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Aramid Fiber for Use as Oceanographic Strength Members

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This report is a summary of information presently available for use in selecting and specifying Kevlar® aramid ropes for ocean engineering and construction applications. The publication includes data obtained from private industry, Government facilities, and studies initiated by the authors. It is based on available technical data which are representative of state-of-the-art knowledge of the material, rope design, manufacturing processes, test procedures, and application engineering.

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20. Abstract (Continued)

The first portion covers the positive and negative features of the aramid fiber. Then the various aramid fiber rope constructions available are compared with similar constructions of other materials, including wire rope, and comments are made on the relative merits of each for different ocean engineering applications.

In addition, this report provides information on splices and terminations for aramid rope so that the engineer will understand joint efficiencies, reliability factors, and load constraints involved in selecting and specifying splices and terminations. It discusses service considerations such as sheave sizing, abrasion, fake-down requirements, fishbite protection, environmental exposure, and related application information which is needed to specify handling and protective requirements.

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ARAMID FIBER FOR USE AS OCEANOGRAPHIC STRENGTH MEMBERS

PREFACE

The objective of this report is to present information for use in selecting and specifying Kevlar® aramid ropes for ocean engineering and constructions applications. It is based on available technical data which is representative of state-of-the-art knowledge of the material, rope design, manufacturing processes, test procedures, and application engineering.

The report discusses the unique properties of aramid rope, which include

1. Very low stretch
2. High tensile strength
3. Very high strength-to-weight ratio
4. Excellent fatigue resistance
5. Good performance over large temperature range
6. Low creep
7. No shrinkage
8. Minimum snap-back hazard
9. Good chemical stability.

The negative aspects of the fiber, also covered, include

1. Low transverse modulus
2. Self-abrasion of the fibers
3. High material cost.

The various constructions available are compared with similar constructions of other rope materials, including wire rope, and comments are made on the relative merits of each for different ocean engineering and construction applications. This comparative data between aramid fiber rope and rope made from other materials is an aid to help support objective decisions by an engineer in selecting rope materials. Since cost factors are important considerations in the selection process, the relative cost of comparable ropes of various materials are presented.

In addition, this report provides information on splices and terminations for aramid rope so that the engineer will understand joint efficiencies, reliability factors, and load constraints involved in selecting and specifying splices and terminations. It discusses service considerations such as sheave sizing, abrasion, fake-down requirements, fishbite protection, environmental exposure, and related application information which is needed to specify handling and protective requirements.

Manuscript submitted July 13, 1976.

KEVLAR® ARAMID FIBER

Introduction

Kevlar® is the registered trademark for a family of aromatic polyamide (aramid) fibers introduced by E.I. du Pont de Nemours & Company, Inc., in 1972. The material's unique chemical structure earned for itself and for one other du Pont product (Nomex®) the new generic designation "aramid". (In this report, use of the word aramid refers only to Kevlar®.) Kevlar® aramid fiber has a very high tensile strength, a modulus approaching that of steel, more compliance than steel, and dielectric properties near those of glass. Its strength-to-weight ratio is approximately seven times higher than steel in air, and roughly 20 times higher than steel in water. It is corrosion resistant and has very low creep characteristics, yet it is as light and as easy to handle as polyester. Moreover, when the fiber is used as a strength member in electromechanical cables, the small amount of elongation under load does not present serious difficulties with regard to electrical conductor stretch. This combination of properties appears to be tailored to the requirements for suspended cable.

Three different types of Kevlar® aramid fibers are currently available from du Pont: Kevlar® — formerly "Fiber B," Kevlar® 29 — formerly "PRD-49 IV," and Kevlar® 49 — formerly "PRD-49 III." Kevlar® was developed primarily for tire reinforcement, and since its properties are simular to those of Kevlar® 29, it will not be discussed separately in this report. Both Kevlar® 29 and Kevlar® 49 have many other industrial uses besides ropes; however, this discussion is limited to aramid ropes.

