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AIR VEHICLE TECHNOLOGY DEPARTMENT

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STRUCTURES TECHNOLOGY FOR LIGHTER-THAN-AIR VEHICLES

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This technical memorandum documents the work performed in the area of airship structures technology in support of the Advanced Navy Vehicle Concepts Evaluation Program. This work provides an assessment of contemporary rigid airship structural design technology and recommendations for future work. It was concluded that modern airship structures will be significantly more efficient than historical designs, and that the most attractive concepts for achieving these improvements are the geodetic

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SUMMARY

This technical memorandum documents the work performed in the area of airship structures technology in support of the Advanced Navy Vehicle Concepts Evaluation Program. This work provides an assessment of contemporary rigid airship structural design technology and recommendations for future work. It was concluded that modern airship structures will be significantly more efficient than historical designs, and that the most attractive concepts for achieving these improvements are the geodetic design, the modernized versions of the Akron/Macon construction as was used in the ANVCE point designs, and the sandwich structure for very large sizes.

INTRODUCTION

This report summarizes the work performed on LTA structures technology. The objectives of this effort were to review recent studies of structural approaches for LTA vehicles and comment on their credibility and feasibility, to assess and evaluate the design technology associated with the various approaches, including conventional rigid, geodetic and metalclad, and to make recommendations for optimum LTA vehicle design approaches which incorporate vehicle integrity, relatively low risk and reasonable cost for fabrication and operation.

A major part of this work was a contract to Turbomachines, Inc. of Irvine, California for the Study of Metalclad Airship Hulls. This was a five-month program in which current technology in structures, materials and design was applied to the design and evaluation of the metalclad concept.

The remaining work reported here was performed in-house and much of it is survey type information in which the work of others is reviewed and evaluated.

RECENT LTA STRUCTURES TECHNOLOGY

A considerable amount of time was spent during this activity in reading the items listed in the bibliography. Much of this material is old, particularly the Burgess memorandums, and was included in the reading for background information and for comparison to current technology. The primary sources of information for current airship technology were those listed as references 1 to 8.

Current literature and current studies are classifying the types of structure being considered as rigid, nonrigid, metalclad, sandwich monocoque or geodetic. The first three, of course, are old concepts, while the last two represent two of the most popular contemporary concepts. Two methods are being used in an attempt to improve structural efficiency. One is by using the modern high strength materials such as Kevlar, composites and the new aluminum alloys, and the other is to use a better, more efficient

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structural arrangement, examples being the sandwich and geodetic concepts mentioned above. One concept which combines both of these ideas is Kevlar Doweave for a cover material.

In general, the studies which have been performed have concluded that today's airship would be much more efficient structurally, with a reduction of about 40% in both empty weight to gross weight ratio and empty weight to gas volume ratio. In addition, it was found that the rigid, non-rigid and metalclad concepts all are competitive in the primary size range of interest, 5 to 15 million cubic feet, with the sandwich monoroque being 10 to 15% heavier. Both the sandwich and the metalclad concepts suffer somewhat from minimum gage limitations at small sizes.

In two different studies it has been projected that a modernized Macon would have a structural weight ratio of about 25% to 35% less than the original. This is accomplished by using either a composite geodetic construction or by substituting a combination of composite materials and modern aluminum alloys in the basic Macon type structure.

ANALYSIS AND TRADEOFFS

In this section the results of three short analyses which were performed in-house are reported. These analyses were virtually "back of the envelope" type analyses which were done to make certain comparisons and to develop a feel for certain situations. The results are presented in that context and are not intended to preclude the results of other studies being performed in more depth.

Survey of Maximum Design Bending Moment

Several of the prominent equations for calculating maximum design moment on the hull and methods for distributing design moment over the length of the hull were examined and compared. Some of these are old formulations and some are newer ones.

a. Goodyear (1975) Reference 9.

$$M = \left(.11 + \frac{3F}{80}\right) \frac{u}{v} q V \qquad (1)$$

where

F = fineness ratio

u = gust velocity

v = airship speed

q = dynamic pressure

V = airship volume

For

$F = 5.91$

$u = 35$ ft/sec

$v = 122$ ft/sec

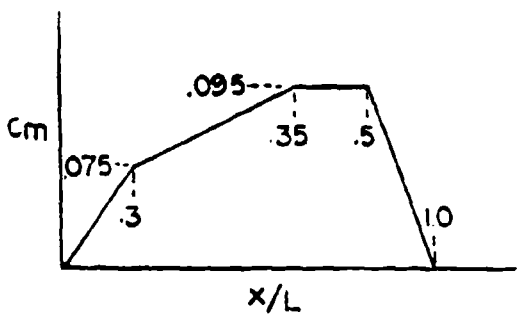
This reduces to

$$M = .095\ q\ V \tag{1a}$$

b. Burgess (1944) Reference 10

$$M = C_m q V \tag{2}$$

where is a coefficient defined in the sketch below and distributed over the length of the hull as indicated.

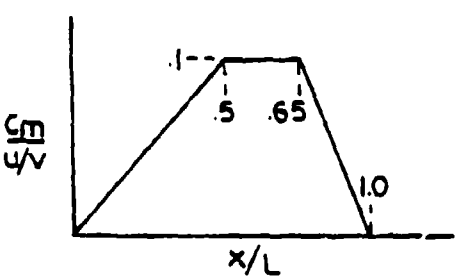


It can be seen that this gives the same value of maximum design moment as equation 1a.

c. Woodward (1975) Reference 11

$$M = C_m q V^{2/3} L \tag{3}$$

In this case Cm is defined as shown below.



For $u = 35$ ft/sec and $v = 122$ ft/sec, $Cm = .029$.

d. Burgess (1937) Reference 12

$$M = .02\ q\ V^{2/3}\ L \qquad (4)$$

This is similar to but less conservative than equation 3, and is applicable only to sizes and shapes in the Akron/Macon range.

e. Burgess (1944) Reference 10

$$M = K \rho\ v\ V\ L^{.27} \qquad (5)$$

where

K = a constant

ρ = air density

L = airship length

L = 800 feet

u = 35 ft/sec

v = 3.5 u

K = .96

For comparison, the maximum moment calculated by these five equations was compared for the following values:

$V = 10 \times 10^6\ ft^3$

u = 35 ft/sec

v = 168.9 ft/sec (100 knots)

The following results were obtained.

Equation	Moment
(1)	21.2×10^6 ft lb.
(2)	29.5×10^6 ft lb.
(3)	25.9×10^6 ft lb.
(4)	25.1×10^6 ft lb.
(5)	22.9×10^6 ft lb.

It was concluded from this exercise that equation (1) for calculating maximum moment and the distribution method of method (b) are preferred techniques by this writer. Equation (1) is general enough to allow its application over some range of the important variables. It should be pointed out that it is valid over a fineness ratio range of about 3 to 5, since it is a straight line fit to potential flow theory over that range.

The distribution technique of method (b) is in better agreement with measured data over the forward half of the hull than that of method (c), hence its preference where an actual analysis is not made.

Gross Thickness Requirements -

In this section, skin thickness requirements are developed for resisting maximum bending moment applied to the hull. This considers strictly the normal case of moment on a hull of circular cross section subjected to a gust load. It does not account for any erection, handling, one cell out, or other load conditions which might, in fact, require greater thickness. This was done simply to get a feel for the thickness associated with various volumes and the internal pressure required to keep the skin in tension, as is done for the metalclad design.

