unnecessary with method (5), the tank-wing trailer, or method (6), the tank gliders, which support their own weight on the ground as well as in the air. The trailer has been successfully flown by the British, who suggested the method. The use of two gliders trimmed to fly outboard of the airplane wing tips in the manner of figures 5 and 6 is of interest because of the substantial increase in miles per pound of fuel which can be obtained by this arrangement.

The upper limit to the range that can be obtained by going to larger and larger towed trailers or gliders is set, in general, by take-off considerations. Accordingly, the take-off problem was investigated in detail.

In the case of the tank-wing trailer, satisfactory stability was observed by the British in their experiments, but some consideration has been given in this report to the trailer fin area for adequate weather-cock stability. The stability of towed, pilotless gliders has been the subject of an extensive investigation by the Experimental Engineering Section of the Army Air Forces at Wright Field. No analysis of the problem is attempted here.

## BASIS FOR COMPUTATION

### Range Determination

I - Bomber with tank-wing trailer. - The range of any airplane arrangement is given by the Breguet formula

$$\text{range} = 863 \left(\frac{\eta}{C}\,\frac{L}{D}\right) \log_{10} \frac{W_f}{W_e} \tag{1}$$

where

$\eta$ propeller efficiency (average for all engines)

$C$ specific fuel consumption, pounds per brake horsepower-hour (average for all engines)

$L/D$ lift/drag ratio at a particular airplane gross weight

$W_f$ weight full (at start of flight)

$W_e$ weight empty (wt. full minus fuel consumed)

The bar on the term $\left(\overline{\frac{\eta}{C}\frac{L}{D}}\right)$ indicates the effective average for the flight computed from the average miles per pound. In this investigation, $\eta/C$ was assumed constant and $L/D$ was taken as the optimum value. This optimum $L/D$ varies as fuel is consumed from the trailer or glider, and account was taken of this in forming $\left(\overline{\frac{\eta}{C}\frac{L}{D}}\right)$.

A bomber with a tank-wing trailer constitutes a biplane system with large negative stagger. Munk's stagger theorem states, in effect, that stagger has no effect on the total induced drag of the system. Hence, ordinary biplane theory for the case of zero stagger is applicable, and the $L/D$ may be written

$$\frac{L}{D} = \frac{\text{lift of bomber + lift of trailer}}{\text{drag of bomber + drag of trailer + interference drag}}$$

In the above formula, conventional expressions were substituted for the first four terms, and an expression for the interference term was obtained from biplane formulas (reference 1, p. 184). This led to the following expression for the maximum $L/D$ of the combination

$$(L/D)_{max} = (L/D)_{1max} \times E \tag{2}$$

where

$$(L/D)_{1max} = \text{maximum } L/D \text{ for the bomber alone} \tag{2.1}$$

$$E = \frac{1 + \frac{L_2}{L_1}}{\sqrt{C_{D_o}/C_{D_{o_1}}} \cdot \sqrt{\tau}} \tag{2.2}$$

$$\tau = 1 + 2\sigma\left(\frac{b_1}{b_2}\right)\left(\frac{L_2}{L_1}\right) + \left(\frac{b_1}{b_2}\right)^2\left(\frac{L_2}{L_1}\right)^2 \qquad (2.3)$$

$L_2$ lift of trailer

$L_1$ lift of bomber

$C_{D_o}$ profile-drag coefficient of combination (based on bomber wing area)

$C_{D_{o_1}}$ profile-drag coefficient bomber alone (based on its own wing area)

$b_2$ effective span of trailer

$b_1$ effective span of bomber

biplane interference factor, a function of $h/(b_1 + b_2)$ and $b_2/b_1$, where $h$ is the effective biplane gap of the combination (reference 1: curves of $\sigma$, p. 183; table of $\sigma$, p. 184)

Substituting equation (2) in the Breguet formula (1) gave for that part of the range during which the trailer is attached (hereinafter referred to as the trailer-borne part of the range):

$$R_{t.b.} = 863\left(\frac{\bar{\eta}}{\bar{C}}\right)\left(\frac{L}{D}\right)_{1max} \times \bar{E} \log_{10}\frac{W_f}{W_{t.e.}} \qquad (3)$$

where

$W_f$ weight of combination at start of flight

$W_{t.e.}$ weight of combination when the trailer is empty but the airplane still carries its full load and fuel supply

E may be termed the trailer range efficiency factor since the trailer-borne part of the range is proportional to its effective average value $\bar{E}$

It was desired to determine the necessary loadings and dimensions of the trailers to provide a 6000-mile range for the bombers. The 18-percent-thick profile of figure 7 was chosen to provide a large fuel capacity with its center of gravity near the aerodynamic center. No attempt was made to achieve laminar flow. With this section the fuel capacity is $0.75bc^2$ gallons, where $b$ is the span and $c$ is the chord of the trailer. The structural weight was assumed to be 3.5 pounds per square foot, giving the trailer weight as 3.5bc pounds. The largest reasonable assumption of the structural weight per square foot would alter only slightly the calculated results.

The selection procedure was as follows. From the bomber high speed, the corresponding maximum engine power, and related data, as given in the Air Corps specifications (see table I), the parasite-drag coefficient $C_{D_{o_1}}$ and the maximum lift/drag ratio $(L/D)_{1max}$ were calculated. A suitable average $(\eta/C)$ was determined by using this value of $(L/D)_{1max}$ in the Breguet formula with the range values given in the mentioned specifications and/or Air Corps Experimental Engineering Section chart E. O. 441-1-23, drawing S42D1103, by Rasmussen and Brown, 12-16-41, entitled, "Table - Wt., Bal., & Performance with Torpedo and Four Factors."

On the basis that the bomber jettisons the trailer when empty (at the halfway point or before), drops a 2000-pound bomb at the halfway point, and returns to its base, a suitable fuel load was assigned to be carried internally to supply the bomber after the trailer has been dropped. This fuel load was chosen as large as practicable on the basis of either load-factor considerations or take-off considerations, whichever appeared to be more critical for a particular case. The corresponding range without trailer varied from 3000 miles for the B-26C to 3750 miles for the B-24D.

An estimate of the necessary trailer fuel load was then made and tentative trailer dimensions were chosen to provide this capacity. The trailer efficiency factor $E$ was calculated for the conditions trailer full, trailer half empty, and trailer empty, and the effective average $\bar{E}$ was substituted into formula (3) to obtain the trailer-borne part of the range corresponding to the assumed trailer dimensions and loading. Successive trial assumptions were made until the result brought the aggregate range to 6000 miles.

The process of approximation was guided by certain general rules concerning the efficiency factor $E$. A study of the formula showed that $E$ increases rapidly with the trailer span, for fixed chord, and decreases slowly as the chord is increased, for fixed span. <u>The span should be comparable with that of the bomber for good efficiency, even though structural considerations require that the corresponding section depth, and hence the chord, be</u>

considerably larger than necessary for the required fuel capacity. It will be noted in this connection that the trailers finally selected for the B-17E and the B-24D have of the order of 40 percent excess fuel capacity.

II - Bomber with single towed glider. - If the glider is towed directly behind the bomber - that is, if it has no sidewise displacement relative to the bomber - the induced drag of the combination will be the same as that of the bomber with a trailer of the same span and weight as the glider and having the same vertical displacement (biplane gap). If the glider is identical with the type of trailer described in I, except for the addition of stabilizing surfaces and the replacement of the twin booms by a much longer tow hose, the parasite drag for the glider will be larger than that for the trailer. The tow hose will be by far the greatest contributor, and the uncertainty in its calculation is such that the small increment in drag due to the addition of the control surfaces may be neglected in comparison.