Both products are available as continuous filament yarns in a range of deniers and finishes. Various cordage and electromechanical cable companies are able to purchase the yarn and to construct several types of general and special application ropes. The fiber can be used as obtained on conventional textile twisting, stranding, or braiding equipment to produce soft yarn cordage as is done with nylon. Some manufacturers impregnate or encapsulate the yarn with a low modulus material such as a polyurethane or neoprene; it also may be used in conventional textile equipment. A third possibility is a more rigid resin impregnation, in which case the strands must be handled like wires in steel rope manufacturing equipment. For electromechanical ropes, electrical conductors can be included during the stranding or braiding process. Finally, the rope can be jacketed for protection. The process of making aramid ropes is no different than for making other types; however, because of the material's self-abrasion tendencies and its lack of yield prior to rupture, more care must be exercised in processing.

Aramid Fibers

A rope is a cylindrical symmetrical structure, usually circular in cross section. It can transfer tensile loads only along its longitudinal axis and cannot support any bending, shear, or compressive forces. The mechanical loading characteristics of the rope are directly related to the mechanical loading characteristics of its composite fiber.

The aramid filament, like other synthetic filaments, is anisotropic; the macromolecules are aligned parallel to the fiber axis. Its very high tensile strength requires breaking carbon bonds in a longitudinal direction, but only molecular van der Waals' forces are broken in a transverse direction. Kevlar® 29 has a longitudinal elastic modulus of 82.74 GPa (12 X 10^6 lb/in.^{2}); Kevlar® 49's is 131.0 GPa (19 X 10^6 lb/in.^{2}). The transverse modulus is about two orders of magnitude below the longitudinal modulus, according to Phoenix [1], although testing by du Pont indicates that the transverse modulus is about 1/10 that of the longitudinal modulus.

Each fiber is produced as a continuous length of material with a diameter of 0.00121 cm (0.000478 in.). At the present time the filaments are a translucent straw color; however, methods are being developed to enable dyeing. The rope manufacturer may use the yarns as obtained, he may ply several yarns together, or he may induce a slight twist into the yarn. Simple geometry indicates that the strength will decrease as the twist increases; a twisted fiber can form a shear component of force which will weaken it. However, as shown in Fig. 1, a small twist increases the average break strength of the yarn, due to frictional contact of the filaments and a more even distribution of the tensile load. For example, for a 1000 denier Kevlar® 29 yarn, the optimum amount of twist is approximately 2.5 turns/in; for 1500 denier, about 2.0 turns/in.; and for 15,000 denier, it is about 0.6, turns/in. [2]. Twisting, however slight, does not improve the tensile strength of Kevlar® 49. The modulus is too high to accommodate the random slack that is generated in the fibers.

The designer must determine whether or not to use yarn with a finish applied. The yarn can be obtained with no finish at all, a "standard" finish, or a "cordage" finish. The end use determines the one selected. "Standard" finish or no finish yarn is usually chosen when a rope manufacturer wishes to impregnate the yarns with another material. "Cordage" finish yarn is the usual selection when "soft" cordate is to be made directly from Kevlar® yarn.

