STATE OF THE ART OF METALCLAD AIRSHIPS

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ABSTRACT: This paper will deal with metalclad airship development of the past history and with the immediate prospects for continuation of the development of these airships. The metalclad airships promise high safety even in highly inclement weather, are capable of high speeds, while lifting high useful loads. Metalclad airships which in first cost would compare favorably with the costs of sea-going ships and in operating costs promise to be lower than airplanes.

HISTORY

First flight by man was in a balloon. It was inevitable that as soon as a prime mover was available, man would install it under an elongated balloon, now called an airship or a dirigible, and drive it directionally. At the time of the first flight in an airplane, the airship was well understood and for that time, daring prospects were already under way, in sizes that dwarfed the small airplanes. The historically unforgettable names of these pioneers, Zeppelin, Parseval, Schutte-Lanz in Germany; Forlanini in Italy; Clement-Bayard, Lebaudy and Santas-Dumont in France; Welman and Baldwin in the United States, etc., will always live in the mythology of airship development. One of them was Schwartz, an Austrian army officer, who succeeded in building an all aluminum, cylindrical airship, which at least floated in the air. Ultimately, Zeppelin, a master industrialist, besides a daring and imaginative inventor, organizer and engineer, brought the

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rigid airship to a high state of perfection. A parallel development arose in Germany, headed by Professor Schutte and financed by the known firm of Lanz, makers of farm implements. This group was even more daring and innovative than Zeppelin. They built their first th. ships of plywood, as the aluminum alloys were still being developed; later on of tubular steel girders; their ships were aerodynamically least resistant bodies, with many innovations, later considered indispensable to airship concepts.

In the early 1920s, with Zeppelin returning back to civil aviation and resuming the highly successful passenger transport service by Delag and Schutte-Lanz terminating their existence under the limitations of the Versailles Treaty, two men emerge in the Unit.d States, from different directions but with a common interest - all-metal dirigibles; Carl B. Fritsche and Ralph H. Upson.

Each one was unlike the other, and in fact each complemented the other. Carl was a pragmatic, outgoing man; a man of immense energy and vision, dedicated to purpose, ingenious in finding roads to those in power, convincing and enthusiastic, not above removing persistent obstacles with impatient gusto. Ralph was a rare product of American culture; a practical idealist, intellectual of profundity, in the class of Adlai Stevenson, highly educated and intelligent. To us, young ones, it was a delight to be daily exposed to these two men, who so well provided indispensable and different talents to the development of metalclad airships. Due to their cultural diversities, each vaguely and subtly distrusted the other with a solidly built in, but never admitted mutual plea of, "Please do not leave me, I need you".

Ralph laid down the principles of all metal hull design in the days when the great majority of the aircraft industry doubted that all metal airplanes were feasible. Carl worked the intricate paths to the powers of decision; somehow obtained private money from many sources in what still must be one of the best examples of free enterprise, and eventually found all doors of established agencies in Washington closed to any hopes for contract money. In this situation, he did what must be equivalent to climbing of Mt. Everest; he went directly to the U. S. Congress and with his persuasion he managed a rider to the Naval Appropriations Bill for the funds to build the ZMC-2, an experimental all-metal airship.

It is most proper to commence this talk with a sincere tribute to these two men, no longer with us; to their genius in the services of humanity, their attractive human qualities and their vision, which welded us all into a unique group of workers. I am sure that they had in mind what we shall talk about now. It is the ultimate egalitarianism of nature that singular men do not live longer than others. We now must do the utmost to take up the slack due to their absence and continue, and I am certain that both, Ralph and Carl, imagined this day might sometime come, when airships would continue.

The results of efforts of Carl and Ralph was the ZMC-2, (Picture No. 1). The primary objective was to demonstrate the all-metal or metalclad hull principle; the secondary objective was to use the ZMC-2 in training airship pilots. It was delivered in August, 1929 to Lakehurst by then Captain W. E. Kepner, the test pilot of the ZMC-2 and it served at Lakehurst for twelve years, until 1942, when it was decommissioned to gain space for larger airships. It had a length of 149 ft. 5 in.; diameter of 52 ft. 8 in.; displacement of 202,200 cubic feet of which 151,600 cubic feet was lifting and originally was fabricated from a .006 inch thick 17ST alloy. This alloy corroded so badly in spite of anodic treatment that soon after commencing the fabrication of the hull, it appeared wasteful to go any further and our Navy was asked to pressure the aluminum industry to develop either an effective protection against corrosion or to come up with a noncorrosive alloy. Alcoa did just that, developing the Alclad sheet from which also most airplanes have been made since 1933. Alclad was developed for the ZMC-2.

The Alclad plating was .095 inches thick, riveted by a wire-rivet automatic machine developed by E. Hill; and the plating was cut in frustum cone envelope sheets and was riveted in peripheral and staggered longitudinal seams. Mr. Roda, who was deeply involved in the fabrication and assembly of the ZMC-2 will tell you more about its construction as well as the construction of modern metalclad airships to come.

