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TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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Chap IV 81

No. 478

THE CELLS OF GIANT AIRPLANES

By ~~E. Offermann~~ A. R. Weyl.

From Offermann's "Riesenflugzeuge," 1927

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Washington
September, 1928

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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By ~~E. Offermann.~~ A. R. Weyl.

Increasing the Size of Airplanes

The "Superairplane"

The beginnings of the superairplane extend back into the prewar period. If the historical airplane of the Englishman, Hiram Maxim, be disregarded, the honor doubtless belongs to the Russian engineer Sikorsky for having designed and built the first serviceable superairplane. The first Sikorsky four-engined airplane was begun in 1912 and was finished and flown in 1913. Four or five improved airplanes of this type were built for the Russian Army before the beginning of the war.

Strictly speaking, the original Sikorsky biplane cannot be called a giant airplane, since the engines were not ordinarily accessible during flight and the division of the power plant was not alone sufficiently distinctive for classification purposes. Long before Sikorsky's, there were airplanes with a divided power plant (Bleriot-Voisin 1907-8, Short 1911, Rumpler-Lutzkoy 1912). Nevertheless, the dimensions and weight of the Sikorsky airplane were much greater and its carrying capacity was great enough to include a mechanic as one of the crew.

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*From Offermann's "Riesenflugzeuge" (1927), pp. 184-193.

The span of the second Sikorsky airplane "Ilia-Murometz" was 37 m (121.4 ft.), length 20.2 m (66.3 ft.), wing area 142 m^2 (1528 sq.ft.). The power plant consisted of four German Argus engines of 100 HP. nominal rating each and had a temporary maximum output of about 420 HP. and a permanent output of 320-350 HP. The engines were installed on the lower wing on both sides of the long fuselage and each one actuated a tractor propeller by direct drive. As already stated, accessibility during flight was possible only in case of emergency and at the risk of life. The normal flying weight (full load) was given as 3500 kg (7716 lb.) which seems too small. This would make the wing loading only 23.2 kg/m^2 (4.75 lb./sq.ft.), an improbably small value for an airplane of such dimensions. It is estimated that the wing loading of this airplane, under full load, may have been about 30 kg/m^2 (6.14 lb./sq.ft.). The advertised speed of 110 km (68 mi.) per hour corresponded to the prewar state of aviation. The very first Sikorsky four-engined airplane, the "Russky Witiaz," was discarded before the war, as a purely experimental airplane, since its performances were far exceeded by the above-described "Ilia Murometz" (1913-14). The latter, in test flights with 15 occupants (in January, 1914), attained an altitude of 300 m (984 ft.) in 18 min. 10 sec. with a useful load of 1310 kg (2888 lb.): During the spring and summer of 1914, flights of six and more hours were made with this airplane.

Such was the state of development of the "superairplane" at the beginning of the war. The design of the first Siemens airplane, of the Forsmann type, was derived directly from the Sikorsky airplane, while Baumann and Hirth adopted new ideas in designs, which had taken shape, even before the war, on the announcement of Sikorsky's success.

During the war the development of superairplanes continued without regard to any limits. It was sought especially to increase the radius of action, carrying capacity and safety of operation. The application of the law of similitude and the lessons learned in the construction of giant airplanes showed, however, that the enlarging of airplanes is probably limited by the fact that the empty weight increases disproportionately with the enlargement, so that finally the gradually decreasing carrying capacity would disappear altogether and then assume a negative value (See Everling, "Die Vergrösserung der Flugzeuge" in Technische Berichte der Flugzeugmeisterei"). This principle applies to all enlargements of a normal airplane.

Attention was called to this fact in 1916 by the English aeronautic engineer Lanchester (F. R. Lanchester, "Development of the Military Airplane: The Problem of Enlargement," Engineering, 1916, p.212). His views were accorded much consideration, even outside of England, and in many places gave rise to an expectant attitude.