The following Akron/Macon characteristics are used to relate, in an approximate way, volume, radius and fineness ratio:

$$V = 7{,}401{,}000 \text{ ft}^3$$

$$L = 785 \text{ ft}$$

$$D = 132.9 \text{ ft} \quad (R = 66.45 \text{ ft})$$

The fineness ratio, F, is

$$F = \frac{L}{D}$$

$$= 5.91$$

If the volume is expressed as

$$V = KR^2L$$

$$K = \frac{V}{R^2L}$$

$$= \frac{7{,}401{,}000}{(66.45)^2 785}$$

$$= 2.135$$

Therefore

$$V = 2.135R^2L$$

$$= 4.27\ FR^3$$

and

$$R = \sqrt[3]{\frac{V}{4.27F}}$$

Assume the following values:

$$F = 4.5$$

$$u = 70 \text{ ft/sec (includes S.F. = 2)}$$

$$v = 168.9 \text{ ft/sec}$$

$$q = 31.1 \quad 16/ft^2$$

From equation (1) is the previous section

$$M = (.11 + \frac{3F}{80}) \frac{u}{v} q V$$

$$= 3.6 V$$

The unit longitudinal load in the hull at maximum diameter is

$$N_x = \frac{M}{R^2}$$

$$= \frac{3.6V}{R^2}$$

And since

$$R = \sqrt[3]{\frac{V}{4.27F}}$$

$$= \sqrt[3]{\frac{V}{19.21}}$$

$$= .37 \sqrt[3]{V}$$

$$N_x = 8.37 \ V^{1/3}$$

In order to prevent compression from developing on the compression side of the hull an internal pressure is applied to balance this longitudinal load. The value of this pressure is

$$P = \frac{2N_x}{R}$$

$$= \frac{16.74 \ V^{1/3}}{R}$$

$$= 45.2 \quad lb/ft^2 \ (.314 \text{ psi or } 8.7 \text{ in. } H_2O)$$

Note that with the form of the moment equation used the required pressure is independent of volume. The skin thickness is determined by the circumferential stress due to the internal pressure and is given by

$$t = \frac{P\,R}{F_t}$$

$$= \frac{45.2\ (.37\ V^{1/3})}{F_t}$$

$$= \frac{16/7\ V^{1/3}}{F_t}\ \text{ft} \quad \text{or} \quad 1.39\ \frac{V^{1/3}}{F_t}$$

where V is in ft^3

F_t is in psi

Figure 1 shows this requirement as a function of volume and F_t, design allowable stress.

Effect of Number of Longitudinals

A tradeoff was made to investigate the effect on weight of the number of longitudinal numbers used to resist bending. For this analysis, it was assumed that the longitudinals take all the moment and that they are stabilized in compression, i.e., buckling is not considered.

Two situations were considered, as shown in Figure 2. The moment of inertia in case (a) of the longitudinals is

$$I = \frac{N}{2}\ AR^2$$

where N is the number of equally spaced longitudinals and A is the cross sectional area of each. The required area, assuming equal areas in all members is

$$A = \frac{2M}{N\bar{\sigma}R}$$

$\bar{\sigma}$ is the working stress in the longitudinal.

The total weight of the longitudinals is

$$W = KNA$$

$$= \frac{2KM}{\bar{\sigma}R}$$

K is a constant which incorporates length and density. It can be seen that weight is independent of the number of members.

For the situation depicted in Figure 2b the moment of inertia is also

$$I = \frac{N}{2}\ AR^2$$

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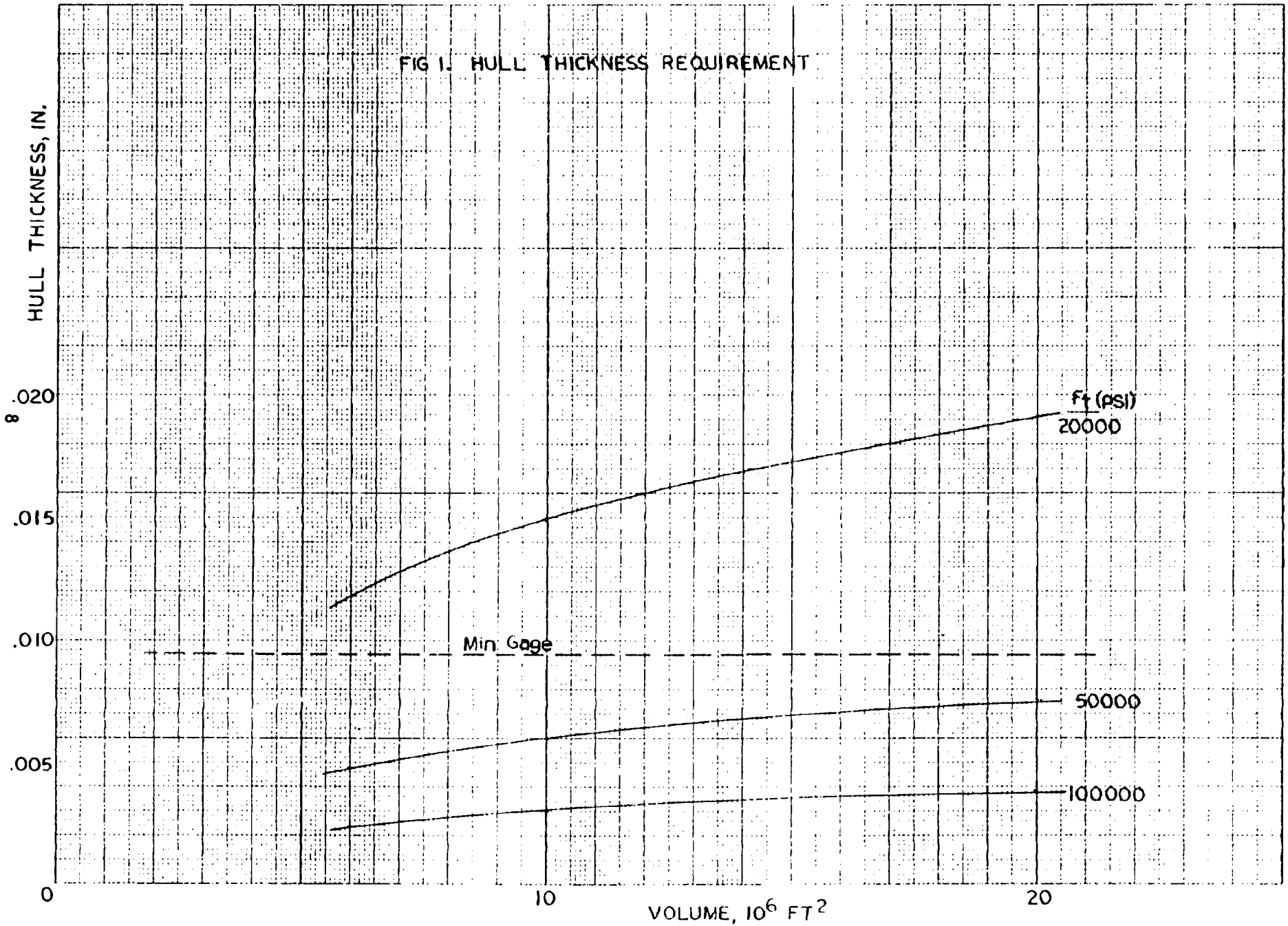


But due to the different location of the neutral axis than in case (a) the required area varies with N and can be expressed as

$$A = \frac{kM}{N\sigma R}$$

k is a constant which depends on N, but is less than 2. As N increases its value approaches 2. Therefore, case (b) is less critical than (a) and the previous conclusion that weight is independent of N still holds.

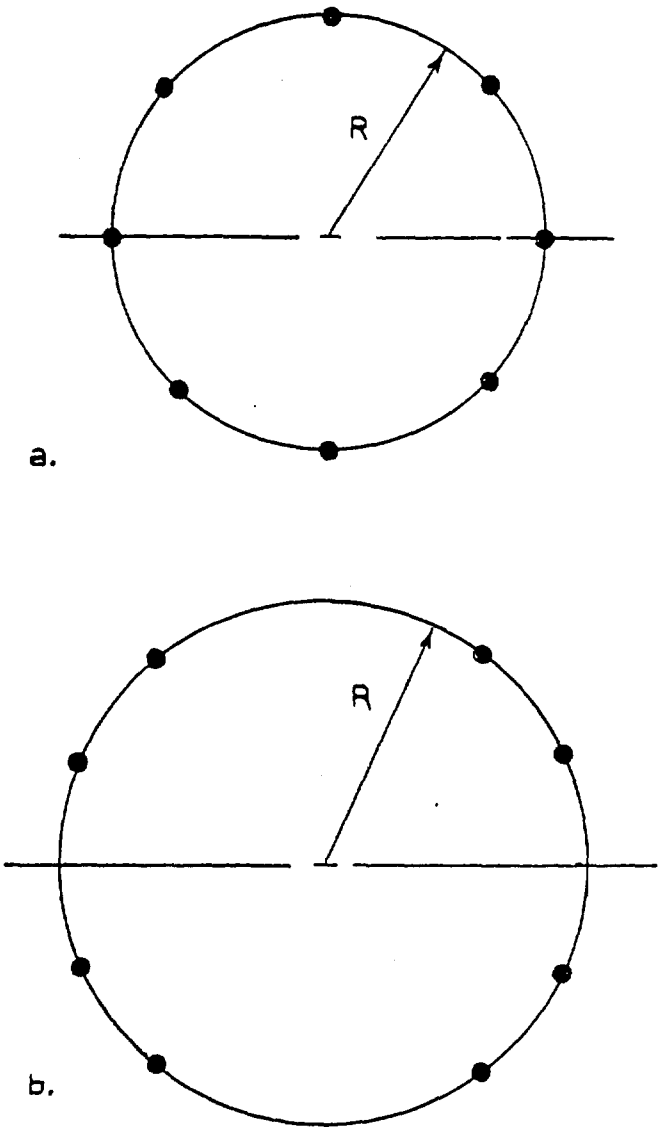


Figure 2.

