Some Design Aspects of the Rigid Airship

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This paper reviews earlier airship design and present-day trends in the light of modern design practice as exemplified in the construction of large size airships such as the "Akron" and "Macon.

It is pointed out by the author that a saving in specific deadweight has always accompanied increases in airship size, except in those cases where specifications have been markedly altered or where the designer has deliberately sacrificed a weight advantage for an expected improvement in performance.

The design of bulkheads and main frames is discussed with regard to the restraint of gas cells and the distribution of planar loads. The influence of the number of corridors in strengthening the main frames against torsion and in assisting in the support of the intermediate frames is also discussed.

There have been few developments in the engine field during the past few years but it does appear that in the matter of power-plant location the "inboard" installations will have the advantage over "outboard" installations for the faster long-range airships now projected for commercial service.

In discussing means of maintaining the ship's equilibrium under varying conditions the author touches on disposal of ballast and aerodynamic lift to compensate for localized loss of gas, water recovery from the exhaust to replace the weight of the fuel consumed in a ship using liquid fuel, some advantages and disadvantages of gaseous fuels, and general design problems involved in guarding against uncontrolled descent.

In a paper presented to this Society in 1927 and published in the 1928 Transactions, the possible development of large rigid airships was generally discussed, based on an extrapolation from the known performance data on the medium-size airship Los Angeles. It was suggested in this earlier paper that the ideas advanced should be reviewed after the actual construction of a large-size airship. In line with this suggestion, it is proposed

(1) To revise the data on specific deadweights
(2) To offer additional information on the subject of rigid mainframes and bulkheads
(3) To discuss the functions of multiple corridors
(4) To give a comparison of inside and outside power plants, and

5) To point out the general design problems in connection with loss of gas and forced uncontrolled descent.

Revision of Data on Specific Deadweights

In 1928, when the original paper was presented, the largest airship in existence was the Los Angeles. Her volume, at a nominal inflation of 95 per cent, was about 2,500,000 cu ft. The experience and weight data associated with the design of this airship were important factors in the preparation of the curves presented in that paper.

In the intervening five years the world has witnessed the construction of five large rigid airships, all of them appreciably larger than the Los Angeles, and two of them more than twice as large. During this period the viewpoint on some of the basic design assumptions has changed appreciably. This appears to be an opportune time to review the earlier assumptions and to adjust the conclusions to be derived therefrom.

The earlier paper presented a graph showing the decrease in the unit weight for the entire deadweight of an airship as the volume was increased. While the basic trend of this curve is still correct, there have been changes in design requirements during the intervening years which have rendered the absolute values obsolete. As a specific case a designer extrapolating from past experience might have concluded that a 5,000,000-cu ft airship could be built for from 135,000 to 140,000 lb, and yet the construction of the British R-100 and R-101 airships showed that even their expected deadweight of 90 tons could not be met.

The original data should be revised in the light of modern experience and the newer design specifications. The nature and magnitude of the revisions may be determined from a consideration of the assumptions used in formulating the original graphs.

Our original prediction assumed that a light-weight, low-fuel-consumption, reversible engine, built along the lines of American airplane engines, would become available for airships and that as larger airships were built these engines would become available in larger power units, thereby decreasing the unit weight per horsepower. This prediction has not yet come true. The Graf Zeppelin and the Macon are both equipped with Maybach 600-hp engines weighing about 4.5 lb per hp.

Progress is being made in the design of such light-weight American engines for airship use, and the engine situation may improve in the future. There is, however, considerable pressure for the use of the so-called "safe fuel" in airship engines, and it is possible that airship Diesel engines may become available before suitable safety-fluid engines can be developed. The Diesel engines will have a high-unit weight, possibly higher than that of the present Maybach gasoline engines, so that it seems advisable to predict future development on the basis of heavier engines. A large portion of the overweight in the British-built R-101 can be attributed to the use of Diesel engines weighing 8 lb per hp.

For simplicity in the original calculations a common airspeed of 70 knots was used for all sizes. In actual practice there has been a gradual increase in speed from the Los Angeles to the Macon, which, incidentally, is the fastest airship ever built. The original predictions, therefore, are subject to correction for the increased speeds which have been realized in practice.