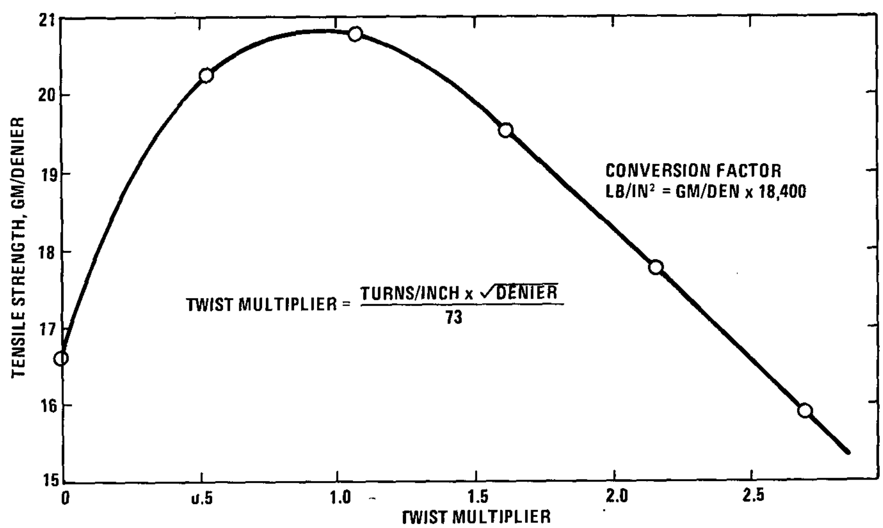

Fig. 1 — The effect of twist on the tensile strength of Kevlar® 29 (textile units) (from E.I. du Pont, Wilmington, Del.)

Several experimental finishes and lubricants are under evaluation which give much improved abrasion resistance to Kevlar® 29 and Kevlar® 49 yarns. These are described in a later section for utilization by the trade, but are not yet available on yarn as supplied by du Pont.

There exists a certain amount of variation in the mechanical properties of the fiber as obtained from du Pont. At this time, there is some discussion as to its magnitude. The du Pont Company suggests that the coefficients of variation (Standard Deviation/Mean Value) of tensile strength, modulus, and elongation are all about ± 3%. This is much higher than the deviation normally found in steel wires, but only slightly higher than that in other synthetic fibers. Nevertheless, the problem does exist, and if one is designing for maximum use, good quality control procedures must be followed.

Mechanical Properties of Kevlar® Aramid Fibers

Tensile Strength, Modulus of Elasticity, and Creep

Table 1 is a listing of the properties of the Kevlar® 29 and Kevlar® 49 aramid fibers produced by du Pont [2, 3]. The table shows the density and the ultimate tensile strength of two yarns to be similar. Notice though that the modulus of Kevlar® 49 (131.0) is higher than that of Kevlar® 29 (82.74), resulting in a lower elongation. In tensile tests, yarns of either fiber display a nearly linear stress-strain relation [4] (Fig. 2). The yarn can be modeled by a Hookean spring since the stress-strain curve is linear and the material exhibits very low creep. Figure 3 shows the creep of the Kevlar® 29 and Kevlar® 49 loaded at 50% of ultimate strength [4]. After the initial constructional stretch (which is small) has been removed, the creep in six months is less than 0.2% for Kevlar® 29 and less than 0.1% for Kevlar® 49. Figure 4 gives an extrapolation of the time-to-rupture vs percentage of ultimate load of Kevlar® 49 yarn. The creep properties while wet appear to be the same as those dry.

Figure 5 is a plot of specific tensile strength (strength ÷ density) vs specific modulus of elasticity (modulus ÷ density) for several fibrous materials. Graphite, for example, is very strong, extremely stiff, and fairly light; therefore it appears in the upper right portion of the graph. The region of greatest interest, however, is in the upper left area of the chart, which includes materials that are very strong, quite light, and neither excessively stiff nor extensible. The aramid fibers appear above the glass fibers because of the greater density of the glass. A comparison of the properties of the various materials for rope construction are summarized in Table 2. It is apparent that the new aramid fibers can compete favorably with all existing rope materials.

Fatigue and Abrasion

The aramid fibers have inherently good fatigue properties, as shown by Table 3 [4]. Figure 6 compares the tension-tension fatigue properties of Kevlar® to steel and nylon. At 10^7 cycles it will withstand 1.7 times the stress of steel and 3.4 times the stress of nylon. Earlier tests ascribed low fatigue values to the bare yarn; however, the real culprit was self-abrasion. The filament has a hard surface which can be removed by friction; in some

