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The Study includes a historical overview of airships and the materials used in their construction and includes sections dealing with the following: current status of materials and their use for LTA applications; experimental work; and conclusions and recommendations.

INTRODUCTION

Under the auspices of the Naval Air Systems Command (AIR-03P3) and at the direction of the Office of the Chief of Naval Operations (OP-96V), the Air Vehicle Technology Department (AVTD) is providing technical support to the Advanced Naval Vehicles Concepts Evaluation (ANVCE).

ANVCE is a program to evaluate potential air and sea vehicles for Advanced Naval Operational Requirements (1980-2000). Lighter-Than-Air (LTA) vehicles represent one of the four main categories of air vehicles being studied.

Recent interest in the Navy has developed concerning new uses for LTA vehicles such as reconnaissance, transportation, heavy lift operations. etc. Historically, the Navy abolished its LTA program in 1961. No rigid airship has been built in the United States since 1934. The last non-rigid airship built for the Navy was constructed in 1959-1960. Other than hot air balloons, about the only LTA vehicles still in use today are the Goodyear Blimps.

During the dormancy years of the airship, no real research and development on materials for airships has taken place. Technological disciplines, however, have made large advances.

The Aero Materials Laboratory of AVTD has been requested to assess the current and projected future of material technology as applied to airships. The study includes a historical overview of airships and the materials used in their construction and sections dealing with the following: Current status of materials and their use for LTA applications; experimental work; and conclusions and recommendations. Related material specifications on the last non-rigid constructed and experimental work sponsored by ARPA under the direction of NASA are presented in Appendices A and B, respectively.

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SUMMARY

Rigid airship envelope materials are lightweight coverings primarily to provide a smooth aerodynamic shape and prevent environmental degradation of the airship system. These materials are usually well supported by the rigid skeleton and do not experience the loading stresses encountered by a non-rigid hull material. The gas cells are in the interior of the airship and provide lift.

Non-rigid airship envelope material are flexible structural fabrics which are designed to accomplish two basic functions in a pressure rigidized structure: (1) Support the internal and external structural loads; and (2) contain and protect the pressurizing medium. The primary material structural properties associated with the first function are tensile strength and dimensional stability. Air-filled ballonets are used in non-rigids for trim and pressure control.

Progress in material engineering over the last few decades has been considerable. Based upon an assessment of current technology compared to the state-of-the-art of material usage for the rigid airships in the 1930's and non-rigids in the 50's, the following conclusions, with supporting observations, have been reached.

1. The main structural requirements of LTA systems can be met, in general, by state-of-the-art materials although the development of a strong, more durable lightweight structure is needed for critical weight applications.

2. If the material is to be used primarily as a gas container, the required strength is determined by the design super-pressure and the method of transferring lift of the gas to the structure. The cyclic variations of pressure and flexing and atmospheric conditions must be anticipated and considered. The resistance of the material to manufacturing and handling damage and resistance to tearing must also be considered. Abrasion, flex resistance and impermeability are the prime requisites for ballonets and lifting gas cells.

3. When material serves as a hull and a gas container, such as in a non-rigid airship, strength and other requirements are severe. The parameters combine to exceed the properties of film laminates. Thus far, only the higher efficiencies obtained from closely spaced filamentary materials such as textiles, appear to be satisfactory.

4. Modern lifting gas cells and ballonets are available with an order of magnitude less permeability and about half the weight of the traditional rubberized cotton.

5. Advances in flexible material technology has resulted in reducing unit weight for an airship hull by approximately 50% and increasing strength by 100%.

6. Presently, two types of fabric geometry are being used to meet the requirements of dimensional stability. These are (1) Two-ply biased fabric coated on two sides and (2) Single-ply fabric bonded to a high modulus film. The double substrate coated two sides provides exceptional stability with increased tear resistance but tends to be heavy. The single substrate fabrics are generally lower in weight. In order for a single substrate fabric to have good dimensional stability, it must be combined with a film having a high modulus. This can result in a stiff material having a poor flex life.

7. Biased ply fabric evolution has led from cotton to Fortisan to nylon to polyester (Dacron). Polyesters are strong and resilent, do not crease easily and demonstrate satisfactory elongation; they absorb very little moisture and have good resistance to degradation by light.

8. The development of Kevlar represents the potential for another forward step. The exceptional strength to weight ratio of Kevlar offers advantages where weight is critical. Kevlar, however, is sensitive to ultraviolet light and has less resistance to flex fatigue at small bend radii than other organics.

9. Woven fabrics must be coated with an elastomeric material or bonded to a film of sufficient thickness to prevent high gas loss. All non-rigid airships built to date have employed the first method - a coating as the gas barrier. For two or more ply construction, the bonding of the fabrics is also accomplished by an elastomeric coating. An outer coating, often of a different material from the inner, is applied to the surface exposed to the airstream. This outer coating provides resistance to and control of environmental effects. The net result of such construction is a material which consists of about half cloth and half elastomer.

10. Thin films can be manufactured to provide a much less porous surface than can be obtained with an equal amount of elastomer. For applications where the film is only a gas barrier, such as in ballonets, the minimum gage theoretically would be limited to that required to eliminate microscopic holes and obtain a given rate of permeability.

11. Mylar film has found the greatest use in laminates because of its high tensile and shear strength and low permeability. It has the disadvantages, however, of being moderately stiff, difficult to bond and the least tear resistance of all the available films. Hytrel would seem to be a likely candidate as a substitute for Mylar since it has greater flexibility, extreme toughness and should perform well as a gas barrier.

12. Polyurethane, because of its excellent coating properties, has been used as a protective coating for single and multiply fabric structures. Recent developments of thin case films, with significant lower permeability, has increased its versatility. Urethane has superb handling characteristics but displays high creep.

13. Tedlar PVF film is the optimum material for weathering and ultraviolet stability, but suffers from problems with poor adhesion.

14. While the elongation of nylon makes it unsuitable for use as an envelope fabric, it is an optimum candidate for ballonets and lifting gas cells. The elasticity of nylon and great strength provides a high degree of crease resistance and shape retention.

15. New methods of making fabrics exist today, i.e., triaxially woven fabric and spun bonded fabric. These techniques tend to give isotropic properties in the plane of the fabric. Theoretically, this makes possible a single-ply envelope.

16. In the area of adhesives, aliphatic polyesters have shown considerable improvement over conventional, partially aromatic adhesives. Also, the linear hydroxyl-end capped amorphous polybutadienes show superior thermochemical characteristics over the aliphatic materials. Shell Kraton and Phillips 406 SBS block copolymers appear the most promising, if antioxidant and ultraviolet additives can be developed.

17. Modern 7000 series aluminum alloys are 50% stronger than those used in the 1930's and 100% better in yield strength. Corrosion resistance treatments have been developed for aluminum alloys and can be further improved by the use of epoxy primers and a polyurethane topcoat.

18. Newer construction such as sandwich materials have higher strength/weight ratios than older aluminum alloys. A sandwich material of Al skin faced Al honeycomb construction can be used at load concentration points for efficient load distribution. Sandwich construction is an excellent lightweight structure but is expensive to manufacture and difficult to maintain.

19. A major bar to the introduction of new materials in LTA is the unreliability of short term tests for predicting long term behavior. A related obstacle is the lack of data on the performance of materials and components in service. Such data are basic, not only to the use of current material but for the development of short term tests and, otherwise, predict the behavior of materials.

HISTORY AND BACKGROUND

An airship is a vehicle which may be lighter than air, neutral in air, or heavier than air but which depends substantially upon a gas - lighter than air - to obtain lift, reference (a). The vehicle must also be steerable with a propulsion system. Airships are commonly classified as non-rigid (pressurized), semi-rigid (pressurized), rigid (non-pressurized), or monocoque (pressurized). These various types are illustrated in Figure 1.

The non-rigid airship maintains its shape by internal gas pressure. Stress is borne by the envelope and internal cables. Blimps are non-rigid airships.

Semi-rigid airships are similar to the non-rigid airship with the addition of a keel member to reduce shear and bending. Additionally, the bow section is structurally stiffened.

In the rigid airship, metal girders are used to maintain the shape of the airship. The typical structural framework consists of circular rings and longitudinal members. The Zeppelin was a rigid airship covered with a fabric envelope and receiving lift from pressureless gas cells within the hull.

In the monocoque airship, the envelope provides substantial structural support, such as with a metallic covering. Pressurization may be employed to provide additional support.

The designer has to choose whether to maintain an aerodynamic configuration by means of a non-pressurized external skin supported by an internal rigid structure or by a combination of both.

A. Airship Development

The first true airship flight was made in 1852 by Henri Gifford, a Frenchman, reference (b). Other pioneers included Charles Renaid, and Captain A. C. Kreles in 1884 and Alberta Santos-Dumont, a Brazilian working in Paris in 1901.

The first rigid airship, with an interior framework for shape, was constructed in 1895 in Petrograd by David Schwartz, an Austrian. A second ship, all metal (aluminum), was constructed by Schwartz in Berlin in 1898.

On July 2, 1900, Count Ferdinand von Zeppelin and a crew of four others launched the first "Zeppelin" from Lake Constance and in 1908, the Schutte-Lanz Company launched its first airship.

In 1915, Schutte-Lanz and Zeppelin combined forces (resources and patents) to develop the L-30 class of dirigible or "super Zeppelins". They were used during World War I for raids on Allied cities and war vessels. France and Great Britain also built airships for war use, and one of these - the British R-34 - crossed the Atlantic twice shortly after World War I in 1919 - the first airship to accomplish that feat. The United States Navy operated a non-rigid airship on a number of evaluative flights in 1917 and in the same year, the Zeppelin L-59 flew a 4,000-mile nonstop round trip from Jamboli, Bulgaria to South Africa.

As part of the reparations following World War I, the United States Navy acquired the German-built Los Angeles, which it operated from 1924 to 1939.

The Germans continued with their success in dirigibles, and the LZ-127 Graf Zeppelin operated from 1928 through 1937, carrying more than 14,281 passengers and traveling more than a million miles.

The largest airship ever built, the German LZ-129, or Hindenburg, was completed in 1936. Unable to obtain helium, the Hindenburg was lifted by highly-flammable hydrogen. In May 1937, at the end of its 37th Atlantic crossing, the Hindenburg was racked by explosions and crashed at Lakehurst, New Jersey. Essentially, this was the end of the airship era, except for the non-rigids.

The Germans began to construct the LZ-130 and LZ-131 as successors to the Hindenburg, but these were abandoned when the Germans decided to concentrate on heavier-than-air aircraft for their World War II venture. One of the oddities of the era was the ZMC-2, the metalclad blimp construction for the U.S. Navy in 1929. Known as the "Tin Bubble", it had a 202,000 cubic foot hide of 0.0095 Alclad alloy. It was dismantled in 1942 at Lakehurst. Another all-metal airship was the "City of Glendale". Airship engineering for rigid types ended in 1935 in the United States and in 1938 in Germany.

The Navy operated a World War II K-class, non-rigid blimp in Air Sea Warfare (ASW) operations. These blimps were twin-engined, and ranged in size from 416,000 to 456,000 cubic feet. The final Navy non-rigids were 1.5 million cubic feet - ZPG-3 ASW airships of the late fifties. The U.S. Navy abolished its Lighter-Than-Air program in 1961. Goodyear constructed 244 blimps for the Navy and Army under contract - 55 more for commercial uses, and a 300th for use as a commercial vehicle in Europe. Besides Goodyear, Wallenkamper has produced some in Germany and delivered one to Japan.

B. Materials Used in Airship Construction

Table I presents an overview of the state-of-the-art in material usage for rigid airships in the 1930's and for non-rigids in the 1950's.

1. Rigid Airship Materials

The classical rigid airship consisted of a framework structure, an external cover, interior gas cells and auxiliary structures such as fins, crew cars, engine cars, payload accommodations, etc. The traditional materials were 17SRT aluminum for girder and frame members, and hard-drawn stud wire for rigging and bracing. The external covers were cotton and acetate doped fabric, reference (c), to provide a smooth aerodynamic shape and prevent environmental degradation of the airship system. These materials were usually well supported by the rigid framing and did not experience the severe loading stresses normally encountered by a non-rigid hull material. Anticipated aerodynamic loading conditions were used to size the requirements of envelopes for rigid airships. Table II presents physical test data on the materials used in LTA applications in the 30's, reference (d).

2. Non-Rigid Airship Materials

The non-rigid airship incorporates the load carrying structure and the external cover in a single flexible unit, stabilized by interior pressure and using air filled ballonets for pressure control.

Aviation pioneers used laminated fabrics to construct non-rigid airships for the first steerable air flights, reference (e). To solve the problems of the changing shape (elongation) and bending of these early airships, studies of weave design and biaxial loading effects were made in the years 1910 to 1913. From these studies developed high strength cloth, woven in plain and basket weave, diagonal laminations to control elongation and the use of left and right bias laminations in alternate panels. These improvements in fabric design helped eliminate elongation problems.

Since larger airships could be more readily designed in the rigid type airships, little development work was done on non-rigid airships until World War II. The bonded fabric used in non-rigid airships of 1940 to 1950 was similar to the earlier materials, Table II, except that neoprene was used in place of natural rubber.

The fabric envelope served as a gas-proof container for the lifting gas, reference (f). The envelope consisted essentially of the main envelope panels; fabric ballonets in the envelope; air lines for ducting air to and from the ballonets; sleeves for dampers, air valves and gas valves; internal and external catenary curtains for the airship suspension cable system; car fairing for streamlining the car with the envelope; catenaries and fan patches for ground handling lines and empennage; and miscellaneous provisions for bow stiffening, instruments and equipment. Rip panel(s) were incorporated in the top surface of the envelope to allow emergency release of gas. The envelope fabrics were required to withstand the static stresses caused by the envelope gas pressure; the dynamic stresses developed in-flight; the transverse, vertical and longitudinal stresses caused by the suspension of the car and empennage; and the destructive effects of weathering.

The development of larger airships was necessitated by the use of electronics for submarine detection and employing airships as mobile radar in the early warning network. These airships were required to be in-flight for longer continuous periods. As a result, the fabric received considerable more environmental exposure. The large size of these airships resulted in considerable loss of helium. The laminated cotton fabric had a loss of 1/8 cubic foot per square yard per 24 hours. The high strength fabric requirement for these airships was met by a bias-plied cotton fabric, Figure 2. A 6.0 oz/sq yd cotton fabric was used for both plies of the fabric for the ZPG-2W early warning airship of 1,000,000 cubic foot volume. A 7.5 and 8.0 oz/yd^2 cloth was used for the ZPG-3W airship of 1,500,000 cubic foot capacity. The heavier cotton yarns in these cloths produced a rough surface necessitating increasing amounts of coatings to provide adequate permeability and weather resistance. The weights of these bias-ply coated fabrics were approximately 20 oz/yd^2. To cut down on the use of increased coatings, work was directed to the selection of high strength to weight synthetic textiles yarns of a smoother nature.

a. Yarn

Nylon, Dacron polyester and Fortisan fibers were considered, Figure 3. The strongest fiber is nylon, nearly twice as strong as cotton. The strength of Dacron and Fortisan are approximately equal, 6 to 7 grams per denier on a strength to weight basis; only slightly lower than nylon. Strengthwise, laminated fabrics of any of these synthetic yarns would have been satisfactory. As a matter of fact, airship envelopes were made of each.

The strength of textile materials is affected by atmospheric conditions, Table III. Moisture has an appreciable effect; nylon loses 10% and Fortisan loses 15% when wet. The strength of Dacron is unaffected by moisture while the strength of cotton increases by 10-30%.

The effect of temperature is important when evaluating laminated fabrics for use in airships; softening of the fiber or loss of adhesion can reduce strength at high temperatures. Laminated fabrics of Fortisan were found to have a 40% loss in strength and a 50% loss in adhesion when tested at 140°F. Strength and adhesion at room temperature on Fortisan fabric (after exposure at 150°F for 6 days) showed no loss in strength; test results were equal to the initial test values.

Another basic property for an airship fabric is low elongation. Cotton and Fortisan have approximately 6 to 7% elongation at ultimate strength. The elongation of nylon and Dacron fibers depend upon the degree of orientation received during manufacture. The high tenacity Dacron has approximately 14% elongation compared to 19-20% elongation for high tenacity nylon, reference (g).

The stress strain curve for Dacron, Figure 3, however, shows that the major portion of the elongation occurs after 85% of the ultimate load has been applied. Thus, under operating load conditions, the elongation of Dacron cloth would be less than that of a cotton cloth.

Fiber elongation also affects flex and crease resistant properties. Bending yarns of low elongation fibers will stress the fibers beyond their rupture point. This effect was moderately severe on Fortisan yarns. Large envelope size will result in considerable creasing and folding during manufacture and erection. For this reason, Fortisan cloth was not considered for large size envelopes. In addition, Fortisan and cotton were both subject to attack by fungi and bacteria, including mildew.

b. Fabric and Geometry

The cloth properties are governed by the strength necessary to conform to airship design requirements. Since envelope weight subtracts from the available lift, the envelope cannot be subjected to a high weight disadvantage resulting from high factors of safety. The maximum operating pressure in an envelope is designed to set fabric stress at 25% of the fabric's ultimate strength. This strength is determined on cylinders 8 inches in diameter and 15 inches long, tested under rapid loading of 5 to 10 seconds. Time load studies based on 1 x 6 inch specimens have indicated that application of the maximum designed load for 8 to 10 years would cause failure. However, maximum loads are only applied for short periods (1 minute) and specimens removed from airships have not shown strength losses that could be attributed to sustained loads.

The airship for which an improved fabric was initially desired was the ZA2G-1 design. This envelope has a total length of 282 feet, a maximum diameter of 67 feet, and a volume of 650,000 cubic feet. The fabric stress is at a maximum during ascent when the gas pressure is at 3.5 inches of water. The fabric stress under these conditions is 66 pounds per inch in warp and 58 pounds per inch in filling. Therefore, the nominal strength requirement in the directions of the inner (straight) cloth is 265 pounds per inch in warp and 220 pounds per inch in filling. This is equivalent to loads of 12,000 to 15,000 psi. The cotton cloth previously used for both plies in the laminated fabric weighed five ounches per square yard and was woven in a 4 x 1 twill weave.

The nominal weight of this laminated fabric was 18.8 ounces per square yard of which 6 ounces per square yard consisted of neoprene between the plies.

The properties of a cloth are affected by its weave as it governs the surface characteristics and yarn interaction. Cloth permeability, adhesion of the coating, weather resistance, and breaking resistance strength and elongation are modified by the weave. The type of yarn and degree of twist also affect surface characteristics. Selection of cloth details must be based on a combination of factors and no one construction can be said to be the optimum.

The desired cloth construction from a manufacturing aspect is one that would permit its use in both plies. The unavailability of yarns of suitable strengths and deniers to obtain desired strength and optimum surface conditions prevented this type of construction. Thus, a heavier cloth for the straight direction was developed. This cloth weighed 4.35 ounces per square yard and was woven in 2 x 2 basket weave from type 51 Dacron. The nominal breaking strength by the strip method was 205 pounds per inch in warp and filling directions. A cloth weighing 3.35 ounches per square yard and woven in a 3 x 2 twill weave from type 55 Dacron was developed for the outer ply. This cloth had a strength of 110 pounds in the warp and 100 pounds in the filling. The strength of the outer bias cloth is proportionately lower than that of the inner cloth since high strength type 51 Dacron yarns of the necessary denier were not available. Usually, there was a greater number of warp than fill yarns per unit area of airship cloth. As a result, tensile strength in the warp direction was normally stronger than the fill direction. The weaving process produced greater resistance to elongation in the warp direction. Consequently, airship cloth was both stronger and less liable to distort in the warp direction.

Most two ply envelopes were constructed of a biased ply construction. The biasing operation not only dimensionally stabilizes the structural fabric, but also reduces the tendency of the fabric to distort in the fill direction. At the same time, the two ply construction increased the fabric tear strength.

c. Elastomers

A considerable variety of elastomer coatings have been used to provide a good gas barrier in the constructions of fabrics for the hull and ballonets.

In the 20's, gas cells of the rigid airships were made of hundreds of thousands of gold beater's skins, the prepared outside membrane of the large intestine of cattle, reference (a). The goldbeater's skins were cemented to a high strength, low weight cotton cloth. The skins had to be washed, scrapped, and otherwise thoroughly cleansed of any fat or dirt before they could be applied to the cotton cloth. While awaiting application, they had to be kept in a solution of water and glycerine, requiring that they be wrung out by hand before cementing. A technique for applying the skins to the fabric had to be developed. After considerable experimentation, rubber cement was selected as the adhesive. Following cementing, the skins were given a light coating of varnish. Goldbeater's skins, so-called because of their use in beating and separating Gold leaf, were at the time one of the most gas-impervious materials known, Table II.

A flexible gelatine compound was developed by the U.S. Bureau of Standards. When applied to a rubber surface and tested in the laboratory for permeability, a test result of 0.8 $1/m^2/24$ hours was obtained. In actual use during the 30's, the permeability of the gel latex coating was 2.0 $1/m^2/24$ hours, Table II.

Natural rubber was used to provide a good gas barrier for many years. The natural rubber was used between cotton plies and as a coating for the interior and exterior of the fabric. The low modulus and strength to weight ratio of the cotton base cloth and the rather large amount of rubber required to ensure acceptable levels of helium permeability resulted in laminated materials weighing from 16 to 20 oz/yd^2 with tensile strength on the order of 60 lbs/in. The permeability was on the order of 15 $l/m^2/24$ hours, Table II.

Advancements in materials led to the replacement of natural rubber with neoprene, a synthetic rubber with many of the properties of natural rubber.

Figure 2 shows the construction of fabric used for the early barrage balloons and for airships hulls of the 50's using neoprene as the gas barrier. The material was a cotton structural fabric with neoprene outer coating and neoprene between the straight and bias ply fabric. The strength varied with weight. The permeability was between 2.5 to 3.0 $\ell/m^2/24$ hours. The material was quite durable.

The smooth surface of continuous Dacron filament yarns produce a flatter fabric. Less coating is needed on Dacron cloths for permeability and weathering resistance. In order to improve weather resistance of this Dacron fabric, the outer surfaces were coated more heavily than is customary with cotton airship fabrics. In addition, the aluminized coating layer was compounded of chlorosulfonated polyethylene known commercially as Hypalon. This coating has good ozone resistance and provided good weather resistance.

This laminated fabric of Dacron had a slightly higher cylinder bursting strength, half the permeability, and weighed approximately 3.0 ounces per square yard less than the comparable cotton laminated fabric. This weight reduction resulted in a weight saving of slightly over 800 pounds for a ZS2G-1 envelope. The weight reductions on larger airships were greater, as high tenacity yarns were used in both plies. Studies were made to determine the minimum coating weight for permeability and weathering properties.

The permeability of the laminated fabric can be affected by the shearing stresses applied during service. Some fabrics developed for airship envelopes, have shown a considerable increase in permeability when tested under tension. When the tension is removed, the fabric rapidly returns to a low permeability state. The tensions in this test are applied in the warp and filling direction of the inner cloth. Thus, the shear stresses on the inner coating layer are small. To increase coating shear stresses, a test axis of 30° to the filling of the inner cloth was selected for a cyclic application of load. This direction was used, as elongation of the fabric is higher since the load is carried by filling yarns of both plies. The specimen was cut in a "dumbbell" shape 6 inches wide at the 4 inch long central portion and flared out to a 10-inch width at the ends. A load equal to 25% of the breaking load of an identical specimen was applied at 30 cycles a minute. A total of 10,000 cycles were applied with the specimen at 140°F. The permeability of fabrics subjected to this cyclic test showed good correlation with permeability of similar constructed fabrics removed from airships.

The evaluation procedures performed on the Dacron laminated fabrics were based on conditions occurring during airship service. In-service, however, these various conditions usually occur simultaneously and are not duplicated by various combinations of laboratory tests. Thus, exposure in-service was necessary for a complete evaluation.

Actual records indicated that the loss of helium was considerably less in the Dacron envelopes than that experienced with the cotton laminated airship fabric. Dacron laminated fabrics were used to make the last few airships made for the Navy. Even today, Goodyear makes 200,000 cubic foot volume airships of Dacron and neoprene.

Each material from the hull and ballonet materials to the seal tapes and T tapes was tailored to its specific task. The requirements for each material differ. Appendix A reflects the varied materials used to meet specific tasks.

d. Fabrication

Fabric was cut into panel segments which were cemented, sewed and taped together to form the airship envelope. The panels formed a series of equal gores extending lengthwise from bow to stern; each gore was delineated by a longitudinal seam of the envelope. The panels also formed a series of rings around the envelope; delineated by the circumferential seams.

The ballonets were constructed of fabric panels which were not sewed but cemented and taped together. The deflated ballonet would be flat against the ineer contour of the envelope. Ballonet shoes cemented the ballonets and envelope securely in place.

The cleaning, priming and bonding operations for making the above joints were both time-consuming and costly.

3. Metalclad Airship Materials

The metalclad concept is more akin to the non-rigid blimp than to the classical rigid airship:

The metalclad airship exemplified by the Navy ZMC-2 used a pressure stabilized metal shell of 0.0095 24 ST Alclad. A few frames of 24 ST and wire bracing were incorporated for interior support.

Ballonets were constructed of woven pima cotton and were coated on both sides with neoprene and weighed 18.4 oz/yd^2. The warp tensile strength was 140-150 lbs/in. and permeability varied from 4.0 - 5.0 $\ell/m^2/24$ hours. These ballonets were heavy and cumbersome to handle.

C. Recent Inspection of Non-Rigid Airship Envelopes

The Navy discontinued the use of airships as operational aircraft in June 1961 and placed the airship components in storage at NAS, Lakehurst, New Jersey. During the intervening years, all but two of the airship envelopes were scrapped. The remaining airship envelopes were a ZPG-3W and a ZPG-2. The ZPG-3W envelope was a cotton fabric type 1,496,000 cubic feet in volume, with manufacturer's Serial Number D-621. The ZPG-2 was a 975,000 cubic foot Dacron (polyester) type, Serial Number GDC-5.

These envelopes were stored in the envelope storage fingers of the Fabric Shop, Building No. 123, which were specifically designed for such a purpose and was originally equipped to maintain controlled environmental conditions. During the years of storage, however, efforts to furnish a controlled atmosphere stopped and the air conditioning equipment had been removed. In addition, the building itself was in need of repair. Hence, both envelopes were subjected to temperature and humidity variations produced by climatic changes and to accumulations of rainwater from leaks in the roof.

Because of recent interest in the Navy in new uses for LTA vehicles, a possible need was seen for employing the stored envelopes in experimental programs. Preliminary examinations of the envelopes were made while they were in storage. These included removal of a few specimens of fabric for physical tests. On the basis of these tests, and the visual appearance of the fabric, it was concluded that a full and detailed inspection was warranted to determine airworthiness and the NAVAIRDEVCEN (Naval Air Development Center) was charged by the NAVAIRSYSCOM (Naval Air Systems Command) (AIR-03P3) to conduct the inspection, reference (o).

The detailed inspection was performed primarily by personnel from NAVAIRDEVCEN and National Aeronautics and Space Administration Headquarters, assisted by personnel from the United States Air Force Range Measurement Laboratory.

On removal from storage and during the "unrolling", the ZPG-3W cotton hull was found to contain large quantities of water within the folds, especially concentrated on the top center area. The forward and aft ends had been folded into and laid on the center top.

The aft end of the envelope had the characteristic musty smell of mildew and the fabric was uniformly stained with the naturally produced pigments of mildew. Mildew had fed on the cotton fibers of the aft end completely rotting and weakening the fabric.

Other fabric areas, in contact with water, were similarly stained but to a less degree. Sample fabric discs were removed from both stained and unstained areas. Physical tests confirmed the degradation of the strength in the stained areas, Table IV.

The decision was made to scrap the ZPG-3W envelope and to validate the airworthiness of the ZPG-2 Dacron envelope, (GDC-5).

On removal from storage, and after the unrolling, the center top of the ZPG-2 hull (GDC-5) was found to be wet The inspection consisted of internal and external examination and removal and test of specimens. The GDC-5 envelope was in good condition generally. An area of the upper surface exhibited low interply adhesion, Table V.

CURRENT STATUS OF MATERIALS AND THEIR DEVELOPMENT FOR LTA APPLICATIONS

As long as a LTA vehicle requires buoyancy or static lift for any part of the mission, there will be certain features common to all in terms of material requirements. These requirements stem from the fact that buoyancy of any usable amount requires large displacement. All LTA aircraft will be large vehicles, always exceeding in size any of their heavier than air counterparts by at least several factors, reference (h).

Large size or volume is accompanied by large surface areas on which unit air loads are low, much lower than normal airplane surfaces carry. Ultra lightweight structural design is required to provide the external contours of such vehicles without sacrificing lifting efficiency. The need for fabrics, lightweight high-stiffness structural members, etc., is well established. Minimum material gage is often a problem in design and construction.

Since airships are pressure sensitive vehicles, there is usually a need for at least part of the gas container to be capable of volume changes and to be constructed of flexible material.

If the material is to be used primarily as a gas container, the required strength would be determined by the design super-pressure and the method of transferring lift of the gas to the structure. The cyclic variations of pressure and flexing and atmospheric conditions must be anticipated and considered. Some thought must also be given to the resistance of the material to manufacturing and handling damage and resistance to tearing.

When material is required to serve as hull structure as well as gas container, such as in a non-rigid airship, strength and other requirements are considerably more severe. The stresses are higher, the environmental effects are a major factor and gas retention becomes a serious problem.

Since flexible materials find use in both rigid and non-rigid airship construction, the current status of these materials will be discussed first:

A. Flexible Materials

1. Yarn Candidates

While cotton and Fortisan yarns dominated early LTA applications, these were obsoleted by the introduction of high strength nylon and polyester Dacron yarns. In addition to higher strength to weight, both yarns showed improved resistance to abrasion, heat and mildew attack, Table III.

A more recent development in yarns for high strength to weight applications are the Aramids. Kevlar 29, one of the Aramids, has been the most advanced structural yarn being used in Aerostat applications, reference (e). Typical mechanical properties of twisted Kevlar 29 are shown in Table VI compared with other organic fibers. Stress strain curves are presented in Figure 4. Kevlar 29 has twice the strength of other organics and nearly an order of magnitude higher modulus.

Stress strain curves for nylon and Dacron, like most organic fibers, show a linear portion at lower stresses and non-linear portion at higher stresses. Kevlar is an exception in that its stress strain curve is linear regardless of stress.

Materials which show no linearity on their strain curve are not acceptable for airship envelopes. Uncontrolled stretch results in distortion of the envelope shape which affects the aerodynamic performance of the airship. It also produces severe problems with the rigid components which are attached to the envelope such as nose stiffening, suspension systems, cars, fins, etc. This is the reason why polyester Dacron yarns are usually preferred to the use of nylon; nylon has better tensile strength but greater stretch. The polyester fabrics, such as Dacron, demonstrated satisfactory elongation and are standard for use in most airships and tethered balloons today.

2. Fabric Geometry

Currently, there are two basic methods of designing materials for structural integrity, (1) multiple ply coated material, and (2) single ply with film or coating. Each will be discussed separately.

a. Multiple Ply Coated Fabric

(1) Bias Ply Construction

Textiles have been conventionally woven of two sets of threads or yarns crossing each other in an orthogonal pattern. The warp yarns extend the length of the roll; fill yarns are woven across these warp yarns. Orthogonally woven fabrics are effective in transmitting stress in their respective directions, warp and fill, but not in any diagonal direction such as the bias. Such weaves are considered to be dimensionally unstable. The usual solution to providing dimensional stability was to bond two or more plies of cloth together such that one is oriented 45° to the other. The bias plying of one fabric to another places a major axis in all directions and dimensional stability is achieved. The dimensional stability or shear stiffness afforded by the biasing operation can be illustrated by Table VII showing shear stiffness of several fabrics both before and after biasing. Figure 5 illustrates the yarn orientation of a two ply biased material.

(2) Spun-Bonded Construction

A second method which can be utilized to achieve dimensional stability is to ply a spun-bonded fabric to the structural fabric. Spun-bonded is a generic term coined to differentiate it from other textile materials. Spun-bonded fabric is a sheet structure made with continuous filaments which are formed into a sheet or web and then bonded into position.

