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AIR FORCE GEOPHYSICS LABORATORY AERODYNAMICALLY SHAPED TETHERED--ETC(U)
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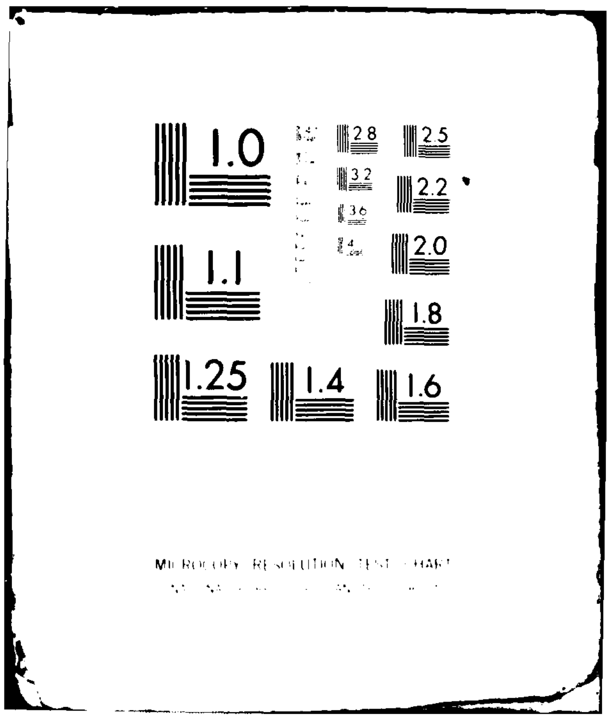
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AFGL-TR-80-0367

AIR FORCE GEOPHYSICS LABORATORY AERODYNAMICALLY SHAPED TETHERED BALLOON, 45,000 FT^3

AD A096758

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R.W. Lawrence

ILC Dover
P.O. Box 266
Frederica, Delaware 19946

December 1980

Final Report
1973 February - 1979 June

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Final Report of USAF Geophysics Laboratory program undertaken in 1973 to develop superior tethered balloon material and design and fabricate a 45,000 ft³ tethered balloon from the developed material. A new empennage ripstop fabric of combined Kevlar and pre-heat set Dacron yarns, and a new hull fabric which is a biaxially woven fabric stabilized with an oriented non-woven polyester fabric, were developed. A 45,000 ft³ balloon was designed, fabricated and tested. The new material is suitable for construction of balloons in the 100,000 ft³ range. The hull fabric developed on this program

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Was later scaled-up and is currently used in USAF 250,000 ft^3 Seek Skyhook Aerostats.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES (CONTINUED)

FINAL REPORT

AERODYNAMICALLY SHAPED TETHERED BALLOON

45,000 FT^3

1.0 INTRODUCTION

The goal of this contract since its beginning was to develop, and to substantiate by test, improved balloon materials.

This report delineates all activities accomplished on Contract F19628-73-C-0155. It covers the design study effort and the sequentially developed 45,000 cubic foot aerostat assembly as shown in figure 1. It details the corollary materials research and structural development efforts. Then too, this report presents and explains the design criteria and the engineering decision rationale employed throughout the entire program.

The report has not been specifically structured to present only the positive aspects of the development, but rather to delineate all avenues of approach realistically.

ILC Program Management personnel feel that this program was a challenging extension of aerostat technology. The materials development and testing efforts have confirmed that this advancement in technology was feasible. This confidence is heightened by the fact that on the basis of this report, AFGL personnel can now bring to bear the weight and impact of their technical direction.

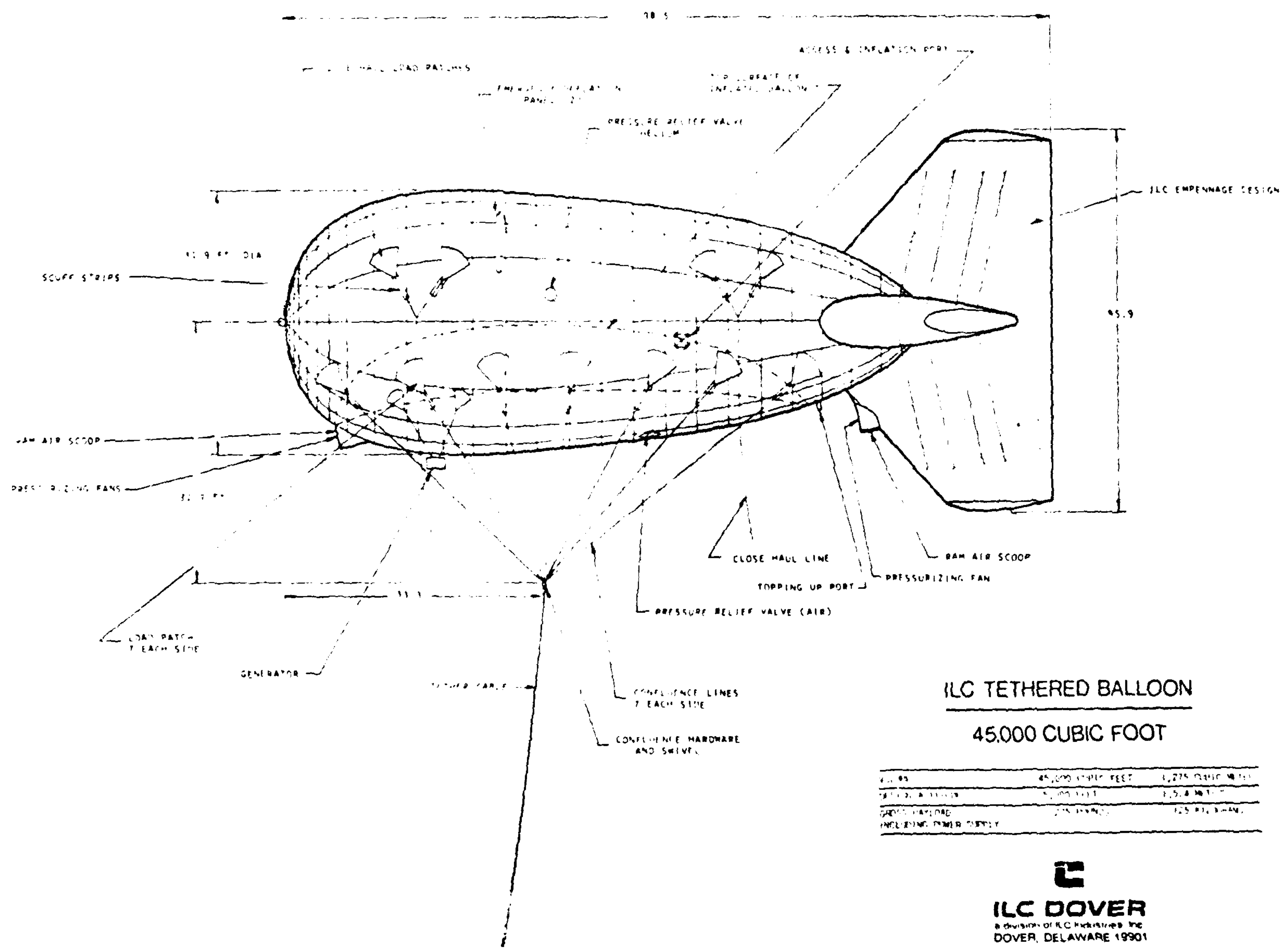


Figure 1 45,000 FT^3 Aerostat Assembly

2.0 TECHNICAL REQUIREMENTS AND OBJECTIVES

2.1 General

The overall contract requirement was to develop a new superior balloon material and, after material development, to design and manufacture a 45,000 ft^3 aerodynamically shaped tethered balloon. Additionally, the materials and basic balloon design were to be useable on a scaled-up 100,000 ft^3 balloon. The program was divided into, and approached, in four separate but interrelating phases as follows:

a. Design material and produce test specimens.
b. Develop a testing procedure for approved material.
c. Design balloon.
d. Fabricate balloon.

2.2 Requirements

2.2.1 Basic Function

The use of flexible fabric in pressurized structures requires that the fabric perform two basic functions:

a. Support the structural loads.
b. Contain the pressurizing media.

2.2.2 Basic Fabric Requirements

The selection of a fabric for an inflatable balloon structure is based primarily upon the necessary skin strength required to sustain internal and external loads, however, other important requirements include:

a. High strength to low weight.
b. Environmental resistance.
c. Weatherability.
d. Ease of balloon fabrication.
e. Long term life.

2.2.3. Fabric Categories

In order to build an aerodynamically shaped tethered balloon with superior performance, more than one type of fabric is required. These fabrics fall into three major categories; hull fabric, ballonet fabric, and empennage fabric. Each of these fabrics performs a different function and consequently should meet a different specification. Attributes of superior hull, empennage and ballonet fabric are described in tables 1 and 2.

TABLE 1

Attributes - Hull and Empennage Fabric

impermeability to helium
impermeability to air
hydrolytic stability
abrasion resistance
tear strength
dimensional stability
UV resistance
ozone resistance
chemical resistance
thermal reflectivity

TABLE 2

Attributes - Ballonet Fabric

impermeability to helium and air
hydrolytic stability

2.2.4 Balloon Design Criteria

The operational specifications established early in the program resulted in the following design criteria:

a. Lifting gas volume of **45,000 cubic feet.**
b. Ballonet volume to accommodate flight from sea level to 10,000 feet mean sea level (MSL).
c. Balloon to be aerodynamically shaped and trimmed to fly at an altitude of 10,000 feet MSL.
d. Capable of carrying a 200-pound payload to 10,000 feet MSL when launched from an elevation of 5,000 feet.
e. Balloon must support a tether cable weighing 100 pounds per thousand feet.
f. Lifting gas to be helium.
g. Balloon materials shall be adequate for use with a 100,000 cubic foot balloon with an operational altitude of 10,000 feet MSL.
h. Balloon must withstand wind velocity of 60 knots at sea level.
i. Balloon must withstand an internal pressure of 3.5 inches of H_2O (no safety factor).
j. Tension in flying line load patches shall not exceed 10 pounds per inch.
k. Minimum factor of safety of 3 on balloon material loading.

2.3 Design Objectives

ILC has studied the static and dynamic strength requirements for fabrics to be used in hull, ballonet, and empennage of a 100,000 cubic foot balloon for wind velocities of 60 knots at sea level. This study has indicated there is little increase in longitudinal or circumferential strength requirement over and above internal static pressure due to dynamic loads. However, there could be a substantial increase in bias loads due to dynamic loads. Based on this study, table 3A represents the original design objectives for hull, ballonet and empennage materials.

TABLE 3A

Original Design Objectives
Hull, Ballonet, and Empennage
100,000 Cubic Foot

Characteristic	Value		
	Hull	Ballonet	Empennage
Weight (Oz/Yd^2)	7.5 max.	4.0 max.	6.0 max.
Breaking Strength (lbs/in)			
Machine	100 min.	60 min.	60 min.
Transverse	100 min.	60 min.	60 min.
Bias	100 min.		

TABLE 3A (Continued)

Characteristic	Value		
	Hull	Ballonet	Empennage
Adhesion (lbs/in)	10 min.	10 min.	10 min.
Permeability (Liters/m^2/24 hours) Helium	1.0 max.	.5 max.	
Air			1.0 max.
Tear Strength (lbs)			
Tongue Method			
Machine	20 min.	10 min.	15 min.
Transverse	20 min.	10 min.	15 min.
Low Temperature Flex	No cracks @ -40^{o}F	No cracks @ -40^{o}F	No cracks @ -40^{o}F
Width	52" min.	52" min.	52" min

During the course of the material design and test phases, it became apparent that some of the above design objectives could be met or surpassed, while others could not. Subsequently, the original design objectives were re-evaluated on a more knowledgeable, realistic basis. Table 3B represents the design objectives after the re-evaluation.

TABLE 3 B

Re-evaluated Design Objectives

Hull, Ballonet, and Empennage

100,000 cubic foot

Characteristic	Value		
	Hull	Ballonet	Empennage
Weight (Oz./yd^2)	8.0	4.0	6.0
Breaking Strength (lbs./in.)			
Machine	100	60	140
Tranverse	100	60	140
Bias	100		
Adhesion (lbs./in.)	7.0	7.0	7.0

TABLE 3B Con't.

Characteristic	Value		
	Hull	Ballonet	Empennage
Permeability			
(Liters/m^2/24 hours)			
Helium	< 1.0	< 1.0	
Air			< 1.0
Tear Strength (lbs.)			
(Tongue Method)			
Machine	20	5	12 min.
Transverse	20	5	12 min.
Low Temperature Flex	No cracks @ -40^{o}F	No cracks @ -40^{o}F	No cracks @ -40^{o}F
Width (inches)	52	52	52

3.0 MATERIAL DESIGN AND SELECTION ANAYLSIS

3.1 General

Design and selection of balloon materials required, first, a thorough analysis of yarns, fabric construction, and coating and films at their base level. Secondly, based on those analyses, and balloon design requirements, preliminary selections of candidate yarns, fabrics, films and coatings were made for possible use as ballonet, empennage or hull material. The following paragraphs detailing the material design and selection process, are presented in that order.

3.2 Yarn Considerations

Pioneering investigators found that polyester yarns indicated the most promise of any natural or synthetic organic fiber for construction of aerostat envelope fabrics. The primary factors contributing to the suitability of polyester for aerostat envelope fabrics are:

- high strength to weight
- high initial modulus
- resistance to ultra violet radiation

However, great strides have recently been made in development of new fibers available for fabrication of superior cloth. One such family of fibers known as aramid's of which Kevlar 29 is a member, are presently available in deniers fine enough to make lightweight fabrics with excellent physical properties. In addition, very fine deniers can be made in a pilot plant operation at modest cost. Figure 2 illustrates the magnitude of difference between the stress-strain characteristics of high tenacity polyester and aramid yarns.

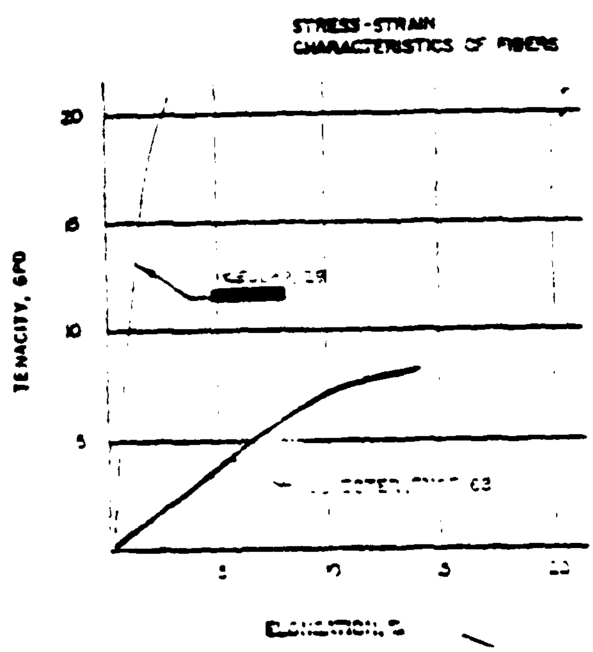


FIGURE 2

3.2.1 Specific Gravity of Fibers

Table 4 lists the specific gravities of polyester and aramid fibers. Specific gravity is defined as the ratio of a substance's unit volume weight to that of water at 4^{o} C.

TABLE 4
Specific Gravity of Polyester
and Aramid Fiber

Material	Specific Gravity
Dacron polyester	1.38
Kevlar aramid	1.40

3.2.2 Fiber Strength and Tenacity

When subject to a tensile force, the total strength of a fiber is dependent upon both its intrinsic ability to remain intact and upon its dimensions. The absolute value of a fiber's strength may be meaningless until it is related to its cross sectional area or its linear density, that is, weight per unit length. As is the custom, with all engineering materials, fiber breaking strengths can be listed on a pounds per square inch (psi) basis. More commonly, however, the textile trade uses the term "tenacity" to describe strength on a grams per denier (gpd) basis. This is because it is easier to determine a fiber's or yarn's weight per length than its cross sectional area, and because yarn weight is an important textile physical and economical factor. Since denier is based upon weight per unit length, it is obvious that tenacity is influenced by the specific gravity of the fiber, while strength per unit area is not. In Table 5 fiber tenacities are listed in psi and grams per deniers.

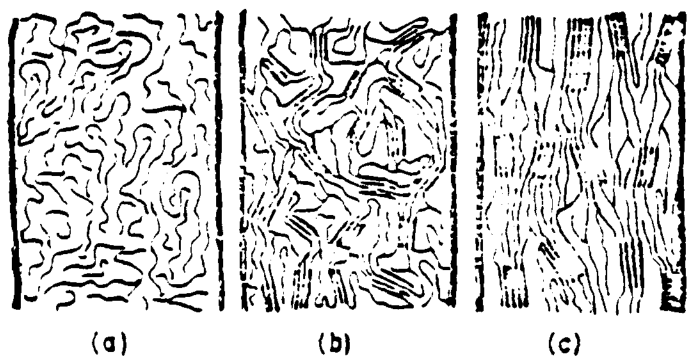
TABLE 5

Fiber Tenacities

Material	Grams per Denier (gpd)	Pounds per Square Inch (psi)
Polyester, Type 55	4.3	78,000
Polyester, Type 52	8.0	138,000
Aramid, Kevlar 29	22.0	400,000

3.2.3 Orientation and Crystallinity

Figure 3 shows diagrams of fibers (a) with a low degree of crystallinity and orientation; (b) with a high degree of crystallinity and a low degree of orientation; and (c) with a high degree of crystallinity and orientation. Crystallinity



Schematic representation of an amorphous polymer (a) a crystalline polymer (b), and an oriented crystalline polymer (c).

FIGURE 3
FIBER ORIENTATION AND CRYSTALLINITY

and orientation are accomplished by the combined effects of heat and mechanical stretching of the extruded filament. Temperature will critically influence the rate of crystal growth and their size, while stretching or "drawing" controls orientation.

When fibers become highly oriented through being stretched under suitable conditions, they usually require certain properties, these are:

- high tenacity
- low elongation

The better the orientation, the higher the tenacity. This is the natural outcome of the stretching process in which the denier is very greatly reduced, whereas the breaking load is substantially unaffected. Table 6 well illustrates the effect of orientation on the tenacity of fibers.

TABLE 6

Effect of Orientation of Fibers

Fiber	Orientation	Tenacity (gpd)	Elongation (%)
Kevlar 29	Extreme	22.0	3
Dacron, Type 68	High	9.2	13 - 14
Dacron, Type 55	Moderate	4.3	30

3.2.4 Yarn Properties of Kevlar 29

Kevlar 29 has a non-linear curve in the same strength/modulus range as glass fibers but shows significant advantages over glass in yarn strength uniformity, low density and resistance to surface damage and creep rupture under high stress. The stress-strain curve of Kevlar 29 can be further altered by subsequent textile processing operations, such as the addition of twist in the yarn, to lower the modulus so that a functional end use soft goods item can be produced.

Unlike other organic yarns, Kevlar 29 demonstrates an increase in tenacity rather than a decrease when twist is applied. Table 7 illustrates this unique characteristic.

