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TECHNOLOGY UPDATE - TETHERED AEROSTAT STRUCTURAL DESIGN AND MATERIAL DEVELOPMENTS

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ABSTRACT: Requirements exist for an extremely stable, high performance, all-weather tethered aerostat system. This requirement has been satisfied by a 250,000 cubic foot captive buoyant vehicle as demonstrated by over a year of successful field operations. This achievement required significant advancements in several technology areas including composite materials design, aerostatics and aerodynamics, structural design, electro-mechanical design, vehicle fabrication and mooring operations. This paper specifically addresses the materials and structural design aspects of pressurized buoyant vehicles as related to the general class of Lighter Than Air vehicles--the subject of this Workshop.

INTRODUCTION

In the late 60's, Sheldahl, under sponsorship of ARPA (Advanced Research Projects Agency), undertook a project to design, develop and fabricate three 200,000 cubic foot tethered aerostats under the direction of the Air Force Range Measurement Laboratory (RML). Starting with the limited balloon and non-rigid airship technology that existed at the time, considerable effort was devoted to extend the applicable advanced design and analytical techniques already used by aerospace engineers to the design of aerodynamically shaped, buoyant, pressurized vehicles. Despite the fact that the 250,000 cubic foot Captive Buoyant Vehicle, which eventually evolved and is employed commercically today by TCOM (Tethered COMmunications, a division of Westinghouse Electric Company), is to some extent a marvel of art, it represents a significant technological improvement over previous LTA vehicles in terms of performance, reliability and ruggedness. The structures and materials technology advancements played a dominant role in the success of the aerostats being deployed worldwide today for communications, monitoring, and surveillance applications.

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Figure A

250,000 CU. FT. AEROSTAT IN-FLIGHT/MOORED

OPERATIONAL/PERFORMANCE HISTORY

The CBV-250 is shown in flight and moored in Figure A. Each aerostat is completely rigged and checked out (including a proof pressure test) at a hangar facility in Elizabeth City, North Carolina and then sent to its operational site. The first CBV-250 was operationally deployed in the Bahamas in the summer of 1973 and has provided valuable system design feedback since that time. The aerostat was flown in all types of weather typical of that climate including severe electrical storms and a hurricane. In October of 1973, during Hurricane Gilda, winds exceeding 82 knots were sustained by the aerostat flying at 3,000 feet with no apparent damage. Other experiences time and again demonstrated the structural ruggedness, stability, and operational advantages of this vehicle. The CBV-250 and the CBV-350 with payload capabilities of 4,000 pounds and 6,000 pounds respectively are compared in size in Figure B1.