It was found convenient, however, to assume that the parasite drag of the glider is equal to that of the trailer of the same span and weight. Then the previous analysis for the case of the trailer could be considered to apply to the glider also, and the effect of the drag of the tow hose could be introduced later as a correction to the required glider fuel capacity. Accordingly, the results of the calculations for the trailer were given the caption "Trailer or Single Glider." The effect of the tow hose is considered in the discussion.

III - Bomber with twin gliders disposed so as to increase the effective span. - The two fuel-carrying gliders of this combination are considered to be trimmed to glide banked outboard of the points of towline attachment so that the gliders are almost entirely in the wing upwash. The glider wing tips are considered to overlap the bomber wing tips by about 5 percent of the bomber span. This arrangement is equivalent to a marked increase in the aspect ratio providing a considerable increase in the L/D of the combination.

The previous analysis for a tank-wing trailer can be applied to the case of twin gliders with slight modification of the formulas. The range efficiency factor E of equation (2.2) becomes

$$E_{2\ \text{gliders}} = \frac{1 + \dfrac{2L_2}{L_1}}{\sqrt{C_{D_o}/C_{D_{o_1}}} \cdot \sqrt{\tau}} \qquad (2.21)$$

and $\tau$ is redefined as

$$= 1 + 4\sigma_1 \left(\frac{b_1}{b_2}\right)\left(\frac{L_2}{L_1}\right) + 2\left(\frac{b_1}{b_2}\right)^2 \left(\frac{L_2}{L_1}\right)^2 \qquad (2.31)$$

if the small mutual interference between the two gliders is ignored. $L_2$ and $b_2$ refer to one glider. $C_{D_o}$ is the profile-drag coefficient of the combination including both gliders. $\sigma$ is designated $\sigma_1$ because it is no longer the usual biplane interference factor by reason of the lateral displacement of the gliders. It was necessary to calculate the values for the gliders by graphical integration of the upwash (reference 1, p. 183). Because the gliders are largely in the upwash rather than the downwash, the interference factor comes out negative, indicating favorable interference. This favorable interference is sufficient to produce an improvement in $\bar{E}$ of from 9 percent to 22 percent over that for the case of the single glider and the trailer wing. This corresponds to a reduction in the weight of fuel necessary in almost the same proportions.

## Take-Off Determination

Differences in the circumstances when the airplane is towing a trailer wing or one or more gliders make it necessary to analyze in detail the take-off distance to clear a 50-foot obstacle. Because this distance may, in some cases, be the limiting factor, it was further thought advisable to refine the computations by taking account of the effect of the propeller slipstream on the lift and drag (reference 2) and the ground effect.

The take-off distance comprises the ground run, the transition phase, and the steady climb to 50 feet.

Ground run. - For the ground run it was assumed that the airplane was maintained at the attitude of minimum resistance given in reference 3. Following this reference, the acceleration was assumed to be inversely proportional to the square of the speed, on which basis the ground run could be written

$$S_{G.R.} = \frac{0.0336\ V_{t_{mph}}^{\ 2}\ W}{T_{e0.7}} \tag{4}$$

where $V_t$ is the take-off speed in miles per hour, $W$ is the combination gross weight, and $T_{e0.7}$ is the excess thrust at 0.7 take-off speed.

In the calculation of $T_{e0.7}$, the reduction in the airplane induced drag due to ground effect was obtained from the biplane interference formulas of reference 1, page 184. Because of the close proximity to the ground and the effect of the end plates, the induced drag of the trailer or glider was taken as zero. Propeller data were obtained from reference 4, figure 10. The drag of the landing gear of the B-17E was obtained indirectly from specification data (see table I), and values for the other bombers were estimated from it by assuming the coefficients to be in proportion to the respective wing loadings. The coefficients, based on the bomber wing area, were:

| | |
|---|---|
| B-17E | 0.022 |
| B-24D | .03 |
| B-25A | .03 |
| B-26C | .03 |

The coefficient of ground friction was taken as 0.02, appropriate for a hard-surface runway.

Transition phase. - In all cases the take-off speed was chosen so that the trailer, glider or gliders would be airborne before the towing bomber. Because in marginal take-offs the airborne phase is a relatively large fraction of the total take-off distance, it was assumed that the climb would be made at or near the speed of best angle of climb.

In some instances this was near $C_{L_{max}}$, and in others it occurred at a considerably lower lift coefficient. In the former case the transition was calculated on the basis of take-off at $0.9C_{L_{max}}$ using the formula (reference 5):

$$S_{\Delta_1} = \frac{0.011 \left(V_{t_{mph}}\right)^2 W}{T_e} \tag{5.1}$$

where $W$ is the weight of the combination, $V_{t_{mph}}$ is the take-off speed in miles per hour, and $T_e$ is the excess thrust at take-off speed.

In the latter case the transition was calculated on the basis of sufficient excess lift so that the flare could be accomplished without forward acceleration. The formula is

$$S_{\Delta_2} = 0.067 \left(V_{t_{mph}}\right)^2 \frac{\partial D}{\partial L} \tag{5.2}$$

where

$\partial D/\partial L$ = rate of change of induced drag with lift

$$= \frac{2}{\pi} \left[\frac{W_1}{q_1 b_1{}^2} + \frac{\sigma W_2}{b_1 b_2 \sqrt{q_1 q_2}}\right] \tag{5.21}$$

$V_{t_{mph}}$ take-off speed in miles per hour

$W_1$ weight of airplane

$W_2$ weight of trailer or both gliders

$q_1$ dynamic pressure at airplane wing

$q_2$ dynamic pressure at trailer or glider

$b_1$ effective span of airplane

$b_2$ effective span of trailer or glider, and $\sigma$ has the value and sign appropriate to a trailer and a single glider, or to twin outboard gliders, as the case may be (See discussion following equation (2.31).)

$\partial D/\partial L$ was obtained from biplane theory (reference 1, p. 184).

The excess lift at take-off necessary for the assumptions of the formulas of case 2 is

$$\Delta C_L = \frac{26.4T_e}{S_{\Delta_2}A_1} \tag{5.22}$$

where $A_1$ is the airplane wing area. The ratio of the quantity $\Delta C_L$ to the actual excess lift available, for take-off at the speed for best angle of climb, formed the criterion for distinguishing between the two cases in the calculations.

Climb. - The distance covered during the steady climb to clear the 50-foot obstacle is

$$S_c = \frac{50W}{T_e}$$

where W is the weight of the combination and $T_e$ has its usual meaning.

## RESULTS

The results of the calculations are summarized in table I. The column headed "Trailer or Single Glider" applies to the specified bomber with a single tank-wing trailer or glider; the column headed "Twin Outboard Gliders" applies to the bomber with the twin towed glider arrangement previously described. The table gives the trailer and glider dimensions and loading, the bomber loading, the average cruising speed at 15,000 feet during the trailer- (or glider-) borne part of the range, and the take-off distance to clear a 50-foot obstacle. The calculations are based on the assumption that the towed tankage is jettisoned when empty. In the case of the gliders, the drag of the tow hose has been neglected in the preparation of the table. The effect of this hose is discussed later in the text.

The values of the parameters used in the range computations of table I are presented in table II. The origin of the data is indicated. Similar information for the take-off computations is given in table III.

The contemplated arrangement of the trailer wing is shown in figures 1 through 4, for each of the respective bombers. The vertical position of the single towed glider is similar to that of the trailer although it will be further behind the airplane. No drawings of the single-glider arrangement are given. The arrangement of the twin outboard gliders is shown for only two airplanes, the B-24D (fig. 5) and the B-26C (fig. 6). The tank-wing profile assumed for all the trailers and gliders is shown in figure 7.