In Everling's conception of Lanchester's train of thought, Lanchester proceeds from an airplane with a given carrying capacity (in addition to the fuel load). Whatever gain is then made in carrying capacity increases the amount of fuel which can be carried and consequently the flight duration. Lanchester considers only geometrically similar airplanes, whose wing loading and speed remain constant. If subordinate influences are disregarded, the power loading must then remain the same for aerodynamical reasons. Since the weight of the power plant is almost proportional, within narrow limits, to the power, the former increases in the same ratio as the flying weight (full load), i.e., the ratio of the weight of the power plant to the flying weight of the airplane is the same for the small airplane as for the enlarged airplane. Lanchester assumed the weight of the power plant to be about one-fourth of the full load. This ratio was higher for giant airplanes of the war period, being 38-45% of the full load. According to Lanchester, another quarter of the full load consisted of the fuselage, empennage, and landing gear. Though a few parts can be made relatively lighter on a large airplane, this is offset by the greater weight of the landing gear. According to Lanchester, there remains only half of the full load for the wings and the useful load (including the fuel). The estimation of the useful load or of the limit of enlargement depends on the ratio of increase in the weight of the wings as compared with the increase in the full load.

According to Lanchester, the following is the case. The full load, like the wing area, must be proportional to the square of the span (Constant wing loading!). In geometric enlargement, however, the volume (and consequently, the weight of the wings) is proportional to the cube of the span. Hence it follows that the weight of the wings must increase in proportion to the 1.5 power of the full load. In doubling the dimensions, the span would therefore be increased twofold, the wing area and full load fourfold, but the weight of the wings eightfold the original value, the strength of the thus-enlarged wings remaining the same. The ratio of their weight to the full load, however, is doubled. This indicates a rather low limit to the enlargement of airplanes. Giant airplanes, like the ones built during the war, must accordingly be considered uneconomical in the narrower sense.

Lanchester's reasoning applies, however, only to geometrically similar enlargements of airplanes. In reality, there is no such thing. Consequently, the enlargement limit is higher than the one originally found. The ratio of the weight of the power plant to the full load will diminish with the enlargement, even when there is geometric similarity, since both the weight of the engine alone and the weight of the whole power plant has been found by experience to decrease with respect to the power. On the other hand, in an enlargement which is not geometrically similar, the unit weight of a divided power plant is less favorable in comparison with that of an undivided one. Moreover, the fact is disregarded that weight can be saved in the enlarged parts by structural devices, all the more when it is considered that many parts must be made stronger in view of local stresses on small airplanes, than is necessary for the strength of the whole. Everling investigated these influences, on the basis of experimental data obtained from a large number of airplanes, and found that, as compared with normal airplanes, the ratio of the weight of the wings to the full load actually increased, but not to nearly so large a degree as assumed by Lanchester.

Rohrbach finds, moreover, in contrast with the results of Everling's researches that, as regards the giant airplanes built during the war, Lanchester's theory, concerning the increase in the ratio of the weight of the wings to their size, is confirmed, if the Everling data are evaluated in accord with the Lanchester views on the assumption of equal strength (load factors) and equal wing loading. Rohrbach* accordingly reduced all the wing weights collected by Everling** to a load factor of 5 and a wing loading of 40 kg/m (8.19 lb./sq.ft.) as the basis of comparison. The breaking load of the reduced wing is therefore about 200 kg/m (40.96 lb./sq.ft.). In agreement with Everling, it was thereby assumed that an increase of 100% in the breaking load of the wing increases the weight of the wing 50% per unit area. Under the simplifying assumption of a linear dependence of the breaking load of the wing on its calculated

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*A. Rohrbach, "Bausicherheit und Kurvenflug," Zeitschrift für Flugtechnik und Motorluftschiffahrt 1922, p. 1 (N.A.C.A. Technical Note No. 107, 1922). See also "Neue Erfahrungen mit Grössflugzeugen," Berichte und Abhandlungen der W.G.L., July, 1925, pp. 29-36 (N.A.C.A. Technical Memorandum No. 355, 1926).

**E. Everling, "Die Vergrösserung der Flugzeuge," Technische Berichte, III.

weight per unit area, which appears justifiable for the wing weights of the war-time airplanes, Rohrbach bases the calculation of the wing weight per unit area on the following equation

$$\frac{G_{F_{red}}}{F} = \frac{G_F}{F}\left(0.5 + \frac{100}{\sigma\,\frac{G}{F}}\right),$$

in which

F = wing area (m²),

G = full load (kg),

G_F = actual weight of wings (kg),

$G_{F_{red}}$ = converted weight of wings (kg),

σ = actual load factor.

