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MATERIALS AND METHODS OF CONSTRUCTION IN LIGHT STRUCTURES

By Adolf Rohrbach

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By Adolf Rohrbach

I wish first to thank the W.G.L. (Wissenschaftliche Gesellschaft für Luftfahrt) for inviting me to speak on the problems of light construction.

At first I did not know just what this subject was intended to cover but, after corresponding with members of the lecture committee of the W.G.L., I decided to discuss principally material and production problems.

Lecturing on these practical questions is a little difficult for me as the representative of an airplane-construction firm, since my knowledge is naturally one-sided and, being still at the beginning of the development of airplane construction, it is not yet easy to formulate general principles.

Since I cannot therefore give a comprehensive and accurate description of the methods of production of wood and metal airplanes employed in foreign countries and by other German firms, I will simply present my own views, hoping that just this one-sidedness will call forth a fruitful discussion and corresponding contributions from the representatives of other firms regarding other methods of construction.

The many conditions which must be satisfied in the construction of an airplane, fall into two principal groups, namely, conditions of construction and of use.

The most important conditions of use are, e.g., all the factors affecting the performances, such as structural safety, one or more wings, one or more engines, aspect ratio, flight characteristics, arrangement of seats, landing gear, floating stability (of seaplanes), bulkheads, strength of bottom stiffeners, protection against corrosion, etc.

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*"Entwurf und Aufgaben des Leichtbaues." From Yearbook of the Wissenschaftliche Gesellschaft für Luftfahrt, Dec., 1926, pp. 64-78.

Other conditions are equally important as regards both production and use, such as the choice of wood or metal, duralumin or steel, metal or fabric covering, rectangular or tapering wings.

The predominant constructional condition is the shape of the individual parts, such as the fittings, wing ribs, transverse frames of the fuselage, interior wing structure, junctions and points of separation between the different parts.

Knowledge regarding the conditions of use and the best ways to meet them is much further advanced than regarding the conditions of production. This is due to the fact that existing airplanes are quite perfect in most cases and are compared by fairly disinterested persons. Airplane structures can therefore be rather quickly adapted to their conditions of use from the data thus obtained. By this adaptation to the conditions which are alike for all airplanes, different firms arrive at very similar solutions in a comparatively short time. I will mention only the different single-engine commercial airplanes and the smaller combat airplanes. The final solutions, and consequently the similarity of different structural parts, are reached sooner on small airplanes than on large ones, because the problems are simpler and because the greater number of small airplanes in use enables the more rapid accumulation of the requisite data.

For the contrary reason the development of large airplanes proceeds much more slowly, and hence they still exhibit a great variety of arrangements of the wings, power plants, landing gears and, in fact, of all parts. A fairly standard type of large airplane will probably be developed, however, within a few years.

Questions of form and material, which principally concern the conditions of production, will require the longest time for their best solution so that airplanes from different firms will become more or less similar, as is already the case with automobiles. A better or poorer solution of production problems is expressed essentially only in the price of the product. This difference is often due much more to political or financial conditions than to technical ones. By way of illustration, I will only remind you of the fact that the average pay for a capable locksmith, expressed in gold marks, differs greatly in different localities, often amounting to 100% and sometimes to 400%, as shown by the following figures: Berlin, 1.25 gold marks; Stuttgart, 0.98; Copenhagen, 1.70; Italy, 0.40; England, 1.35.

Political influences may affect the cost of production similarly to the above-mentioned differences in wages. In this connection your attention is called to the position of the French firms, some of which manufacture on a very large scale, and to most of the German and many of the English firms, which now make only single airplanes or very small series.

In the course of time, however, the rates of exchange and the wage levels of the different countries will approach one another near enough so that the production costs will be everywhere approximately the same, provided the different efficiencies of the individual workmen, as also the different taxes, special levies, duties, etc., are considered.

The W.G.L. has hitherto devoted itself almost exclusively to aerodynamic or strength problems. In this respect, we have already made so much progress that a reduction of 10% in the drag or in the weight of an airplane represents a remarkable improvement.

As regards production problems, however, we have made so little progress that differences of 100% or more in the production time are almost the rule for airplanes which, at first glance are seemingly similar and which, moreover, seem equally well adapted to their purpose.

As a scientific society, the W.G.L. can take no direct interest in the costs as such, but only in so far as they determine the limits for the application of scientific data with respect to the greatest possible fulfillment of purposes and practical development in particular directions, in which applied science must precede in order to assist in solving the aerodynamic and strength problems involved. This influence of the production problems has always been present, but in the future it will be increasingly decisive for the success of certain designs, because they will differ so little in their suitability for a given purpose, but probably very much at first in their production costs.

I will now discuss briefly a few questions which affect the conditions of production and use, and then show, by illustrations from our own factory, how the production costs depend on suitable methods of construction and other conditions.

Wood or Metal?

I think it can now be said that this problem has been definitely decided in favor of metal for large airplanes. Large airplanes are still being made of wood in some countries, but probably only because the particular firms cannot be transformed quickly enough and are not given by their governments the opportunity to do so by the withdrawal of orders. The English air ministry has already announced that, after a transition period of two to three years, it will place orders for only metal airplanes.

Even for small airplanes the use of metal construction, in my opinion, will continually increase, but will require more time for its development. The reason for this lies in the fact that the construction of a metal airplane requires considerably more experimental data, as also, due to the multiplicity of parts, more preliminary drafting and mathematical work than a wood airplane. The cost of such preliminary work increases relatively slowly with the size of the airplane and therefore represents a smaller share of the cost of a large airplane than of a small one. Quantity production of small airplanes would so reduce the ratio of the preliminary work as to render the use of metal profitable for them also. This must be on quite a large scale, however, for the cost of the special apparatus for quantity production (including the expense of testing the same) must be added to the cost of the preliminary experimentation and designing. On the contrary, considerably more primitive and relatively cheaper apparatus suffice for the smaller number of large airplanes. As soon, however, as a market is found for a large number of small metal airplanes, the wood airplane will be a thing of the past, since in this event, it will always be more expensive than the corresponding metal airplane.

I will not enter into any detailed discussion of the comparative weight of wood and metal airplanes. I consider it settled that metal has the advantage even in this respect, although a strict comparison can seldom be made, because a good metal airplane generally differs as a whole or in its exterior dimensions from the corresponding wood airplane, so that a skeptic can have doubts as to whether the better performance of the metal airplane is not ascribable to the more favorable dimensions or to the better weight ratio.

Duralumin or Steel?

Corresponding to the specific weights of duralumin and steel, tension members made of the latter are first equivalent to duralumin members of the same weight at a tensile strength of 110 kg/mm² (156,460 lb./sq.in.).

Different duralumin parts are generally joined by duralumin rivets of the same strength, so that such junctions involve only the weakening of the rivets. In this respect steel construction is less favorable because there are no rivets of 110 kg/mm² tensile strength, but ordinarily of only 30-40 kg/mm² (42,670 to 56,890 lb./sq.in.). Hence relatively many rivets must be used to join such steel parts and, in order to provide sufficient rivet area, more for steel than for duralumin. If the cross section of the steel member is to be fully utilized, there must be an enlargement of the rivet field at the junction place in order to provide space for all the rivets, which in turn denotes a similar loss in weight. In order therefore to preserve the equal weight of the whole steel structure, the steel would need to have a strength of about 130 kg/mm² (185,000 lb./sq.in.) with respect to this loss. Since the tools are not sufficiently stronger than such hard structural steel, much time would be required for the work, which would be accompanied by great wearing of the tools.