## DISCUSSION

### Trailer

Trailer height. - A hydraulic or other jacking mechanism for changing in flight the incidence of the tank wing relative to the towing booms is desirable to get the trailer out of the tail gunner's cone of fire. Getting the trailer up high is aerodynamically desirable, also, in that biplane theory indicates a reduction in induced drag. A steep boom-to-wing-chord angle is to be avoided, however, since it would tend to overstress the wing by adding to the lift an appreciable component of the boom tension. Practical positions are shown in figures 1 to 4, and it was presupposed in making the calculations that these respective positions are to be maintained throughout the flight, presumably by a jacking mechanism.

The jacking mechanism can be omitted. With a fixed angular setting relative to the boom, the trailer will automatically swing up to change its angle of attack from the take-off value to the cruising value. Moreover, the trailer will continue to rise as it empties. The trailer will not attain sufficient height, however, and the resulting increased drag will require from 1.5 to 5 percent additional fuel for the trailer-borne part of the range for optimum fixed trailer-boom incidence. Three percent to 9.4 percent additional fuel will be required for the trailer-boom incidence assumed in the take-off calculations.

Stability. - The original experimental investigations of the British revealed a lack of stability on the ground. They found that with the castering trailer undercarriage the trailer is subject to lateral oscillations of large amplitude while, with fixed undercarriage, the pilot has no control over the direction of his take-off path. It is understood that the British have since arrived at an arrangement of undercarriage and booms which provides satisfactory ground handling, but the details have not been available. Captain Cooper, of the Materiel Center, has suggested that the instability on the ground could be avoided by permitting lateral freedom of the booms at the wing and trailer juncture and linking the wheels to the booms in a manner equivalent to that of figure 8. The wheels are mounted in dollies which are left behind at the take-off. By contrast, the booms of the trailers shown in figures 1 to 4 have bracing wires to permit no lateral motion.

The directional stability in the case of braced booms is modified by the presence of the trailer. The rearward shift of the resultant center of gravity reduces the effective lever arm of the tail and correspondingly reduces its weathercock effect. The fin effect of the trailer end plates is intended to counteract this reduction, and preliminary calculations indicate that the areas shown are of the right order of magnitude. Where the booms have lateral freedom, the above considerations do not apply. Captain Cooper contemplated coupling rudders on the trailer to the booms to obtain directional stability. In figure 8 the end plates are shown movable and are linked to produce a similar effect.

Whether or not the booms have lateral freedom, the longitudinal stability should be affected very little by the presence of the trailer since the booms are free to move about a hinge line in the wing parallel to the Y axis.

Control. - The elevator control should be satisfactory due to the hinging of the booms at the wing. The rudder effectiveness with the booms laterally braced will be considerably decreased by the rearward shift of the center of gravity and the fin effect of the trailer end plates. Where the booms have lateral freedom, the rudder effectiveness should be little impaired. The aileron effectiveness will be considerably reduced in either case by the additional damping in roll contributed by the trailer. The control is felt, however, to be sufficient for the transport type of operation contemplated while the trailer is attached.

Fuel transmission. - It appears that the problem of getting fuel from the trailer to the airplane does not involve excessive difficulties. Considerations of strength will require the booms to have sufficient diameter to contain adequate fuel lines. The manner of obtaining a flexible coupling where the booms are hinged to the wing will require a special examination which cannot be gone into here.

Take-off calculations. - During the air-borne phase of the take-off, the decrease in the induced drag due to the ground effect and the increase in the induced drag due to the time rate of increase of the lift (so-called unsteady drag) were both neglected. The values for the induced drag assumed in the calculations are therefore likely to give conservative results due to the preponderance of the former effect. By comparison with experimental data in reference 6, it is estimated that for the take-off calculations of the subject bomber combinations the ground effect should account for a reduction in the take-off distance of some 300 feet from the tabulated values.

Bombs in trailer. - Additional bombs might be carried in the oversize trailers of the B-17E and B-24D if the corresponding increase in take-off run could be permitted. The range would be unaltered if 300 pounds of fuel were added for each 1000 pounds of bombs.

## Single Towed Glider

Glider height. - For the trailer calculations to apply to a glider of the same span, weight, and parasite drag, the glider must be trimmed to maintain the same height relative to the towing airplane as the trailer in figures 1 to 4, respectively. The maintenance of this height is a part of the general problem of the stability of a towed glider and is outside the scope of this report.

Stability and control. - The stability of the glider itself has been the subject of investigation at Wright Field. The stability of the towing bomber is not expected to be appreciably affected by the presence of the glider. The control should likewise be practically unaffected.

Tow-hose drag. - The length of the tow hose will influence the stability of the glider. Until the stability problem is solved, therefore, no definite value may be assigned to the tow-hose drag. Some indication of the probable magnitude of this drag can be obtained by assuming several probable hose sizes and lengths. It is very unlikely that the glider may be towed with a hose of less than 200 feet in length. With this length, an internal diameter of approximately 1 inch will be required to transmit the fuel for 400 horsepower at a rate of 0.5 pound per horsepower per hour with a pressure drop of the order of 4 inches of mercury. A wall thickness of 1/4 inch is assumed as reasonable for the strength requirements, giving an outside diameter of 1.50 inches for the tow hose.

It was found that the tension in this hose due to the drag of the glider is sufficient so that the sag is very small (less than

3 ft in 200) and the tow-hose drag is principally skin friction. On this basis, it was concluded for the conditions assumed that the drag of the tow hose should reduce the maximum L/D by the order of 0.6 percent for the single-glider arrangements studied.

As the length of the tow hose is increased, the size must be increased in order to obtain the same rate of fuel flow for the specified pressure drop of 4 inches of mercury in the hose. The sag of the hose also increases with the length. Both these factors tend to increase the tow-hose drag, but the effect of sag does not become appreciable until the length is 400 feet and the diameter 2 inches. Estimates for a 400-foot length of hose, for which the size for the specified fuel flow is 1.75 inches, give a reduction of maximum L/D of 1.5 percent, indicating the hose drag increases somewhat faster than linearly with the length for constant fuel-flow resistance. The effect of hose diameter is also important; going to a 2-inch hose of this same length changes the estimated reduction of the maximum L/D to 2 percent. Beyond these dimensions the increasing influence of sag causes the tow-hose drag to rise very rapidly with length and size.

Twin outboard gliders. - It may prove difficult to maintain a stable glider configuration like that proposed in this report. This arrangement was included, however, principally for comparison. The supposition was that if the calculations should show that the outboard-glider arrangement could provide the required range with substantially less towed tankage than could the trailer or single glider it would be worth-while to attempt to solve the stability problem. Comparison of the two columns of table I shows that the fuel carried by the two outboard gliders weighs from 12 percent to 23 percent less than that carried by the corresponding single glider or trailer wing. This improvement should be measured against the difficulty with stability, but first the figures must be corrected for the effect of the drag of the tow hose.

Each of the twin outboard gliders has only of the order of one-seventh the drag of the much larger single glider. This is to be attributed to the considerable reduction in induced drag attendant on their location in the towing-bomber upwash. The sag due to the lightness of the tension and the lateral displacement of the gliders relative to the tow points combine to multiply the tow-hose drag, compared with the value for the single glider. This drag was estimated for several assumed hose dimensions on the basis of the data in reference 7 on the drag of wire and cable inclined to the wind. The hose size was chosen appropriate to half the rate of fuel flow considered above for 4-inches-of-mercury pressure drop.