V. EVALUATION OF MODERN METALCLAD DESIGN

A. Objectives and Criteria

A study was performed by Turbomachines, Inc. on the use of modern metalclad designs for airship hulls. The primary objective of this study was to determine the weight of metalclad airship hulls in the range of gross displacements between 10 million and 20 million cubic feet. This was accomplished by designing and sizing the structure for five hulls in this size range. In order to do this with an acceptable accuracy of results it was necessary for the contractor to formulate a design architecture for the metalclad structure, to analyze the effect of maximum external loads, to determine thickness and size of skin, frames, and longerons, to design efficient joining seams, to explore the interaction of the skin with the hull structures, to determine hull air pressure requirements, to consider the division of the hull volume into sub-volumes and gas cells and devise means for inflating the hull with as little contamination by air as possible, and to investigate the extreme case of loss of pressure and lift of the maximum volume all during flight.

The criteria for this study was a design speed of 100 knots and a gust velocity of 35 fps. The hull structure was designed using 7050-T6 aluminum. Internal pressure was used to keep compressive stresses from developing during normal operating conditions, and the stiffening structure was designed to carry loads at a reduced course speed, for a loss of pressure and lift condition. Factors of safety were 2.0 on ultimate stress and 1.5 on yield.

B. Description of Metalclad Structure

The following discussion of the metalclad structure has been excerpted from the final report draft submitted to NADC by Turbomachines, Inc.

" In the simplest definition, a Metalclad hull has a rigid internal structure capable of supporting an elastically deformable thin, gas-tight metal skin shell in deflated state, without lifting gas in the hull. The supporting structure is made rigid by the firmly attached shell skin, and supports this metal skin without harm to it. The structure is comprised of three distinct elements: The main frames, which are rigid rings with the ultimate purpose of transferring weight loads into the skin by shear, the secondary frames, which are approximately equidistantly spaced between the main frames, the longerons, running fore and aft along the hull contour spaced at equal distances peripherally and firmly attached to the main frames and secondary frames. All structure is attached to the skin. This assembly of structural girders and skin comprises all the lifting Metalclad hull structure. The girder structure alone, without the skin, is not capable of self-support and would collapse if not stabilized by the skin. The skin alone, in deflated condition, would collapse without the support of the girder structure. However, in combination, attached to each other, the girders and the skin shell form an overall rigid body in deflated condition with harmless local elastic instability of the skin.

The secondary frames and the longerons are essential to the hull structure during erection and also when the hull is deflated. They are not essential to the inflated hull under pressure. The main frames are essential to the hull structure during erection, assembly and when the hull is deflated; they hold the longerons and the skin in place and support their weight. When the hull is inflated, the main frames are the principal structure for gransfer of weight loads into the hull skin shell by shear.

Due to inflation with gas and principally to supercharge air pressure, the thin metal shell becomes taut with tension. All elastic buckles disappear and the hull body becomes rigid locally in addition to overall rigidity inherent in the structure without pressure.

The hull study described in this report is based on cellular principles in all structure. This approach is consistent with the Metalclad concept of indivisible attachment of structure to the skin as well as with modern light structures. A typical main frame of the Metalclad hull is shown in Figure 2, and a typical girder for Metalclad secondary frames and longerons is shown in Figures 3 and 4 respectively.

A typical main frame, Figure 2, is in itself a Metalclad structure, composed of corrugated side walls as surfaces of frustum cones, riveted to either extruded or rolled circumferential base cornices attached directly through the base skin to the external longerons. At the apex, the cornice is composed of two circumferential curved sections, attached together with the corrugated sidewalls to make a curved apex girder of high stability. All cornices are held fixed, element by element, by corrugated sloping sides. The base cornices are also stabilized by the base plates, which are thicker than the local hull skin. All three cornices will support high compression stresses without buckling, due to the high degree of fixity of their elemental support and resulting stability.

Past experience indicates that in similar configurations, the cornices ultimately fail at stresses near the yield point of the metal in compression.

The main frame, instead of being a skeletal frame is actually a continuous circular beam with lighter or heavier cornices where bending moments demand it and with corrugations of thickness according to local shear loads.

All main frames in all hulls have a constant height parameter of (.108)xR, except far forward in the bow and far aft in the stern, where main frames with the above parameter would be too low in height for human access. The minimum actual height (apex cornice to base) of any main frame is 86 in. for any hull. The cornices of the main frames can be easily spliced and also reinforced by doublers where needed. There are no girder cross joints, only riveted seams.

The main frame structure is also basic to other hull structures viz. the secondary transverse frames and the longerons; both are derived from the main frame structure. The guiding principle is to obtain light, simple structures in all cases, with simplicity of construction, high redundancy and the most efficient use of material in fabrication.