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3 Contributed by the Aeronautic Division and presented at the Annual Meeting, New York, N. Y., December 4 to 8, 1933, of The American Society of Mechanical Engineers.

4 See Fig. 13 of original paper.
Speed has a double influence upon the weight of the airship. In the first place the installed power-plant weight varies with the cube of the maximum speed to be obtained. A ship like the Macon, designed for a top speed of 72.5 knots, could be expected to carry 12 per cent more power-plant weight than a ship of the same size designed for only 70 knots. (Actually, with attained speeds of 74 to 75 knots, the Macon power plant would have been justified in being 20 per cent overweight by the old 70-knot standard.) The second influence of speed is noticed in the weights of the hull and the empennage. The beam strength of the hull, with the exception of the bow section, can generally be taken to vary with the square of the maximum speed. The fins and rudder structure must also be increased in strength and weight in accordance with the increase in the square of the design velocity.

The higher flight speeds also require additional outer cover support in the panels and along the fin and control surfaces. The accidental ripping of the fin covering on both the Graf Zeppelin and the R-101 during squalls encountered on transatlantic flights has resulted in the use of more rigid outer cover supports in ships built since that time.

The practice of deriving strength calculations for the hull of an airship on the assumption of a hypothetical bow force, representing the action of a gust on an airship as it was flown at full speed into a zone of cross-wind, was not adopted until after the Shenandoah disaster. There had been no incentive for serious consideration of this case in the design of the Los Angeles and other early German airships since much reliance was placed upon the experience factor; that is, the knowledge of what strengths had proved adequate in the wide range of operation conditions actually experienced in the past. C. P. Burgess subsequently analyzed a series of airships in the light of this hypothetical gust theory and from his knowledge of the structural strength built into the various airships concluded that the maximum gusts they could withstand with safety at full speed were 17, 20.6, and 56 fps for the Shenandoah, Los Angeles, and Akron, respectively.

There is a strong possibility that commercial ships of the future will be designed to a similar type of bow-force specification. In some respects this would correspond to the practice in naval architecture where surface vessels are designed to resist the action of a hypothetical wave. It appears that a correction for this item must be introduced if the original data are to be used for predictions of the weights of future commercial airships.

Our opinion regarding interior arrangements for the crew has changed considerably. The allowances made for the quartering of the crew had been admittedly low, being based on the wartime practise of letting the crew sleep in hammocks or bunks arranged along the gangways with little wall or floor space. In both the Los Angeles and the Graf Zeppelin the quarters appear meager compared to the light, ventilated state rooms for the crew of the Macon. Improved standards of living and the maintenance of high crew morale during long flights suggest that the crew be given accommodations superior to those of wartime ships, but probably not necessarily as ample as those carried by the Macon.

In utilizing these predicted weight curves one must keep in mind the fact that they apply only to the basic operating weights. Commercial equipment like the state rooms of the Los Angeles and the commodious passenger accommodations in the Graf Zeppelin must be charged against the commercial payload. In the same manner the weights built into the Akron and Macon for military equipment, such as gun emplacements, inside airplane compartments, airplane landing trapezes, etc., all belong in the military load and not in the basic deadweight. They should not be used in arriving at prediction curves for a range of sizes.

It is evident, therefore, that a fair comparison will involve two sets of changes; one adjusting the basic unit-weight curve of the original prediction to the present standards of strength, comfort, and reliability, and the other a correction of the reported deadweights by the removal of those portions of the reported weight which are attributable to the useful load and their reduction to the basic design values. The weight statements for the last six rigid airships to be built have been analyzed and adjusted in conformance with the preceding discussion, the final comparative unit weight values being presented in Table 1.

The adjusted prediction values in the first column have been obtained from the original values presented in the 1928 paper by the addition of reasonable weight allowances for those items which have been discussed as representing new standards or specifications in the airship industry. These revised unit weights represent the values which are now considered necessary if airships are to be built according to modern standards. For this reason they may be compared with the corresponding reported weights of airship structures and the "theoretical" overweight determined.