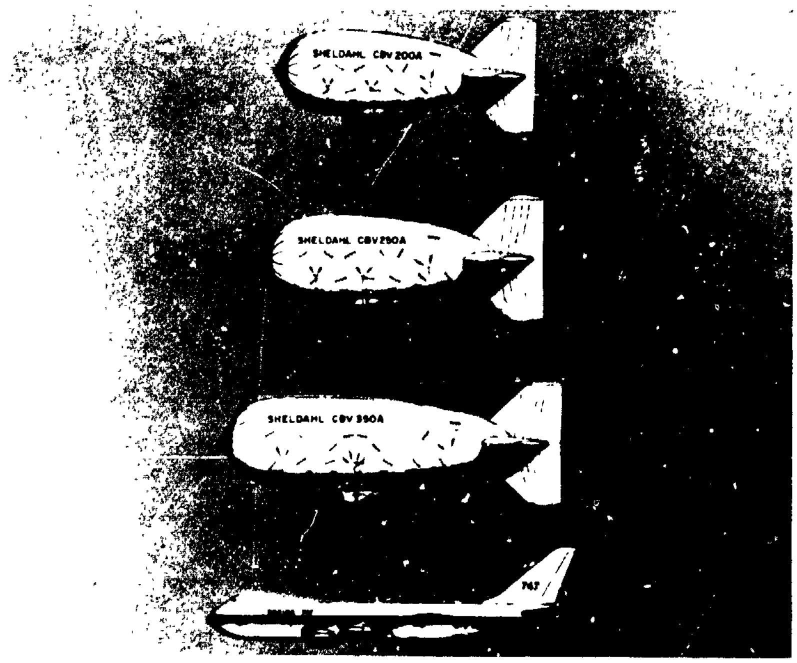


Figure B1
AEROSTAT SIZE COMPARISON

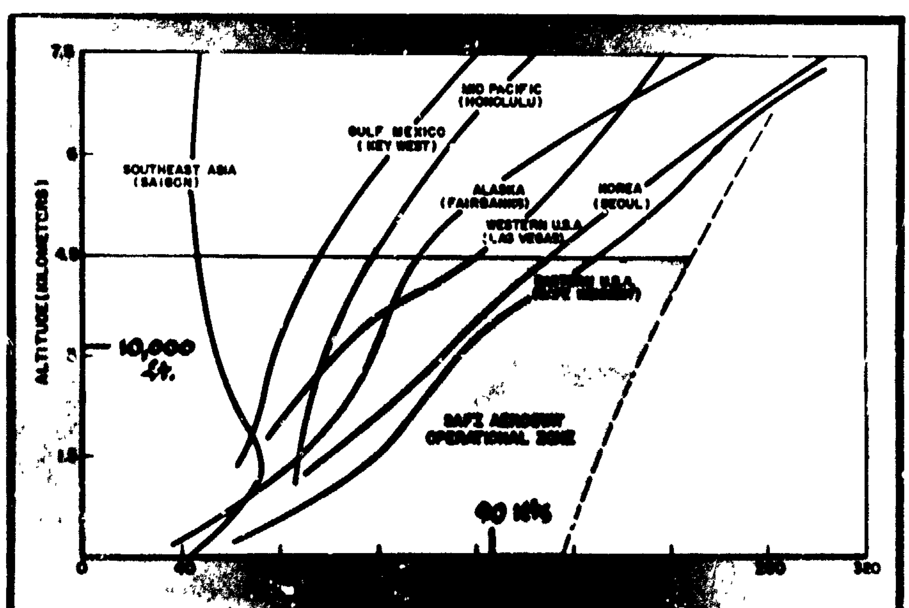


Figure B2
SAFE OPERATIONAL ZONE

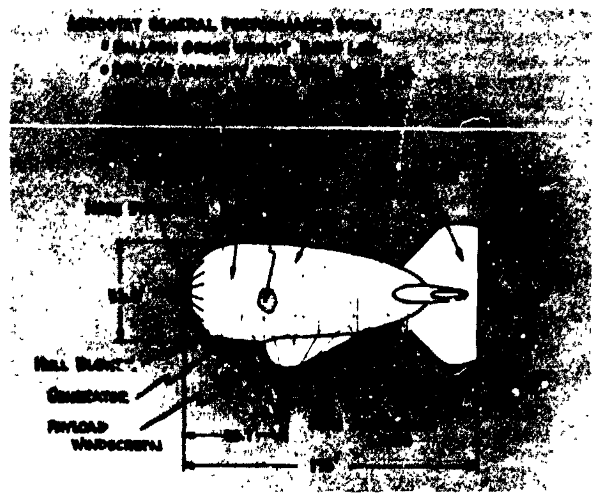


Figure C

MAJOR AEROSTAT SUBSYSTEMS

ENVIRONMENTAL REQUIREMENTS

The aerostats are being deployed in the Far East, the Mideast and other parts of the world--requiring design to climatic extremes. MIL-STD-210B has served as a valuable guide in establishing environmental requirements. The aerostats are designed to sustain winds of 85 knots at 10,000 feet with a minimum structural safety factor of 2. Winds aloft at various worldwide locations are also depicted in Figure B2 indicating the safe operational envelope of these vehicles. Temperature design criteria include the extremes from +120°F down to -40°F. A ten year life with minimal maintenance is required of the major structural envelopes, the hull and empennage. Other design criteria include requirements for blowing sand, hail and lightning to enable around-the-clock operational capability.

PRIMARY SUBSYSTEMS

The major subsystems of the CBV-250 aerostat are depicted in Figure C. Note the overall dimensions and general performance data. The payload is accessibly housed in the windscreen.

AEROSTAT MATERIALS

The fabrics of construction are pictorially described in Figure D. Most of the materials are composite adhesive bonded laminates of TEDLAR PVF film, for weathering and UV stability, MYLAR polyester film for helium impermeability and shear strength, and Dacron polyester plain weave cloth for the strength member. Urethane coatings are used where excessive material flexing occurs such as the windscreen and ballonet.

PRESSURE CONTROL SYSTEM

Pressure sensors, compartmental valves, and blowers comprise the pressure control system maintaining each main compartment at some level above freestream dynamic pressure, q, as shown in Figure E. The power is supplied by two on-board 18 hp Sachs-Wankel rotary combustion engines coupled to a static brushless generator with a static voltage regulator.