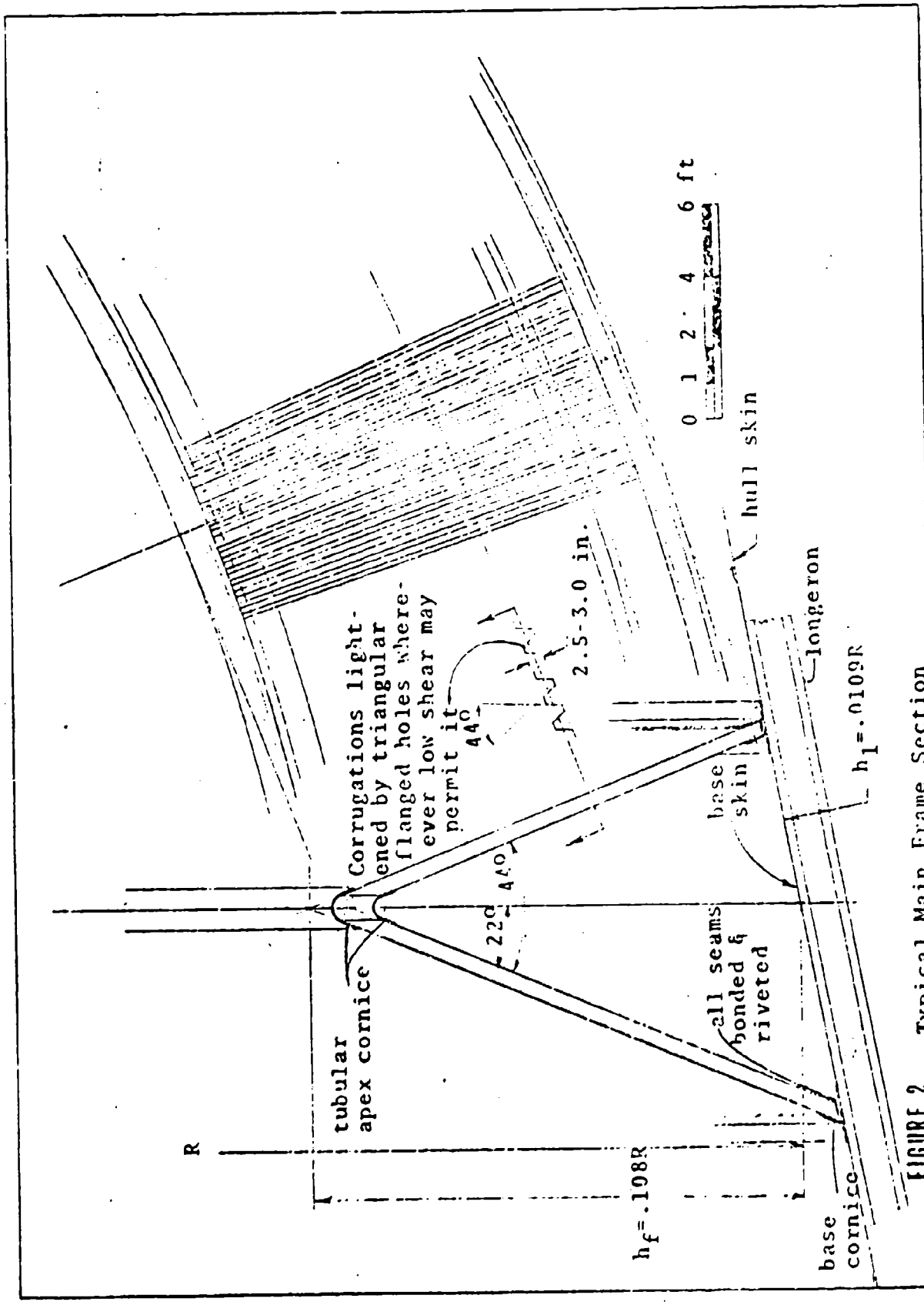


FIGURE 2. Typical Main Frame Section

FIGURE 3. Typical Secondary Frame Section

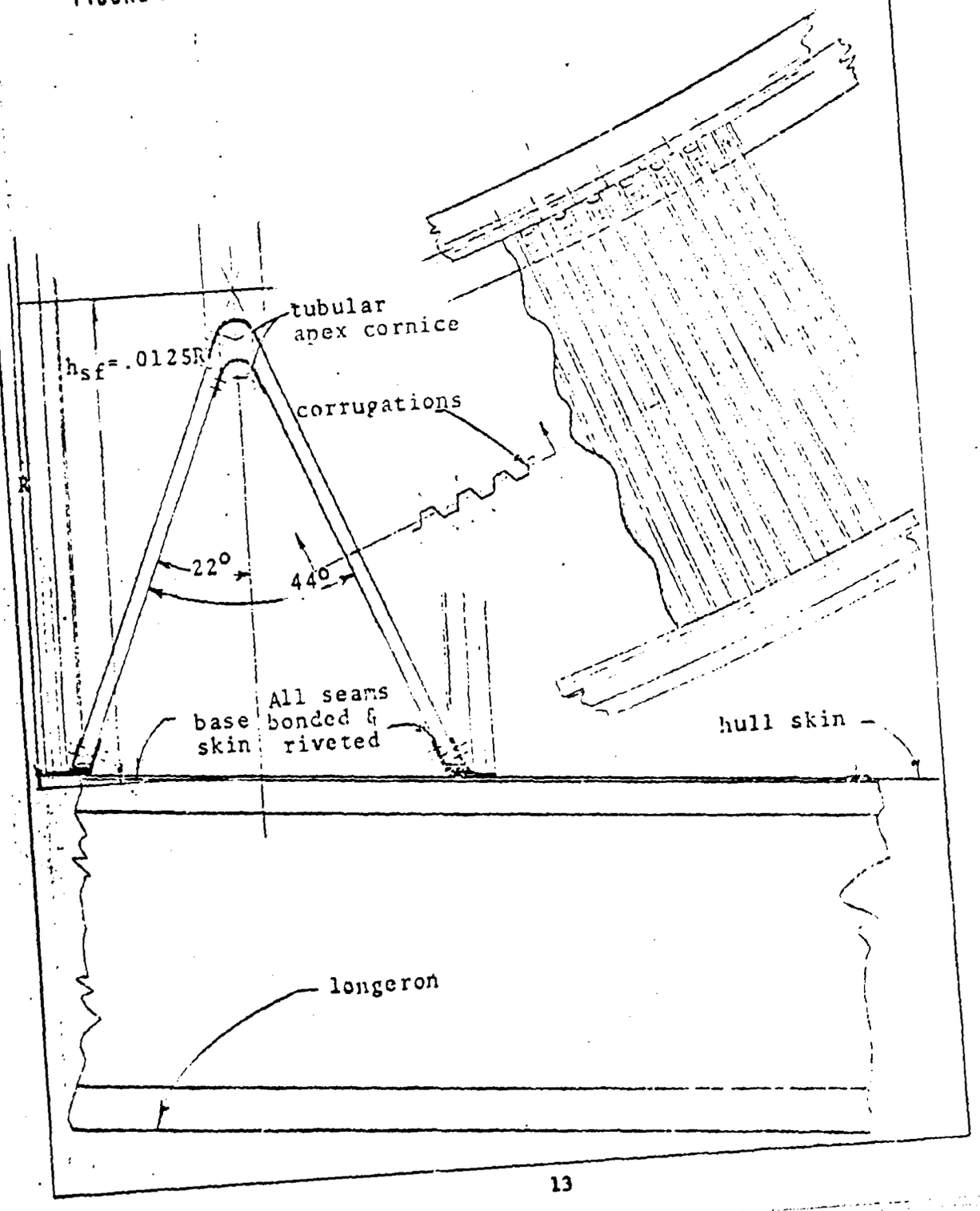
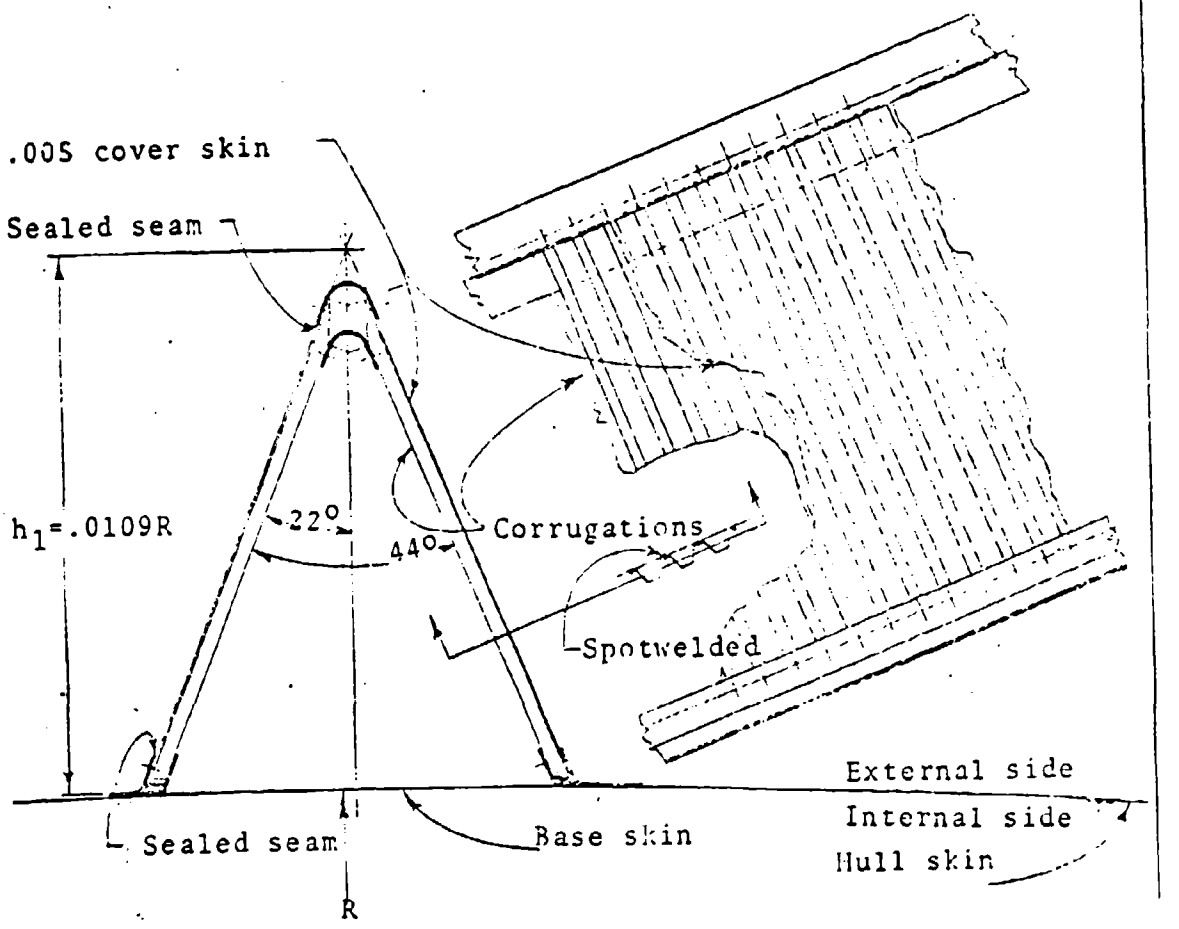


FIGURE 4. Typical Longeron Section



In all hull studies of this report, another fundamental principle is used, viz, to eliminate, as much as possible, all structural joints necessary for the crossing of structural elements. This is a new concept to Metalclad construction and is a logical step in its progressive development. Splicing joints cannot be eliminated and are not unduly heavy, nor complex. On the other hand, joints required for the crossing of structure, e.g., the main or secondary frame crossing a longeron, are always complex, heavy, expensive and insecure. Structures generally fail first at joints.