Moreover, Rohrbach resolves the wing weight into an "ideal wing weight" and an "actual additional weight," the latter being simply the weight of the additional material theoretically necessary to withstand all the stresses with the desired margin of safety. The actual increase includes all the weights added in order to facilitate the production of the structural parts and to give them sufficient strength to withstand all local stresses (Fig. 2).

Lanchester's conclusions accurately apply to the ideal wing weight, which increases with the 1.5 power of the ratio of the increase in weight with increasing size of the wings. The greater the wing, the smaller the actual weight increase in proportion to the ideal wing weight. The actual increase for very large wings approaches a certain limit which cannot be exceeded by further enlargement. The structural nature of the wing has an important bearing on the actual weight increase.

A smaller increase in the ratio of the wing weight to the full load appears possible therefore, when the wing loading is increased. Then, however, the landing speed will also necessarily be higher. On the other hand, the power loading must also simultaneously be reduced somewhat, i.e., the ratio of the power-plant weight to the total load. The wing loading and power loading, in fact, aerodynamically involve one another. Rohrbach investigated the problem of how far the enlargement of airplanes can be economically carried, when the wing loading is thereby increased. The giant airplanes of the war period generally had wing loadings but little higher than those of normal airplanes, which therefore corresponded to the Lanchester method of enlarging with constant wing loading. Rohrbach recognized that the limit of the full load is much higher, when the wing loading is increased with the full load. The four-engined monoplane of the Staaken Zeppelin Works with over 80 kg/m² (16.39 lb./sq.ft.) was created from this viewpoint, having been designed by Rohrbach (Fig. 1).

In the Rohrbach method of enlargement, the wing loading increases with the full load, as already mentioned. Hence smaller wing areas are obtained for the same ratio of the wing weight to the full load, so that the greater weight of the wing per unit area, connected with the greater wing loading, can be accepted into the bargain. The ratio of the weight of the airplane without the power plant to the full load therefore increases slower here than for the usual method of enlarging during the war with nearly constant wing loading. The following comparative table of the two methods of enlarging was taken from an article by A. Rohrbach, "Die Vergrosserung der Flugzeuge," Berichte und Abhandlungen der W.G.L. 1922, p. 37.

According to	Lanchester	Rohrbach
Ratio of lengths	$\alpha^{0.5}$	$\alpha^{0.333}$
" " wing areas	α	$\alpha^{0.667}$
" " full loads	α	α
" " flight speeds	1	$\alpha^{0.167}$
" " engine powers	α	$\alpha^{1.167}$
" " wing loadings	1	$\alpha^{0.333}$
" " power "	1	$\alpha^{-0.167}$
" " curve radii	1	$\alpha^{0.333}$

The method of enlarging proposed by Rohrbach rests on the possibility, supported by good climbing performances, of building large airplanes, so that they will have a model similarity in their flight characteristics, especially in curving flight, to the smaller airplanes. They are based therefore on model similarity of the flow diagram, i.e. on the enlargement law commonly used in building ships. Such was not the case with the giant airplanes built during the war. Instead of the Rohrbach method of enlarging, one can, of course, imagine other methods, in which the wing loading increases systematically with the full load. It would then be necessary to apply only one of the other enlargement laws of the mechanics of similarity (Cf. M. Weber, "Aehnlichkeitsmechanik," Hütte (24), Vol. I, p. 401).

The enlargement method proposed by Rohrbach is not based, however, on the intention to endow large airplanes with flight characteristics similar to those possessed by small airplanes. This method was first developed from the consideration of the various characteristics of maneuverability, reaction to gusts, structural strength, weight of airplane minus power plant, weight of power plant, etc. As in every enlargement method, including Lanchester's, it is assumed that the large airplanes perfectly resemble the small airplanes, both in their dimensions and in their weight distribution. Of course this is never actually the case and must not be forgotten in using any enlargement method.

In short the Rohrbach enlargement method, as compared with the Lanchester method, yields the following results, which were set forth by Rohrbach in 1922 in his lecture at the regular meeting of the Wissenschaftliche Gesellschaft für Luftfahrt in Bremen.