Table 1 — Properties of Dry Twisted Kevlar®* Yarn†

Property	Kevlar® 29	Kevlar® 49
Density	0.0520 lb/in^3 1.44 g/cm^3	0.0520 lb/in^3 1.44 g/cm^3
Filament Diameter	0.00047 in 0.00119 cm	0.00047 in 0.00119 cm
Fiber Elongation At Break	4%	2.4%
Tenacity	22 gpd	22 gpd
Tensile Strength	400,000 lb/in^2 2.76 GPa	400,000 lb/in^2 2.76 GPa
Specific Tensile Strength	7.7 × 10^6 in 19.5 × 10^6 cm	7.7 × 10^6 in 19.5 × 10^6 cm
Modulus	12 × 10^6 lb/in^2‡ 82.74 GPa	19 × 10^6 lb/in^2‡ 131.0 GPa
Specific Modulus	2.3 × 10^8 in‡ 5.8 × 10^8 cm	3.6 × 10^8 in‡ 9.1 × 10^8 cm

*Trademark for du Pont's aramid yarn.
†From E.I. du Pont, Wilmington, Del.
‡Modulus of single filaments or ASTM D2343 Resin Impregnated Strand.

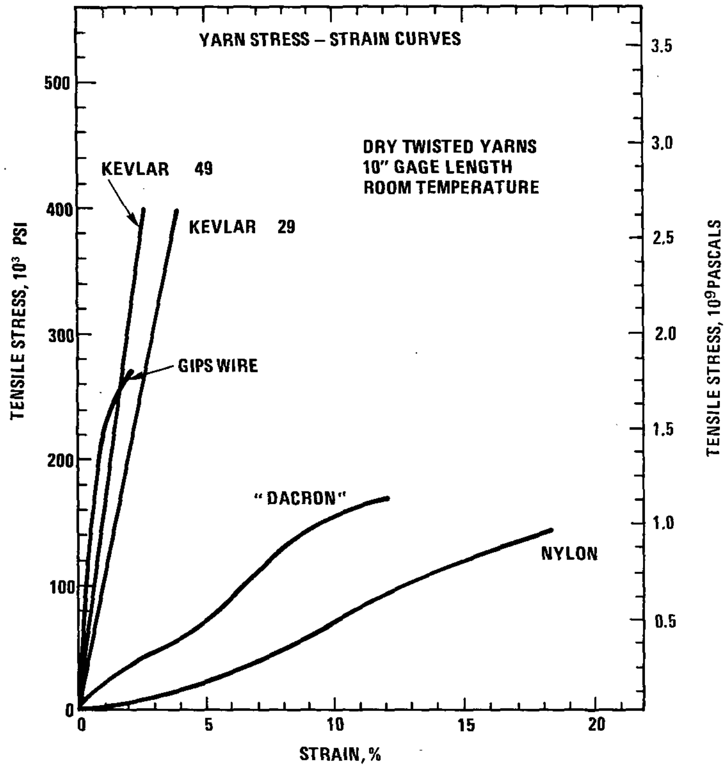

Fig. 2 — Stress-strain relation of various materials (from E.I. du Pont, Wilmington, Del.)