Moreover the cross sections of such steel members are very small, and they must therefore be made in the form of hollow sections or profiles with respect to an adequate inertia moment, the result being a very thin wall. Such profiles must generally be strengthened by all possible kinds of longitudinal corrugations, in order to prevent local buckling. Such profiles are very difficult to join together and could never be used in practical machines.

Since the hollow members mostly consist of several parts joined by longitudinal rows of rivets, another difficulty in connection with the joining is occasioned by the fact that the rivets in the vicinity of the junctions must be removed by drilling or must be hammered down, and their distribution is often unsuited to the other dimensions of the gusset plates.

In order to avoid the constructional difficulties of light steel structures, less strength is often tolerated. For example, the flanges of the Dornier spars, so far as I know, are made from steel of 70-80 kg/mm² (99,560 to 113,780 lb./sq.in.) strength.

In order to avoid the loss in weight occurring at the junction points in using steel of less strength, Dornier uses duralumin for these parts. In so doing, he sacrifices to a considerable extent, however, the advantage he claims for the great resistance of steel to fatigue, which here concerns only the spar flanges, while the spar itself is just as liable to break from the failure of the diagonal or perpendicular bracing members. As a matter of fact, I consider steel and duralumin equivalent with respect to fatigue, for the so-called "fatigue" is nothing but a matter of ultimate yielding, after the frequent stressing of the material beyond the proportionality limit.

Material of 35-40 kg/mm² (49,780 to 56,890 lb./sq.in.) is used for welded tubular construction, whereby the weight loss in comparison with duralumin is partially offset by the almost total elimination of other junction-point losses.

In comparison with steel, duralumin has the advantages of greater wall thickness, simpler forms and greater rapidity of working.

I do not care to speak now of the other light metals, such as lautal, which has given very good results in technical tests, but is not yet furnished in suitable form for manufacturing, or "skleron," which is too hard.

Elektron is too sensitive to water to be used for important airplane parts, but can well be used for small fittings, lightly stressed levers, etc.

Open or Closed Profiles?

Open sections or profiles are made by passing strips of sheet metal between suitably shaped rollers. In preparing small quantities for experimental purposes (up to several hundred meters), it is cheaper to use a drawplate, thus saving expense for tools and apparatus.

Closed sections or profiles are about 20% more expensive than open ones, since they must consist of at least two open profiles with longitudinal riveting. Even duralumin tubes are considerably more expensive (40-60%) than duralumin profiles, because they are relatively brittle and, between the drawing operations, must be repeatedly annealed in salt baths, which are likewise very expensive on account of the great heat consumption. Many duralumin tubes must be heated 30-40 times during the course of their production.

The junctions of closed profiles are often heavier and more expensive than the junctions of open profiles with gusset plates. As compression struts, closed profiles are generally lighter than open profiles. This advantage is often nullified, however, by the greater weight of the junctions. In our airplanes, therefore, we have increasingly restricted the use of closed profiles. Open profiles can also be more readily protected against corrosion than closed ones, the inside of which can neither be inspected nor painted.

The danger of corrosion is of especial importance for seaplanes, on which, for the same reason, all duralumin parts must be painted before being riveted together. In order to effect a still further improvement, we have recently adopted measures to make all spaces between the profiles and adjacent parts so tight that water cannot get between any structural parts, but can only wet their exterior surfaces and evaporate without doing any harm. In particular, every closed profile on a seaplane constitutes a corrosion risk, chiefly, of course, in the parts constantly in contact with the water. Even in the most careful construction, it is difficult to prevent the water from getting between the metal sheets and the closed profiles. Even if this is prevented on the new seaplanes, the parts will surely be sprung in use, so that water can get in and cause corrosion without being noticed at first.

Metal or Fabric Covering?

The fabric covering of wings must be renewed once in six months to two years according to the climate. On the occasion of such renewal, the inner structure can be inspected and, if necessary, again put in order. According to the Luft Hansa (a German air traffic company), renewing the fabric covering of a wing costs 20-25 marks per m^2 (fifty to sixty cents per square foot). For our commercial airplane Ro VIII with its 88 m^2 of wing area the cost would therefore be nearly 2000 marks ($500). If we assume a life of six years for the airplane and eight renewals of the covering during this period, the cost would amount to about 16,000 marks ($4000) or about 10% of the cost of the airplane.

On the other hand, the life of the metal covering is unlimited, the covering is heavier (2-4% of the empty weight of the airplane), and its cost greater (2-4% of the cost of the cell). The metal covering generally has the same disadvantage as the fabric covering, that it renders the inside of the wing inaccessible.

In my opinion the metal covering is practical only when the wing is so made that the inside is rendered accessible by the simple unscrewing of a portion of the wing without further cost and without greatly disturbing the outer covering. Aerodynamically the metal covering seems to be just as good as one of fabric, since the bulges and rivets are all in the boundary layer and therefore not exposed to the full air flow. We are about to institute a systematic investigation of these questions, concerning which no report can be made, however, until we have obtained considerable data.

When the wing is made so it can be taken apart, the greater cost of the metal covering will be offset, on the one hand, by its greater durability and, on the other hand, by the ease of inspecting the inner wing structure.

My general conclusion regarding the four above-treated problems, as you doubtless already anticipate, is that large airplanes can best be made chiefly from smooth duralumin sheets and strips, i.e., from the cheapest form of this metal.

Where the material has to be profiled for the obtention of greater buckling strength, the profiles should be open. From this there results a type of construction similar to that of a ship, with a supporting covering, and the necessity of making the wing and tail of separate riveted parts assembled by screws and bolts.

The suitable location of the junctions greatly affects the cost of production. Formerly we screwed the wing spars to the stubs projecting from the fuselage. We then constructed a triple wing girder, the middle piece of which was secured by screws in a recess in the top of the fuselage and to which, moreover, both the other pieces were screwed. Subsequently we screwed the middle section of the three-part wing to the top of the fuselage and joined the outer wing spars to it as before. In later airplanes we returned to the former method of joining the wings to the stubs projecting from the fuselage. Fittings of high-resistance steel were used at the junctions.

Despite the fact that chrome-nickel steel has quite a high electric tension as compared with duralumin, corrosion in these junctions can be entirely prevented by carefully painting the steel fittings with ocher, so that no water can get into the joints.

Although I consider the constructional method introduced by us, with smooth metal sheets and open profiles, as the simplest, I do not wish to be understood as not recognizing the advantages of wood airplanes or steel-tubing fuselages for special purposes. I regard all these other constructional methods, however, only as convenient transitional methods, which sooner or later will be gradually replaced by the simpler duralumin construction.

After these more general remarks, I will now try, by means of a few examples, to give you an idea of how we are endeavoring to reduce the cost of production. The factory can operate economically only when the material and all working instructions are carefully prepared. This means the presence of absolutely complete working drawings and lists of parts.