1. <u>Maneuverability</u>.- Large airplanes designed on the Rohr-

bach principle respond slower to the controls than model-similar small airplanes, but considerably quicker than large airplanes of like weight designed on the Lanchester plan. Likewise they require more energy to operate the rudder and a greater rudder deflection than model-similar small airplanes, but considerably less energy and a smaller rudder deflection than Lanchester airplanes of like weight.

2. Reaction to gusts.- Large Rohrbach airplanes fly steadier than small ones in gusty air. Moreover, they are much less affected by gusts than Lanchester airplanes of like weight.

3. Taking off and landing.- Large Rohrbach airplanes, in comparison with small airplanes and in contrast with large Lanchester airplanes, require larger landing places and have a greater landing speed. In taking off and in landing, they are less affected, however, by ground winds and gusts.

4. Weight of airplane minus power plant.- This increases faster than the full load both on Lanchester and on Rohrbach airplanes of like structural strength. The increase in weight is slower, however, by the Rohrbach enlargement method than by the Lanchester method. Consequently the weight of a large Rohrbach airplane without the power plant is considerably less than that of a large Lanchester airplane. Nevertheless, large Rohrbach airplanes can be made more resistant to local stresses.

5. Dimensions.- As regards structural drag, the Rohrbach enlargement method is somewhat more unfavorable than the Lanchester method. The dimensions of the Rohrbach airplanes are relatively smaller, however, which facilitates their housing.

6. Power plant.- By both enlargement methods the fuel consumption increases for a given flight distance, as likewise the weight of the fuel tanks with relation to the full load. On large Rohrbach airplanes, however, the greater engine-power requirement is offset by the greater flight speed.

The quantitative results obtained by the two methods are given in Table II. The data were taken from Rohrbach's article (Figs. 3-4):

Table II. Enlargement of Airplanes

(2000 kg airplane as the starting point)

Method		Lanchester				
Full Load	kg	2000	4000	8000	16000	32000
1 Wing area	m²	50	100	200	400	800
2 Span	m	20	28.4	40	56.8	80
3 Wing loading	kg/m²	40	40	40	40	40
4 Engine power	HP	250	500	1000	2000	4000
5 Power loading	kg/HP	8	8	8	8	8
6 Power per unit area	HP/m²	5	5	5	5	5
7 Landing speed	km/h	80	80	80	80	80
8 Flight speed	km/h	170	170	170	170	170
9 Radius of smallest flight curve	m	70	70	70	70	70

Table II (Cont.)

Enlargement of Airplanes

Method Full Load		Lanchester				
	kg	2000	4000	8000	16000	32000
10a Time required to change from rectilinear flight to like curves	s	2	2.83	4	5.66	8
10b Distance required to change from rectilinear flight to like curves	m	85	120	170	241	340
11 Take-off time	s	15	15	15	15	15
12 Take-off and landing run	m	120	120	120	120	120
13 Ideal weight of wing per unit area	kg/m²	2.8	3.96	5.60	7.92	11.20
14 Actual addition factor		1.95	1.60	1.35	1.20	1.20
15 Actual weight of wing per unit area (Safety Factor 5)	kg/m²	5.45	6.33	7.55	9.50	13.50
16 Actual weight of wing	kg	272	633	1510	3800	10800
17 Actual weight of airplane minus power plant	kg	710	1645	3930	9880	28100
18 Weight of airplane minus power plant in % of full load	%	35.5	41.1	49.2	61.8	87.8
19 Weight of power plant in % of full load	%	18.8	18.8	18.8	18.8	18.8
20 Weight of fuel in % of full load	%	13.3	13.3	13.3	13.3	13.3
21 Weight of crew & instruments in % of full load	%	4.0	4.0	4.0	4.0	4.0
22 Useful load in % of full load	%	28.4	22.8	14.7	2.1	-23.9
23 Useful load	kg	577	910	1175	335	-7650
24 Mean time required to fly 600 km (373 miles)	h	4	4	4	4	4

Table II (Cont.)