The ZMC-2 hull was inflated with Helium and the hull was kept under a pressure of approximately 2.5 inches of water by two ballonets, used also for pitch trim. Throughout all twelve years of service, no seam leakage of Helium has been recorded and the experience is that a lifting gas can be contained inside a metal hull indefinitely with minimal additions from time to time. The external metal surface in the highly salty air of Lakehurst, shows pitmarks of corrosion after twelve years, some of it caused by impact erosion by grains of sand. The aluminum layer of the .095 inch thick Alclad is extremely thin and this is probably the main factor. The internal surface appeared still as bright as when it left the mill, even inside the ballonets where too, it was exposed to salty air. In large ships, the electrolytically protective external aluminum layer will be thicker due to the thicker gages of the sheet, and possibly, Alclad sheet can be rolled for large all metal ships with one side, the external side, having a greater thickness of aluminum than the internal side. The fineness ratio of the ZMC-2 was 2.83, yet the hull was still stable and manueverable. The sheet thickness was excessively great, for reasons of facilitating fabrication and it was planned that the ship be overweight for this reason although the final weight met the estimates with some 270 lbs. underweight. Such a limitation will not again arise in larger hulls. To countermand this penalty, the fineness ratio was selected low, in order to obtain a low surface-volume ratio. Another influence on this decision was the desire to secure as high a hull curvature longitudinally as possible; more than sufficient thickness of the hull plating permitted high-hoop loads at still low-hoop stresses.

In Figure 2 is shown the inside of the hull of the ZMC-2, inflated with air under a low pressure. The hull plating under pressure was taut and smooth without wrinkles. When the pressure was released, the plating buckled, entirely elastically and the hull was then supported in its general shape by the frame and longeron structure, as a rigid airship hull. The lifting gas was contained by the plating, while two separate ballonets were attached to the plating by cemented shoe strips. The pressure inflation-deflation cycle was repeated many times before the ship flew and it must have been repeated very frequently during the lifetime of the ship without any notice of fatigue.

The ZMC-2 hull was inflated first with carbon dioxide, from the bottom, displacing the air toward the top and out. Subsequently the carbon dioxide gas was pushed out from the top to the bottom by Helium, until the gas volume of the hull was full with Helium. This method of inflation resulted in a very thin interface layer of mixed gases, air-carbon dioxide and subsequently carbon dioxide-Helium. In larger hulls it will not be necessary to resort to this process of inflation, as we shall see further on.

The fundamental principle of a metalclad hull was and remains the use of the lifting gas pressure and of the inflation pressure for strength and rigidity of the hull. The fabric-covered rigid airship hull also is subject to the forces of the lifting gas pressure of the cells. But this pressure, in a rigid airship hull, has to be contained by the wire and girder structure and contributes only very little to the strength of the hull as a beam, while loading adversely the girders in bending, in addition to compressive loads imposed on them by bending moments of the hull. In rigid airships, the gas pressure or the lift, generates unwanted and high secondary loads which the structure has to contain without any gain in strength for the carrying of basic hull loads. The lift forces in rigid airships require additional weight in longitudinal girders and frames. In Figure 3 is shown the Zeppelin L-129 airship. At the top of the drawing can be seen the gas-cell fabric supported by a planar network of wires anchored to the longitudinal girders and frames, which in turn take the lift forces by bending to the transverse frames. The girders of the frames are also loaded in bending by the forces from the retaining wire network. The lifting structure, the cells and the girders with wire netting between adjacent members, are then covered by external fabric whose sole purpose is to streamline the whole hull structure. This is the original concept of the Zeppelin rigid airships and in spite of its defects, it has served well. In Figure 4 is shown a number of transverse sections of the L-129 hull, illustrating well the sequences of the transfer of the lift forces to the longitudinal girders in bending. The peripheral space between the cells and the outer fabric surface is filled with air and is ventilated to the outside at numerous stations.

This space of course, is lost to the lift; in Hydrogen airships of this type, this peripheral volume always was the greatest hazard to the safety of the hull because at times, it was filled with a mixture of leaked-out Hydrogen and air. It is a credit to the discipline of operating crews of rigid airships that in only one, the last case, an airship was lost by fire in peacetime operation; R-101 ran into ground and burned afterward.

The metalclad hull principles, as laid down by Upson before SAE in 1926, are now classical to the modern airship design. These principles recognize that an airship hull must be an all-metal, gas-containing body, simply, **a shell.** The presence of the lifting gas pressure is not a nuisance but a design asset that automatically can benefit the strength and rigidity of the hull. It is not necessary to design it out, at the cost of complexity and weight, but rather it is desirable to design it in, with a gain in safety, simplicity and improved structural quality. The metal hull of the Upson airship was to be rigid, noncollapsible, so even if gas were to be lost from a cell, the hull still would retain its form, not collapse, and get the airship home at reduced speed.

To this end, he went further and specified that the hull be held under pressure by air in the gas dilatation volume or volumes that we call ballonets. Upson outlined a principle that may be considered a hybrid between the rigid ship and a collapsible hull nonrigid or semirigid airship and, advanced this concept, by making the self-supporting hull completely of metal. Hybrids often, but not always, are superior to the original individual components; this definitely is the case in metalclad airships, although we see proposals for some hybrids combining airships and airplanes which make one wonder.

Upson's concept not only utilizes the lift forces for strength and rigidity but also uses additional pressure to keep the whole hull skin under tension and imparts to it a high capability to support shear stresses as well as high compressive loads due to bending. The use of pressure provided by nature as well as by the designer in an all-metal hull, has opened wide the prospect of constructing all-metal airships of very large sizes and flight capabilities, especially speed, heretofore not possible even of consideration. Upson's system has given us means to create airships of high speed which will be reliable, strong and powerful to ride out storms if need be, that non-pressurized rigid airships should not dare to come near.