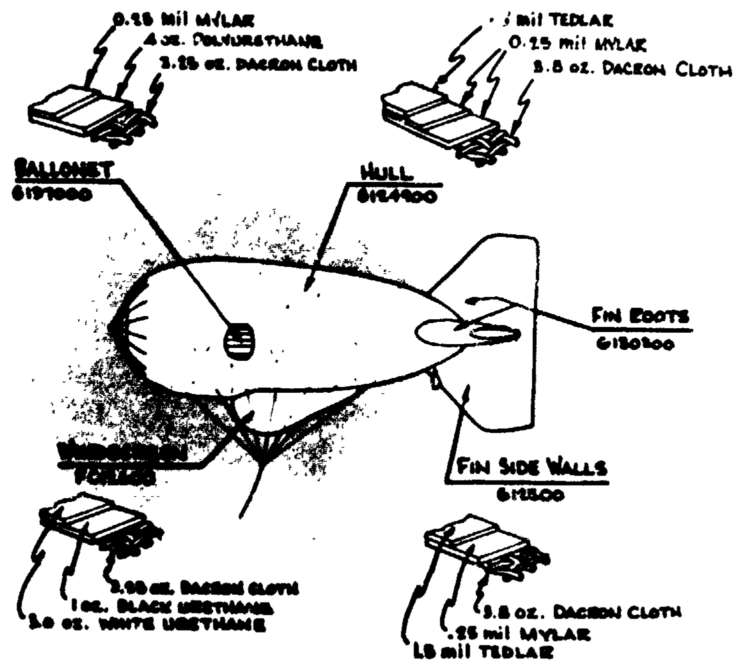


Figure D
AEROSTAT MATERIALS

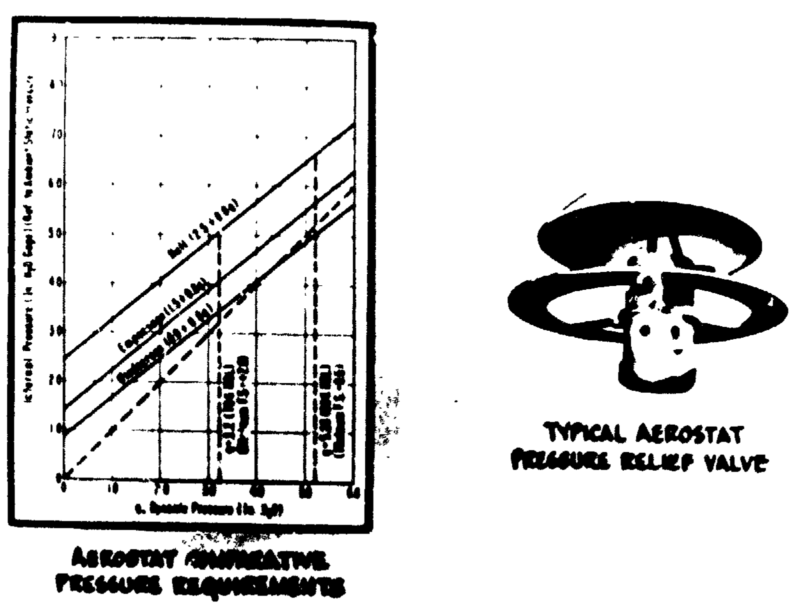


Figure E
AEROSTAT PRESSURE REQUIREMENTS AND RELIEF VALVE

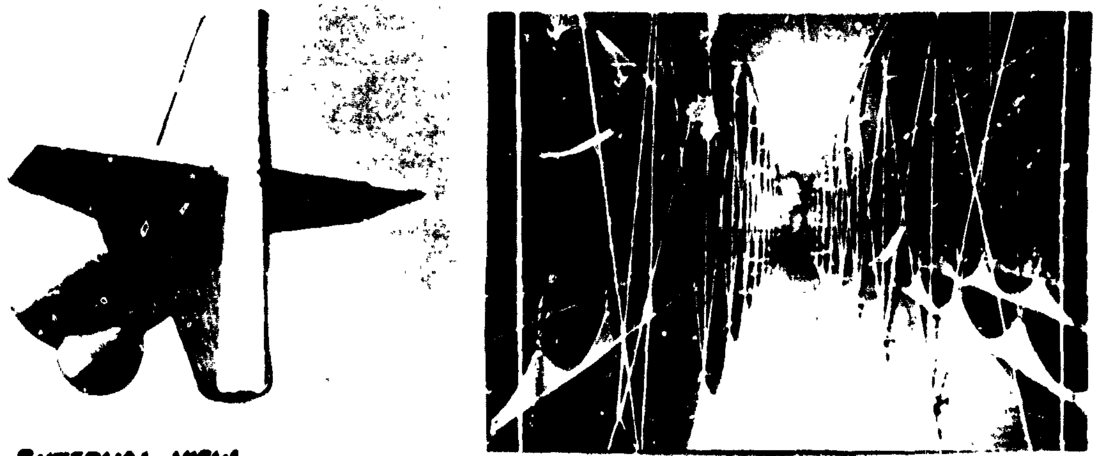


Figure F
AEROSTAT EMPENNAGE

EMPENNAGE

The aerostat Empennage* as illustrated in Figure F is the product of a long-term development effort. The entire pressurized assembly is quite large and well aft on the hull--dictated by aerodynamic stability considerations. Fin ribs run spanwise for maximum flexural and shear stiffness and are quite unique--borrowing from the concept of a uniform load distributing parabolic shape, and are laced with Dacron cord. The aft hull is pressurized slightly above the empennage to allow for natural curvature. The fins are guyed one to another to prevent large rigid body rotations.

NOSE STRUCTURE

The nose structure illustrated in Figure G is the primary load transfer structure for the moored aerostat. A high strength, light weight tubular aluminum nose cone, and 16 aluminum nose beams, which are laced to the hull, react mooring load equivalent to 90 knot surface winds based on a mooring dynamic analysis. The nose beams transfer the load into the hull fabric as a shear load.

PAYLOAD ATTACHMENT

The gimbaled payload is suspended from a welded aluminum truss structure laced to the underside of the hull. The hull is at a higher pressure than the windscreen to prevent the interface from wrinkling and going flat.

SUSPENSION LOAD PATCH

The primary load carrying suspension patches also utilize the parabolic scallop design approach to uniformly distribute the 2,500 pound maximum suspension line load into the hull fabric. The suspension lines are sized based on stiffness in addition to strength to optimize distribution of the main tether load.

* Patent pending.