Enlargement of Airplanes

Method Full Load	kg	Rohrbach				
		2000	4000	8000	16000	32000
1	m^2	50	79.2	126	200	317
2	m	20	25.2	31.8	40	50.4
3	kg/m^2	40	50.4	63.6	80	100.8
4	HP	250	562	1260	2830	6350
5	kg/HP	8	7.1	6.35	5.66	5.05
6	HP/m^2	5	7.12	10.0	14.15	20.0
7	km/h	80	90	101	113	127
8	km/h	170	191	214	240	270
9	m	70	88	111	140	176
10a	s	2	2.25	2.5	2.8	3.2
10b	m	85	85	85	85	85
11	s	15	17	19	21	24
12	m	120	151	190	240	305
13	kg/m^2	2.8	4.45	7.05	11.2	17.8
14		1.95	1.60	1.35	1.20	1.20
15	kg/m^2	5.45	7.10	9.50	13.50	21.4
16	kg	272	562	1200	2700	6780
17	kg	710	1460	3120	7020	17640
18	%	35.5	36.5	39.0	44.0	55.0
19	%	18.8	21.0	23.6	26.6	29.7
20	%	13.3	12.9	12.5	12.2	11.9

Table II (Cont.)

Enlargement of Airplanes

Method Full Load	kg	Rohrbach 2000	 4000	 8000	 16000	 32000
21	%	4.0	4.0	4.0	4.0	4.0
22	%	28.4	25.6	20.9	13.2	-0.6
23	kg	577	1015	1670	2110	-192
24	h	4	3½	3	2-3/4	2½

Attention has already been called to the fact that a large airplane cannot be produced simply by enlarging a small airplane. If, for example, we adopt the Lanchester method of enlarging and make the large airplane with the same wing loading as the small airplane, we will generally obtain a larger power loading, due to the disproportionately large increase in the weight of the airplane aside from the power plant. Aerodynamically this means that it must fly at a larger angle of attack than the small airplane and that it will also have a lower speed. For the wing structure this means that the induced drag will assume correspondingly greater importance than on a small airplane. In order to remedy this defect, the induced drag can be expediently diminished by giving the large airplane a more favorable aspect ratio and a greater wing gap than the small airplane. This, however, destroys the assumption of geometric similarity. As a matter of fact, there is no giant airplane which, even disregarding the power plant, can be regarded as a geometrically similar enlargement of a normal small airplane. The greatest similarity is found in the Linke-Hofmann R II biplane.

In the Rohrbach method no geometric enlargement can properly be assumed. Even in the contour of the wings the designer is forced to seek the utmost reduction of the induced drag. The airplane will then fly normally, because high wing loading is combined with moderately high power loading. In the Rohrbach method, moreover, it is noteworthy that, due to the increased wing loading, the wing area does not increase in proportion to the full load. Aeromechanically the structural drag of an airplane finds expression only in relation to the wing area. With like wing areas and structural drags, the drag conditions are less favorable on the Rohrbach type of airplane. This necessitates the utmost reduction in the structural drag. In general the structural drag of a large airplane is proportionally smaller than that of a small airplane. With a completely divided power plant, however, the conditions may be quite different. This is still more true, when the wing loading is disproportionately increased. The constructor must then find some other way to reduce the drag to a reasonable value.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