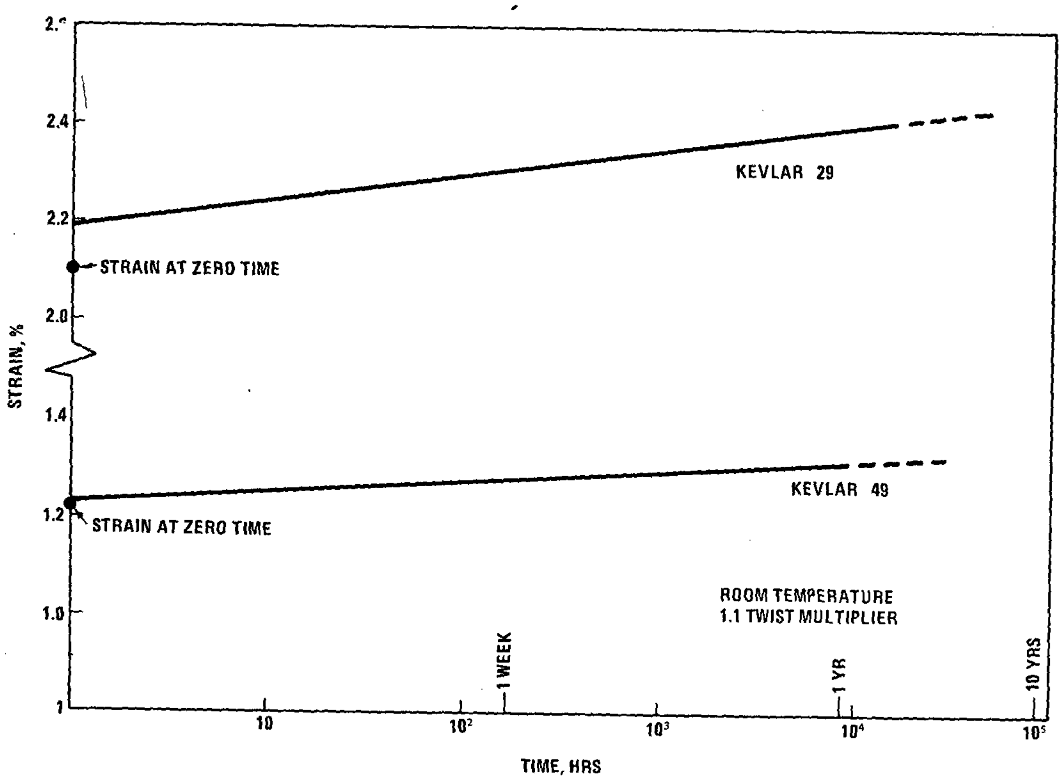

Fig. 3 — Creep of Kevlar® 29 and Kevlar® 49 aramid yarns at 50% of ultimate strength (from E. I. du Pont, Wilmington, Del.)

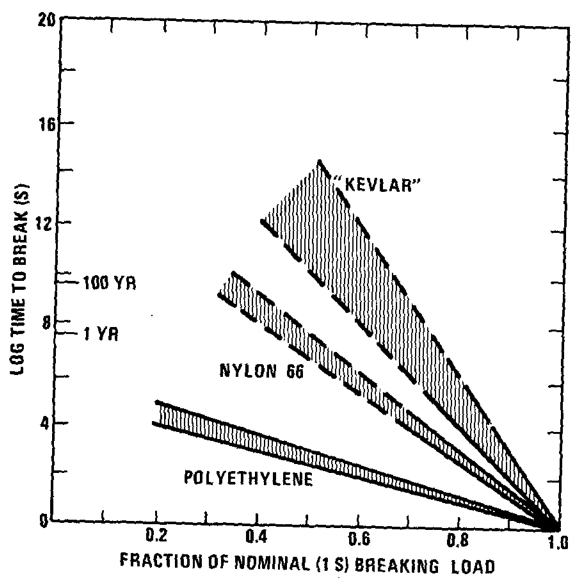

Fig. 4 — Tensile strength vs time under fixed load (from E. I. du Pont, Wilmington, Del.)

