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POTENTIAL CONTRIBUTION OF HIGH STRENGTH, HIGH MODULUS ARAMID FIBERS TO THE COMMERCIAL FEASIBILITY OF LIGHTER THAN AIR CRAFT

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ABSTRACT: This paper reviews Kevlar® aramid fiber, fabric, rope and cable performance, and economics relevant to the material, structural, and reliability aspects of lighter than air craft.

I. INTRODUCTION

Kevlar® 29 and Kevlar® 49 are two high strength, high modulus, and low density organic fibers recently introduced by Du Pont. These unique aramid fibers offer for the first time textile processibility combined with the highest specific strength (tensile strength/density) available commercially for any material, and a specific Young's modulus (modulus/density) intermediate between fiberglass, steel and aluminum on the low side, and the more exotic graphite and boron fibers on the high. The excellent tensile properties of "Kevlar" have generated extensive trade development programs and commercial sales into rubber and plastic reinforcement uses, many of which have requirements similar to those anticipated for the construction, operation and maintenance of lighter-than-air craft.

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A. Tensile Properties

The basic "Kevlar" characteristics are summarized in Table I. Organic fibers such as nylon and Dacron® polyester have long been used successfully in many industrial applications; but their properties limit their ability to perform in end uses requiring very high strength and low stretch (e.g., wire rope and electromechanical cables). "Kevlar" 29 and "Kevlar" 49 aramid fibers with their combination of high strength (400×10^3 psi), high modulus (9 to 19×10^6 psi), or low stretch (2.4 to 4%) that approach steel (Figure 1), combined with light weight ($\sim$1.45 g/cc) permit the realization of systems not practical with steel or other synthetic fibers. The yarn properties of "Kevlar" are compared to those of steel, nylon and "Dacron" polyester in Table I. A comparison of the strength and stiffness per unit weight, also called specific strength and specific stiffness, versus other fibers and metals is shown in Figure 2. Note that "Kevlar" offers the highest specific strength of any known commercial material, and a specific modulus intermediate between conventional fibers and metals on the one hand, and more exotic fibers such as graphite and boron on the other.

B. Temperature Effects

The high level of room temperature strength and modulus versus more conventional textile fibers is retained at elevated temperatures as shown in Fig. 3 and 4. In addition, low temperatures that could be encountered in polar service do not reduce the strength or unduly embrittle the fiber, Table II. More extreme lower temperatures, as those required for the containment of liquified gases are also innocuous to the fiber. Work by NASA has shown that "Kevlar" 49 fiber that had a room temperature (75°F, 297°K) tensile strength of 425×10^3 psi, only decreased in strength to 386×10^3 psi when tested at liquid H_2 temperatures (-423°F, 20K), Ref. 1.

C. Creep

A further design consideration for inflatable structures, such as the skins of balloons, is that they must remain in tension for long period of time without excessive creep. The high crystallinity of "Kevlar" 29 and 49 make creep negligible up to significantly high percentages of the ultimate tensile strength (UTS) of the fiber, Fig. 5. Comparison of the creep rates of "Kevlar" 29 and "Dacron" polyester, measured by the slopes of the curves in Fig. 6, gives further indication of the superiority of the aramid in this respect.

D. Creep Rupture

Strong but brittle materials have difficulty sustaining high percentages of their ultimate tensile stress for useful periods of time due to their creep-rupture behavior. This causes cracks that initiate at some point in the material to rapidly propagate, leading to the collapse of the entire item. The substantial advantage over glass of the fibrous polymeric structure of "Kevlar" in preventing this brittle fracture has been documented elsewhere (Ref. 2). This characteristic could be of value in the design of pressure vessels required for vehicle altitude control and/or ground storage of helium.