One important advance in the control of airships was introduced also by Upson in the form of multiple fins. All airship hulls in motion build up a thick boundary layer along the length of the hull. The classical cruciform fins are largely submerged in this boundary layer on the hull of high fineness ratio, also partly due to their low aspect ratio. The multiple fins can have a higher aspect ratio and therefore, are more effective and can be smaller. Furthermore, the multiple fin loads, being individually smaller and more numerous, are better distributed into the hull structure, and the stern structure weight can be markedly reduced. All rigid airships of the past suffered from low lift in the stern, due to the hull slenderness, still further aggravated by high structural weights and consequent high bending moments. This limitation has now been either reduced or done away with at no increase in drag. The multiple fins of the ZMC-2 were successful and did not have to be reworked as is often the case with airplane tail surfaces. ZMC-2 suffered in flight from a swinging roll, which can be analyzed as originating from the swirling slip-stream of the propellers, both rotating in the same sense. This should not occur again.

ZMC-2 was the first airship of this system. After its completion, we continued working on a larger ship, the ZMC-38, a 3,800,000 ft.^{3} displacement with lifting gas volume of 3,500,000 ft.^{3}, Fig. 5, of 1930, which, while still of a small scale would have incorporated all features of a working airship of much larger size. ZMC-38 was projected for 100 mph top speed. It had a fineness ratio of 4.5; at this fineness ratio, the hull already reaches its minimum drag coeff., which does not change significantly toward higher fineness ratios.

The hull form was arrived at with highest diligence and desire to obtain a high prismatic coefficient (.63) at low drag and therefore, the maximum practical surface/volume ratio. It also provided high lift in the stern. The envelope curve, so called E-H curve, Fig. 6, is a combination of an ellipse from the bow to the maximum diameter station with a hyperbola from approximately 40% length to 80% length and finally a second hyperbola in the stern for the remaining 20% of the hull length. At all stations of change from one geometrical curve to another, the first derivatives are on a smooth curve as anywhere else on the whole hull. Also, the second derivatives, the rate of change of the slope are on a smooth, continuous curve at all longitudinal stations. The hull plating was to be approximately .018 inches thick 2024 ST Alclad, although the thickness was to vary over the hull, according to the local needs. Fig. 7 shows the wind-tunnel model of the ZMC-38.

The main frames were deep only in those segments where transverse bending moments are high. The main frames had everywhere sufficient depth for free movement of a man, one or more, but at the low side of the hull, the depth was large enough for spacious habitation. The intermediate frames and longerons were to be made of lattice girders, as of course were the main frames. The design you see is now 44 years old, an immense age in the aviation history; yet today, as we apply modern technology to this effort, nothing needs to be altered in principle, although the influences of technical advancements on the design as it might be constructed now, are many as we shall see. The λ ratio (weight empty/total lift) of ZMC-38 was $\lambda = (.6838)$, a rather high figur compared to the Hindenburg, adjusted for Helium gas, $\lambda = (.5991)$, until we consider the scale of the two hulls and also that the ZMC-38 was to be a 100 mph ship, compared to Hindenburg's 77.7 mph. In general, these numbers have changed noticeably now, in view of modern technology.

Since 1930, the project year of the ZMC-38 several other metalclad airships were design-studied, among them MC-59, MC-72 and in 1939, Upson studied MC-11.9. In late times, we have been exploring parameters of metalclad airships of as much as (50-55) X (10^6)ft^3 hull displacement and up to 200 mph top speed.

MODERN METALCLAD AIRSHIP POSSIBILITIES

The resumption of metalclad airship design and construction cannot, at this time, be focused on a large ship. Such a program would be too demanding on the designers, builders and operating crews. Instead a rational program has to be considered which would resume at where we stopped 40 years ago and bring the art as rapidly as possible to a useful state with larger and larger ships to follow.

Historically, this procedure has been followed by the Portugese King, Henry the Navigator in his most farsighted program for sea voyages to discover the rest of the world and in our times by the NASA in the Apollo program. A metalclad airship of (3-4) X 10^6 ft ^{3} displacement appears to be highly justified for this purpose as the next ship to build; this initial class could even be named the "Caravelle" class. Not only one ship but several, will be needed before all participating in the return of airships would be ready for large airships.

The purpose of this new MC-38 is to organize an imaginative and productive design group with the responsibility for designing successful large and fast ships; to establish a dedicated construction group, reliable and trustworthy, and to train operating crews, first on simulators, as the assembly of the first ship commences and later by actual flight experience and overall, to continue the further development of airship technology in all completeness.

One of the first ships should continue to be experimental, heavily instrumented and should be for some time, in a never-ending state of rebuilding for trying new structures, power plants, boundary layer control, computerised operation, thrustors, thermodynamic management of lift, ground handling, etc. An MC-38 airship has approximately 100 tons gross lift with Helium and should be useful for several tasks of Naval as well as Coast Guard and civilian nature, so it would not be a waste any more than many other devices we operate as a nation for our collective benefit or protection.

In Fig. 8, is shown a sketch of such an airship, the MC-38 of the vintage of 1974. The hull contour curve is the same as that of the ZMC-38, shown before, as is its fineness ratio; possibly, the stern hyperbola could be made still fuller, but only wind tunnel tests could decide this. The only striking difference is that six instead of five fins are projected. We shall come to the reason for this later on. In the design of the hull, we shall have the luxury of computer programs for shells and it will be possible to determine precisely the thickness of the plating locally, based on wind-tunnel pitch and yaw test, with notable saving of weight.

First of all, let us orient ourselves with respect to areas in which significant gains have been made since 1930, in an itemized arrangement as follows:

Materials

The first significant gain is in materials now available to us, in aluminum and other metal alloys. Alclad is to be used again, with 7075 or 7178 series for hull plating, frame structures and longitudinals. For forgings, excellent aluminum and also magnesium alloys are available. Titanium alloys may be used in some applications, although Titanium will be appreciated more in bigger ships to come. Similar advancements have been made in steels, superalloys, fabrics, synthetics, bonding materials, etc., even in cables, all tending toward lower weights.