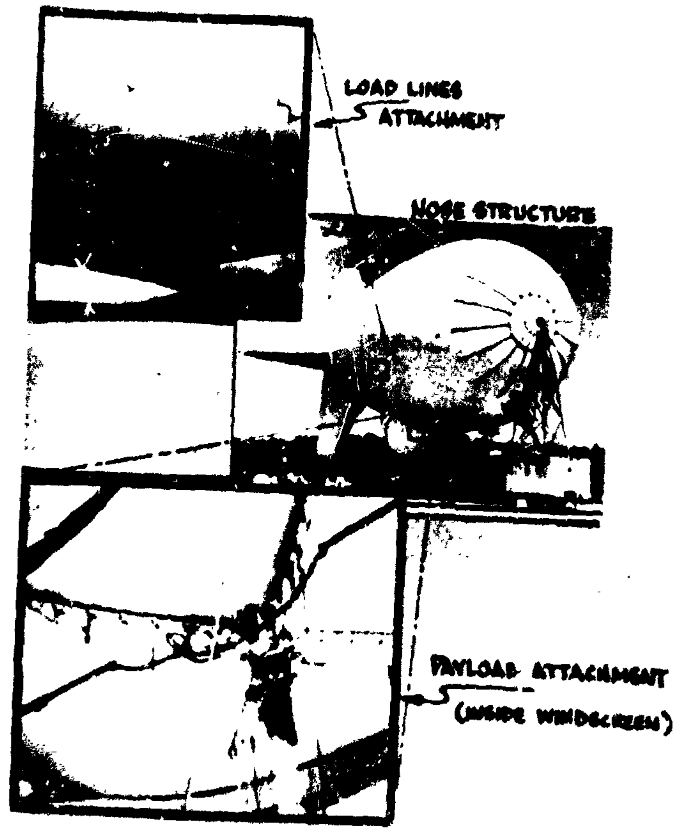


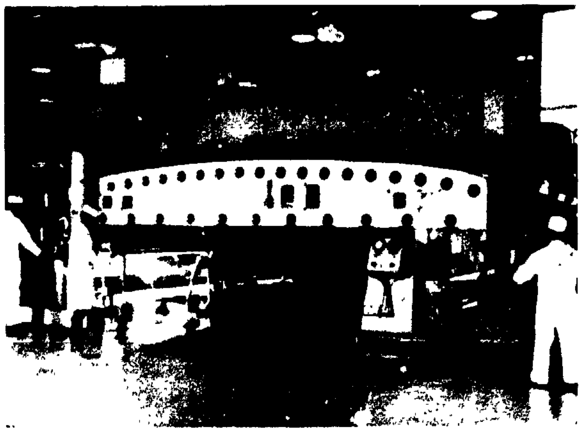
Figure G
LOAD ATTACHMENT HARDWARE

MATERIALS FABRICATION

The Dacron cloth is supplied by speciality weavers and is "set" by running the woven cloth through an adhesive bath. This permits the woven cloth rolls to be shipped to Sheldahl, wherein they are combined with the TEDLAR x MYLAR x MYLAR tri-laminate using special purpose polyester adhesives. All laminating variables are precisely controlled resulting in a consistent product. Figures H and I show a laminator, the flying thread loom (used to manufacture structural tape), and the weaving loom.

AEROSTAT FABRICATION

The flexible material sheet goods are then accurately cut into various shaped panels using full scale patterns. The panels are then bonded together using specially designed thermal impulse sealing equipment. The panel-to-panel bonds are constructed as butt joints using a two tape system--a structural tape on the inside and a weather protection TEDLAR cover tape on the outside.

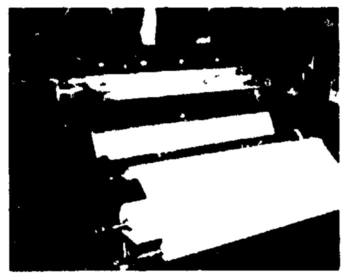


84" WIDE LAMINATOR

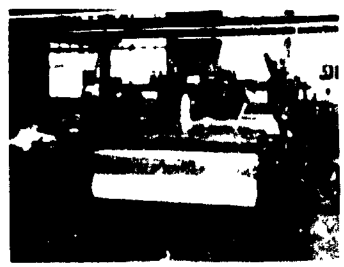
FLYING THREAD LOOM

Figure H
MATERIAL FABRICATION - SHELDAHL

TRAVELING SEALER



MATERIAL COATER



CLOTH LOOM

Figure I
AEROSTAT FABRICATION

STRUCTURAL DESIGN CRITERIA

The aerostat is designed to operate in winds to 70 knots MSL and at a constant q of 3.2 in. H_2O aloft. At 70 knots, there is a minimum factor of safety of two on fabric stresses (both direct and shear) and a factor of 1.5 on hull or fin buckling. Based on wind tunnel tests the angle of attach, α, was predicted to be ~6 degrees and this has been verified in flight tests. Additionally, the aerostat is designed to sustain 90 knot MSL winds with no structural safety factor; however, this requirement is less critical than the former. A dynamic mooring loads analysis established the nose structure load criteria of 25,000 pounds axial and 13,000 pounds side loads. A minimum factor of 1.5 is required on all metallic members. Tear propagation data for this particular material has been experimentally derived and is summarized in Figure J. During the checkout phase, each aerostat is thoroughly inspected for defects in the cloth such as burn marks; and, all such defects effecting more than 2-3 yarns are reinforced. Each aerostat is then proof pressure tested to equivalent 90 knot levels to insure that no design or fabrication defects remain. In-flight loads at 70 knots are predicted to be less critical than proof pressure loads--hence a successful proof pressure test is evidence of a reliable vehicle.