The working drawings must cover not only the principal parts, such as the wings and fuselage, but also all small parts, such as control rods, engine governor, instrument arrangement, floor supports, etc. Even the points of attachment of all those parts are indicated in the corresponding drawings, so that arrangements can be made for them in the construction of these parts. The working drawings represent every part and every rivet down to the smallest detail. Our flying boat Ro III has about 1800 drawings and 700 lists of parts.

In order to simplify and accelerate the execution of the working drawings, they are undertaken only after adequate preparation. A complete project is first worked out in all its details, and all aerodynamic and strength calculations are made in special sections of the construction office, so that the individual constructor has little to do with those problems, but is supplied with all the materials in suitable form and dimensions.

The drawings now ready for the first airplane of a new type are so complete that a series of twenty could be built, without any further drafting work, from the same drawings and lists of parts.

Of course all the drawings must be clear in their manner of presentation, so that less time will be lost in the factory in interpreting them. On the basis of the drawings and lists of parts, the factory undertakes the task of production and causes to be collected in a special room the requisite material for its execution, which it is endeavored to shorten by simple devices.

I believe an especial advantage of this method of construction with smooth metal sheets and open profiles, as well as of the divisibility of the wings, is the cheapness of the factory equipment. This cheapness has, on the one hand, the technical advantage that the production of a new type need not be long delayed by waiting for the equipment and, on the other hand, the financial advantage that not much capital is tied up in the equipment. Consequently, the cost of the equipment does not constitute an obstacle to progress, as is the case in other more expensive methods, where one hesitates to consign the expensive equipment to the scrap heap. Just as the smaller equipment cost is important for the rapid development of new types, it is likewise important for a prompt increase in the output in case of need.

On the other hand, it is often argued in favor of a complicated constructional system that, though it is not suited to small-scale production, it may be very economical in mass production. In mass production it is, of course, obvious that even expensive equipment may not ultimately greatly increase the cost of the individual airplane. Of course cheaper equipment would still further reduce this cost. Moreover, even an article in mass production can be superseded by better types, thus causing the loss of much capital through the scrapping of the expensive equipment while, in the contrary case, conversion of the factory would be greatly facilitated. Obviously the equipment for making a given type of airplane would always be more extensive and complete, the larger the series to be produced. The difference in cost between the equipment required for an airplane of simple design and one of more elaborate design will therefore always be relatively the same.

In individual construction, all the transverse frames, ribs, fittings, etc., are tested separately, in order that any defects may not be first discovered in assembling, when they would cause loss of time, or even later in the finished airplane, where they might do still more harm. The assembling is greatly accelerated by having all connections, bearings for the conduits, control rods, instruments and all the parts ready in advance. By such methods we have effected a saving of 30-50% in time.

All orders are calculated by a practical system and their corresponding production times compared. Thus a record is obtained of the work expended on the airplane itself and also of the "unproductive" work expended on the factory equipment. In like manner a record is kept of the time spent in the preparation of the working drawings. Thus all time-robbing methods were tested and in many instances were greatly simplified.

All changes in design are immediately introduced into the drawings. In order that this may not be overlooked, the head of the workroom calls attention in writing to all corrections and changes, which must then be made in the drafting room. A complete set of the drawings and lists of parts is filed for every airplane, so that, in connection with any subsequent experiences of this airplane, it is always possible to tell just how any given part was made.

The whole system of cooperation between the drafting, construction, and mathematical departments is naturally being gradually improved and extended on the basis of our experience. An exhaustive description of it would take several hours.

I will now describe briefly a few illustrations of what I have already said.

Figure 1 is a comparison of the time consumed in the manufacture of six consecutive seaplanes of the same type, Ro III. The numbers do not denote the actual number of hours, but only the relative number, 100 being adopted for the first one of the series. Moreover, this was not the first seaplane of this type to be built, but was built considerably later, after the type as such had become fully stabilized. The number 30 at the right of the figure indicates the approximate result we would expect to obtain were we to begin the work over again to-day. In order to shorten the working time, as already mentioned, the various individual working times are determined and compared with one another, with a view to ascertaining where further economies are possible.

Table I shows the relative working times for the processes involved in the construction of one of our wing girders. (Figure 2.) In order to be able to compare the construction times of the wing girders a and b, which are of different sizes, they are referred to the same weight. The wing girder a belongs to an outer wing section of the seaplane Ro III, while the wing girder b belongs to an outer wing section of our three-engine commercial airplane.

Table I. Working Times for Wing Girders

Kind of work	Airplane a	Airplane b
a) Production of all parts without riveting	30%	27%
b) Assembling and riveting all transverse walls	3	5
Assembling and riveting all longitudinal walls	13	8
Assembling and riveting upper flange	28	30
Assembling and riveting lower flange	26	30
Total	100%	100%

When referred to equal weight, somewhat less than 60% of the working time used for the wing girder a was required for the wing girder b of the commercial airplane. This improvement extended to all parts of the wing girder, since the shares of the different working times were approximately equal for the girders a and b.

The greatest saving was probably in the assembling and riveting of the longitudinal walls, whereby working times in the ratio of 13/8 were attained. This improvement was effected, in the first place, by a simple stamping process, by which the edges of the openings in the longitudinal walls, corresponding to a template, were worked out by a stamping tool, and in the second place by machine riveting. (Figures 3 and 4.)

Figure 5 shows the longitudinal wall of a wing girder in which the diagonals are reinforced by riveted sections or profiles instead of by bending out the edges of the openings. The present method of bending out the edges of the openings according to a template is considerably more practical, however.

Table II gives the relative working times for the production of the whole wing, whose girders formed the basis of Table I.

Table II. Working Times for the Wings

Kind of work	Airplane a	Airplane b
Making wing girder	51%	55%
" leading-edge formers	10	11
" end-rib formers	7	7
" aileron "	10	9
" ailerons	18	6
" wing cap	-	8
Assembling wing	4	4
Total	100%	100%

If the working time for the whole wing is referred to equal weight, the saving for wing b, as compared with wing a, is only 31.5% against 40% for the girder alone. This is because the rounded wing tips, which we here made for the first time, are quite expensive. The time required for assembling the wing is quite small; much smaller, in fact, than the saving made in the individual parts due to their easy accessibility from all sides.

Figure 6 shows that much working time can be saved by practical workroom measures alone, even without structural improvements and without increasing the scale of production. The here diagrammatically represented leading-edge formers and end-rib formers before the ailerons belong to both airplanes, like the previously considered wings and wing parts.

Conversely, Figure 7 shows how the working time for the production of rudders was shortened by purely structural methods.

Table III shows how the working times for the construction of a certain transverse frame were reduced by a combination of structural and workroom methods. (Fig. 8.)

Table III. Working Times for Making a Transverse Frame in a Three-Year Development

Working times referred to equal weights					
Airplane	a	100	Airplane	e	98
"	b	129	"	f	42
"	c	120	"	g	41
"	d	102	"	h	28

The working times are again referred to equal weight, as I am not allowed to give the actual working times. The comparison is correct, however, in that it concerns the same transverse frame and the weight of this frame on the different airplanes remains the same, despite the variations in structure. It therefore concerns almost exclusively the rapidity of construction.

In the original transverse frame of the first airplane the profiles were joined by gussets in two planes, which required very complex dollies for riveting. For this reason the structural method was changed, so that only one gusset was used between the profiles. Nevertheless, the working time increased, since the workroom was very busy and many inexperienced workmen had to be employed.