E. Ultra-Violet Stability

Precaution should be taken to protect "Kevlar" ropes, cables and fabrics from degradation due to prolonged UV exposure. Because "Kevlar" is self-screening, if degradation of the outer perimeter of a rope, or the outer plies of a coated fabric, can be tolerated, they will protect the interior from damage. More economically, ropes and cables can be jacketed with UV resistant braids (e.g., "Dacron"), or an extruded pigmented thermoplastic. A pigmented film as the outer layer of a coated fabric lamination is also an effective UV screener.

III. FLAMMABILITY

Flammability characteristics can be crucial in the selection of material for the applications of interest to this audience. The Limiting Oxygen Index (LOI) is an accepted method of ranking the relative flame retardance of textile fabrics, Table III. Note that the performance of "Kevlar" 29 and "Kevlar" 49 is similar to high temperature resistant Nomex® aramid. Table IV compares the flame and smoke characteristics of "Kevlar" 49 fabric reinforced resin laminates with identical glass fiber reinforced configurations, where precaution has been taken to select a halogenated epoxy as the matrix. Data show "Kevlar" 49 to meet stringent specifications in effect for commercial aircraft interiors.

IV. ELECTRICAL PROPERTIES

The dielectric constant of a "Kevlar" laminate is about one unit lower, and the loss tangent equivalent, to that of a glass fiber reinforced item that uses the same resin. Thus, "Kevlar" is transparent to electromagnetic radiation and can be used advantageously as radome material. Both electrically and thermally it is an insulator, Table V. Its good dielectric properties also make it an ideal material for antenna guy wires that do not interfere with signal transmission.

V. COST

Presently, "Kevlar" sells on a dollars per pound of breaking strength basis at 20 to 40% premium over improved galvanized plow steel wire. The very significantly higher strength per unit weight of "Kevlar" vs. steel compensates for the difference in cost per unit weight. At realistic projected prices, the cost for equivalent strength with "Kevlar" 29 and 49 should be lower than for steel wire.

VI. APPLICATIONS

We will now describe applications for "Kevlar" which take advantage of its properties described above, and which have relevance to material, structural and reliability aspects of lighter-than-air craft. We will purposely exclude "Kevlar" reinforced plastics applications in the aircraft, missile, marine and recreational equipment field that are well-documented elsewhere in the literature (Refs. 4-7). We have specifically selected for review "Kevlar" uses in high performance ropes and cables, coated fabrics, and industrial hose. The relevance of the performance demonstrated by "Kevlar" in these uses to the anticipated requirements of materials for lighter than air craft should become clear in what follows.

A. Ropes and Cables

1. Advantages

The primary advantage of "Kevlar" fibers is an excellent strength-to-weight ratio in very long cables such as those used in oceanographic and aerospace markets. Fig. 7 illustrates the "free" length "Kevlar" will support in both air and water as compared to steel. With the highest specific strength of any material known, "Kevlar" offers increased payloads and permits easier handling with smaller, lighter, and more economical systems.

In addition to the high strength-to-weight ratio, "Kevlar" also offers the following advantages:

- High modulus (resistance to stretch)
- Corrosion resistance
- Non-conductivity
- Flexibility

These characteristics are advantageous in many applications where "Kevlar" is now under evaluation. These include:

Mechanical Lines -

- Oil well rig mooring lines
- Buoy mooring lines
- Tug boat towing lines
- Running and standing rigging
- Helicopter hoist lines
- Balloon tether lines
- Antenna guys
- Parachute shrouds
- Leader lines

Electromechanical Cables -

- Data and sonabuoy mooring cables
- Air and sea towed antenna cables
- Deep ocean work system cables
- Subsea television cables
- Balloon tether cables

Data developed to date in these applications confirm the anticipated strength-to-weight advantages of "Kevlar". In mooring lines, now being developed for offshore oil rigs, a mechanical line of "Kevlar" with 1 million pounds breaking strength exhibits an 80% weight savings in air versus steel. Deep ocean electromechanical cables being developed by the Navy have also shown the high strength-to-weight ratio allows higher payloads in water (20X) at the same safety factor as an equal size steel cable. In addition to the easier handling of these lighter lines and cables, the corrosion resistance provides safer, longer lasting systems, with no significant strength loss occurring after one year in sea water.