Structure

The structural configuration is markedly different in detail. No longer the intricate, embroidery-like girders of the past. The basic structural element will be the honeycomb components, solid panel surfaces, with minimum of joints. A joint in any structure is a liability; it makes for a structural discontinuity, has to restore the elemental strength and is usually the first part to fail; it is always heavy and expensive without contributing to the structure. The honeycomb panel frames and structures in general, do not have point concentration of forces and where concentrated loads enter the structure, the local reinforcing structure is easy to fabricate and low in weight and cost.

The honeycomb structure will be used all over the bow hull surface, without framing and longitudinals, with suitable doublers, as well as at other parts of the hull and over the fins, particularly at all locations loaded with concentrated shears, such as valve openings and hull cut-outs for any purpose. All transverse frames will be peripherally continuous (Fig. 9) circular, not polygonal, without individual joints except for reinforcements where local loads enter. To further carry out the policy of structural integrity and light weight and low cost, all longitudinals will be external, on the outer surface of the hull. Aerodynamically, this is a minimal compromise with a small aerodynamic penalty but a vast gain in strength, rigidity, lower weight and also cost. The longitudinals also will be designed as internal honeycomb structures, most likely of semicircular sections, riveted over the plating seams. The structure inside the hull will be everywhere circumferential, while outside the hull, it will be exclusively longitudinal. There will be no specific joints between them, except as they cross, one inside the other with the hull plating between them.

Hull Plating

The ZMC-2 hull was assembled from straight-sided frustum cone envelopes of thin sheet as rings. For large hulls, long and deep thinking concludes, it is more practical and also aerodynamically perfect, to assemble the hull out of gores, as Mr. Roda will describe later on. We already have facilities in the aerospace industry for stretch-forming panels of the maximum sheet sizes. This system requires a minimum of length of seams on the hull surface, the large panel gores can be lifted and manipulated by vacuum pads and in the quality of surface of finished hull, it is doubtful that a more aerodynamically perfect structure can be fabricated; this is important in view of the high speeds at which future metalclad airships will sail.

Not the least important of the structural components are the means of joining the structure. While the first ships will be riveted, we are intensively thinking of EB welding, Laser welding, thermoplastic bonding and we shall consider any other method that may yet come to notice. We know from experience that sealing will not be a problem; all hull seams will be in the immediate proximity of rigid structures, eliminating possibilities of local flexure. All hull seams will be made of flush 100° rivets, not so much for reasons of low surface roughness although that too, is important, but for reasons of high fatigue resistance. These rivets are driven in with one pneumatic hammer blow and fill the dimpled hole cavity in the sheets by plastic flow of the rivet metal to a tight, prestressed fit. They are not only stronger but also highly fatigue resisting; people flying airplanes do not realize when they look at the flush rivets along a door jamb as they enter, that they are catching a glimpse of one of the most powerful, yet lightest fasteners.

The honeycomb light structures are well developed in a multitude of configurations and their use in the metalclad airship construction is one example of modern technology making available for airships most useful means for the purpose of achieving light, rigid and strong structures. In the history of airships, it has usually been the other way around.

Fig. 10 is a picture of a tanker. Two of these are being built by Cammel-Laird in England. It is a 55,000 tonner and as tankers go, it is therefore a baby tanker. It is 680 ft. long, fully 151 ft. longer than MC-38. Its beam is about the same as the MC-38 diameter. The two structures, MC-38 and this tanker are comparable in size but designed for different elements; the airship for sailing in the air space and the tanker on the interface between oceans and atmosphere, the roughest and most hostile boundary on the earth. The purpose of showing this picture is to compare these two structures. The tanker structure is obviously highly complex compared to the metalclad airship structure and it has to be. The amount of fitting and welding of elemental components in the tanker hull, compared to the simplicity of the metalclad airship structure, is simply staggering. The tanker has four longitudinal, full depth bulkheads; without them it would come apart. The design and the labor in thousands of joints connecting the structure into a force-resisting shell, is in startling contrast to the continuity of structure of a metalclad hull, requiring only seams for joining. This has a direct bearing on the cost and weight of the two structures. This may at least allay some apprehensions about the cost of fabrication of metalclad hulls. The comparison goes further in contrasting the mechanical equipment in the tanker hull; the main engine room and its ancillary facilities, the pump room in midships and the electric and pipe lines not completely visible. In this respect also, the airship is either simpler and at worst, not as complicated as the machinery of a tanker. It is constructive to keep this in mind when considering costs in particular.

The airship hull as well as the fin structure, will be provided on all metalclad ships with permanent strain sensing transducers which will report at all times to the flight engineer's panels and will inform the captain during storms. The hull will be equipped with orthnicon transducers observing the cell fabric, functioning of valves, and of movable surfaces, of power plants and any other strategic elements. The flight engineer will know local gas temperatures as well as the surface temperatures of the hull; after all, he is managing not only an aerodynamic but also thermodynamic engine. He will also learn quickly of any internal leakage; in fact, the airships will be thoroughly instrumented for continuing surveillance of strains in the structure and state of the lifting gas as well as of the controlling air.

Propulsion

If the available materials and structural concepts, useful for metal-clad airships are spectacular in their merits, the contribution of turbomachines to airships is even more dramatic. Here it is best to itemize the possibilities, as follows:

A. Forward and reverse propulsion.
B. The control of the boundary layer in flight.
C. Thrustors for the automatic as well as the manual control of airships in the proximity of the ground, without any laboring crew.