The frame was then somewhat further simplified in small details and, beginning with airplane f, piecework was introduced with the result that the working times were immediately reduced more than one-half. The improvement from g to h was then effected by a structural change which, unfortunately, I cannot yet describe for reasons connected with its patenting.

Similar examples could be mentioned in any desired number. For example, the working time for the production of externally similar floats was reduced 40% by the simplification of the frame and a practical method for the main fastening.

I think there is no need of further examples to show how great savings in working time can yet be made. I am confident that, even without very large-scale production, provided we obtain enough orders to maintain the factory personnel at the present number of several hundred, in a year or two we can attain working times of less than half the present fairly short ones. Metal airplanes, even when made on a small scale, will then cost considerably less than wooden ones do now.

In the W.G.L. lectures, problems are discussed from all standpoints and possibilities, as to how performance can be increased per unit weight of the airplane or per unit weight of fuel, etc. Therefore, I wish to thank the W.G.L. for this opportunity to discuss the possibilities of an hour of human work, which is, after all, our most valuable asset.

Comments

Engineer Spiegel.- Dr. Rohrbach's address is especially welcome, because it introduces pure production problems into the circle of those previously discussed before the W.G.L. Even though, as the speaker remarked, such questions have little to do with pure science, they still stand in mutual relations with the latter. Science, on the one hand, assigns certain tasks to the producer while, on the other hand, production problems often afford the incentive to new scientific researches.

It would therefore be very desirable in future to have such questions often discussed before the W.G.L., and thus develop a lively exchange of ideas between the different producers. How advantageous such an exchange of ideas and experiences may be for the development of a particular industry has been well exemplified in America.

Just at the present time, when more firms are ever turning to light-metal construction, tremendous amounts of money and energy could be saved, if each firm did not have to start anew with the initial researches and overcome all the primary difficulties by itself, only to arrive ultimately at the same results already obtained by others. Of course there should be perfect mutual cooperation, and no firm should refrain from participation for ostensible competitive interests.

Such an exchange of ideas might take the form of an agreement by which, for the solution of especially difficult problems, a definite task would be undertaken by each firm entering into the agreement. On this plan, systematic investigations might be made of such problems as the torsional resistance of composite cross sections, buckling resistance of compression members, conservation media, etc. With the advice and cooperation of the D.V.L. (Deutsche Versuchsanstalt für Luftfahrt) very useful work could thus be done, despite the generally limited means available for the further development of German aircraft.

As regards Dr. Rohrbach's address, I wish first to remark that, in my opinion, the use of wood in airplane construction is still justified for many purposes and will be continued. Especially in light airplane construction, where the rapid development of new types is often involved, wood is the most suitable material. Without time-consuming preliminary work in the construction bureau and with the help of very simple tools, wood enables the construction of a new airplane in a fraction of the time required for an all-metal (especially light-metal) airplane.

However, if a certain type is to be made in large numbers, the case is then quite different, and metal construction may be preferable on account of its special advantages.

Wood is also more suitable for small airplanes, because the dimensioning and correct shaping of small metal parts is very difficult if, for the obtention of the requisite local rigidity, a great increase in the weight is undesirable, in contrast with wood whose dimensions can be easily controlled.

These difficulties do not exist for large airplanes, where there is generally an abundance of time at one's disposal and where the cost of the first airplane is not generally so important, so that wood is eliminated.

As regards the relative merits of steel and light metal, I wish to call attention to the fact that, in various cases for the dimensioning of certain parts, not the strength but the stiffness is the determining factor. For example, in heavily loaded cantilever monoplane wings, torsion corrugations for ailerons, etc., the ratio $\frac{\text{modulus of elasticity or shear}}{\text{specific weight}}$ is determinative for the behavior of the various metals with respect to stiffness.

This ratio is approximately the same for steel and light metal, whereby it must, however, be remembered that the modulus of elasticity always has approximately the same value of 2,150,000 for nearly all kinds of steel, even those of less strength. Hence if one is compelled, for the sake of rigidity, to make a part larger than would be necessary for strength alone, a poorer quality of steel of 50-60 kg/mm^2 (71,118 to 85,340 lb./sq.in.) can safely be used, without making the part heavier than light metal, with the advantage of being considerably cheaper.

As regards the advantages and disadvantages of open and closed profiles, I agree entirely with the speaker. It cannot be denied, however, that for very large airplanes, due to the given structural possibilities, the closed profile, especially in the form of tubes, may have decided advantages, when it is possible to avoid the disadvantages otherwise inherent in the closed profile. This can be easily accomplished by special constructional devices. The chief advantages of a tube over a combination of two open profiles are:

1. Greatest utilization of the cross section, especially for heavily stressed compression struts;

2. Elimination of the longitudinal seam;

3. Convenient workability and hence gradual adaptability of the cross section to the generated forces by simply screwing one section over another;

4. The butt joints can be made with simple screw

connections which require only a fraction of the weight of the riveted strips used to join the combination of profiles.

Furthermore, if all drilling of the tubes is avoided by a suitable form of junction, it is easily possible to make such a tubular girder so tight that no water can get inside, even when the tube is distorted. Moreover, it is always possible to protect the inside of the tubes by pouring some conserving liquid through them before using. An example of this method of construction is the Rumpler transoceanic airplane.

Very advantageous for the use of tubes with large cross sections is the fact that, in the aluminum industry, endeavors are being made to increase considerably the maximum weight of one-piece parts made from high-strength materials. Hitherto, this weight was only 25-30 kg (55-66 lb.), so that very frequent joints were required for large cross sections. An increase in the weight of the part would mean a saving in the structural weight and amount of work.

Also as regards the supporting covering, the relations may change for very large airplanes. The dimensions of the covering are determined chiefly from its resistance to local conditions. They will therefore be only slightly greater for very large airplanes than for smaller ones. While for the latter the thickness of the covering stands only in a certain accord with the dimensions of the inner structural parts and the covering can therefore serve, with slight reinforcement, as a supporting member, a serious disproportionateness arises, for large airplanes, between the dimensions of the framework and of the covering. The gain from the application of the covering in such a case would therefore be vanishingly small and would not justify the weight increase due to the requisite reinforcements. On the Rumpler seaplane the thickness of the walls of the spar flanges went as high as 2 cm (0.79 in.), while the covering was only 1-1.5 mm (0.039-0.059 in.) thick.

I have voiced only a few thoughts suggested by the address of Dr. Rohrbach and, in conclusion, I wish to express the hope that, through mutual cooperation, the development of our airplane industry may be greatly accelerated.

<u>Director Hüttner</u>.- I consider it a particularly happy thought of the W.G.L. to give one of our most prominent airplane constructors the opportunity to speak at this year's session on airplane material and production problems. This subject is especially appropriate for the present time, when our airplane industry, largely freed from the bonds of the London ultimatum, is on the threshold of a new phase of development. As compared with the industries of other countries, our German airplane industry is obliged to struggle for existence because, aside from a few sport airplanes, it can produce only commercial airplanes, since it is barred from the most important field, that of military airplanes. It must therefore stake everything on developing the field remaining to it as thoroughly as possible, a problem which will be solved only when it succeeds in an ever increasing extension of air traffic and in reducing the cost so that great numbers of our people will be enabled to travel by airplane.