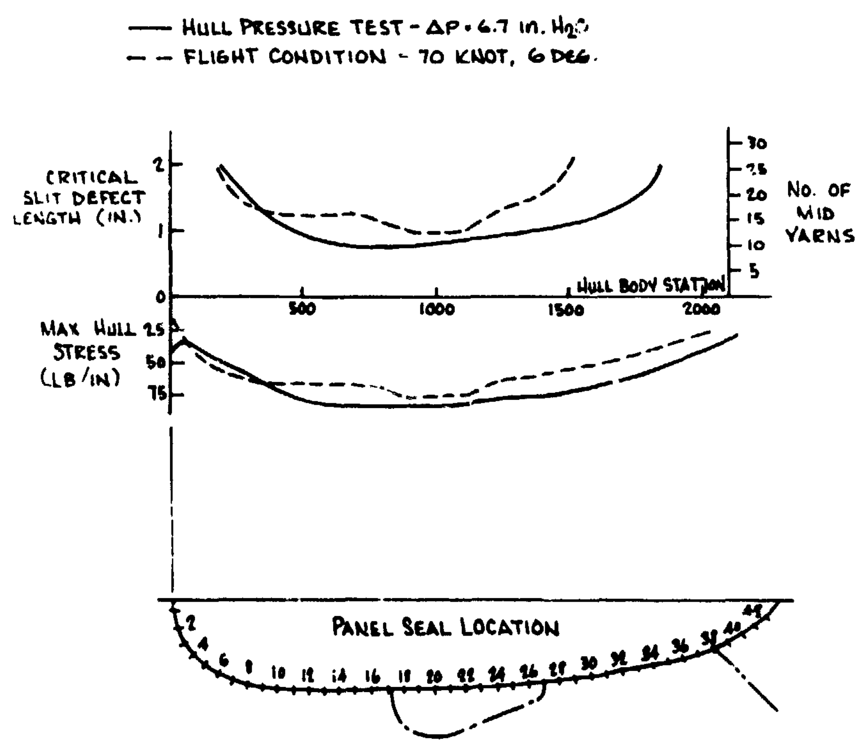


Figure J

CRITICAL DEFECT LENGTH FOR TEAR PROPAGATION OF SHELDAHL CBV-350A AEROSTAT

STRUCTURAL ANALYSIS

The principal analytical tool used in the stress and deformation analysis of fabric portions of the aerostat was the large scale finite element computer program designated LD3DX, Large Deformation Analysis of Three-Dimensional Structures Extended. The program accommodates non-linear geometry behavior and orthotropic materials. Additionally, the program is designed such that external loads (buoyancy, aerodynamic pressure, skin friction drag, tether load, etc.) can be applied sequentially as they occur in service. Figure K illustrates the gross finite element computer plot of a horizontal fin and the aerodynamic pressure distribution on the fin as established by wind tunnel tests.