Forward and Reverse Propulsion

The airships of the forseeable future will be propelled by gas turbines. These are the lightest, most reliable and durable power plants available now; any talk about Stirling engines, Diesel engines, or for that matter any reciprocating engines, is sheer retrogression. Gas turbines even in the small size projected for the MC-38, have a fuel consumption now of (.40) lb/SHPh and by the time the first ship will be ready for them, this should diminish to approximately (.35-.36) lb/SHPh.

The MC-38 uses three power plants, approximately 2,000 HP maximum capability, and without BL control of the hull, although even for 100 mph it may be less. Two power plants are one on each side, driving CR, CP propellers, the 100 mph speed being still too low for turbofans. The third unit is in the main frame supporting the fins, driving air through a tunnel toward the stern exit end. With all three power plants running, the speed is 100 mph; with two side power plants running at full fuel imput, the speed is 87 mph, while the central unit is at standstill. With the central unit only running, the speed is 63 mph. Thus we have three modes of operation, obtaining three high economy cruising speeds with lower economy speeds in-between. The latter case, propelling by the stern power plant alone, is particularly suitable for exploration of oceans at 60 mph and lower speeds, with a silent driving engine inside the hull, surrounded by accoustically impermeable lifting gas. The central turbine may have a lower maximum output than the side turbines.

Reversing is to be done by propellers in either all three power plants, or preferably only in the two side power plants. All propellers are specified as CR, to eliminate the wake swirl, not only for neutral approach toward the fins, but also for efficiency reasons. All power plants are telecontrolled from the bridge, no crew is needed for on the spot supervision.

The problem of weight-lift equilibrium with respect to fuel cannot anymore be solved by exhaust vapor condensation. For one reason, it is difficult to condense moisture from gas turbine exhaust, but most importantly, it is a clumsy method, dirty in its product, with resistance to flight and heavy. The most suitable and acceptable way to deal with this necessity is to burn Hydrogen gas as a supplementary fuel to the liquid fuel. Hydrogen is to be contained in balloons, in Helium cells, completely isolated from air, Fig. 11. Their volumetric content is just right for lifting the fuel and it is to be consumed at the corresponding rate to the liquid fuel consumption so that there is maintained a continuing lift-weight equilibrium at all times. For complete equilibrium of lift-weight, the Hydrogen has to contribute 17.73% of the total heat input into the turbines, based on one pound of liquid fuel requiring 14.22 ft^3 of Hydrogen for lift. Only the three main power plants will run with supplementary Hydrogen; all others, in thrustors and boundary layer control units, will run exclusively with liquid fuel and the figures just noted will increase above 20% of the total heat input to the main turbines. The volume of Hydrogen for a 25-hour trip at full power in MC-38, is 11.85% of the total displacement. The supplementary use of Hydrogen as fuel is the ultimate solution of the lift equilibrium problem with our present means. It is safe and dependable, simple and efficient, does not involve any increase in drag and very little if any additional weight. The reduced tankage for the liquid fuel should compensate for the fabric weight of the Hydrogen cells in the Helium compartments.

The gas turbine is of tremendous value to airships. Not only is its specific weight low, but the structure supporting it from the hull can be also much lighter than with piston power plants. Furthermore, it requires no major cooling and complexities associated with it. It is the most reliable power plant requiring low maintenance we could have dreamed of and in a honeycomb structure cell, it is not excessively noisy; two side power plants are provided to give the Captain an additional freedom of horizontal directional control. The power plants are so small and compact that mounting them inside the hull is not justified for the side units.

The Control Of The Boundary Layer In Flight

The MC-38, as in fact the metalclad shell principle at last makes possible effective boundary layer control. Boundary layer control is now an old technology, discovered already in 1904 and developed in the 1920's to a point of usefulness but not applied to aircraft generally, because at the speeds the heavier-than-air vehicles fly, it requires a considerable power plant to energize. For MC-38, it is projected that each of the seven main frames will be provided with surface orifices to remove the boundary layer that grows in the longitudinal direction between the main frames, by suction. The expectations are that a large reduction of the mean thickness of the BL along the length of the hull will be achieved, an approach toward the goal of a thin and constant BL thickness all over the hull. Similarly, the fixed parts of the fins will also be provided with suction slits or orifices to reduce the BL build-up on them. The prior work on this control is most encouraging and in our experiments with advanced turbomachine cascades, we have achieved extraordinary results in preventing separation of flow with only negligible expenditure of energy.

Each main frame will have a suction power plant for this purpose; a suction compressor driven either electrically or by a small gas turbine. It is a fact that no known dynamic compressor system can attain as high a negative (suction) entry pressure, as the centripetal contrarotating compressor. It will be mandatory to use these compressors for the removal of the BL.Their energy consumption will be small, particularly in relation to the fuel amount that would be needed without the reduction of drag by the boundary layer removal. These little suction power plants, if gas turbines, will run only on liquid fuel, without Hydrogen admixture. The electrical load in a modern metalclad airship will be high, due to the automation of controls, orthnicon cameras of the closed TV system in the hull, power pressurizing system (no scoops), computer load and also the transient de-icing demands by electrofilmed surfaces over known strategic areas.Electricity generating power plants will also be gas turbines.

It is known that drag can be reduced by removal of the BL on a body of revolution to less than one half of that with BL. We have attained similar results on compressor cascades with only one station of suction; to begin with, it appears reasonable at this time to expect that with seven stations along the length of the hull, it should be possible to reduce the drag, on a metalclad, pressurized airship hull to at least 66% of the drag without the BL control; the drag coefficient therefore would be approximately .043, with fins, controls gondola and two-sided turbines. This expectation could not be realized on a fabric-covered rigid airship hull, even if the fabric were to be pressurized to a low pressure to prevent flapping of the surface. The fabric instability of the surface of rigid airships is a source of high drag. I have seen fabric waves on the R-100 dirigible which must have been at least four feet crest-to-crest. Metalclad hull surface is stable with almost perfect curvature when at atmospheric pressure, will not exhibit deep buckles in the ship of the size of the MC-38 and larger.