A 200-foot, 1.2-inch hose was estimated to reduce the maximum L/D of the combination by about 2.5 percent. A 400-foot, 1.4-inch hose has the same fuel-flow resistance; for this length, the estimated reduction in maximum L/D is about 7 percent. For a 2-inch hose of the same length, however, the estimated reduction in the maximum L/D comes to 37 percent. The values of twin-outboard-glider fuel capacity, specified in table I, should be increased by very nearly these percentages for operation with the respective tow hoses. It is evident that for the conditions considered the tow-hose drag goes up somewhat faster than the length for fixed-fuel-flow resistance and very much faster than the diameter for fixed length. The drag is still small enough for the 400-foot, 1.4-inch tow hose so that the fuel-saving advantages of the outboard-glider arrangement are appreciable.

## CONCLUDING REMARKS

1. It was found that trailers which would achieve the required 6000-mile range weigh, in the full condition, one-fourth to one-third as much as the bombers, heavily loaded, to which they are attached. Their span is about three-fourths that of the bomber for the heavy bombers, about the same as that of the bomber for the medium bombers.

2. Single towed gliders which would achieve the 6000-mile range have approximately the same weight and span as the corresponding trailers, provided the tow-hose diameter is not over 2.0 inches and the tow-hose length is not over 400 feet.

3. Each of the two gliders in the outboard-glider arrangement which would achieve the 6000-mile range weighs one-seventh to one-fifth as much as the bomber to which it is attached. Their span is

about half that of the bomber in all the cases. The necessary towed fuel is approximately 9 to 20 percent less than that carried by the corresponding single glider or trailer if the tow hoses are 200 feet long and 1.2 inches in outside diameter. The reduction in towed fuel depends critically on the length and diameter of the tow hoses.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 31, 1942.

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TABLE I

SUMMARY OF RESULTS OF THE CALCULATIONS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

| irplane and ecifications | | Trailer or single glider | Twin outboard gliders | | Trailer or single glider | Twin outboa gliders |
|---|---|---|---|---|---|---|
| -17E, Air orps Spec. o. C-212-5A, une 4, 1941, oeing Air- raft Co. | Span | 80 ft | 50 ft | Bomber gross weight | 56,500 lb | 56,500 lb |
| | Chord | 8 ft | 6 ft | Internal fuel | 2,780 gal | 2,780 gal |
| | Weight empty | 2000 lb | 2400 lb (2) | Combination weight | 75,900 lb | 74,100 lb |
| | Fuel | 2900 gal | 2540 gal (2) | [1]Average cruising speed | 189 mph | 175 mph |
| | | | | Take-off/50 ft | 4,700 ft | 4,700 ft |
| -24D, Air orps Spec. o. DA-C-212- , May 12, 941, (Con- olidated odel No. 32 omber) | Span | 80 ft | 51 ft | Bomber gross weight | 56,500 lb | 56,500 lb |
| | Chord | 8 ft | 5.5 ft | Internal fuel | 2,850 gal | 2,850 gal |
| | Weight empty | 2000 lb | 2200 lb (2) | Combination weight | 74,500 lb | 72,100 lb |
| | Fuel | 2670 gal | 2240 gal (2) | [1]Average cruising speed | 181 mph | 169 mph |
| | | | | Take-off/50 ft | 7,300 ft | 6,000 ft |
| -26C, Air orps Spec. o. C-213-8, une 27, 1941, lenn L. artin Co. | Span | 72 ft | 30 ft | Bomber gross weight | 36,500 lb | 36,500 lb |
| | Chord | 7 ft | 7.1 ft | Internal fuel | 1,630 gal | 1,630 gal |
| | Weight empty | 1700 lb | 1600 lb (2) | Combination weight | 54,100 lb | 51,500 lb |
| | Fuel | 2650 gal | 2240 gal (2) | [1]Average cruising speed | 230 mph | 214 mph |
| | | | | Take-off/50 ft | 6,900 ft | 6,500 ft |
| 25A, Air orps Spec. o. C-213-1A, pril 11, 940, North merican odel P-442- 4 (NA-62) | Span | 67.5 ft | 30 ft | Bomber gross weight | 33,000 lb | 33,000 lb |
| | Chord | 6.75 ft | 6 ft | Internal fuel | 1,730 gal | 1,730 gal |
| | Weight empty | 1600 lb | 1400 lb (2) | Combination weight | 47,000 lb | 44,000 lb |
| | Fuel | 2070 gal | 1600 gal (2) | [1]Average cruising speed | 209 mph | 195 mph |
| | | | | Take-off/50 ft | 5,700 ft | 5,550 ft |

t 15,000 feet; average for trailer- or glider-borne part of flight.

TABLE II

ELEMENTS OF THE RANGE CALCULATIONS

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| | B-17E | B-24D | B-26C | B-25A |
|---|---|---|---|---|
| **From specifications** | | | | |
| Wing area, square feet | 1420 | 1048 | 602 | 610 |
| Span, feet | 104 | 110 | 65 | 67.5 |
| **Assumed** | | | | |
| Efficiency factor $e$ for airplane[1] | .81 | .81 | .81 | .81 |
| Trailer or single-glider height, feet | 23 | 19 | 16 | 15 |
| $\frac{\text{Effective span}}{\text{Geometrical span}}$ for trailer and single glider[2] | 1.155 | 1.08 | 1.08 | 1.08 |
| $\frac{\text{Effective span}}{\text{Geometrical span}}$ for outboard gliders[2] | 1.04 | 1.08 | 1.082 | 1.125 |
| **Estimated** | | | | |
| Propulsive efficiency $\eta$ at high speed | .84 | .85 | .84 | .87 |
| Parasite coefficient $C_{D_{o_2}}$ for trailer and gliders[5] | .012 | .012 | .012 | .012 |
| $(\overline{\eta/c})$ (from known range values and L/D) | [3]1.86 | 1.87 | 1.91 | 1.87 |
| **Calculated** | | | | |
| Parasite coefficient $C_{D_{o_1}}$ for airplane[5] | .0249 | .0363 | .0271 | .0303 |
| Maximum (L/D) for airplane, $(L/D)_{1max}$[4] | 13.91 | 14.22 | 12.61 | 12.50 |
| Interference factor $\sigma$ for trailer and single glider | .43 | .46 | .45 | .45 |
| Interference factor $\sigma_1$ for outboard gliders | -.225 | -.225 | -.225 | -.225 |
| Range efficiency factor $\overline{E}$ for trailer and single glider | .964 | .97 | .953 | .98 |
| Range efficiency factor $\overline{E}$ for outboard gliders | 1.102 | 1.10 | 1.089 | 1.101 |

[1]This efficiency factor was used in calculating $C_{D_{o_1}}$. The ratio of the airplane effective span to the geometrical span was taken as unity, however, for the calculations involving biplane formulas.

[2]Sufficient end-plate area was assumed to be provided to give these respective values; the areas shown in the drawings are only approximate.

[3]This value was calculated with the aid of propeller charts and the specific fuel consumption chart of the article by Scoles and Schoech, reference 8.

[4]Strictly speaking, $(L/D)_{1max}$ need not have been calculated; an average value of $\left[\frac{\eta}{c}\left(\frac{L}{D}\right)_{1max}\right]$ could have been obtained by substituting specification range values in the Breguet formula. The former procedure seemed clearer for purposes of exposition.

[5]The coefficients are based on the respective wing areas in each case.