MATERIALS QUALIFICATION

Every material used in Sheldahl's CBV-250 aerostat, from the hull and ballonet composites to the seal tapes and T-tapes, is tailored to its specific task. Despite the fact that each material is designed to different requirements, the design approach is the same: 1) define the requirements, and 2) perform qualification tests on the conditioned candidate materials. Figure L delineates the test equipment necessary to condition and qualify these materials and also illustrates the specially designed biaxial cylinder test machine which is used to determine the stress-strain characteristics of the composite laminate used as input to the structural analysis.

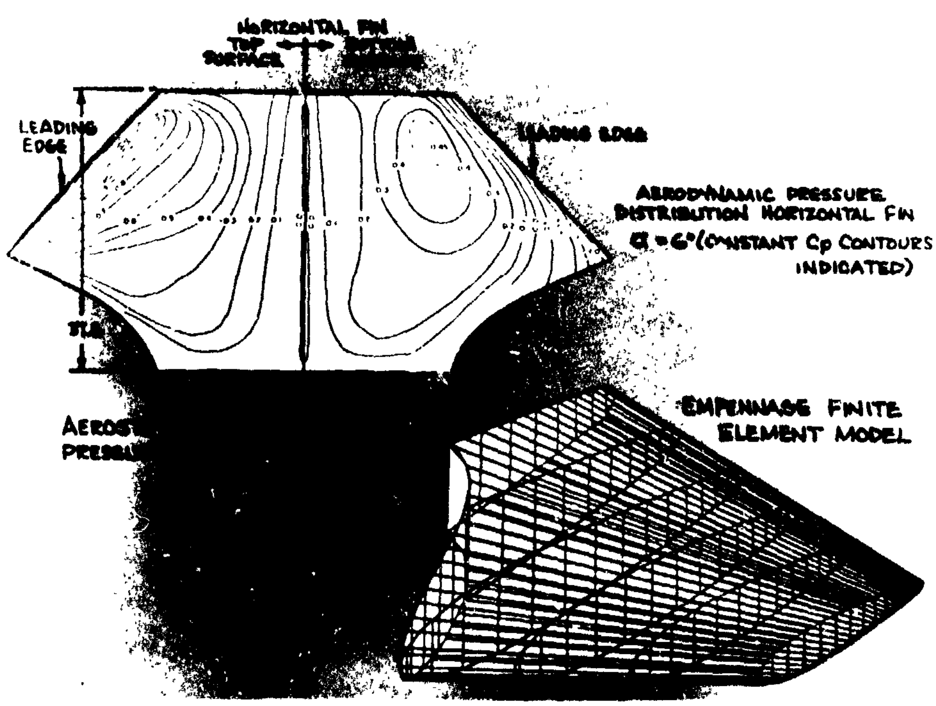
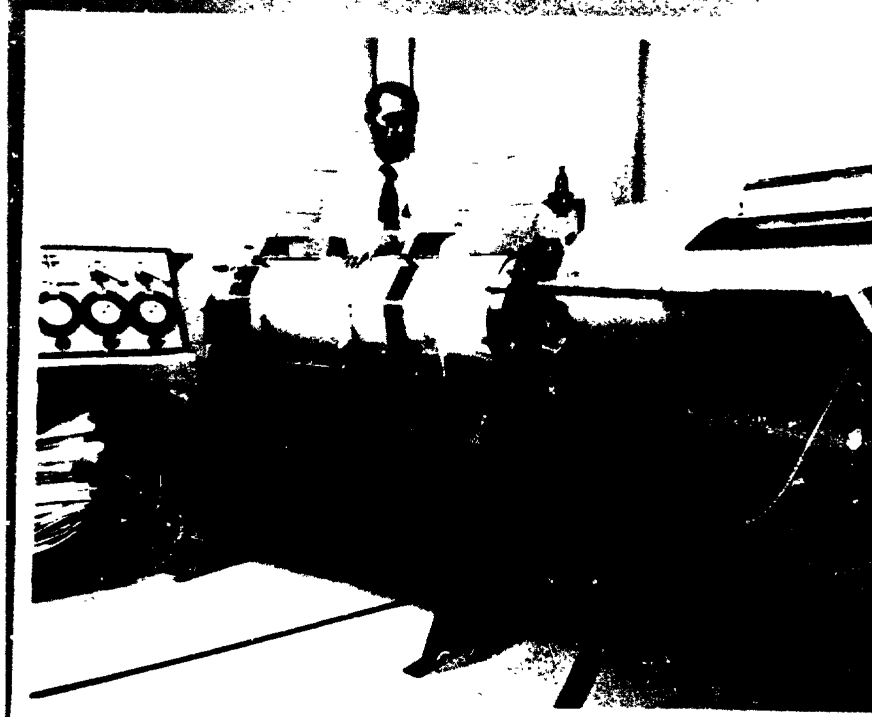