The filaments are bonded together at the crosspoints and these bonds hold the fibers together in the sheet-like structure. This provides a uniform appearance and good cover or hiding power coupled with high porosity. Photomicrographs of the structure reveal that they are fine webs of randomly arranged continuous filament fibers. Use of this type of fabric affords high tear and tensile strength.

Random fiber arrangement gives the structure its isotropic nature.

The distinctive characteristics of spun-bonded fabrics include high tensile strength, optimal fiber orientation, outstanding tear strength and toughness, and excellent dimensional stability. The advantage of utilizing spun-bonded fabrics in place of very lighweight orthogonal fabric to dimensionally stabilize the structural fabric is that no biasing operation is necessary. Figure 6 illustrates this construction. The advantage of no biasing realizes a savings in cost and laminating time and requires fabrication of only a single fabric, that is, no left or right hand bias.

b. Single ply with film

Another material construction which can be used to increase the dimensional stability of an orthogonal base fabric involves the lamination of an unsupported high modulus film to the base substrate. In this construction, the high modulus film is analogous to the bias ply previously described and must lock the fabrics rectangular weave geometry and prevent yarn slippage and distortion. In this construction, the film provides a tensile member in the bias direction.

The effectiveness of a film reinforced orthogonal fabric is very dependent upon the ply adhesion between the substrates. If this adhesion is low, ply separation can occur resulting in an unstable fabric. Tests run on sample materials, Table VIII, using this stabilizing technique has indicated that several layers of high modulus film are required to achieve a marked improvement in a fabrics resistance to bias distortion.

c. Triaxially Woven Construction

A recent patented development, Doweave, provides for transfer of stress in the bias direction by having three yarn sets. The three threads are intermeshed in a single fabric to provide quasisotropic properties and eliminate the need for bonding two or more plies together. Theoretically, this should make possible the construction of single ply envelopes.

In the triaxial fabric, the yarns of the three yarn system are oriented 60 degrees apart as shown in Figure 7. As a result of this construction, the fabric yarn geometry forms triangular intersections which serve to prevent bias distortion, insure dimensional stability, and increase tear strength over comparable biaxial fabric.

The basic-weave, the simplest triaxial configuration, has no counterpart in conventional fabric construction. The yarn courses are not interwoven at all; they do not pass alternately over and under each other. The horizontal yarns are over all the "eleven o'clock yarns" and under all the "one o'clock yarns"; the "elevens" are also over all the "ones", as shown in Figure 7. If the warp simply lays on top of the fill throughout the fabric, no weave would exist to hold them together.

In contrast to the incomplete instability of a lay-up of two yarns, the basic-weave is stable both in the small and in the large. In the small, the locking characteristic of the yarn cross-overs resists sideways slippage of any of the yarn courses. In the large, the triaxial symmetry is such that there is no bias direction at all, and for the first time, a fabric can approach isotropy. Such a fabric provides essentially uniform resistance to distortion in all directions.

d. Other Reinforced Films

The basic concept of laminating a conventional biaxial base fabric to a high modulus film was extended in an effort to improve bias strength and stability. Although this research was done primarily on materials for free balloon applications, it is presented here to illustrate the importance of bias strength and the effects of bias reinforcement on the behavior of a composite balloon material.

This bias reinforced material was produced on the Flying Thread Loom (FTL) developed by Sheldahl. In this process, a high modulus film was used as a base. As the film passes through the FTL, individual yarns impregnated with a polyester adhesive were laminated to the film at various angles. Three basic yarn directions are used simultaneously to yield a triangular reinforcement pattern. Experiments were conducted on several yarn orientation systems and it was found that the most favorable configuration was the placement of yarn 60° apart such that a equilateral pattern was formed. The results of the preliminary testing of this construction provides encouraging results. Although these materials were very open weaves (only 1 to 4 yarns per inch) and were not sizes for application in large pressurized airships, the results of preliminary tests indicated that multiple yarn systems could provide significant improvements in the dimensional stability of balloon materials.

In the flying thread scrim, for optimum results, the yarns are laid at 60° angles. The yarns, however, are not interwoven but rather mechanically bonded with adhesive, Figure 8.

This bonding is especially complicated when all three yarns cross at one point. Triaxially woven fabric which, although not interwoven, is interlocked.

The need for a continuous film to reinforce such non-wovens in shear has been generally recognized and provided. The more complicated problems of "coupling" between extentional and bending (perhaps better described as "curling") distortions of a three layer-non-woven have been mostly unresolved. The dissymmetries, produced by yarns running in different directions at different levels, make more difficult the achievement and maintenance of wrinkle-free surfaces even in broad areas of simple shape.

3. Elastomeric Candidates

Low permeability to the lifting gas is a general requirement for the hull fabrics and ballonets of non-rigid aerostats and for ballonets of rigid aerostats. Primarily, elastomers are used to render fabric constructions impermeable to the inflation gas. A second function of an elastomer coating is to protect the fabric yarns from abrasion and degradation by handling an environmental exposure.

In practice today, more than one elastomer is normally used with each having a prime function. In lightweight construction, where static and dynamic stresses are low, or where weight is critical, one or two elastomers having a balance of properties may be used. In heavier constructions, and when long service life is important, three or more elastomers may be used.

Table IX provides a matrix for selection based on specific characteristics of the various elastomers. By weighing the values in the table according to the priority in end use, selection can be made. In the final analysis, however, past performance fabrication and testing will establish those combinations which are most feasible in production and provide the best all around performance in specific applications.

4. Film Candidates

During the 1950's, a balloon form was developed - the natural shape. The contour of the envelope was determined by the gas head pressure and resulted in all stresses being carried in the vertical direction. Theoretically, there would be zero circumferential (parallel to equator) tension. Such design enabled use of oriented polyethylene and later use of vertical tapes.

A great deal of work was done in the 1960's to develop unmanned balloon systems for scientific experimentation and military operation. The high altitude scientific balloon used film as the envelope.

One parameter peculiar to balloons of this type, which does not necessarily apply to airships, is that of high altitude environment. In such an environment, the envelope is directly exposed to low temperatures and high ultraviolet radiation.

The development of very thin films of significantly higher strength and very low permeability together with the technology of bonding these films to themselves, other films and fabrics have resulted in a totally new concept in envelope construction; the lamination of an unsupported high modulus film to a base substrate. Some reference was made to this material construction under the discussion of fabric geometry.

A number of candidate films for LTA applications exist, Table X. Those with the most promising characteristics are as follows:

a. Mylar

Mylar, because of its high tensile and shear strength and low permeability properties, is used predominately in either very thin unsupported film structures or as thin films laminated to lightweight Dacron and Kevlar scrims. It has excellent quality and can be obtained in oriented strength. It has the disadvantage, however, of being moderately stiff, difficult to bond and possesses the least tear resistance, reference (j). Its application in laminated constructions, however, appears to be limited due to destructive shear forces which develop in the adhesive bond as film and fabric strength increase.

b. Hytrel

Hytrel is beginning to appear as a substitute for Mylar. It has greater flexibility and extreme toughness and should perform as well as gas barriers.

c. Nylon

Nylon films are competitive with Mylar films and have similar applications. The lower modulus and improved bonding characteristics make the nylon films more compatible to laminated structures. As such, they are most effective in the transition area between very light systems and the heavier multi-ply fabric structures.

d. Polyurethane

Polyurethane, because of its excellent physical properties, has been used as a protective coating for single and multi-ply fabric structures. More recent development of thin case films of significantly lower permeability and even better physical properties, has increased its versatility. It is not only readily bonded to itself but can be thermally bonded to a wide variety of fabrics and other films.

Urethane displays high creep behavior but has superb handle characteristics. In fact, polyurethane films are superior to elastomeric coating in tensile strength, tear strength and abrasion resistance. The urethane has a less useful temperature range than either Mylar or Nylon.

e. Tedlar

Tedlar films cannot be compared in its physical properties to Mylar, nylon or polyurethane. Tedlar, however, possesses the unique property of being totally resistant to UV radiation or other forms of natural aging. Even in very thin films, Tedlar effectively blocks penetration of UV to underlying structures. In real-time outdoor exposure tests, Tedlar surpassed all other standards of evaluation. Tedlar suffers from some problems with poor adhesion but it has been effectively laminated to most films and elastomers and should be considered for the exterior of any LTA system in which long service life is required.

Higher strength films are obtained by reinforcing with some kind of filament, usually bonded to the film and oriented in an orthotropic pattern. Table XI lists a few examples of films and their characteristics. It is anticipated that similar constructions to these reinforced balloon films will find use as gas cells, reference (h). Reinforced films are also much more difficult to tear.

Polyethylene film was used exclusively for early high altitude balloon experiments and is still used extensively. Polyethylene film is noted for its low cost. Its mechanical properties are also low. Nevertheless, when used conservatively in designs, it has performed successfully at a minimum cost. The relatively high permeability of this film and inability to bond to other materials, however, makes it unsuitable for advanced LTA systems such as airships. Polyethylene has, in addition, a short life in UV radiation.

5. Adhesive Candidates

In most of the balloon applications, the materials fabricated are dependent upon constructing and assembling of films, fibers and fabrics by use of suitable adhesives. Figure 9 shows typical fabrication of contemporary lightweight and heavy-weight balloon fabrics. The Dacron yarn reinforced Mylar film shown in figure 9a weighing approximately 41 gm/m^2 (1.2 oz/yd^2) is a typical lightweight material used in natural shapes (onion shapes) high altitude balloons of sizes up to $1 \times 10^6 m^3$ (35×10^6 ft^3). Figure 9b shows the multi-layer laminate used for aerodynamic shaped tethered balloon (blimp shape) that ranges in sizes up to $5.7 \times 10^3 m^3$ (2×10^5 ft^3). Adhesives are used to attach the reinforcement fiber or to combine the films and incapsulate the structural fabric as in the case of the heavy-weight laminate.

For high altitude and polar uses, these composite materials are subjected to a severe environment of winds, ultra-violet radiation and temperature ranges from 100° to -50°C in the Artic and -70°C in the tropopause region of the upper atmosphere.

Both flight experience and laboratory experiments have indicated that the structural integrities of such fabrication are greatly degraded by material embrittlement at low temperatures, references (j) and (k). Furthermore, it has been found that the adhesives show embrittlement far in excess of the base films and are suspected of initiating material failures. Lack of continuity and homogenity in the application of adhesive were apparent in a microscopy study of low temperature. In sub-zero environments, discontinuities and geometric changes, combined with the fracture sensitive embrittled adhesive, produced premature stress failure that propagated in the film.

Photomicrography of films revealed the conditions shown in Figure 10. Figure 10a shows the film surface after coating with a thin film of adhesive. The highly discontinuous surface is attributed to "roller kiss". Figure 10b shows the splotchy spattered membrane that results from laminating roller coated yarns on untreated films. Figure 10c shows the impressions left by the roller. Tests at Langley Research Center (LRC) made with roller coated yarns showed obvious degradation at cold temperatures that led to rejection of that method of fabrication. Films precoated with thermoplastic adhesive and laminated with uncoated yarns showed better homogeneity of the product and yielded better mechanical properties. These findings led to studies to either maintain the laminations above tropopause temperatures or to make them tolerant to the environment.

Investigation of the thermal characteristics of the typical lightweight reinforced films used in high altitude ballooning have shown that the adhesive embrittlement problems can be alleviated by daytime launches of balloons with tinted films to increase absorption of solar radiation. For example, on Figure 11, the temperature history is shown for a clear Mylar film balloon as it ascends to an altitude of 37 km (120,000 ft.). Also shown is the temperature history for the same film tinted with only 1% carbon black; this raises the ratio of absorptivity to emission from 0.14 to 0.87. The effect is to raise the minimum film temperatures in the tropopause from -69°C to -40°C. Light tinting can effectively control the film temperature on both the sunny and shaded sides.

The increased absorptivity, however, results in superheating which increases ascent rates and over-altitudes unless helium is rapidly vented. Cooling at night would result in large losses in altitude unless quantitites of ballast are dropped. Consequently, modifications to the thermal characteristics of the materials must be accompanied by appropriate changes in other systems.

The critical materials problem is encountered in the tropopause prior to the balloon reaching its fully inflated shape. The flapping and ruddering mode of behavior of the folded material is particularly adverse for the material in the embrittled state. A potential solution to the mission impact due to tinting is to tint with sublimating or photochromic material. If the proper time phasing can be achieved, the tint could sublime or the chromic change would occur by the time the mission acquires float altitude.

A second approach to solving the tropopause embrittlement problem is to obtain or modify the thermochemical properties of the adhesives such that the glass transition occurs below the tropopause minimum temperature.

The thermomechanical transitions are readily observed from the amplitude and frequency data obtained from Torsional Braid Analyses. A braid impregnated in the polymer to be characterized is mounted in a controllable environment to form a torsional pendulum. The pendulum is excited and the temperature related changes in elastic properties of the polymer braid are deduced from the torsional frequency and amplitude decay. Data of this sort are shown in Figure 12 for four types of polymers. At the top of the figure the thermomechanical stiffness (rigidity) spectra are shown for aromatic, aliphatic, polybutadiene, and styrene-butadiene-styrene polymers. Various compounds in each of these polymer classes were evaluated by the torsional braid method and in the sequence of the listing. Most conventional balloon adhesives are partially aromatic polymers. Early research indicated considerable improvement could be had in lowering the glass transition by employing aliphatic materials. This transition is evidenced on the figure by approximately one order of magnitude increase in rigidity as temperature is lowered.

The related damping data shown on the bottom of Figure 12 provides a second method of defining the transition points. In some respects, the temperatures of interest are made more salient by the sudden peaks in damping associated with the midrange of the glass transition.

Of the four industrial adhesives tested, the G. T. Sheldahl candidate B formulation appeared to be most suitable for balloon applications having a glass transition at -25°C and a minimum damping temperature below the -70°C use temperature (i.e., tropopause temperature).

The thermomechanical characteristics of the aliphatic polyesters show vast improvements over the conventional partially aromatic balloon adhesive as well as the four industrial adhesives. However, the temperatures of minimum damping of the aliphatic materials are found to be near the minimum use temperature (-70°C), whereas it is preferable to acquire adhesives with T_{min} well below -70°C.

The linear hydroxyl end-capped amorphous polybutadienes show thermomechanical characteristics substantially superior to the aliphatic polyesters. Polybd™ R-45M procured from the ARCO Chemical Company has the most promising characteristics. After curing, the material exhibited a Tg of -68°C, T_{min} of -100°C, and a T_β of -125°C. The material was tack-free, cured easily, and provided a T_g at approximately the tropopause temperature.

The two SBS block copolymers (Shell Kraton™ 1101 and Phillips Solprene™ 406) had glass transitions temperatures (-92° and -90°C) well below the use temperature (-70°C). These results are for materials using benzene as the solvent. Further study is needed using methylene chloride as the solvent since it is more compatible to industrial use. In addition, the SBS adhesives would require antioxidant and UV protecting additives in order to be used in balloon applications.

The reactive adhesives investigated were all thermosetting, whereas thermoplastic adhesives are more versatile and amenable to existing industrial practices.

6. Fabrication Techniques

Modern soft goods fabrication procedures utilize several different techniques to join envelope material panels as well as load spreaders, catenary curtains, and other soft goods interface assemblies. Normally several different methods are used on a single assembly, the correlation of technique to application being based primarily on reliability, manufacturing versatility and production cost tradeoffs.

a. Sewing

Numerous types of sewing machines are available with multiple needle heads or special feed and folding assemblies for use on large production items such as the LTA soft goods subassembly. Stitching would normally be confined to uncoated components or components which do not serve as direct gas barriers. Catenary curtains, load patch reinforcement webbings, and loop tape tie down assemblies are typical soft goods assemblies which would utilize various sewing techniques.

Often, if a sewn seam must be made on a direct gas barrier or through a coated material which would result in direct leakage or wicking through the substrate fabric yarns, a lightweight tape can be cemented over the seam to prevent loss of the buoyant fluid. This tape is sometimes a coated fabric, but since it carries no structural loads, it is often an unsupported film of a relatively impermeable material.

b. Cement Bonding

Cement bonding of seams is a very important manufacturing capability. Usually much slower than automated heat sealing processes, cemented seams are often necessary on final assembly where the component parts are too large to be readily accessible by sealing machines.

The many specialized adhesive systems available today enable such cemented seams to exhibit excellent reliability and resistance to extreme environmental conditions. The capability of using a fast drying solvent based cement on the envelope of LTA vehicles will enhance field operations and field repair of the ships. Minor rips, tears and holes in the envelope can be readily repaired without requiring unscheduled vehicle "downtime" for envelope panel replacements. The envelope can be field patched to continue its mission and the damaged panel replaced during the next scheduled service appointment.

c. Thermal Sealing

One type of heat induced polymer joining is simple thermal impulse sealing. In this technique, a hot bar, die, or roller is made to apply pressure to the seam area. The heat is resistance generated and passes through a heated bar and through the seam by normal conduction. Adjacent layers of polymer on the overlapped panel edges or on seam tapes are then fused together.

d. Dielectric (RF) Sealing

This process utilizes the electrical properties of polymer which are moderately polar in nature. The dielectric heat is caused by the work (dielectric loss) produced using an alternating electric field at a relatively high frequency which results in a heat build-up at the interface. A seal is accomplished by placing two similar films between two matched sealing dies and activating the high frequency current for a specific dwell time. Sufficient pressure is applied to the dies to force the two layers of film together so that the interfaces come into intimate contact. The greatest advantage in dielectric heat-sealing is the control of the system and the repeatability of results. This sealing process will form a bond between fabrics which is greater than the strength of the fabric.

e. Thermal Adhesive Bonding

The thermal adhesive bonding techniques utilizes a heat-activated film adhesive to effect a bond between two fabrics. The film is used in conjunction with a vacuum frame and a thermal heating blanket which provides uniform pressure and heat to the bonding area.

This process is ideally suited to sealing load patches in place on aerostat envelopes. A sketch of this apparatus is shown in Figure 13.

f. Ultrasonic Sealing

Another unique joining technique is ultrasonic sealing. In this process, two materials are passed through a machine which has opposing rollers which can be smooth or patterned, and are caused to vibrate at ultrasonic frequencies. This vibration and pressure is transmitted to materials passed between the rollers and provide the intimate contact between faying surfaces needed to produce a seal.

g. Typical Seams

Two basic seams are shown in Figures 14 and 15. The first is a lap seal in which normal stresses on the seal of the first two films are in a shear mode. The strength of the seams is affected by the seal beads which are formed at the outer edges of the seal. Pinked tapes are used on one side of the modified lap seam to prevent the formation of a straight line material modulus jump which would create a high stress line and a potentially low tear edge. A cross-sectional view of four panels joined in this manner is illustrated in Figures 16 and 17. Irrespective of the bonding method used, it is necessary that the joined surfaces be of adequate dimensions to insure that shear stresses at the interface do not exceed the bond strength of the bonded coatings to the substrate.

7. Application of Flexible Materials to LTA Vehicles

Technological disciplines have made large advances particularly in the use of films during the last two decades.

Research balloons are used to monitor the ecology, to make meterology measurements, to serve as launch platforms for runway tests and are used as decelerators for atmospheric entry. Military applications include navigation aids, pilot rescue and recovery, border surveillance and cargo carriers. Industrial uses involve recreational ballooning, sky hooks for harvesting timer, and microwave relay and communication platforms. Other prospective applications are in new generation airships and semi-buoyant aircraft.

The light materials have been used extensively in free-floating natural shaped balloons and primarily for high altitude research. These balloons have been built and flown for sizes up to 1.7×10^6 m^3 (60×10^6 ft^3). The application for heavyweight materials is primarily for blimplike and airship-like vehicles.

a. Balloon Applications

(1) Lightweight Materials

The selection of an appropriate balloon material is governed not only by the unique requirements of the overall system but by the imagination of the designer and flexibility of the manufacturing techniques. In general, it would be desirable to have a system that is impermeable to the lifting gas, transparent to the entire spectrum of radiation, experiences no volume change during pressurization and survives rough ground handling. Unfortunately, no existing material can be used with conventional manufacturing techniques to achieve this goal. Reasonable success, however, has been attained in the past using laminated polyester films and modern design and manufacturing techniques. In these designs, the film itself must provide the stiffness for the system since there is no circumferential load carrying capability except through the film.

Most current balloons use several materials in combination to enhance strength, gas barrier efficiency or other properties. Polyester film, super-pressure balloons, are generally made of two film layers bonded together to seal small holes in the stock film. Most heavy load natural shape balloon envelopes consist of polyethylene film reinforced with high strength fibers bonded along the seam. The modulus versus temperature characteristics of various polyethylene films have been determined, figures 18 and 19, reference (q). Typical yield stresses versus temperature characteristics are shown in figure 20.

Successful flights of 0.35 mil Strato-Film balloons have been accomplished. The fabrication of the largest balloon ever, a 48 million cubic foot volume was made for the Air Force. It appears that 0.35 mil is the limit for Strato-Film in regard to the extrusion of uniform film. A nylon film has been extruded which is reported to have excellent film properties and has a strength of about four times that of polyethylene of the same weight. It is possible to extrude a uniform quality film of nylon material as low as 0.2 mil thickness.

In general, it has been difficult to obtain a characterization of materials used in the natural shape balloon envelopes. The information available is of a description nature rather than a characterization of the material.

As a result of the demand for higher altitudes and heavier payloads, there has been an increased emphasis on continual evaluation of materials, fabrication, balloon design and launching techniques. The following are two specific examples of the use of lightweight materials for high altitude applications.

(a) BLDT

A lightweight high-strength reinforced Mylar laminate has been developed in connection with the Balloon Launch Decelerator Test (BLDT) project of the Viking program. The material is for use as the gas bag structure of the main (lower) balloon of the large free-flight, two-stage balloon used to carry aloft the Mars reentry capsule and decelerator system of the Viking payload.

The near isotropic reinforced membrane material of Dacron and Mylar was flown repeatedly. The material was fabricated of 0.35 mil Mylar S film, precoated with 0.15 mil of a partially aromatic polyester adhesive with an isosceles triangle Dacron yarn reinforcement pattern thermoplastically attached, figure 21. The material was made on the Flying Tread loom. The longitudinal yarns are 1300 denier and the diagonal yarns are 440 denier. The finished material weighed 41 gr/m^2 (1.2 oz/yd^2). The material strength was 26 N/cm (15 lbs/in.).

(b) HASPA

The hull envelope material for the High Altitude Superpressure Aerostat (HASPA) was a film scrim laminate shown in figure 22.

Because the size of the HASPA is very sensitive to hull envelope weight, a high strength to weight ratio was achieved using a Kevlar scrim laminated to a single-ply Mylar film. The scrim had six 1000 denier yarns in the fill (TD) direction compared to three 1000 denier yarns in the warp (MD). There is an appropriate two-to-one skin stress ratio between the hoop and axial directions in the maximum stress region. The laminate was oriented with the fill yarns in the hoop direction. The tensile strength of the Mylar-Kevlar laminate was degraded by dead load, weathering and handling, Table XII.

In actual use, the first HASPA hull was proof pressure-tested and failed catastrophically at a calculated skin stress corresponding to 48% of the design strength value (65 lbs/in.).

A material improvement program is presently underway the principal focus of which is to define fabrication parameters necessary to preserve the original strength of the Kevlar filaments. Four material combinations, triaxially woven Kevlar/urethane, laminated Kevlar/Mylar, bi-laminated Kevlar/Mylar, an orthogonally woven Kevlar/urethane/Mylar hybrid are under current evaluation.

(2) Heavyweight Materials

In World War II, balloons were used to raise steel-cable barrages over cities, beach and supply areas and ships at sea. Figure 2 showed the construction of the fabric used for these early barrage balloons, a cotton and neoprene combination of approximately 12 oz/yd^2 and tensile strength slightly better than 17,500 N/m (100 lbs/in.), reference (p).

Small improvements in the material performance of a modified balloon barrage was accomplished with the use of nylon, figure 17. The material construction was similar to the earlier fabric, except nylon is used in place of cotton. The limit weight of the material was slightly reduced to 0.38 kg/m^2 (11 oz/yd^2); the warp and fill yarn strengths were slightly increased to 224 n/cm (128 lb/in.) and 240 n/cm (137 lb/in.), respectively.

A new type of buoyant vehicle was developed as a result of a program launched by the Pentagon's Advanced Research Project Agency (ARPA) in the mid-60's to devise improved reconnaissance for use in Southwest Asia, references (1) and (m). Larger improved versions of the World War II tethered barrage balloon was developed as a long endurance airborne platform that could hover at altitudes up to 10,000 feet and operate satisfactorily in gale-like winds. Two new designs were developed.

Initially, one of the original BJ type barrage balloons was obtained from Britain in 1968. Unlike the more familiar Goodyear blimp which used metal fins for the empennage, the BJ type used fabric fins that were inflated simply by ram air from winds aloft. If the fins were inflated with helium, like the hull, they would expand and lose their aerodynamic shape as the balloon ascended to altitude. These World War II tethered barrage balloons were aerodynamically unstable and relatively fragile.

This prompted the idea of using motor-driven blowers to maintain the fins and aft portion of the hull. The aft portion of the hull must provide structural support for the fins inflated to the required pressure as a function of both altitude and wind velocity. Sheldahl, under contract to ARPA, modified several BJ balloons to add the above feature. In addition, the hull was enlarged by adding three more longitudinal gores.

ARPA's principle military agent for evaluating the resulting aerostat for the mission was the USAF Range Measurement Laboratory (RML) at Patrick AFB, Florida.

The BJ+3 model was tested by RML in 1969. The BJ+3 with a helium filled hull volume of 84,000 square feet showed sufficient promise for ARPA to draw up specifications for an operational prototype aerostat, rugged enough for military use and able to carry a useful avionic payload of approximately 1000 pounds in addition to its electric power supply. The new vehicle called ARPA Family II underwent four configuration changes as a result of wind tunnel tests conducted by 1970-71. The final design was a 162 foot long vehicle with a helium filled hull volume of 200,000 cubic feet (at sea level) designed to carry a total payload of approximately 2,000 pounds to an altitude of 10,000 feet as well as support the associated ground tether: Currently used tether weighs about 200 pounds 1000 feet.

Two material geometries were used for the Family II balloons: (1) Double substrate (bias-ply) coated on two sides; (2) Single substrate bonded to film.

The first of the three Family II aerostats made by Sheldahl used material similar to that used in airships of the mid-50's. The Family II, No. 201 was constructed of a bias-ply coated fabric, figure 24. This material has an outside layer of hypalon for ultraviolet and handling and environmental protection. Two layers of Dacron fabric were used in a manner similar to the earlier materials with alternate layers of neoprene. The improvements of this material were at the expense of a slight increase in unit weight, 0.44 kg/m^2 (13.0 oz/yd^2) over the use of nylon. The strength continued to improve to 266 n/m (150 lbs/in.) in both warp and fill. This first aerostat performed successfully but was heavy. It is noted that this material construction is similar to that currently used by Goodyear Aerospace Corporation for the hull envelope of their blimps.

Sheldahl developed a single-ply multilayer laminate for balloons No. 202 and No. 203. This new single-ply laminate, figure 25, offered the potential for significant reduction in weight and cost. The fabric consists of Dacron, which is the main source of strength and two layers of Mylar which supplies high shear strength and stiffness and serves as the membrane to retain the helium gas. The outer layer consists of Tedlar which provides weather resistance. The unit weight was drastically reduced to 0.29 kg/m^2 (8.6 oz/yd^2). Isotropic material strength was achieved at 394 n/cm (225 lb/in.). The helium permeability was reduced to about one-fourth that characteristic of earlier materials. Traditional adhesive techniques were used for seams which subsequently experienced severe leakage problems. This laminate was unsuccessful in its first application to a full-scale balloon. Only Vehicle No. 202 was flown. There was only one successful flight using this fabric.

Early in 1972, Westinghouse Electric, which has been under contract to ARPA to supply military sensors for evaluation aboard the agency's aerostat, created a subsidiary to apply the same technology to civil applications. The company is called Tethered Communications, Incorporated or TCOM for short.

TCOM contracted with Sheldahl to build a larger version of the Family II Aerostat with a 250,000 cubic foot volume. This aerostat, CBV-250, is designed to carry a 35,000 pound payload to an altitude of 10,000 feet in a 75-knot wind. An improved multilayer laminate material of Mylar and Dacron was developed by Sheldahl and was used successfully on the commercial TCOM balloons.

Improved techniques for sealing the laminate have been developed, including special machines. One such machine, the Traveling wheel sealer, automatically applies sealing tape to two adjacent gores of material, heats the tape adhesive to a controlled temperature for a prescribed time and applies a controlled pressure.

ILC Industries, a newcomer to the balloon field, but an experienced fabricator of leakproof garments such as the Apollo spacesuits, won the ARPA program to construct three improved model aerostats. The main hull fabric that ILC is using is a bias-ply coated fabric with butyl as the gas barrier, figure 26. The outer layer with weather and ultraviolet resistant qualities is polyurethane. Underneath is a 1.1 ounce polyester layer to provide bias strength and stability. Next is a layer of butyl which serves to retain the helium. This is followed by a layer of 3.25 ounces polyester for primary structural strength and another layer of polyurethane polyester. This hull material weighs approximately 10.8 oz/yd^2, approximately 20% heavier than the hull fabric used by Sheldahl. The ILC fabric seems to offer dimensional stability and ease of fabrication. ILC employs radio frequency induction heating to bond the seams of the gores. The material from two adjacent gores is overlapped and bonded thermally; the polyurethane polyester materials flow together to form the seal. Different types of fabrics, however, are used in various portions of the aerostat design. Material construction is varied and tailored to use in the balloon taking into consideration the encountered stress and strain, the permeability needs and environmental protection requirements.

Figures 26-29 show the construction and physical properties of the coated fabrics currently being used by ILC in the Family II Aerostat. Originally, a heavier weight fabric (1.4 oz/yd^2) was used as the outer cloth ply and less urethane (0.5) was placed on the inside of the material. Figures 26a, 27a and 28a show the construction of the original materials used to make the Family II No. 204 and No. 206 aerostats. The improved ILC materials differs in that there is more urethane on the inside and outside of the fabric and the outer cloth is somewhat lighter.

The materials used by ILC are basically coated polyester fabrics, similar in construction to the earlier materials used in airship construction. In keeping with the technological material advances of recent years, however, different elastomers have been used. In a sense, this construction is merely an extension of the state-of-the-art of the 50's in aerostat design and manufacturing techniques. Butyl replaces the neoprene as the gas barrier and polyurethane provides the bonding agent as well as abrasion and environmental protection.

The fabrics of construction used by Sheldahl in the TCOM balloons are pictorially described in figure 30. Most of the materials are laminate constructions composed of Dacron cloth, Mylar and Tedlar. The Dacron is the main strength member used to carry stresses (hoop and longitudinal). Mylar serves th dual function of providing high-shear strength and stiffness and serving as the impermeable membrane. The Mylar provides the same structural function as the biased cloth in conventional coated fabrics. The Tedlar is not a structural membrane; it is the weathering protection for the Mylar and Dacron cloth. The material construction and properties for the hull material are presented in figure 31.

Specific areas of the aerostat do require a higher shear material, notably, the nose of the hull and the root areas of the fins. The nose of the hull must sustain the high shear loads along the nose beams and in the root areas of the fins reverse shear cycling occurs quite frequently. Material properties and construction for the fin material are presented in figure 32.

Materials are continually being improved and Table XIII presents the physical properties of laminate material currently being used by Sheldahl for hull empennage, ballonet and windscreen. The TCOM balloons apparently have performed adequately, although hydrolysis of polyester materials have been a problem in countries with a very hot climate.

The G1444, Figure 33, ballonet material consisting of a laminate of polyurethane coated fabric and Mylar is currently being used with Government approval for the new ballonet in Family II, No. 205 balloon. The G1428 hull and G1429 fin materials are identical to the materials used in nine TCOM aerostats to date, except that the polyester adhesive has been changed to provide improved hydrolytic stability, figures 34 and 35.