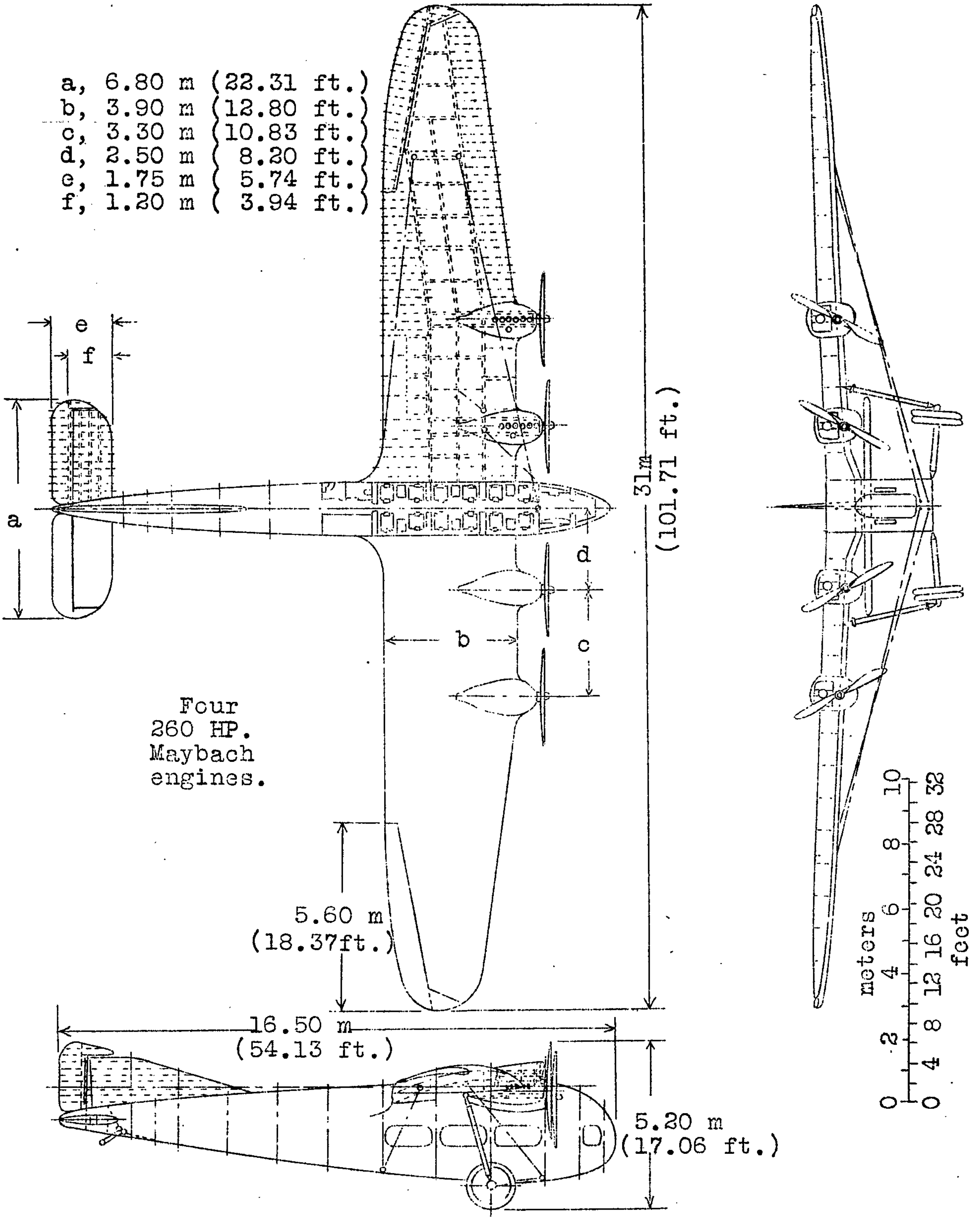

Fig.1 Rohrbach giant monoplane built by the Staaken Zeppelin Works.