Figure K

AEROSTAT EMPENNAGE - AERODYNAMIC LOADS AND STRUCTURAL MODEL



FLEXIBLE MATERIALS CONDITIONING/QUALIFICATION TEST EQUIPMENT

	TEST ITEM	PURPOSE
1.	DIAPHRAGM PULSER, 12" DIAMETER	BIAXIAL STRESS CYCLING
2.	TWIST-FLEX	HANDLING SIMULATION
3.	PUNCTURE	PUNCTURE LOAD
4.	WEATHER DIAPHRAGMS, 18"	WEATHER AGING
5.	WALK IN OVEN 80 SQ FT	LONG TERM TESTING (150° F MAXIMUM)
6.	DISPATCH OVEN	HIGH TEMPERATURE (500° F)
7.	STATIC [illegible]	STATIC [illegible] LOAD
8.	[illegible]	CRITICAL TEAR STRENGTH
9.	CYLINDER TESTER	BIAXIAL AND SHEAR MODULI
10.	SAND ABRASION	ABRASION RESISTANCE
11.	BALLY-FLEX	CREASE LIFE
12.	COLD CHAMBER	LOW TEMPERATURE TESTING (-100° F)
13.	BAR COATER	ADHESIVE APPLICATION
14.	CYLINDER END CAPS	STATIC BIAXIAL LOAD (BURST)
15.	CABLE ABRASION	CYCLIC ABRASION

Figure L

AEROSTAT MATERIALS TEST EQUIPMENT

TECHNOLOGY ADVANCEMENT

Figure M summarizes the more significant technological advances relating to the design and fabrication of pressurized buoyant vehicles as developed during this program.

Figure M

SUMMARY OF TECHNOLOGY ADVANCES IN STRUCTURES AND MATERIALS FOR LTA (1960'S TO 1974)