Testing of this new hydrolytically stable polyester at Sheldahl over the past year has shown a marked improvement over the polyester adhesive used in G1249, G1250 and numerous other Sheldahl laminates. For example, after four weeks exposure to 100-percent relative humidity and 160°F, seals made with the old adhesive failed at 50-pound per inch dead load within several minutes, while seals made with the new hydrolytically stable adhesive continue to support a dead load of 170 pounds per inch without sign of seal failure.

One other big plus for the new adhesive system is that no refrigeration is required, which greatly facilitates shipping to remote sites, as well as on-site storage. The windscreen material F014300 is a polyurethane-coated fabric with the polyurethane compounded to offer good weathering properties, hydrolytic stability and resistance to UV, ozone, fuel, oil, etc.

Experimental work on the development of further improved fabrics at ILC has resulted in the proposed use of material constructions shown in figures 36, 37, 38, and 39. The use of oriented non-woven polyester fabric provides the same structural function as the bias cloth but is considerably lighter in weight.

8. Candidate Materials For Airship Applications

The development of specific materials for application to LTA construction must consider many factors. The first consideration must be the tensile stresses to which the material will be exposed. These can be accurately predicted from a static stress analysis and wind tunnel tests on model structures. The hull fabric analysis must consider what part the material plays in the total structure. In non-rigid LTA's, the hull fabric provides all of the structural support and also serves as a permeability barrier. In rigid or semi-rigid LTA's, the hull fabric plays a lesser role and may only be required to withstand local dynamic wind loadings. In both cases, the overall size and performance; i.e., speed and maneuvering requirements are prime factors in determining the structural requirements.

Each of the material constructions discussed above is a candidate non-rigid envelope material. It is apparent from past experience that each has specific characteristics which make it a good envelope material construction, but at the same time, some other properties which might make it less attractive.

Final specification of an envelope material must be based on a comprehensive evaluation of the specific application for which it is intended. A materials development tradeoff would be required in which all properties of the candidate materials could be compared and evaluated.

a. Hull Materials

After determining the structural requirements of the hull fabric, including adequate safety factors for reliability and long life, the structural material strength requirements can be specified. At the present time, ply biased fabrics, film reinforced fabrics, coated triaxial fabrics and spun-bonded fabrics are all potential envelope materials. Thus far, only the higher efficiencies obtained from closely spaced filamentary materials, such as textiles, appears to be satisfactory for non-rigid airships.

In selection of coatings for hull fabrics, service life and service environment are prime considerations. In non-rigid LTA's, permeability to the lifting gas is an equally important consideration. Ease of application of the coatings to be fabric and to themselves or other coatings, must also be considered.

Polyurethane is rapidly evolving as the most versatile and reliable of currently available coatings in providing an optimum balance of the above properties. Its mechanical properties are unexcelled, and its permeability and weather resistance can be effectively augmented, when required by, application of a thin film of Tedlar.

Tables XIV and XV list candidate materials of the two constructions described above for rigid and non-rigid envelopes. Projected weight and strength data have been included for both Dacron polyester and Kevlar 29 yarns and are plotted in Figures 40 and 41. It is apparent from the curves that a significant weight savings can be realized with Kevlar. This savings will be of great significance when it is realized as additional payload capacity of the system. Nevertheless, polyester yarns are a viable candidate for use in LTA applications where weight is not the prime consideration.

b. Ballonet Materials

Non-rigid LTA's employ air cells, ballonets, to maintain the LTA shape (pressure) and for static balance and trim. These cells are formed by diaphragms within the LTA hull which are not subjected to external structural loading but must be of adequate strength and resiliance to withstand significant inertial forces associated with the mass properties of the contained air. In addition, low permeability to the lifting gas is essential.

The mechanical stresses on the ballonet material can be calculated based on their size and shape and on the inertial forces resulting from LTA maneuvers. While significant, these forces are less than those normally imposed on the hull and permit lighter constructions. The ballonets are seldom fully inflated, however, and must be highly resistant to continuous flexing. For this application, and in the absence of requirements for high stability, single ply biaxial Dacron structural fabrics are more suitable than they would be in the hull. Lightweight Kevlar biaxial and triaxial fabrics still offer advantages where weight is critical.

Nylon is an optimum candidate for ballonets and lifting gas cells. The elasticity of nylon and great strength provides a high degree of crease resistance and shape retention. Nylon is a tough resilent fiber that can be bent thousands of times without breaking. It also has a high resistance to abrasion.

The lower tensile requirements of the ballonets and greater emphasis on flex resistance results in the gas barrier coating playing a greater roll in structural design of the material. Urethane again is an outstanding choice in coating selection. Its elastomeric properties and abrasion resistance are specifically suited to long flex life.

Table XVI compares today's material alternatives with those of the 1950's.

c. Lifting Gas Cells

Rigid LTA's normally employ a number of impermeable bags which contain the lifting gas. They are characteristically captured by and transmit lift to the LTA through a system of nets and lines to the rigid structure. In this manner, structural loads on the cell fabric is minimized. Since the size and shape of the cells is controlled by the restraint system, the cell material can be standardized to make optimum use of available fabrics and coating. Abrasion, flex resistance and impermeability are the prime requisites. Structural films such as mylar, nylon, polyurethane films are all candidates for this application. Mylar is outstanding in tensile properties and requires minimum fabric reinforcement. Its poor tear propagation resistance and limited bonding potential, however, somehwat offset its advantages. Nylon films have much greater tear resistance and are readily bonded, however, in adequate thickness to be comparable to Mylar in permeability, they tend to be stiff and less manageable. Polyurethane is only slightly more permeable than nylon but retains its elastomeric properties better. Based on overall performance and ease of bonding, it is a prime candidate.

The continued development of inflatable material must involve the foregoing basic products in films, coating, reinforcement geometries, yarn bundles, and in woven fabrics. Combinations of these constituents tailored to specific applications represent a vast and continuing development program.

B. Metalclad Airship Materials

Significant improvements in materials and processing compared to the same during the development of the ZMC-2, make the modern metalclad a superior vehicle to its earlier counterpart. One of these new developments is the 7050 aluminum alloy which has superior properties to high strength 7075 aluminum alloy. The 7050 - T76 alloy has significantly higher tensile and compressive ultimate and yield strengths and fatigue strength than the 24ST aluminum alloy used on the original ZMC-2.

	7050-T76	24ST
U.T.S.	78	58
Y.S.	75	38
% Elong.	9	16%

The cost of producing the 7050-T76 alloy in sheet form would be slightly higher (10-20%) than comparable 7000 series aluminum alloys in sheet form primarily due to problems with reclamation of scrap, etc., in connection with maintaining the required Zr content of the alloy.

The use of 7000 series aluminum alloys precludes the possibility of welding of primary structure for a metalclad airship. A reliable efficient method for joining is the use of riveting in conjunction with adhesive bonding. Higher strength rivets are possible with 7050 Al as compared to 2024 Al along with good resistance to stress corrosion cracking in the fastener. Additionally, new methods of riveting such as stress wave riveting, which can provide better fatigue properties, exist today. Better uniformity and reproducibility can be achieved with riveting processes such as these which were nonexistent in 1929.

There are a number of room temperature curing adhesive systems possessing good properties which may be used in concert with the riveting processes for metalclad airship fabrication. The adhesive will reduce the stress concentration around the rivet holes and provide greater spacings between rivets, saving weight. The adhesive would serve both as a bonding agent and a sealant. The original ZMC-2 employed a drying oil to achieve sealing on the metal seams, however, this material could not contribute to the strength of the joint, and was also heavier than present adhesive systems.

Present day adhesives cover a multitude of generic classes as listed in Table XVI. Practically all of these can be used for metal/metal bonding with the proper surface preparation and will give a broad gamut of properties depending on the system and particular operating condition. In general, operating temperatures from -65 to 500°F are possible with organic adhesives with lap shear strength of 2000 - 4000 psi at room temperature. Properties such as peel strengths will vary from system to system and the use of a scrim cloth although adding weight (.06 and .1 lbs/ft^2 weight are common on film adhesives with scrim) also add considerable peel strength to the adhesive system. These systems can be cured at longer times at room temperature, or shorter times at elevated temperature and usually cure to a joint thickness of about approximately .0006 - .008 inches. Epoxy or polyurethane adhesives would be well suited for metal to metal bonding required in the metalclad airship, with its mild temperature excursions. As stated earlier, there was essentially no available metal/metal bonding agents available during the 1920's. The neoprene listed in Table XVII was used as a bonding agent in the seams of the ballonets.

Modern metalclad airship design can employ use of Al skin faced Al honeycomb core sandwich construction. The 7000 series aluminum skins can be adhesively bonded to 5056 corrosion resistant core which is available in a number of different densities, cell sizes, and core depths. The sandwich construction can be used at all load concentration points such as openings, attach points, mooring points, etc., to effectively distribute these loads.

A larger portion of the mission of the metalclad airship would be spent in close proximity to the ocean's surface. The corrosion of the metallic hull can be a problem which must be considered. The old ZMC-2 utilized simply an alclad 24ST skin for corrosion protection. Reference (n) states that although tensile strengths were not affected, the pitting of the ZMC-2 had progressed to noticeable depths. Once the alclad coating was penetrated, the rate of pitting would increase through the underlying aluminum alloy skin. Additional protection can be achieved in a modern metalclad airship by applying an epoxy primer (1 mil) and polyurethane topcoat (2 mils) system to the exterior of the airship (a total weight of 2.97 lbs/100 ft^2). The interior which is exposed to salt saturated air would need only the epoxy primer coat (1 mil) (.75 lbs/100 ft^2).

EXPERIMENTAL WORK

In support of the Advanced Navy Vehicle Concepts Evaluation (ANVCE) and to advance the state-of-the-art of point design data for LTA applications, NADC had two types of triaxially woven fabrics made. These were:

1. B20K (Kevlar 29 18.5^3 1.5 oz/yd^2)

    a. All Kevlar - urethane coated
    b. Kevlar warp with polyester fill-urethane coated

2. BP21P (Dacron, Type 52, 37^3)

    a. All polyester - urethane coated
    b. Polyester warp with Kevlar fill-urethane coated

Physical testing on each fabric will include the following:

1. Tensile Strength (grab method)
2. Tear Strength
3. Environmental - weight gain - moisture (humidity 95% at 140°F)

    a. Tensile strength

4. Crease resistance
5. Permeability

The fabric samples were identified as follows: BP21P is a bi-plain triaxial fabric composed of 210 denier polyester yarns; BP21PK is a bi-plain triaxial fabric with a 210 denier polyester warp and a 200 denier Kevlar filling; B20K is a basic triaxial fabric composed of 200 denier Kevlar; and B20KP is a basic triaxial fabric with a 200 denier Kevlar warp and a 210 denier polyester filling. Figure 43 shows a comparison of the bi-plain and basic triaxial weave.

The results of the test program completed to date are presented in Tables XVIII and XIX.

Fabric tensile strength was determined on uncreased and creased specimens in the machine, bias and crosswise (transverse) directions using the grab breaking techniques. Also, tear strength was measured in the machine and crosswise directions by both the tongue and trapezoid methods.

A comparison of breaking strength values for the triaxial fabric samples is given in Table XVII. The breaking strength is stated in pounds per inch (breaking load in pounds divided by jaw width in inches). Normalized breaking strength adjusts the data for differences in fabric weight and is stated in pounds per inch divided by ounces per square yard.

The values in Table XVII indicate that the BP21P (the polyester sample) is as strong as B20K (the Kevlar sample). It is well known that Kevlar has over twice the breaking strength tenacity of polyester. Obviously, a considerable amount of damage occurs in the passage of the Kevlar warp yarns through the triaxial weaving machine while little, if any, damage occurs in manipulation of the polyester warp yarns. Consequently, the advantage of the Kevlar over polyester as a warp system is a loss during weaving. The Kevlar warp samples all show a greater loss in strength due to creasing. The sample demonstrating the highest relative strength is BP21PK (the polyester warp with Kevlar filling).

A comparison of tearing strength values for the triaxial fabric samples is made in Table XVIII, tongue and trapezoid tear strength are reported in pounds of tearing force, or load. The tear strength data are also normalized to adjust for differences in fabric weight and are reported in ounce per square yard.

Kevlar fabrics exhibit much greater resistance to tear than comparable polyester fabrics, regardless of tear technique. It is well established that Kevlar fibers have an extremely high resistance to transverse loading. Consequently, Kevlar yarns should provide high tear strength values in any fabric construction.

The results of this evaluation show that, unless Kevlar can be processed through the triaxial weaving machine without substantial damage, the polyester warp - Kevlar filling construction is the best choice. Perhaps Kevlar warp yarns can be sized and lubricated for improved manipulation through the triaxial machine. However, in addition to proper yarn sizing, Kevlar filaments must avoid critical compressive loading which is accentuated at any small radius of curvature or point of concentrated pressure.

A considerable effort on testing, evaluation and analysis of experimental candidate fabrics was done as NASA, Langley and by NASA contractors. ARPA funded these efforts and Appendix B covers the experimental evaluation of balloon materials.

Recent discussions with Vernon Alley of NASA, Langley have reaffirmed that there is a need for far more experimental work to characterize balloon materials to the point where reasonable accurate response and service life predictions can be made.

Problem areas that remain unsolved include the following: (1) Does an acceptable fatigue life exist for seam and fabric; (2) how does creep recovery characteristics vary under long-term load and temperature conditions; and (3) the problem of joining two materials of the same composition or of differing composition, etc.

CONCLUSIONS

1. The main structural requirements of LTA systems can be met, in general, by state-of-the-art materials although the development of a stronger, more durable lightweight structure is needed for critical weight applications.

2. If the material is to be used primarily as a gas container, the required strength is determined by the design super-pressure and the method of transferring lift of the gas to the structure. The cyclic variations of pressure and flexing and atmospheric conditions must be anticipated and considered. The resistance of the material to manufacturing and handling damage and resistance to tearing must also be considered. Abrasion, flex resistance and impermeability are the prime requisites for ballonets and lifting gas cells.

3. When material serves as hull and gas containers, such as in a non-rigid airship, strength and other requirements are severe. The parameters combine to exceed the properties of film laminates. Thus far, only the higher efficiencies obtained from closely spaced filamentary materials such as textiles, appear to be satisfactory.

4. Modern lifting gas cells and ballonets are available with an order of magnitude less permeability and about half the weight of the traditional rubberized cotton.

5. Modern advances in flexible material technology have resulted in reducing unit weight for an airship hull by approximately 50% and increasing strength by 100%.

6. Presently, two types of fabric geometry are being used to meet the requirement of dimensional stability. These are: (1) Two-ply biased fabric coated on two sides and (2) Single-ply fabric bonded to a high modulus film. The double substrate coated two sides provides exceptional stability with increased tear resistance but tends to be heavy. The single substrate fabrics are generally lower in weight. In order for a single substrate fabric to have good dimensional stability, it must be combined with a film having a high modulus. This can result in a stiff material having a poor flex life.

7. The forward steps in the biased ply evaluation have been from cotton to Fortisan to nylon to polyester (Dacron). Polyesters are strong and resilent, do not crease easily and demonstrate satisfactory elongation; they absorb very little moisture and have good resistance to degradation by light.

8. The development of Kevlar represents the potential for another forward step. The exceptional strength to weight ratio of Kevlar offers advantages where weight is critical. Kevlar, however, is sensitive to ultraviolet light and has less resistance to flex fatigue and small bend radii than other organics.

9. Woven fabrics must be coated with an elastomeric material or bonded to a film of sufficient thickness to prevent high gas loss. All non-rigid airships built to date have employed the first method - namely a coating as the gas barrier. For two or more ply construction, the bonding of the fabrics is also accomplished by an elastomeric coating. An outer coating, often of a different material from the inner, is applied to the surface exposed to the airstream. This outer coating provides resistance to and control of environmental effects. The net result of such construction is a material which consists of about half cloth and half elastomer.

10. Thin films can be manufactured to provide a much less porous surface than can be obtained with an equal amount of elastomer. For applications where the

film is only a gas barrier, such as in ballonets, the minimum gage theoretically would only be limited to that required to eliminate microscopic holes and obtain a given rate of permeability.

11. Mylar film has found the greatest use in laminates because of its high tensile and shear strength and low permeability. It has the disadvantages, however, of being moderately stiff, difficult to bond and the least tear resistance of all the available films. Hytrel would seem to be a likely candidate as a substitute for Mylar since it has greater flexibility, extreme toughness and should perform well as a gas barrier.

12. Polyurethane, because of its excellent coating properties, has been used as a protective coating for single and multiply fabric structures. Recent developments of thin case films, with significant lower permeability, has incre[illegible] its versatility. Urethane has superb handling characteristics but displays high creep.

13. Tedlar PVF film is the optimum material for weathering and ultraviolet stability, but suffers with problems with poor adhesion.

14. While the elongation of nylon makes it unsuitable for use as an envelope fabric, it is an optimum candidate for ballonets and lifting gas cells. The elasticity of nylon and great strength provides a high degree of crease resistance and shape retention.

15. In LTA applications, significant progress can be made by the development of a single substrate with dimensional stability. The materials with the best potential for achieving this goal are triaxially woven fabric and spun-bonded fabrics. Coating these materials with an elastomer or elastomers will provide the gas retention and environmental barrier necessary for a functional airship material. These materials are also quite promising for reducing the weight of airships.

16. In the area of adhesives, aliphatic polyesters have shown considerable improvement over conventional partially aromatic adhesives. Also, the linear hydroxyl-end capped amorphoris polybutadienes show superior thermochemical characteristics over the aliphatic materials. Shell Kraton and Phillips Solprene 406 SBS block copolymers appear the most promising if antioxidant and ultraviolet additives can be developed.

17. Modern 7000 series aluminum alloys are 50% stronger than those used in the 1930's and 100% better in yield strength. Corrosion resistance treatments have been developed for aluminum alloys and can be further improved by the use of epoxy primers and a polyurethane topcoat.

18. Newer construction such as sandwich materials have higher strength/weight ratios than that of older aluminum alloys. A sandwich material of Al skin faced Al honeycomb construction can be used at load concentration points to effectively distribute the load. Sandwich construction is an excellent lightweight structure but is expensive to manufacture and difficult to maintain.

19. A major bar to the introduction of new materials in LTA is the unreliability of short-term tests for predicting long-term behavior. A related obstacle is the lack of data on the performance of materials and components in service. Such data are basic, not only to the use of current material, but for the development of short-term tests and otherwise to predict the behavior of materials.

RECOMMENDATIONS

It is recommended that efforts be directed to the development of a stronger more durable lightweight structural fabric for use in critical weight applications in LTA vehicles.

It is further recommended that experimental work continue with triaxially woven fabrics. Efforts should be directed to improving the manipulation of Kevlar warp yarns through the triaxial weaving machines. Possible areas for exploration are the effects of sizings and lubrication on the physical properties of the fabric.

It is further recommended that work be initiated on spun-bonded fabrics to develop a data base for possible LTA applications.

It is recommended that work be initiated to develop better test methods for the characterization of materials for LTA applications. Tests are needed for the characteristics of durability (physical and chemical), safety, reliability, serviceability, and maintainability.

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TABLE I

STATE OF THE ART IN MATERIALS USED IN THE CONSTRUCTION OF THE LAST AIRSHIPS (RIGID AND NON-RIGID)

RIGID AIRSHIPS

1930 ALTERNATIVES	
17 SRT ALUM ALLOY LOW CARBON STEEL STAINLESS STEEL	FRAMING
DOPED COTTON FABRIC 17 ST ALCLAD	COVERING
GELATIN-LATEX/COTTON GOLDBEATERS SKIN/COTTON	CELLS
PIANO WIRE	WIRING

NON-RIGID AIRSHIPS

1950 ALTERNATIVES	
COTTON/NEOPRENE DACRON/NEOPRENE RAYON/NEOPRENE	ENVELOPES
STAINLESS STEEL GALVINZED WIRE	CATENARY CABLES

TABLE II

TEST DATA ON MATERIALS FOR LTA APPLICATIONS IN 1930

Description of Materials	Strength lb./in.	Weight oz./yd.^{2}	Permeability $\ell/m^2/24$ hrs.
Racing balloon fabric, single-ply 3 oz. cloth, rubberized	60	6.3	
Spherical balloon fabric, single-ply 4 oz. cloth, rubberized	80	7.8	
Cel-latex cell fabric, 2.0 oz. cloth	38	4.9	2.35
Cel-latex cell fabric, 3.0 oz. cloth	60	6.3	2.55
Gold-beater skin cell, 8.0 oz. cloth		4.5	2.0
Rubberized gas cell, 2.0 oz. cloth	40	5.0	
3-ply aluminized fabric, 2.0 oz. cloth	80	13.4	15.0
2-ply aluminized fabric, 2.0 oz. cloth	60	9.5	15.0
K-class airship, 1-ply basket-weave and 9 plies HH cloth	190	16.1	15.0
Riveted alclad sheet, .010" thick	300	21.0	
Steel wire, 220,000 lb./in.^{2}			Not
Basket weave cloth	120	5.5	gas-
HH cloth	40	2.05	tight
BB cloth	58	2.00	materials

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TABLE III

PROPERTIES OF COTTON, NYLON, DACRON AND RAYON (FORTISAN)

	Tenacity g/d	Tensile Strength lbs/sq.in.	Elongation %	Elastic Properties	Density	Moisture Effects % Regain	Heat Effects	Age Effects	Sunlight Effects	Micro Organisms	Resistance to Abrasion
Cotton	3.3-5.0	40,000-120,000	6-7	Relatively inelastic rigid fiber, cotton fabrics have a 3% circumference surface elongation factor	1.54	Absorb moisture, fibers strength increases when wet by 10-30%, 8.5% moisture regain	Excellent Res. decomposes at 150°C; Burns readily in air	Small loss	Gradual loss of strength; severe at high temp. & in presence of moisture	Attacked by fungi & bacteria	High
High Tenacity Nylon	5.2	50,000-130,000	19-24 (21-28 when wet)	Highly elastic, Nylon fabrics have a 6% circumference surface elongation factor	1.14	Absorbs only small amounts of water, Regain - 4-4.5% Low moisture absorption encourages accumulation of static electric charge fibers lose 10% strength when wet	Withstands up 150° for many hrs. Melts at 250°C, less inflammable than cotton; melts & tends to drop away	Negligible	Gradual loss of strength	Not weakened by mold or bacteria	High; extremely hard wearing
High Tenacity Dacron	6.0-7.0	105,000-125,000	1-3	Moderately elastic Dacron fabrics have a 2% circumferential elongation factor	1.38	Absorbs very little water, Regain 0.4 to 0.8; encourages the accumulation of static charge	Excellent Res. to prolonged exposure, melts at 240°C, In contact with flame - retracts	Negligible	Good res. surface gradual loss only after prolonged exposure	Not attacked by mold or bacteria	
Fortisan	6.7	136,000	6.0-7.0	Relatively rigid fiber	1.50	Resists stretching, under both wet & dry conditions; neither expands or shrinks, loses 15% strength when wet, moisture regain of 10.7%	Similar to cotton, Burns; 40% loss at 140°F		Similar to cotton	Similar to cotton	Poor

TABLE IV

COMPARISON OF TEST RESULTS OF SPECIMENS FROM THE ZPG-3W, COTTON ENVELOPE, D-621 TESTED BY NADC (1976) AND GAC (1959)

Panel/Gore		40I Slightly Stained		40H Unstained		41I Badly Stained		84I Unstained	
Original Fabric Identification		N 113 A520		N 113 A530		N 113 A520		N 113 A510	
Fabric Roll No.		8472		8470		8465		8483	
Tested by:		NADC	GAC	NADC	GAC	NADC	GAC	NADC	GAC
Tensile Strength (lbs./in.)									
Straight Warp			Not available		Not available				
	Avg.	182		236		64	223	217	211
Filling			Not available		Not available				
	Avg.	168		239		42	234	189	212
Bias Warp			Not available		Not available	No test			
	Avg.	148		192			213	208	214
Fill			Not available		Not available	No test			
	Avg.	201		201			238	205	249
Weight (oz/yd.^{2})		29.6	Not available	28.0	Not available	25.3	25.25	26.0	24.10
Helium Permeability L/sq. m/24 hrs.			Not available		Not available				
	Avg.	125		5.4		Over 400	3.1	2.2	3.3
Ply Adhesion			Not available		Not available	No test			
	Avg.	11.5		15.4			13.3	13.0	14.7

TABLE V

ZPG-2 [illegible] 1976 TEST DATA ([illegible] AND [illegible]) COMPARED TO THE ORIGINAL 1960 (GRC) TEST VALUES

Panel/Zone	[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]		43 Car Canopy	
Original Fabric Identification	[illegible] 311 E76-15A		311 Be 76-15A		311 E76-15A		111 E76-15A		311 F76-15A		311 R65-15A		311 R61-16	
Fabric Roll No.	251		271		[illegible]		[illegible]		[illegible]		[illegible]		249	
Data Generated By:	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC
Tensile Strength (lbs/in) Straight Warp Avg.	286	272	314	296	286	261	297	273	304	280	290	283	236	235
Fill Avg.	254	254	271	295	264	262	258	250	266	258	247	250	272	251
Ply Adhesion (lbs/in) Straight Warp Avg.	3.7	11.2	6.2	8.0	5.1	11.3	2.6	16.1	1.92	18.8	2.2	14.4	12.0	13.4
Helium Permeability L/sq. m/24 hrs. Avg.	0.9	0.5	0.8	1.2	1.1	0.3	1.0	0.7	---	0.1	1.0	0.1	1.0	1.9
Weight (ozs/yd²)	16.22	16.11		15.82	15.73	15.90		16.03	16.32	16.11	16.[illegible]	16.11	15.2	15.79

Panel/Zone	[illegible]		46 Car Canopy		[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
Original Fabric Identification	311 E76-15A		311 B61-15		311 E76-15A		311 E76-15A		311 E76-15A		311 Be 76-15A		311 ER76-15A	
Fabric Roll No.	230		149		218		218		280		262		265	
Data Generated By:	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC	Test MASC	Original GRC
Tensile Strength (lbs/in) Straight Warp Avg.	292	273	243	235	280	287	291	287	276	279	302	293	300	275
Fill Avg.	259	256	224	231	270	242	252	242	252	265	281	280	293	279
Ply Adhesion (lbs/in) Straight Warp Avg.	1.6	16.1	9.9	14.3	No test —	15.8	7.8	16.8	6.9	22.1	6.0	18.0	10.9	15.9
Helium Permeability L/sq. m/24 hrs. Avg.	1.1	0.7	0.6	1.9	0.89	1.3	0.6	1.3	—	1.5	0.9	0.3	0.9	0.7
Weight (ozs/yd²)	No test	16.03	15.9	15.79	16.16	14.98	No test	14.98	No test	15.40	15.73	15.79	No test	15.98

TABLE VI

YARN PROPERTIES

	"Kevlar" 29	T-728 Nylon	T-73 "Dacron"
Tenacity, gpd*	21.7	9.8	9.5
psi	400,000	143,000	168,000
Modulus, gpd*	500	55	115
psi (10^6)	12^+	0.8	2.0
Specific Modulus, in., 10^8	2.3	0.3	0.6
Density (g/cc)	1.44	1.14	1.38
Elongation, %	4	18.3	12.0
Loop Tenacity, gpd	10.5	7.7	5.8
Knot Tenacity, gpd	7.5	-	-
Filament Diameter, in.	0.00047	0.0027	0.00024
Equilibrium Moisture Content, 55% RH, 72°F	6	3.6	0.4

*gpd = grams per denier. Denier is the weight in grams of 9000 meters of yarn. Gpd is a specific strength (or modulus) determined by dividing the yarn break load in grams by yarn denier.

+Single filament modulus.

PGR:lep

TABLE VII

SHEAR STIFFNESS BEFORE AND AFTER BIASING

Fabric	Before Biasing	After Biasing w/ 1.1 oz/yd^2 (37.3 gm/m^2) at 45°
2.1 oz/yd^2 (71.2 gm/m^2)	23 lbs. (102 n.)	82 lbs. (364 n.)
3.25 oz/yd^2 (110.2 gm/m^2)	32 lbs. (142 n.)	99 lbs. (440 n.)

TABLE VIII

SHEAR STIFFNESS OF BIAXIALLY REINFORCED FILMS

Construction	Before Laminating	After Laminating
Dacron Scrim 13 x 13 Count (Resin Impregnated) Laminated to 1 Mil Tedlar	36 lbs. (160 n.)	36 lbs. (160 n.)
Dacron Scrim 13 x 13 Count (Resin Impregnated) Laminated to .5 Mil Mylar	36 lbs. (160 n.)	36 lbs. (160 n.)
Dacron Scrim 13 x 13 count (Resin Impregnated) Laminated to 2 Layers of .25 Mil Mylar and 1 layer 1.0 Mil Tedlar	36 lbs. (160 n.)	89 lbs. (396 n.)
Kevlar Leno Scrim 5 x 5 Mesh (Laminated with 1.0 Mil Tedlar Film)	4 lbs. (18 n.)	25 lbs. (111 n.)

TABLE IX

MATERIAL PROPERTIES OF ELASTOMERS

	Tensile * (1000 PSI)	Elongation (%)	Tear (gm/mil)	Density (gm/cc)	Max. Temp.	Serv. °F-°C	Min. Temp.	Serv. °F-°C	Abrasion Resist.	Weather Resist.	UV Resist.	Mildew Resist.	Flamm.
Elastomers:													
Neoprene	3.0-4.0	550	FG	1.25	240	(116)	-40	(-40)	G	G	G	G	SE
Butyl	2-5-3.0	750	G	.90	300	(149)	-50	(-46)	G-E	G	G	F	B
Polyurethane	5.0+	650	E	1.25	240	(116)	-65	(-54)	E	G	G	F	SE
Hypalon	1.5-2.5	500	FG	1.2	325	(163)	-40	(-40)	E	E	F	E	SE
Viton	1.5-2.0	450	FF	1.4	500	(260)	-10	(-23)	G	E	F	E	SE
Natural Rubber	3.5-4.5	600	E	.93	180	(82)	-60	(-51)	E	F	P	P	B

CODE

E - Excellent
G - Good
F - Fair
P - Poor

B - Burn
SB - Slow Burn
SE - Self-Extinguishing
NF - Non-Flammable

*To convert tensile to Newtons/cm^2 multiply value in column by 689.

**Elemendorf Tear

TABLE X

MATERIAL PROPERTIES OF FILMS

	Tensile * (1000 PSI)	Elongation (%)	Tear (gm/mil)	Density (gm/cc)	Max. Temp.	Serv. °F-°C	Min. Temp.	Serv. °F-°C	Abrasion Resist.	Weather Resist.	UV Resist.	Mildew Resist.	Flam.
Films:													
Mylar	20-35	130	15	1.39	250	(121)	-80	(-62)	E	E	F	E	SB-SE
Sylon	9-13	400	75	1.12	380	(193)	-100	(-73)	E	E	F	E	SE
Polyurethane	5-10	550	710	1.22	190	(88)	-100	(-73)	E	E	F	F	SB
Tedlar	7-18	250	100	1.5	225	(107)	-100	(-73)	E	E	E	E	SB-SE
Polyethylene	1.6-3.0	800	170	0.92	180	(82)	-70	(-57)	E	E	P	E	SB
Teflon FEP	2.5-3.0	300	125	2.15	500	(260)	-425	(-254)	E	E	G	E	SF
Polyimide Kapton	25	70	8	1.42	730	(390)	-450	(-268)	E	E	E	E	SE
Hytrel													

CODE:

E - Excellent
G - Good
F - Fair
P - Poor

B - Burn
SB - Slow Burn
SE - Self-Extinguishing
NF - Non-Flammable

*To convert tensile to Newtons/cm^2 multiply value in column by 689.