Also, the non-conducting characteristic of "Kevlar" provides added safety in lines, and prevents the strength member from shorting out conductors in electromechanical cables, or interfering with the reception of antennas. High altitude meterological balloon tethering cables have been deployed and are performing satisfactorily. Pultruded "Kevlar" 49 reinforced plastic guy wires have been operational since 1972 on the radio telescope of the Arecibo Observatory, Puerto Rico (Ref. 7).

A further benefit, confirmed in hydroplane work by the Navy and Woods Hole Oceanographic Institute, is that cables of "Kevlar" are much quieter in operation than steel cables.

2. Forms

"Kevlar" 29 and "Kevlar" 49 can be used either as "soft" yarns (like nylon and "Dacron" polyester) on conventional textile twisting, stranding or braiding equipment, or as resin impregnated strands which may be handled like steel wire on wire stranding, cabling and braiding equipment.

Types of rope and cable structures which have been demonstrated include: 3-strand, 8-strand, plaited, single and double braids, parallel strands, 1x7, 1x19, 7x7, 7x19, 19x7 ropes, and center core and contrahelically wound cables. Typical properties of some rope constructions are shown in Table VI. The construction is chosen to achieve the optimum balance of strength, modulus and flexibility required for specific application. Notice that the strengths of the "Kevlar" items are equal or better than for steel at about one-fifth the weight of cable.

3. Cost

Cost comparison of "Kevlar" and nylon or polyester ropes, Table VII, shows "Kevlar" to be comparable in cost at equal breaking strength.

B. Coated Fabrics

Table VIII shows Hypalon® coated nylon fabric (5.1 oz/yd^2), intended as air supported shelter material, compared to a "Kevlar" analog that utilizes fabric of less than half the basis weight (2.1 oz/yd^2). The "Kevlar" item is 20% lighter, stronger and more tear resistant. We are currently evaluating fabrics coated with other elastomers.

Work by Sheldahl Advanced Products Division in tethered balloons (Ref. 8) has shown that ply laminates of "Kevlar" offer significant strength-to-weight improvements, are less permeable, and have equal or better abrasion resistance than conventional "Dacron" reinforced counterparts (Tables IX-XI).

C. Industrial Hose

Small diameter industrial hoses (3/16"-1/2") with thermoplastic resin inner liners braided with "Kevlar" and covered with PVC have been shown to support internal pressures up to 40 x 10^3 psi. Such industrial hoses are now commercial. "Kevlar" is expected to offer considerable advantage in automotive radiator and heater hoses with temperature capabilities up to 300°F.

Gates Rubber Company has recently reported (Ref. 9) use of "Kevlar" in anhydrous ammonia hose with high burst, low volumetric expansion and superior chemical resistance than incumbent products; and in high pressure hose which is nonconductive and more flexible than their steel reinforced counterparts.

VII. CONCLUSIONS

"Kevlar" in its regular (9 x 10^6 psi) and high (19 x 10^6 psi) modulus forms offers a combination of physical properties heretofore unavailable among man-made fibers. In spite of its superior performance, "Kevlar" retains the handleability normally associated with more conventional textiles. This allows processing using existing equipment and techniques that result in high performance products of attractive economics.

The high level of tensile strength per unit weight of "Kevlar" combined with its balance of other properties has allowed the reduction to practice of systems concepts in mechanical and electromechanical applications not possible with other materials. The new dimensions in design and economics available with "Kevlar" we think can help improve the performance/cost effectiveness of the lighter than air craft concept.