TABLE III

ELEMENTS OF THE TAKE-OFF CALCULATIONS

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| Bomber with trailer or single glider | | | | | | | |
|---|---|---|---|---|---|---|---|
| Airplane | Lift coefficient during ground run | | At take-off | | Take-off speed, mph | Ground run (ft) | Total distance to clear 50 ft obstacle |
| | Airplane | Trailer or glider | [1]Airplane | Trailer or glider | | | |
| B-17E | 0.30 | 0.82 | 1.08 | 0.82 | 120 | 3750 | 4700 |
| B-24D | .57 | .80 | 1.46 | .80 | 120 | 3670 | 7300 |
| B-26C | .32 | .70 | 1.05 | .70 | 150 | 5380 | 6900 |
| B-25A | .30 | .66 | 1.16 | .66 | 135 | 4440 | 5700 |
| Bomber with twin outboard gliders | | | | | | | |
| | Airplane | Gliders | Airplane | Gliders | | | |
| B-17E | 0.30 | 1.05 | 1.40 | 1.05 | 105 | 2685 | 4700 |
| B-24D | .57 | .75 | 1.46 | .75 | 120 | 3280 | 6000 |
| B-26C | .32 | .81 | 1.40 | .81 | 130 | 3500 | 6500 |
| B-25A | .30 | .83 | 1.46 | .83 | 120 | 3130 | 5550 |

[1]The circumstances of the take-off were chosen to minimize the distance to clear a 50-foot obstacle. The ground run in the cases of the B-17E, B-26C, and B-25A, each with trailer, would be some 25 percent shorter if the take-off were made at $0.9C_{L_{max}}$.

L-591

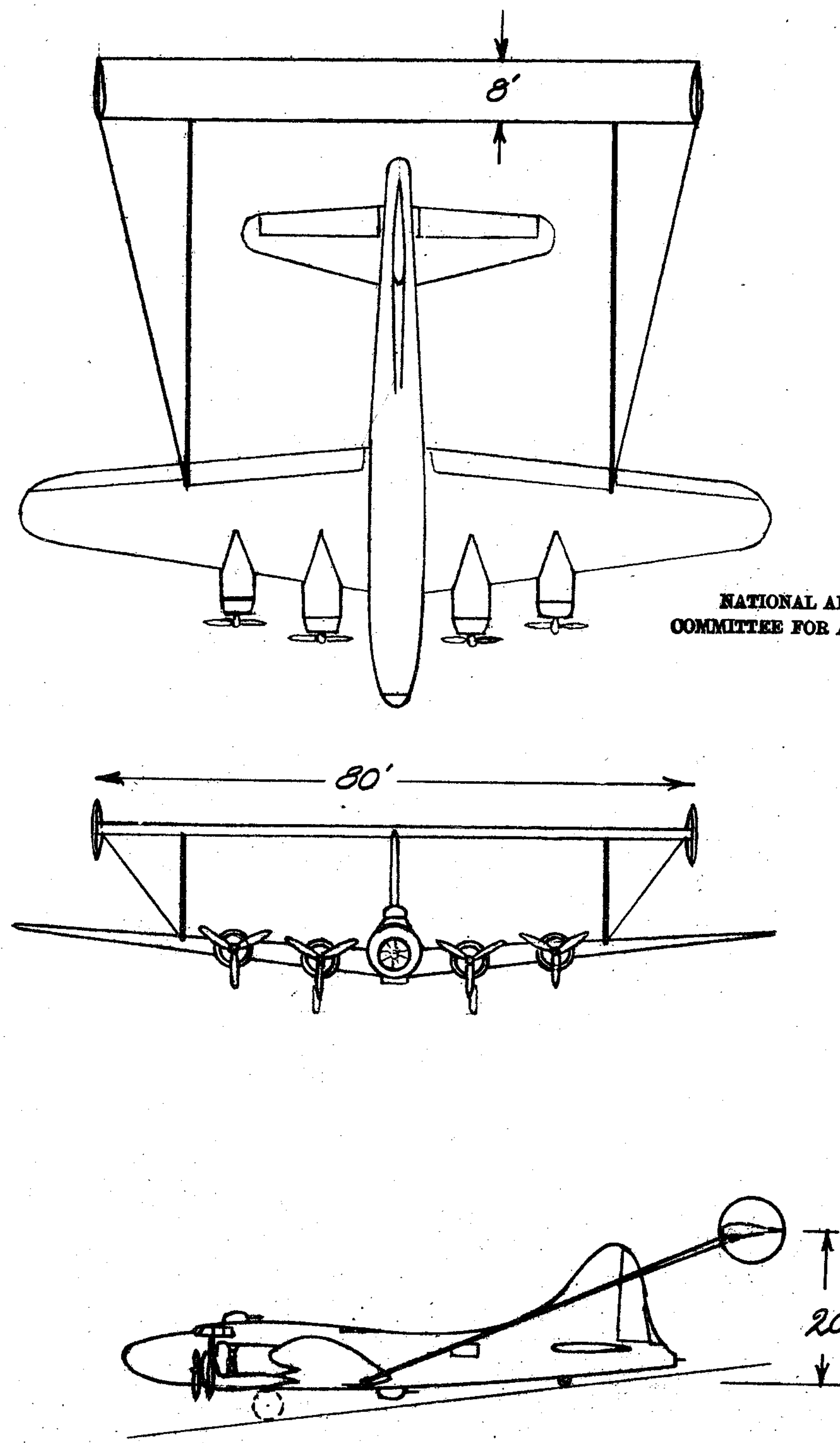


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Figure 1.
BOEING B-17 E WITH TRAILER