**Elmendorf Tear

TABLE XI

BALLOON FILMS AND POTENTIAL GAS CELL MATERIALS

Film	Reinforcement	Weight Oz./Yd.^{2}	Tensile Strength Lbs./In. Warp	Permeability L/m^2
Polyethylene	None	0.3	15	1.00
2 Ply Mylar	None	1.6	30	0.30
Mylar	Dacron Scrim	1.6	45	1.75
Nylon	Nylon Cloth	1.9	50	2.00

TABLE XII

HASPA MATERIALS REVIEW

ENVIRONMENTAL TESTS

- TENSILE STRENGTH DEGRADED BY DEAD LOAD, WEATHERING AND HANDLING

CONDITION	TENSILE STR (LB/IN) WARP	FILL
AS LAMINATED	135	264
DEAD LOADED	77	151
DEAD LOADED - HIGH TEMP (120° F)	71	129
ARIZONA EXPOSURE	82	164
TWIST FLEX	90	160

(COMBINED EFFECTS NOT EVALUATED)

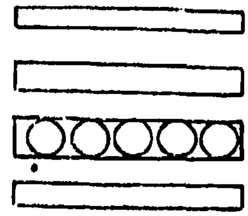
TABLE XIII - MATERIAL PROPERTIES OF SHELDAHL LAMINATE MATERIALS

Property	MATERIAL Hull G1428	Empennage G1429*	Ballonet G1444	Windscreen F014300	Test Method
Strip tensile (lb/in.)	257 MD 231 TD	225 MD 225 TD	121.6 MD 55.0 TD	198.2 MD 179.0 TD	FTMS-191-5102
Tongue tear (lb)	140 MD 112 TD	60 MD 60 TD	5.8 MD 5.8 TD	7.3 MD	FTMS-191-5134
Helium permeability ℓ/m^2/day	0.6	N/A	0.9	N/A	FTMS-191-5460
Elongation at ultimate strength (%)	26.4 MD 20.7 TD	Unspecified (MD) Unspecified (TD)	23.5 MD 35.7 TD	34.7 MD 33.7 TD	FTMS-191-5102
Minimum ply adhesion (lb/in. any ply)	2.0 and material failure (Mylar ply)	2.0 and material failure (Mylar ply)	5.7	12.1**	ASTM-D-1876
Weight (oz/sq yd)	8.2	7.5	7.3	7.3	FTMS-191-5041
Flex life (minimum cycles to lose air integrity)	<500	Unspecified	~60,000	~20,000	Bally Flexometer Test
Environmental durability					
Rain release					
Repairability	Heat seal or Staley adhesive	Heat seal or Staley adhesive	Heat seal or Staley adhesive	Heat seal or Staley adhesive	--
Reflectivity					
Abrasion resistance					

*Specification values (no test data available; however, very high confidence in values shown due to similarity with hull material)

**Coating adhesion

BIAXIAL CONSTRUCTION CANDIDATES



Tedlar

Polyurethane

Fabric

Polyurethane

Kevlar 29

Tensile (lb/in)	Weight (oz/yd^2) Urethane	Fabric	Urethane	Tedlar	Total
188	1.0	1.0	1.0	1.0	4.0
262	1.0	1.4	1.0	1.0	4.4
310	1.0	1.6	1.0	1.0	4.6
438	1.5	2.3	1.0	1.0	5.8
524	2.0	2.8	1.0	1.0	6.8
621	2.5	3.3	1.5	1.0	8.3

Polyester

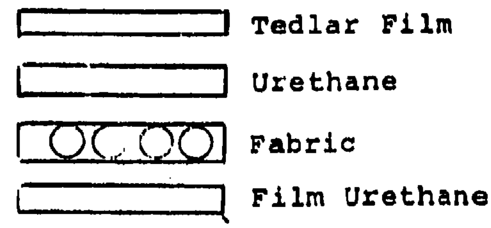
Tensile (lb/in)	Weight (oz/yd^2) Urethane	Fabric	Urethane	Tedlar	Total
122	1.0	1.8	1.0	1.0	4.8
173	1.5	2.5	1.0	1.0	6.0
207	1.5	3.0	1.0	1.0	6.5
216	1.5	3.2	1.5	1.0	7.2
244	2.0	3.6	1.5	1.0	8.1
292	2.5	4.3	1.5	1.0	9.3
462	3.5	6.8	2.0	1.0	13.3

NOTE: It is anticipated that the minimum weight shown in the table represents the lightest composite weight that can readily be manufactured and handled using normal equipment and processes.

Conversion factors: 1 oz/yd^2 = 33.91 gm/m^2
1 lb/in = 1.75 n/cm

TABLE XV

TRIAXIAL CONSTRUCTION CANDIDATES



Kevlar 29

Count*	Yarn**	Tensile (lb/in)	Weight (oz/yd^2) Film Urethane	Fabric	Urethane	Tedlar Film	Total
18.5 x 3	140/1	105	1.5	1.0	1.0	1.0	4.5
18.5 x 3	200/1	150	1.5	1.5	1.0	1.0	5.0
18.5 x 3	400/1	370	2.0	3.1	1.4	1.0	7.5
18.5 x 3	400/2	740	2.0	6.2	1.8	1.0	11.0
18.5 x 3	400/3	1100	2.5	9.3	2.2	1.0	15.0
18.5 x 3	1000/2	1850	4.0	15.4	3.6	1.0	24.0
10.0 x 3	1500/3	2250	4.2	18.8	4.0	1.0	28.0
10.0 x 3	1500/4	3000	6.0	25.0	4.5	1.0	36.5
18.5 x 3	1500/3	4150	7.0	34.7	5.3	1.0	48.0

Dacron Polyester

Count*	Yarn**	Tensile (lb/in)	Weight (oz/yd^2) Film Urethane	Fabric	Urethane	Tedlar Film	Total
18.5 x 3	200/1	65	1.5	1.5	1.0	1.0	5.0
18.5 x 3	400/1	130	2.0	3.1	1.4	1.0	7.5
18.5 x 3	400/2	260	2.0	6.2	1.8	1.0	11.0
18.5 x 3	400/3	390	2.5	9.3	2.2	1.0	15.0
18.5 x 3	1000/2	650	4.0	15.4	3.6	1.0	24.0
10.0 x 3	1500/3	790	4.2	18.8	4.0	1.0	28.0

* ends per inch x # of axes
** yarn denier/# of plies

NOTE: It is anticipated that the minimum weight shown in the table represents the lightest composite weight that can readily be manufactured and handled using normal equipment and processes.

Conversion factors: 1 oz/yd^2 = 33.91 gm/m^2
1 lb/in = 1.75 n/cm

TABLE XVI

COMPARISON OF 1950 AND PRESENT DAY NON-RIGID AIRSHIP ALTERNATIVES

NON-RIGID AIRSHIPS

1950 ALTERNATIVES		1976 ALTERNATIVES
Cotton/Neoprene Dacron/Neoprene Rayon/Neoprene	Envelopes	Dacron/Polyurethane Kevlar/Polyurethane
Stainless Stell Galvinized Wire	Catenary Cables	Kevlar Ropes

TABLE XVII

COMPARISON OF 1929 AND PRESENT DAY METALCLAD AIRSHIP MATERIALS ALTERNATIVES

METALCLAD AIRSHIPS

1929 ALTERNATIVES		1976 ALTERNATIVES
24ST LOW CARBON STEEL STAINLESS STEEL	FRAMING	7075/7050 ALUM ALLOY TITANIUM STAINLESS STEEL KEVLAR GRAPHITE FIBERGLAS
24ST ALCLAD	COVERING	7075/7050 ALCLAD 7075/7050/5056 CR SANDWICH CONSTRUCTIONS
NEOPRENE/COTTON	CELLS	KEVLAR/POLYURETHANE MYLAR FILM DACRON/POLYURETHANE KEVLAR/POLYESTER/POLYURETHANE
PIANO WIRE	WIRING	KEVLAR ROPES
NEOPRENE	ADHESIVES	EPOXIES EPOXY - PHENOLICS EPOXY - POLYAMIDES EPOXY - POLYSULFIDES EPOXY - SILICONES PHENOLICS
DRYING OILS	SEALANTS	POLYSULFIDES SILICONES

TABLE XVIII

BREAKING STRENGTH OF TRIAXIAL FABRIC SAMPLES

	BP21P U	BP21P C	BP21PK U	BP21PK C	B20K U	B20K C	B20KP U	B20KP C
Breaking Strength (lbs/inch)								
Machine Direction	333	337	260	286	206	155	221	195
Bias Direction	252	235	235	273	104	-	125	123
Crosswise Direction	198	204	185	205	201	127	81	80
Average	261	259	227	255	170	141	142	133
Fabric Weight (oz/sq.yd)	7.5		6.25		4.35		4.86	
Normalized Breaking Strength $\left(\frac{\text{lbs/inch}}{\text{oz/sq.yd}}\right)$								
Machine Direction	44	45	42	46	47	36	46	40
Bias Direction	34	31	38	44	24	-	26	25
Crosswise Direction	26	27	30	33	46	29	17	17
Average	35	35	36	41	39	32	29	27

U = uncreased fabric
C = creased fabric

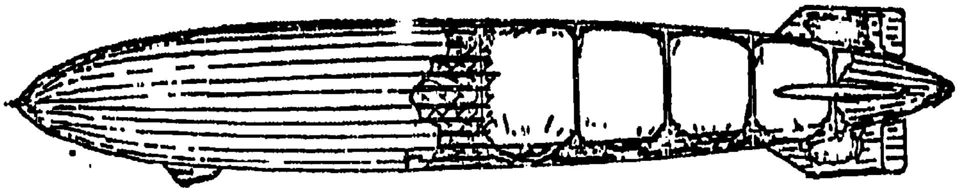
TABLE XIX

TEAR STRENGTH OF TRIAXIAL FABRIC SAMPLES

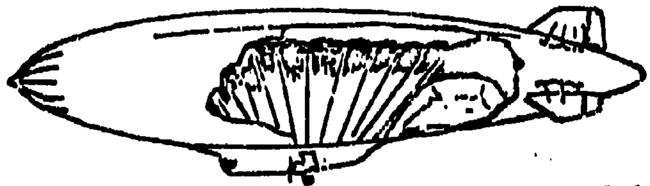
	Tongue Tear				Trapezoid Tear			
	BP21P	BP21PK	B20K	B20KP	BP21P	BP21PK	B20K	B20KP
Tear Strength (lbs)								
Machine Direction	10	40	35	39	28	37	42	46
Crosswise Direction	10	39	33	19	48	73	35	54
Average	10	40	34	29	38	55	39	50
Coated Fabric Weight (oz/sq.yd)	7.5	6.25	4.35	4.86	7.5	6.25	4.35	4.86
Normalized Tear Strength $\left(\frac{\text{lbs}}{\text{oz/sq.yd}}\right)$								
Machine Direction	1.3	6.4	8.0	8.0	3.7	5.9	9.7	9.5
Crosswise Direction	1.3	5.2	7.6	3.9	6.4	11.7	8.1	11.1
Average	1.3	6.3	7.8	6.0	5.1	8.8	8.9	10.3

*Tear strength readings are the highest peak values in each of the first five centimeters of the Instron chart according to ASTM Standard D2261.

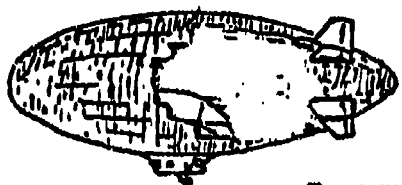
AIRSHIP STRUCTURAL TYPES



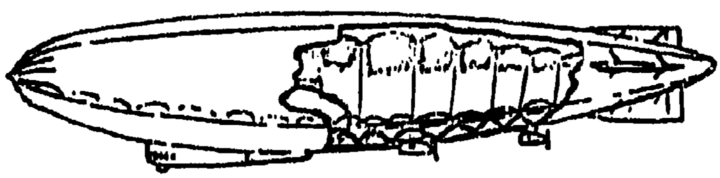
Non-pressure rigid



Pressure non-rigid



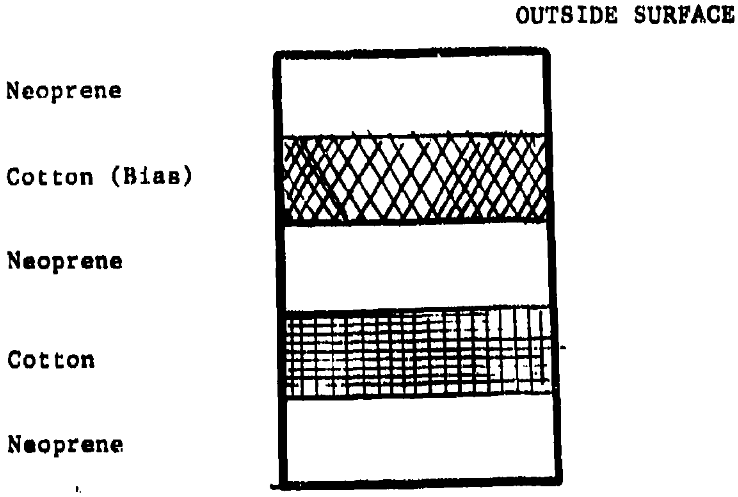
Pressure rigid



Pressure semi-rigid

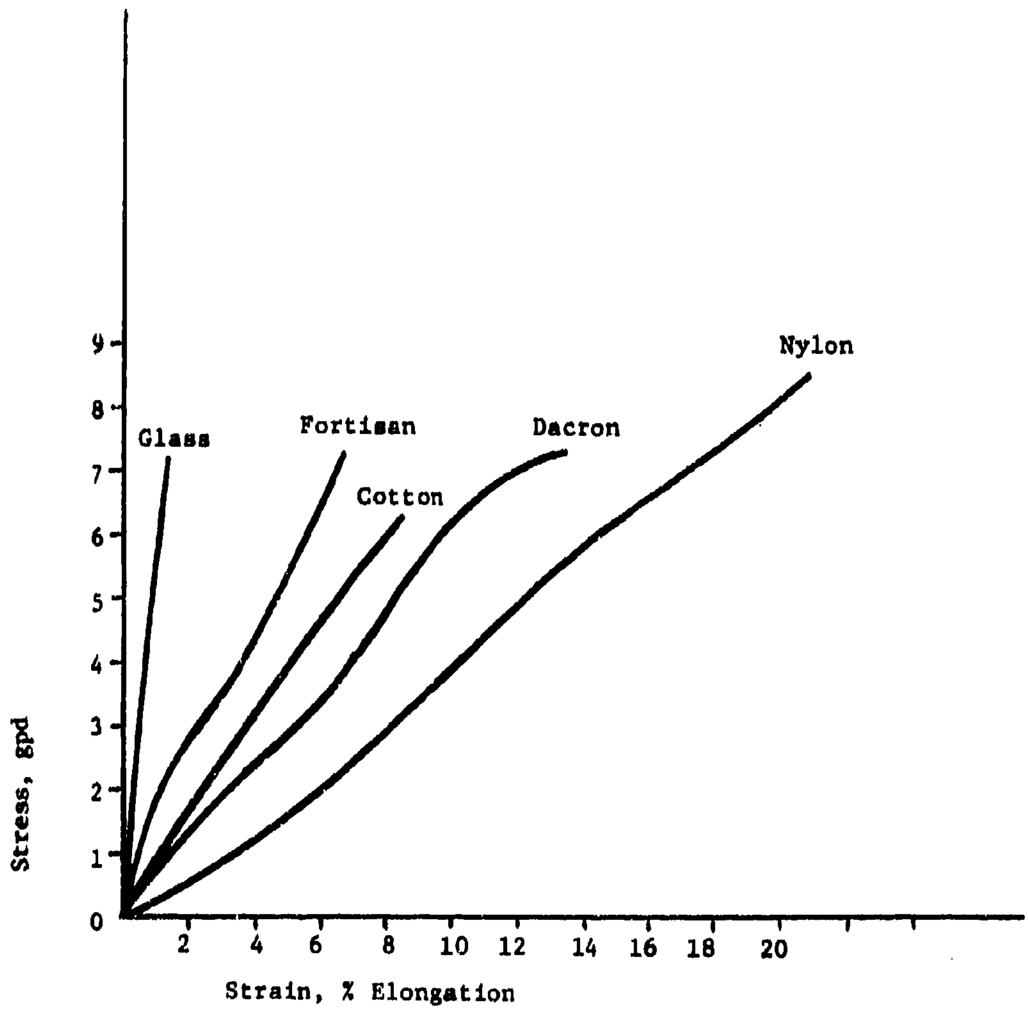
Figure 1

MATERIAL CONSTRUCTION (HULL)



MATERIAL PROPERTIES (HULL)	(For Early Tethered Balloon)	(For Airship Hull of 50's)
WEIGHT	kg/m^2 (OZ/YD^2) 406 (12)	(OZ/YD^2) (20–22)
TENSILE		
WARP	N/m (LBS/IN) 20,650 (118)	(220)
FILL	18,375 (105)	(210)
COATING ADHESION		(13–14)
PLY ADHESION		
HELIUM PERMEABILITY ($1/m^2/24$ hrs)	2.5	(3.0)

FIGURE 2 - Early Fabric Construction for LTA Applications



gpd = grams per denier. Denier is the weight in grams of 9000 meters of yarn. Gpd is a specific strength (or modulus) determined by dividing the yarn break load in grams by yarn denier.

FIGURE 3 - Stress Strain Curves for Cotton, Dacron, Fortisan, Glass and Nylon

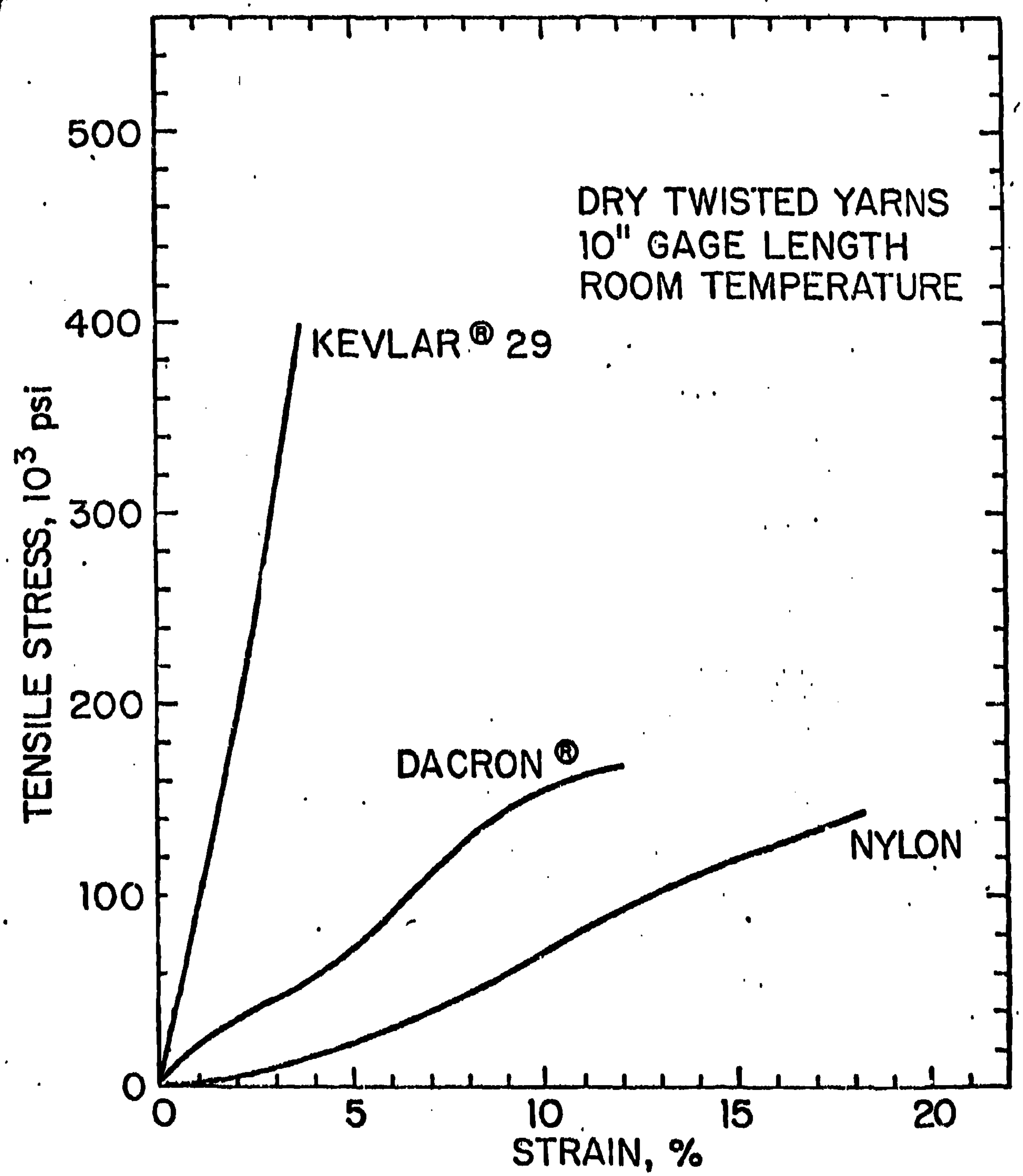


FIGURE 4 - Yarn Stress Strain Curves of Dacron, Nylon and Kevlar

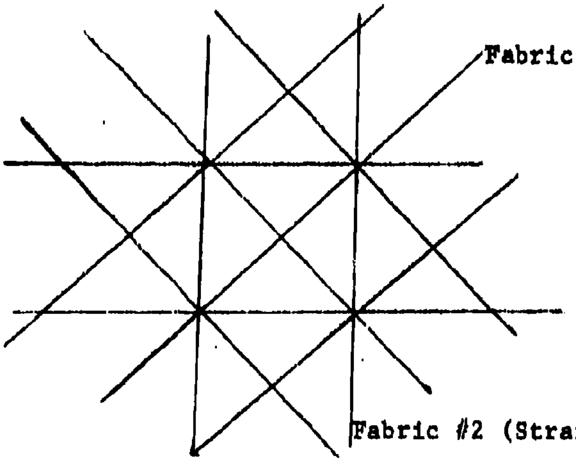


FIGURE 5 - YARN ORIENTATION OF BIASED ORTHOGONAL FABRICS

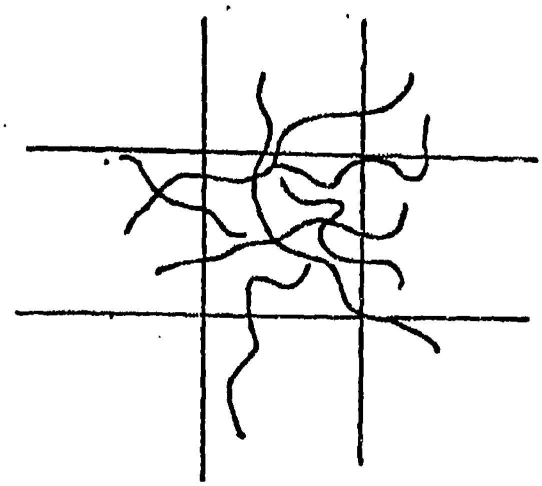


FIGURE 6 - Random Yarn Orientation of Spunbonded Reinforced Fabrics

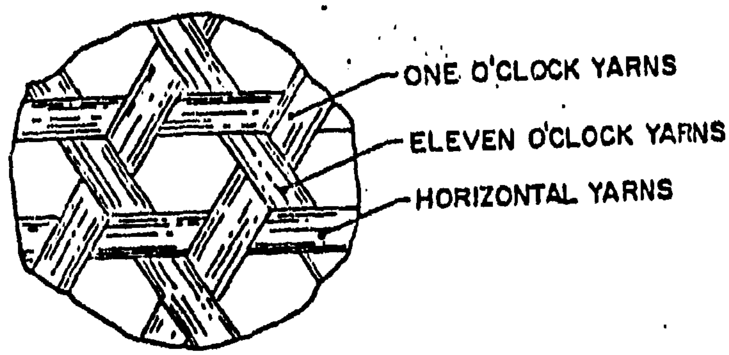
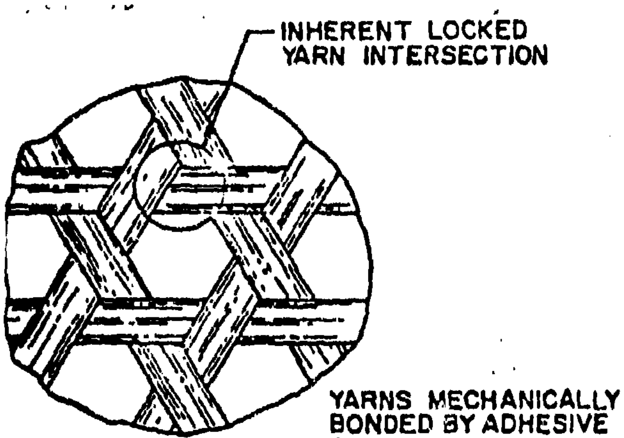
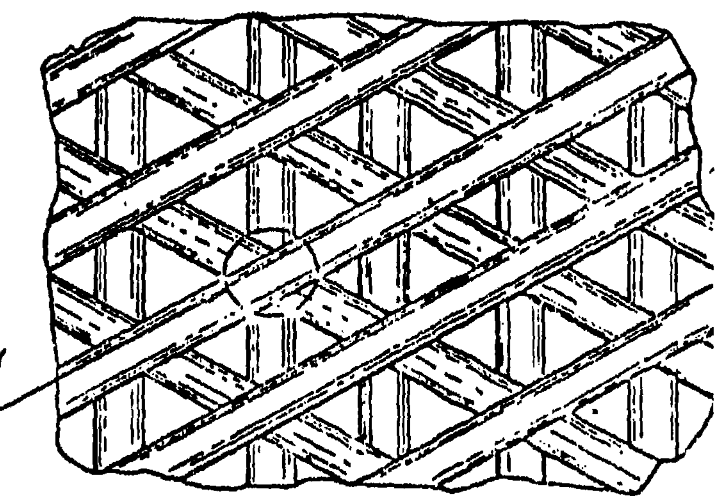


FIGURE 7 - DOWEAVE CONSTRUCTION



a Doweave



b. FTL

FIGURE 8 - Doweave Construction Compared to FTL

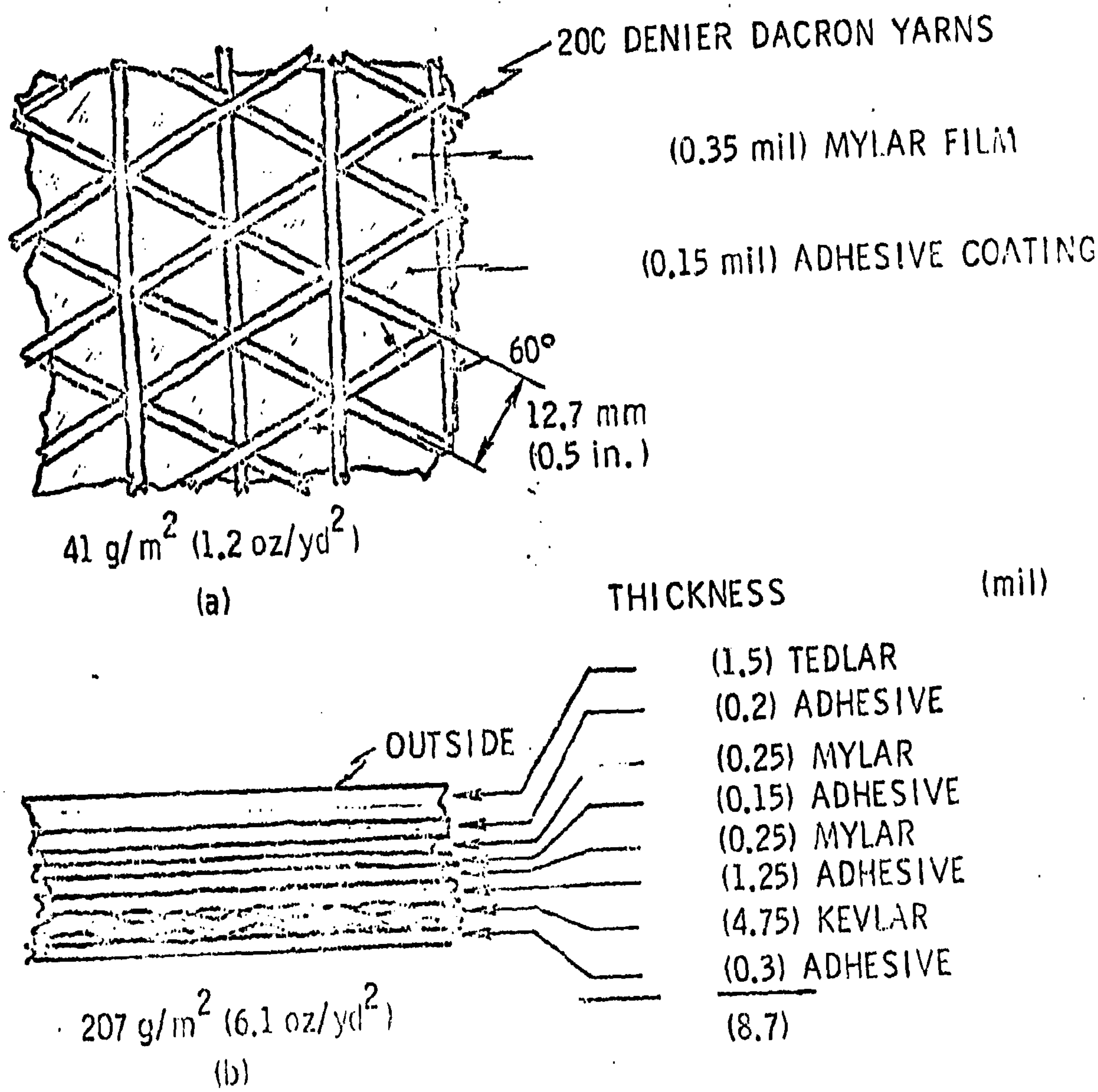


FIGURE 9 - Typical fabrication of material for inflatable structures.