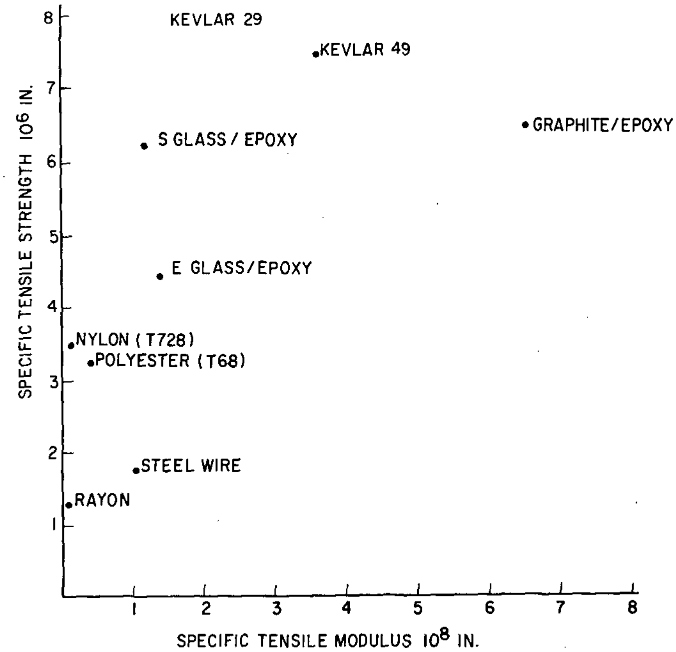

Fig. 5 — Values of specific tensile strength vs specific tensile modulus for oceanographic strength member materials

Table 2 — Comparison of Yarn, Filament, and Wire Nominal Properties

Material	Tensile Strength psi × 10^3 (GPa)	Elastic Modulus psi × 10^6 (GPa)	*Elongation* at Rupture (%)	*Density* (lb/in^3) (g/cm^3)	Specific Tensile Strength × 10^6 (in.)	*Specific* Modulus × 10^8 (in.)	Dielectric Constant	*Melting* Point °F(°C)
Kevlar® 29†	400	9	4.0	0.052				800
	(2.76)	(62.05)		1.44	7.7	1.73	3.4	(430)
								(Chars)
Kevlar® 49†	400	16.0	2.4	0.052				800
	(2.76)	(110.3)		1.44	7.7	3.08	3.4	(430)
								(Chars)
Steel Wire	500	29.0	1.1	0.285				2250
	(3.45)	(199.9)		7.86	1.8	1.02	—	(1400)
Dacron				0.050				
Polyester	168	2.0	15.0	1.38	3.2	0.40	—	480
Type 68†	(1.16)	(13.8)						
Nylon				0.041				450
Type 728†	143	0.73	19.0	1.14	3.5	0.12	—	(232)
Rayon†	(0.986)	(5.0)		0.055				
Viscose†	70	0.4	17.0	1.52	1.3	0.07	—	(Chars)
S Glass*	(0.482)	(2.76)		0.09				
	400	12.4	3.1	2.50	4.4	1.38	4.5	1540
	(2.76)	(85.5)						(840)
E Glass*				0.092				1290
	575	10.5	3.1	2.55	6.3	1.14	4.5	(700)
H S Graphite*	(3.964)	(72.4)		0.054				
	350	35.0	1.9	1.50	6.5	6.48	5.0	6600
	(2.41)	(241.3)						(3650)

*ASTM D2343 (Resin Impregnated)
†Twisted Yarn Properties

Table 3 — Tension-Tension Fatigue of Kevlar® 29 Yarns*

Construction	Cycled Between % of Ultimate Tensile Strength		Cycles	Strength Loss
	Low	High		
1500 Denier/ 2 Ply Cords	45	74	1000	0
2 Ply Cords	29	52	1000	0
2 Ply Cords	8	31	1000	0
1500 Denier Yarn	0	10	13×10^6	5

* from E. I. du Pont, Wilmington, Del.