The column headed "reported value" has been obtained by dividing the reported deadweight of each airship by its estimated air volume. The values for the deadweights used here are those published by the designers in recognized aeronautical journals or released by governmental agencies during the course of investigations. The "basic value" figures have been obtained by making appropriate allowances for items generally included in the reported weight but more properly attributable to the useful load.

The difference between the reported and basic values for the Los Angeles and the Graf Zeppelin is due to the removal of the weights for passenger accommodations. The correction of the data for the British airships has been complicated by the absence of published detailed weight statements. The reported deadweight of R-100 has been reduced by 17,700 lb. This is a combined correction making allowances for passenger accommodations and the use of light-weight engines. A total of 26,000 lb was subtracted from the deadweight of R-101 to correct for passenger accommodations and for excessively heavy engines.

The Akron and Macon values are entitled to a correction of about 22,000 lb of directly removable weight. Something like two-thirds of this weight is in water-recovery apparatus (not carried by the other ships in the table of comparison), the remainder being made up of such miscellaneous items as airplane compartment, accessibility features, machine-gun stands, the elaborate control stand in the lower fin, and an unusual amount of handling equipment.

The first and third columns of Table 1 may be used for comparisons, but there is one other correction which should be applied to the Graf Zeppelin, Akron, and Macon weights in order to make the comparison fair and complete. This is the allowance for deliberate "overweight" built in by the designers with the knowledge that it would be more than paid back by the improved performance and the reduction of the fuel load needed to ar

<table>
<thead>
<tr>
<th>Airship</th>
<th>Adjusted prediction</th>
<th>Reported Basic value</th>
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</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>30.0</td>
<td>32.1</td>
</tr>
<tr>
<td>Graf Zeppelin</td>
<td>28.6</td>
<td>30.3</td>
</tr>
<tr>
<td>R-100</td>
<td>28.3</td>
<td>34.7</td>
</tr>
<tr>
<td>R-101</td>
<td>29.0</td>
<td>42.0</td>
</tr>
<tr>
<td>Akron</td>
<td>27.1</td>
<td>30.9</td>
</tr>
<tr>
<td>Macon</td>
<td>27.1</td>
<td>28.6</td>
</tr>
</tbody>
</table>

Table 1 Comparative Unit Weights (Lb per 1000 cu ft of air volume)
AERONAUTICAL ENGINEERING

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complish any given mission. The combined weight of the lifting-gas cells and fuel-gas ballonets in the Graf Zeppelin is considerably greater than the weight of the lifting-gas and liquid-fuel tankage for a conventional airship of the same type. The efficiency of the fuel-gas system, however, more than offsets the increased dead-weight allowance. If the Graf Zeppelin were to be converted to straight liquid-fuel operation the modified unit weight would be in excellent agreement with the adjusted prediction in Table 1.

The inside power-plant arrangement of the Akron and Macon will be discussed later in this paper. From the weight standpoint it can be shown that an outside power-plant installation would require the expenditure of at least 10,000 lb more fuel to attain the same maximum cruising range as the Macon. The specification of this airship stated that it was to be used “primarily for scouting at sea” where long range is a necessity. The comparative or basic value for the Macon may, therefore, be lowered by about 1.3 units, thus bringing it into agreement with the adjusted prediction.

In preparing this plot, these three ships have been left in their comparative positions in the “basic” table. Actually, in these cases, the designers were able to build airships with the unit weights in the “predicted” table if they so desired, but they chose the alternative of building heavier ships because they expected that the improved performance of the heavier designs would more than compensate for the apparent waste of weight.

RIGID MAIN FRAMES AND BULKHEADS

The earlier paper described main frames consisting of a series of diamond-shaped trusses, the ends of which were connected by a system of taut bracing, as typical for “medium-size class” airships, and discussed the type of built-up rigid ring frame which it was planned to adopt for “large-size class” airships.

The paper also mentioned the possible use of a loose flexible network as a bulkhead in connection with these built-up frames, leaving the carrying of load entirely to the rigid ring. The rigid ring frames of the Akron and Macon were designed to carry the specified loads without the assistance of the bulkheads, but the original alternative plan of using loose bulkheads between adjacent gas cells was abandoned in the early stages of design development as soon as it became apparent that it would not permit a desirable degree of static stability with the original type of construction.