In the studied hulls the longerons are external to the hull while all main and secondary frames are internal. Between the frames and the longerons the thicker base skin of all frame structures of a Metalclad hull are serving as an incidental gusset plate at each structural crossing. The structures are as firmly joined as conceivable by simple by-pass crossing without discontinuity of girders. All studied hulls require a relatively large number of longerons. The increase of drag from external longerons is due to friction and is minimal, estimated at no more than 2%-3% of the total hull friction resistance. The gain in weight reduction with this type construction will be significant. The principal advantages are in the simplicity of structure and increased structural integrity of the hull. Equally as advantageous is the circumferential smoothness of the internal walls of Metalclad hulls. The cell diaphragms will not encounter longitudinal ridges over which to drag, nor will there arise any air spaces entrapped between the cell diaphragm and internal longerons during inflation.

In summation the Metalclad main frames, secondary frames and longerons are very efficient structures. The base cornices are stabilized element-by-element by the base skin of greater thickness than the local hull skin, and by the corrugated sides of the complete section. The apex cornice is stabilized also element-by-element, by the corrugated side webs; both, the apex and the base cornices will reach high compressive stresses approaching the compression yield point of the metal.

When supercharged with air pressure, the elastic skin becomes taut, the wrinkles and buckles totally disappear and the hull becomes a smooth body, with exact compound curvature all over. The longerons "float" with the skin in its radial deflection as do the secondary frames; all become generally unloaded from weight loads and loaded by forces from elastic deformation of the skin shell and impose small restraining forces on the skin.

All hull structures in this report are proposed to be controlled by dynamic thrustors in Z and Y coordinates; the thrustors will be located in the bow and stern on the main frames. No weight allowance has been made for the structure restraining the forces of the controlling thrusts because these forces are not a part of the gas lifting equilibrium. It is to be noted however, that the thruster control forces will act, in most cases, as couples and their moments on the hull will be considerably smaller than the moments from rudders or elevators."

C. Results

The results of this study were basically the sizes and weights of the hull structure for the volume range considered. Table 1 gives a summary of some of the pertinent values from the Turbomachines, Inc. final report. Also included as Figure 3 of this report is the final weight fraction results determined by Turbomachines, Inc. Note that these weight fractions are based on sea level lift.

D. Final Comments

The final comments given below were excerpted from the Turbomachines, Inc. final report and represent their conclusions on some of the major points of metalclad design.

"The study described in this report has confirmed the soundness of the structural concepts used in Metalclad airships. Metalclad principles have never been in doubt, but there have been some uncertainties regarding the technology to make them realistically feasible. These uncertainties have now been evaluated again and indicate a capability of construction which is very reasonable in its approach.

The required technology has now been either developed to the state of dependable application or is approaching the end of complete development and will be available when needed. For example, hull shell structures can now be constructed from high-strength light alloys with means for joining them as thin sheets by efficient, strong seam joints. The seam joint emerges as one of the most determining and basic elements of Metalclad construction. A riveted seam with a sealant alone, of the ZMC-2 vintage, successful as it was, is no longer adequate.

Structural continuity and a high degree of redundancy is inherent to Metalclad hulls; every element of the shell structure works with the skin as well as the skin working with the structure; there is no separation of duties. The redundancy includes an insensitivity to local damage from human contact; Metalclad structures are highly invulnerable to incidental damage and will continue to function dependably even if locally damaged.

Furthermore, Metalclad structures, as proposed in this report, as inherently responsive to forces from the skin, thus still further reducing all relative deformations of the skin-structure assembly. The work already accomplished and reported in this volume, assures that this is not a design problem but rather a design condition that can be always satisfactorily resolved and provided for without weight increase, because the thicker skin base of all Metalclad structures is actually a necessary part of the weight of the structure itself.

Closely related to skin seam strength and to interface deformations of structures and skin, is the hull air supercharge pressure. In all past projects of large Metalclad hulls, the maximum allowable pressure had to be,

TABLE 1. SUMMARY OF METALCLAD AIRSHIP HULL STUDY RESULTS

	MC-100	MC-125	MC-150	MC-175	MC-200
Volume ($10^6 Ft^3$)	10.0	12.5	15.0	17.5	20.0
Length (Ft)	728.6	784.8	834.0	878.0	917.9
Maximum Diameter (Ft)	161.9	174.4	185.3	195.1	204.0
Surface Area (Ft^2)	297467	345220	389799	431981	472201
Number of Main Frames	9	9	9	9	9
Number of Secondary Frames	19	19	19	19	19
Number of Longerons	42	42	44	46	48
Number of Gas Cells	9	9	9	9	9
Maximum Skin Thickness (In)	.020	.022	.024	.024	.024
Internal Pressure (In H_2O)	17.0	16.6	17.4	16.5	15.5
Skin Weight (Lb)	100690	124143	148434	173638	199794
Main Frame Weight (Lb)	30328	37910	45492	53073	60655
Secondary Frame Weight (Lb)	7881	9852	11822	13792	15763
Longeron Weight (Lb)	35528	41227	46556	51594	56398
Gas Cell Weight (Lb)	17538	20354	22982	25469	27841
Total Hull Weight, Unpainted (Lb)	191965	233486	275286	317566	360451
Paint System Weight (Lb)	13812	15937	18061	20185	22310
Painted Hull Weight (Lb)	205777	249423	293347	337751	382761
Painted Hull Weight/Useful Lift @ SL	.321	.300	.303	.299	.296