TABLE 7

Effect of Twist on Kevlar 29 Yarns

Denier	Twist Per Inch (TPI)	Tenacity (gpd)	Elongation at Break (%)
200	0	(min) 17, (avg) 21	3%
200	5	(min) 21, (avg) 24	4%
200	9	(min) 19, (avg) 23	7%

Kevlar 29 yarns can be handled in all textile processes without difficulty. Knot strength is 37% and loop strength 50% of straight tensile strength. Retention of strength after conventional weaving is 90% of virgin yarn strength. The individual filaments of the yarn have a round cross-section and have a diameter of .47 mils. When pulled tight over an edge, they do not break sharply but bend while retaining high tensile strength.

Kevlar 29 fibers also have high thermal stability. When tested at 320°F in air, Kevlar 29 exhibits essentially zero shrinkage. When tested at 400°F unprotected yarns evidence only 18% loss of physicals.

The unprotected fibers are also highly resistant to strong acids and bases, organic solvents, fuels, lubricants and hydraulic fluids. The ultra-violet light resistance of unprotected Kevlar 29 yarns is similar to nylon.

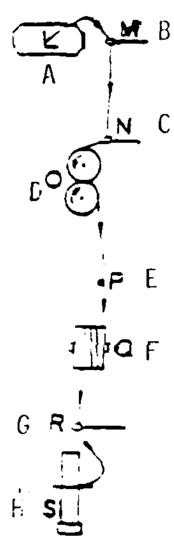
3.2.5 Properties Of Polyester Yarns

The tenacity and elongation at break of Dacron can be varied over a considerable range, according to the degree of drawing that is applied to the undrawn yarn. High tenacity and normal tenacity yarns are made from the same polymer, but they are drawn to different extents after spinning; the higher the draw or stretch the higher the tenacity and the lower the elongation of the resulting yarn, thus high-tenacity yarn is drawn to a greater extent (possibly 60%) than normal-tenacity yarn.

The stress-strain curve of Dacron polyester can be further altered by subsequent textile processing operations. For a higher modulus of elasticity and tensile the yarn may be hot-stretched and pre-shrunk. This drawing procedure allows the yarn product to obtain thermal stability. During yarn preparation of a singles polyester yarn, for example, after twisting, the yarn is hot-stretched and pre-shrunk at a temperature of about $300^{\circ}F$. This sets and balances the twist in the yarn structure, makes it heat stable, and in addition produces greater strength per width and lower rupture elongation - ideal yarn characteristics of aerostat materials. By proper manipulation of temperature, tension, strain (elongation), and relaxation desired strength, elongation, and thermal shrinkage properties can be incorporated into hot-stretched, pre-shrunk yarns.

During subsequent engineering studies of hot-stretched, pre-shrunk Dacron polyester yarns it became apparent that the potential demand for this type of yarn was far greater than the supply. In view of the short supply of hot-stretching equipment and the potential demand for this improved yarn structure an alternative approach was investigated, that is, cold drawing.

Generally speaking, fine filament yarns, like polyester, are always hot-stretched, but the yarn can be stretched or drawn cold, but less easily and less uniformly than when hot. The cold stretching operation is simple and is illustrated in Fig. 4.



The Dacron yarn is pulled off the bobbin A, which is the primary spinning package (twisted); it passes round guides B and C, between a pair of nip rollers D, which determines its initial speed, and goes over a deflector E and then two or three times around roller F which has a linear speed about five times that of roller D; then it passes through a guide G, and onto a take-up bobbin H. The cold draw, or degree of stretch, is equal to the ratio of the linear speeds of rollers F and D.

Figure 4 - Cold Stretching Yarn

After the take-up package is completed it is heat-stabilized to insure dimensional stability, reduce stresses, removes the torque caused by twisting and sets the yarn. Table 8 illustrates the impact of either hot or cold-stretching of high tenacity polyester yarn.

TABLE 8

Effect of Hot and Cold-Stretching of Polyester Yarns

	Original				Final		
Material	Denier	Tensile (gdp)	Elongation (%)	Operation	Denier	Tensile (gdp)	Elongation (%)
Dacron, Type 52	55	8	14	Hot-Stretching	42	6.5	13%
Dacron, Type 52	55	8	14	Cold-Stretching	45	7.0	12%

Heat-setting of Dacron yarns can be carried out in steam under pressure, but this method is undesirable because it causes some hydrolysis of the ester groups in the polymer chain, and the fiber is party depolymerised, with a resultant loss in tenacity. Dry heat-setting is the best process, and the dimensional stability which is thereby conferred on Dacron is one of its greatest assets.

3.2.6 Investigation Of Plied Yarn Construction

The study of ply construction of yarns was limited to factors relating to control of textile physical properties such as elongation and weaveability. The plied yarn structure lowers the yarns modulus; thus increasing elongation. For aramid yarns, where elongation is minimum, plying is ideal for it increases elongation. However, for polyester yarns, where elongation is high to start, plying only further increases yarn elongation, an undesirable condition.

Two yarns of 200 denier Kevlar 29 plied results in a yarn structure with a diameter too great for this aerostat application, although it might be ideal for a larger aerostat application. The splitting of Kevlar 29 yarns and plying component parts, although possible, is not practical because of very high cost and lengthy delivery. Therefore, this development program was limited to single ply yarns.

3.2.7 Investigation of Twist In Yarn Construction

Twist is necessary in order to give integrity, compactness, snag and abrasion resistance to filament yarns. However, too much twist results in a lower strength to weight ratio, lower tear strength, and potentially greater coating difficulties. On the other hand, not enough twist will result in broken filaments, thus poor quality fabric.

Yarn studies conducted during this program indicate that minimum twist in polyester yarns is ideal, but the yarn must be either hot or cold-stretched to ensure a high degree of modulus. Contrary to polyester, aramid yarns increase their strength to weight ratio when twisted, thus furthering to improve yarn properties. Table 9 illustrates the effect of twist on polyester and aramid yarns.

TABLE 9

Effect of twist on Aramid yarns

Material	Twist per inch (TPI)	Tenacity (gpd)	Elongation (%)
Kevlar 29, 200 Denier	0	(min) 17, (avg) 21	3
Kevlar 29, 200 Denier	5	(min) 21, (avg) 24	4
Kevlar 29, 200 Denier	9	(min) 19, (avg) 23	7

3.3 Fabric Construction Considerations

After considerable study on the numerous possible combinations of materials to build balloon fabrics, ILC Dover placed major emphases on two major fabric constructions;

- Two-Ply Biased Fabric
- Triaxially Reinforced Film

3.3.1 Two-Ply Biased Fabric

This construction was a two-ply fabric composed of a dimensionally stable scrim laminated to a lightweight ripstop constructed fabric. The advantage of utilizing dimensionally stable scrims in place of a very lightweight fabric is that no biasing operation is necessary. This advantage realizes a savings in cost and laminating time and requires fabrication of only a one-direction fabric.

A thorough investigation of the non-woven scrim market yielded two possible candidate materials for this application:

Tyvek - Spunbonded olefin
Reemay - Spunbonded polyester

However, subsequent testing indicated that fabrics fabricated from Tyvek were unacceptable. This is due to the incompatibility in temperature resistance of the Butyl and spunbonded olefin during the curing operation.

The structural ripstop fabric was designed to incorporate both high tenacity Dacron and Kevlar 29 yarns, whereby the Kevlar 29 yarn is used as the ripstop in both the warp and fill directions while the Dacron yarns are used for ground.

Because of the high cost of the Kevlar 29 yarn, ILC Dover ran a study to minimize the Kevlar 29 usage.

3.3.1.1 Ripstop Fabric Design Criteria

The following objectives were established to insure that the developed ripstop construction would possess excellent fabrication versatility.

DESIGN OBJECTIVES

CHARACTERISTIC	REQUIREMENT
Weight	2.0 oz/yd^2
Breaking Strength	140 lbs/in x 140 lbs/in
Count	100 x 100
Tear Strength	12 x 12
Material	Dacron, Type 52, 70 Denier Kevlar 29, 200 Denier

The following equation was used to determine what percentage of the construction should be Kevlar 29 and what percentage should be Dacron, Type 52. The objective here, was to minimize the use of Kevlar 29.

$$\sigma \text{ (lbs/in)} = \epsilon E_x D_x X + \epsilon E_y D_y Y \ldots$$

where:
- σ - Ultimate Fabric Stress (lbs/in)
- ϵ - Ultimate Elongation (in/in)
- E - Tenacity (gpd)
- D - Denier
- X, Y - Number of Years per Inch

$$140 = \frac{(.033)(75)(70)X}{454} + \frac{(.033)(530)(000)Y}{454}$$

$$140 = .3815X + 9.1520Y$$
$$100 = X + Y$$
$$X = 100 - Y$$
$$140 = (.3816)(100-Y) + 9.1580Y$$
$$140 - 38.16 = .3816Y + 9.1580Y$$

$$Y = \frac{101.34}{8.777}$$

$$Y = 11.5$$

$$X \quad 88.4$$

As a result of this study, a ripstop fabric was engineered whereby 88 percent of the construction was 70 denier, Type 52 Dacron and 12 percent of the construction was 200 denier, Kevlar 29. This construction increases the breaking strength of an all Dacron fabric by 50 percent while tripling the tear strength without any increase in weight. Table 10 compares an all Dacron fabric with the first iteration Dacron/Kevlar ripstop fabric.

TABLE 10

ALL DACRON FABRIC vs. DACRON/KEVLAR RIPSTOP FABRIC

CHARACTERISTIC	ALL DACRON FABRIC	DACRON/KEVLAR FABRIC
Weight, oz/yd^2	2.1	2.3
Breaking Strength, lb/in.	90 x 90	156 x 145
Tear Strength, lb.	4 x 4	28 x 26
Count	100 x 100	100 x 100

The experimental Dacron/Kevlar ripstop fabric, employed as the structural membrane, was coupled respectively with a lightweight biased fabric and a lightweight spunbonded fabric. Figure 5 shows the cross sections of the two experiemental two-ply constructed fabrics. The two experimental constructions and a control were tested, and primary representative properties are given in Table 11.

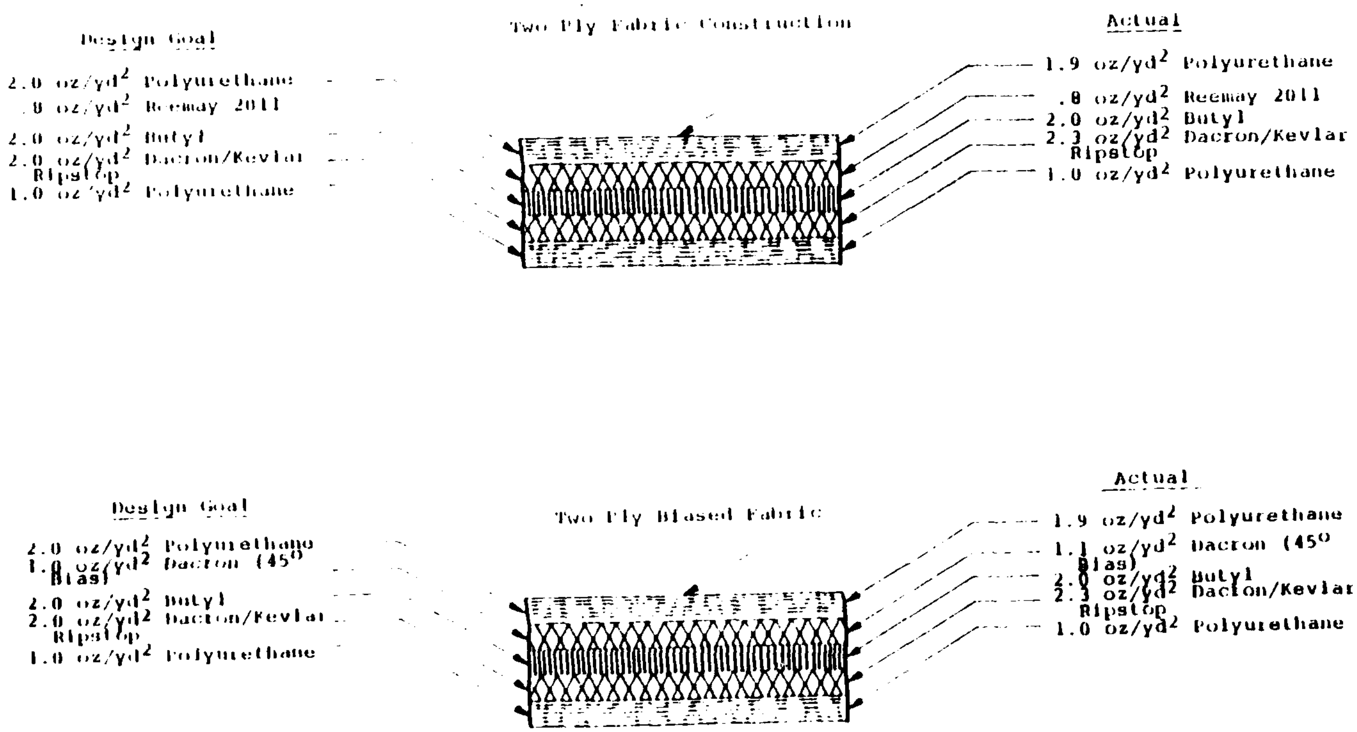


Figure 5 - Experimental Two-Ply Dacron-Kevlar Ripstop Fabric Construction

TABLE II

EXPERIMENTAL TWO-PLY HULL FABRICS

CHARACTERISTIC	DESIGN GOAL	BASE LINE ILC P/N A105002	BIAS RIPSTOP	SPUNBONDED RIPSTOP
Weight, oz/yd^2	8.0	8.3	8.3	8.0
Tensile, lb/in				
Machine	100	106	85	84
Transverse	100	105	103	91
Bias	100	95	105	85
Tear, Tongue				
Machine	20	10.6	27.8	17.3
Transverse	20	8.5	25.2	11.9
Leakage				
L/M^2/24 Hr.	< 1	< 1	< 1	< 1
Shear Resistance (lbs)	60	85	95	63

3.3.1.2 Empennage Envelope Material

In addition to developing the ripstop fabric as the structural membrane for the two-ply fabric construction, engineering was initiated to similarly design a ripstop fabric for use as the envelope material in the empennage. The initial empennage design required both coated and uncoated fabric; the uncoated fabric to be used as the restraint for the empennage bladder assembly and the coated fabric for the protective skin. Therefore, the design objectives for the empennage ripstop fabric were as follows:

DESIGN OBJECTIVES

EMPENNAGE RIPSTOP FABRIC

CHARACTERISTIC	REQUIREMENTS UNCOATED	COATED
Weight, oz/yd^2	1.5	3.5
Breaking Strength, lb/in	60 x 60	60 x 60
Tear Strength, lbs.	15 x 15	15 x 15

Figure 6 shows the cross section of the experimental empennage ripstop fabric, and primary representative properties are given in Table 12.

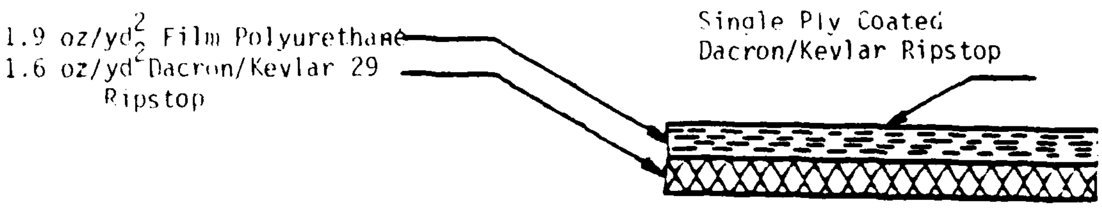


Figure 6 - Experimental Empennage Ripstop Construction

TABLE 12
EXPERIMENTAL EMPENNAGE FABRICS

	DESIGN GOAL UNCOATED	BASELINE ILC P/N A105009	DACRON/ KEVLAR RIPSTOP	BASELINE COATED ILC P/N A105001	DACRON/ KEVLAR RIPSTOP COATED
Weight, oz/yd^2	1.5	2.0	1.6	4.0	3.5
Tensile, lb/in					
Machine	60	90	50-80	90	50-80
Transverse	60	90	50-80	90	50-80
Tear, Tongue, lbs.					
Machine	15	4	17.0	2	14.2
Transverse	15	4	16.8	2	20.4

3.3.1.3 Problems Encountered

The development of the Dacron/Kevlar ripstop fabric was initiated using commercially available yarns. Because of this decision, the fabric ends up being unacceptable for coating due to the excessive shrinkage in the Dacron yarns and no shrinkage in the Kevlar 29 yarns. This problem was alleviated by the use of pre-shrunk heat-set Dacron yarns.

The dissimilar moduli of the Kevlar 29 and Dacron Type 52 yarns prevented the satisfactory culmination of this design effort. As a result, although one physical fabric was woven, two definite breaking strengths resulted. The first breaking strength indicated the breakage of the Kevlar 29 yarns. The second breakage indicated the breaking strength of the Dacron yarns. Analysis indicates this type of fabric failure defeats the purpose of the fabric design . If the Kevlar 29 yarns fail, although the Dacron yarns maintain adequate tensile to sustain static loads, the increased tear strength, due to the Kevlar 29 yarns, is totally lost. Therefore, this construction is unacceptable.

Thorough analysis of the problem of mixing dissimilar moduli materials resulted in an approach to perfect the Dacron/Kevlar ripstop construction. The conceived idea was to change the orientation and crystallinity of the Dacron yarn, thus increasing the modulus, while twisting and plying the Kevlar 29 yarn to reduce the modulus.

Therefore, the next design iteration consisted of lowering the twist per inch in the Dacron yarn, increasing the twist per inch in the Kevlar 29 yarn, 2-plying the Kevlar 29 yarn and changing from two strands of Kevlar 29 for the ripstop to one strand. The changes resulted in increased elongation of the Kevlar and resulted in a fabric having a minimum breaking strength of either yarn system of 80 pounds per inch, however, the Kevlar 29 yarn still broke first. In addition, the single strand of Kevlar 29 yarn only had 10 pounds of tear strength and the two-ply Kevlar 29 yarn presented excessive bulk at the cross-over. This bulk presented considerable coating difficulty.

As a result, another design iteration was considered. Considerations for this design iteration were:

- cold-stretched, pre-shrunk 140 denier Dacron yarn in lieu of 55 denier pre-shrunk Dacron yarn
- lower twist per inch in the Dacron yarn
- higher twist per inch in the Kevlar 29 yarn

The rationale for this design iteration was to provide for a flatter fabric, thus enhancing the coating capability, while bringing the yarn moduli closer together. Figure 7 shows the cross section of the proposed experimental empennage ripstop fabric, and primary properties are given in Table 13.