In other words, it was feared that the gas cells would surge excessively under conditions of pitch unless some more rigid method of holding the cell ends in place was adopted. The expedient of using a netting which was installed under sufficient initial tension to give the desired control of the gas-surging tendency was to be preferred and, in addition, the netting installed in this manner stiffened the main frame in a way similar
to the wire bracing which had been used in smaller ships like the Los Angeles. The new type of initially taut netting was attached to the majority of the main frames through the medium of resiliency devices. (See Fig. 1.) These devices could be set so that the netting would have an initial tension sufficient to give a reasonable control of the surging tendencies during normal flight. Under more severe conditions, and particularly with a deflated cell, the resiliency devices would elongate, allowing a

discharged by some simpler automatic extension device, or even by devices which could be operated by the crew at the time of the emergency.

The load-distributing effect of a bulkhead of the netting type can be best demonstrated from wire stress measurement made in connection with frame-loading tests. Fig. 3 shows the typical participation of a bulkhead of the netting type in the transmission of planar loads. The dotted inner circle shows the initial tension uniformly distributed over the ring. Vertical loads increased the tensions in the vertical plane and decreased those in the horizontal plane. The amount of load carried by the bulkhead can be varied at will by adjustment of the wire lengths. It can be reduced by equalizing the tensions, or it can be increased by shortening the wires in the vertical plane and lengthening the wires in the horizontal plane.

The installation of a radial or cord-type bulkhead in a rigid ring frame is also a possibility. Comparative tests with the netting and the radial type of wiring are being conducted. Both types may have merits. The netting probably will allow somewhat better elasticity under side pressure and will dis-

change in the effective length of the netting and permitting it to assume a better shape for the transmission of the bulkhead load to the longitudinals. This combination of built-up ring frames, netting, and resiliency devices was successfully incorporated for the first time in the Akron and Macon class. (See Fig. 2.)

While the deflated cell condition is perhaps the most severe which the design of the frame and wiring must meet, it must also be suitable for the transmission of the concentrated loads to be experienced particularly in ground handling. In this respect, the built-up main frame has the advantage that a locally applied load is distributed over a large sector of the frame, and, therefore, affects a large portion of the netting. A frame consisting of consecutive diamond trusses is not so well adapted for the ready distribution of concentrated loads and the brunt of them must be borne by the wires connected to the particular joint under load. It appears that inherently rigid ring frames offer better distribution of concentrated loads.

The resiliency devices can be readily adjusted with sufficient initial tension so that they will not start to elongate under the radial component of any external concentrated load which is likely to occur. Where the external loads are expected to be very high, as is the case with the frames to which the ground-handling gear is attached, it may be desirable to eliminate the devices entirely. This step has already been made on some of the frames in the Akron design and the combination of built-up frames and wiring alone has been found to be practicable.

The resiliency devices are automatic units, the functioning of which is particularly important in the case of a deflated cell. Since this emergency seldom arises and since the units add to the initial cost, maintenance, and deadweight, there is some thought that they might be dispensed with altogether or their function

Fig. 3 Typical Participation of Bulkhead in the Transmission of Load
MULTIPLE CORRIDORS

The earlier paper discussed two main-load-carrying lower corridors located 45 deg from the vertical axis, as well as the use of a gas-valve inspection corridor on the top of the ship. It is evident that the two side corridors apply the loads to the structure in a very efficient way, since the weights are brought close to the shear-transmitting equatorial part of the structure and there is a minimum of distortion in the frames.

The multiple-corridor arrangement permits the whole airship structure to be observed, inspected, and repaired in flight in a manner heretofore impossible. The two load-carrying corridors also provide more space for the installation of fuel and ballast.

The three-corridor arrangement costs some weight and gas space, but it offers the advantage of a structural support to the intermediate frames and main frames. The intermediate frame must change its contour under the buoyant forces and finds support from the three keels, thus also benefitting the longitudinals indirectly. The main frames have, among other load conditions, to take care of a twisting load in case of side pressure on a bulkhead. Again, the three corridors relieve the main frames of a part of this torsion.