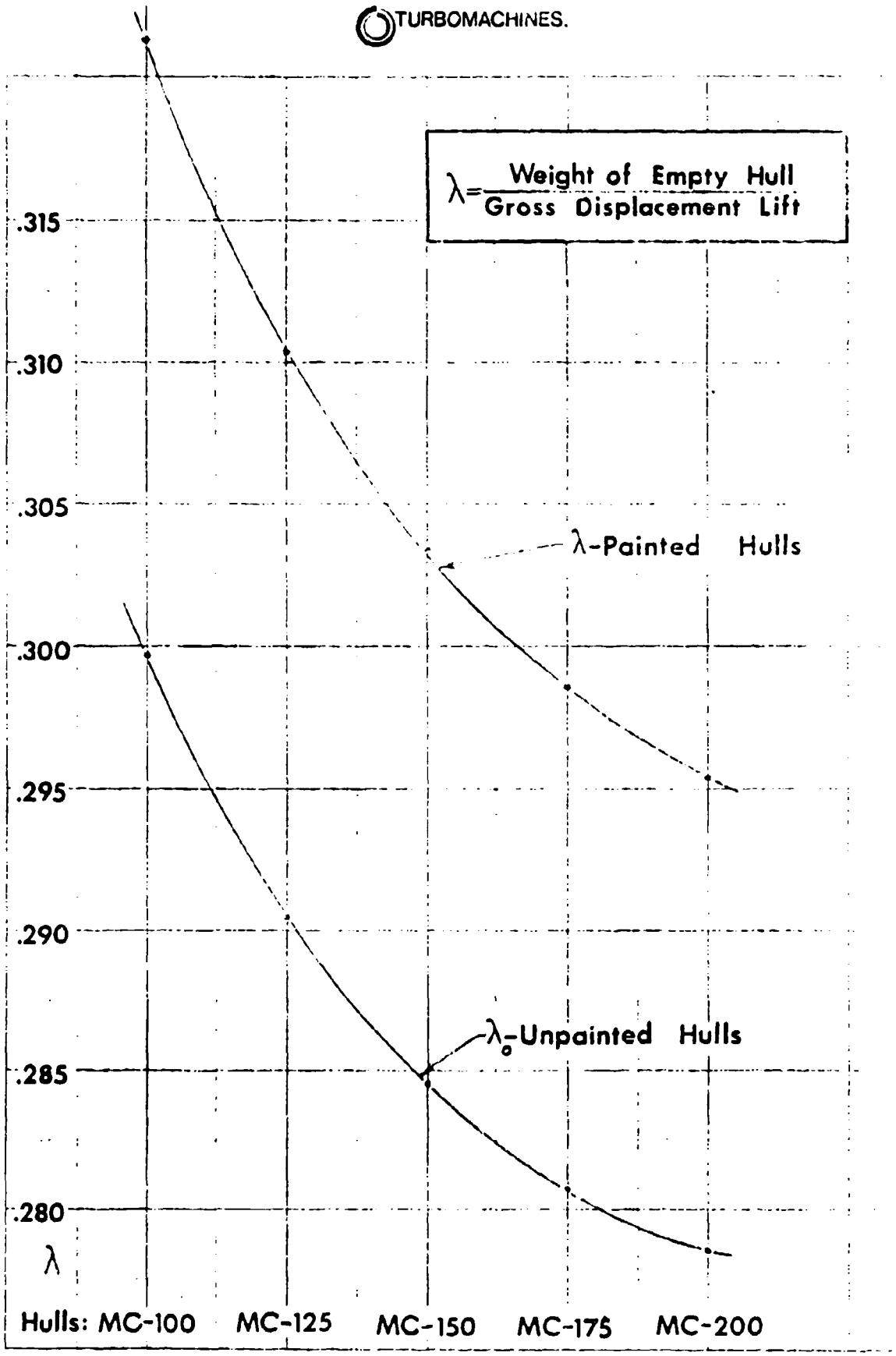

TURBOMACHINES.
$\lambda = \frac{\text{Weight of Empty Hull}}{\text{Gross Displacement Lift}}$
.315
.310
.305
.300
.295
.290
.285
.280
λ
λ-Painted Hulls
λ_o-Unpainted Hulls
Hulls: MC-100 MC-125 MC-150 MC-175 MC-200

FIG 3

and always was, low. The state of Metalclad technology of 45 years ago was then a cause for concern in large Metalclad airships of the future. It was brought about not only because the air pressure had to be low due to low values of attainable hoop stresses and therefore sensitive to control, but also because it was not possible to provide sufficient tension in the longitudinal direction of the skin to resist imposed hull moments without relying on longerons to prevent the appearance of wrinkles in the skin while in flight. This problem is now completely resolved and this study report shows that the hull pressure can always be comfortably high within the factor of safety of two with respect to the ultimate strength of metal, and the range of pressure variation can be broad without losing tension in the skin, even under the most severe imposed moments on the hull. The supercharged air pressure in all studied hulls is substantially a constant value.

Although air pressure control will be inherently sensitive, thanks to modern instrumentation, there is no specific condition that it must be held steady within narrow limits. The reason for this must be credited once more to the high efficiency of skin seam joints which permit high hoop stresses and therefore relatively high air pressure, and to higher specific strengths of modern light alloy metals, such as the Alclad 7050-T76."

CURRENT STRUCTURES TECHNOLOGY ASSESSMENT

In this study an attempt has been made to look at today's structures technology, and objectively evaluate that technology in light of the needs and requirements of future airships. Furthermore, a comparison with the state of structural design as it existed in the airships of 1930's, the rigids in particular, is made and a synthesis of data from these old airships and data from current design and parametric studies is evaluated. Based on this, a technology position is formulated and recommendations are made for further words in design, analysis and manufacturing technology.

Let it be pointed out at the outset that the state of structural design is more or less where it was 40 years ago. It is generally accepted that with innovative design, better materials, modern fabrication techniques and computerized analytical techniques airship structures could be made much better, i.e., more efficient, stronger, etc. However, there has been little or no serious effort to implement this outside of paper studies, and perhaps appropriately so since the first priority is to establish the need, show the mission feasibility and demonstrate the potential usefulness and desireability. Two possible exceptions to this are the design and analysis work by Lightspeed, Inc. on the lightship design concept, a covered geodetic framework, and the work by Turbomachines, Inc. in which preliminary design has been performed on a modern metalclad structure and plans for fabrication and assembly are formulated, reference 13.

The most often mentioned ideas for structural design improvements are composite materials, geodetic structures, sandwich structures, improved metalclad design and Kevlar. If the application of these concepts plus a general upgrading of the structures technology which goes into their design parallels the improvements in airplane design, which have seen the structural weight fraction improve significantly in the last 40 years, then it is reasonable to expect significant improvements in airship structures also.

In spite of the rigid airship disasters which led to their demise in the 1930's, the techniques used to define loads, together with the factors of safety which were used, resulted in structures which had sufficient strength for their intended usage. Most, if not all, of the accidents involving United States airships were caused by improper handling, overloading, unexpectedly severe weather, or poor repair and maintenance.

The Macon, the last of the U.S. rigids, is perhaps a good example. Its ultimate loss was attributed to fin damage which was incurred in severe weather in an overloaded condition, damage whose repair was being delayed until a normally scheduled overhaul. The point of this is that while better loads analysis techniques could and should be utilized, the main thrust of structures design technology should be to develop structures which are more efficient, less complex and capable of being manufactured at an affordable price.

Airships of the 1920's and 1930's had a tremendously large number of parts with all the intricacies of lacing, wires, etc. On today's labor market this would result in high fabrication costs, and so, simplicity of design and reduced parts count should be given serious consideration, indeed should be a development objective.

A prominent concept for achieving simplicity and at the same time eliminating the dependency on internal pressure is the sandwich structure. In references (1) and (9) it was concluded that for large airships the sandwich construction is competitive and warrants further consideration.

The critical design condition for rigid airship structures and for metalclads, and hence the weight driver, is the deflated cell condition. With sandwich structure this need not be a critical condition, and so the sandwich has an inherent advantage over other designs in this respect. Since sandwich structure has traditionally been an efficient construction it does seem prudent to pursue it further, even though the results in reference 2 for a composite sandwich were not too encouraging.

On the area of geodetic type structures, two concepts have been reviewed and evaluated, one by Lightspeed, Inc. and one by Boeing-Vertol. The Lightspeed design, references 7 and 8, incorporates several interesting and innovative features, including the tubular geodetic structure, scalloped frames, multiple gas and air cells and a scalloped type outer envelope which reduces local membrane stress. The nature of the construction provides for failsafeness, redundancy, and damage tolerance. Although at first glance it appears to be complex and to have many parts, it is relatively simple in its fabrication concept. Present designs use developed aerostat materials and future plans allow for use of highly efficient composites, specifically Kevlar covers and graphite-epoxy geodetic structure, which will further reduce the structural weight on the order of 30 to 40%. Considering everything, the Lightship designs may be the best new entry into modern airship structural design, a design which is imaginative but at the same time one which is engineered as a practical product.

The composite geodetic design selected by Boeing-Vertol, reference 2, as the most likely approach to rigid airship structural design consists of an outer composite skin reinforced by composite geodetic numbers. It claims to be simple to construct and the analysis performed indicates a weight reduction of 26% compared to 1930 Akron type construction.

These two approaches both use composite materials to increase structural efficiency. It has also been shown, reference 1, that by substitution of composites in the Macon type structure, the structural weight could be reduced on the order of 25%, and when combined with weight reductions in other subsystems a reduction in the empty weight to gross weight ratio of over 40% could be realized.

One other aspect of composite application is the use of the Doweave configuration which could use Kevlar yarn in its weaving. Doweave is a

self locking fabric with good shear resistance and holds promise as a future cover material. It is currently being tested at NADC and details are reported in the Materials Technology report.

Composite materials are the latest state-of-the-art technology in other aerospace applications and certainly should be investigated for airship application.

In order to look at gross trends and to synthesize the data for various airship designs into some kind of basis of comparison, three curves were prepared. These curves show the following relationships:

a. Structural Weight/Gross Weight x Speed vs Volume

b. Structural Weight/Volume x Speed vs Volume

c. Unit Structural Weight/Speed vs Volume

These parameters are similar to ones usually seen in the literature except that design speed has been put into the denominator. This was done in order to make a more consistent comparison of data since speed has a direct influence on design moment, propulsion needs, fuel, etc., and therefore, weight. Note also that most of the designs were based on a gust velocity of 35 fps. Therefore, in order to make a valid comparison, the design speed of those concepts which used gust velocities greater than 35 fps was increased to an equivalent speed, which reflects the greater hull moment due to the higher gust velocity. Values used to plot the points are given in Table 2.