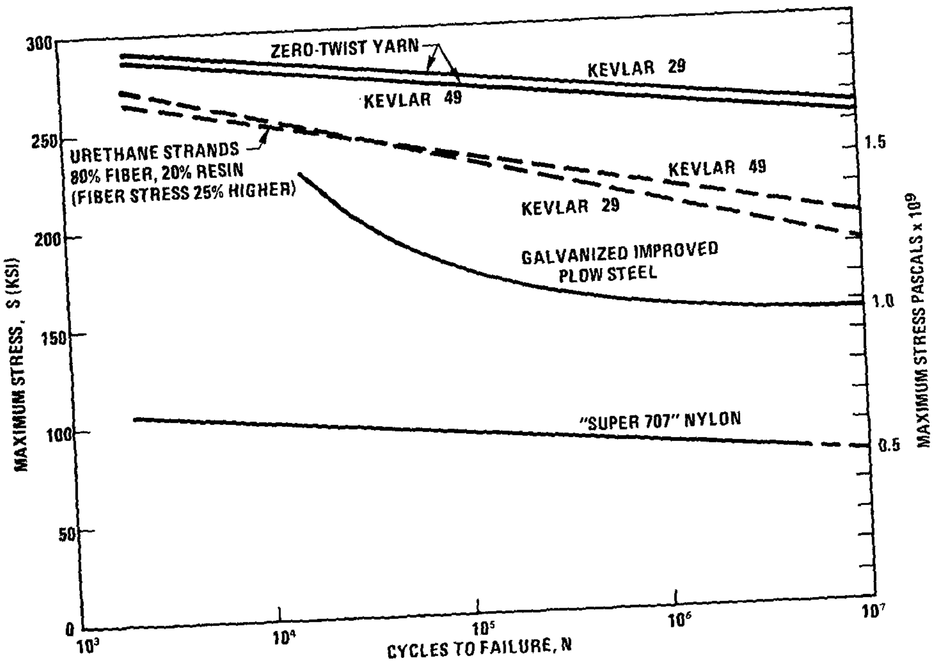

Fig. 6 — Comparative tension-tension fatigue data (from E. I. du Pont, Wilmington, Del.)

fatigue tests the filaments may abrade one another, which can cause early failure. Microscopic observation of the damaged ends can easily distinguish the difference between abrasion and fatigue failures. The self-abrasion resistance of aramid yarns is much poorer than that of nylon or polyester, although the finishes that are available help to some extent. One partial solution to this problem is to encapsulate or impregnate the yarns with a low modulus material such as a polyurethane. This can be especially effective under dry conditions, but wet abrasion of impregnated strands as well as yarns is usually much poorer than dry. The abrasion resistance of impregnated strands can be improved significantly by applying a 3 - 6% overlay of a wax such as paraffin on the impregnated strands, bringing the self-abrasion resistance to levels above nylon and polyester yarns. A slight twist (≈ 1 twist multiplier) in yarn prior to resin impregnation also can yield significant improvements in abrasion resistance.

With unimpregnated yarns, self-abrasion resistance superior to nylon and polyester can be achieved through a combination of slight yarn twist ($\approx$ 1 twist multiplier) and the application of resin-bonded solid lubricants such as MoS_2 or graphite. Improvements in internal and external abrasion resistance of fabricated ropes can also be achieved by imbibing the ropes with resin-bonded solid lubricants or various waxes such as paraffin or microcrystalline waxes.

Environmental Stability

The aramid fibers have good chemical resistance to common solvents, oils, greases, and water. Table 4 shows how aramid reacts to a wide variety of chemicals, indicating that strong mineral acids and concentrated bases will degrade the yarn [4]. The uncoated fiber absorbs water from immersion or from a humid atmosphere. Kevlar® 29 will pick up about 6% moisture by weight and Kevlar® 49 will pick up about 3% at 22°C (72°F) and 55% RH [4]. There has been no indication that this in any way affects the properties of the material. However, there is some strength loss due to hydrolysis when the material is exposed to both high temperature and moisture such as saturated steam. The du Pont Company has also noted that specimens submerbed in the ocean for one year show little loss in strength or modulus.* Tests are presently underway at the Naval Research Laboratory to check this.

Kevlar® fibers have very little shrinkage with increasing temperature. The longitudinal coefficient of thermal expansion is -2×10^{-6} in./in./°C. As the temperature increases, both the tensile strength and the modulus decreases. Figures 7 and 8 show the effect of rising temperature on various yarns [4]. Short exposures to temperatures as high as a 176°C (about 350°F) epoxy cure cycle cause no discernible changes in tensile properties, but over long periods oxidation effects do take place which slowly degenerate the material. Although both fibers are still useful above 204°C (about 400°F), long term service above 149°C (about 300°F) is not recommended.