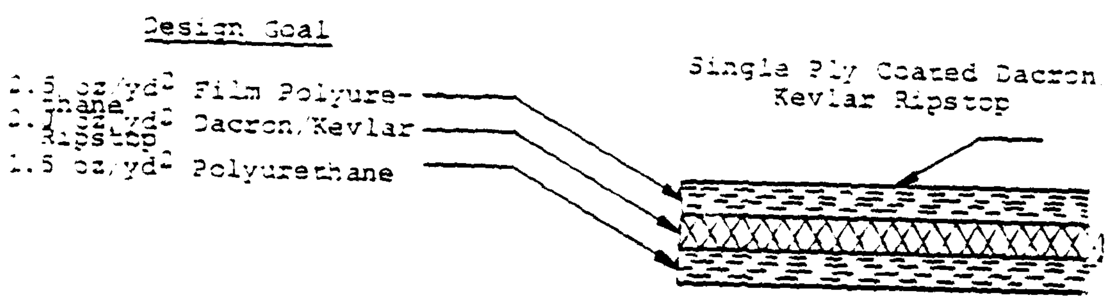


Figure 7 - Experimental Empennage Ripstop Cross-Section

TABLE 13
EXPERIMENTAL EMPENNAGE FABRIC PROPERTIES

CHARACTERISTIC	DESIGN GOAL UNCOATED	TEST VALUES UNCOATED	COATED
Weight, oz/yd^2	2.0	2.41	5.8
Tensile, lbs/in			
Machine	60	83	76
Transverse	60	98	70
Tear, Tongue, lbs.			
Machine	15	32	16
Transverse		32	15

3.3.2 Triaxially Reinforced Films

For particularly demanding requirements such as those for structural balloon fabric, the triaxial approach appears to offer a number of advantages over orthogonal weaves:

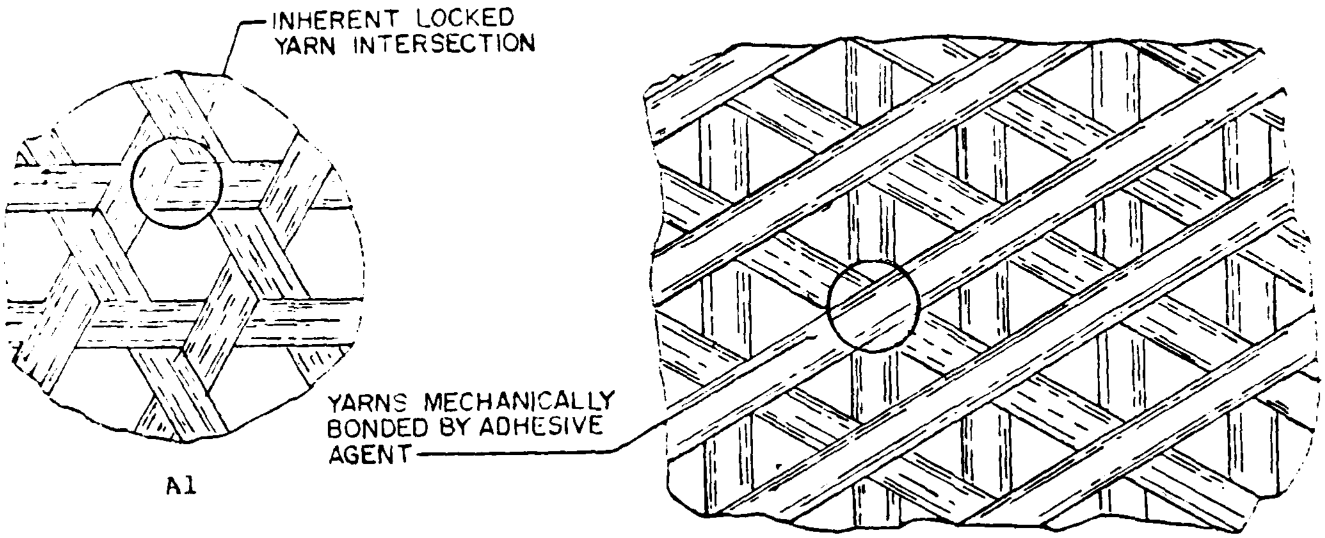
- Eliminates the requirement for laminating two fabrics.
- Triaxial fabric is the only single plane textile fabric strong in the bias direction.
- The nature of the triaxial configuration precludes tear propagation.

Due to the revolutionary nature of the triaxial configuration and the limited capabilities of those machines available, only two variants of triaxial weave were considered; the basic-weave, and the sixteenth variant.

The nature of triaxial machinery and the mechanisms associated with them, unlike conventional textile machinery, dictate certain design parameters, such as yarn count and yarn diameter.

5.3.2.1 Triaxial Flying Thread Scrim

Sketch A2 represents the flying thread scrim concept whereby yarns are laid up at 60^0 angles, however, the yarns are not interwoven. Sketch A1 illustrates a triaxially woven fabric which although is not interwoven is interlocked.



A1 A2

In contrast to the inherent stability of triaxial woven fabrics are the inherent instabilities of triaxially non-woven layups. The non-wovens depend upon an adhesive bonding agent to maintain their integrity, and also, generally, upon an associated film for resistance to shearing distortions while in triaxial fabrics the truss-like, response which provides shearing resistance is derived from the mechanical interlocks at the yarn intersections; in the non-wovens, only the adhesive that bonds the yarns together provides the locking. This bonding is especially complicated when all three yarns cross at one point, as is the configurations used in most such constructions. With three layers of yarns the forces tending to separate or delaminate the non-woven structure are in sharp contrast to the way the corresponding forces tend to snug the yarns together in the triaxially woven fabric.

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 or 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. This coupling effect is completely avoided with the triaxial woven fabric.

3.3.2.2 Tear Resistance

ILC Dover has evaluated the tearing behavior of triaxial fabric. Experimental results indicate a substantial gain in tear strength from the triangular structure when compared to orthogonal fabric. In particular, the tear behavior is very much complicated by the presence of three sets of yarns and the triaxial fabric shows tear characteristics very different from those of orthogonal fabrics. While it may be difficult to induce a tear in an orthogonal construction, usually the tear can be propagated at a relatively low load. However, not only is it extremely difficult to induce a tear in the triaxial construction, it is also extremely difficult to propagate any tear.

The tearing behavior is extremely important in many fabric applications, particularly those for aerostats. This property improvement can be further illustrated by analyzing personal tearing experiences. As is known, the tearing resistance "on the bias" is greater than in the warp or fill direction. To tear a triaxial fabric, one is always tearing "on the bias", and the overall improved tear properties result.

Because the basic-weave is the simplest possible triaxial configuration, the analysis of its tearing behavior forms an ideal starting point, on both theoretical and experimental grounds, in the investigation of the tearing characteristics of triaxially woven fabric.

Theoretically, the basic-weave should possess the lowest tear strength of any triaxial configuration. As the interlacings become more complex, as in the first, second, and third variants, the tear strength should similarly increase. This has been empirically shown to be true by virtue of comparison of the basic-weave with the sixteenth variant.

For the purposes of evaluating the tear strength of triaxial fabric three different tear methods were investigated:

- tongue tear
- trapezoid tear
- slit tear

In the tongue tear test a specimen 6 x 8 inches is cut so that the yarns to be ruptured during the tear lie in the shorter dimension. A cut three inches in length is made along the longer centerline of the fabric. This cut thus produces two 3 x 3 inch tongues which are placed in the upper and lower jaws of the testing machine.

As the yarn courses are subjected to increasing tension the angle between the eleven o'clock and one o'clock warp yarns increases allowing the yarn courses to bunch up against each other. As the tear progresses the tongues become progressively longer. The del becomes very large, and the yarns bunch up to reinforce each other, so that tearing is extremely difficult. The tearing action is manifested on the tensile tester recorder as a diagram of progressively increasing and then sharply decreasing loads. Results of the tongue tear tests are shown in Table 14.

TABLE 14

Tongue Tear Strength of
Kevlar Triaxially Woven Fabric

CONSTRUCTION	FABRIC WEIGHT, oz/yd^2	TEAR STRENGTH, LBS. MACHINE	TRANSVERSE
Basic-Weave 16 x 16 x 20	1.5	90*	50*

*The tear did not propagate at the tongue slit, but took the path of least resistance.

For the trapezoid tear test the specimen is 8½ x 5-3/8 inches with a one inch slit placed midway along the longer direction. The sample is inserted on the bias between the jaws of the testing machine so that the yarns are caused to fail progressively. This test is entirely of a tension type, and has little meaning in terms of the practical tearing characteristics of the fabric. In fact, unless the sample size is extremely large, the warp yarns are never placed in tension. Therefore, comparative test results are only obtainable in the machine direction. Results of the trapezoid tear tests are shown in Table 15.

TABLE 15
TRAPEZOID TEAR STRENGTH OF
KEVLAR TRIAXIALLY WOVEN FABRIC

CONSTRUCTION	FABRIC WEIGHT, OZ/YD²	TEAR STRENGTH, LBS. MACHINE	TEAR STRENGTH, LBS. TRANSVERSE
Basic-Weave 16 x 16 x 20	1.5	104	65*

*The warp yarns were not under tension, therefore, the resultant tear strength is not comparative to a similar orthogonal construction.

For the slit tear test a specimen 6 x 7 inches is cut such that the sample has a 1-1/4 inch wide slit across the center of the sample at right angles to the longest dimension. This test is designed to determine the force necessary to propagate a tear in damaged fabric. Unlike conventional orthogonal woven fabric, the triaxially woven fabric shows no sign of tear propagation. The transverse yarns are brought into tension until rupture occurs with no evidence of tear propagation. Although only a few warp ends are placed in tension, no tear propagation results. Results of the slit tear tests are shown in Table 16.

TABLE 16

Slit Tear Strength of
Kevlar Triaxially Woven Fabric

CONSTRUCTION	FABRIC WEIGHT, oz/yd^2	TEAR STRENGTH, LBS. MACHINE	TRANSVERSE
Basic-Weave 16 x 16 x 20	1.5	265*	860*

*Failure was in tensile. The sample showed no signs of tear propagation.

As a result of the in-depth study of the tearing behavior of triaxial fabric, the following conclusions are drawn:

a) The nature of the triaxial configuration precludes tear propagation.

b) Tongue tear results are a magnitude better than conventional orthogonal fabrics.

c) Trapezoidal tear tests have little meaning in terms of practical tearing characteristics.

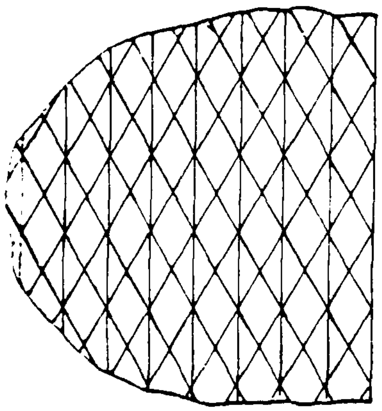
Table 17 illustrates those triaxial woven constructions considered.

TABLE 17

TRIAXIAL CONSTRUCTION

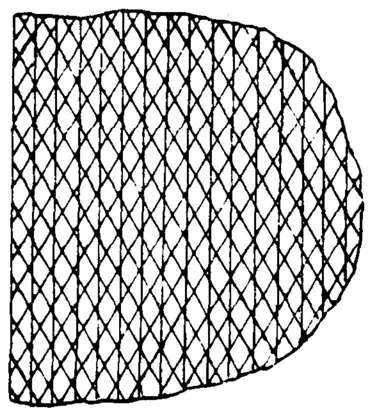
WEAVE	COUNT
Sixteenth Variant	32 x 32 x 32
Basic-Weave	16 x 16 x 16
Basic-Weave	8 x 8 x 8
Basic-Weave	4 x 4 x 4

Sketch B illustrates the difference between two triaxially woven fabrics having the same weight, same tensile, but with different yarn count. As can be seen by comparing Sketch B1 with B2, there is one half the number of yarns, Yarn intersections, and surface area in the 4 x 4 x 4 fabric construction.



4 X 4 X 4

B1



8 X 8 X 8

B2

No acceptable technique has yet been developed for the structural bonding of open weave scrim except for using abnormally wide, tight-woven fabric sealing tapes. From a balloon standpoint, this would create rippling effects due to significant section modulus differences between base material areas and seam-sealing tape areas. Therefore, it is concluded that the optimum choice for base substrate would be a triaxially woven fabric of the highest count possible yet achieving minimum weight and maximum tensile.

3.3.2.3 Triaxial Fabric Design

The following objectives were established to ensure that the developed triaxial fabric construction would possess excellent fabrication versatility.

DESIGN OBJECTIVES

CHARACTERISTIC	REQUIREMENT
Weight, oz/yd^2	3.3
Breaking Strength, lb/in	100 x 100 x 100
Tear Strength, lbs.	20 x 20
Material	Dacron, Type 52

Investigation was initiated with the triaxial fabric manufacturer, Doweave, Inc., to develop a lightweight triaxially woven fabric of the sixteenth variant configuration. Included in this development effort were the following weight fabrics.

3.6 oz/yd^2 Triaxially Woven Fabric
Warp - 280 Denier, Type 52 Dacron
Fill - 280 Denier, Type 52 Dacron

3.4 oz/yd^2 Triaxially Woven Fabric
Warp - 280 Denier, Type 52 Dacron
Fill - 220 Denier, Type 52 Dacron

3.3 oz/yd^2 Triaxially Woven Fabric
Warp - 280 Denier, Type 52 Dacron
Fill - 200 Denier, Kevlar 29

Test results of the above are summarized in Table 18.

TABLE 18

EXPERIMENTAL TRIAXIAL FABRIC

COUNT	WEIGHT	TENSILE	SHEAR RESISTANCE TO DEFORM THE SAMPLE 1/2"
32 x 32 x 32	3.6 oz/yd^2	215 x 180	186 pounds
32 x 32 x 32	3.4 oz/yd^2	215 x 170	188 pounds
32 x 32 x 32	3.3 oz/yd^2	215 x 285	235 pounds

Although the above fabrics are ideal for 100,000 ft^3 balloons, it is felt that a lighter weight triaxially woven fabric could be designed without severe loss of other properties. The resultant fabric being lighter in weight should yield a balloon fabric with excellent strength to weight ratio for a 45,000 ft^3 balloon.

A lightweight triaxially woven fabric, of the basic-weave pattern, was engineered by ILC Dover and Doweave. Included in this development effort were the following weight fabrics:

1.89 oz/yd^2 Triaxially Woven Fabric
Warp - 280 Denier, Type 52 Dacron
Fill - 280 Denier, Type 52 Dacron

1.5 oz/yd^2 Triaxially Woven Fabric
Warp - 200 Denier, Kevlar 29
Fill - 200 Denier, Kevlar 29

Test results of the above are summarized in Table 19.

TABLE 19

Experimental Triaxial Fabric
Design Iteration Number 2

Count	Weight oz/yd^2	Tensile lbs/in	Shear Resistance to Deform the Sample 1/2"
16 x 16 x 16	1.89	115 x 114 x 90	110 pounds
16 x 16 x 16	1.50	120 x 120 x 120*	180 pounds

* The Kevlar 29 yarns were sized with polyacrylic acid. This proved to effect the tensile by as much as 50 percent.

The experimental triaxial fabric, employed as the structural membrane, was laminated to a cast film polyurethane and then coated on the reverse side. Figure 8 shows the cross section of the experimental triaxially reinforced films. The two experimental constructions were tested, and primary representative properties are given in Table 20.

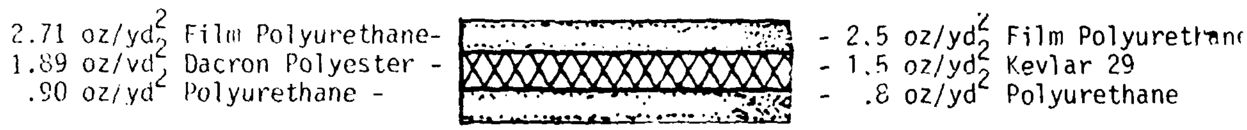


Figure 8. Experimental triaxial envelope laminates

TABLE 20

EXPERIMENTAL TRIAXIAL HULL FABRICS

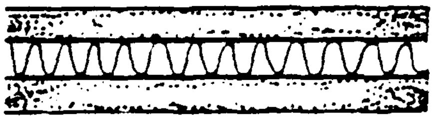
	Base Line ILC Part No. A105002	Polyester Triaxial	Kevlar Triaxial
Weight, oz/yd^2	8.3	5.5	4.8
Tensile, lb/in			
Machine	106	115	120
Transverse	105	114	120
Bias	95	90	120
Tear, Tongue			
Machine	10.6	23.5	35
Transverse	8.5	23.2	35
Leakage $L/M^2/24$ hr.	< 1	< 1	< 1
Shear Resistance (lbs)	> 82	> 130	> 240

It was learned from the preliminary run of experimental triaxial hull laminate constructed of all Kevlar 29 yarns that the anticipated lower elongation (vs. all Dacron) was attained, however, the higher strength-weight ratio was not reflected in the cylinder bursting strength. In the formula T = PR, where T is the breaking strength of the laminated fabric in lbs/in, P is the bursting pressure in PSI and R is the bursting radius in inches, it is seen that the breaking strength is dependent not only on the strength of the fabric but also on the elongation that occurs before it breaks. The use of polyacrylic acid sizing on the Kevlar 29 yarns reflects not only a 50 percent reduction in yarn breaking strength, but also a severe reduction in yarn elongation.

As a result, another design iteration was considered. Considerations for this design iteration were:

- *elimination of all sizing on yarns*
- twist the Kevlar 29 yarns with 9 turns per inch of 7 twist

The rationale for this design iteration was to provide for lower yarn modulus thus resulting in higher fabric elongation. Figure 9 shows the cross section of the proposed experimental envelop laminate, and preliminary properties are given in Table 21.



- 2.5 oz/yd² Film Polyurethane
- 1.5 oz/yd² Kevlar 29
- 1.0 oz/yd² Polyurethane

Figure 9. Proposed Experimental Triaxial Envelope Laminate

TABLE 21

PROPOSED EXPERIMENTAL KEVLAR
TRIAXIALLY REINFORCED FILM

	DESIGN GOAL
Weight, oz/yd²	5.0
Breaking Strength, lb/in	
Machine	120
Transverse	120
Bias	120
Tear Strength, lb.	
Tongue Method	
Machine	50
Transverse	50
Trapezoid Method	
Machine	50
Transverse	50
Slit Tear	
Machine	100
Transverse	100
Leakage L/M²/Day	1.0 Max.
Shear Resistance, lbs.	150

3.3.2.4 Economic Benefits

The inherent strength of triaxially woven fabric will allow lighter weight fabric substrates to be used in coated and multiply fabrics. In some applications the lighter substrates will result in raw material savings in excess of 30 per cent. Since raw material costs represent approximately 60 per cent of fabric costs, this savings is significant.

An inherent characteristic of the weaving process is the potential to produce 50 per cent more fabric than conventional weaving for each pass of the shuttle across the loom. The number of shuttle passes is a main factor limiting production speeds, and since, in a triaxial machine, only one third of the yarns must be carried across the loom by the shuttle, rather than half, two triaxial machines will do the work of three conventional looms.

Triaxial woven fabrics will be competing with conventional woven, knitted, and non-woven products produced by the large textile organizations. Improved fabric performance, potential manufacturing cost reductions, and raw materials savings are significant reasons why triaxial woven fabric should fare well in the aerostat marketplace.