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TABLE I - YARN PROPERTIES

	"Kevlar" 29	"Kevlar" 49	GIPS*	Nylon	"Dacron"
Tenacity, gpd**	21	21	2.9	9.8	9.5
" psi	400,000	400,000	285,000	143,000	168,000
Modulus, gpd	500	1000	200	55	115
" psi(10^6)	9	19	29	0.8	2.0
Specific Modulus, in., 10^8	1.7	3.6	1.0	0.3	0.6
Density (g/cc)	1.44	1.45	7.86	1.14	1.38
Elongation, %	4	2.4	2.0	18.3	12.0
Cost ($/lb)	7.50	8.50	0.80	0.80-1.00	0.75-1.05
" ($/lb Break Force x 10^{-8})	99	112	80	25	27

*Galvanized Improved Plow Steel
**gpd = grams per denier

TABLE II - "KEVLAR" 29* PROPERTIES AT ARCTIC TEMPERATURE

	75°F	-50°F
Tenacity, gpd	19.1	19.8
Elongation, %	4.1	3.9
Modulus, gpd	425	521
Loop Tenacity, gpd	8.3	7.7
Loop Elongation, %	2.0	1.8

*4500 Den.

TABLE III - LIMITING OXYGEN INDEX

T-728 Nylon	0.20	Nomex®	0.28
Virgin Wool	0.25	"Kevlar" 29	0.29

TABLE IV - FLAME AND SMOKE PROPERTIES IN EPOXY* RESIN

	"Kevlar" 49	Glass
Flammability FAA 25.853 Test		
Burn Length (in.)	5.5	7.75
Time to Extinguish (min.)	0.70	0.75
National Bureau of Standards Smoke Chamber		
Max. Specific Optical Density flame ignition	148	197
Max. Specific Optical Density radiant ignition	54	77

*Flame retardant

TABLE V - ELECTRICAL PROPERTIES OF "KEVLAR" 49 AND GLASS FABRIC LAMINATES IN FR-4 EPOXY RESIN

	"Kevlar" 49	Glass
Dielectric Constant (ASTM D-150, 10^6 Hz)	4.12	5.15
Dissipation Factor (ASTM D-150, 10^6 Hz)	0.0239	0.0210
Dielectric Strength, volts/mil (ASTM D-149)	957 (29.7 mils)	793 (36.1 mils)
Volume Resistivity, ohm/cm (ASTM D-257)	5×10^{15}	2×10^{15}
Surface Resistivity, ohm/square (ASTM D-257)	5×10^{15}	3×10^{15}
Arc Resistance, seconds	125	123
Volume % Fiber	48	44

Conditions: Tests at R.T. after samples had been conditioned at 73°F for 24 hours at 50% R.H.

TABLE VI - TYPICAL ROPE CONSTRUCTIONS

	Diameter (in.)	Lbs/100 Ft	Break Strength (lbs)
3-Strand			
"Kevlar" 29	1/2	-	14,300
"Dacron"	1/2	-	6,900
Nylon	1/2	-	8,000
Braid			
"Kevlar" 29 (med. pick)	9/16	10.8	34,000
"Dacron"	9/16	10.0	16,000
"Kevlar" 29 (long pick)	3/1[illegible]	1.5	6,500
8-Strand Plaited			
"Kevlar" 29	1/2	8.6	17,500
"Dacron"	1/2	7.0	6,400
Nylon	1/2	6.8	7,100
H.B.L. Plaited			
"Kevlar" 29 w/"Dacron" cover	23/23	13.2	31,500
Nylon w/"Dacron" cover	1	18.9	24,600
Wire Rope			
1x7: "Kevlar" 29	1/8	0.8	2,500
Galv. Aircraft Strand	1/8	3.5	2,100
1x19: "Kevlar" 29 Stainless Steel	3/16	1.4	4,700
Galv. Aircraft Strand	3/16	7.7	4,700
7x7: "Kevlar" 29	5/16	3.5	12,000
Galv. Aircraft Strand	5/16	16.7	9,200
7x19: "Kevlar" 29	1/2	8.0	25,000
Galv. Aircraft Strand	1/2	45.8	22,800