The displacement of the joints of the intermediate frames in their own planes under the influence of the buoyant forces has been the subject of very extensive research by actual full-size measurement. Ingenious apparatus was devised by which an observer stationed on the dock floor could, by looking through a powerful telescope, actually read the relative displacements of intermediate joints against an optical chord line between main frames. Readings were obtainable to an accuracy of a millimeter, either while the ship was on its assembly towers or while it was floating free in the dock. An optical system of scales, lenses, and mirrors was so worked out that the accuracy of the observations did not depend on the exact location of the telescopes. This expedient made it practical to follow these measurements on hundreds of joints for several weeks. Fig. 4 shows the character of displacement of the joints of a typical intermediate frame under the effect of the forces from the buoyant gas at 90 per cent inflation. The plot reveals the predominance of expansive forces in the upper quadrant and a contractive flattening out of the arcs between the lateral gangways and the equator. From this actually observed behavior in the presence of three gangways, the probable type of distortion that can be expected if two additional corridors were installed, has been approximated in the same figure by dotted lines.

In order to study the effect of the side gas pressure transmitted through a bulkhead adjacent to an empty cell upon the twist of the main frame, a series of interesting experiments was carried out in cooperation with Professor Plummer of Case School of Applied Science, Cleveland, Ohio. Students, there, have built a model of a trussed main frame of celluloid tubes as girders and brass wires for bracing elements, as shown in Fig. 5. This model was designed to obey, as nearly as was possible, the laws governing elastic similitude. These laws are that homologous forces, applied to the model and to the full-size prototype, produce geometrically similar deformations, when all model forces are reduced in magnitude according to a definite scale. Suitable selection of materials and load conditions permits of the study of elastic deformations greatly in excess of those occurring in full-size service, and thus renders them amenable to much more accurate measurement. This ring model was subjected to twisting loads, the twist of all sections being measured in several experiments with restraint offered by five or three gangways respectively. These investigations are being continued and are throwing considerable light on the extent to which the multiple corridors stiffen the main frame against torsion.

COMPARISON OF INSIDE AND OUTSIDE POWER PLANTS

The merits of inboard and outboard power plants can be impartially compared only when the same required design speed is taken into consideration. The attainment of a specified air speed with outboard plants requires the expenditure of more
power than would be necessary with an inboard installation for
ships of the same size and other similar characteristics.

It is interesting to compare the merits of the outboard in-
stallations of some previous ships with the inboard installation of
the Macon (see Fig. 6), using the propulsive coefficient \( K \) as a
measure of merit. The propulsive coefficient \( K \) can be expressed
as being in direct proportion with the third power of the speed
and the two-thirds power of the volume, and in inverse propor-
tion with the required horsepower:

\[
K = \frac{\rho v^3 \times \text{vol}^{2/3}}{550 \text{ hp}} \quad [1]
\]

\( K \) can also be defined as twice the propulsive efficiency di-
vided by the ship's drag coefficient. It is a measure of the
efficiency of the drive and the aerodynamic qualities of the ship,
combined. Table 2 shows the improvement of the propulsive
coefficient of the Macon over that of previous ships:

<table>
<thead>
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<th>TABLE 2</th>
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<tr>
<td>Ship</td>
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<tr>
<td>Air volume, cu ft</td>
</tr>
<tr>
<td>Speed, knots</td>
</tr>
<tr>
<td>Horsepower</td>
</tr>
<tr>
<td>Power-plant weight, lb</td>
</tr>
<tr>
<td>Unit weight lb per hp</td>
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<td>( K )</td>
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It is interesting to consider hypothetical versions of these
earlier ships having the nominal volume of the Macon (6,500,000
cu ft) and her guaranteed top speed of 72.5 knots. The power
required for the propulsion of such ships may be roughly esti-
mated from a consideration of the ratio of the cubes of the actual
and hypothetical air speeds and the ratio of the increase in volume
to the two-thirds power. Values of these ratios, or "power
multipliers," are given in Table 3.