ILC Dover is working closely with the traixial fabric manufacturer, Doweave, Inc., to develop optimum substrate fabrics for aerostat programs. ILC Dover's efforts in coating development for these materials have been consolidated with the E. I. DuPont de Nemours Co., Inc. DuPont is presently engaged in an extensive effort to develop coatings and techniques to fully exploit the capabilities of triaxial fabric. Foremost in this effort is their integrated activity with ILC Dover and Doweave to optimize the coating system for aerostat materials.

3.4 Coating and Film Considerations

The second major function of balloon cloth is to protect and contain the pressurizing media. The ultimate choice of polymer for outstanding resistance to varying environmental conditions is dependent on the material and the conditions it will encounter in service. In balloon construction, all surfaces do not encounter the same conditions and therefore, a variety of polymers can be exploited to the maximum for their permeability, strength, fabrication ease, weight, cost and other characteristics.

Several outstanding polymers have previously been used for balloon construction with varying degrees of success such as Mylar, Neoprene, Nylon, Urethane, Tedlar, Hypalon and Butyl. Each are excellent polymers in their own right, but each will perform differently as conditions change. For example, temperature variations will change the elastomeric qualities of all these polymers to different degrees; also formulations of the same polymers from different vendors can vary to such an extent that the physical parameters will change, thus requiring vendor formulation selection.

The above polymers plus others such as Teflon, Saran and EPDM have been evaluated for their advantages and disadvantages in film thicknesses applicable to lightweight balloon construction. The relative general properties of elastomer types are given in Table 22.

TABLE [illegible]

General Properties of Elastomers

	Urethane	Butyl	Neoprene	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Permeability									
Helium	ex	ex	good	poor	poor	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	ex	ex	good	poor	poor	[illegible]	[illegible]	[illegible]	[illegible]
Specific gravity	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tensile strength	high	low	med	med	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	high	med	med	[illegible]	high	[illegible]		[illegible]	[illegible]
Tear strength	ex	fair	good	good	fair	good	[illegible]	[illegible]	poor
Temperature effect									
[illegible]	[illegible]	good	[illegible]	good		[illegible]	[illegible]	[illegible]	poor
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	poor
[illegible]	ex	fair	[illegible]	ex	fair	fair	fair	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	fair	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	good	fair	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	fair	[illegible]	fair	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	high	low	med	low	low	low	low	low	[illegible]
[illegible]	med	med	med	med	[illegible]	high	high	[illegible]	high
[illegible]	med	med	med	med	[illegible]	low	low	low	low
[illegible]	high	low	med	[illegible]	low	med	high	[illegible]	low
[illegible]	ex	ex	ex	[illegible]	[illegible]	ex	[illegible]	fair	[illegible]
[illegible]	ex	fair	good	fair	poor	poor	poor	poor	[illegible]
[illegible]	yes	no	no	[illegible]	[illegible]	yes	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	yes	[illegible]	yes	[illegible]	[illegible]	[illegible]	no	[illegible]
[illegible]	yes	[illegible]	no	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	poor	good	[illegible]	[illegible]	fair	fair	[illegible]	[illegible]
[illegible]	[illegible]	fair	[illegible]	[illegible]	[illegible]	fair	fair	[illegible]	fair

Requirements for superior aerostats dictate that the polymer have attributes as shown below.

POLYMER ATTRIBUTES

- Impermeability to helium
- Low temperature flex characteristics
- UV resistance

In addition to the above attributes, the polymer or film must be bondable to the substrate and to itself without degradation at low temperature. After a comprehensive trade-off study of the numerous possible combinations of materials to build balloon fabrics the following films and polymers and combinations thereof were evaluated:

Nylon
Mylar
Neoprene
Butyl
Tedlar
Polyurethane

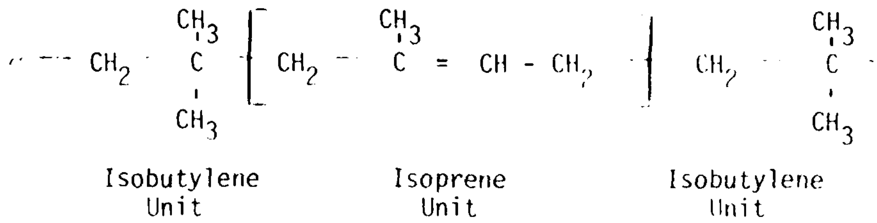
3.4.1 Coating Between Plies

Butyl rubber is recommended by ILC Dover, instead of neoprene, for the middle layer of all two ply biased laminated constructions. The comparative properties of butyl and neoprene are summarized in Table 22. Its lower specific gravity allows a reduction in the coating between plies of .4 oz/yd^2 for the same thickness, thereby effecting a significant weight reduction.

Also, the low unsaturation of the butyl polymer makes it outstanding in resistance to permeability of gases and water-vapor, ozone, oxidation, and sunlight aging, when compared to neoprene. Butyl rubber is more flexible at high and low temperatures than neoprene rubber, and therefore more crack-resistant in service and in storage.

The effect of hydrolysis on neoprene is more pronounced in thin films than on thick films. Low unsaturated rubbers such as butyl, however, are not subject to this phenomenon. This unique property is primarily the result of its low unsaturation (fewer double bonds) as compared to other polymers.

BUTYL RUBBER MOLECULE



The number of double bonds per molecule or chain length is fewer than neoprene. Since the double bond is the most reactive and most easily attacked by ozone, oxygen, and ultraviolet light, more resistance is obtained from polymers with fewer double bonds.

The same molecular construction reduces the permeability to air, gas, water, and water vapor. The long linear chains of buytl rubber with few double bonds for crosslinking provide a more impermeable membrane, as compared to neoprene which has a shorter chain length and higher degree of unsaturation.

The lower specific gravity of butyl is an added factor in determining film thickness and weight considerations. With butyl, the weight and film thickness can be reduced below that of neoprene and still provide better protection from environmental attack and a higher degree of impermeability.

3.4.2 Outer Surface Coatings

It is ILC's recommendation that polyurethane be utilized as the surface coating on all laminated fabrics. This selection will permit heat-sealing and/or cementing of joint seams with a greater reliability. Thin coatings of light-stabi ized polyurethane are superior in resistance to abrasion, utraviolet rays, hydrolysis, ozone, and oxidation.

It has been proven that the polyester polyurethanes have better inherent light, oxidation, and ozone stability, and that the light-stability, hydrolysis, and fungus resistance can be improved by chemical additions and use of light-stable isocyanates.

Pigments can be incorporated into the urethane compounds for increased UV-resistance and light-reflectance. The added coatings neither detract from the physical properties nor retard heat-sealing or cementing. They provide the added advantage of weight saving by eliminating the requirement for Hypalon overcoating.

Thermoplastic polyurethane elastomers are the newest, fastest-growing members of the very versatile polyurethane family. Polyurethanes are essentially linear in structure and can be processed by methods customarily used with thermoplastics, yet the polymers exhibit many of the properties of a rubbery vulcanizate including excellent strength, toughness, and abrasion resistance, as well as high extensibility and elasticity.

In the early stages of development, little was known of the effects of hydrolysis, ultraviolet light, oxidation, ozone, or fungus resistance on the polyurethane polymer. As these effects became known, two distinct families of thermoplastic polyurethanes became dominant: the polyesters and the polyethers.

The primary difference between the two is the polyglycol used in the polymerization. If a polyesterglycol is used, the end product becomes a polyester urethane. If a polyetherglycol is used, the end product becomes a polyether urethane. Because of this difference, however, each family exhibits somewhat different properties and is affected differently by environment and chemicals. A prime example is the effect of hydrolysis on polyester urethane. Hydrolysis is the chemical decomposition of a substance, caused by water. The primary hydrolytic reaction is as follows:

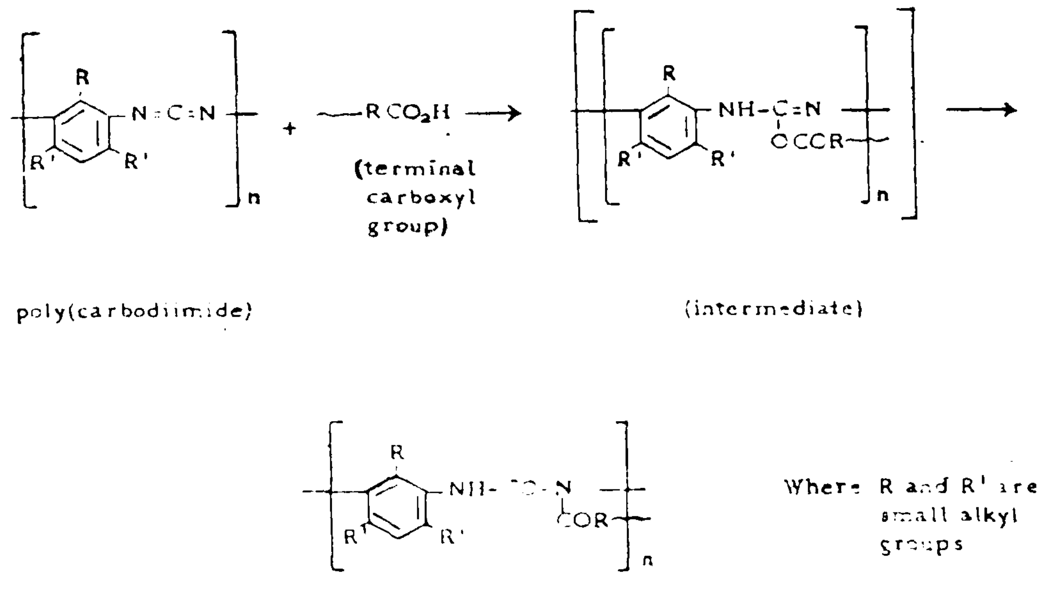
$$\text{OCO}\ (\text{CH}_2)_4\ \text{C}\underline{\underline{\text{O}}}\text{-O} - (\text{CH}_2)_2\ \text{O-CO-NH-R-NH-CO-O} - + \text{H}_2\text{O} \rightarrow$$

$$\text{OCO}\ (\text{CH}_2)_4\ \text{COOH} + \text{HO-}(\text{CH}_2)_2\ \text{-O-CO-NH-R-NH-CO-O}$$

The water attacks the point doubly underlined and breaks the polymer chain. One of these chains ends in a hydroxyl group (-OH) which is very stable by itself. The other chain ends in a carboxyl group (-COOH) which is acidic. This acidic carboxyl group speeds up further hydrolysis of the polyester segments in the polyester-urethane and the degradation becomes autocatalytic.

However, neutralizing the carboxyl-containing fragments of the hydrolyzing polyester as they are generated stabilizes the polymer and retards hydrolysis. A class of materials, polycarbodiimides, patented in 1965, effectively tie up the carboxyl group as shown below.

Reaction of a Poly (Carbodiimide) with Carboxyl Groups



(N-acyl aromatic urea)

Attributes to the above reaction include: non-volatility, resistance to extraction, good compatibility with plastics and elastomers containing ester groups, and self-polymerization tendencies.

The sequence of reactions as described above prevents autocatalysis of the hydrolysis reaction by neutralization of the carboxyl groups as they are formed. In addition, since each stabilizer contains several carbodiimide groups, it can mend the broken polymer chains which terminate in carboxyl groups.

The number of carboxyl groups in a polyester glycol is also a determining factor in the number of clevage points in a polymer chain. Neutralization of the carboxylic acid by potassium hydroxide is an effective method for the determination of the acid number in amacroglycol. The lower the acid number, the fewer points exist for potential clevage by water.

Figures 10 and 11 show the effects of the use of high and low acid numbers of a macroglycol and the effects of polycarbodiimide in a polyester urethane.

Figure 10

EFFECT OF ADDED POLY(CARBODIIMIDE) ON HYDROLYSIS STABILITY OF A THERMOPLASTIC POLY(ESTER-URETHANE) MADE FROM HIGHER ACID NUMBER MACROGLYCOL

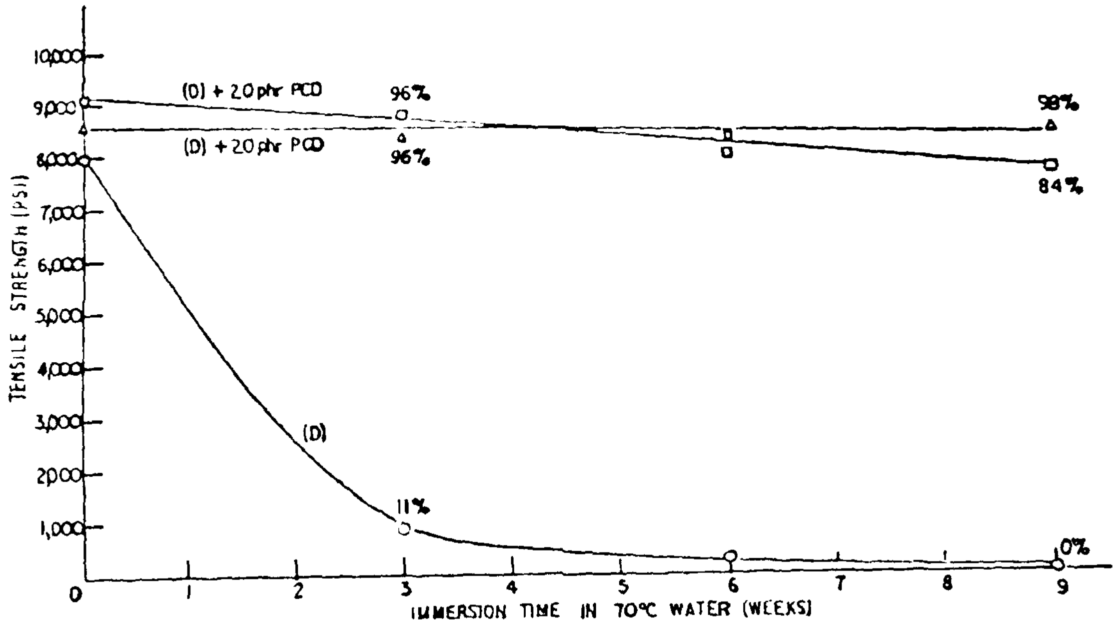
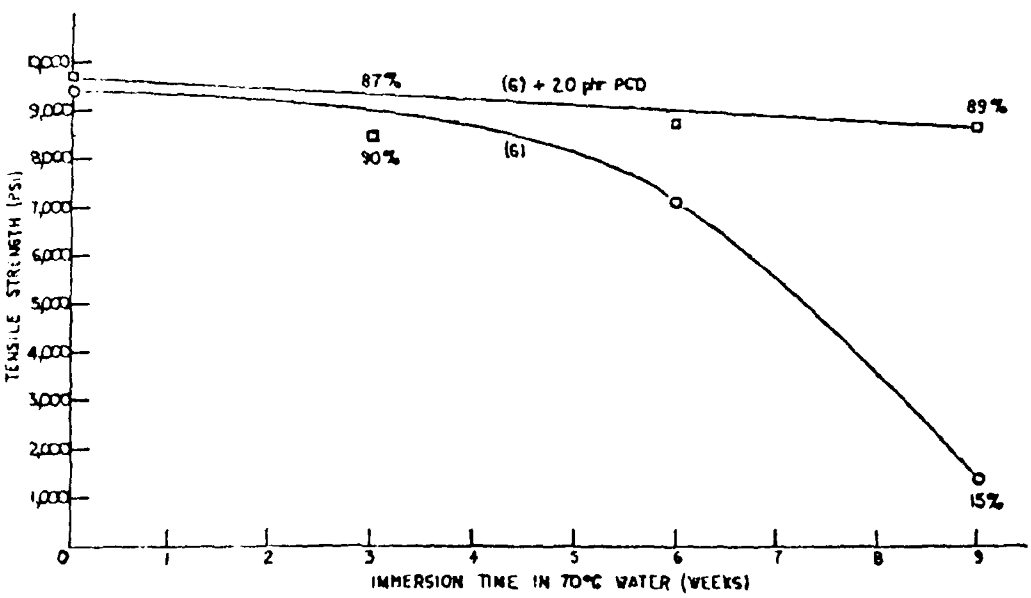


Figure 11

EFFECT OF ADDED POLY(CARBODIIMIDE) ON HYDROLYSIS STABILITY OF A THERMOPLASTIC POLY(ESTER-URETHANE) MADE FROM LOW ACID NUMBER MACROGLYCOL



In recent years, aliphatic and cycloaliphatic diisocyanates have gained considerable importance in the building of light-stable and color-stable polyurethane polymers. Their long-chain structures, devoid of double bonds, as are the aromatics, make them less susceptable to ultraviolet clevage. (Again, double bonds are more reactive than single bonds.)

An Atlas carbon-arc Fadometer and an Atlas Dry Weatherometer (xenon light source) have been used to test the relative resistance of various polyurethane elastomers. Results show that the aliphatic diisocyanates are superior in resistance to ultraviolet degradation as compared to the aromatics.

In addition, the polyesters are even more resistant than polyethers to UV light by the nature of their polvmer structure. Still further resistance can be effected in both the polyester and polyether-urethanes by the use of pigmentation and ultraviolet screening agents.

In summation, a polyester urethane made with an aliphatic diisocyanate and pigmented with an ultraviolet-resistant pigment has outstanding resistance to UV. Ozone and oxygen degradation is not a serious factor in the polyesters, since their normal resistance to these two elements is outstanding.

Respresentative FadOmeter results are presented in Table 23.

TABLE 23

Comparative Resistance of Polyurethane to Ultraviolet Radiation

	ORIGINAL DATA	AFTER AGING 500 HOURS
Ultimate Tensile Strength (psi)	5500	4000
Modulus at 300 Elongation (psi)	4000	3000
Modulus at 100 Elongation (psi)	1200	1200
Ultimate Elongation (psi)	370	350

Mylar and nylon exhibit poor UV resistance and require adhesives which are prone to cracking and strength degradation at low temperatures.

Tedlar, however, can be successfully bonded with acrylic or polyurethane adhesive systems capable of withstanding low temperatures.

Thin films of Tedlar are essentially transparent to solar radiation in the near ultra-violet, visible and near infra-red regions of the spectrum. Ultra-violet absorbing types of Tedlar are available for protection of substrates aginst UV attack. Thin films of Tedlar, when exposed to a low temperature of -70^{o}F, show signs of brittleness but because of a high elongation are not readily susceptible to cracking.

Selection of Tedlar, however, requires the use of special adhesives and bonding procedures, to provide contamination free sealing surfaces for seam fabrication.

3.4.3 Coating Methods Evaluated

There are several methods presently available for applying resinous coating substances to textile substrates and, in general, the selection of any one procedure is governed largely by the end use requirements of the coated fabric. Selection is also influenced by the physical and mechanical properties of coating and base fabric, together with the associated processing economies. The following coating methods were used to fabricate test samples:

- knife coating
- transfer coating

In the knife or spread coating operation the viscous coating material is spread onto the fabric surface, which is then passed under a closely set metal edge called a coating knife. This knife serves to spread the coating uniformly across the entire width of the substrate fabric, simultaneously controlling the weight of coating material applied.

Unfortunately, knife coaters have two fundamental processing problems, one of which is streaking of the coating, and the other is the limited amount of coating which may be applied in one pass. Whereas the streaking may be eliminated by using smoothing bars or air brushes, multiple passes must be made if substantially air tight coating thicknesses are required.