TABLE VII - COST* COMPARISON IN ROPES

	"Kevlar" 29	Nylon or Polyester
Breaking Strength, lbs		
1 1/4"	153,000	64,000
2"	302,000	164,000
Weight, lbs/100 ft		
1 1/4"	61	53-60
2"	156	135-135
Cost/Foot, $		
1 1/4"	4.78	1.83
2"	12.42	4.64
Cost/Lb Breaking Strength ($ x 10^{-5})		
1 1/4"	3.12	2.86
2"	3.17	2.82

*Wall Rope "Uniline" price list May 1974.

TABLE VIII - AIR SUPPORTED SHELTER MATERIAL

	Nylon	"Kevlar" 29
FABRIC PROPERTIES		
Weight, oz/yd^2	5.1	2.1
Tensile Strength Grab Method (WxF), lbs	380 x 375	215 x 230
Burst - Mullen, psi	800	930
COATED* FABRIC PROPERTIES		
Weight, oz/yd^2	15.0	11.3
Tensile Strength Grab Method (WxF), lbs	300 x 300	380 x 335
Tongue Tear Strength (WxF), lbs	20 x 20	20 x 25
Burst - Mullen, psi	840	900

TABLE IX - TENSILE STRENGTH OF "KEVLAR" 29 COATED FABRIC LAMINATES (Ref. 8)

Test Temp. °C	1-Ply "Dacron" 3.8 oz/yd^2 MD (lb/in)	1-Ply "Dacron" 3.8 oz/yd^2 TD (lb/in)	2-Ply "Dacron" 2.25 oz/yd^2 MD (lb/in)	2-Ply "Dacron" 2.25 oz/yd^2 TD (lb/in)	1-Ply "Kevlar" 1.8 oz/yd^2 MD (lb/in)	1-Ply "Kevlar" 1.8 oz/yd^2 TD (lb/in)	2-Ply "Kevlar" 2.7 oz/yd^2 MD (lb/in)	2-Ply "Kevlar" 2.7 oz/yd^2 TD (lb/in)
60	230	220	173	148	257	300	331	303
22	262	263	184	154	269	330	394	420
-51	258	261	216	210	321	334	460	457

MD = Machine Direction
TD = Transverse Direction

TABLE X - HELIUM PERMEABILITY DATA (Ref. 8)

$1/m^2/24$ hr @ 300 N/m^2 Pressure

Single-Ply "Dacron"	Single-Ply "Kevlar" 29	Two-Ply "Dacron"	Two-Ply "Kevlar" 29
0.4	0.3	0.7	0.5

TABLE XI - ABRASION DATA* (Ref. 8)

	Cycles
1-Ply "Dacron"	40,000
1-Ply "Kevlar"	69,000
2-Ply "Dacron"	21,000
2-Ply "Kevlar"	21,000

*Number of cycles required to expose the fabric when abraided against themselves.