It should be remembered, however, that the propulsive co-
efficients will not remain constant over this range between the
actual and the hypothetical ships, but will improve slightly with
increasing size and speed. This "scale effect" influence is also
listed in Table 3. The probable horsepower needed to attain
the desired performance in these hypothetical ships has been
computed with the help of these "power multipliers" and the
"scale effect" adjustment.

<table>
<thead>
<tr>
<th>TABLE 3</th>
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<tr>
<td>Ship</td>
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<tr>
<td>Ratio of cubes of speeds</td>
</tr>
</tbody>
</table>
| Ratio of two-thirds powers of
volumes | 2.150 | 2.314 | 1.886 | 1.000 |
| Allowance for scale effect, per
cent | 13.5 | 15 | 10 | \( \ldots \) |
| Original horsepower (as built) | 1500 | 1200 | 2000 | 4480 |
| Hypothetical horsepower | 7274 | 6443 | 5102 | 4480 |
| Hypothetical power-plant
weight, lb | 72,013 | 65,435 | 53,061 | 50,412 |

The figures of Table 3 assume that ships of the size and speed
of the Macon were built under the status of the art existing at the
time of construction of the original ships. The contention may
be made that the art of outboard-power-plant design has im-
proved in the intervening years, and this is undoubtedly true,
but one must remember that the Macon inboard power plant has
by no means exhausted the design potentialities of this type
and much further improvement is still possible. In any event
the figures of Table 3 strongly indicate that the inside arrange-
ment may possess advantages for high-speed airships.

As previously stated, more power is required to attain a given
air speed with outboard than with inboard plants, but the unit
weight (pounds per horsepower) for an outboard plant is generally
less than that for an inboard installation. The total power re-
quired depends not only on the drag of the ship but also on that
of the power plant itself, so that the importance of the drag
varies with the speed to be attained. The greater the speed
required, the more important the drag due to power plant be-
comes. In other words, the greater the relative drag area con-
tributed by any power-plant arrangement, the sooner the weight
increase necessary for a further increase in speed assumes im-
pedimental proportions. Under certain circumstances there is a
speed at which the weights of the two competitive arrangements
would be the same. At higher speeds the weight advantage would
pass from the one to the other. The speed for which the total

\[ \nu = \sqrt{\nu_0^2 (w_d - w_i)} \quad \ldots \quad [2] \]

where

\( \eta \) = the propulsive efficiency (assumed the same in both
cases)
\( w_d \) = specific weight, lb per hp, for outboard plants
\( w_i \) = specific weight for inboard power plants
\( d_i \) = specific drag area, sq ft per hp, for outboard power plants
\( d_o \) = specific drag area for inboard plants

If \( w_i \) were equal to \( w_o \), the inboard power plant with its smaller
drag area would have the advantage at all speeds. Since, how-
ever, outboard power plants are lighter than inboard, they have the deadweight advantage for low speed. As they have more drag area per horsepower, however, they lose out on the higher speeds where more horsepower is required.

Assuming practical numerical values for \( w_0 \) equal to 0.7, 0.8, and 0.9 times the value of \( w_1 \): \( d_1 \) as two, three, and four times as great as \( d_1 \) (ratios which are not out of order), and taking a reasonable value for \( \eta \) then the “equivalent weight” speeds will be those shown in Fig. 7 where the shaded area represents the range of contemporary projects. A clue as to the relative drag areas of inboard and outboard power plants is given in Fig. 8, which presents the results of tests made on models of outriggers similar to those employed on the Macon and power cars like those of the Los Angeles and Graf Zeppelin.

The center region of the shaded field (see Fig. 8) indicates that with a design speed of about 100 mph, the net weights of the power plants, inboard and outboard, are on a par. Of course, other things being equal, the low-drag ship having the engines within the hull will always hold an advantage in the way of fuel consumption, over the other, regardless of the length of the flight.

The fuel consumption at cruising speeds is an even more important criterion. In fact, an actual advantage may be gained from the inboard plants on an airship of present or contemplated sizes at speeds considerably below 100 mph. For any given speed, the hourly fuel consumption is proportional to the drag at that speed. Therefore, even if the higher drag airship has less initial deadweight it will eventually have consumed enough fuel to outweigh the difference in power-plant weights. If the time required for this to happen is well within the flight duration scheduled for the service for which the airship is intended, there remains no question as to the advantage of the inside power plant from the weight standpoint; even though it may be heavier, it may start its flight with a much lower fuel load, offsetting the deadweight penalty.