L-591

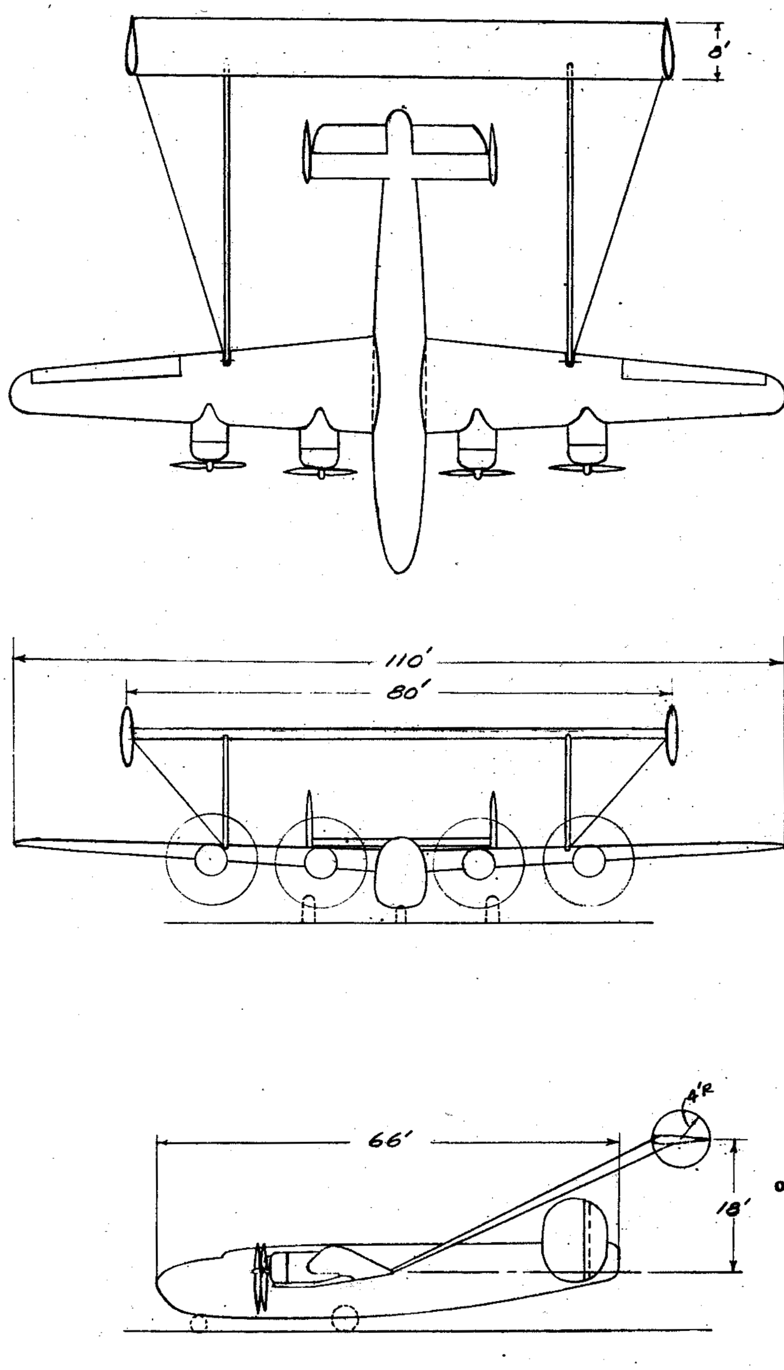




Figure 2.
Consolidated B-24D Airplane with Trailer.

L-591

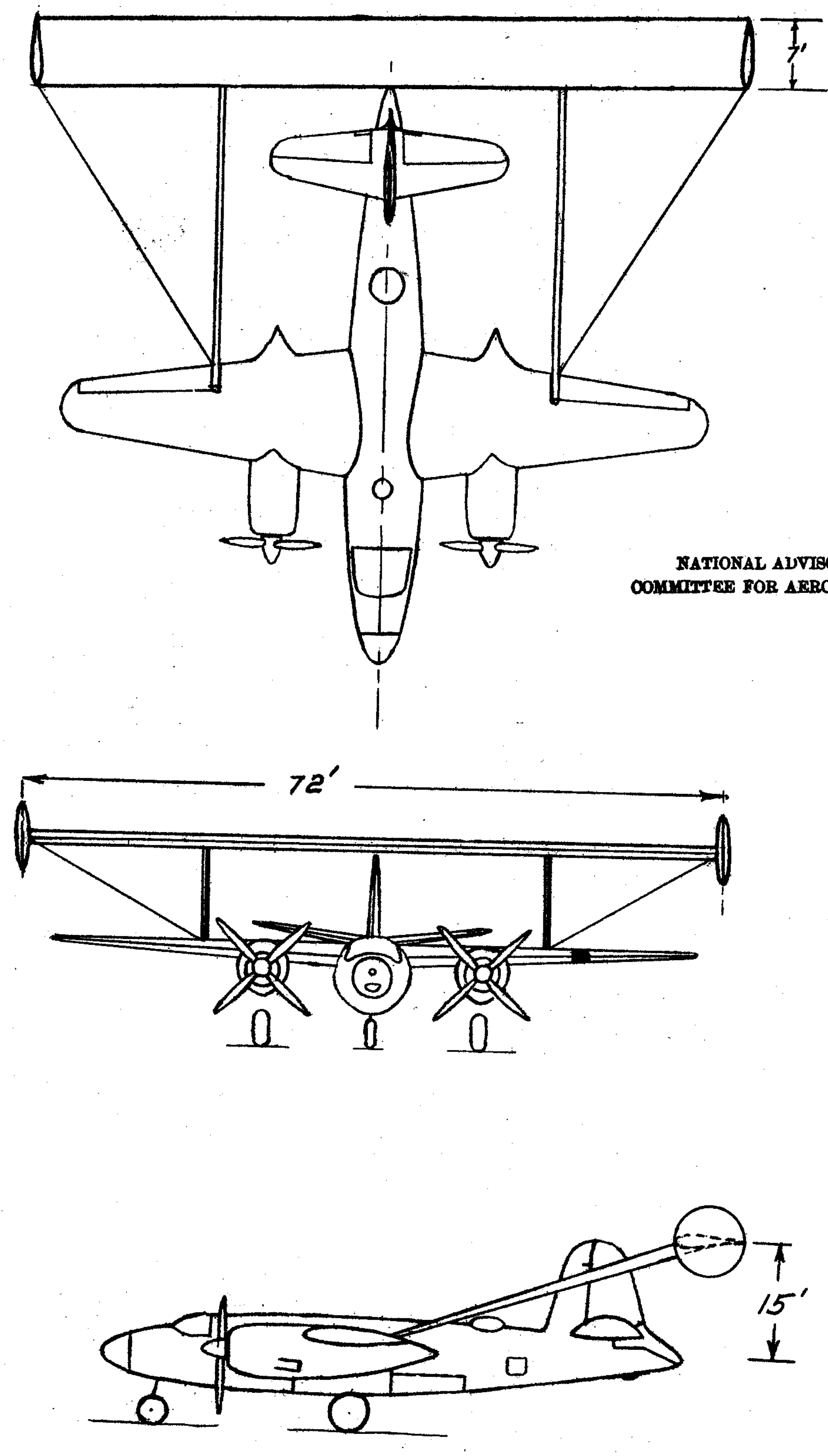


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Figure 3
Martin B-26C Airplane with Trailer.