The cost of flying depends chiefly on three factors: fuel consumption, original cost of airplane, and amortization. When calculated per passenger for all three of the factors a considerably less favorable result is obtained than for transportation by railroad or automobile. Airplane manufacturers and air-traffic companies must therefore cooperate to reduce these costs. The fuel problem may soon be solved favorably for German air traffic since, although Germany constitutes but a small part of the world's fuel market, there is just developing an advance of the powers on the German market, which betokens possibilities regarding its relative importance and which may again change Germany from an object to a subject of world politics. The work of the dye trust in obtaining liquid fuels from coal is becoming increasingly important and may yet make Germany independent of other countries for its fuel supply and considerably reduce the cost of the fuel.

In the second place, the cost of flying depends on the original cost of the aircraft and, through this, also on the third factor, the cost of amortization. Though the amortization of the engine is a more important factor than that of the cell, the latter constitutes, however, so large a percentage that any reduction in its cost must materially affect the cost of amortization. Hence, if air traffic is to be made cheaper, the airplane industry can make a substantial contribution by reducing the cost of production. Dr. Rohrbach has already indicated, in his very interesting address, the savings effected by piecework and also in the case of the last airplane of a series of several as compared with the first one of the series. A still larger reduction in the cost of production can surely be effected by making airplanes on a larger scale than heretofore and by the standardization of materials and individual parts. You all know what a struggle for existence the German automobile industry had to go through in competition with American automobiles. That it has succeeded in improving the sales ratio of German cars to American cars is, aside from the quality of the German cars, principally due to the standardization, which the German automobile industry has so vigorously prosecuted for the last two years, that the original very considerable American lead has already been largely abolished and the production cost of the German cars has been substantially reduced.

The opinion may be held that airplane construction is still in such a stage of development that any standardization would harmfully affect the freedom of the constructor. Doubtless any such extensive standardization as has been effected in automobile construction would yet be unsuited to airplane construction, but there are, however, many parts and materials for which standardization is very desirable, such as connections, fittings, instruments, tubes and wires. As to parts for which no rigid standardization is yet feasible, the preparation of provisional standardization sheets would be very helpful. In airplane construction where, of course, not so many pieces of a kind are wanted, as in automobile construction, the creation of apparatus and instruments cannot be profitably carried so far, because the cost of many of the parts would thereby be too greatly increased. Hand work must therefore be done which, however, is more expensive and not nearly so good as machine work. By careful investigation many a part can be found which is the same or similar on all airplanes and could be standardized and made much cheaper.

Group manufacturing would enable considerable economies in lessening transportation costs, simplifying revision, etc. Division into very small units would also enable the employment of cheaper labor. Unfortunately the small number of airplanes to be made prevents any extensive introduction of this method.

Engineer M. Neubert.- In his discussion of the question "Duralumin or steel?" Dr. Rohrbach took as his basis a comparison of the tensile strengths of these materials and made the condition that for equal weights the steel must have a strength of 40 (7.8 : 2.8) = about 110 kg/mm^2 (156,459 lb./sq.in.).

This condition, however, is not fully applicable, because the choice of a material can never be based on its tensile strength alone. At best this could be the case for purely tensile parts, and then only when the latter are not combined with other parts which could be affected by their deformation. An example will illustrate this. A cantilever girder is supported by a rod which is a purely tension member. On the assumption that the rod is a steel one with a tensile strength of 80 kg/mm^2 (113,788 lb./sq.in.) requiring the area F, a corresponding rod of duralumin would require an area of 2F. On this assumption and on the basis of the tensile strengths alone, we obtain for the steel rod a weight excess of 7.8 : (2 × 2.8) = 1.39 as compared with the duralumin rod. In order, however, for the girder to receive the same stresses in both cases, the deformation of both rods must be the same. Hence we must have $F_D = (220 : 70)\ F_S = 3.15\ F_S$ (the expression 220 : 70 representing the ratio of the moduli of elasticity of the materials compared).

Since the ratio of the specific weights is only 7.8 : 2.8 = 2.8, the aluminum rod, on the above assumptions, will be heavier to the amount of 3.15 : 2.8 = 1.12. If, therefore, the duralumin rod should be given only the same weight as the steel rod, then under certain conditions, a corresponding excess weight would have to be given the girder.

The above statement is likewise applicable to compression struts. Such a strut, if it satisfies the Euler formula, can be made lighter of steel than of duralumin. Even a girder subjected to bending stresses, in which some bending deformation is to be expected, can be made lighter of steel than of duralumin.

In lattice girders the lattices can well be duralumin, since the effect of their deformation on the total deformation of the girder is extremely small (See Schwengler, "Elastizitätstheorie im Eisenbau"). In an actual girder test, the deformation of the lattices was found to be only 5% of the total deformation.

An important factor in the choice of the materials is also the ratio of the proportionality and elasticity limit to the tensile strength. The longer the material conforms to Hooke's law, just so much better will be the utilization of the material. In many countries there is now required a certain breaking strength of an airplane expressed as a multiple of its weight. This requirement, moreover, necessitates exceeding the proportionality limit. As soon as the material no longer conforms to Hooke's law, the secondary stresses increase very rapidly, occasioned by the no longer computable greater deformations. These secondary stresses may then cause a premature break of the structural members. The ratio is here more favorable for alloyed steel than for duralumin. (Fig. 9.)

Very recently the Dornier-Metallbauten G.m.b.H. (Dornier Metal Works, Ltd.), in cooperation with one of the leading German steel works, has instituted a series of experiments with profile and rivet material, which have given very favorable results.

Even the resistance of the materials to corrosion cannot be disregarded. As regards corrosion, steel is considerably better than duralumin.

Likewise, economy may be the determining factor in choosing the material. The cost of a kilogram of finished steel construction is only 0.8 of the cost of a kilogram of plain duralumin, even taking into consideration the fact that eventual weight and time requirements are necessary for steel. Any comparison in this respect can be made only on the basis of accurate calculations. On introducing the general expenses, the ratios for duralumin again become more favorable, however, in that the differences in cost no longer affect the results to so great a degree. The factor of economy will be much more favorable to steel, if a method of duralumin construction is chosen which leaves a high percentage in trimmings and waste material. In using duralumin tubes, this ratio is still more unfavorable to duralumin, since their cost, as already mentioned, is about 50% greater than that of duralumin sheets or strips. The longer time required for steel construction is offset, on the other hand, by the greater time required for the production of duralumin.

Furthermore, in connection with the matter of riveting, Dr. Rohrbach stated that the rivet-hole relations are less favorable for steel than for duralumin. This statement must surely rest on an error since, according to the speaker, duralumin rivets made from the same alloy, and hence with the same tensile strength as the riveted material, are used, while it has long been customary in steel construction to use iron rivets considerably softer than the riveted steel. Consequently, the rivet-hole relations can in no case be less favorable for steel with iron rivets than for duralumin with duralumin rivets. The relation is unfavorable, however, for duralumin with iron rivets. As stated by the speaker, the Rohrbach Company uses steel for spar fittings. It is obvious that these steel fittings for duralumin can never be lighter than steel fittings for steel.