	IN 1960'S	IN 1974	IMPROVEMENT
BASIC MATERIALS			
. WEATHERING LAYER	HYPALON	TEDLAR	MAINTENANCE FREE 20 YEAR LIFE AS OPPOSED TO ANNUAL MAINTENANCE
. GAS IMPERMEABLE LAYER	URETHANE OR NEOPRENE COATING	MYLAR	FROM 1.0 TO 0.5 $l/m^2/24$ HR REDUCTION IN PERMEABILITY
. STRUCTURAL CLOTH	HIGH COUNT NYLON OR DACRON	LOW COUNT DACRON	GREATER TEAR STRENGTH, BETTER DIMENSIONAL STABILITY
. BIAS STRENGTH/ STIFFNESS LAYER	BIASED NYLON/ DACRON CLOTH	MYLAR	WEIGHT REDUCTION OF 1-3 OZ/YD^2
MATERIAL COMPOSITE			
. COMPOSITE WEIGHT	12.9 OZ/YD^2	7.8 OZ/YD^2	40% DECREASE
. COMPOSITE STRENGTH	195 LBS/IN	225 LBS/IN	30% INCREASE
. ADHESIVE IMPROVEMENTS	PRIMARILY COATINGS	FILM/FILM, CLOTH/FILM	GREATER PEEL, INTERPLY SHEAR STRENGTH
. STRESS-STRAIN CHARACTERIZATION	UNIAXIAL INSTRON	BIAXIAL CYLINDER	DETERMINE SIX CONSTITUTIVE COEFFICIENTS OF COMPOSITE
. MATERIALS CONDITIONING/ QUALIFICATION	BASICALLY ASTM TESTS	MANY SPECIAL PURPOSE TESTS	RELATIVE COMPARISON OF MATERIAL CHARACTERISTICS
VEHICLE DESIGN			
. VEHICLE ENVIRONMENTAL REQUIREMENTS	LIMITED STANDARDS	MIL-STD-210B NASA-TMX-64589	ENVIRONMENTAL REQUIREMENTS FOR WORLDWIDE OPERATIONS THRU ALTITUDES OF INTEREST
. COMPUTERIZED FINITE ELEMENT STRUCTURAL ANALYSIS	NONE AVAILABLE	LD3DX COMPUTER PROGRAM	ALLOWS GROSS AND FINE ELEMENT MODELING USING ORTHOTROPIC MATERIALS AND ARBITRARY LOADS.
. LARGE, SHAPED, STRUCTURALLY SOUND EMPENNAGE	EITHER RIGID PANELS OR LIGHT WIND INFLATABLE DESIGNS	AERODYNAMICALLY SHAPED FINS	INFLATED FIN SIMULATES A NACA FIN PROFILE WITH CHORDWISE AND SPANWISE TAPER
. VEHICLE DYNAMICS	LIMITED ANALYTICAL TECHNIQUES	COMPUTER PROGRAMS PREDICT DYNAMIC RESPONSE	PREDICTIONS OF INFLIGHT STABILITY, AND INFLIGHT AND MOORED DYNAMIC LOADS
VEHICLE FABRICATION			
SEALING METHODS	HAND SEALED	100% MACHINE CONTROLLED SEALING	IMPULSE, RF, AND TRAVELING WHEEL HEAT SEALERS
. QUALITY CONTROL	LIMITED CHECKS ON SEALS	100% Q.C. INSPECTION AND PRESSURE TEST	PROOF PRESSURE TESTS VERIFY RELIABILITY OF EVERY VEHICLE
. LOAD ATTACHMENTS	UNRELIABLE PERFORMANCE OF EXISTING ATTACHMENTS	ALL LOAD ATTACHMENTS REDESIGNED AND PROOF TESTED	VIRTUALLY ALL LOAD ATTACHMENT METHODS ARE DESIGNED TO SPREAD LOADS UNIFORMLY INTO HULL

AREAS FOR FURTHER MATERIALS RESEARCH

In terms of improving the material composites for aerostats and for LTA vehicles in general, several areas require further research to improve performance and provide a more reliable product. Included are:

- Optimization of composite design in terms of strength and stiffness--tailored to a particular application at minimum weight.
- Evaluation of KEVLAR as a potential replacement for Dacron as the primary load carrying member.
- Develop fracture mechanics techniques applicable to pressurized fabric structures, and evaluate weight tradeoffs versus increased tear propagation strength.

Also, improvements in puncture resistance, sand abrasion, flexing, and thermal control would be beneficial for greater potential utility of these vehicles.

SUMMARY

While it is quite evident that much of the technology described herein is applicable to the design and development of airships, it is not quite so obvious as to what form the initial vehicle should take. If a minimum risk approach is contemplated, the following criteria are suggested:

- A semi-buoyant hybrid airship using helicopters for lift-off and in-flight control--interconnected by a rigid truss structure supported a non-rigid aerodynamically shaped pressurized hull.
- Attached to the hull for stability would be inflatable fins--designed to buckle under extreme gust loads prior to structural failure of the hull.
- Utilize the material composites and sealing techniques described herein. Employ tear stop features.
- Use a ballonet/s--which has been proven, and results in minimum hull pressure stresses.
- Utilize a pressure control system to regulate compartmental pressures.
- Plan to proof pressure test every vehicle.
- Moor at bow--allowing the vehicle to weather vane.