The data shown is for the following airships or airship designs:

1. ZMC - 2
2. Los Angeles
3. Macon
4. LS-12 (Lightspeed, Inc.)
5. LS-60 (Lightspeed, Inc.)
6. Metalclad (Turbomachines, Inc.)
7. Modernized Macon
8. Goodyear - SAB
9. Martin - FAB
10. Goodyear Sandwich
11. Goodyear ZPG-X

The first three of these represent the old technology of the 1930's, one metalclad and two rigid. The rest are intended to portray current technology utilization. Recognize that these data points are not in themselves completely consistent, since different types of construction, different buoyancy ratios, different mission requirements, etc. are represented. Even though this is somewhat of an "apples and oranges" mix, it is felt that it gives an indication of what might be reasonable, or what various companies are saying can be done, with today's technology compared to historical trends, and it forms a base against which future comparisons can be made.

TABLE 2. AIRSHIP STRUCTURAL WEIGHT FRACTION DATA

Code	Vehicle	Volume (V) (ft^3)	Gross Lift @5000' (L) (lb)	Structure Weight (W) (lb)	Design Speed (V) (knots)	Surface Area (A) (ft^2)	$\frac{W}{LV}$ (10^{-2}) (knot)	$\frac{W}{Vv}$ (10^{-3} lb) (ft^3knot)	$\frac{W}{Av}$ (10^{-2} lb) (ft^2knot)
1	ZMC-2	202000	10549	6511	60.8	19436	1.0	.53	.55
2	Los Angeles	2800000	131960	53070	65.2	-	.62	.29	-
3	Macon	7400000	347666	148201	72.2	291000	.60	.28	.71
4	LS-12	450000	23576	10200	90[a]	38262	.34	.18	.21
5	LS-60	2213878	115506	29000	80[a]	110679	.22	.11	.23
6	MC-100	10000000	551879	205777	100	297467	.38	.21	.69
	MC-125	12500000	692665	249243	100	345220	.37	.20	.72
	MC-150	15000000	833478	293347	100	389799	.36	.20	.75
	MC 75	17500000	974264	337751	100	431981	.36	.19	.78
	MC-200	20000000	1115021	382767	100	472201	.35	.19	.81
7	Modern Macon	7400000	347666	98814	72.2	291000	.39	.18	.56
8	Goodyear SAB ANVCE	3216000	155980	66385	150	149500	.28	.14	.30
9	Martin FAB ANVCE	9320000	486150	109200	80[b]	300000	.18	.09	.29
10	Sandwich	100000000	4535127	2346000	118	1455500	.44	.20	1.36
11	Goodyear ZPG-X	1490000	71520	25200	90	84890	.39	.19	.33

(a) Gust Velocity - 50 fps

(b) Gust Velocity - 55 fps

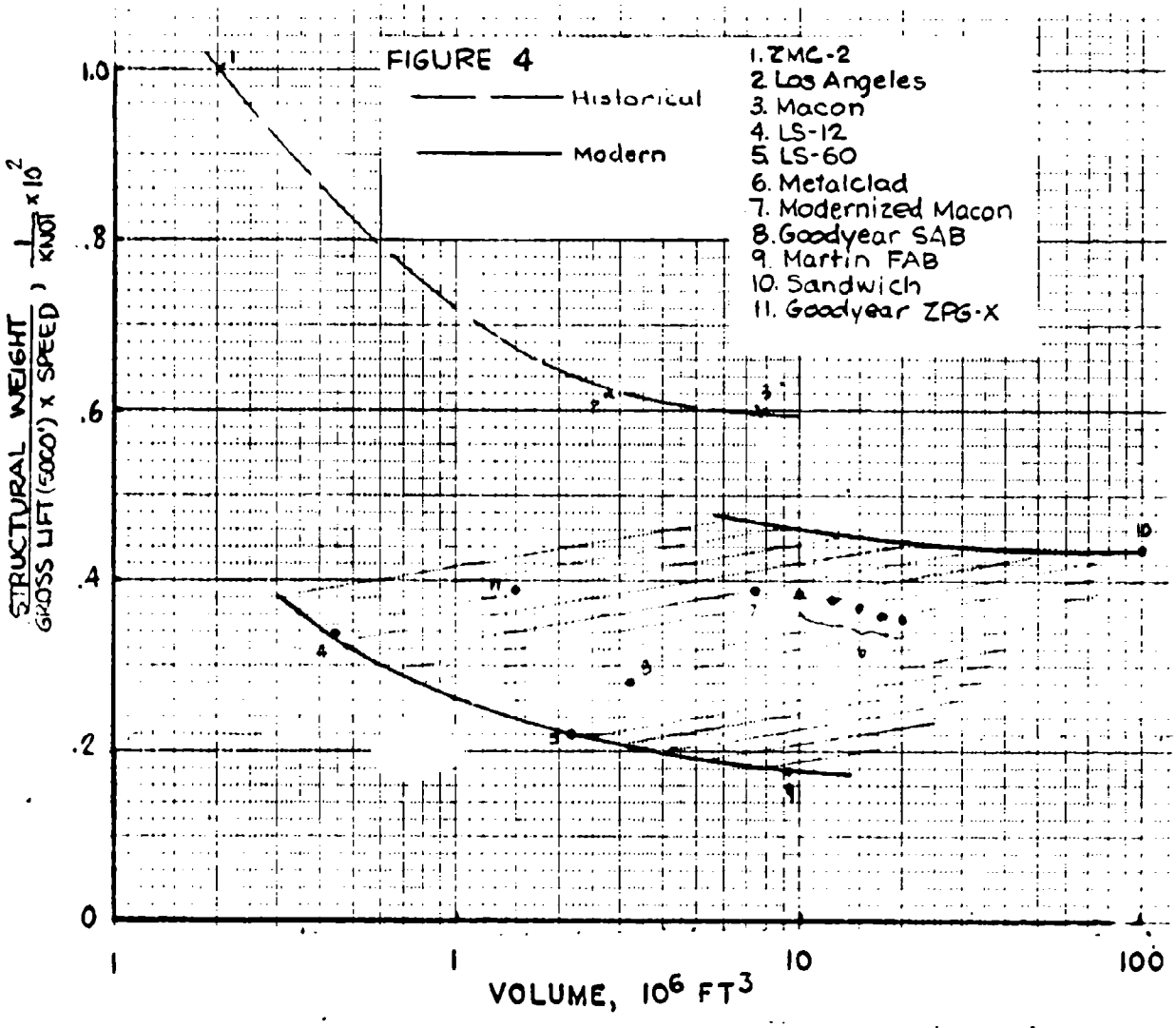


FIGURE 4
Historical
Modern
1. ZMC-2
2. Los Angeles
3. Macon
4. LS-12
5. LS-60
6. Metalclad
7. Modernized Macon
8. Goodyear SAB
9. Martin FAB
10. Sandwich
11. Goodyear ZPG-X
STRUCTURAL WEIGHT / GROSS LIFT (5000') x SPEED , 1/KNOT x 10^2
1.0
.8
.6
.4
.2
0
1
10
100
VOLUME, 10^6 FT^3