I would summarize my conclusions regarding the choice of materials as follows. The choice of building materials can be made only from consideration of the given static relations, economy and practical experience for each individual case. I assume it to be obvious that the whole material problem can relate only to the construction of highly stressed structural parts. As a matter of experience it is known that the weight of such parts constitutes about 8% of the dead load of an airplane and the time required to construct them, about 7% of the time required to build the whole airplane.

Former naval architect Baatz.- Dr. Rohrbach spoke on the question of airplane materials. On the one hand he compared wood and metal and, on the other hand, duralumin and steel. His contention is probably correct that the development of the airplane will follow the course of development of all other vehicles, cars, ships, etc., from wood to metal construction. This is due to the difficulty of obtaining sufficient wood of uniform structure for the production of any article on a large scale. As to what the metal of the future is to be, there is still a great divergence of opinion. Dr. Rohrbach compares steel having a tensile breaking strength of over 100 kg/mm² (142,235 lb./sq.in.) with aluminum alloys having a breaking strength of 40 kg/mm² (56,890 lb./sq.in.). The general fact that metal of specifically great strength unfortunately has a very small elongation, has compelled mechanical engineers in general to refrain from approaching the upper limit of strength and to prefer materials with a relatively great elongation. I recall, for example, that steel, with a strength of 50-60 kg/mm² (71,118 to 85,340 lb./sq.in.) and an elongation of 10-12%, can be produced cheaply in any desired quantity. Nevertheless, there is used in great quantities, in the construction of vehicles steel of low strength, about 40 kg/mm² (56,890 lb./sq.in.) with an elongation of 18-20%. The reason for this tendency in the choice of materials is that a vehicle is liable to collide with stationary objects and in such an event it is better for the girders to bend instead of breaking immediately. Hence a material is generally demanded with a very great elongation, which first becomes permanent above 60% of the breaking strength. For the latter reason, the use of a few special high-resistance steels, with excellent strength and elongation, is rendered difficult, since permanent elongation begins with them at about 30% of the breaking load. These include, for example, the V2a steel, which has recently become famous.

A similar tendency to use metals of somewhat less strength but greater elongation now seems to be invading the field of light metals. This tendency is increased by the fact that the softer materials, like duralumin and lautal which have breaking strengths of 36-37 kg/mm² (51,200 to 52,625 lb./sq.in.), can generally be worked cold, so that the expensive and troublesome process of annealing is eliminated and the softer alloys seem to withstand corrosion somewhat better.

Especially important is the behavior of those alloys in sea air and also in sea water for a long time, say about 1.5 years. While the strength of the material, even in the unstressed parts, diminished only about 10%, the elongation diminished 60-70% in places, and finally became entirely too small when its initial elongation was only 10-12%. The corrosion of the material in combination and its prevention, i.e., the preservation of the individual parts, might well be determinative therefore in the choice of the material. At present, however, there seems to be no reliable means of protection for light-metal alloys, such as the galvanizing of steel. Opinions differ regarding the effect of sea water on the various alloys. On the whole, the sea-water resistivity of duralumin and lautal is practically the same, while that of the other alloys is somewhat poorer. In combinations of steel and light-metal alloys the light metal does not appear to be the endangered part. According to experiments which have been verified by the material testing section, the light alloys seem to change their role with respect to iron, according to the duration of the experiment. While iron and steel at first stand higher than the light-metal alloys in the electrolytic row, a change seems to occur after 24 hours, i.e., in structural parts containing both light metal and steel, the light metal is never attacked. These experimental results are confirmed by experience.

Although I naturally agree with Dr. Rohrbach that entirely closed profiles do not wear as well in use as open ones, a good protective coat inside a closed profile lasts better than a like coat on exposed surfaces. Experience has shown that structural parts suffer most where, through lack of proper care, the protective coat is removed by mechanical injuries and fails to be renewed. It seems to be established that light-metal parts require the greatest attention, even in use.

Dr. Rohrbach's arguments were especially interesting as regards the possibility of reducing the production costs by suitable equipment. In general, the equipment increases the so-called unproductive capital. I would be grateful to the lecturer if he could tell us in what ratio the sum of the unproductive and productive capital is reduced by suitable equipment. It might be still more difficult to answer the second question, as to whether the cost reduction of a piece is due simply to the familiarization of the worker with the production method, or in what proportion it is ascribable to the equipment. I would appreciate having Dr. Rohrbach give us further information on this point.

Engineer Schrenk.- Thus far nothing has been said today concerning an important method of joining steel parts, namely, by welding.

I have just come from the welding session of the V.D.I. (Verein Deutscher Ingenieure) in Hamburg, where I learned how the process of welding is continually making progress in all fields of mechanical construction. It is by no means new in airplane construction. (See N.A.C.A. Technical Memorandum No. 453, "Welding in Airplane Construction," by A. Rechtlich and M. Schrenk.)

The advantages of welding are obvious, namely, the possibility of making the most difficult junctions with a minimum increase in weight, especially of joining tubes in the simplest way imaginable without increase in weight, and the economy of this method.

Many persons, however, entertain serious doubts as to the advisability of welding in airplane construction. They regard it as unreliable. The strength of the weld cannot be calculated and cannot be tested on the finished piece. A riveted junction can be calculated by long-established formulas, though the inside of the rivets cannot be inspected and a feeling of confidence is instilled only by their great number. These doubts apply also to shipbuilding, which occupies a position similar to airplane building, as regards reliability and safety. In the former, however, the process of welding is being increasingly employed.

The great reliability of welded junctions has long been demonstrated by innumerable laboratory and practical tests and many years of experience with suitably welded airplane parts, especially fuselages. Of course, certain conditions are requisite, such as experienced welders, suitable materials for welding and allowance, even in the designing, for the special peculiarities of the welding process. There is urgent need of these conditions, and it is accordingly to be expected that the work already begun in many places will be successful.

Another disadvantage is the relatively low strength of the welded junctions, which is about 35-40 kg/mm² (49,780 to 56,890 lb./sq.in.) for the metals now commonly used. This does not matter so much in fuselages where there are always slender compression struts which buckle under even slight stresses. It is less satisfactory for wing structures or other parts which are subjected to tensile, compressive and bending stresses. Many endeavors are being made to discover by systematic experimentation steel alloys with a high tensile strength and yield point in the annealed state and with good welding properties. There is a good prospect of obtaining welds with a tensile strength of 60-70 kg/mm² (85,340 to 99,565 lb./sq.in.). The advantages of welding will then be still greater, especially for large structures. I may add that the D.V.L. is giving much attention to this matter.

Engineer Focke.- Referring to Dr. Rohrbach's address, I shall endeavor to make, from the standpoint of wooden-airplane construction, a comparison of the properties which result from the peculiarities of both materials in practical use.

1. In England, after a period of transition, only metal airplanes are to be ordered by the military authorities. It is said, however, that this decision is not at

all due to considerations regarding the suitability of the material, but that it is simply a question of the difficulty of obtaining wood in war time. In the event of war, however, the quicker and cheaper supply of wooden airplanes, in comparison with the use of metal, would play a decisive role, since the possible longer life of metal airplanes would be more than offset by their rapid destruction and by the types becoming obsolete.