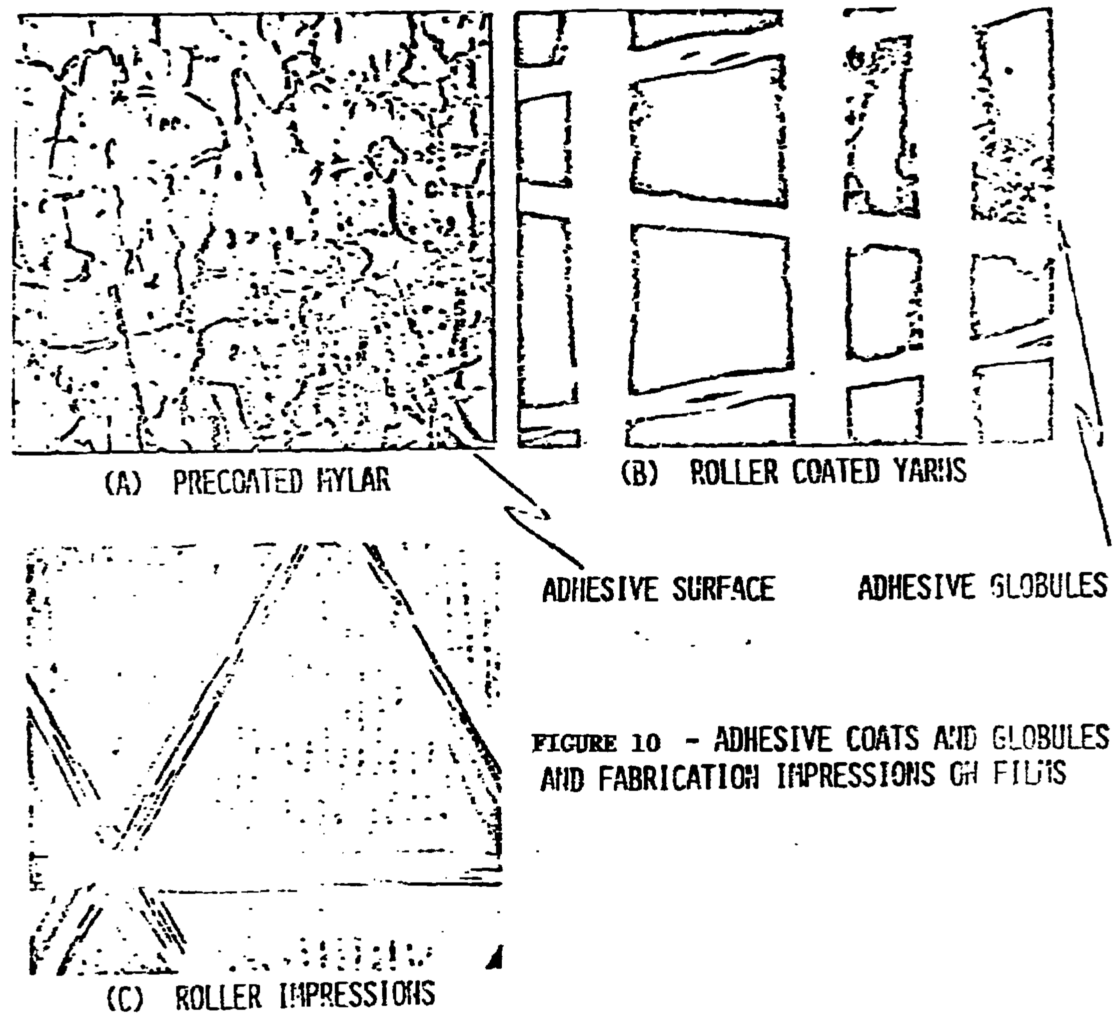


FIGURE 10 - ADHESIVE COATS AND GLOBULES AND FABRICATION IMPRESSIONS ON FILMS

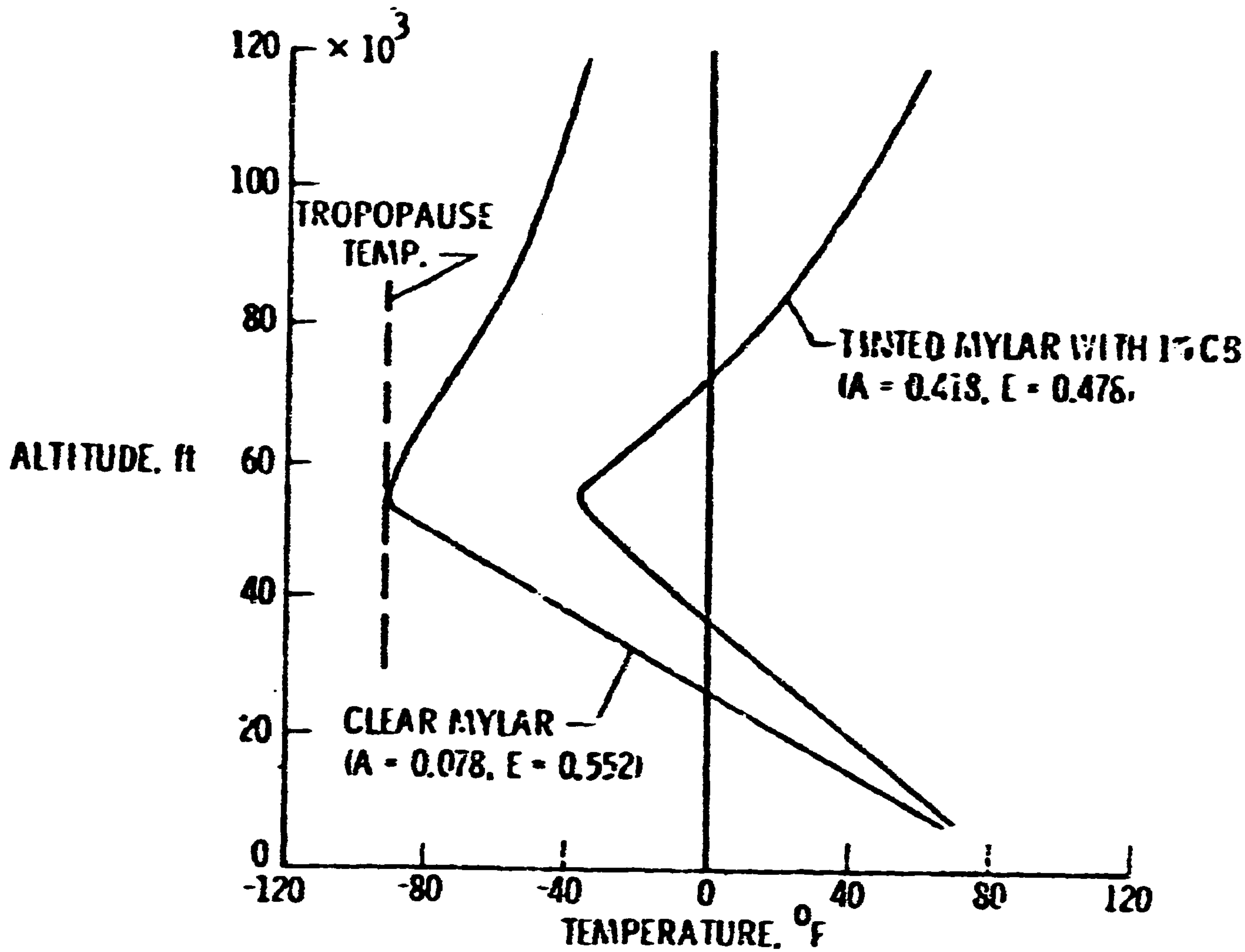


FIGURE 11 - Film Temperature Versus Altitude for Tinted Mylar Balloons

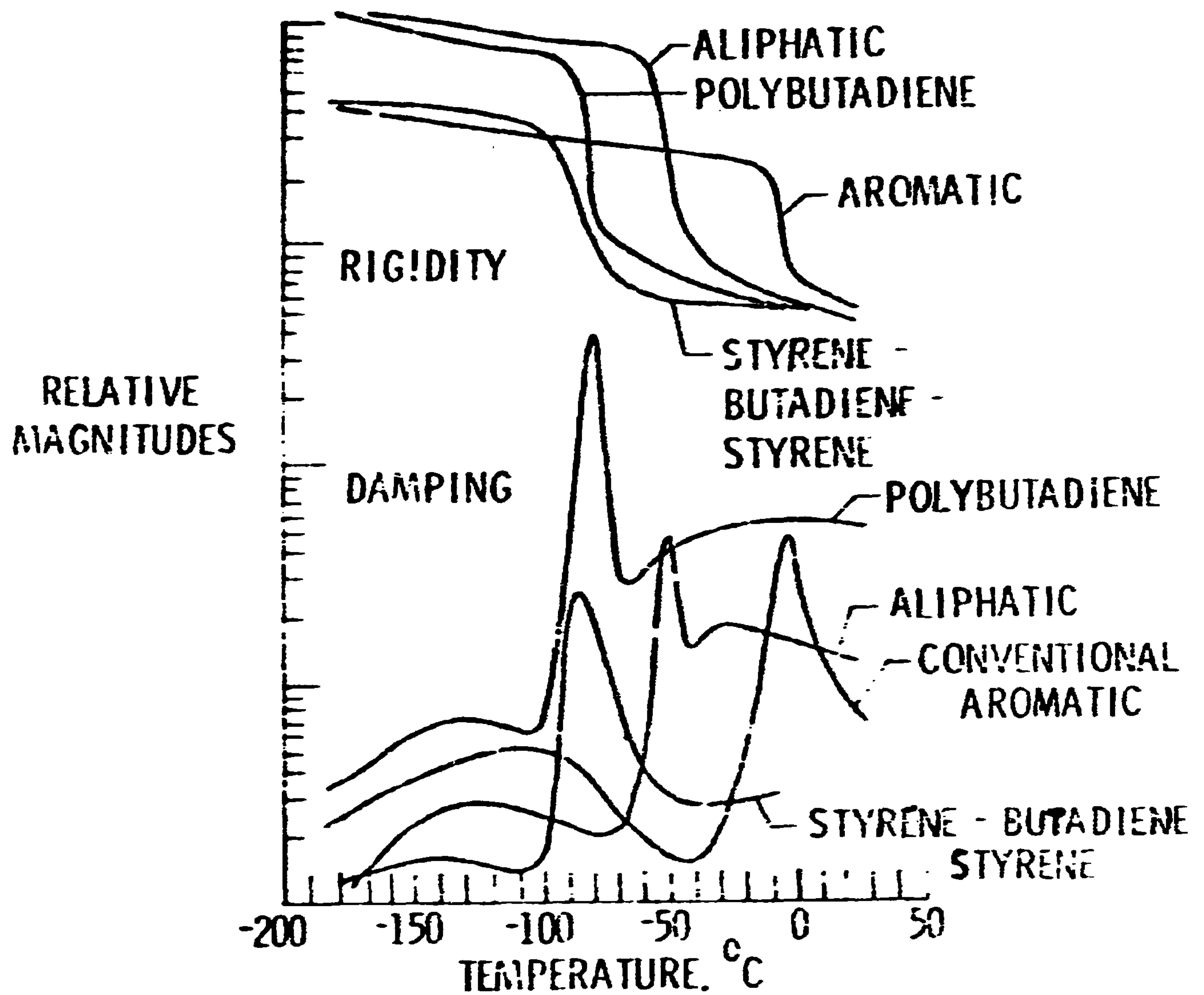


Figure 12. Thermochemical Spectra of Four Classes of Polymers

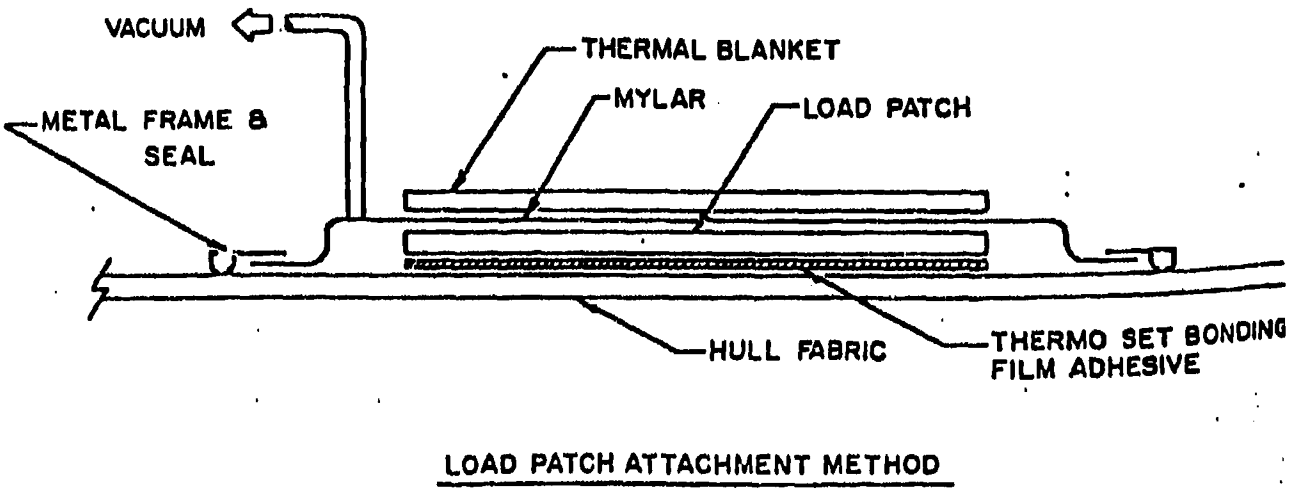
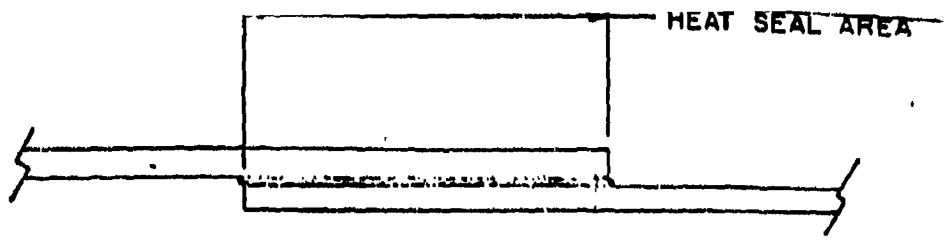
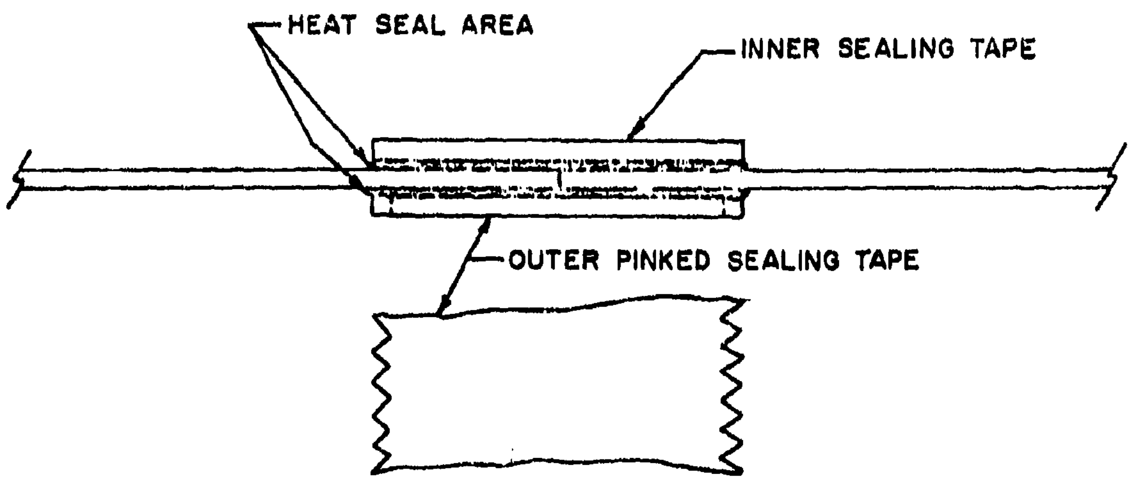


FIGURE 13 - Load Patch Attachment Method



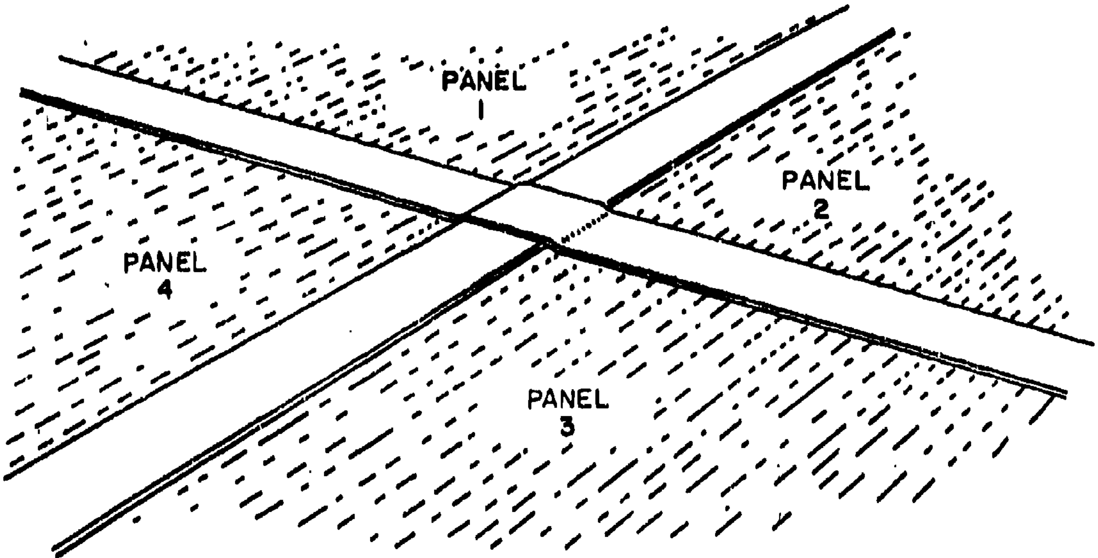
BASIC HEAT-SEAL LAP SEAM

Figure 14



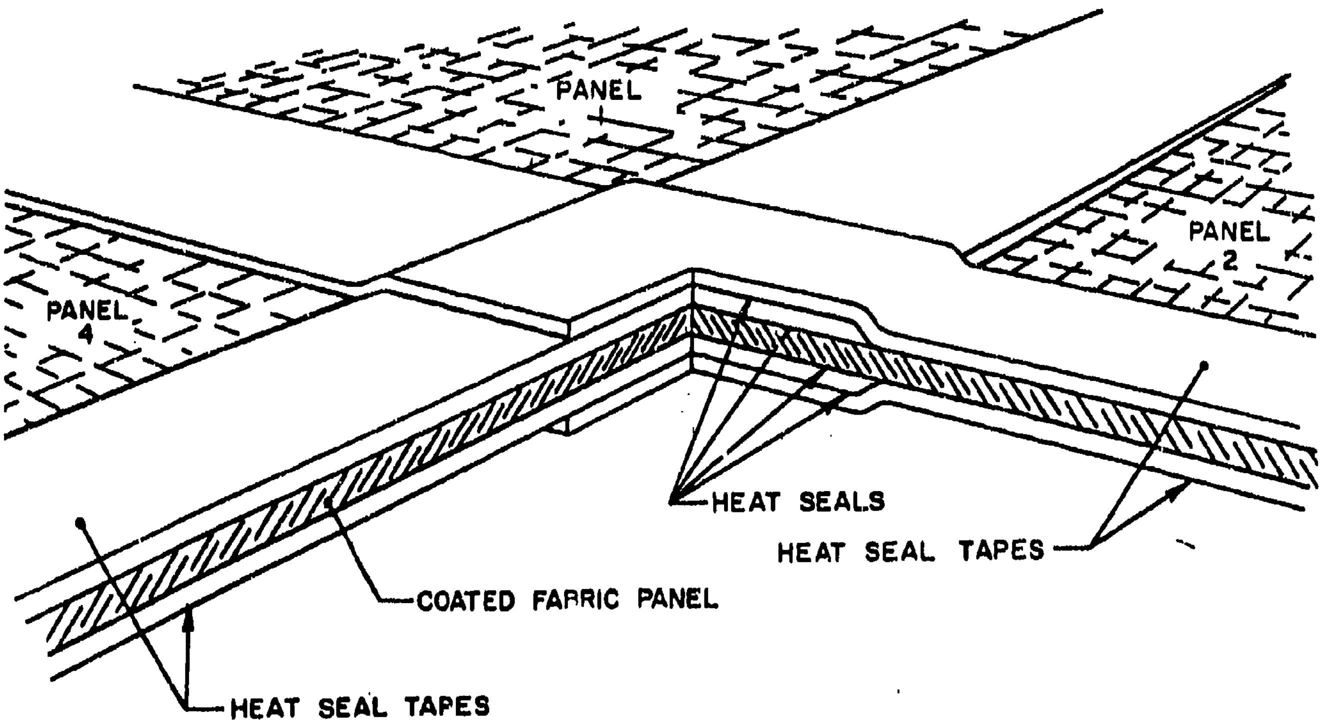
MODIFIED HEAT-SEAL LAP SEAM

Figure 15



PANEL AND SEAM CONSTRUCTION

Figure 16



METHOD FOR JOINING FOUR
PANELS BY HEAT-SEALING
TYPICAL HEAT SEAL INTERSECTION

Figure 17

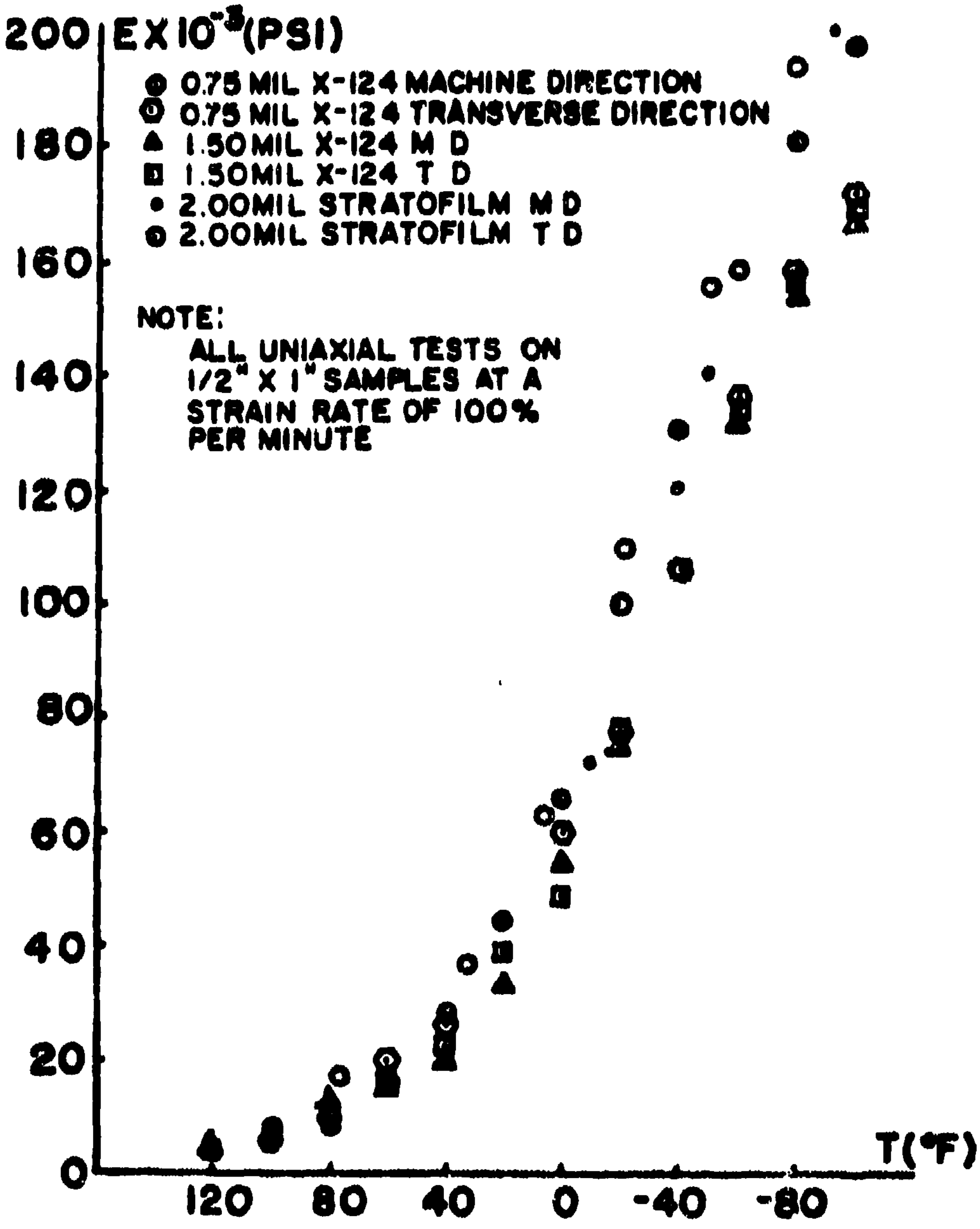


Figure 18 Modulus Versus Temperature for Polyethylene Balloon Films

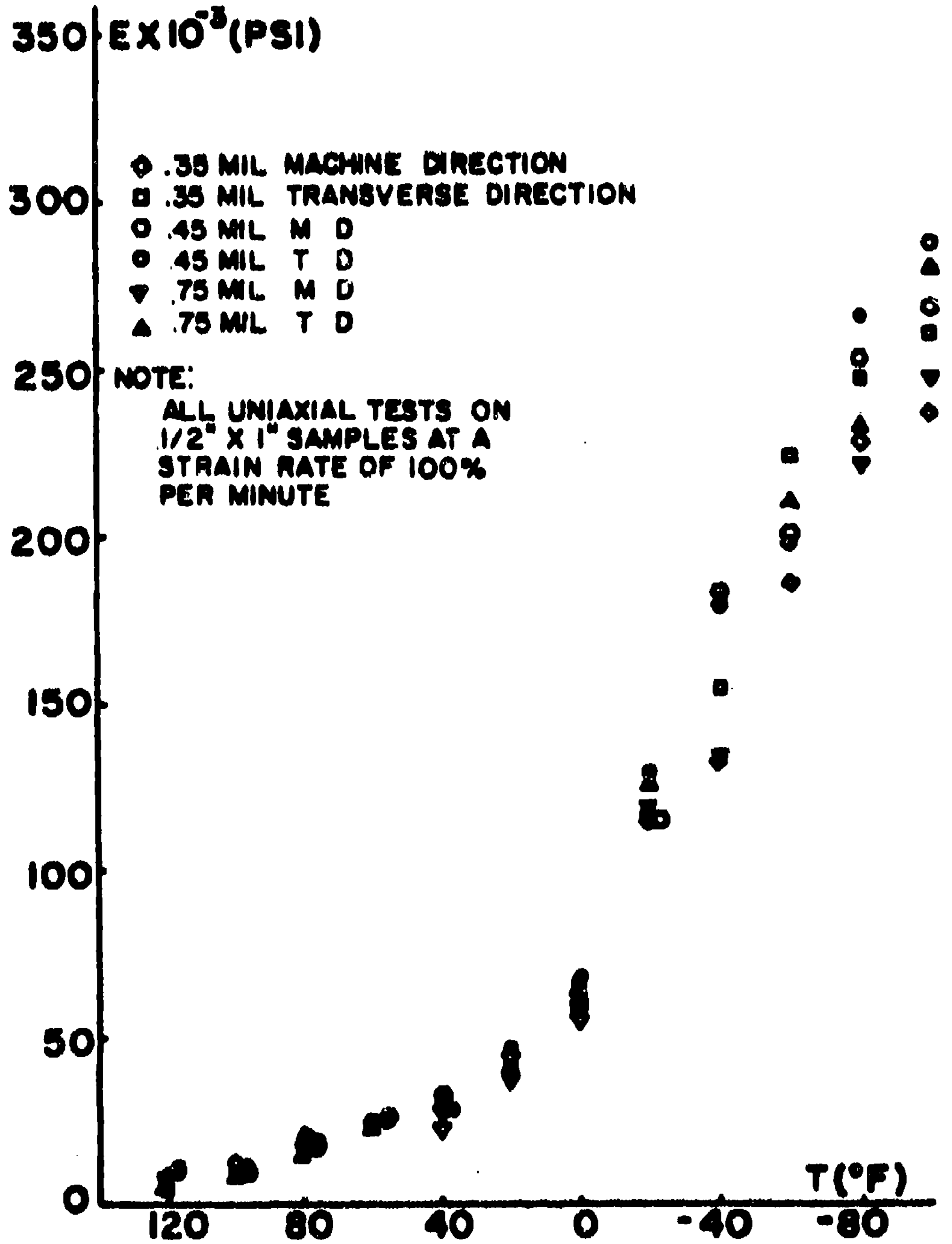


Figure 19 Modulus Versus Temperature for Thin StratoFilm

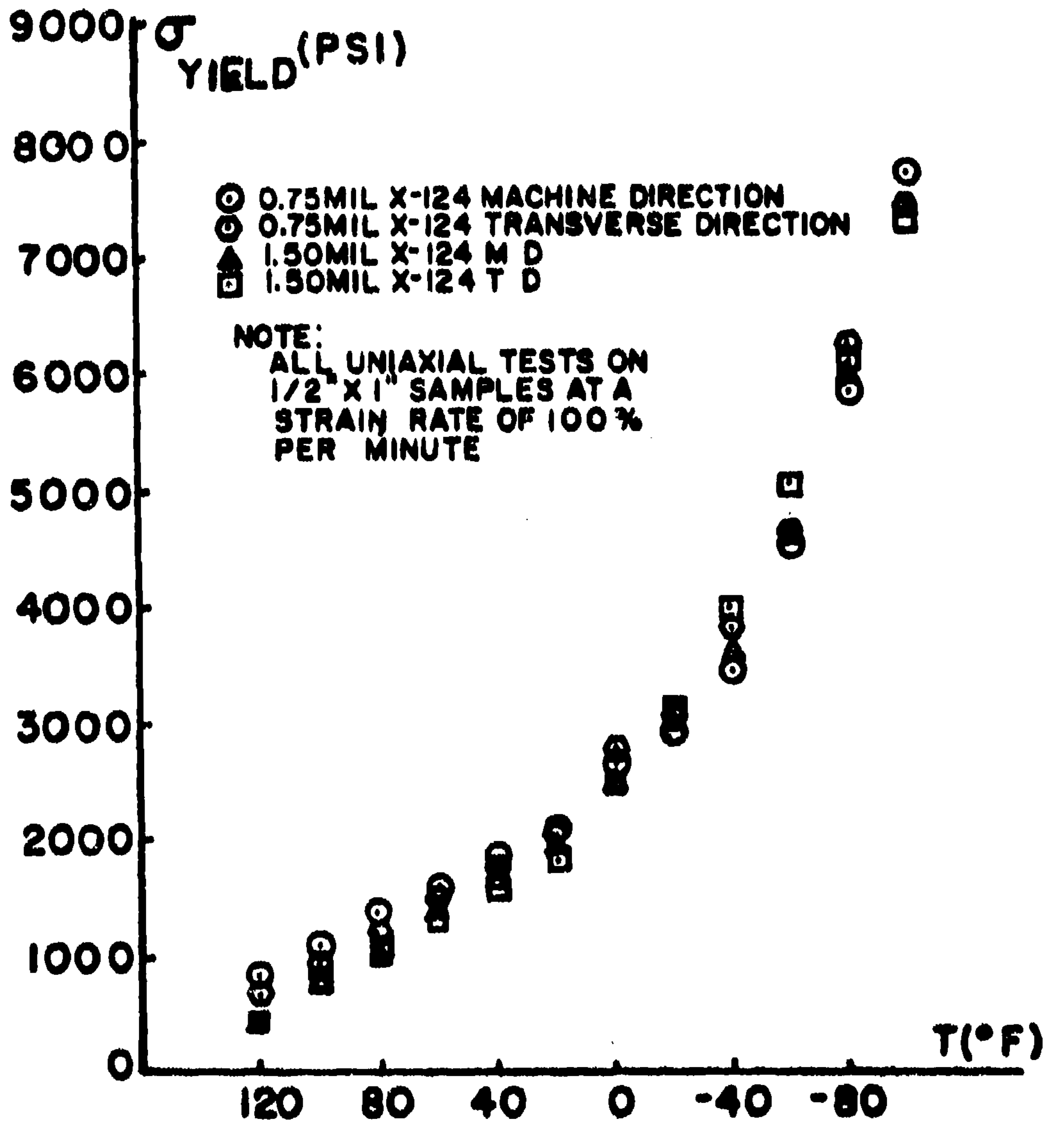
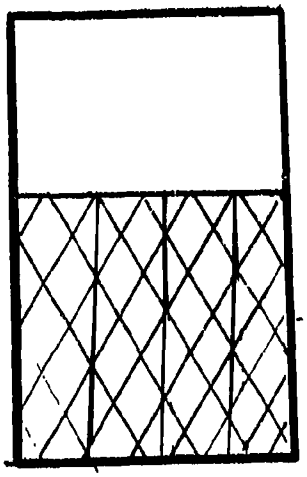


Figure 20 Yield Stress Versus Temperature for Polyethylene Balloon Films

MATERIAL CONSTRUCTION (HULL)



0.35 Mylar = Film (precoated with 0.15 mil polyester adhesive)

Dacron

Longitudinal yarn - 1300 denier

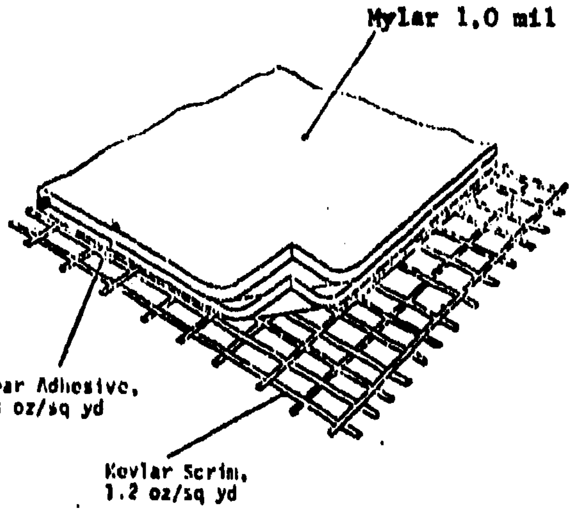
Diagonal yarns - 440 denier

MATERIAL PROPERTIES

	kg/m^2	oz/yd^2
Weight		1.2
Tensile	n/m	lbs/in
Machine (Warp)		15
Transverse (Fill)		9
Bias		6
Coating Adhesion		
Ply Adhesion		
Helium Permeability $\ell/m^2/24$ hrs.		