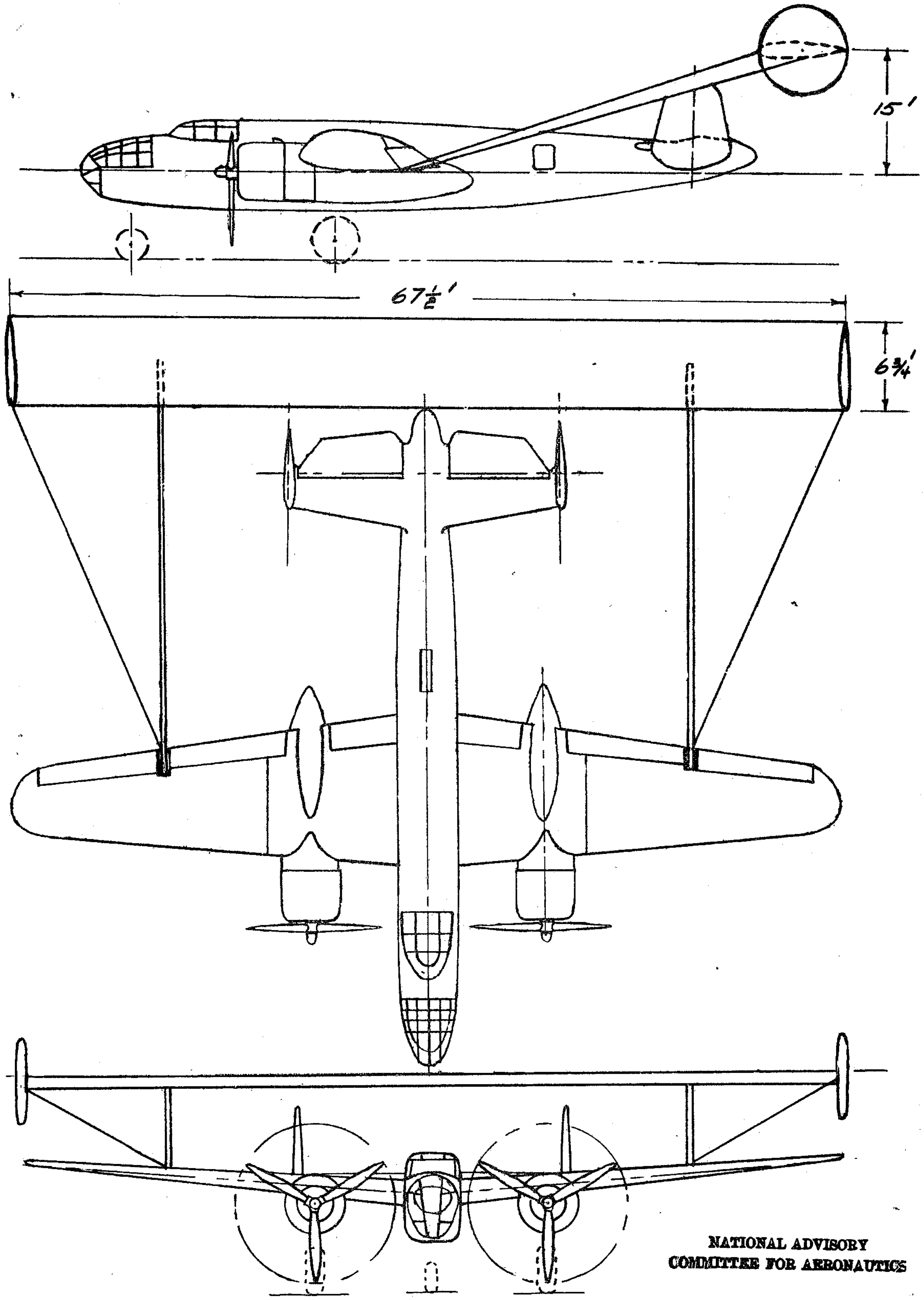


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Figure 4.
North American B-25A Airplane with Trailer.

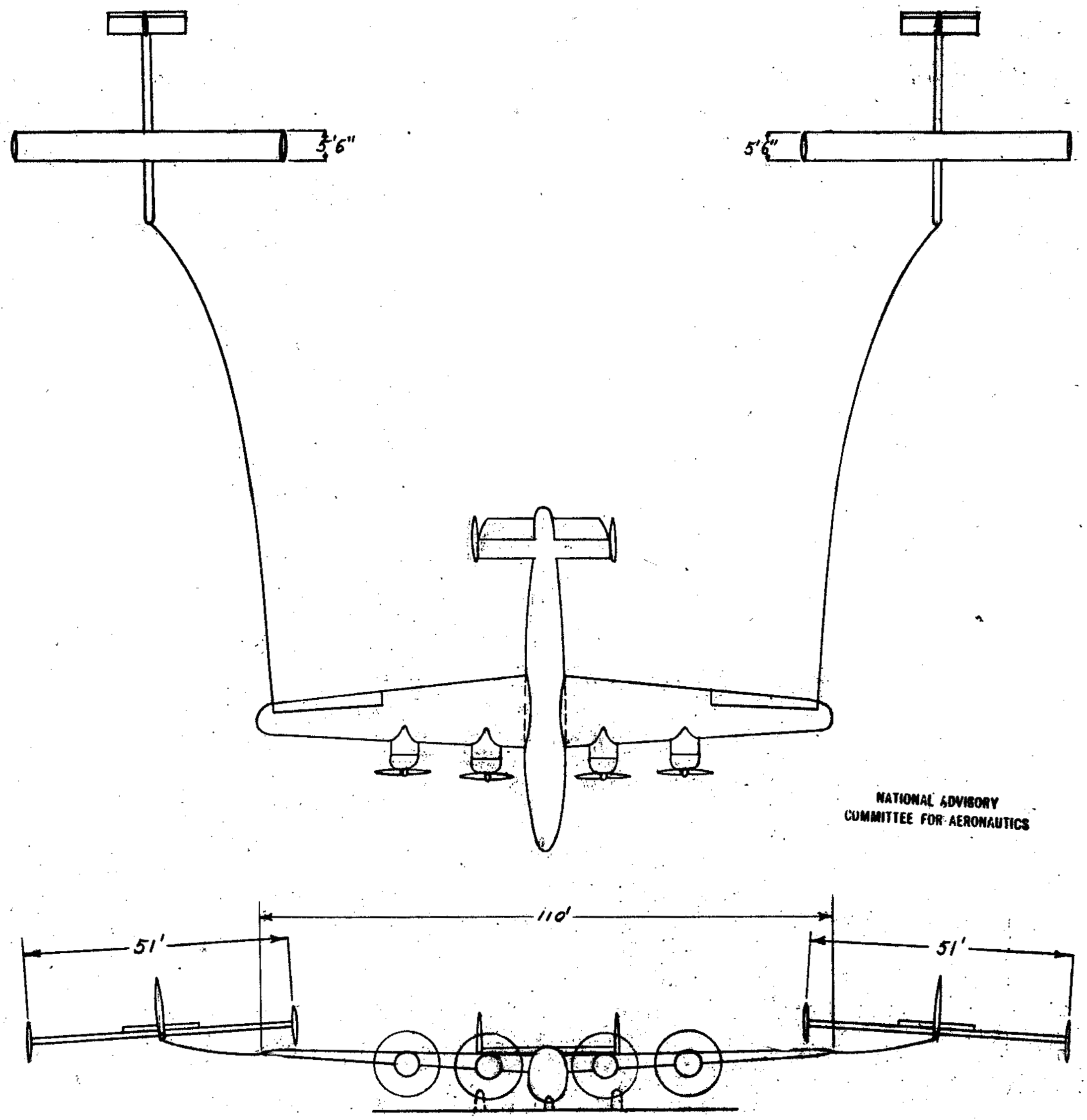





FIGURE 5.