2. The greater cost of a metal airplane cannot be due alone to the extensive preliminary work of a constructive nature. This is demonstrated by the fact that, in metal construction, the necessity of further division of the structure into many small parts directly affects the working times even in quantity production. For obvious reasons Dr. Rohrbach does not give the absolute working times in metal construction, so that no direct comparison is possible in this respect. An approximate idea can be obtained, however, from the prices of similar airplanes built on about the same scale. This applies, for example, to the Junkers K 16 and the Focke-Wulf A 16, the sale prices of which bear approximately the ratio of 2 : 1.

3. As regards weight, wood construction still has the advantage, naturally with the fulfillment of the same strength requirements. Here also we can compare Junkers K 16 and Focke-Wulf A 16. With the same engine (75 hp Siemens) the K 16 carries only one pilot and two passengers and has a correspondingly smaller wing area than the A 16, which carries one pilot and three passengers at a somewhat higher speed. Nevertheless, the ratio of the dead load to the pay load is about the same for both airplanes.

4. One of the fundamental faults which can be imputed to the light metals of to-day, is their fatigability under varying stresses, though the danger from this phenomenon has always been contested, especially in Germany, but without any counter-evidence. American and Dutch experiments show that, under some circumstances, the figures obtained for varying stresses (vibration strength) are only 40% of those for static loading. Though Dr. Rohrbach says that fatigue phenomena were observed only above the proportionality limit, there always remains the consideration that no absolute definition of the proportionality limit can be made for any material. It has been found that accurate measurements enable the recognition of very

small permanent deformations even with very small loads and more or less for every material. In testing materials it has therefore been found necessary to establish, for such permanent elongations, arbitrary minimum limits, such as the measure of the elasticity and proportionality limits, i.e., in other words, any determination of the proportionality limit, independently of arbitrary assumptions is practically impossible. Even from these relations, it is obvious that the problem of fatigue cannot be regarded as definitely solved. Experience shows that, in airplane parts which are exposed to vibrations, unexpected breaks, some of them dangerous, repeatedly occur, as they never occur in the same way with wood.

The physical properties of metals and wood differ fundamentally. All metals have a crystalline structure, i.e., the material is not homogeneous and its strength characteristics cannot possibly be uniform as regards the component particles. On the contrary, cellulose, the chief constituent of wood, is an amorphous substance. It does not have, like metals, separating surfaces between adjacent crystals whose cohesion, always weaker than that of the rest of the material, can be still further weakened by mechanical action. In other words, the metal, being of a crystalline structure, is gradually weakened by the engine vibrations, while the wood, being amorphous, is not thus affected.

5. As regards the corrosion of light metals in comparison with the weathering of wood, very few exact and comprehensive data are yet available. An unprejudiced judge, however, receives the impression that the corrosion of the light metals is as important as the weathering of wood, at least in our climate, and requires corresponding precautionary measures. Like wood, no metal structure can last long without a good protective covering of paint or varnish.

The defect most commonly imputed to wood, namely, its liability to warp, generally plays a very subordinate rôle in accurate investigation. Previously it had always been said, for example, that ordinary wood-and-wire fuselages very easily become distorted. More accurate investigation nearly always shows, however, that no changes have occurred in the length of the wood, but that the trouble is almost always caused by the slackening of the brace wires due to poor terminal fastenings. Aside from warping, the only other consideration in connection with wood is the actual chemical changes or, in other words, the various kinds of foulness. Probably every one will admit, however, that even under the most unfavorable conditions (outside the tropics) any real foulness can be prevented for decades by suitable protective measures. For comparison it is not fair to use the still existing wooden airplanes from the time of the war, whose protecting coats were almost always very inadequate, due to the hasty war-time production.

6. Wood, of course, always has one other defect, namely, the lack of uniform strength. This results in a greater weight than would otherwise be necessary. This defect does not signify, however, because any weight comparison still favors wood.

7. Fireproofness is always claimed as an advantage of metal. Experience has shown, however, that the fire hazards of an airplane are not determined by the building material but by the engine fuel. So long as such inflammable fuels must be used, the danger, in case of fire, will consist in the large amount of fuel on board. The simultaneous burning of a few wooden parts does not appreciably affect the catastrophe.

8. If the problems of fatigue, corrosion and cost were all satisfactorily solved, I would immediately advocate metal construction. Furthermore, it cannot be denied that the preference for metal construction does not rest alone on technical grounds. The engineer has a certain instinctive fear of working with unfamiliar materials. From the laity, which in this case is the flying public, we often hear such expressions as "Metal does not go to smash."

It may also be added that, with a metal covering, the always necessary external stiffeners (e.g., corrugations) have, according to the latest experiments, a very unfavorable aerodynamic effect, in that they increase the drag by retaining the boundary layer of air. Such stiffeners are practically indispensable, however, with the necessary thinness of the metal covering. To shift them to the inside would involve great difficulties of a constructive nature.

I have tried to explain briefly why wood airplanes are at least not yet entirely obsolete and still compare favorably with metal ones for many uses.

In conclusion, I would express my conviction that I would hardly have been able to sell a single commercial airplane, had I been obliged to ask the price of a metal airplane.

Dr. Rohrbach.- I thank the gentlemen for their interesting remarks which have given us all an abundance of suggestions.

As regards Mr. Spiegal's remarks, I always consent gladly to a rather extensive exchange of experience. In practice, however, this exchange generally fails, due to the fact that the different firms hold different views regarding the keeping secret of certain details and thus cooperation is lacking.

Especially as regards the tubular junction of the transocean plane, I must say that the sketch seems rather to support my contention (namely, that fundamentally only open profiles should be used, because everything would otherwise be too complicated) than that of Mr. Spiegal. As regards the objections of Mr. Spiegal to the supporting covering, I can only say that, with the large airplanes we are now building, i.e., up to several thousand horsepower, we have experienced no difficulty from the thinness of the sheet metal.

Time is too short for me to discuss in detail the contributions of the different speakers. I particularly welcome the demand of Director Hüttner for the extensive subdivision of airplanes into independent structural groups, which I also consider of especial importance for the further development of airplane construction.

I thank Mr. Neubert for his supplementary remarks on the strength and elasticity of steel and duralumin. If the attempts to make rivets of the strength of the alloyed steel were successful, steel construction would become more frequent than hitherto, especially on large airplanes.

Steel itself corrodes less than duralumin but, since it is almost always used with duralumin parts, it causes, especially with strong nickel or chromium content, very great corrosion of the duralumin at their points of contact. I can only agree with Mr. Neubert's general conclusion that the construction material must be chosen for each individual case. We differ only in one point, in that I am of the opinion that duralumin is better in a series of cases where Mr. Neubert thinks steel should be preferred.

It would take too much time to discuss all these details, which, after all, can be satisfactorily settled only by the experience of the next few years.