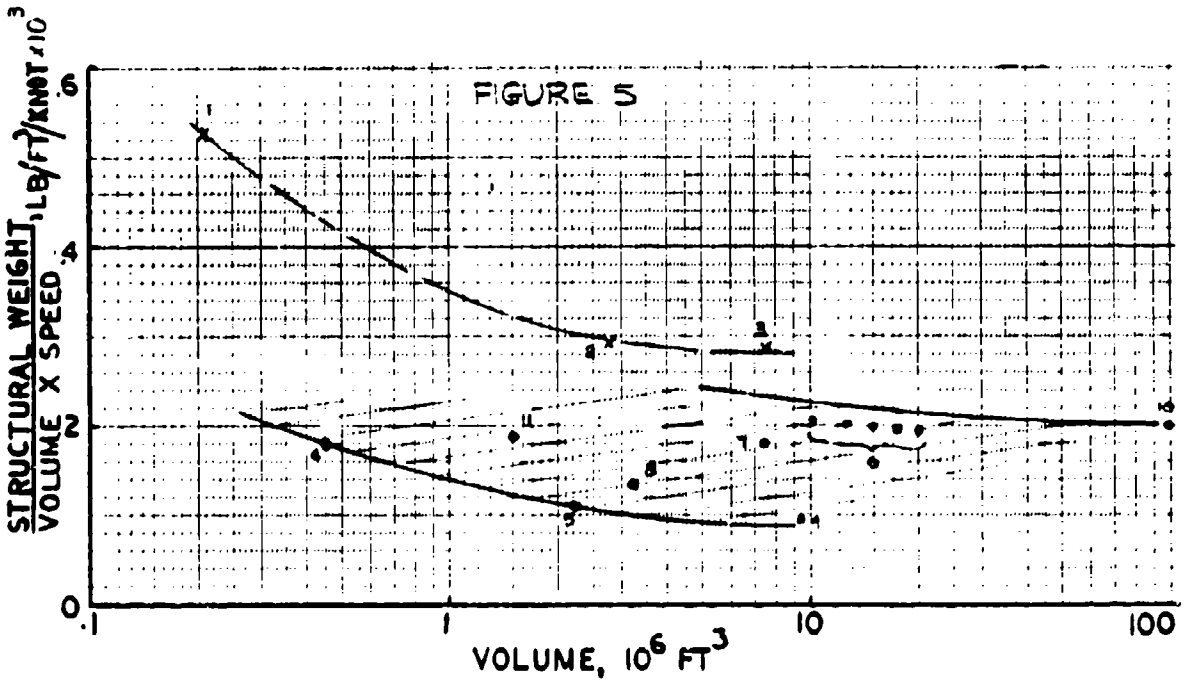


FIGURE 5
STRUCTURAL WEIGHT / VOLUME X SPEED , LB/FT^3/KNOT x 10^3
.6
.4
.2
0
.1
1
10
100
VOLUME, 10^6 FT^3

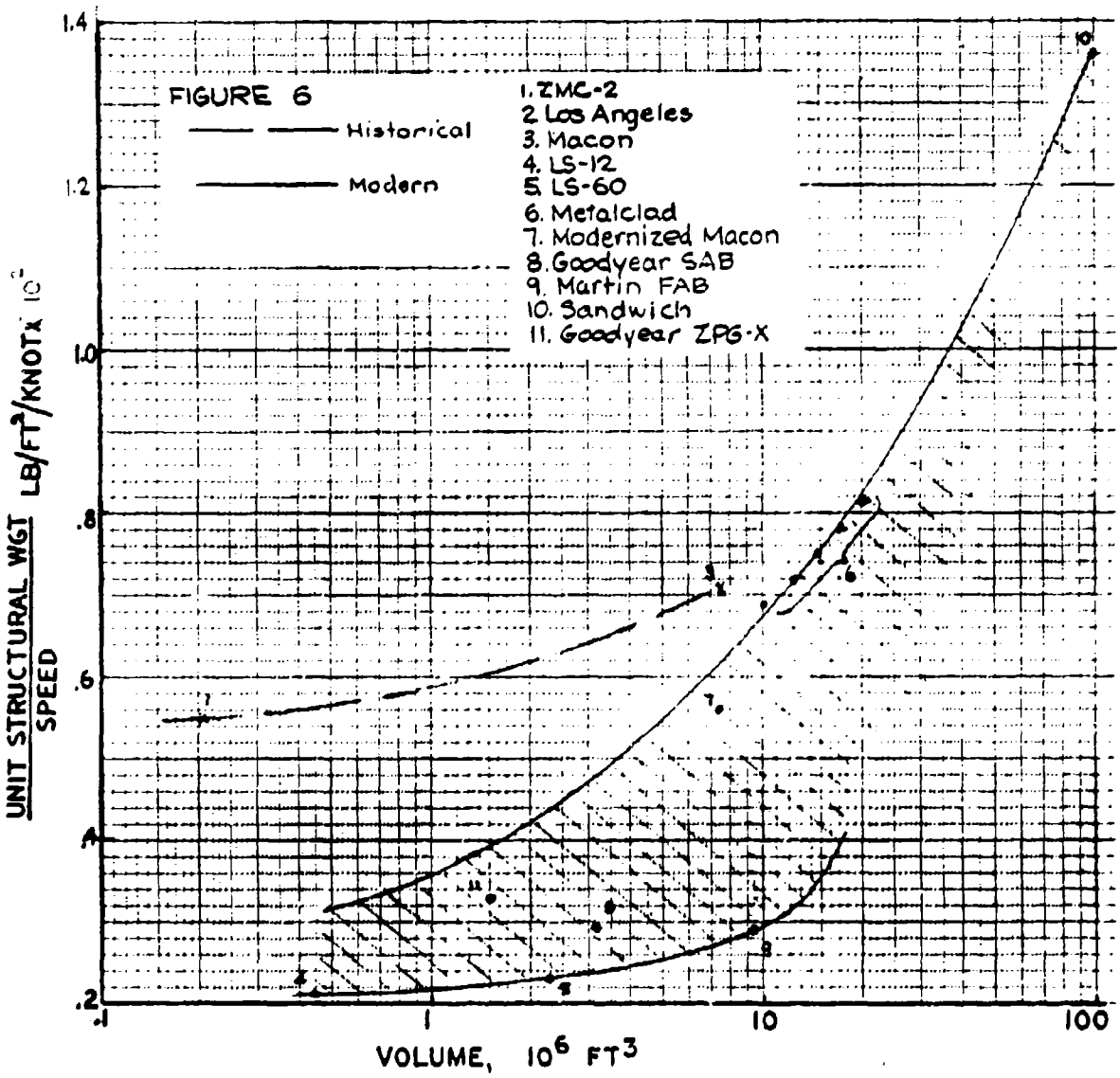


FIGURE 6
Historical
Modern
1. ZMC-2
2 Los Angeles
3. Macon
4. LS-12
5. LS-60
6. Metalclad
7. Modernized Macon
8. Goodyear SAB
9. Martin FAB
10. Sandwich
11. Goodyear ZPG-X
UNIT STRUCTURAL WGT / SPEED LB/FT³/KNOT x 10⁻³
VOLUME, 10⁶ FT³
1.4
1.2
1.0
.8
.6
.4
.2
.1
1
10
100

In all cases, Figures 4 to 6, the trends indicate that structures designed and built with modern technology should be more efficient than those of the old airships. How much better will depend on a lot of things, but, as indicated in these figures, volume is certainly one of the critical parameters. It would also appear that the overall efficiency in terms of structural weight fraction, Figures 4 and 5, improves as volume increases, while the unit weight of structure increases with volume, Figure 6.

CONCLUSIONS AND RECOMMENDATIONS

The application of modern materials, structural concepts, methods of analysis and fabrication techniques will surely make airship structures lighter, stronger and more efficient. Parametric design studies have tended to confirm this. There is a need, however, assuming that lighter-than-air vehicles are going to be pursued, to begin some development efforts in structural design in which actual structures will be engineered. Except for the work by Turbomachines, Inc. and Lightspeed, Inc., most of the recent structural design effort has been of a parametric nature which was good for its intended purpose. However, the next level of work, that of preliminary design, must be started in order to determine if the projected savings can be realized in a practical cost effective design.

It would appear that the design of future airship structures will take one of two paths, the Akron/Macon type construction with the substitution of modern materials, both metals and composites, or a completely new type of construction such as the sandwich or the geodetic. Which of these will emerge as the most attractive depends on additional work and more detailed investigation. Cost of manufacturing and assembly will be a most important factor, and recognizing the cost elements which exist today, simplicity of design is a goal of paramount importance.

Recommendations for future work are as follows:

a. Investigate further the geodetic hull construction, particularly, the Lightspeed design, which offers redundancy of load path, failsafeness, damage tolerance and efficiency.

b. Investigate in more detail the sandwich structure proposed by Goodyear, which is simple and not dependent on internal pressure for its structural integrity.

c. Determine areas of application for the highly efficient composite materials, including glass, Kevlar and graphite.

d. Perform loads analysis with currently used computer techniques to establish the methodology for an up to date treatment of critical conditions, rather than the semi-empirical ones of the past.

e. Conduct an investigation of the modern metalclad, the Lightship, a sandwich structure and a modernized Macon, each working to the same size, design criteria and mission so that a consistent set of weights can be derived and compared.

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