One incidental benefit of the BL control will be the reduction of the size of the fins, due to the thin BL at their bases, as compared to the relatively large part of their span made ineffective by a thick noncontrolled BL. This gain manifests itself in two ways. First of all, it is possible to rely on only six fins, with dual elevators and single rudders, on the top and bottom dorsal fins. The second gain is in the increased aspect ratio of the fins, compared to eight surfaces.

The fact is that without BL control, it would be prohibitive to operate even low drag hulls of metalclad airships at high speeds. The metalclad airship hull has even in the case of the ZMC-2, a very smooth surface. With the projected gore construction, the smoothness of surface and the correctness of shape, will be the ultimate that can be reached with any hull, non-deformable by aerodynamic forces, unlike with fabric pressurized hulls. With hulls of this precision of form and low surface friction, it is effective to practice BL control and reduce the virtual drag to a minimum attainable within the practicability of the means. The fuel requirements for doing this will be very modest, because the powers involved are low. Also, the weight of the turboblowers for this purpose will be low, of the order of .20lb/lb ofT. Gas turbines have an excellent record of reliability of starting; statistics of our Navy for instance, are completely reassuring on this and there is no doubt, that the BL control power plants, as well as the thrustors will be similarly reliable in response to the starting switch.

Thrustors for the Control Of Airships

The third power plant system on board the MC-38 will be the thrustors. This is a fairly recent technology, developed first for docking of large ocean ships and now also used in spectacular manner on drilling rig platforms on high seas, for example in the North Sea, one of the roughest oceans.

What has been accomplished already and is being used on an increasing scale with drill rigs and ocean liners, can be duplicated with airships of the highly rigid metalclad hull system. The MC-38 is to be provided with turbine thrustors in the bow and in the stern. In the bow, on top of a hull main frame will be a vertical, downward thrustor of approximately 1000 lb. maximum thrust, although the final thrust size will be determined by extensive consultations with the captains of the past airships and by wind-tunnel tests. On each side of the hull is to be located also one thrustor, for starboard thrust and port thrust.

On the bottom of the hull but closer to the center of buoyancy, will be a group of three thrustors in the bow and three on the stern, for vertical upward thrust. The vertical positive lift thrustors are projected in triplicate in the bow as well as in the stern, in order to secure a high vertical lift for a heavy lift-off. All thrustors will be identical in size and in positive vertical lift which is the only critical direction, there is a safety factor of 3 on response to starting and availability. All will be operated by a computer with captain's override, through accelerometers sensors.

There arises a new and peculiar problem associated with aerodynamic thrustors. Similar thrustors are being manufactured and several firms produce them. They are used for vertical lift platforms and in all present applications their long time speed response lag is not highly important.

In the airship control, the long time lag in speed response of the aerodynamic thrustors is extremely important. The hydraulic thrustors in ships have a short lag, because they are low-speed machines. In high-speed aerodynamic machines, the time lag is a function of the cube of speed of rotation and is too long for this control method with single-rotating thrustors, which would have to be run up beforehand and left running at full speed, or near-full speed, while the airship is under their control; the forces of control would have to be derived from opening and closing of gates. This is a complex, heavy, fuel consuming method.

However, contra-rotating thrustors are capable of alleviating this lag because for the same output, their time lag is eight times shorter on thrust delivery either rising or decreasing. This is a promising use and it should satisfy the requirements for high responsiveness even for airship control without structural complexities of gating. The thrustor control is an indispensable means for airship handling near land and during approach to the mast and taking over the anchoring by heavy land tractors, a method initiated by Zepplin works already in 1935.

The concept of control of airships by thrustors completely changes the experiences and preconceptions of the past and requires the abandonment of the insecurity and unpredictability of handling of airships near and on the ground. This concept, now available and in fact indispensable to all future airships, is contingent on a rigid hull; without this quality of structure, thrustors would actually be dangerous - again the metalclad pressurized airship meets this prerequisite condition and will be capable of making use of thrustors from the first ship to come.

Hull Cells and Pressure Control (Thermodynamic Managemont of Lift)

The ZMC-2 was a single cell lifting gas hull. In larger ships, the problems arise with containment of the lifting gas. One is the inflation with lifting gas. The second is the problem of division of the hull into individual lifting compartments. The third one is the pressure and lift control. In Fig. 12 is shown a practical solution of the problem of inflation and subdivision of the hull. The upper half diametral area of each main frame contains a semicircular curtain of reinforced fabric, which separates two adjacent cells. At a station a short distance from the center line of the hull is attached to the horizontal edge of this curtain, a semicylindrical cell, with a half-circle fabric wall at each end and a half-perimeter cylindrical fabric wall connecting the two semicular ends. The upper part of the metalclad hull and the walls of the main frames are the remaining containing walls of each cell. After installation, the cells, one by one, will be deflated by pumping the air out at the top of a main frame. The pumping will continue until a low vacuum is reached, to draw all air out in order to reduce the contamination of the lifting gas.

Next step will be the inflation of the cell space, at this time reduced to zero, with the lifting gas, with the lower, fabric-cylindrical curtain of the cell ultimately floating above the bottom part of the hull, thus creating a control air space below each cell. At two specific main frames will be provided reinforced fabric, separating the hull into three individual air spaces for hull trim control.