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

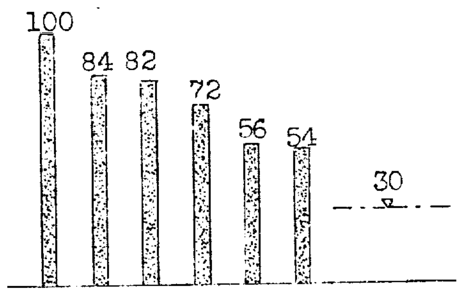


Fig.1

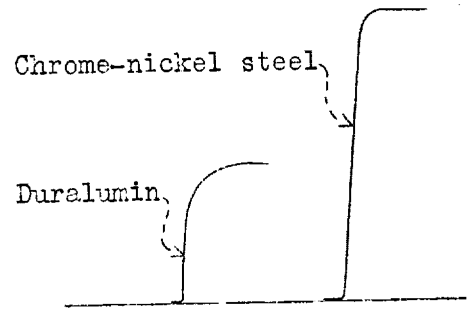


Fig.9

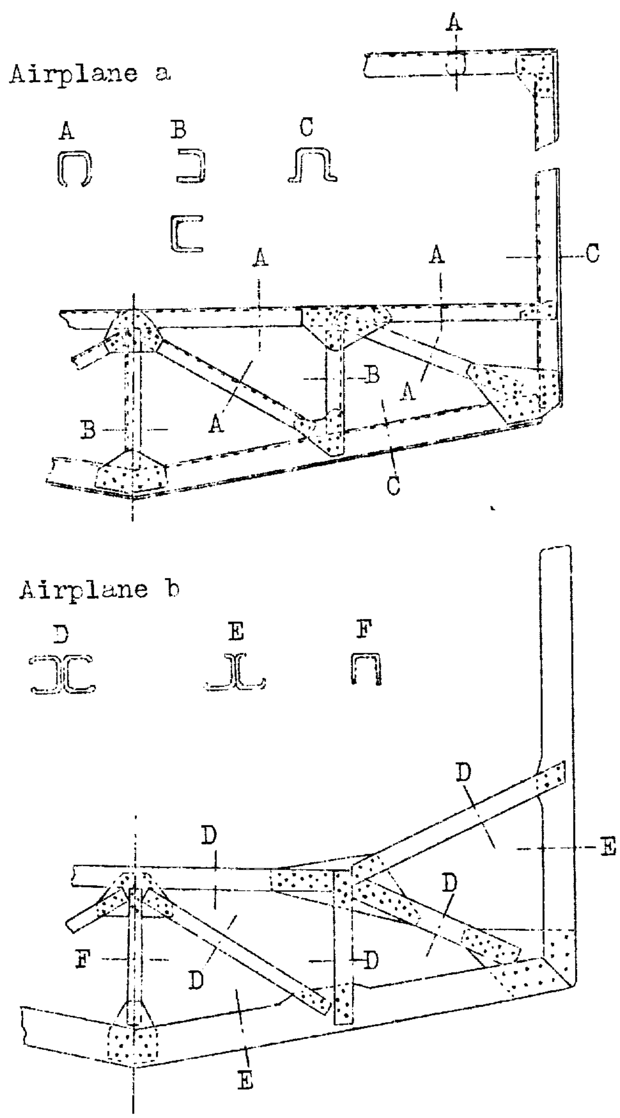


Fig.8

Fig.2

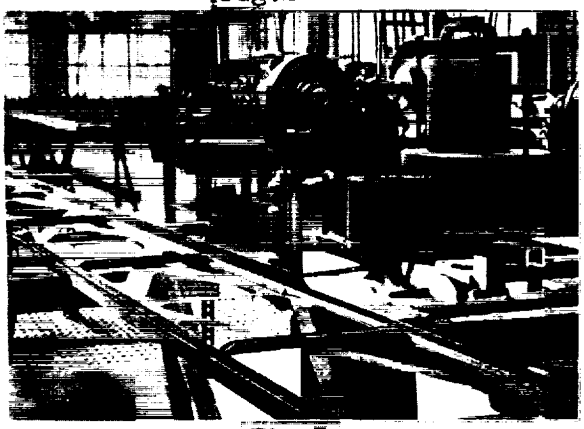


Fig.3

Fig.4

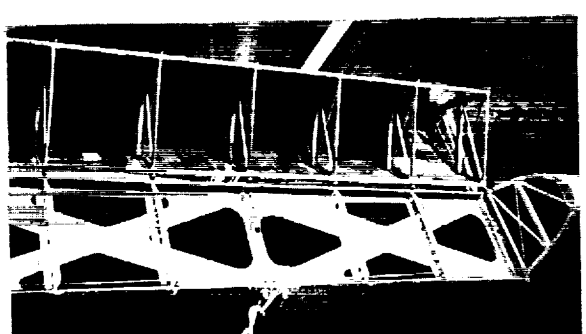


Fig.5

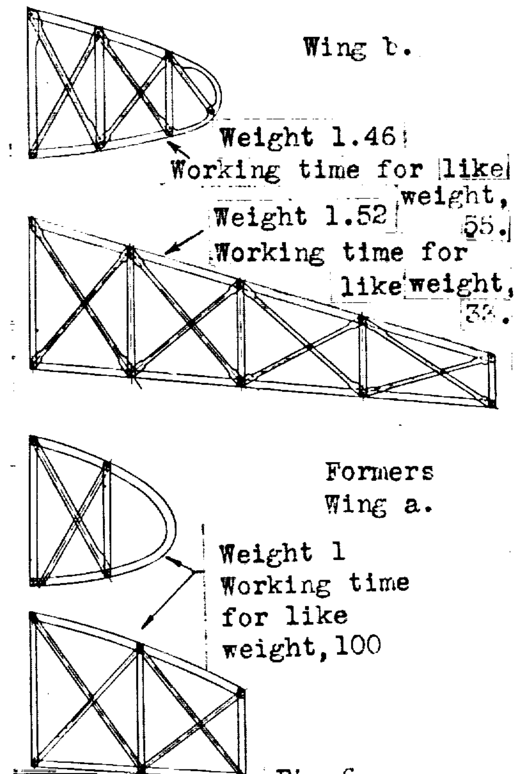
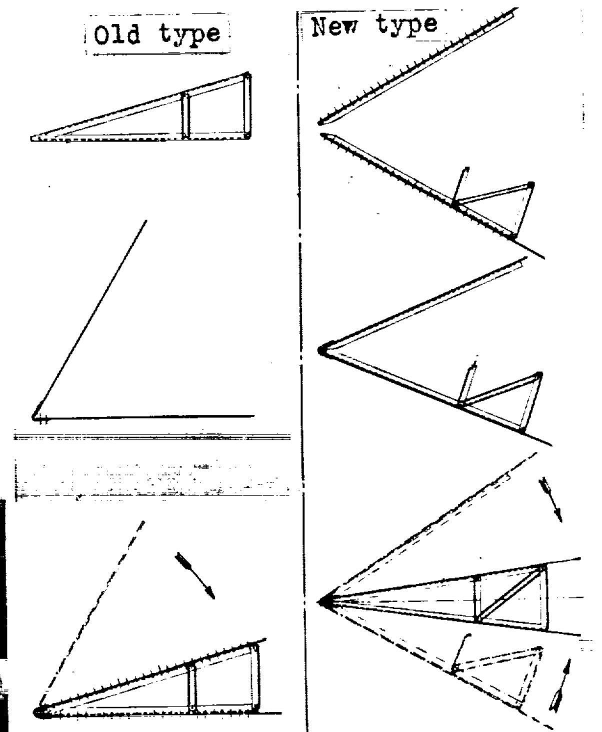


Fig.6



Weight 1

Working time for like weight, 100

Fig.7

Weight 0.8

Working time for like weight, ?

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