FIGURE 21 - BLDT Viking Reinforced Films (Dacron)

MATERIAL CONSTRUCTION (HULL)

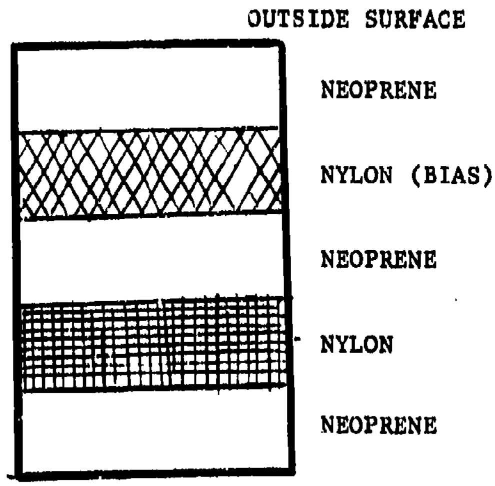


MATERIAL PROPERTIES

Weight, oz./yd^2	2.7
Tensile Strength, lbs/in.	
Warp	135.0
Fill	264.0
Ply Adhesion, lbs/in	
Fill	1.5
Helium Permeability, l/m^2/24 hrs.	1.1

Figure 22 HASPA, Reinforced Film (Kevlar)

MATERIAL CONSTRUCTION (HULL)

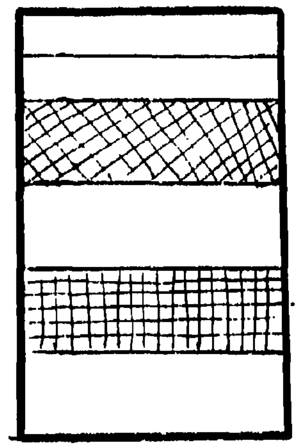


MATERIAL PROPERTIES (HULL)

	kg/m^2	(OZ/YD^2)
WEIGHT ------------------	.376	(11.06)
TENSILE		
WARP ------------------	N/m (LBS/IN)	
	22,400 (128)	
FILL ------------------	23,975 (137)	
COATING ADHESION -----------	1,225 (7)	
PLY ADHESION---------------	2,450 (14)	
HELIUM PERMEABILITY--------- (1/m^2/24 hrs)	2.0	

FIGURE 23 - Modified Balloon Barrage

MATERIAL CONSTRUCTION (HULL)



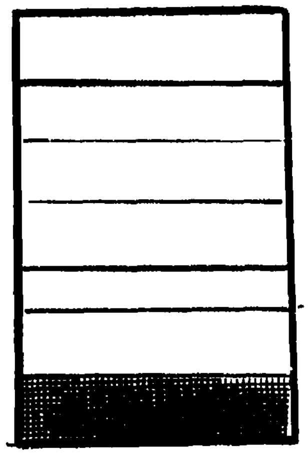
	OUTSIDE SURFACE oz/yd^2
HYPALON	0.9 (alum peg)
NEOPRENE	1.5
DACRON (BIAS)	3.25
NEOPRENE	3.6
DACRON	3.25
NEOPRENE	0.3

MATERIALS PROPERTIES (HULL)

	(tethered aerostate fabric)	
WEIGHT	kg/m^2	(OZ/YD^2)
	.439	(12.9)
TENSILE		
WARP	N/m	(LBS/IN)
	26,250	(150)
FILL	26,250	(150)
COATING ADHESION	1,225	(7)
PLY ADHESION	787.5	(4.5)
HELIUM PERMEABILITY (1/m^2/24 hrs)		2

FIGURE 24 - Hull Bias Ply Fabric (F007400 - Sheldahl)

MATERIAL CONSTRUCTION (HULL)



	OZ/YD^2
Tedlar (film)	1.9
Adhesive (black)	
Mylar (film)	0.25 (.25 mil)
Adhesive (black)	
Mylar	0.25 (.25 mil)
Adhesive	
Dacron (Open weave)	3.8

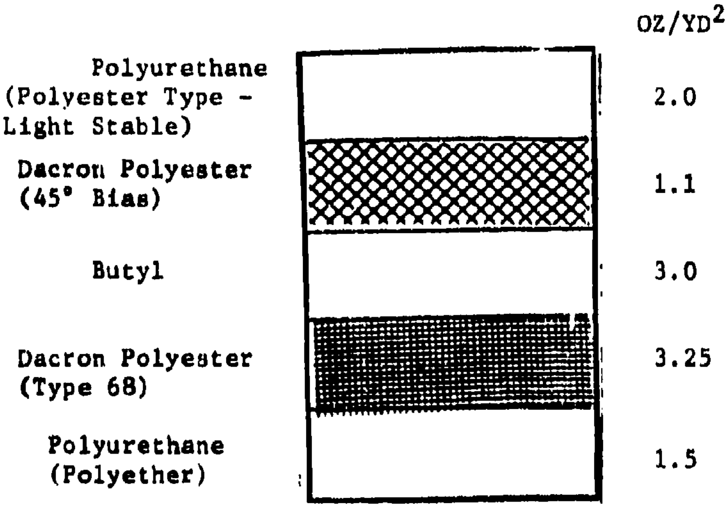
MATERIAL PROPERTIES

	kg/m^2	(oz/yd^2)
Weight	0.292	8.6
Tensile	N/m	(lbs/in)
Warp	39,375	225
Fill	39,375	225
Tongue Tear		
Warp	10,500	60
Fill	10,500	60
Peel	1,750	10
Helium Permeability ($1/m^2$/24 hrs)	0.5	

FIGURE 25 - Hull Multilayer Laminate (G-124900 - Sheldahl)

MATERIAL CONSTRUCTION (HULL)

Coated Fabric



MATERIAL PROPERTIES

WEIGHT, OZ/YD^2 ------------------ 10.85

LOW TEMPERATURE FLEX - No cracks (1/8" mandrel @ -40°F)

TENSILE, LBS/IN

WARP -------------------------- 175
FILL -------------------------- 160

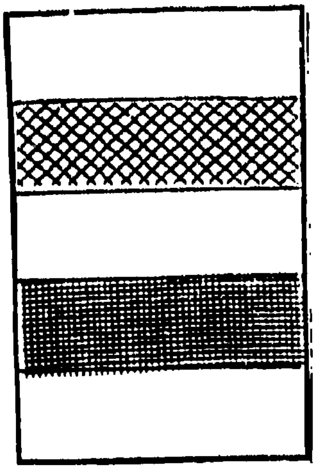
ADHESION, LBS/IN

COATING ---------------------- 7.0 min
PLY -------------------------- 7.0 min
BIAS SEAM -------------------- 4.0 min

PERMEABILITY, $\ell/m^2/24$ hrs 1.0 max.

FIGURE 26 - Hull Bias Ply Coated Fabric (A105003E-ILC)

MATERIAL CONSTRUCTION (HULL)



OUTSIDE

2.3 oz Wht, light stab. polyester type polyurethane

1.4 oz Typ. 55 Dacron, bias, 100x100x40D

3.0 oz Butyl rubber

3.25 oz Typ. 68 Dacron, st. 52x52x220D

0.5 oz Clear, polyether type polyurethane

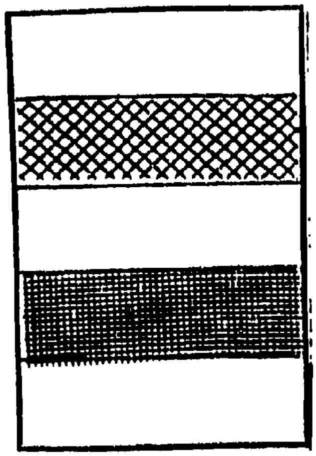
MATERIAL PROPERTIES

WEIGHT, OZ/YD^2	10.5
TENSILE, LBS/IN	
WARP	180
FILL	180
BIAS	
PERMEABILITY, ℓ/m^2/day	0.5

FIGURE 26a - Hull Bias Ply Coated Fabric (A105003-ILC)

MATERIAL CONSTRUCTION (BALLONET)

Coated Fabric



MATERIAL PROPERTIES (BALLONET)

WEIGHT, OZ/YD^2 ------------------ 5.8 +.75 -0.5

TENSILE, LBS/IN

WARP ------------------------- 40 min
FILL ------------------------- 40 min

ADHESION, LBS/IN

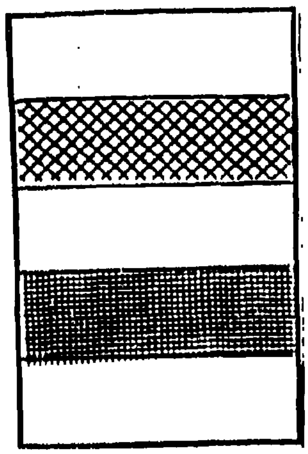
COATING ---------------------- 7.0 min
PLY -------------------------- 7.0 min
BIAS SEAM -------------------- 4.0 min

PERMEABILITY, $\ell/m^2/24$ hrs. 1.0 max

Low Temperature Flex (1/8" mandrel) No Cracks at -40°F

FIGURE 27 - Ballonet Bias Ply Coated Fabric (A-105004C-ILC)

MATERIAL CONSTRUCTION (BALLONET)



Upper (Helium) Side

.5 oz Clear polyether type polyurethane

1.4 oz 55 Dacron bias 100x100x40D

2.6 oz Butyl rubber

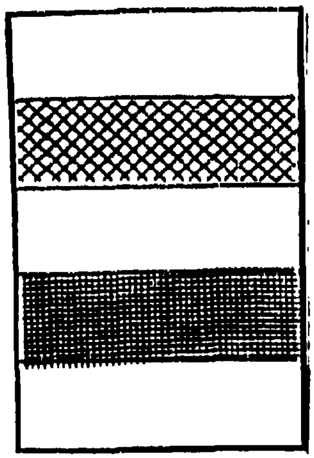
1.4 oz 55 Dacron st. 100x100x40D

.5 oz Clear polyether type polyurethane

Lower (Air) Side

FIGURE 27a - Ballonet Bias Ply Coated Fabric (A-105004-ILC)

MATERIAL CONSTRUCTION (WINDSCREEN)



	OZ/YD^2
Polyurethane (Polyester-light, stable)	2.5
Dacron Polyester (45° Bias)	1.1
Butyl	2.6
Dacron Polyester	2.1
Polyurethane (Polyether)	1.0

MATERIAL PROPERTIES

WEIGHT, OZ/YD^2 ---------------------- 9.3

Low Temperature Flex - No cracks (1/8" mandrel) @-40°F

TENSILE, LBS/IN

- WARP ------------------------------ 95 min
- FILL ------------------------------ 95 min

ADHESION, LBS/IN

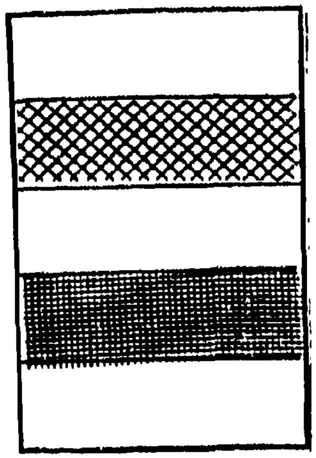
- COATING ------------------------ 7.0
- PLY ------------------------------ 7.0
- BIAS SEAM ---------------------- 4.0

PERMEABILITY, ℓ/m^2/24 hrs.

- HELIUM ------------------------- 2.0

FIGURE 28 - Windscreen Bias Ply Coated Fabric (A105002D-ILC)

MATERIAL CONSTRUCTION (WINDSCREEN)



OUTSIDE

1.5 oz Wh. light-stable polyester type polyurethane

1.4 oz 55 Dacron, bias, 100x100x40D

2.6 oz Butyl rubber

2.1 oz 52 Dacron st. 100x100x70D

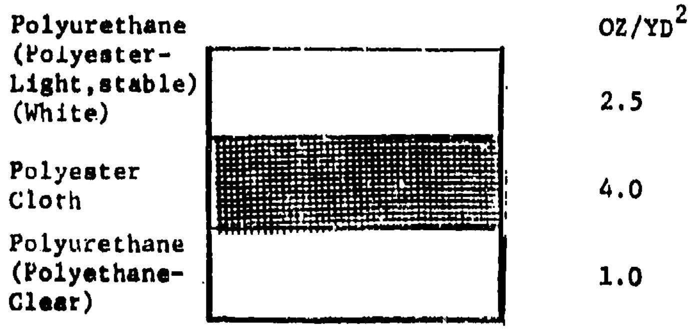
.5 oz Clear polyether type polyurethane

INSIDE

FIGURE 28a - Windscreen Bias Ply Coated Fabric (A105002-ILC)

MATERIAL CONSTRUCTION (FIN)

Single Ply Coated Cloth



MATERIAL PROPERTIES

WEIGHT, OZ/YD^2 ------------------- 7.5 $\pm$0.5

TENSILE, LBS/IN
  WARP --------------------------- 200
  FILL --------------------------- 200

ADHESION, LBS/IN

  COATING ----------------------- 7.0 min

PERMEABILITY, ℓ/m^2/24 hrs.

  AIR --------------------------- 2.0

TEAR, LBS ---------------------- 8.0

Low Temperature Flex
 1/8" mandrel No cracks at -40°F

FIGURE 29 - Fin Single Ply Coated Cloth (A-106002-ILC)

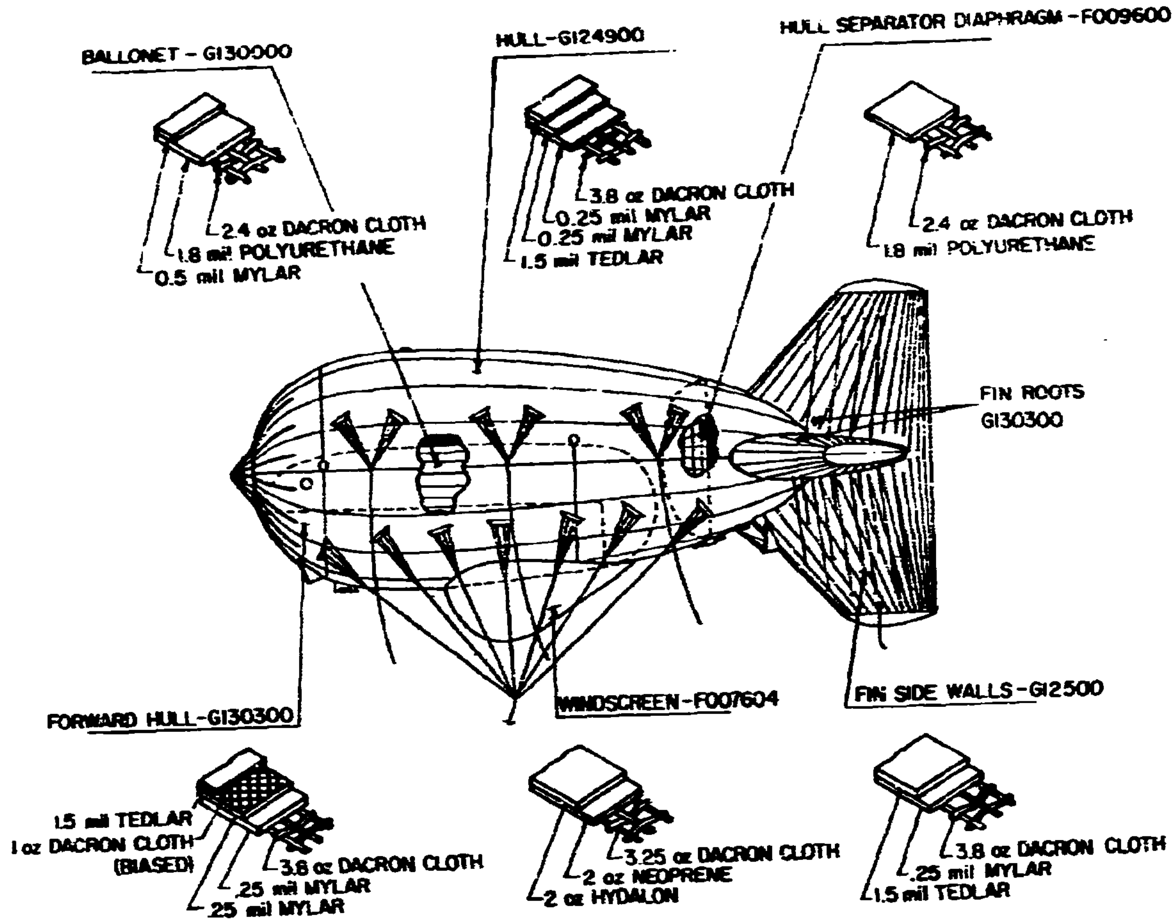
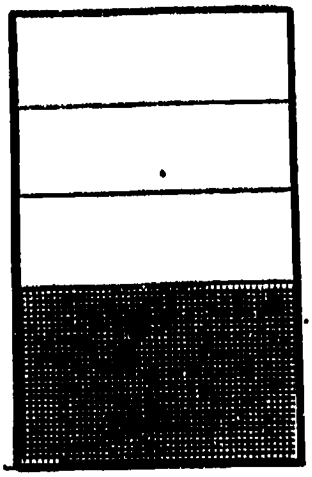


FIGURE 30 - Fabrics Used in Construction of ICOM Aerostat

MATERIAL CONSTRUCTION (HULL)



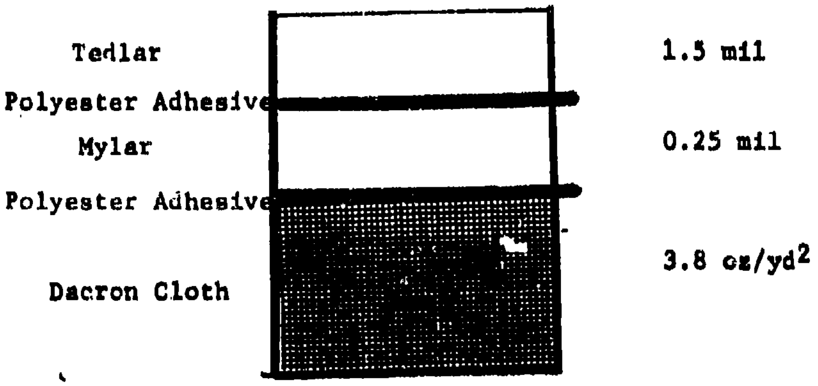
TEDLAR (WHITE)	1.5 mil
	Polyester Thermoset Adhesive (Black)
MYLAR	0.25 mil
	Polyester Thermoset Adhesive (Black)
MYLAR	0.25 mil
	Polyester Thermoset Adhesive (Clear)
DACRON	3.8 OZ/YD^2

MATERIAL PROPERTIES

WEIGHT, OZ/YD^2	8.0 $\pm$1.0
TENSILE STRENGTH, LBS/IN Min.	
WARP	225
FILL	225
TONGUE TEAR, LBS Min.	
WARP	60
FILL	60
HELIUM PERMEABILITY, Max. Liters/$meter^2$/24 hours	0.5
PEEL, LBS/IN Min.	
As received	10.0
After immersion in distilled water for 72 hours	8.0

FIGURE 31 - Hull Multilayer Laminate for TCOM Aerostat (G1249 - Sheldahl)

MATERIAL CONSTRUCTION (FINS)



MATERIAL PROPERTIES

WEIGHT, OZ/YD^2	7.5 $\pm$1.0
TENSILE STRENGTH, LBS/IN Min.	
WARP	225
FILL	225
TONGUE TEAR, LBS. Min.	
WARP	60
FILL	60
PEEL, LBS/IN Min.	
As received	10.0
After immersion in distilled water for 72 hours	8.0

FIGURE 32 - Fin Multilayer Laminate for TCOM Aerostat (G125000 - Sheldahl)

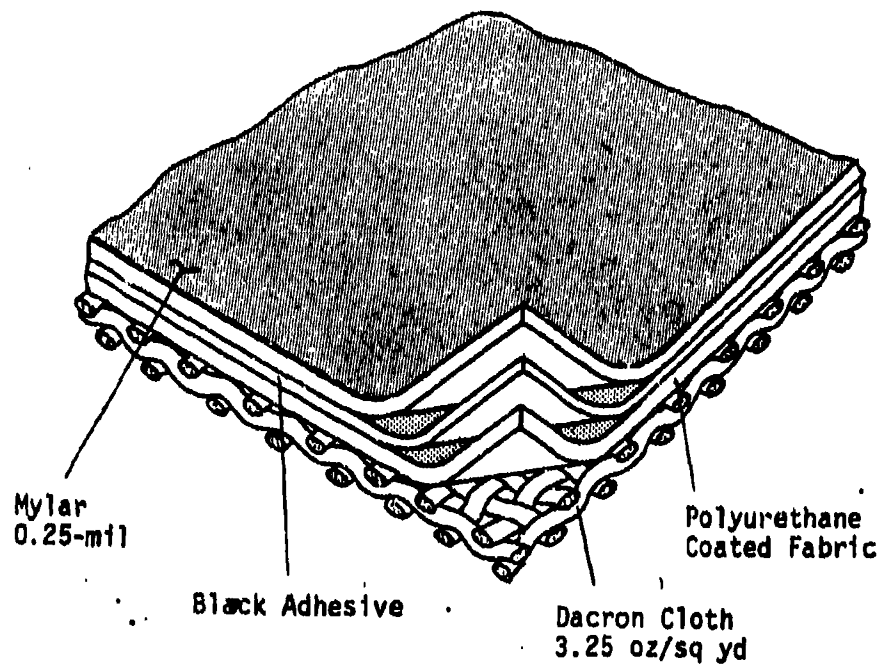


FIGURE 33 - Ballonet Laminate (G144400-Sheldahl)

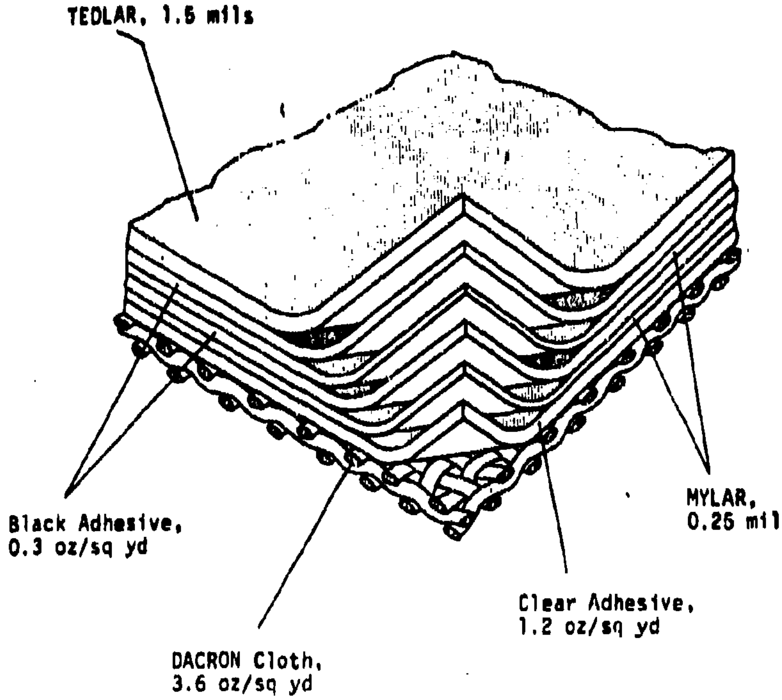


FIGURE 34 - Hull Laminate (G142800) (Sheldahl)

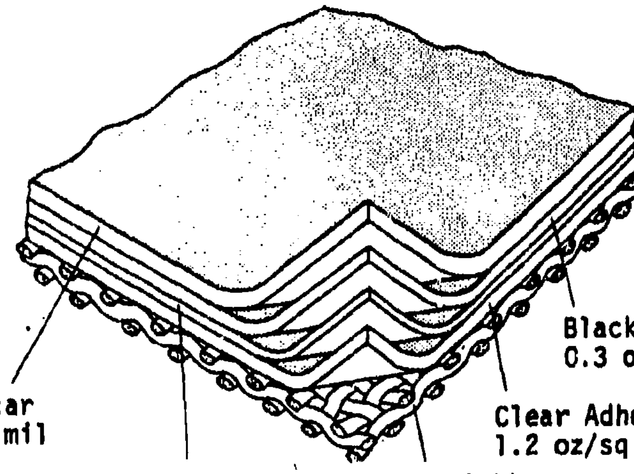
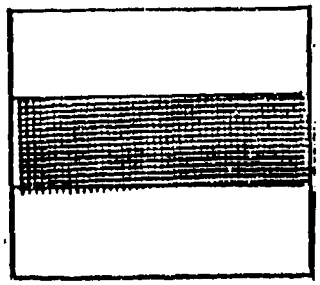


FIGURE 35 - Fin Laminate (G142900) (Sheldahl)

MATERIAL CONSTRUCTION (BALLONET)

Value



3.0 oz/yd^2 Polyether polyurethane film (black)

1.15 oz/yd^2 Polyester cloth, 210 Denier 18 x 17 count

2.15 oz/yd^2 Polyether polyurethane (black)

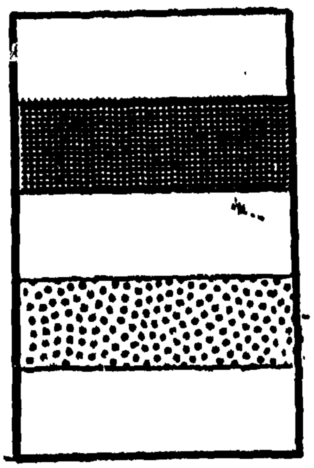
6.3 oz/yd^2 $\pm$ .5

Weight	
Breaking Strength (lbs)	
Strip Method	
Machine	60 min.
Transverse	50 min.
Tear (Tongue Method)	
Machine	8 lb. min.
Transverse	6 lb. min.
Adhesion (lbs/in)	
Coating*	10 min.
Permeability to Helium	1.0 liter/m^2/ 24 hrs. max.
Low Temp. Flex	No cracks @ -40° F.
Width	52" min.

*Coating adhesion to be determined by using AF770 and RF sealing.

FIGURE 37 - Ballonet Single Ply Coated Fabric (Ref. No. 15707-ILC)

MATERIAL CONSTRUCTION (WINDSCREEN)



2.5 oz/yd^2 Light Stable Polyester Polyurethane film (white)

2.3 oz/yd^2 Polyester fabric, 210 Denier 41 x 39 count

1.0 oz/yd^2 Polyether Polyurethane (Black)

0.8 oz/yd^2 Oriented Non-woven Polyester fabric

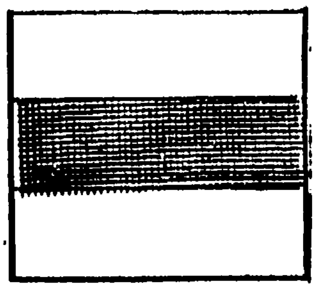
1.0 oz/yd^2 Polyether Polyurethane (Black)

Weight	7.6 oz/yd^2 + .75 - .5
Breaking Strength (lbs)	
Strip Method	
Machine	120 min.
Transverse	80 min.
Tear (Tongue Method)	
Machine	8 lb. min.
Transverse	8 lb. min.
Adhesion (lbs/in)	
Coating*	10 min.
Ply	10 min.
Permeability to Helium	1.0 liter/m^2/24 hrs. max.
Low Temp. Flex	No cracks @ -40° F.
Width	52" min.

*Coating adhesion to be determined by using AF770 and RF sealing.

FIGURE 38 - Windscreen Oriented Non-Woven Ply Coated Fabric (Ref. No. DV8080-111-ILC)

MATERIAL CONSTRUCTION (FIN)



2.5 oz/yd^2 Light Stable Polyester Polyurethane film (white)

2.3 oz/yd^2 Polyester cloth, 210 Denier 41 x 39 count

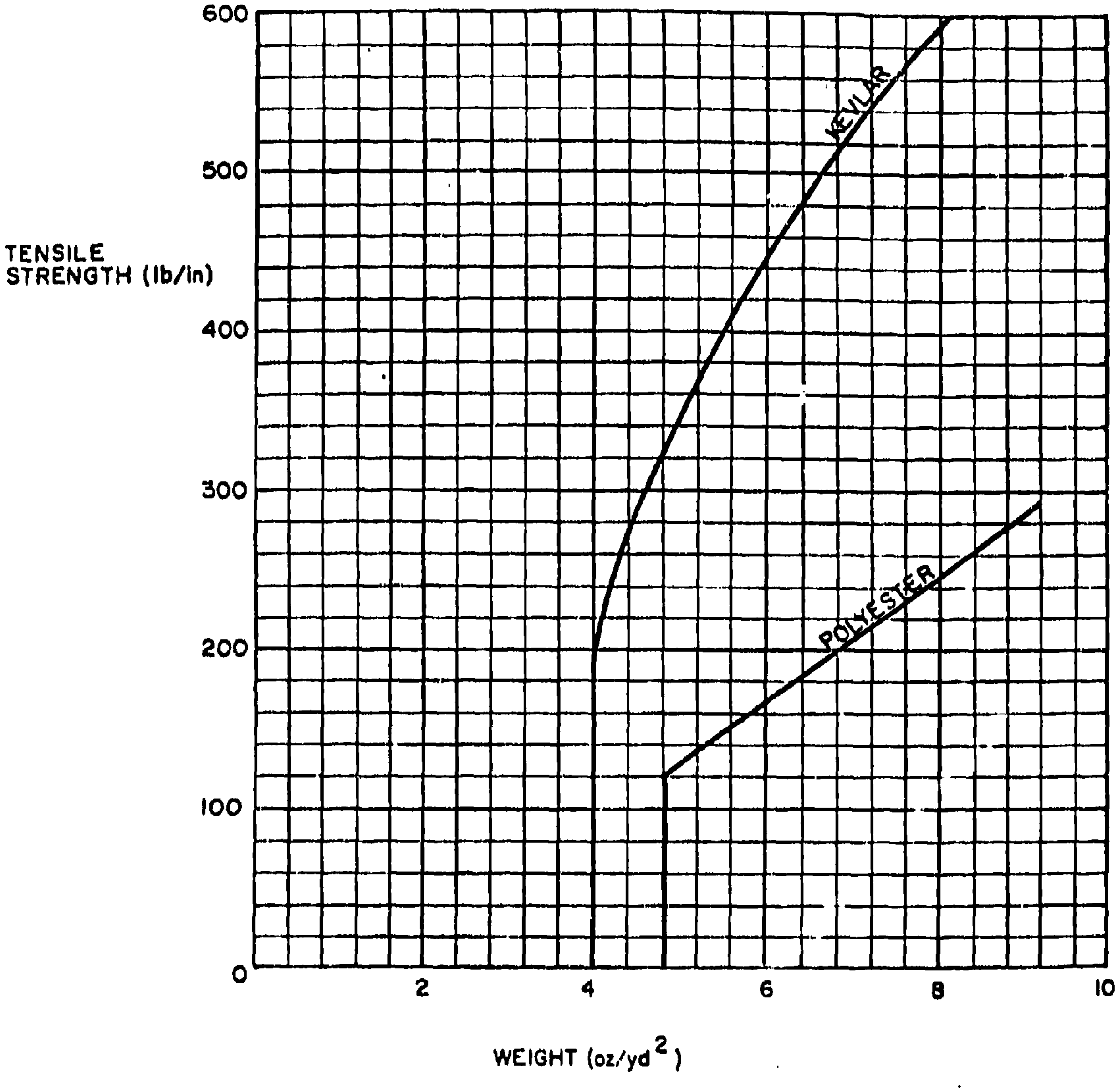
2.0 oz/yd^2 Polyether Polyurethane (Black)

Weight	6.8 oz/yd^2 $\pm$ .5
Breaking Strength (lbs)	
Strip Method	
Machine	100 min.
Transverse	100 min.
Tear (Tongue Method)	
Machine	8 min.
Transverse	6 min.
Adhesion (lbs/in)	
Coating*	10 min.
Permeability to Helium	1.0 liter/m^2/24 hrs. max.
Low Temp. Flex	No cracks @ -40° F.
Width	52" min.