In the case of transfer coating, a lightweight homogenous film, which was previously cast, is transferred to the surface of the substrate fabric. Because of the homogeneity of the cast film, less coating is required to produce the same net permeability resistance in the finished fabrics. Table 24 illustrates the effect of coating method on permeability.

TABLE 24

Effect of Coating Method on Permeability

Fabric Construction	Coating Method	Permeability, H_2
1.5 oz/yd^2 Polyurethane 1.0 oz/yd^2 Dacron Polyester 1.5 oz/yd^2 Polyurethane	Knife	3 3 L/M^2/Day
2.5 oz/yd^2 Polyurethane 1.0 oz/yd^2 Dacron Polyester .5 oz/yd^2 Polyurethane	Transfer	4 L/M^2/Day
3.0 oz/yd^2 Polyurethane 1.5 oz/yd^2 Kevlar Triaxially Woven Fabric 3.0 oz/yd^2 Polyurethane	Knife	Gross Leakage
2.7 oz/yd^2 Polyurethane 1.5 oz/yd^2 Kevlar Tiaxially Woven Fabric 1.0 oz/yd^2 Polyurethane	Transfer	.2 L/M^2/Day

Figure 12A serves to illustrate the effect of knife coating on the cross-section of a fabric, while Figure 12B serves to illustrate the transfer method.

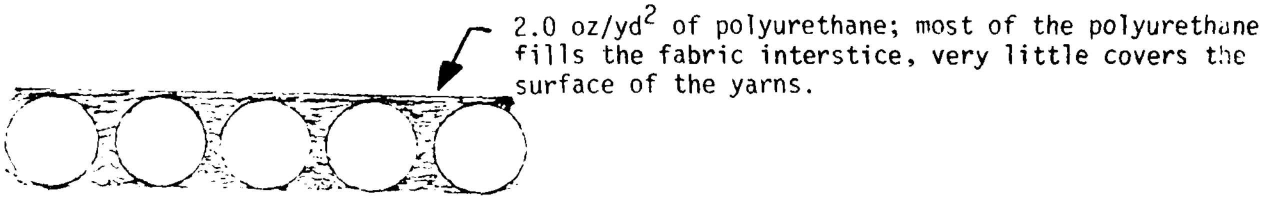


Figure 12A

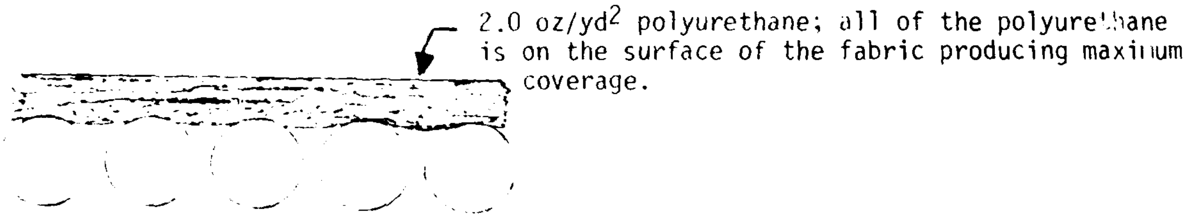


Figure 12B

3.5 Ballonet Material

3.5.1 Discussion

The initial design goal for ballonet fabric was to develop a single-substrate fabric, rather than using a previously developed and used double-substrate fabric. The primary reason for this choice was the trade-off between dimensional stability, helium permeability and weight. It was assumed that the single-substrates low weight and low helium permeability attributes would, in the final analysis, overcome it's lack of high dimensional stability. Refer to Table 25 for comparison of actual double-substrate and goals for single-substrate material.

The approach was to first develop, test and compare lightweight fabrics and secondly to perform a coating evaluation and perform final tests on the coated fabrics.

The first material chosen was a 1.15 oz/yd^2 open weave polyester cloth having a 210 denier and 18 x 17 count. The low weight and high tear strength and flexibility of this cloth was considered ideal. To form a helium permeability barrier the polymer chosen was a polyether polyurethane. The side of the fabric which sees the helium was coated with a transfer film and the opposite side received a direct knife coat. Due to the large interstices in this open weave fabric, a rather thick layer of polymer is required to add good dimensional stability and permeability features to the basic fabric. The physical properties of the coated ballonet candidate material are shown in Table 26.

Table 25 - Comparison of Double-Substrate and Single-Substrate Ballonet Materials

PROPERTY	Actual Double-Substrate Value	Single-Substrate Design Goal Value
Construction	.5 oz/yd^2 Polyether Polyurethane 1.4 oz/yd^2 Dacron Polyester (45° Bias) 2.6 oz/yd^2 Butyl 1.4 oz/yd^2 Dacron Polyester .5 oz/yd^2 Polyether Polyurethane	1.5 oz/yd^2 Polymer 1.0 oz/yd^2 Fabric 1.5 oz/yd^2 Polymer
Weight	6.4 oz/yd^2 + .75 -.5	4.0 oz/yd^2
Adhesion (lbs./in.)		
Coating	7.0 min.	10.0 min.
Ply	7.0 min.	
Bias Seam	4.0 min.	
Breaking Strength (lbs./in.		
Strip Method		
Machine	40 min.	60 min.
Transverse	40 min.	60 min.
Permeability to Helium	2.0 liter m^2/day max.	.5 liter/m^2/day max.
Low Temperature Flex (1/8" mandrel)	No cracks @ -40°F	No Cracks @ -40°F
Tear Strength		5 lbs.
Width	42 inches min.	42 inches min.

Table 26 - Physical Properties of Ballonet Material ST12C582

No.	Characteristic	Requirement	Test Method
1.	Construction	3.7 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)	Vendor Certification
2.	Weight	7.0 oz/yd^2 $\pm$ .5	FED-STD-191, Mtd. 5041
3.	Breaking Strength (lbs/in) Strip Method - Machine Transverse	 60 min. 50 min.	FED-STD-191, Mtd. 5102
4.	Adhesion Coating (lbs/in) ST30A093 and RF Seal	7 min.	FED-STD-191, Mtd. 5970
5.	Tear - Tongue Method (lbs)	8 min. (machine) 6 min (transverse)	FED-STD-191, Mtd. 5134
6.	Permeability to Helium	1.0 liter/m^2/24 hours max.	ILC-STP-029
7.	Low Temp. Flex (1/8" mandrel)	no cracks @ -40°F	ASTM-D2136
8.	Width	52 inches min.	FED-STD-191, Mtd. 5020

As can be seen in Table 26, the average total weight of 7 oz/yd^2 was required to obtain a good helium permeability rating, with most of the weight attributable to the permeability barrier (film). The material surpassed or came close to the initial design objectives, except for weight.

The major achievements thus far on the ballonet material over the double-substrate ballonet material have been; 1) Reduced helium permeability from 2.0 to 1.0 liter/m^2/24 hours; 2) Vastly increased flex life from approximately 3000 cycles to in excess of 10,000 cycles; 3) Reduced fabrication time by approximately 50 and; 4) Reduced material costs by 50 .

As the result of the balloon preliminary design study, a total weight reduction was deemed necessary. It was determined that the hull, empennage and ballonet fabrics could be made lighter for the purpose of building a 45,000 cu. ft balloon by using thinner elastomeric/polymeric coatings. No structural penalties would be incurred by this change and a decision to increase coating thickness at a later date for use in a 100,000 cu. ft. balloon where weight was not so critical would create no serious process changes. The weight and balance evaluation required a total ballonet weight of 3.5 oz/yd^2.

It became readily apparent that to maintain some degree of helium permeability, the only way to reduce ballonet weight so drastically was to use a less pourous fabric which would not require such a heavy layer of permeability barrier (polymer). It was also apparent that a tight weave, lower denier fabric would have less tear strength.

Past experience with balloon materials led to selection of a 1 oz/yd^2 nylon ripstop, 30 denier fabric. This tight weave, lightweight fabric was used in the past and is known for its excellent coating acceptability properties. Again, previous experience indicated that, when coated, the total material weight could be kept under 4.0 oz/yd^2 and still exhibit a 1.0 liter/meter ^{2}/ 24 hour (or less) permeability to helium. A purchase order was placed on Reeves Brothers of North Carolina for test specimens and follow-on production ballonet material constructed from 1.0 oz/yd^2, 42 in. width nylon ripstop fabric coated on one side with 2.0 oz/yd^2 film urethane and on the other with 1.0 oz/yd^2 knife coated urethane.

Several test specimens were made. It was found by graduated decreases in the film thickness that a 1.8 oz/yd^2 polyester polyurethane film still provided a helium permeability of less than 1.0 liter/meter^2/ 24 hours. The physical properties of this ballonet material are shown in Table 27.

TABLE [illegible]7

Physical Properties of Ballonet Material ST12056[illegible]

No.	CHARACTERISTICS	REQUIREMENTS	TEST METHOD
[illegible]	Construction	1.8 oz/yd² Light Staple (film) Polyester Polyurethane (white) 1.0 oz/yd² Nylon Rip Stop Code 6520 1.0 oz/yd² Polyester Polyurethane (white)	Vendor Certificat[illegible]
[illegible]	Weight	3.[illegible] oz/yd² ± 10	FTM-191-5041
[illegible]	Breaking Strength (lb/in) Strip Method	35 x 35 Minimum	FTM-191-5102
[illegible]	Adhesion (lb/in) [illegible]	[illegible] Minimum	FED-STD-191 Method 5970
[illegible]	Permeability to Helium	[illegible] Liter/Meter²/24 hr.	ILC-STP-029
[illegible]	[illegible]	[illegible] Maximum	Visual
[illegible]	Width	[illegible]	FED-STD-191 Method [illegible]
[illegible]	Low Temperature [illegible]	No [illegible]	ASTM-[illegible]
[illegible]	Tear Strength	[illegible]	FED-STD-191 Method [illegible]

3.5.2 Conclusion

The S112C583 ballonet material was ultimately selected for use in the 45,000 cu. ft. balloon primarily due to its low weight and low helium permeability. This material meets or surpasses the construction, weight, width and low temperature flex design goals stated at the beginning of the program (refer to Table 3).

Although no other goals were achieved, the selected material met or surpassed all but one of the properties of the old double-substrate ballonet material. The most disappointing property was, of course, the very low tear strength exhibited by the selected materials. It must be noted that the low tear strength was caused by the requirement to reduce weight for the small 45,000 cu. ft balloon. A heavier material having much higher tear strength such as S112C582 (refer to Table 26) would be used in 130,000 cu. ft. and larger balloons where weight is not nearly as critical.

3.6 Empennage Material

3.6.1 Discussion

It should be noted here that the initially proposed design goal for empennage construction required two to three different types of materials. Use of different materials was dictated by a fin design which used seperate air tubes placed inside a tight skin to reduce parasitic drag. ILC had engineered the design for another larger balloon project but it had not undergone final testing. Shortly after ILC was awarded this contract, testing and evaluation revealed that the seperate tube and skin design was not suitable due to leading edge collapse (unless extremely high air pressure was used) and undesireable maintainability traits. Therefore ILC returned to the basic concept of using one fabric as both the structural restraint and the air retention barrier. The materials discussed herein are based on the one fabric/dual role design (see Figure 13).

The primary purpose of the contract was development of new and/or improvement of inflatable balloon materials. The empennage was used more as a proving ground for development of a new lightweight ripstop fabric which would retain good tear strength characteristics after being coated with polymer. The approach was to first develop, test and compare lightweight ripstop fabrics and secondly to perform a coating evaluation and perform final tests on the coated fabrics. Two design weights (2.0 and 1.5 oz/yd^2) were selected as goals for the basic fabric, before coating. The basic fabric was to be initially woven from a combination polyester /fiber 'B', with the polyester yarn as the ground and the fiber 'B' yarn as the ripstop.

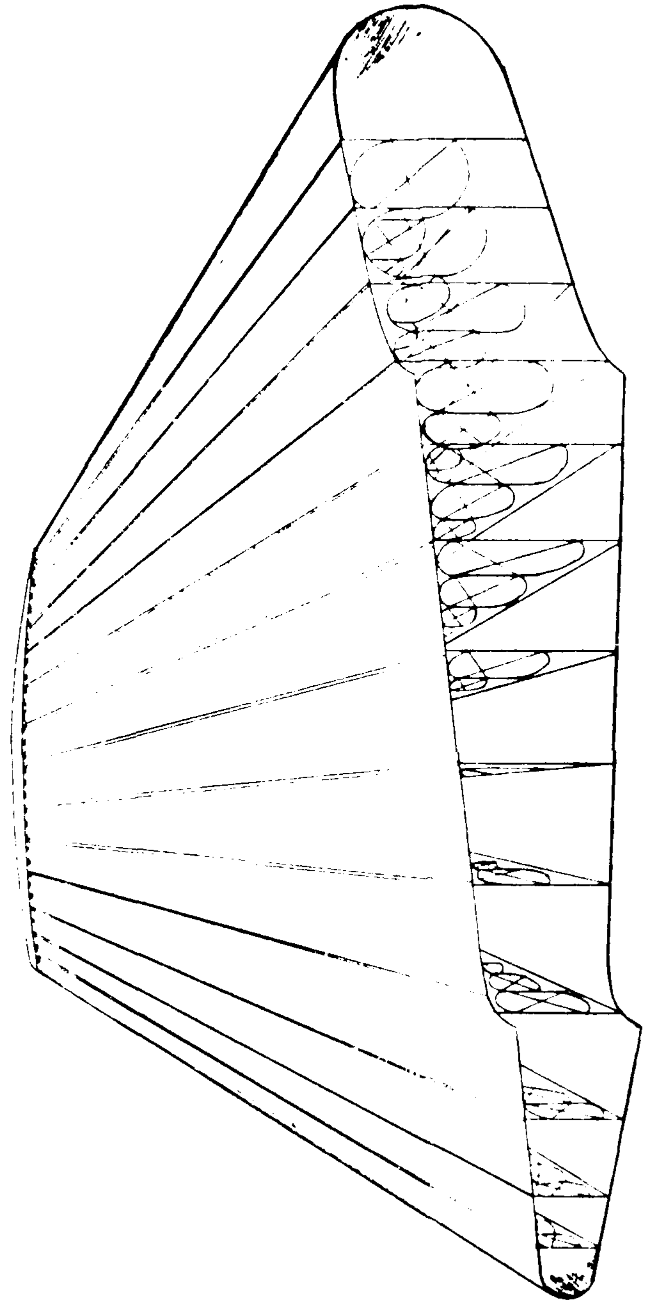


FIGURE 1[illegible] EMPENNAGE FIN CONSTRUCTION

A subcontract was issued to Fabric Development Inc. for development of the 2.0 and 1.5 oz/yd^2 ripstop fabrics.

NOTE: Refer to section 3.3, Fabric Construction Considerations, for detailed discussion of basic fabric construction considerations.

The first 2.0 oz/yd^2 polyester/fiber 'B' ripstop fabric was received approximately five (5) weeks later. Refer to Table 28 for comparison of initial test results vs. design goals.

Table 28 - 2.0 oz/yd^2 Empennage Ripstop Fabric

CHARACTERISTICS	DESIGN GOAL	ACTUAL VALUE
Weight (oz/yd^2)	2.0	2.3
Breaking Strength (lbs/in)		
Warp	140	156
Fill	140	145
Elongation ( )		
Warp	14	15
Fill	14	15
Tear Strength (lbs)		
Tongue Method		
Warp	12	28
Fill	12	26

Although the results of this initial development seemed to indicate all design goals achieved, it was felt that the optimum had not yet been achieved. Therefore the vendor was instructed to fabricate four (4) additional 2.0 oz/yd^2 ripstop fabrics.

The new fabric received was a polyester/Kevlar 29 ripstop fabric. Tests of the fabric revealed the values shown in Table 29.

Table 29

CHARACTERISTICS	VALUE
Weight	2.3 oz/yd^2
Breaking Strength	
Ravel Strip Method	
Warp	103/78
Fill	131/85
NOTE: First breaking strength indicates the breakage of Kevlar 29 yarns. The second figure indicates the breaking strength of polyester yarns.	
Tear Strength	
Tongue Tear Method	
Warp	50 lbs.
Fill	56 lbs.
Shear Resistance	26 lbs.

Tests indicted that the fabric breaking strength was substantially less and the tear strength had been greatly increased over the previous fabric. The fabric samples were then subjected to a polymer coating evaluation. The coating process revealed excessive shrinkage of the polyester yarns and no shrinkage of the Kevlar 29 yarns. It was determined that preshrunk heat set polyester yarns would have to be used to alleviate the shrinkage problem. Use of the preshrunk heat set polyester (DACRON) yarns eliminated the shrinkage problem.

A problem which emerged early resulted from the dissimilar moduli of the Kevlar 29 and Dacron Type 52 yarns. Although one physical fabric was woven, two definite breaking strengths appeared. The Kevlar yarns, although having a higher breaking strength than polyester, had less elasticity than polyester and therefore always broke first. Failure of the Kevlar 29 yarns then placed all the tear loads on the low denier (55) polyester yarns which have an extremely low tear value.

Since the object of the Kevlar 29 yarn is to give the fabric good tear strength, it became apparent that the moduli of the two yarns would have to be brought closer together to achieve both equal breaking strengths and to ensure the Kevlar 29 yarns did not fail before the polyester yarns. The method used to achieve this was to use cold-stretched, pre-shrunk 140 denier Dacron, yarn, lowering its twist per inch to 5Z and maintaining the 200 denier Kevlar 29 yarn, but increasing its twist to 9Z and heat stabiling after twist. Equal breaking strength of the two yarns was achieved.

The results of this design are shown in Table 30.

Table 30

Polyester (5% Twist)/Kevlar 29 (9% Twist) Ripstop Fabric

PROPERTY	REFERENCED TEST METHOD	VALUE
Weight (oz/yd^2)	5040	2.41
Breaking Strength (lbs./inch)	5104	
Ravel Strip Method		
Warp		83.6
Fill		98.2
Elongation ( )	5104	
Warp		18.5
Fill		19.8
Tear Stenath (lbs)	5134	
Tongue Tear Method		
Warp		31.9
Fill		31.8

The design also resulted in a flatter fabric which enhanced the coating capability. The fabric was coated on one side with 2.5 oz/yd^2 film urethane and on the other with 1.5 oz/yd^2 knife coated urethane. No problems were encounted in the coating process. The properties of the coated material are shown on Table 31.

Table 31

Coated Polyester/Kevlar 29 Ripstop Fabric

PROPERTY	REFERENCED TEST METHOD	VALUE
Weight (oz/yd^2)	5040	5.8
Breaking Strength (lbs/inch)	5102	
Machine		76.8
transverse		68.6
Tear stength (lbs)	5134	
Tongue Method		
machine		16.7
transverse		14.6
Coating adhesion (lb/in)	5970	
outside coating		15.4
inside coating		14.4
Permeability to air liters/meter^2/day	5460	.4

3.6.2 Conclusions. The final material selected for use as the empennage structural restraint and air retention barrier, ILC P/N A105036-01, exhibited one of the two basic qualities originally set as goals i.e., low weight and good tear strength. Without increasing weight (but not being able to substantially decrease weight) we were able to achieve a remarkable increase in tear strength by a factor of approximately 15:2.