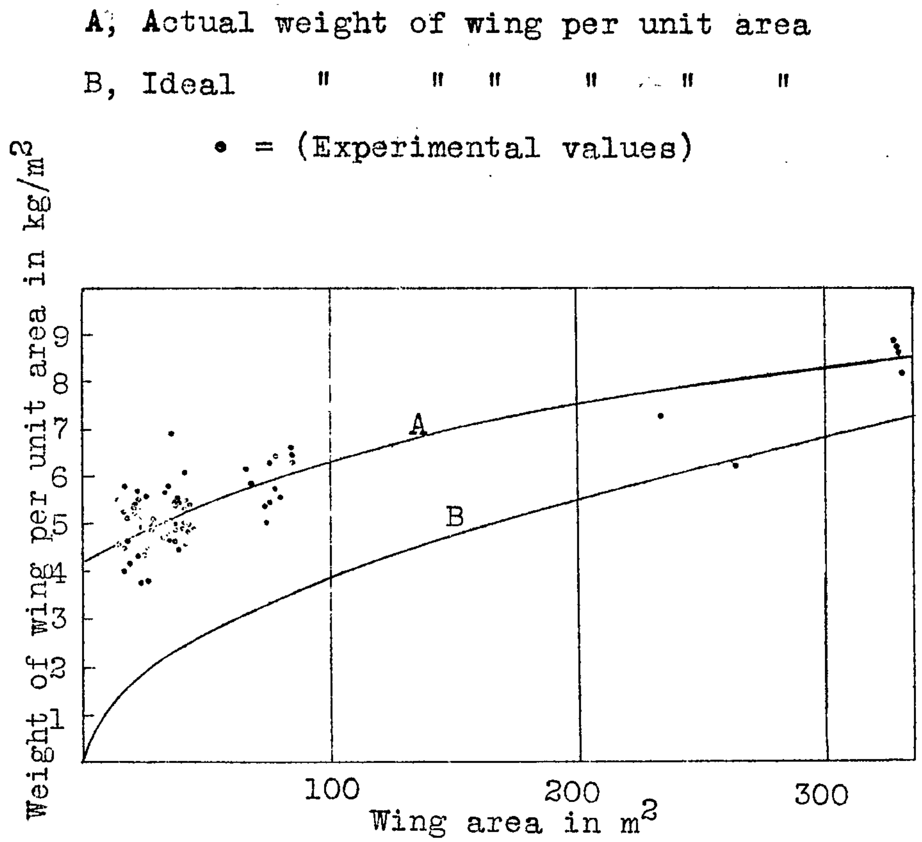

Fig.2 Weights per unit area plotted against wing area and reduced to equal load factors.

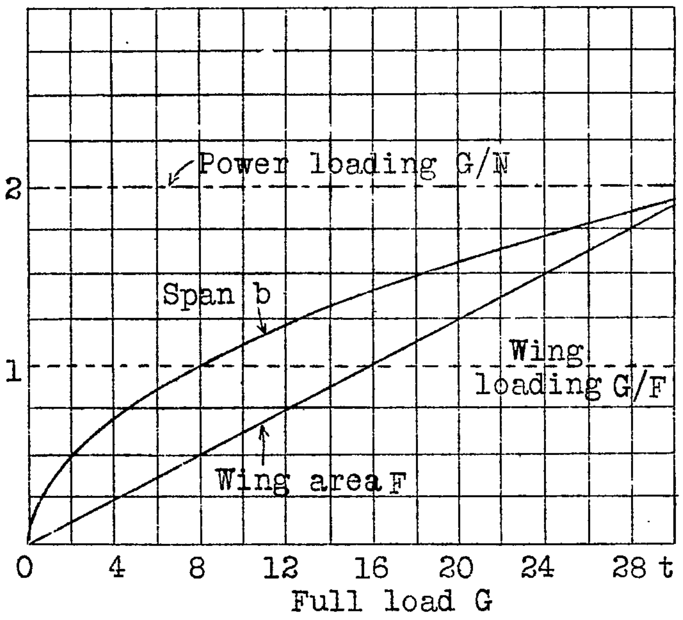

Fig.3 Enlargement according to Lanchester.

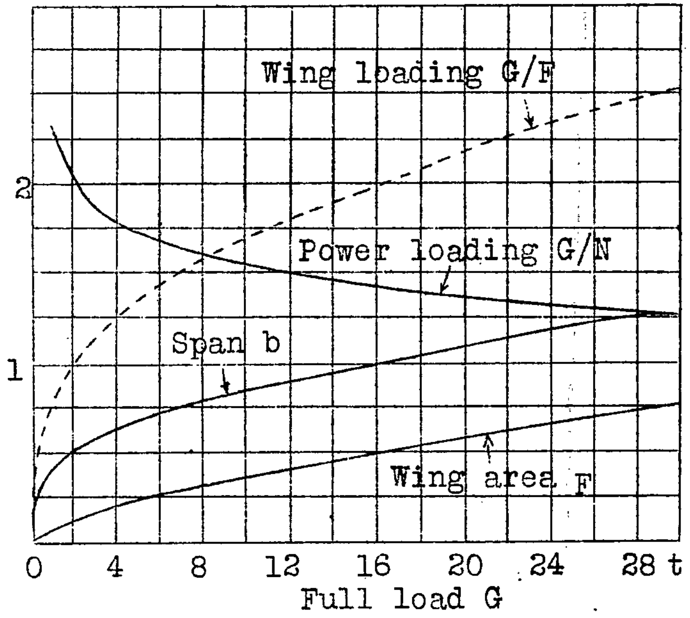

Fig.4 Enlargement according to Rohrbach.

	Mass	[illegible]
Carrier	4	
Battleship	3	
Cruiser	3	
Destroyer	5	[illegible]
P.T.	7	1
P.T.	2	1
Sub.	6	1