The cell fabric is considered to be silk, with Mylar films on each side. The silk industry is in a depressed state and it should not be difficult to obtain this strongest fabric for highly flexible, internal walls. Rapid and noncontaminating inflation and deflation of the metalclad airship hulls is therefore no problem whatever. Both, the air space as well as the gas space will be provided with blow-off valves. For containing the Hydrogen-fuel gas in a Helium-filled hull, one of several possible schemes is to provide a semicircular cell, shown before, from all internal walls of the hull, which would be located between two intermediate frames and piped into the main frames.

So far, we have been talking about Helium filled airships. The first metalclad airships will have to be filled with Helium for reasons which are obvious to all. Yet, we are and always have been aware that the metalclad hull is safe for holding Hydrogen gas; even in case of puncture of the plating, air will not enter the hull, only gas will escape and even if it should burn externally, it cannot burn internally. The lift of Helium is almost 10% less than that of Hydrogen. This reduced lift cannot come from the weight empty of the ship, it has to come from the useful load; in terms of useful load, the 10% difference grows to 25-30% of the useful load of a small airship and this cruel fact would make the Helium airships economically unattractive.

If the airships are to be a factor in transportation they must use Hydrogen for lifting gas. The metalclad hull is safe for containing Hydrogen, but the cell system in Fig. 12 is not. If it were to be used to contain Hydrogen, the leakage through fabric and possibly also at the seams would contaminate the control air volume and we would have the same dangerous situation as in the peripheral interspace of fabric-covered airships. In fact, worse because in the fabric covered hull, the mixture of air and leaked gas eventually and in a short time escapes, but in a metalclad hull, it could remain for a relatively long time. Solution of this problem leads to the concept of using Helium as a separating or shielding gas between Hydrogen and the control air volumes. This is shown in Fig. 13, where we again see a similar cell-fabric structure as with Helium only inflation, but now the cells contain Hydrogen. The space between the fabric cells and the bottom of the metal hull, is containing Helium, completely enveloping all facilities, habitable spaces, controls, and power plants, the Hydrogen cell fabric never coming in contact with the air space. Even the seams on the sides of the main frames are covered with Mylar films to contain possible leakage in spite of seam seals.

The controlling air is contained in ballonets between the Helium volumes and accessible air spaces; the fabric of these inflatable volumes is the only additional weight required, not a great weight.

This containment of Hydrogen is feasible, would be safe and light in weight. The volume of Helium would be no more than 10-15% of the Hydrogen volume at most, therefore, the Hydrogen lift would be reduced only very little. It is inevitable that metalclad airships of the immediate future will fly with Helium but after experience and confidence will set the minds at ease the Hydrogen-Helium metalclad airship is inevitable. In this respect the experience gained with Hydrogen fuel will be reassuring and valuable.

The MC-38 will use blowers for the control of air pressure; this is a simple means, without additional scoops. Of course, the control will be automated and capable of holding the pressure to extremely small tolerances with means that have been available and in use for a long time already in the central power plant stations. There is no fixed value of operating pressure to be set as the optimum. An optimum can be based on speed, on the diameter or on the maximum expected bending moment due to turbulence or a number of other criteria. In MC-38 with 7075-T6 Alclad plating of .018 thickness, with a minimum factor of 2 on Y.P. and seam efficiency of only 75%, the hull could sustain an air gage pressure of $.54^{lb}/in^2$ in a Hydrogen filled hull at sea level. In terms of water column, this amounts to 15.77 inches of water. With altitude, this pressure would be reduced by controls. The operation of a metalclad airship will probably take advantage of the continuously controlable hull pressure, raising it to a safe limit during approach to the ground and during flight in rough weather. The hull pressure will become a variable not only as a function of altitude but also of flight conditions, of speed and also during ground approach. The elevated pressure is desirable at high flight speeds as well as during rapid changes of temperature.

This last observation gets us to the consideration of what has come to be known as the thermodynamic management of lift. It started actually from the desire to control lift without wasting Helium, but instead liquefy it and store it in Dewar containers as the fuel was consumed. This proved to be impractical due to high energy consumption required for liquefying Helium and also due to the lightness of the liquid Helium. Next, we explored liquefied air and discarded that too for simiilar reasons. There is no hope for either one of these cryogenic methods of lift control. However, this thinking then leads into two different directions; one, to use Hydrogen as supplementary fuel for main turbines, which we mentioned already and the second one, to consider heating and cooling of the lifting gas; the thermodynamic control of lift by addition or removal of heat has considerable merit and will be one of the programs for experimentation with the MC-38.

It requires much less energy for a given volumetric change, to manipulate Helium than Hydrogen and this is part of the attraction for applying this method to Helium airship operation. Also, in the Hydrogen ship with Helium barrier, this is convenient; although in the Hydrogen ship the required energy will be greater and the Helium volume will have to change more to control the broader Hydrogen volumetric changes. Obviously, it is much more efficient to heat Helium than to cool it by refrigeration, due to the low thermal efficiency of all refrigerating cycles. The Carnot ratio is always low in refrigeration. It is really fortunate that heating is so efficient, because it is more important in controlling the lifting gas than refrigeration, since it reduces or prevents sinking motion. For this reason, the cooling of the lifting gas will be only a large fraction of the heating capability; during a rising motion, the Captain has also valving besides thrustors at his disposal, whereas during the sinking motion valving is denied him, and for this reason among others, the thrustors for countermanding the sinking motion are more numerous and therefore, more powerful than the thrustors for providing sinking motion.