*Coating adhesion to be determined by using AF770 and RF sealing

FIGURE 39 - Fin Single Ply Coated Fabric (Ref. No. DV8080-111A-ILC)

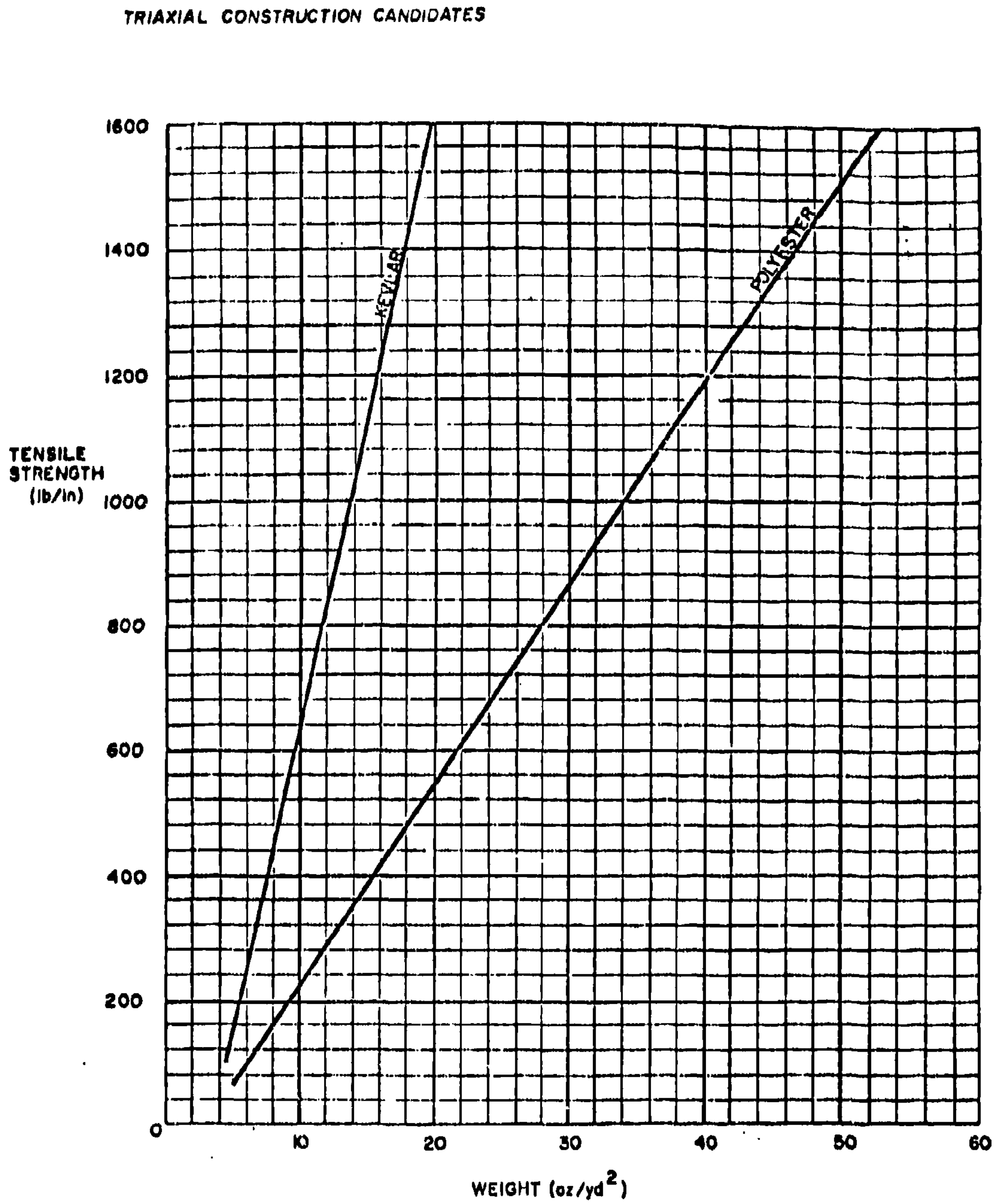
BIAXIAL CONSTRUCTION CANDIDATES



Conversion factors: 1 oz/yd^2 = 33.91 gm/m^2
1 lb/in = 1.75 n/cm

Figure 40

BIAXIAL CONTRUCTION CANDIDATES



Conversion factors: 1 oz/yd^2 = 33.91 gm/m^2
1 lb/in = 1.75 n/cm

Figure 41

TRIAXIAL CONSTRUCTION CANDIDATES

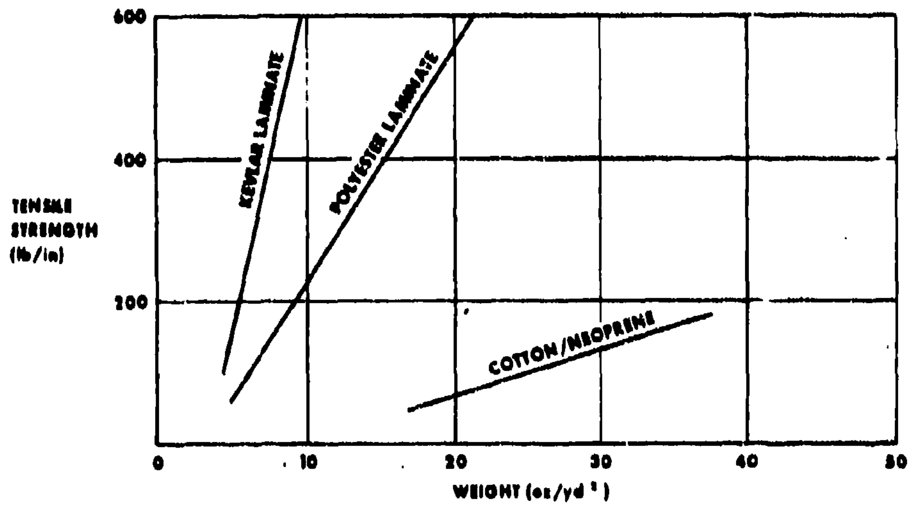


Figure 42 Envelope/Cell Strength/Weight Comparisons of Different Material Combinations

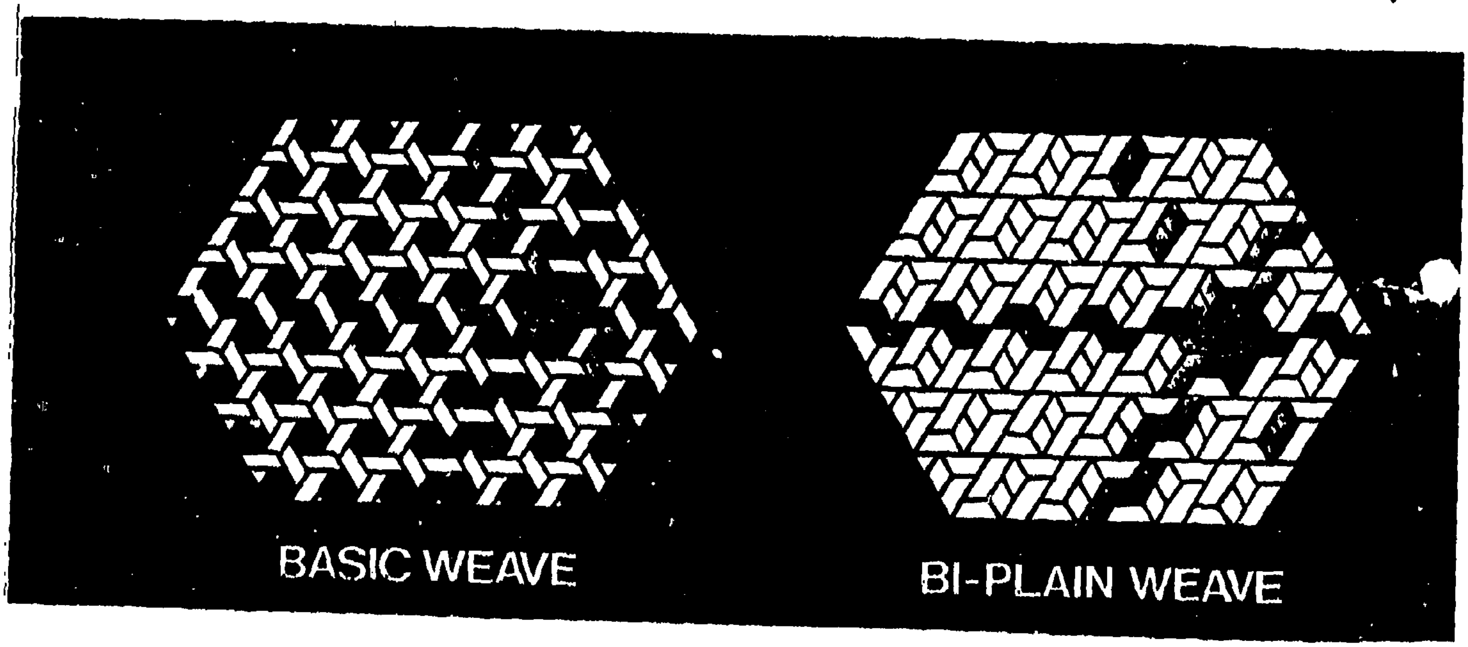


FIGURE 43 - Basic and Biplain Triaxial Weave

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APPENDIX A

MATERIAL SPECIFICATIONS FOR THE GDC-5 AIRSHIP ENVELOPE CONSTRUCTED IN 1959-1960

A detailed description follows of an airship envelope construction of the 1950-1960 and the various material constructions used in the making of one envelope.

Description

The fabric envelope serves as a gas-proof container for the lifting gas used to provide the static lift for the airship. The envelope consists essentially of the main envelope panels; fabric ballonets in the envelope which are air containers used for maintaining envelope pressure and trim; air lines for ducting air to and from the ballonets; sleeves for dampers, air valves and gas valves; internal and external catenary curtains for the airship suspension cable system; car fairing for streamlining the car with the envelope; catenaries and fan patches for ground handling lines and empennage; and miscellaneous provisions for bow stiffening, instruments, and equipment. Rip panel(s) are incorporated in the top surface of the envelope to permit emergency release of gas. The envelope fabrics must withstand the static stresses caused by the envelope gas pressure; the dynamic stresses developed in flight; the transverse, vertical, and longitudinal stresses caused by the suspension of the car and empennage; and the destructive effects of weathering.

Fabric Panels

The fabric is cut into segments called panels which are cemented, sewed, and taped together to form the hull of the airship envelope. The panels form a series of equal gores extending lengthwise from bow to stern, each gore being delineated by the longitudinal seams of the envelope. The panels also form a series of rings around the envelope which are delineated by the circumferential seams. These rings are called patterns because all panels in a ring are cut to the same basic pattern. For reference purposes, each panel is identified by a gore letter and a pattern number, the gores being lettered consecutively from "A," the lowest port gore, to the lowest starboard gore, "L" or "P" (depending on the design of the envelope) and the patterns being numbered consecutively from bow to stern, except when a series of patterns are all cut to the same basic shape. When this situation exists, the number sequence is interrupted, and the similar patterns are identified by the letters W, X, Y, and Z depending upon the number of identical patterns; number sequence is then resumed.

The ballonets are constructed of fabric panels which are not sewed, but cemented and taped together. When a ballonet is deflated the ballonet diaphragm, theoretically, will lie flat against the inner contour of the envelope. Consequently, the fabric panels of the ballonets coincide with the panels of the envelope and are identified for reference purposes with gore letters and pattern numbers of the coincident envelope panels. Ballonet shoes cemented to the ballonets and envelope secure the ballonets in place.

Gas area seam construction is basically the same on all airship envelopes. The panels are overlapped, cemented, double-sewed, and taped. However, the overlap and taping details vary slightly.

Airship Tapes

Airship tapes are narrow lengths of single-ply, bias, neoprene-impregnated, nylon cloth. A layer of uncured neoprene on one side of the tapes serves as a bonding layer for bonding the tapes to freshly cemented surfaces.

The bonding layer is covered with polyethylene film to permit winding the tapes into rolls during manufacture, to protect them from dirt when they are unwound, and to keep the cement from drying out. Tapes are laid on envelope seams to protect the seam threads from abrasion, and to retard gas diffusion through the thread holes and through the cemented areas of the seams; tapes are laid on air-line, and ballonet seams to protect the seams and retard diffusion of gas. Tapes area also used to cover lacings of covers and fairings, to form lighting and bonding wire conduits, and to cover edge seams of accessories and patches to prevent the edges from loosening. In the past, tapes were manufactured from cotton, nylon, and Fortisan rayon. All tapes now supplied are manufactured from nylon and are used to replace any of the older types of tape. Tapes are supplied in aluminized and plain (nonaluminized) finishes. Aluminized tapes are spread with aluminum on the side opposite the bonding layer, and these tapes are applied in areas exposed to the weather. Bias tape made from aluminized fabric has nonaluminized areas approximately every 40 inches. These areas must be painted when the tape is applied. Plain tapes are applied in areas not exposed to the weather. Tapes should be stored under the same conditions as envelope fabrics.

Tapes are readied for laying by stripping off the polyethylene film and wiping the uncured neoprene with either toluene or trichloroethene 1.1.1 (stabilized) to restore the tack (toluene is preferred). Aliphatic petroleum naphtha is not recommended as a tape reactivator. If the tape cannot be reactivated by use of toluene or trichloroethane 1.1.1 (stabilized), several thin coats of neoprene cement may be applied to the uncured neoprene and permitted to reach maximum tack before use.

CONSTRUCTION SPECIFICATION

Use: **Envelope-Main area, bow and stern and outside catenary**

Code: NH311E76-15A

I. Construction	Weight, oz./yd.^{2}
Hypalon (alum.)	1.30
Neoprene	.45
Cloth (Dacron) Bias (Taffeta) #1105	3.40
Neoprene	4.15
Cloth (Dacron) Straight (2x2 Basket) #1106	4.90
Neoprene	1.50
Talc	.30
	16.00 ± .5

II. Tensile Strength	Min., lb./in.
Cylinder Burst - Warp	320
- Fill	280
Bias - Warp	295
- Fill	260

III. Adhesion	7.5

IV. Permeability	Max., L/M^2/24 hrs.
Before Rotoflex	2.5
After Rotoflex	3.5

CONSTRUCTION SPECIFICATION

Use: Above Car

Code: NH311E76-15

I.	Construction	Weight, oz./yd.^{2}
	Hypalon	1.30
	Neoprene	.45
	Cloth (Dacron) Bias (Taffeta) #1105	3.40
	Neoprene	4.15
	Cloth (Dacron) Straight (2x2 Basket) #1106	4.90
	Neoprene	1.50
	Talc	.30
		16.00 ± .5
II.	Tensile Strength	Min., lb./in.
	Cylinder Burst - Warp	320
	- Fill	280
	Bias - Warp	295
	- Fill	260
III.	Adhesion	7.5
IV.	Permeability	Max., L/M^2/24 hrs.
	Before Rotoflex	2.5
	After Rotoflex	3.5

CONSTRUCTION SPECIFICATION

Use: Car Fairing (above propellers), Car Canopy and Miscellaneous

Code: NH311E61-15

I.	Construction	Weight, oz./yd.^{2}
	Hypalon	1.50
	Neoprene	.90
	Cloth + Bias #1103	3.25
	Neoprene	3.40
	Cloth - Straight #1101	4.40
	Neoprene	1.75
		15.20 $\pm$ .5
II.	Tensile Strength	Min., lb./in.
	Cylinder Burst - Warp	285
	- Fill	265
III.	Adhesion	8.0
IV.	Permeability - Maximum-Liters/sq. M/24 hrs.	2.5

CONSTRUCTION SPECIFICATION

Use: Empennage Catenaries, Tank Catenaries, Radome Catenaries, Patches and Miscellaneous Reinforcements

Code: NH311E61-15A

	Weight, oz./yd.^{2}
I. Construction	
Hypalon (alum.)	1.50
Neoprene	.90
Cloth - Bias #1103	3.25
Neoprene	3.40
Cloth - Straight #1101	4.40
Neoprene	1.75
	15.20 ± .5

	Min., lb./in.
II. Tensile Strength	
Cylinder Burst - Warp	285
- Fill	265
III. Adhesion	8.0

	Max., L/M^2/24 hrs.
IV. Permeability	2.5

CONSTRUCTION SPECIFICATION

Use: Inside Catenary Curtains and Accessories

Code: N302060

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	1.00
	Cloth - Straight #1104	3.25
	Neoprene	2.00
	Neoprene	2.00
	Cloth - Straight #1104	3.25
	Neoprene	1.00
		12.50 $\pm$ .5
II.	Tensile Strength	Min., lb./in.
	Strip - Warp	230
	- Fill	220
III.	Adhesion	6
IV.	Permeability	No requirements
V.	Width	Not less than 40 inches To be coated by spread method

CONSTRUCTION SPECIFICATION

Use: Rip Panel

Code: N302X64

I.	**Construction**	**Weight, oz./yd.^{2}**
	Neoprene	1.50
	Cloth - Straight #1101	4.50
	Neoprene	4.50
	Cloth - Straight #1101	4.50
	Neoprene	1.50
		16.50 $\pm$ .5
II.	**Tensile Strength**	**Min., lb./in.**
	Cylinder Burst - Warp	320
	- Fill	320
	Strip - Warp	300
	- Fill	300
III.	**Adhesion**	8.0
IV.	**Permeability**	**Max., Liters/sq.M/24 hrs.**
	Before Rotoflex	2.5
	After Rotoflex	3.5

CONSTRUCTION SPECIFICATION

Use: Center Ballonet Ends, Radar Access Shaft

Code: N202B43

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	0.75
	Cloth-Straight, S&S 2598/15	2.45
	Neoprene	2.75
	Cloth-Straight 7020	1.60
	Neoprene	0.75
		8.30 ± .5
II.	Tensile Strength	Min., lbs./in.
	Strip - Warp	180
	- Fill	140
III.	Adhesion	5.0
IV.	Permeability	Max., Liters/Sq.M/24 hrs.
		8.0

CONSTRUCTION SPECIFICATION

Use: Ballonets - Forward, Aft and Sides of Center

Code: N202B34

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	0.60
	Cloth-Straight 7020/2 Nylon Twill	1.60
	Neoprene	2.20
	Cloth-Straight 7020/2 Nylon Twill	1.60
	Neoprene	0.60
		6.60 $\pm$ .5
II.	Tensile Strength	Min., lbs./in.
	Strip - Warp	80
	- Fill	80
III.	Adhesion	5.0
IV.	Permeability	Max., Liters/Sq.M./24 hrs.
		8.0

CONSTRUCTION SPECIFICATION

Use: Airlines, Sleeves and Miscellaneous Reinforcements

Code: N211W34

I. Construction	Weight, oz./yd.^{2}
Neoprene	0.75
Cloth-Bias 7020/2 Nylon Twill	1.60
Neoprene	1.90
Cloth-Straight 7020/2 Nylon Twill	1.60
Neoprene	0.75
	6.60 $\pm$ .5

II. Tensile Strength	Min., lbs./in.
Strip - Warp	50
- Fill	50

III. Adhesion	5.0

IV. Permeability	Max., Liters/Sq.M/24 hrs.
	8.0

CONSTRUCTION SPECIFICATION

Use: Suspension Sleeve Shoe

Code: N201Y374

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	15.65
	Cloth - Straight 296N	13.20
	Neoprene	21.75
		50.60 $\pm$ 2.0
II.	Tensile Strength	Min., lbs./in.
	Grab Test - Warp	550
	- Fill	475
III.	Adhesion	No requirements
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Drain Tubes, Patches and Miscellaneous Reinforcements

Code: N101P12

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	0.60
	Cloth-Straight W. S. S/5061	4.00
	Neoprene	0.60
		5.20 $\pm$ .5
II.	Tensile Strength	Min., lbs./in.
	Strip - Warp	80
	- Fill	80
III.	Adhesion	8.0
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Suspension Patches and Miscellaneous Reinforcements

Code: N101P12A

		Weight, oz./yd.^{2}
I.	Construction	
	Neoprene - (Alum.)	0.80
	Neoprene	0.70
	Cloth - Straight W. S. S/5061	4.00
	Neoprene	0.50
		6.00 $\pm$ .5
II.	Tensile Strength	Min., lbs./in.
	Strip - Warp	80
	- Fill	80
III.	Adhesion	8.0
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Car Fairing

Code: N101A38

I.	Construction	Weight, oz./yd.^{2}
	Neoprene	0.80
	Cloth - Straight W.S. S/5061	4.00
	Neoprene	3.00
		7.80 $\pm$ .5
II.	Tensile Strength	Min., lbs./in.
	Strip - Warp	80
	- Fill	80
III.	Adhesion	8.0
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Catenary Cable Wrap

Code: N101A45

I.	Construction	Weight, oz./yd.^{2}
	Neoprene - After Cure	0.75
	Neoprene - Before Cure	1.50
	Cloth - Straight 661	2.90
	Neoprene - Before Cure	0.75
	Neoprene - After Cure	1.50
		7.40 ± .5
II.	Tensile Strength	No requirements
III.	Adhesion	No requirements
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Patches and Lacing Strips

Code: N01A150

I.	Construction	Weight, oz./yd.^{2}
	Neoprene - Spread	1.00
	Neoprene - Friction	5.25
	Cloth - Straight 1417	19.80
	Neoprene - Friction	5.25
	Neoprene - Spread	3.50
		34.80 $\pm$ 2.0
II.	Tensile Strength	Min., lbs./in.
	Grab Test - Warp	250
	- Fill	250
III.	Adhesion	8.0
IV.	Permeability	No requirements
V.	Width	Not less than 38 inches

CONSTRUCTION SPECIFICATION

Use: Patch Straps

Code: N101S210

I.	Construction	Weight, oz./yd.^{2}
	Neoprene - Calendar	21.00
	Cloth - 2716	7.08
		28.08 $\pm$ 3.0
II.	Tensile Strength	Min., lbs./in.
		455
III.	Adhesion	No requirements
IV.	Permeability	No requirements

CONSTRUCTION SPECIFICATION

Use: Tapes - Envelope, Outside Catenaries

Code: N210T045A

I.	Construction	Weight, oz./yd.^{2}
	Aluminum Coating	1.20
	Neoprene - Spread	1.00
	Cloth - Bias 3523N	1.20
	Neoprene - Spread	0.75
	Neoprene - Spread - After Cure	2.75
		6.90 $\pm$ .5

Facing - Clear Embossed Polyethylene Film

II.	Tensile Strength	No requirements
III.	Adhesion	No requirements
IV.	Permeability	No requirements
V.	Cut Width	As specified

CONSTRUCTION SPECIFICATION

Use: Tape - Envelope, Ballonets, Inside Catenaries and Miscellaneous

Code: N210T145

I.	Construction	Weight, oz./yd.^{2}
	Neoprene - Spread	1.00
	Cloth - Bias 3523N	1.20
	Neoprene - Spread	0.75
	Neoprene - Spread - After Cure	2.75
		5.70 $\pm$ .5

Facing - Clear Embossed Polyethylene Film

II.	Tensile Strength	No requirements
III.	Adhesion	No requirements
IV.	Permeability	No requirements
V.	Cut Width	As specified

TABULATION OF CODES AND END USES OF FABRICS AND TAPES

CODE	USE
NH311E76-15A	Main Envelope, Car Catenary (external) and miscellaneous reinforcements
NH311E76-15	Main Envelope, above car, miscellaneous reinforcements
NH311E61-15	Car Canopy, Car Fairing (above propellers) and miscellaneous
NH311E61-15A	Empennage Catenaries, Tank Catenaries, Radome Catenaries, Patches and miscellaneous reinforcements
N302C60	Catenary Curtains (internal)
N302X64	Rip Panel
N202B43	Center Ballonet Ends Radar Access Shaft
N202B34	Ballonets-Forward, Aft and Center, sides
N211W34	Airlines, Sleeves and miscellaneous reinforcements
N201Y374	Suspension Sleeve Shoe
N101P12	Drain Tube, Patches and miscellaneous reinforcements
N101P12A	Patches and miscellaneous reinforcements
N101A38	Car Fairing
N101A45	Tape-Catenary Cable Wrapping
N101A150	Patches and Lacing Strips
N101S210	Patch Straps
N210T045A	Tapes-Envelope, Outside Catenaries
N210T45	Tape-Envelope - Ballonets, Inside Catenaries

SPECIFICATION

Cotton Cloth

Code	Weight Oz./Yd.^{2} Nom.	Weight Oz./Yd.^{2} Max.	Count Ends/Inch Warp	Count Ends/Inch Fill	Tensile Lb./In. Warp	Tensile Lb./In. Fill	Weave	Yarn Size and Ply Warp	Yarn Size and Ply Fill
1417	19.80	20.30	19	19	1)285	285	Plain 1 x 1		
W.S. S/5061	4.00		78	76	115	115	Plain Combed		
661	2.90	3.00	115	104	2) 60	60	Plain 1 x 1		

Nylon Cloth

Code	Weight Oz./Yd.^{2} Nom.	Weight Oz./Yd.^{2} Max.	Count Ends/Inch Warp	Count Ends/Inch Fill	Tensile Lb./In. Warp	Tensile Lb./In. Fill	Yarn Denier-Ply Twist Warp	Yarn Denier-Ply Twist Fill	Weave
3523N	1.10	1.30	117	52	2) 50	50	40/13/10Z	70/34/1/2Z	Plain 1 x 1
7020/2	1.60		124	72	3) 50	50	40/1/7Z	70/1/1/2Z	Plain 2 x 1
296N	13.00		40	40	3)625	625			Basket 2 x 2
2716	7.08		45	23	76	9	210/5/3-1/4Z	30/1/1/2Z	Unilateral
S&S2598/15	2.45		80	80	120	120	100/1/7Z	100/1/7Z	Taffeta

Dacron Cloth

Code	Weight Oz./Yd.^{2} Nom.	Weight Oz./Yd.^{2} Max.	Count Ends/Inch Warp	Count Ends/Inch Fill	Tensile Lb./In. Warp	Tensile Lb./In. Fill	Yarn Denier	Yarn Ply	Yarn Twist	Weave
1000HS	2.55		67	67	77	77	70			Twill 2 x 2
1101HS	4.35	4.50	66	66	205	205	220	1	7Z	Basket 2 x 2
1103HS	3.35	3.50	83	80	110	105	70	2	7Z	Twill 3 x 2
1104HS	3.25	3.50	50	51	155	150	220	1	3Z	Taffeta
1105HS	3.35	3.50	54	52	170	150	220	1	2.5Z	Taffeta
1106HS	4.75	4.90	76	73	245	220	220	1	3Z	Basket 2 x 2

1) Tensile by 1" grab method
2) Tensile by 2" die cut method
3) Tensile by 1" raveled method

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APPENDIX B

EXPERIMENTAL WORK UNDER NASA SPONSORSHIP

Various handmade laminate and coated material configurations were evaluated for tensile strength, peel strength, crease effects, tear resistance, flexibility, or "handle", and puncture resistance. One laminated and one coated material with Dacron fabric were used as controls. Adequate peel strength, tear resistance and puncture resistance were demonstrated. The geometric and mechanical factors influencing tear resistance were found to be the same for Kevlar and Dacron materials. Puncture resistance was found to be inversely related to fabric stiffness for the laminated materials and to be inversely related to coat thickness for coated materials. Creasing of Kevlar-based laminates was found to severely degrade its strength. However, only small to moderate degradation was found for the coated Kevlar based materials. After crease degradation, coated Kevlar 49 materials still exhibited about twice the strength-to-weight ratio of the coated Dacron control material. The strength-to-weight advantages of the uncreased Kevlar laminates were largely nullified by creasing. Creased, Kevlar laminate strength-to-weight ratios became comparable to the creased Dacron-control laminate.

The coated materials showed significant improvement over the laminates in fabric handle. By repositioning the Kevlar fabric from an outer-plane to the mid-plane of the coated materials, the flexibility measure, handle modulus, was reduced about 39 percent and the strength loss caused by creasing was reduced from 9 to 22 percent. This demonstrates the importance of constituent laminar arrangement.

Standard coupon tensile testing of materials with diagnonally oriented fabric constituents was found to yield results far below those obtained by other means. High variability of strength and elongation with temperature were found to be a result of thermomechanical phase transitions in the adhesive which influenced the structural contribution of the diagonal fiber elements of the coupon specimens. For applications to be packed and folded, Kevlar is not particularly advantageous unless crease degradation can be controlled. However, the superior performance of Kevlar coated materials compared to similar Dacron coated materials was shown to be practical for applications where creasing occurs.

The test materials investigated are shown in Figure 1. Throughout this report individual test materials are identified by row number and column letter (1a, 1b, etc.). Variations in material constituents occur from left to right (column variable), while variations in material construction occur from top to bottom (row variable). Materials 1 through 4 are laminates, and 5 and 6 are coated fabrics. Materials in column (a) are baseline materials using Dacron fabric. Materials in columns (b) and (c) have Kevlar fabric substituted in place of the Dacron. Materials in column (c) have an additional layer of Kevlar-49 bias yarns. Variations in material construction (3b and 6b) were made to relocate the fabric nearer to the neutral plane. Material 4c was configured to evaluate a Hytrel* coating and is an exception to the conventions above. This material is closely related to material 2c. Hytrel coating could not be directly substituted for the Mylar* film since Hytrel has poor permeability in the thickness considered. A layer of Saran (commercial Saran Wrap film by Dow Chemical) was included in 4c to obtain a laminate with permeability equivalent to 2c.

The basic mechanical properties of the Dacron and Kevlar fabrics used are given in Tables 1 and 2, respectively. Properties of the membranes and coatings are provided in Table 3. Except for variations from the assembly process, total thickness was held constant for all variants in Figure 1.

*Registered tradenames, E. I. DuPont de Nemours & Co., Inc.

Coupon tensile strength data are provided in Table 4 for the ten material types. Data are for the load and sample orientations along the machine direction (MD), transverse direction (TD), 45° to the left and right of the MD. Tests were performed at room temperature, 22°C (72°F), and at the usual environmental extremes for inflatable structures, -51°C (-60°F) and 60°C (140°F). The data are compared graphically in Figures 2 and 3. Data on elongation at failure for the same conditions are provided in Table 5 and Figures 4 and 5.

Careful study of the strength data shows that all Kevlar materials show significant improvement over their Dacron controls along the warp and fill, and moderate or varying improvements along diagonal axes.

The strength data of Figures 2 and 3 and the strain data of Figures 4 and 5 show several trends with temperature, material construction, and specimen orientation. MD and TD tests of Kevlar materials with Dacron-bias fabric, show constant or increased strain with decreased strength for a temperature change from +22°C to -51°C. The corresponding control material having all Dacron reinforcement (5a) shows nearly constant strength, but decreasing strain with temperature drop.

The Kevlar materials with no bias reinforcement, 1b, 2b, and 3b, show consistent loss in strength and increase in strain for the MD and TD tests as temperature is reduced below ambient. However, the same materials tested in the bias direction generally show strength increases and strain decreases as temperature drops.

The all-Dacron control materials perform differently from their Kevlar counterparts. Laminate 1a shows increasing strength with increasing strain for the orthogonal specimens and near-constant stress with decreasing strain for the bias specimens. The all-Dacron coated material, 5a, shows constant strength with decreasing strain for the orthogonal specimens and similar behavior for the bias specimens.

The following effects observed during this effort should be considered in any future development:

1. Locating constituents with high strength and modulus near the mid-plane increases composite strength, improves strength retained after creasing and is significant in reducing the handle modulus.

2. High tensile modulus films increase crease sensitivity and degrade handle and should be avoided whenever gas permeability considerations are secondary.

3. Use of more elastic films in place of high modulus films lowers crease sensitivity and improves handle.

4. Tear strength is increased for open weaves and large denier yarns and decreased for tight weaves and small denier yarns of the same tensile strength.

5. A fabric bias reinforcement appears to be superior to an open scrim bias reinforcement.

6. Puncture resistance in laminates is inversely related to fabric stiffness and inversely related to coating thickness for coated materials.