3.7 Hull Material

3.7.1 Discussion

Although the ballonet and empennage material development required a great deal of expertise, it was the hull material development which presented the greatest challenge to the material specialists and engineers. The challenge to reduce the weight of the balloon's primary structure by 25 to approximately 7.5 oz/yd^2, reduce its helium permeability by 50 to less than 1.0 $liter/M^2/24$ hours and still maintain a dimensionally stable structure having all the good qualities needed to protect the integrity and life of the balloon, was indeed the most difficult and time consuming. At the outset of the hull material development program there were two basic concepts considered:

a. Two-ply Biased Fabric Construction This construction was a two-ply fabric composed of a dimensionally stable scrim laminated to a lightweight ripstop constructed fabric. The advantage of utilizing dimensionally stable scrims in place of a very lightweight fabric is that no biasing operation is necessary. This advantage realizes a savings in cost and laminating time and requires fabrication of only a one-direction fabric.

A thorough investigation of the non-woven scrim market yielded two possible candidate materials for this application:

Tyvek - Spunbonded olefin

Reemay - Spunbonded polyester

However, subsequent testing indicated that fabrics fabricated from Tyvek were unacceptable. This is due to the incompatibility in temperature resistance of the Butyl and spunbonded olefin during the curing operation.

The structural ripstop fabric was designed to incorporate both high tenacity Dacron and Kevlar 29 yarns, whereby the Kevlar 29 yarn is used as the ripstop in both the warp and fill directions while the Dacron yarns are used for ground. Because of the high cost of the Kevlar 29 yarn, ILC Dover ran a study to minimize the Kevlar 29 usage. The following objectives (refer to Table 32) were established to insure that the developed ripstop construction would possess excellent fabrication versatility.

Table 32

Design Objectives - Hull Ripstop Fabric

CHARACTERISTIC	REQUIREMENT
Weight	2.0 oz/yd^2
Breaking Strength	140 lbs/in x 140 lbs/in
Count	100 x 100
Tear Strength	12 x 12
Material	Dacron, Type 52, 70 Denier
	Kevlar 29, 200 Denier

The following equation was used to determine what percentage of the construction should be Kevlar 29 and what percentage should be Dacron, Type 52. The objective here was to minimize the use of Kevlar 29.

$$\sigma \text{ (lbs/in)} \quad \epsilon T_x D_x X + \epsilon T_y D_y Y \ldots$$

where:

- σ - Ultimate Fabric Stress (lbs/in)
- ϵ - Ultimate Elongation (in/in)
- T - Tenacity (gpd)
- D - Demer
- X, Y - Number of Years per Inch

$$140 \quad \frac{(.033)(75)(70)X}{454} + \frac{(.033)(530)(000)Y}{454}$$

$$140 \quad .3815X + 9.1520Y$$

$$100 \quad X + Y$$

$$X \quad 100 - Y$$

$$140 \quad (.3816)(100-Y) + 9.1580Y$$

$$140 \quad 38.16 \quad .3816Y + 9.1580Y$$

$$Y \quad \frac{101.34}{8.777}$$

$$Y \quad 11.6$$

$$X \quad 88.4$$

As a result of this study, a ripstop fabric was engineered whereby 88 percent of the construction was 70 denier, Type 52 Dacron and 12 percent of the construction was 200 denier, Kevlar 29. This construction increases the breaking strength of an all Dacron fabric by 50 percent while tripling the tear strength without any increase in weight. Table 33 compares an all Dacron fabric with the first iteration Dacron/Kevlar ripstop fabric.

Table 33

All Dacron Fabric vs. Dacron/Kevlar Ripstop Fabric

Characteristic	All Dacron Fabric	Dacron/Kevlar Fabric
Weight, oz/yd^2	2.1	2.3
Breaking Strength, lb/in.	90 x 90	156 x 145
Tear Strength, lbs	4 x 4	28 x 26
Count	100 x 100	100 x 100

The experimental Dacron/Kevlar ripstop fabric, employed as the structural membrane, was coupled respectively with a lightweight biased fabric and a lightweight spunbonded fabric. Figure 14 shows the cross sections of the two experimental two-ply constructed fabrics. The two experimental constructions and a control were tested, and primary representative properties are given in Table 34.

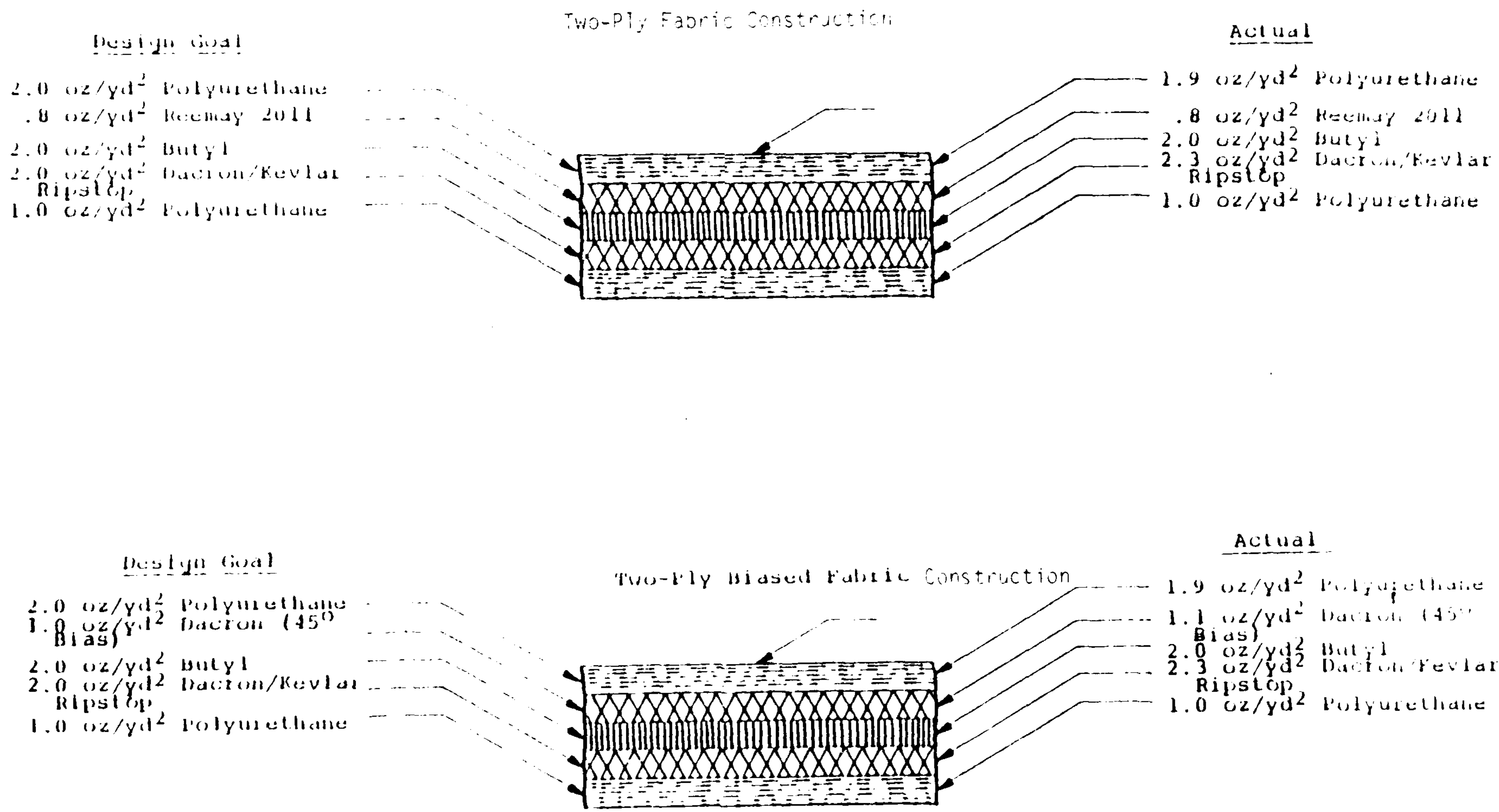


Figure 14 - Experimental Two-Ply Constructions

Table 34

Experimental Two-Ply Hull Fabric Properties

Characteristic	Design Goal	Base Line ILC P/N (Control) A105002	Bias Ripstop	Spunbonded Ripstop
Weight, Oz/Yd^2	8.0	8.3	8.3	8.0
Tensile, lb/in				
Machine	100	106	85	84
Transverse	100	105	103	91
Bias	100	95	105	85
Tear, Tongue				
Machine	20	10.6	27.8	17.3
Transverse	20	8.5	25.2	11.9
Leakage $L/M^2/24$ Hr.	<1	<1	<1	<1
Shear Resistance (lbs)	60	85	95	63

The major advantages anticipated from this type two-ply construction were; 1) permeability layer (butyl) is between two layers and thus protected from abrasion and external weathering; 2) Increased tear strength due to ply construction; 3) Dimensional stability without having to crease left-hand and right-hand bias ply fabrics; 4) High strength to low weight and; 5) Long term life. However, the construction exhibited poor helium permeability and had coating adhesion problems. As these problems seemed to be unsolveable, all effort was then concentrated on the triaxial fabric construction being developed in parallel with the two-ply.

b. Triaxially Reinforced Film Construction

This construction was brought about by a technological breakthrough in weaving machinery. Whereas standard weaving equipment produces a fabric with one yarn running in the machine direction and another yarn running in the transverse direction, triaxial weaving equipment runs one yarn in the transverse direction and one yarn each running on a 60^0 left and right hand bias (see Figure 15).

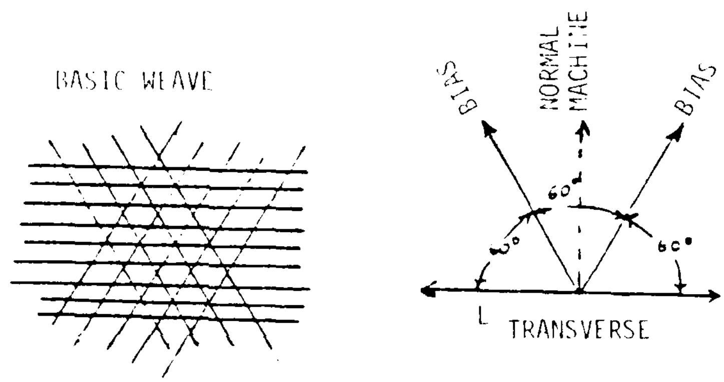


Figure 15. Basic Triaxial Weave

The advantages anticipated from triaxial fabric construction were:

1) Requirement to laminate two fabrics is eliminated due to triax strength in normal machine, transverse and bias directions.

2) Higher tear strength than comparable orthogonal weaves.

3) Reduced weight.

NOTE: Refer to section 3.3, Fabric Construction Considerations, for detailed analysis of triaxial fabric construction.

The design goals set for the triaxial fabric reinforced film hull material are shown in Figure 16 and listed in Table 35.

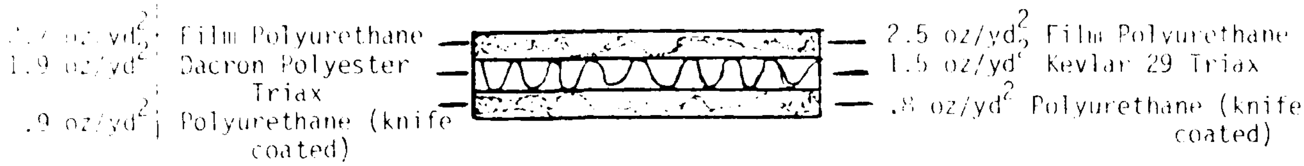


Figure 16. Triaxial Hull Fabric Construction

Table 35

Triaxial Hull Fabric Design Goals

Characteristic	Polyester Triaxial	Kevlar Triaxial
Weight, oz/yd^2	5.5	4.8
Tensile, lb/in		
Machine	120	150
Transverse	120	150
Bias	120	150
Tear, Tongue		
Machine	25	35
Transverse	25	35
Leakage L/M^2/24 hr.	< 1	< 1
Shear Resistance (lbs.)	110	180

It was learned from the preliminary run of experimental triaxial hull laminate constructed of all Kevlar 29 yarns, that the anticipated lower elongation (vs. all Dacron) was attained; however, the higher strength-weight ratio was not reflected in the cylinder bursting strength. In the formula T=PR, where T is the breaking strength of the laminated fabric in lbs/in, P is the bursting pressure in PSI and R is the bursting radius in inches, it is seen that the breaking strength is dependent not only on the strength of the fabric but also on the elongation that occurs before it breaks. The use of polyacrylic acid sizing on the Kevlar 29 yarns reflects not only a 50 percent reduction in yarn breaking strength, but also a severe reduction in yarn elongation.

As a result, another design iteration was considered. Considerations for this design iteration were:

- elimination of all sizing on yarns
- twist the Kevlar 29 yarns with 9 turns per inch of Z twist

The rationale for this design iteration was to provide for lower yarn modulus thus resulting in higher fabric elongation. Preliminary properties are given in Table 36.

Table 36

Re-designed Kevlar
Triaxially Reinforced Film

Characteristic	Design Goal
Weight, oz/yd^2	5.0
Breaking Strength, lb/in	
Machine	120
Transverse	120
Bias	120
Tear Strength, lbs.	
Tongue Method	
Machine	50
Transverse	50

Table 36 Continued

Characteristics	Design Goals
Trapezoid Method	
Machine	50
Transverse	50
Slit Tear	
Machine	100
Transverse	100
Leakage	
L/M^2/Day	1.0 Max.
Shear Resistance, lbs.	150

Several attempts were made to produce new iteration Kevlar 29 triaxial hull material. However, each attempt to put-up the yarn on beams resulted in the appearance of excessive yarn slugs and the beaming process was halted. The technical problems were discussed and analyzed by Dupont, Marionette Mills, Doweave, IIC and Air Force representatives. It was felt that the slugs (Kevlar fibers) could be eliminated by a change in the beamer's tensioning techniques, however a new supply of raw yarn and re-scheduling problems at every processing point indicated that a schedule slip of 3-4 months would result. At this point, the decision was made to concentrate entirely on production of the polyester triaxial hull fabric, due to availability of yarns and processing equipment.

Although earlier sample tests seemed to indicate acceptable properties, the polyester triaxial fabric exhibited an unacceptable percentage of elongation after coating. After examining a piece of the material before heat treatment, a piece after heat treatment, and a piece after coating, it was obvious there was serious shrinkage in the width and a radical change in the basic geometry of the fabric after coating. Again, it was felt that the problem could be solved, but after five (5) months there was little improvement. Ten different samples were tested and rejected primarily for the excessive elongation. Normal elongation value is approximately 0.7% at operational pressure. The average of all polyester triaxial hull fabrics was approximately 4. The excessive elongation would cause interface problems between the hull and the ballonet and empennage as well as a considerable shape change of the hull at higher operation pressures. Therefore the polyester triaxial fabric was eliminated from consideration.

All attention was turned to solution of the hull material problem by using combinations of presently available equipment and materials. One such material utilized a bi-planar Doweave Traixial fabric which was heavier but exhibited much less elongation. Small fabric runs were made. Each time tests were satisfactory but heat setting and subsequent coating operations proved fruitless due to what was referred to as "poor quality of the base fabric". Inability to achieve even yarn tension was the reason for poor quality. It became apparent after nine (9) months of investigations of bi-planar triaxial fabric and more than two years of failures on other triaxial fabrics, that there were no near term, cost-effective solutions in sight for triaxial fabrics in balloons.

3.7.1.1 Return to Two-Ply With the promise of triaxially woven fabrics waning, an iteration of the original alternative concept of stabilizing biaxial fabric with a non-woven material was developed. The differences between the original concept and this iteration are:

a. The non-woven is now oriented with fibers running in the bias direction, rather than randomly.
b. The non-woven is placed on the inside of the base fabric, rather than the outside.
c. The use of a polyurethane precast film rather than a solvent coat for the outside gas retention layer.

Preliminary analysis indicated the finished material would weigh approximately 7.5 oz/yd^2. A limited quantity of full width production run material was ordered. The preliminary specification for the material is shown in Table 37.

Table 37

Two-Ply Hull Material Preliminary Specification

Characteristic	Design Goal
Construction	2.5 oz/yd^2 Film Polyurethane 2.3 oz/yd^2 Polyester Fabric 1.0 oz/yd^2 Polyether Polyurethane 0.8 oz/yd^2 Oriented Non-Woven Polyester Fabric 1.0 oz/yd^2 Polyether Polyurethane
Weight	7.6 oz/yd^2 + .75 -.5
Breaking Strength (lbs)	
Strip Method	
Machine	120 min.
Transverse	80 min.
Tear (Tongue Method)	
Machine	8 lbs
Transverse	8 lbs
Adhesion (lbs/in)	
Coating	10
Ply	10
Permeability to Helium	1.0 Liters/meter^2/24 hours
Low Temperature Flex	No cracks @ -40^0 F
Width	52 in.

After clearing up a problem with both low ply adhesion and low tear strength there remained only one obstacle. It was discovered the non-woven layer could trap and hold as much as six (6) oz/yd^2 of water if the ballonet area of the balloon was subjected to dew point conditions. It was determined that calendering the non-woven from 15 to 4 mils thickness eliminated the trapped water problem. In anticipation that calendering would reduce the overall dimensional stability of the finished hull material, the adjacent polyether polyurethane layer was evaluated for its effect on dimensional stability. Tests indicated that increasing the modulus and changing the coating procedure did increase dimensional stability.

Optimum polyurethane compound formulation and coating procedures were selected and a preproduction lot of 50 yards was ordered to determine if the procedure could be duplicated on production equipment. One final change was to direct coat the outside of the hull material rather than using the film transfer method as the adhesive used with the film transfer method resulted in discoloration after long term exposure to ultra-violet radiation. Testing of the 50 yard preproduction sample indicated the physical properties shown in Table [illegible].

TABLE 38. FINAL PREPRODUCTION HULL FABRIC PROPERTIES

Characteristic	Test Results	Specification Requirements
Weight (oz/yd^2)	8.28	$7.6 \begin{smallmatrix} + .75 \\ - .5 \end{smallmatrix}$
Tensile (lbs/in)		
Machine	172	120
Transverse	117	80
Tongue Tear (lbs)		
Machine	8.9	8
Transverse	5.9	8
Adhesion (lbs/in)		
Coating	8.6	7
Ply	Could not separate	7
Permeability to Helium (Liters/Meter^2/24 hours)	.5	1.0
Low Temperature Flex	Passed	No cracks @ -40°F
Width	Lab Sample	52 in.

Although the 5.9 lb tongue tear strength in the transverse direction was less than the desired 8 lb value, it was greatly improved over prior samples and probably represents the maximum obtainable when the fabric has good coating and ply adhesion. A decision was made to proceed with fabrication of the hull material. Within three months time all hull material (ILC P/N ST12C751)was received, tested and accepted.