CONSOLIDATED B-24
WITH GLIDERS

L-591

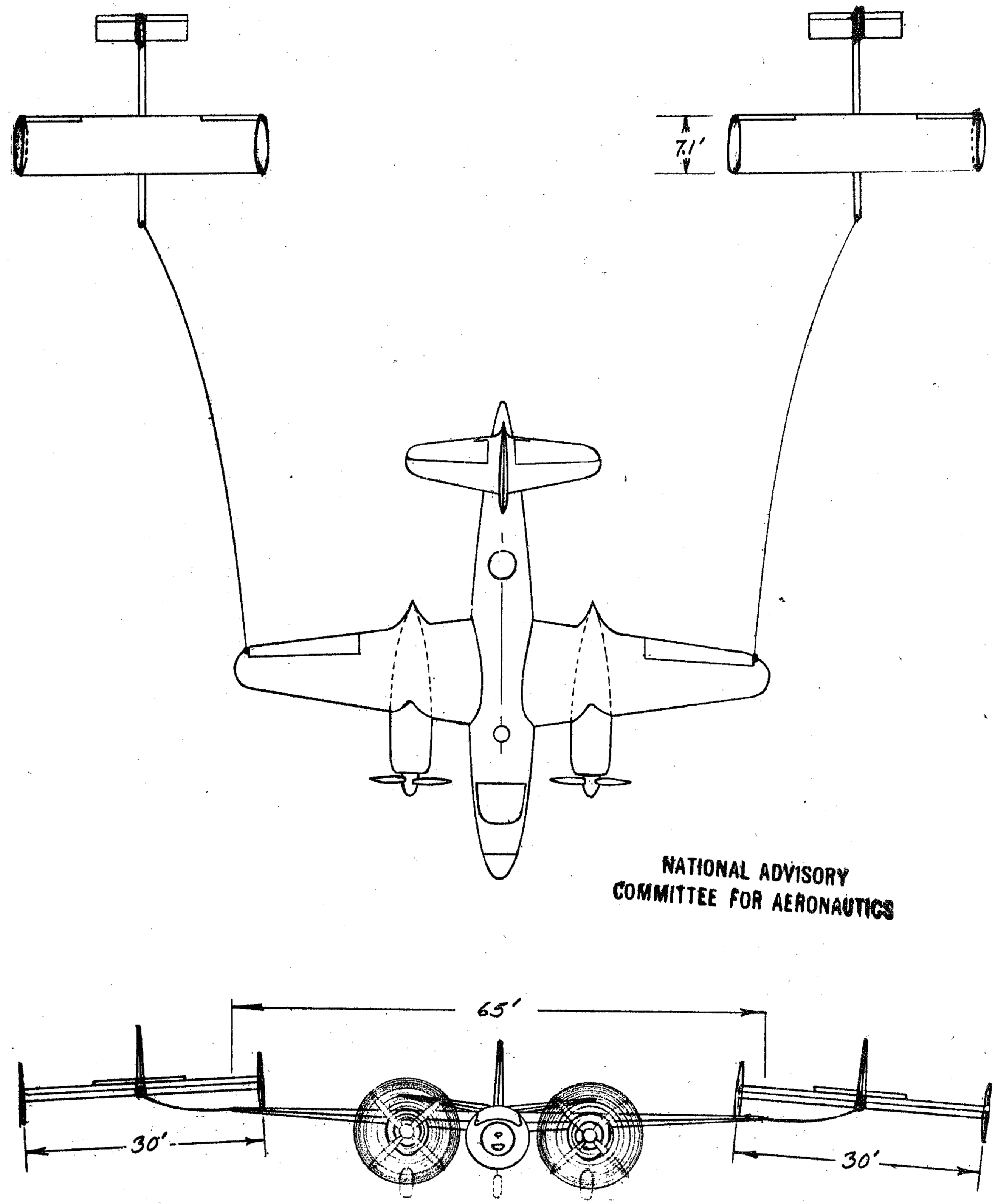
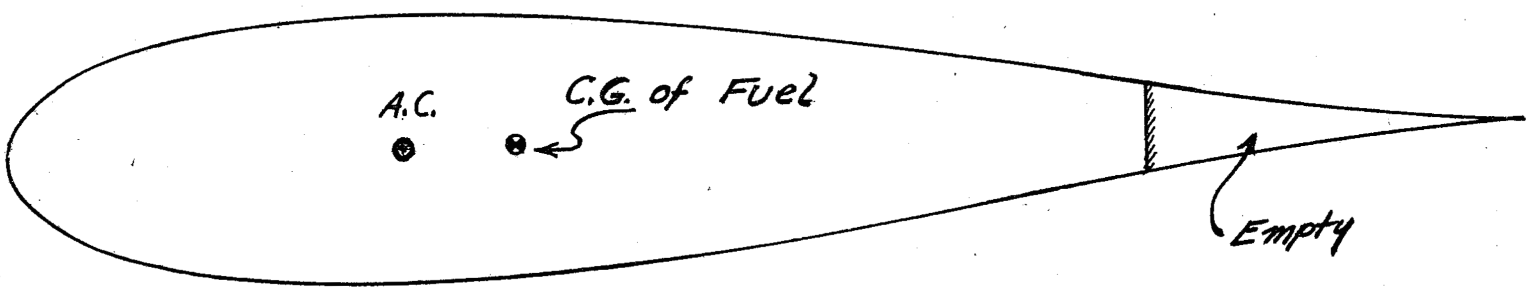





Figure 6.
Martin B-26C Airplane with Gliders




WING SECTION OF TRAILER

Figure 7.

L-591

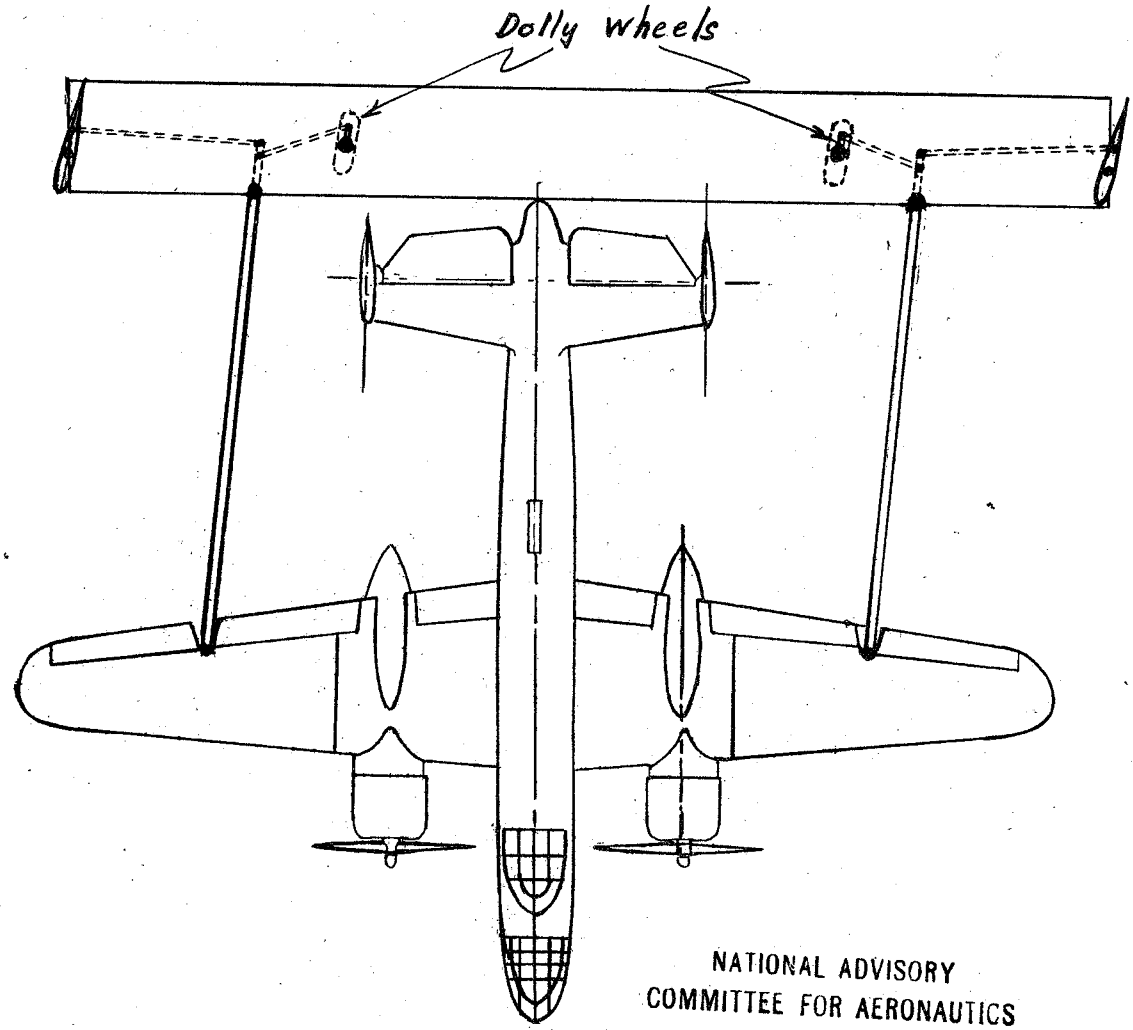



Figure 8.

Trailer Arrangement Considered for Ground Stability (Shown Attached to B-25A Airplane)