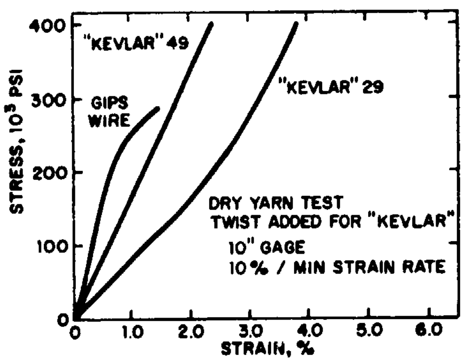

FIG. 1 - STRESS-STRAIN CHARACTERISTICS

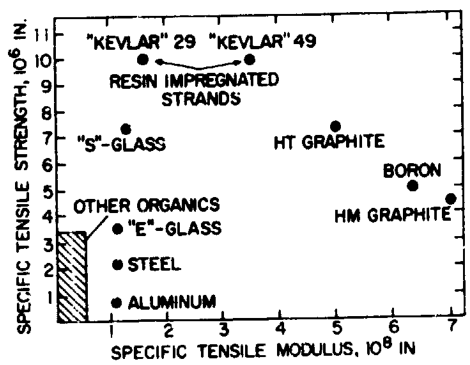

FIG. 2 - SPECIFIC TENSILE STRENGTH AND TENSILE MODULUS

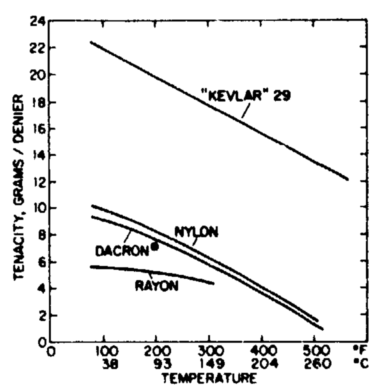

FIG. 3 - EFFECT OF TEMPERATURE ON TENACITY

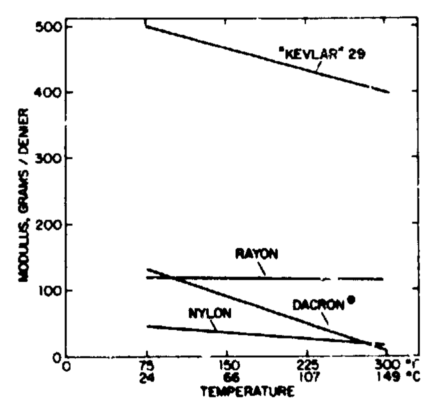

FIG. 4 - EFFECT OF TEMPERATURE ON MODULUS

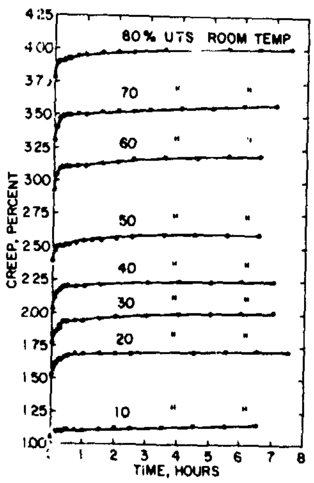

FIG. 5 - CREEP OF "KEVLAR" 29

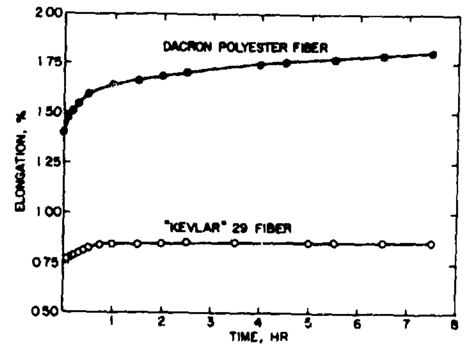

FIG. 6 - COMPARATIVE STRESS-CREEP OF "KEVLAR" 29 AND "DACRON" FIBER TESTED AT 10% OF ULTIMATE TENSILE STRENGTH

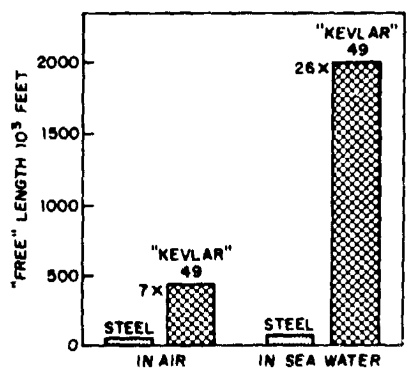

FIG. 7 - "FREE" LENGTH COMPARISON

(LENGTH AT WHICH STRENGTH MEMBER BREAKS OF ITS OWN WEIGHT = TENSILE STRENGTH/DENSITY)