3.7.2 Conclusions

Triaxially woven fabrics, in the present state-of-the-art are not acceptable for use as balloon material primarily due to the inability to achieve equal yarn tension on all three axes and the inability to retain good properties after coating which is caused by the inability to obtain a permanent heatset. Given ample time and budget, it is felt that triaxially woven fabrics can be developed for use as basic hull material capable of overall hull weight savings approaching 50% over today's materials.

Although the weight savings did not meet the original design objective, the two-ply hull material P/N ST12C751 used for the 45,000 cu. ft. balloon is over 2.0 oz/yd^2 less than existing 10 oz/yd^2 materials. Additional effort would most likely achieve some additional weight savings, but not much more than 10%.

4.0 MATERIAL TESTING

A single line item of the contract was devoted to preparation, submittal, approval and subsequent use of an R & D Test and Acceptance Plan. The plan was submitted, ammended and approved for use during the first year of the contract. The plan defined classes of materials, federal, military and industrial testing methods and listed all tests required for acceptance of each material class. In asmuch as the test plan was required to be submitted early in the program, it did not reflect the final fabric constructions, weights or polymer formulations however, the tests required and the individual testing methods did not change appreciably and therefore were useable on the final materials, except where specific values, e.g. breaking strength, weight, etc. no longer applied.

5.0 FINAL MATERIAL DESIGN

The final materials selected for construction of the 45,000 cu.ft. balloon and their specified physical properties are shown in Table 39.

TABLE 33. FINAL MATERIAL DESIGN (35,000 CU.FT. BALLOON)

CHARACTERISTIC	BALLONET - ST[illegible]	EMPENNAGE - A1050[illegible]	HULL - ST120751	TEST METHOD
	REQUIREMENTS			
Construction	[illegible] oz yd² Light Stable Polyester Polyurethane Film White. [illegible] oz yd² [illegible] Fabric. [illegible] oz yd² Polyester Polyurethane White	2.5 oz yd² Light Stable Polyester Polyurethane Film White. 2.3 oz yd² [illegible] 30 Ripstop Fabric. [illegible] oz yd² Light Stable Polyester Polyurethane White	1.7 oz yd² Light Stable Polyester Polyurethane White. 2.3 oz yd² Polyester Fabric, 210 Denier 41 x 39 count. 1.0 oz yd² Polyether Polyurethane, Black. [illegible] oz yd² Inserted non-woven Polyester Fabric. [illegible] oz yd² Polyether Polyurethane Black.	Vendor Certification
Weight oz yd²	[illegible] ± [illegible]	6.[illegible] ± [illegible]	[illegible] ± [illegible]	FTM-191-5041
Breaking Strength lbs in. Grab Method Machine / Transverse	35 Min. / 35 Min.	[illegible] Min. / [illegible] Min.	[illegible] Nominal, 120 Min. / [illegible] Nominal, 90 Min.	FTM-191-5102
Adhesion lbs in. Coating / Ply	7 Min. / ---	- / ---	[illegible] Nominal, 7 Min. / [illegible] Nominal, 7 Min.	FED-STD-191-Mtd. 5970
Tear lbs Tongue Method Machine / Transverse	--- / ---	25 / 25	8.5 Nominal, 6 Min. / 7 Nominal, 6 Min.	FED-STD-191-Mtd. 5134
Permeability (liters/meter² 24 hrs) Air / Helium	--- / 1.0	1.0 / ---	--- / 1.0	FTM-191-5460 ILC-STP-029
Low Temp. Flex (1/8-in Mandrel)	No cracks @ -40°F	No cracks @ -40°F	No cracks @ -40°F	ASTM-D2136
Width (inches)	45 Min.	51 Min.	52 Min.	FED-STD-191-Mtd. 5020

6.0 BALLOON DESIGN AND FABRICATION

6.1 Design

The balloon design criteria were specified in the contract, refer to paragraph 2.2.4 of this report for listing of criteria. During the first five (5) months of the contract a preliminary design study was conducted. The main purpose of the preliminary study was to calculate weight and balance data based on a general balloon configuration. For the purpose of determining the projected weight of the 45,000 cubic foot balloon, the scaled areas of a previously built 201,000 cubic foot hull, ballonet and empennage were used. Seam tapes, patch materials, handling lines, valves, blowers and other hardware and rigging components were also scaled down in the engineering estimate. The weight and balance study indicated the original design weight goals for the hull, ballonet, empennage and tether would have to be reduced in order to achieve a design goal of 10% free lift at altitude.

Subsequent design efforts consisted of dynamic analysis of the proposed balloon system, confluence load identification, determination of load patch size and locations, more specific hardware sizing, material and component configuration and empennage/hull integration, all culminating in the aerostat design section of a contractually required R & D Design and Evaluation Report. The approved report established the 45,000 cubic foot balloon design configuration shown in Figure 17. The balloon is a modified class "C" shape with a four fin cruciform empennage attached to the aft end of the hull for aerodynamic lift and stability. See Figure 18 for final balloon configuration.

6.1.1 Hull Design

The hull design is conventional with longitudinally running gores fabricated from wide panels of material. Fan type load patches and scuff strips attached to key points on both sides of the hull facilitate attachment of flying and close haul bridle lines. The load patches are designed and sized to distribute loads such that fabric stresses are transmitted to the hull at a load density less than 10 lbs./in.around the patch periphery.

6.1.2 Ballonet Design

The ballonet utilizes a polyurethane coated lightweight nylon ripstop material constructed with longitudinally running gores fabricated from wide material panels. The ballonet volume required to fly the balloon from 5,000 to 10,000 feet was computed to be 7,071 cubic feet. This includes a 10 excess volume to account for superheat. The volume of a 201,000 cubic foot balloon ballonet, which was sized for flight from 0-10,000 feet, was directly scaled to this 45,000 cubic foot application. The scaled down ballonet volume was 15,522 cubic feet. Since the hull was also directly scaled from the 201,000 cubic foot balloon, it was decided to use the directly scaled ballonet volume in order to save the unnecessary engineering cost of re-developing a ballonet shape and hull intersection line. The ballonet was cemented to the inside of the hull along the intersection line with a fabric corner strip to prevent the seam from experiencing peel loads.

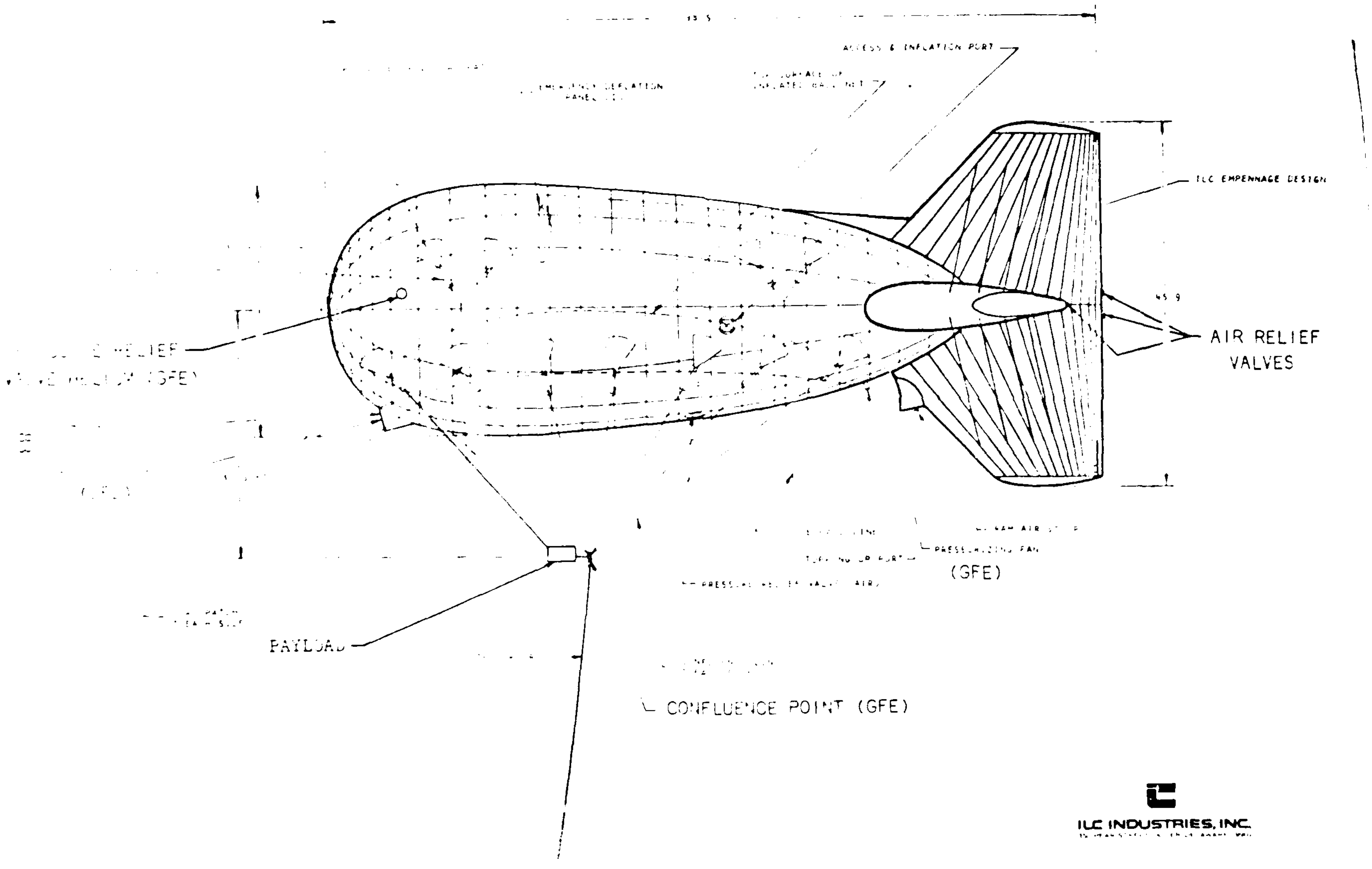


FIGURE 17. EARLY 45,000 CU.FT. BALLOON CONFIGURATION

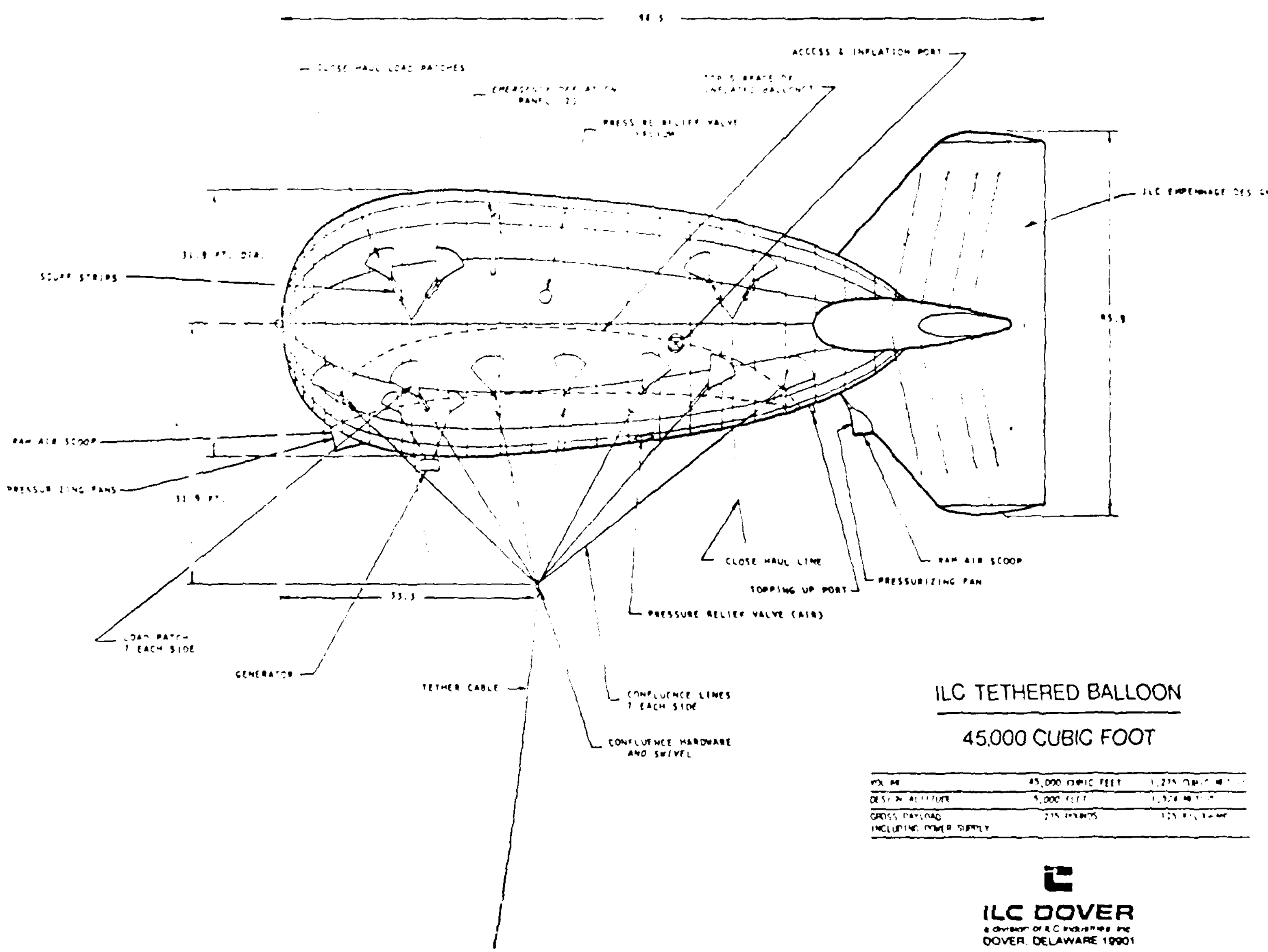


FIGURE 18 FINAL 45,000 CU.FT. AEROSTAT ASSEMBLY

6.1.3 Empennage Design

The basic configuration of the empennage was originally a four fin cruciform and it remained so. The individual fin design orginally proposed utilized inflated tubes placed inside a skin. The tubes were sized to present a good airfoil snape (See Figure 19).

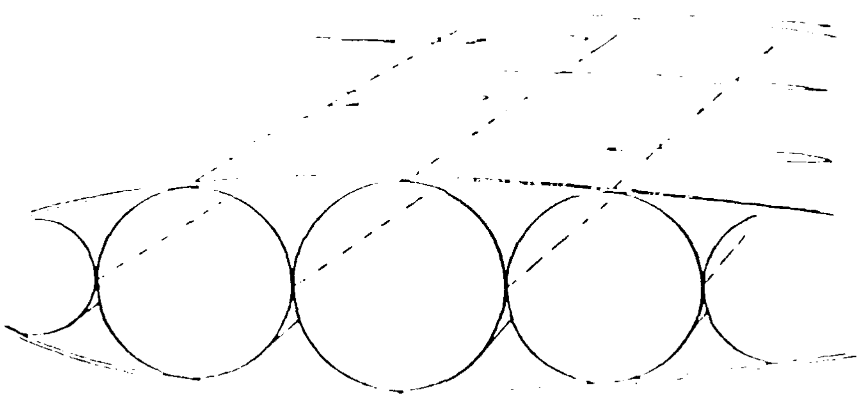


FIGURE 19. ORIGINAL FIN DESIGN

Very early tests proved this design not feasible for two reasons; 1) excessively high air pressure was required to prevent the leading edge from losing it's shape and; 2) leak detection and other maintenance was very difficult and time consuming.

As a result of the tests, a new empennage fin design was engineered. This design configuration (see Figure 20) is a fully pressurized tapered cylinder distorted to an air foil cross-section by means of internal catenary ribs. The fin cross-section is 90% of a NACA 0018 standard air foil. Both catenary and triangular load spreader designs were evaluated. Tests demonstrated the catenary rib design to be the most uniform load distributor and therefore was chosen.

The catenary ribs and the fin skin are made from the same base fabric, a Dacron/Kevlar 29 ripstop fabric. The catenary ribs are uncoated whereas the fin skin is polyurethane coated for air retention. Two factors in this design which enhance all aspects of maintenance and repair are, 1) A single fabric serves both as the structural restraint and as the air retention barrier and; 2) the skin is pressurized, enabling leak detection and repair from the outside. Guy lines were provided between the four fins to provide additional support for aerodynamic loading. Original analysis of the catenary rib design indicated the pillowing effect of the skin panels could be restricted to 5% of the chord depth. The final configuration was measured at 4.6% and was completely satisfactory.

6.1.4 Empennage/Hull Integration

The original concept of using lacing loops for attaching the empennage to the hull was dropped to save weight, prevent possible water pockets and thereby improve performance. The final design has the empennage permanently attached to the hull.

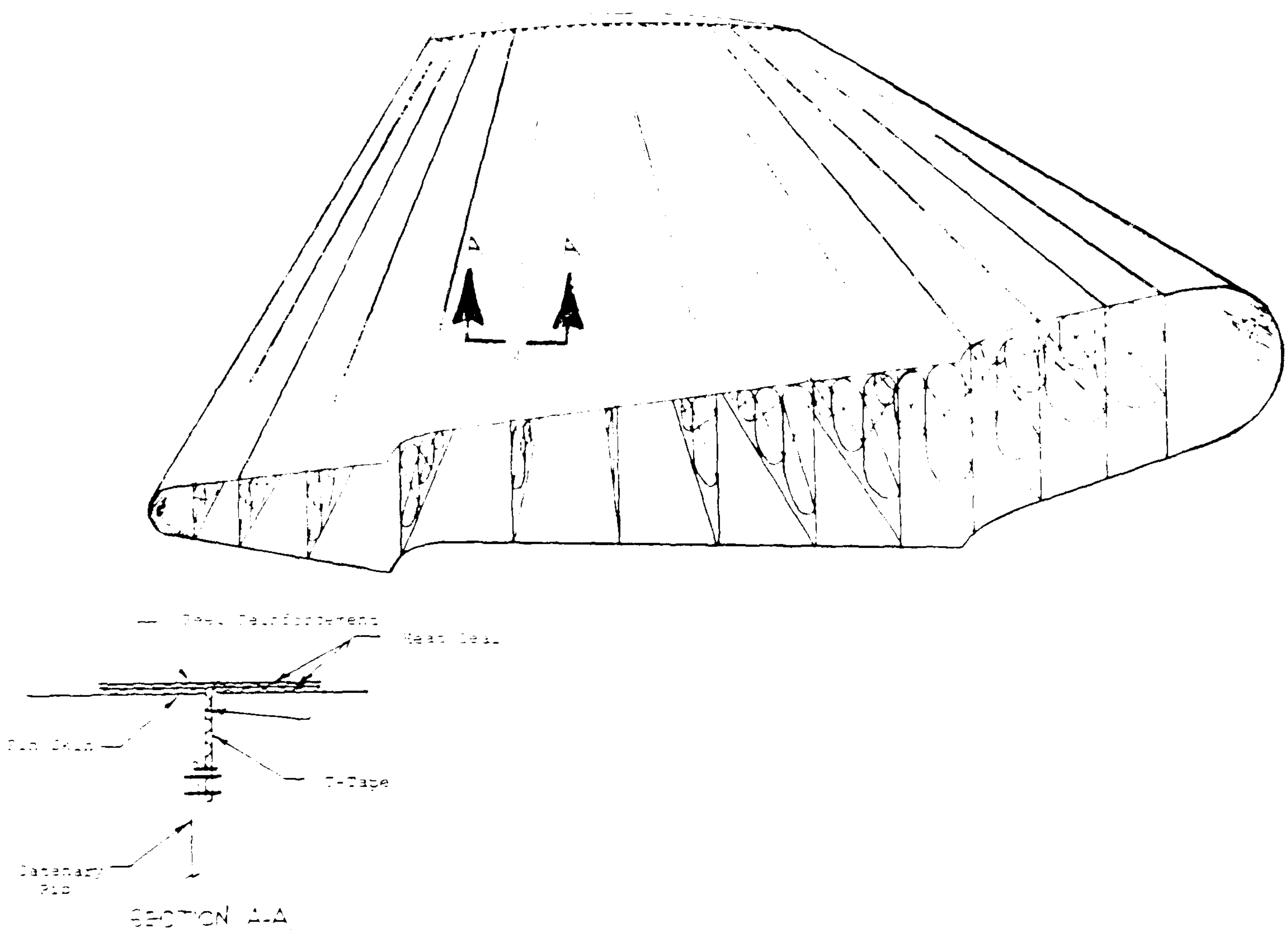


Figure 20 Final Fin Design

6.1.5 Dorsal Fairing

The original balloon design included a dorsal fairing between the hull and upper vertical fin. The fairing was to prevent *hull buckling* due to high lift loads from the empennage at a projected minimum 6^{0} angle of attack. Actual flight testing of the 201,000 cubic foot balloon from which this 35,000 cubic foot balloon was scaled, indicated a 3^{0} minimum angle of attack and much lower hull bending loads. Based on these tests the upper dorsal fairing was eliminated which also saved weight and thereby improved performance.