Under the same assumptions as introduced before, the number of hours which the airship with inboard power plants must fly to overcome its handicap of deadweight can be expressed approximately by

\[
h = \frac{w_1}{F_0} - \frac{w_0}{F_1},
\]

where \( w_1 \) and \( w_0 \) represent the total weights of the ships with inside and outside plants, respectively, and \( F_1 \) and \( F_0 \) their respective hourly fuel consumptions at the same speed. Since the total weights are functions of the power and unit weights and the hourly fuel consumption are functions of power and unit drags, it is possible to arrive at the following expression for the “equalizing time”:

\[
h = \frac{1}{Z_m - d_1} \frac{w_1}{Z_m - d_0} - \frac{1}{Z_c - d_1} \frac{w_0}{Z_c - d_0}.
\]

where

\[
f = \text{specific fuel consumption, lb per hp-hr}
\]
\[
Z_m = \frac{1100}{\rho v_m^2}
\]
\[
Z_c = \frac{1100}{\rho v^2}
\]
\[
v = \text{the cruising speed}
\]

\( \rho \) is the density of air.

The other symbols are the same as those used in Equation [2]. Fig. 9 has been prepared from Equation [4] by substituting a set of reasonable values as before and assuming top speeds of 80, 90, and 100 mph and cruising speeds of nine-tenths of the top speeds (73 per cent power). Again narrowing the field to the more definite limits of contemporary projects, it is seen that a weight advantage is realized after flying for 30 to 35 hr with a ship having a top speed of about 90 mph. It is evident that on commercial airships of the future the inside arrangement will either be worth its weight from the start or will pay for itself on flights of less than 50 hr. Transatlantic flight schedules will probably average more than 50 hr so that in such a service the inside arrangement would be justified.

In this discussion, the greatest emphasis has been placed on weight, since that is a primary consideration. Next in importance is the possibility of exerting a vertical force, positive or negative lift, with propellers in tilted position. In this respect the inboard drive has a positive advantage. Another important consideration is propeller efficiency and gear losses. For the individual power-plant arrangement equipped with reversing and swiveling gear, there is probably no decided difference in efficiency between outside and inside power plants. In the case of the multiple in-line arrangement, similar to the one used on the Macon, some efficiency has admittedly been sacrificed for the benefit of a very practical installation. Among the other points for discussion may be mentioned the comfort of the mechanics, ease of inspection and repair, fireproofness, etc., but most of these items either have a relatively small effect or offset each other in these two types. In the final analysis, the criterion must be combined weight of the power plant and fuel load for the accomplishment of the given service.

The discussion of this controversial subject has been confined to the accepted types of airship power-plant installations as they are now being built. In the future, we may see airships driven by power eggs suspended outside the hull and perhaps utilizing air-cooled engines. At the present time there is considerable reluctance on the part of airship operators to accept any proposal of remote control for airship engines. It may be that this is an old prejudice which could be modified in the light of existing reliability records. Consideration of such units merely involves the use of the appropriate unit weight, drag, and fuel consumption figures in the comparative formulas.
Design Problems in Connection With Loss of Gas and Forced Uncontrollable Descent

In his paper, delivered at the A.S.M.E. Annual Meeting in December, 1933, Commander Garland Fulton has pointed out the importance of maintaining equilibrium during flight while fuel is being consumed. His discussion covers the three possibilities, (a) of valving gas (hydrogen), (b) regaining ballast either by recovery from exhaust gases or by picking it up from the sea or taking it out of the air, and (c) by burning gaseous fuel of about the density of air.

The method selected for maintaining equilibrium during flight has also a bearing on the general design arrangement with regard to the ability of the ship to maintain its equilibrium after loss of buoyant gas.

A reasonable solution of the problem is to so dimension the largest gas cell that the loss of its lift may be offset by disposal of the available ballast or may be carried by the aerodynamic lift of the ship. The combination of these two means of maintaining altitude is naturally permissible although the designer must keep in mind the fact that as the ship approaches its landing, the air speed, and hence the aerodynamic lift, may frequently become very small and for this reason the ship must be reasonably close to buoyancy equilibrium at this time.