The overall purpose is to eliminate the need for carrying water ballast. The ultimate decision not to carry ballast at all will be arrived at gradually; the first airship definitely will still carry some ballast water, although perhaps not as much as without thrustors and thermodynamic control of lift.

FINAL COMMENTS

The MC-38 and larger airships of the future, should be constructed as load carriers, with exchangeable containers, locked into the structure, so that their bodies will integrate into the airship hull and contribute to its flight strength and rigidity; although these containers will be of the same size, their conceptual design will be diverse. One type may be insulated and refrigerated; another may be constructed for carrying liquids; a number of them would be made similar to mobile homes, for habitation, with built-in sanitary facilities, cabins or seats, galley, interconnected social spaces between containers, etc. By carrying different containers, the ship will be capable of conversion into a freighter, or a laboratory, or a passenger ship by selecting loading alone.

There exists a wide speed gap between surface vehicle or sea vessel speeds and the today normal aircraft speeds. This speed gap is at least 450 mph, within which there is no transport means of intermediate speed now available to us. This wide-speed gap will be corrected by airships with speed ranging from say one hundred knots to two hundred knots within five years from the commencement of the airship program. This comparison illustrates how sorely needed airships are, particularly on intercontinental routes, overseas. Equally as much but in a different way, for the surveilance of the oceans.

Small airships of the MC-38 size inevitably have high weight empty/gross lift ratio or λ ratio, and cannot afford a relatively large fraction of their total volume for the compensation of lifting gas dilation. This means that they are low ceiling airships. The MC-38 air-control space would have to be approximately 12% of the total gas volume of the ship for 5,000 ft. ceiling. At this ceiling the MC-38 would still have a useful lift of 30,000 lb with Helium, not bad for a small, purely experimental and training class of ships.

The λ ratio changes, at first rapidly, with increasing displacement. At approximately $(12.825) \times 10^6$ ft^3 hull displacement, the value of $\lambda = .396$, instead of $\lambda = .594$ of the modern MC-38, a gain of 50% in favor of useful load to total displacement. This is a law, one of the laws governing the airship engineering. Therefore, larger ships will be able to reach and stay at higher ceilings without any problems and without excessive limitations of useful load capability. This is an indication of how powerful airships can be in larger displacements, over approximately 10^7 ft^3, and also what broader freedoms of operation are open to them with increasing size.

The favorable decline of λ with increasing size of airship hulls has two other consequences, both desireable and welcome. One is the prospect of very large Helium-lifted airships in which the reduction of the useful lift would be less than the (25 - 30)% characteristic of small ships and the load carrying capability would still be within economically attractive limits. The probable consequence might be that large passenger airships would be lifted with Helium, while the naval ships and freighters, both of which will very likely travel at higher speed, will be lifted with ~~Hydrogen~~-Helium gases.

The second consequence of the declining λ with size, is the freedom of large airships to afford a larger gas dilatation control air volume and therefore, gain in their ceiling capability, without serious limitations on their useful lift. In other words, ceilings of 15,000-20,000 ft. will be economically feasible, if required. This would apply to overland airships; intercontinental airships should have no need of ceilings over 8,000 to 10,000 feet.

Still another conclusion emerges with increasing size of airships. It is the fact that past the MC-200, (20,000,000) ft.^{3} size, the λ ratio declines only slowly and in view of this, it appears doubtful that airships larger than (20-30) (10^6) ft.^{3} total displacement will offer economically more than this maximum size. The impression is that the optimum size of an airship may be approximately MC-250, (25)(10^6) ft.^{3} airship. This size is larger than fabric covered airships should attempt to reach. The λ value of the MC-250 would be approximately = .320 . Dimensionally this ship would have a diameter of 224 ft. and a length of 1,008 ft., which is fully 300 ft. shorter than a 300,000 ton tanker of which over 150 are being built now, all over the world. This could well be a 200 knot ship, capable of 20,000 ft. ceiling, if needed and it could well afford both of these performance figures, whether lifted with helium or with hydrogen-helium combination.

With hydrogen it would have a total lift of approximately 747 tons; with helium, the total lift would be approximately 682 tons. The useful lift of the helium ship would be approximately 464 tons; the hydrogen-helium ship would lift approximately 500 tons of useful load. The difference in total lift due to the specific lifts, has declined to a little over 7% from (25-30%) of useful load in a small ship.

Modern airships will be more complex in detailed facilities and equipment than forty years ago. This is unavoidable and is in fact necessary to achieve as high perfection as possible. We have seen the airplane grow from a simple device into a sophisticated and incredibly reliable transport in spite of its also incredible complexity. In fact it is thanks to this complexity that it has become a safer, dependable and viable transport vehicle. Similar comparison with what used to be holds true also with seagoing ships, power stations or even a locomotive, and it will also be true for airships. Functional complexity imparts desirable and indispensable qualities to every dynamic engine and it will make metalclad airships also highly reliable, safer and trustworthy economical transport ships compared to all our past experience.

ILLUSTRATIONS AND SLIDES TO BE PRESENTED

Figure 1	ZMC-2
Figure 2	Inside of ZMC-2
Figure 3	L-129 -- Longitudinal
Figure 4	L-129 -- Transverse
Figure 5	ZMC-38 -- 1930
Figure 6	E-H Curve for Hulls
Figure 7	Wind Tunnel Model of ZMC-38
Figure 8	MC-38 -- 1974
Figure 9	Perspective view of the MC-38 (1974) Structure
Figure 10	Picture of a Tanker
Figure 11	Cell Diaphragm for helium only
Figure 12	Hydrogen cells in helium
Figure 13	Hydrogen-Helium cell

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