7. Coated Kevlar materials with increased strength-to-weight performances are feasible in applications where gas permeability is not an important consideration.

8. Kevlar laminates provide superior strength-to-weight characteristics in applications where creasing and packaging can be minimized.

9. In applications where weight is not important, Hypalon coating is superior to Tedlar film as a UV barrier because of its lower stiffness.

10. The coated material with Kevlar fabric at mid-plane displayed the best distribution of reinforcement elements and strength isotropy, low crease degradation, the lowest handle modulus, good strength-to-weight properties and acceptable tear and puncture performance. Additional development of this or a similar material would be of considerable value in promoting the objectives of this investigation.

11. The strength and elastic properties of laminates and coated composites are subject to discontinuous changes with temperature where constituents undergo thermomechanical phase changes within the service temperature range.

12. More rigid adhesives and film constituents improve the integration of fiber components in composites and generally reduce strain. However, the associated reduction in ductility of the matrix constituents increases sensitivity to local stress concentrations and reduces average composite strength.

13. The performance of composites is strongly influenced by the strength and ductility of the adhesive. Shear strength of the adhesive used (Sheldahl A-102 resin) was well matched to Dacron tensile properties but bond strength to Kevlar was considerably less than the filament strength. Further adhesive research is essential to increase fiber bond strength and to reduce the phase transition temperature below the service temperature range, if the potential advantages of Kevlar yarns are to be fully realized.

TABLE 1. - Properties of Dacron-Fabric Components, Metric Units
(English units in parentheses)

Characteristic \ Application		5a, 5b, 6b	5a	1a
Weight		$0.047\ N/m^2$ ($1.4\ oz/yd^2$)	$0.108\ N/m^2$ ($3.25\ oz/yd^2$)	$0.126\ N/m^2$ ($3.8\ oz/yd^2$)
Strength:	Warp	6100 N/m (35 lb/in.)	27,000 N/m (155 lb/in.)	39,400 N/m (225 lb/in.)
	Fill	6100 N/m (35 lb/in.)	27,000 N/m (155 lb/in.)	39,400 N/m (225 lb/in.)
Weave Type		Plain	Plain	Plain
Fabric Finish		Scoured and heat set	Scoured and heat set	Scoured and heat set with 5 to 10% by weight of polyvinyl acetate
Yarn Count		39/cm x 39/cm (18/in. x 98/in.)	20/cm x 20/cm (50/in. x 50/in.)	5/cm x 5/cm (13/in. x 13/in.)
Yarn Size		40 denier	220 denier	1000 denier
Yarn Twist		9 turns/cm (23 turns/in.)	1 turn/cm (3 turns/in.)	4 turn/m (0.1 turns/in.)
Filament Count		27/yarn	50/yarn	192/yarn
Filament Strength		$570\ NM/m^2$ ($0.83 \times 10^5\ lb/in.^2$)	$1030\ MN/m^2$ ($1.5 \times 10^5\ lb/in.^2$)	$1030\ MN/m^2$ ($1.5 \times 10^5\ lb/in.^2$)
Filament Modulus		$13.8\ GN/m^2$ ($2 \times 10^6\ lb/in.^2$)	$13.8\ GN/m^2$ ($2 \times 10^6\ lb/in.^2$)	$13.8\ GN/m^2$ $2 \times 10^6\ lb/in.^2$)
Density		$1380\ kg/m^3$ ($0.05\ lb/in.^3$)	$1380\ kb/m^3$ ($0.05\ lb/in.^3$)	$1380\ kg/m^3$ ($0.05\ lb/in.^3$)

TABLE 2. - Properties of Kevlar-49 Fabric Components, Metric Units
(English units in parentheses)

Characteristic \ Application	1b, 2b, ac, 3b, 4c	5b, 6b, 6c
Weight	0.60 kg/m^2 (1.8 oz/yd^2)	0.090 kg/m^2 (2.7 oz/yd^2)
Strength: Warp	39,400 N/m (225 lb/in.)	74,400 N/m (425 lb/in.)
Fill	39,400 N/m (225 lb/in.)	74,400 N/m (425 lb/in.)
Weave Type	Plain	Plain
Fabric Finish	Scoured	Scoured
Yarn Count	13/cm x 13/cm (34/in. x 34/in.)	20/cm x 20/cm (50/in. x 50/in.)
Yarn Size	195 denier	195 denier
Yarn Twist	4 turns/m (0.1 turn/in.)	4 turns/m (0.1 turn/in.)
Filament Count	134/yarn	134/yarn
Filament Strength	3620 MN/m^2 (5.25×10^5 $lb/in.^2$)	3620 MN/m^2 (5.25×10^5 $lb/in.^2$)
Filament Modulus	131 GN/m^2 (1.9×10^7 $lb/in.^2$)	131 GN/m^2 (1.9×10^7 $lb/in.^2$)
Density	1450 kb/m^3 (0.052 $lb/in.^3$)	1450 kg/m^3 (0.052 $lb/in.^3$)

TABLE 3. - Properties of Film, Adhesive, and Coating Components, Metric Units (English units in parentheses)

Characteristic / Component	Application	Description	Tensile Strength at 22°C (72°F)
Tedlar	1a, 1b, 2b, 2c, 3b, 4c	38.1μm (1.5 mil) thick, DuPont polyvinyl fluoride film, type 30, adherable both sides, "L" gloss, titanium dioxide *pigment*	$55 MN/m^2$ (8,000 $lb/in.^2$)
Mylar	1a, 1b, 2b, 2c, 3b, 4c	6.35μm (0.25 mil) thick, DuPont type S polyester film	138 MN/m^2 (20,000 $lb/in.^2$)
Adhesive	A - 1oz	Aromatic polyester resin cured with di-isocyanate for hydrolytic stability	10 MN/m^2 (1,500 $lb/in.^2$)
Hypalon	5a, 5b, 6b 6c	54.5μm (2.1 mil) thick, chloro-sulfonated polyethylene with titanium dioxide pigment	14 MN/m^2 (2,000 $lb/in.^2$)
Neoprene	5a, 5b, 6b	95.3μm (3.75 mil) thick, low temperature noncrystalline poly-chloroprene with lead cure system for hydrolytic stability	24 MN/m^2 (3,500 $lb/in.^2$)
Urethane	5a, 5b, 6b, 6c	71.2μm (2.8 mil) thick, B.F. Good-rich low temperature polyurethane formulated for high hydrolytic stability, ultraviolet resistance and heat stability. Carbon black pigment. Fabric surfaces to be coated are treated with isocyanate-type primer	34 MN/m^2 (5,000 $lb/in.^2$)
Saran	4c	10.0μm (0.75 mil) thick polyvinyl-idene chloride; Dow commercial grade Saran wrap	34 - 55 MN/m^2 (5000 - 8000 $lb/in.^2$)

TABLE 4. - Tensile Properties at Failure

Material Code*	Test Direction	60°C (140°F) N/m (lb/in.)	60°C (140°F) C.V.**	22°C (72°F) N/m (lb/in.)	22°C (72°F) C.V.**	-51°C (-60°F) N/m (lb/in.)	-51°C (-60°F) C.V.**
1a	MD	3.67×10^4 (221)	0.065	4.24×10^4 (242)	0.053	5.36×10^4 (306)	0.035
	TD	3.24 (185)	0.094	4.02 (229)	0.067	5.49 (313)	0.142
	45°L	1.52 (87)	0.065	2.23 (128)	0.046	2.34 (133)	0.103
	45°R	1.00 (57)	0.103	2.02 (115)	0.077	1.68 (96)	0.129
1b	MD	5.57 (318)	0.151	5.49 (314)	0.066	4.72 (269)	0.218
	TD	6.25 (357)	0.127	5.58 (318)	0.088	3.91 (223)	0.354
	45°L	2.28 (130)	0.201	3.12 (178)	0.207	3.21 (183)	0.070
	45°R	2.54 (145)	0.049	2.90 (166)	0.057	3.78 (216)	0.227
2b	MD	5.92 (338)	0.051	5.55 (316)	0.121	3.51 (200)	0.318
	TD	5.85 (334)	0.117	4.82 (275)	0.153	3.62 (207)	0.243
	45°L	2.71 (155)	0.079	3.38 (193)	0.181	3.00 (172)	0.088
	45°R	2.64 (151)	0.113	3.16 (180)	0.030	3.09 (176)	0.301
2c	MD	5.58 (319)	0.023	5.65 (323)	0.048	4.48 (256)	0.098
	TD	6.83 (390)	0.040	6.00 (343)	0.067	4.46 (255)	0.240
	45°L	2.18 (125)	0.029	2.64 (151)	0.262	2.11 (121)	0.061
	45°R	2.21 (126)	0.248	2.73 (156)	0.139	2.46 (140)	0.126
3b	MD	5.80 (331)	0.142	5.87 (335)	0.029	4.52 (258)	0.180
	TD	5.76 (329)	0.045	5.35 (306)	0.091	5.49 (314)	0.199
	45°L	2.58 (148)	0.147	3.51 (200)	0.096	4.21 (240)	0.087
	45°R	2.62×10^4 (150)	0.192	3.79×10^4 (217)	0.039	4.60×10^4 (263)	0.043

*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

TABLE 4. - Tensile Properties at Failure (Concluded)

Material Code*	Test Direction	60°C (140°F) N/m (lb/in.)		60°C (140°F) C.V.**	22°C (72°F) N/m (lb/in.)		22°C (72°F) C.V.**	-51°C (-60°F) N/m (lb/in.)		-51°C (-60°F) C.V.**
4c	MD	5.27 x 10^4	(301)	0.066	5.45 x 10^4	(311)	0.036	3.93 x 10^4	(224)	0.200
	TD	5.89	(337)	0.058	4.39	(250)	0.030	4.50	(257)	0.336
	45°L	1.83	(105)	0.110	3.05	(174)	0.129	2.84	(162)	0.072
	45°R	1.76	(100	0.090	2.63	(150)	0.129	2.29	(131)	0.050
5a	MD	3.61	(206)	0.021	3.72	(213)	0.022	3.83	(219)	0.184
	TD	3.21	(184)	0.017	3.45	(197)	0.044	3.02	(172)	0.052
	45°L	2.39	(137)	0.089	3.23	(185)	0.026	2.81	(160)	0.152
	45°R	2.17	(124)	0.035	2.42	(138)	0.029	2.53	(145)	0.163
5b	MD	5.86	(335)	0.072	6.64	(379)	0.042	5.61	(320)	0.204
	TD	5.31	(304)	0.089	6.91	(395)	0.043	6.14	(351)	0.194
	45°L	3.28	(187)	0.071	4.44	(254)	0.026	3.36	(192)	0.205
	45°R	3.20	(183)	0.099	4.98	(285)	0.041	3.68	(210)	0.175
6b	MD	5.94	(339)	0.094	6.52	(373)	0.052	5.15	(294)	0.191
	TD	6.34	(362)	0.090	8.02	(458)	0.048	6.65	(380)	0.116
	45°L	4.12	(235)	0.071	5.11	(292)	0.062	6.60	(377)	0.085
	45°R	4.26	(243)	0.094	5.83	(333)	0.037	6.01	(343)	0.165
6c	MD	5.83	(333)	0.127	5.71	(326)	0.085	5.42	(310)	0.222
	TD	6.64	(379)	0.067	5.75	(328)	0.061	4.37	(250)	0.158
	45°L	2.46	(140)	0.030	4.51	(258)	0.054	4.39	(251)	0.162
	45°R	3.12 x 10^4	(178)	0.114	4.76 x 10^4	(272)	0.131	4.66 x 10^4	(266)	0.087

*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

TABLE 5. - Tensile Elongation at Failure

Material Code*	Test Direction	60°C (140°F)		22°C (72°F)		-51°C (-60°F)	
		Percent	C.V.**	Percent	C.V.**	Percent	C.V.**
1a	MD	19.8	0.039	16.0	0.053	25.4	0.126
	TD	16.4	0.071	14.8	0.085	24.6	0.247
	45°L	51.8	0.043	47.7	0.077	21.2	0.361
	45°R	38.0	0.142	50.9	0.039	15.0	0.125
1b	MD	5.9	0.047	4.0	0.000	10.0	0.071
	TD	5.4	0.119	4.4	0.064	10.7	0.206
	45°L	37.8	0.059	48.1	0.108	38.0	0.157
	45°R	45.6	0.062	38.6	0.105	32.0	0.337
2b	MD	5.3	0.062	4.8	0.116	7.2	0.267
	TD	5.2	0.097	4.5	0.066	6.6	0.254
	45°L	42.6	0.101	38.7	0.109	23.2	0.239
	45°R	41.2	0.090	32.5	0.077	20.5	0.129
2c	MD	5.9	0.061	5.3	0.000	8.2	0.054
	TD	5.7	0.049	5.4	0.053	10.6	0.143
	45°L	47.3	0.022	43.3	0.044	12.4	0.354
	45°R	43.8	0.153	49.3	0.163	20.0	0.359
3b	MD	5.4	0.101	5.1	0.058	8.6	0.335
	TD	5.3	0.053	4.1	0.122	8.4	0.180
	45°L	45.7	0.057	45.7	0.063	36.8	0.070
	45°R	46.7	0.105	42.6	0.064	36.4	0.227
4c	MD	5.5	0.069	4.3	0.000	12.0	0.144
	TD	5.5	0.033	5.0	0.019	11.8	0.163
	45°L	53.9	0.104	36.3	0.026	13.2	0.196
	45°R	49.2	0.154	52.5	0.207	12.4	0.072
5a	MD	25.7	0.018	26.3	0.050	21.0	0.177
	TD	32.5	0.027	32.0	0.059	23.3	0.243
	45°L	63.5	0.103	71.9	0.051	15.9	0.391
	45°R	60.9	0.091	66.9	0.012	12.8	0.236
5b	MD	8.1	0.064	8.5	0.127	11.3	0.288
	TD	7.3	0.053	5.8	0.062	10.6	0.108
	45°L	65.2	0.050	61.4	0.028	19.3	0.393
	45°R	68.6	0.022	54.2	0.093	29.1	0.262

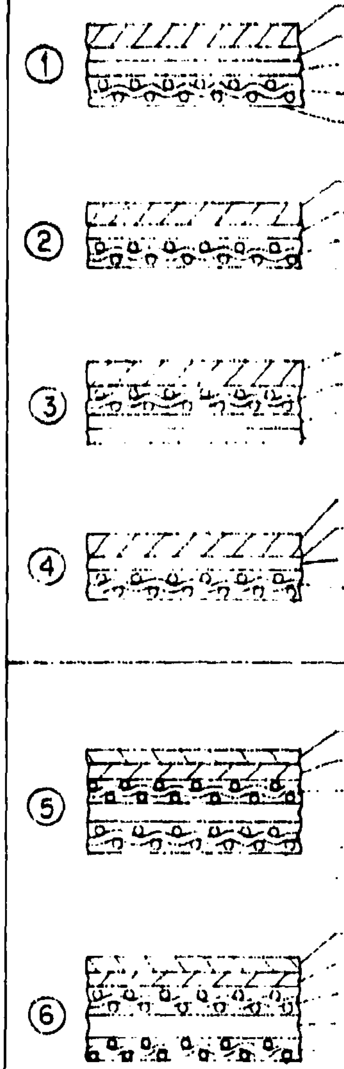
*See Figure 2 for definition of material matrix - row number, column letter.
**C.V. = coefficient of variation.

TABLE 5. - Tensile Elongation at Failure (Concluded)

Material Code*	Test Direction	60°C (140°F)		22°C (72°F)		-51°C (-60°F)	
		Percent	C.V.**	Percent	C.V.**	Percent	C.V.**
6b	MD	10.0	0.192	9.2	0.142	7.6	0.379
	TD	8.4	0.138	7.6	0.072	8.0	0.200
	45°L	59.6	0.122	64.0	0.022	62.8	0.087
	45°R	60.0	0.074	63.8	0.017	42.4	0.182
6c	MD	7.9	0.046	5.9	0.082	5.7	0.168
	TD	5.5	0.054	4.3	0.104	4.4	0.110
	45°L	46.0	0.048	58.9	0.044	36.2	0.074
	45°R	34.4	0.079	45.0	0.063	18.5	0.391

*See Figure 2 for definition of material matrix - row number, column letter.
** C.V. = coefficient of variation.

	a	b	c
	Laminate Materials		
①	Tedlar ▶ Mylar ▶ Mylar ▶ Dacron, 1000 d, 13 x 13 Adhesive (coat)	Tedlar Mylar Mylar ▷ Kevlar-49* Adhesive (coat)	
②		Tedlar ▶ Mylar ▶ Kevlar-49* Adhesive (coat)	Tedlar ▶ Mylar ▶● FTL Bias ▷ Kevlar-49* Adhesive (coat)
③		Tedlar ▶ Kevlar-49* ▶ Mylar ▶ Mylar	
④			Tedlar ▶ Saran ▶ Hytrel ▶● FTL Bias Kevlar-49* Adhesive (coat)
	Coated Materials		
⑤	Hypalon ▷ Polyurethane ▷ Dacron, Bias Ply** ▷ Neoprene ▶ Dacron+ Adhesive (coat)	Hypalon Polyurethane Dacron, Bias** Neoprene Kevlar-49++ Adhesive (coat)	
⑥		Hypalon ▷ Polyurethane ▷ Kevlar-49+ ▷ Neoprene ▶ Dacron Bias** Adhesive (coat)	Hypalon Polyurethane ▷● FTL Bias ▶ Kevlar-49++ ▶ Polyurethane



*61 g/sq m (1.8 oz/sq yd) plain weave fabric.
**48 g/sq m (1.4 oz/sq yd) plain weave fabric.
+110 g/sq m (3.25 oz/sq yd) plain weave fabric.
++95 g/sq m (2.8 oz/sq yd) plain weave fabric.
▷ Peel test interface (attempted).
▶ Peel test interface (successful).
● 380 denier, Kevlar yarn 60° FTL, equally spaced 1.1 cm (0.43 in.) apart

Figure 1. Matrix of Test Materials. Upper layer shown would be the exterior of an inflatable structure

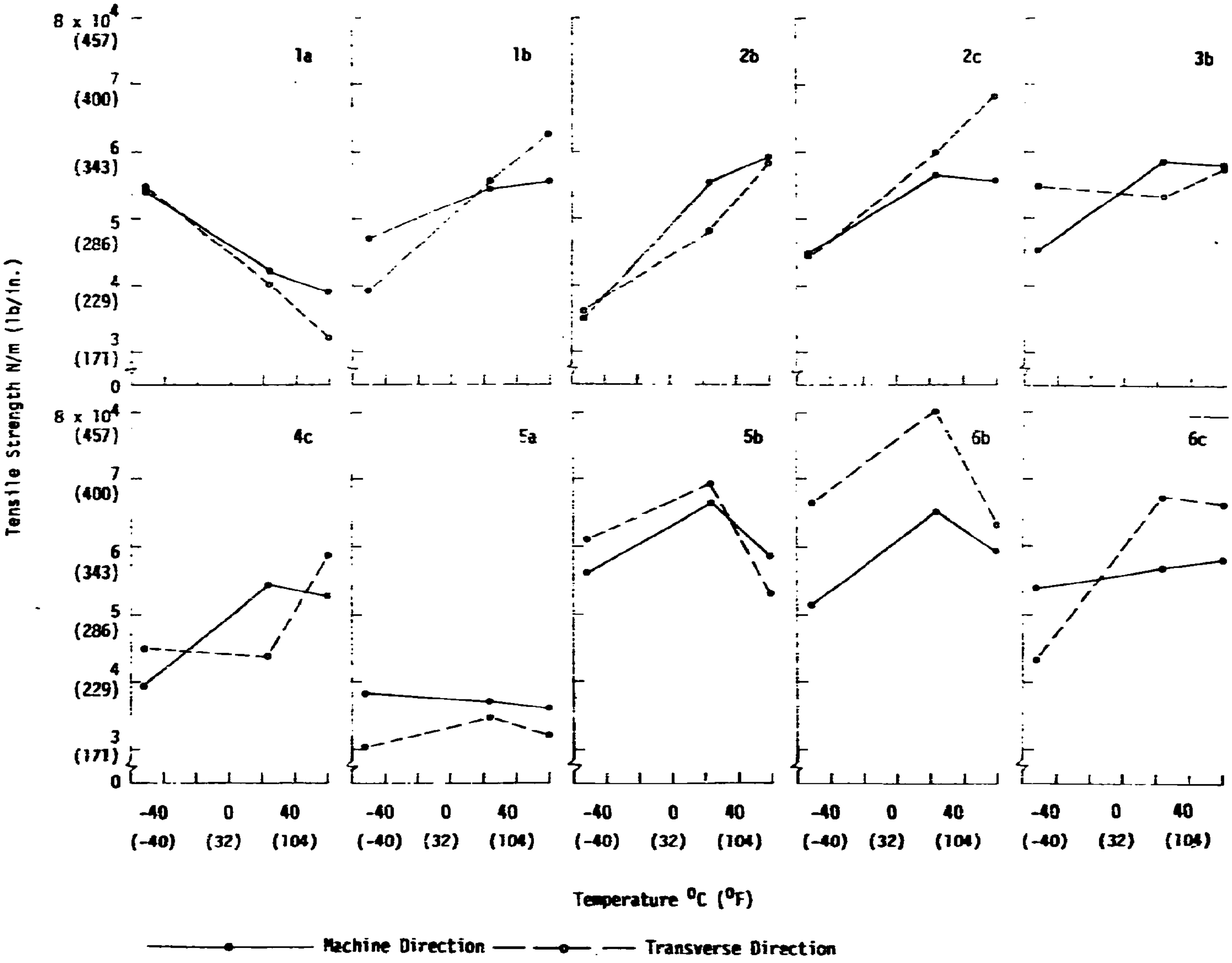


Figure 2. Variation of Tensile Strength at Failure with Temperature

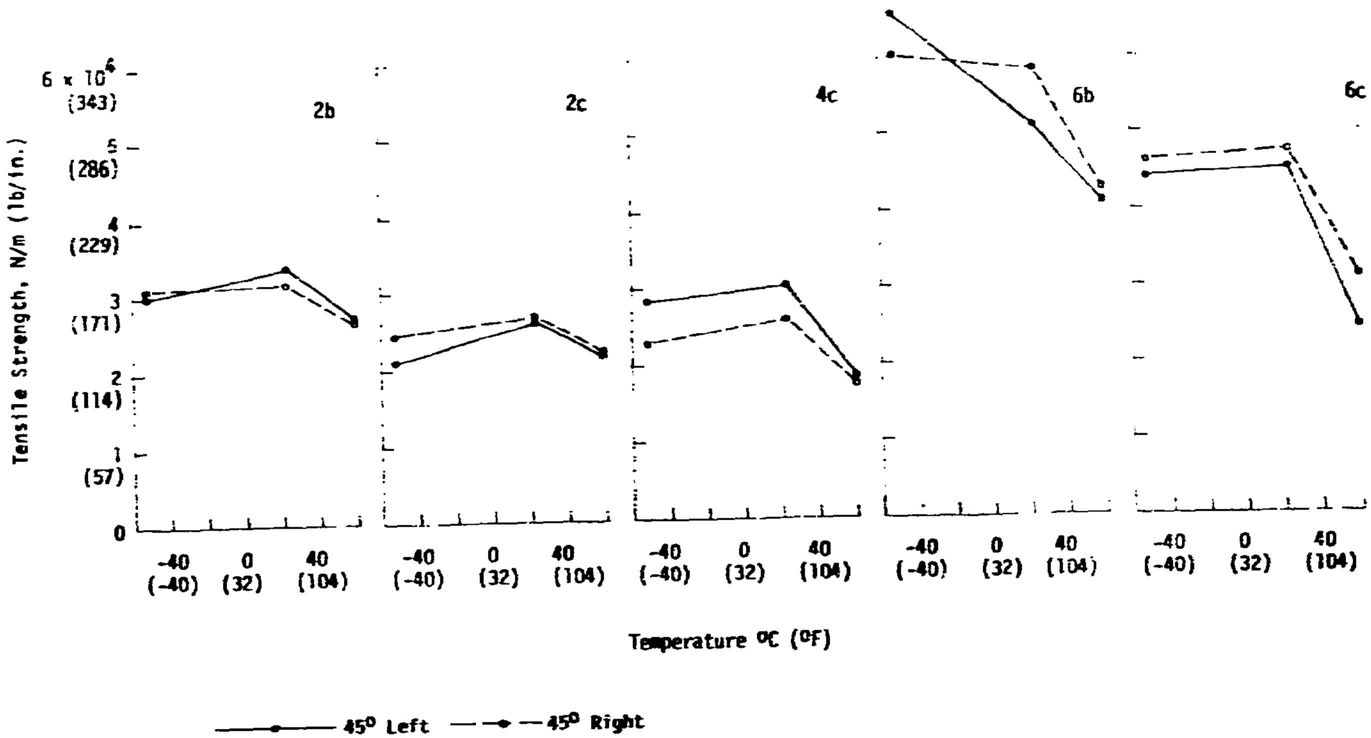


Figure 3. Variation of Tensile Strength with Temperature

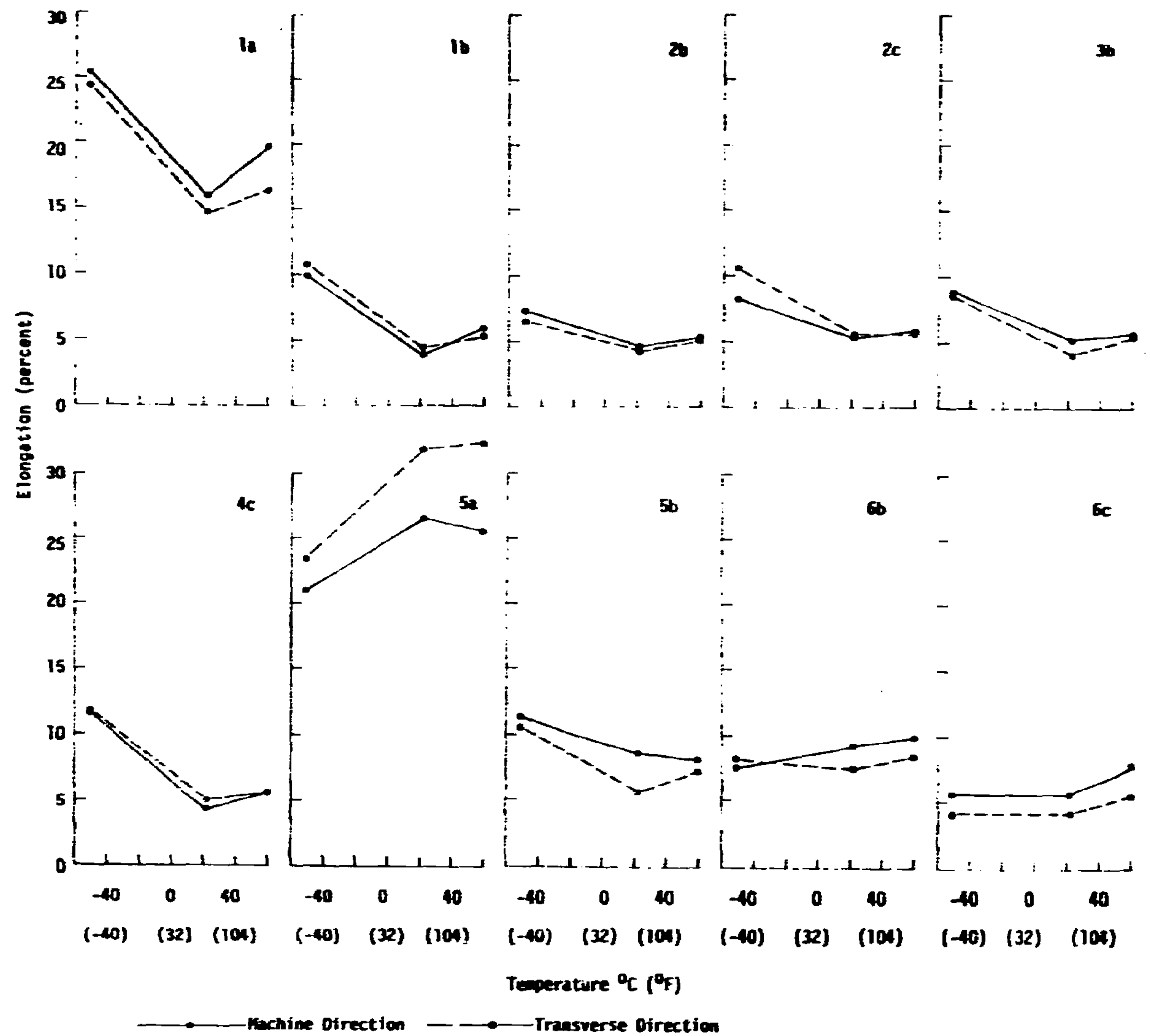


Figure 4. Variation of Elongation at Failure with Temperature

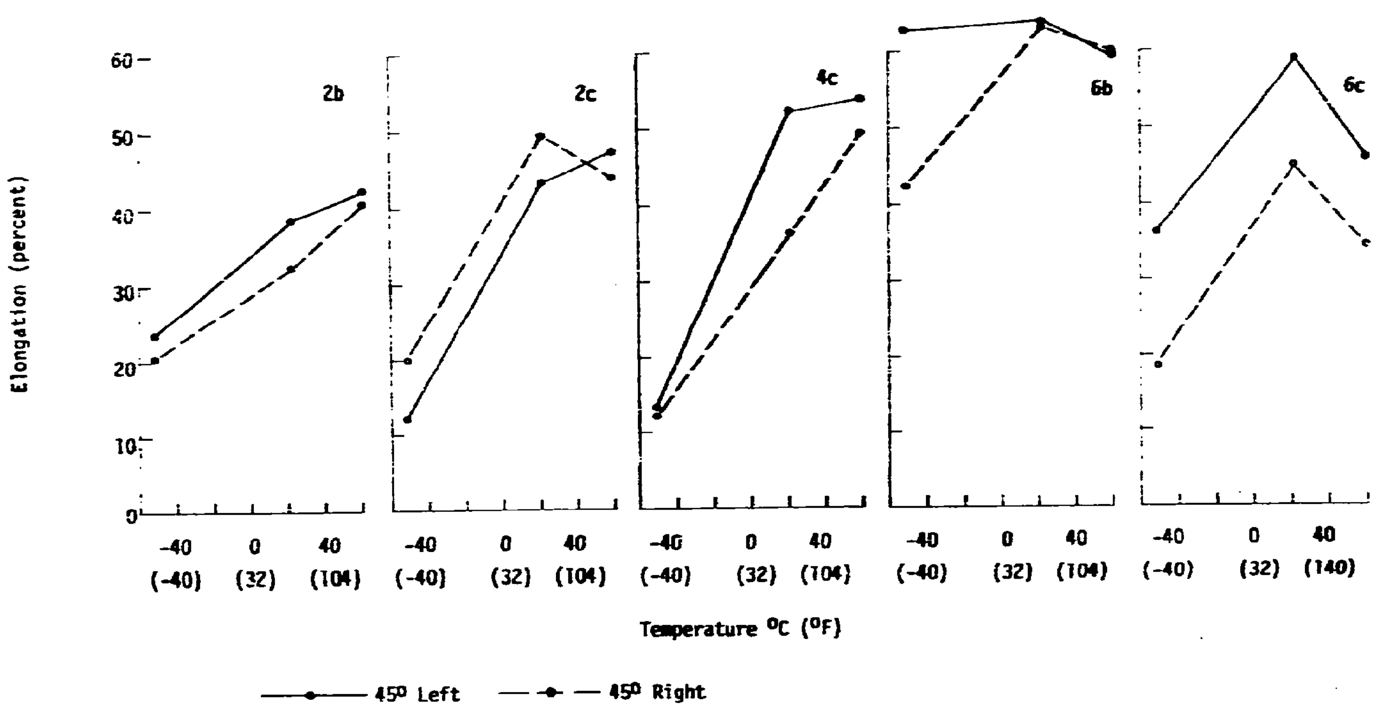


Figure 5. Variation of Elongation with Temperature