6.1.6 Other Equipment

Other operational, maintenance and safety devices assembled to the balloon [illegible]

a. Hull

1. Emergency deflation rip panels (2)
2. Inflation and access ports (2)
3. Helium topping off port (1)
4. Ballonet air scoop (1)
5. Flying lines (13)
6. Close haul lines (4)
7. Also included in the hull are:

    a) Helium pressure relief valve (1)
    b) Air pressure relief valve (1)
    c) Air pressurizing fan (1)

b. Empennage

1. Air scoop (1)
2. Air pressure relief valves (2)
3. [illegible] air pressurizing fan (1)

6.2 *Fabrication Techniques*

Fabrication of the balloon was accomplished by utilizing dielectric (RF) and thermal heat sealing techniques discussed below, plus stitching and cementing. Joining techniques in the critical areas are illustrated in Figures [illegible] through [illegible].

6.2.1 Heat Sealing [illegible]

[illegible]

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AIR FORCE GEOPHYSICS LABORATORY AERODYNAMICALLY SHAPED TETHERED--ETC(U)
DEC 80 G P DURNEY, R W LAWRENCE   F19628-73-C-0155
UNCLASSIFIED   AFGL-TR-80-0367   NL

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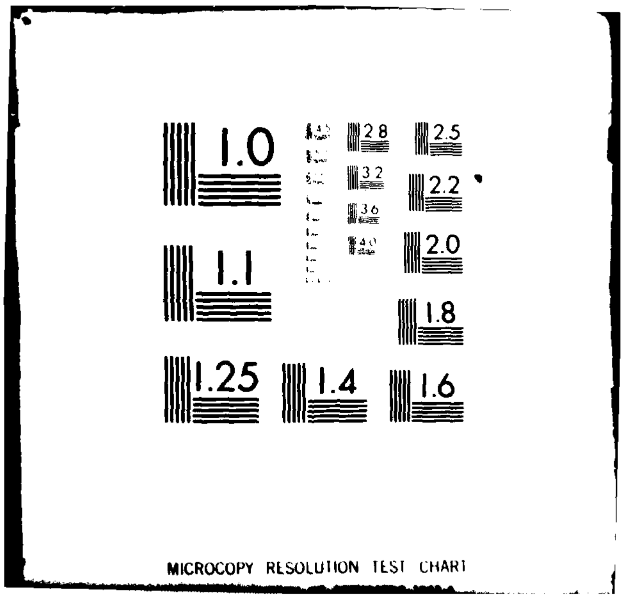
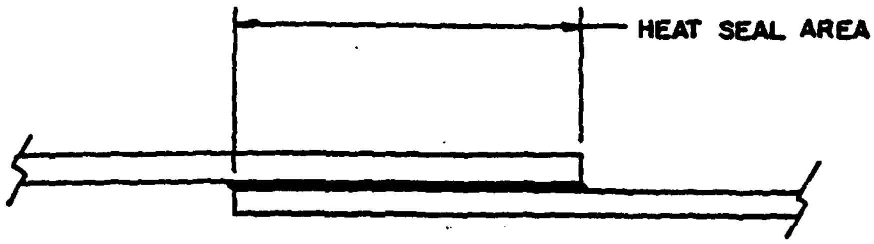

1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART

at the outer edges of the seal. Figure 22 is a variation of Figure 21 and was used for main seams of the hull. A sealable tape is sealed to the coated fabric on each side of the seam. Thus, all loads are shear loads and are distributed to both sides, resulting in an extremely strong seam. A cross-sectional view of four panels joined in this manner is illustrated in Figures 23 and 24.

6.2.2 Dielectric (RF) Heat-Sealing

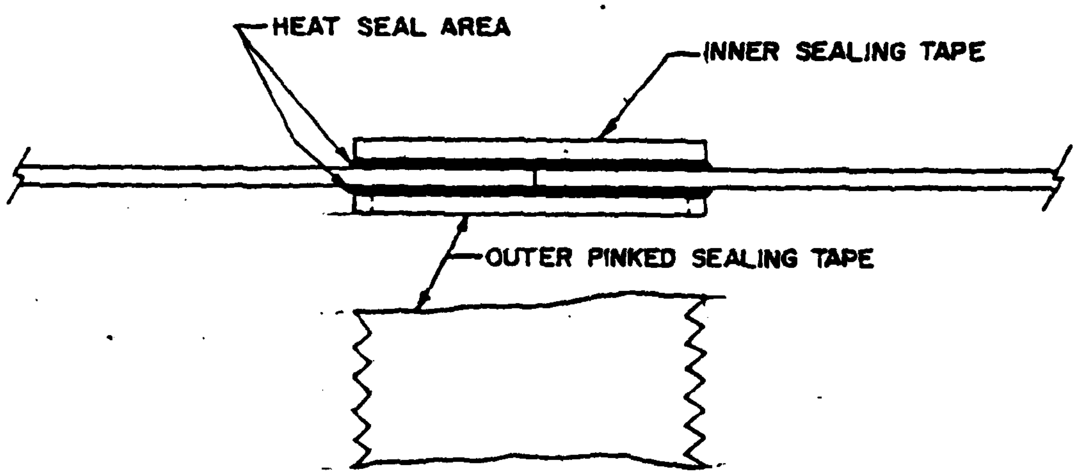
Test results of RF heat-sealing on seam samples of the hull fabric produced excellent results, therefore the hull fabric panels and much of the empennage were joined by RF heatsealing. The process utilizes the electrical properties of films which are moderately polar in nature. The dielectric heating effect 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 interfaces. A seal is accomplished by placing two similar films between two matched sealing dies and activating the high-frequency alternating current for a specified 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.

ILC has incorporated a new quality control capability in its heat-sealing operation. This technique makes use of temperature sensitive dyes which are painted in narrow stripes on the sealing tapes. Two dyes are used in this process, one is activated by the temperature established as the low end of the sealing range and the other is activated by the temperature specified as the upper limit of the sealing range. These temperatures are determined by preparing and evaluating test seams through a wide range of seal temperatures. By observing the two dye stripes after sealing, it can be determined whether the seal temperature was within the desired range. This process provides the capability for a quick, effective quality control inspection of every inch of balloon seam.



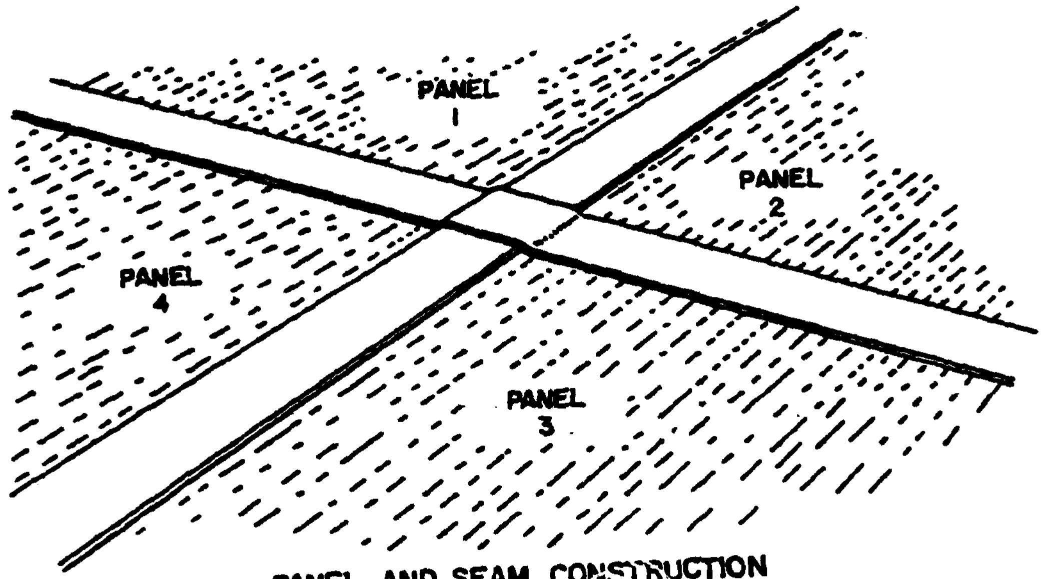
BASIC HEAT-SEAL LAP SEAM

Figure 21



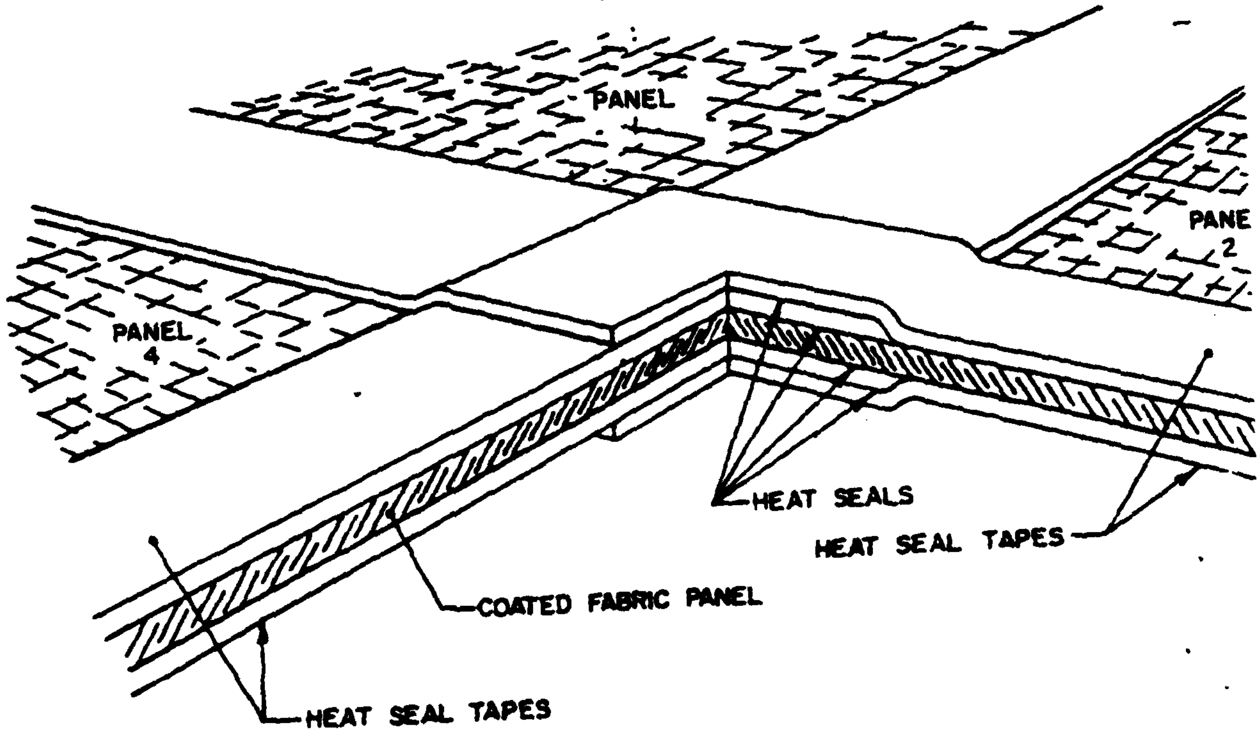
MODIFIED HEAT-SEAL LAP SEAM

Figure 22



PANEL AND SEAM CONSTRUCTION

Figure 23



METHOD FOR JOINING FOUR PANELS BY HEAT-SEALING

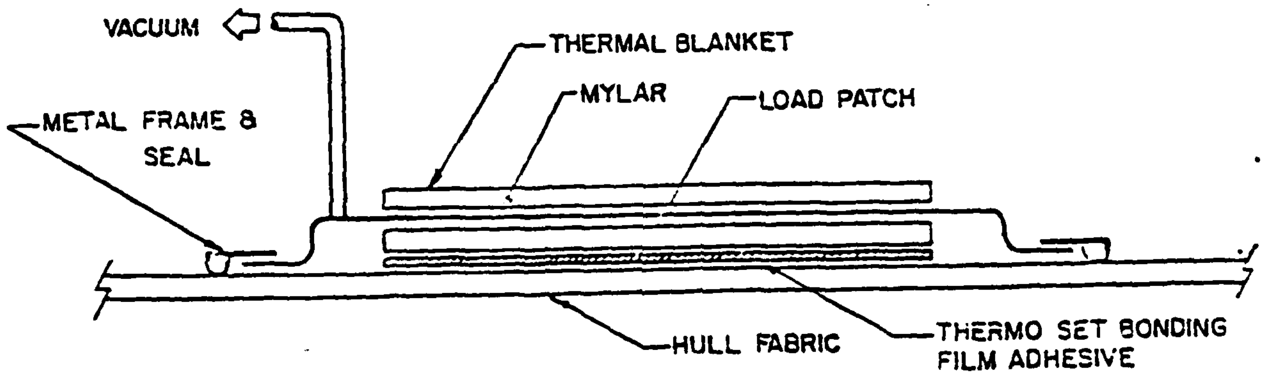
TYPICAL HEAT-SEAL INTERSECTION

Figure 24

6.2.3 Thermal Sealing

Thermal heat-sealing utilizes the principles of both heat and pressure, in conjunction with a heat-activated film adhesive, to create a fabric bond. The film adhesive, when thermally set, will form a bond between fabrics which is greater than the strength of the fabric.

ILC thermally bonded all the patches to the hull by use of a manufacturing technique developed by ILC for bonding Apollo space suit fabrics. This method utilizes a thermal blanket and vacuum which provides equal pressure over the entire sealing surface to achieve thermal/pressure bonding (See Figure 25). The thermosetting film adhesive utilized in all thermosealing meets ILC Specification 03998, Polyester Film Adhesive.



LOAD PATCH ATTACHMENT METHOD

FIGURE 25

6.2.4 Stitches, Seams, and Stitching

All stitching used conforms to Federal Standard 751, Type 301, or as otherwise noted in the specification. Sewing thread utilized in all stitching and seaming also meets this specification.

6.2.5 Cementing

Cementing was limited to those areas where dielectric or thermal heat-sealing was not practical. Adhesives utilized met all the requirements of ILC Specification 03999 for Two-Part Urethane Adhesive.

7.0 PROOF PRESSURE AND LEAK TEST

The last requirement before balloon shipment was conduct of a leak test. Both proof pressure and leak tests were conducted. The balloon was pressurized with air to 3.5 inches of water for a period of 1/2-hour. During the period, the balloon surfaces were visually inspected for proper contour. All surfaces were smooth with no depression or bulges. All seams and joints remained intact.

Due to fluctuating weather conditions and the effect that changes would produce, the leak test was postponed several days until more stable weather conditions existed. When stable weather conditions prevailed the leak test was conducted and within the accuracy capabilities of the test and measurement equipment, there was no measureable leakage of the 45,000 cubic foot helium compartment.

During the course of the test, the ambient temperature,barometric pressure,and balloon delta pressure were monitored (refer to Table 40). During the period from 11:30 a.m. to 2:30 p.m. the apparent balloon air pressure increased from 1.9 to 2.9 inches of water while the ambient temperature increased by 7° F. It was calculated that volume growth due to elongation caused by the increased temperature and pressure was approximately 1%. A 1% volume increase is indicative of a 0.33% linear elongation which is nearly identical to the raw material elongation values

TABLE 40 45,000 FT^3 BALLOON LEAK TEST READINGS

TIME	BALLOON PRESSURE	AMBIENT TEMPERATURE	BAROMETRIC PRESSURE
11:30 A.M.	1.9" H2O	80.0F	
11:45 A.M.	1.95" H2O	80.0F	
12:00 Noon	1.9" H2O	79.0F	12:00 30.38
12:15 P.M.	1.85" H2O	79.0F	
12:30 P.M.	1.79" H2O	79.0F	
12.45 P.M.	1.7" H2O	78.0F	
1:00 P.M.	1.5" H2)	78.0F	1:00 30.39
1:10 P.M.			
1:15 P.M.	1.8" H2O	81.0F	
1:30 P.M.	2.4" H2O	84.0F	
1:45 P.M.	2.59 H2O	84.0F	
1:55 P.M.			
2:00 P.M.	2.4" H2O	83.5F	2:00 30.39
2:08 P.M.			
2:25 P.M.	2.6" H2O	85.0F	
2.30 P. M.	2.9 +" H2O	87.0F	

found during tests between the same pressures (1.9 and 2.9). For these reasons, it was determined that there was no measureable leakage.

8.0 CONCLUSIONS

At this writing flight tests of the 45,000 cubic foot balloon, scheduled for 1981, have not been started and therefore the final conclusions as to the degree of success of this program cannot be drawn. It can be said, however, that the materials and processes developed during the program resulted in attainment of the original goal which was to develop a new superior balloon material. The material is superior for two interrelating reasons; 1) The material is of much lighter weight, while retaining strength, than previously used two-ply fabric constructions and ; 2) elimination of two-ply biasing fabrication techniques greatly reduces the labor cost to manufacture the balloon. Additionally, based on all data obtained up to this time, in can be concluded that the material developed is suitable for use in 100,000 cubic foot and larger balloons.

9.0 RECOMMENDATIONS

The first recommendation is to complete the flight test and other evaluations, e.g. maintainability, reliability, etc. and if successful or satisfactory construct a 100,000 cubic foot balloon with the same materials and processes to prove the theory that it can be done with good results.

Secondly, given ample time and budget, closely monitor industrial establishments for improvement in triaxial fabric weaving and coating technology. If perfected, the triaxial fabric could greatly improve the weight to lift ratio in balloons of the future.

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