The choice of the proper amount of trim ballast is intimately connected with the question of what quantity of disposable load is always available. The answer may depend largely upon the type of airship and the service in which it is to be used. A helium inflated, gasoline-engined ship, like the Macon, when on a long-range scouting expedition, would carry liquid loads of more than 100,000 lb. As the fuel is burned, the exhaust gases are cooled in the water-recovery equipment and an equivalent weight of water is recovered. The airship remains in weight equilibrium since the sum of the fuel and water is always equal to the total liquid load, the liquid load being mostly fuel at the start of the flight and mostly water at the end of the flight. It is evident that in airships of this type the captain has an abundance of liquid ballast at his disposal and that fairly large gas cells are permissible.

Another type of airship is the fuel-gas ship, exemplified by the Graf Zeppelin. This airship operates on a gaseous fuel having a density very near that of air so that the consumption of the fuel does not seriously interfere with the equilibrium of the airship and no water-recovery equipment is required. On the other hand, the lack of effective weight in the fuel renders it practically useless as ballast in the emergency of a deflated gas cell. Ballast must be provided for this contingency and some of it is usually carried in the form of liquid fuel which may be burned in the ship's engines as a reserve fuel, the gaseous fuel being used for all normal operations. It is naturally desirable to keep this liquid ballast (in the form of a fuel reserve) as small as possible since it cannot be fully counted upon as useful load. The smaller quantity of ballast available has necessitated greater subdivision of buoyancy in this design.

The two most recent airship disasters may be analyzed as due to unchecked descent, the descent being perhaps due in one case to a loss of gas and in the other to vertical currents associated with storm conditions. Means of checking such descents are at the captain's command in the form of disposable ballast and powerful aerodynamic control. These two remedies have always been available in the past and to a larger degree than before in recent American designs, but it may be expedient to supply them in even greater quantity or power on future airships.

But there is something just as fundamental as the availability of the remedies: It is the necessity that each remedy be applied at the proper time and in the proper degree to assure recovery and prevent serious consequences. There must be reliable methods of informing the captain of the exact position, motion, and condition of his craft in space. He must be enabled to know why the ship is in downward motion the instant such a motion starts, in order that he may take the proper corrective steps in time.

For this purpose concentration of efforts toward perfection of flight instruments is recommended. The most important of these instruments are an absolute altimeter (reading height above the ground), a dynamic-lift indicator, a gust indicator, and an angle-of-attack indicator. While instruments can never replace human judgment, they can and will present the exact facts of the crisis to the captain in such a manner that he can make a clear-cut decision. Improvement upon the existing instruments of this group and the introduction of new instruments of this type will go a long way toward making airship operations under a conservative operating policy a safe and reliable service.

Discussion

G. V. Whittle. Some of the broader aspects of the design of rigid airships are excellently presented by Dr. Arnstein. It is an illuminating and worth-while procedure to pause occasionally and compare progress already made with that previously anticipated as has been done in this paper. The statistical comparisons given clearly illustrate the great progress in design and the substantial improvement in performance of airships which have been realized in the past decade. There appears to be ample justification for the expectation that the advance in the art of designing, building, and operating airships will be as great in the next decade as it was in the last.

Airship progress has been greatly hampered by non-availability of suitable airship engines. It seems that five or six reliable engine units are a sufficient number for a rigid airship and the present outlook favors units having a power rating of at least 1000 hp. The performance of an airship such as the Macon would be greatly improved if this airship were equipped with six engines having a total power rating equal to the eight engines with which it is now equipped. The weight to be gained by the elimination of two engine rooms and the improvement possible in specific engine weight with a modern engine are only part of the gain, as the reduction in crew with attendant savings in facilities and consumables for the crew would also contribute an appreciable share. The drag of the airship and hence the fuel consumption would also be reduced by the elimination of the two power units. It is hoped that sufficient encouragement will be forthcoming to foster development in this country of suitable high-powered engines for airship use so that this laggard in the path of airship progress may catch up with the procession.