Additional tests were conducted on Kevlar® 29 at -10°C (about -50°F) to simulate Arctic conditions. The results given in Table 5 [4] show that there are no natural environmental temperatures that would cause a problem with the use of Kevlar®.

Table 4 — Stability of Kevlar® 29 and Kevlar® 49 in Chemicals*

Chemical	Conc. %	Temp. °F(°C)	Time Hrs	Strength Loss % Kevlar® 29	Strength Loss % Kevlar® 49
Hydrochloric acid	37	70(21.1)	24	—†	0
Hydrochloric acid	37	70(21.1)	1000	83	—
Hydrofluoric acid	10	70(21.1)	100	12	8
Nitric acid	1	70(21.1)	100	18	5
Sulfuric acid	10	70(21.1)	100	14	—
Sulfuric acid	10	70(21.1)	1000	—	31
Sodium hydroxide	50	70(21.1)	24	—	10
Ammonium hydroxide	28	70(21.1)	1000	10	—
Acetone	100	70(21.1)	24	0	0
Dimethyl formamide	100	70(21.1)	24	—	0
Methyl ethyl ketone	100	70(21.1)	24	—	0
Trichloroethylene	100	70(21.1)	24	—	1.5
Trichloroethylene	100	190(87.8)	387	7	—
Ethyl alcohol	100	70(21.1)	24	0	0
Jet fuel (JP-4)	100	70(21.1)	300	0	4.5
Jet fuel (JP-4)	100	390(199)	100	4	—
Brake fluid	100	70(21.1)	312	2	—
Brake fluid	100	235(112.8)	100	33	—
Transformer oil (Texaco #55)	100	140(60)	500	4.6	0
Kerosene	100	140(60)	500	9.9	0
Freon® 11	100	140(60)	500	0	2.7
Freon® 22	100	140(60)	500	0	3.6
Tap water	100	212(100)	100	0	2
Seawater (Ocean City, NJ)	100	—	1 Yr.	1.5	1.5
Water at 10,000 psi	100	70(21.1)	720	0	—
Water-superheated	100	280(137.8)	40	9.3	—
Steam-saturated	100	300(148.9)	48	28	—

*From E.I. du Pont, Wilmington, Del.
†Indicates data not available.

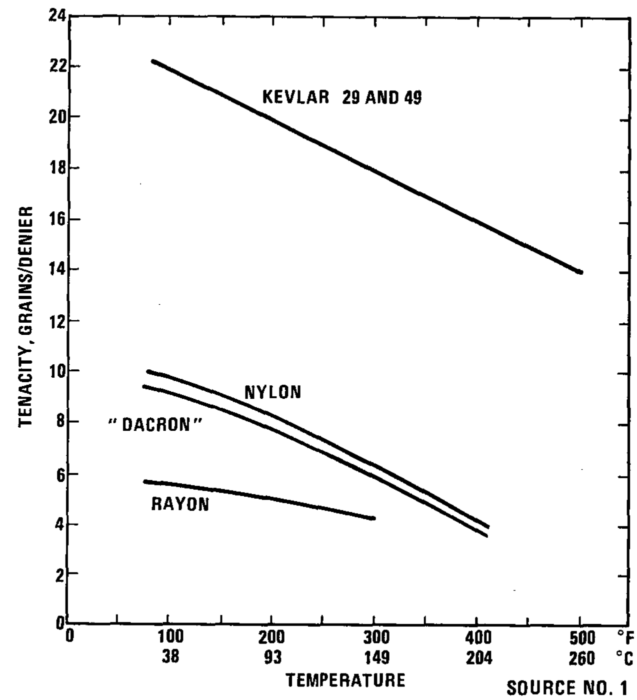

Fig. 7 — Effect of temperature on yarn tensile strength tested at temperature after 5-min exposure in air (from E. I. du Pont, Wilmington, Del.)

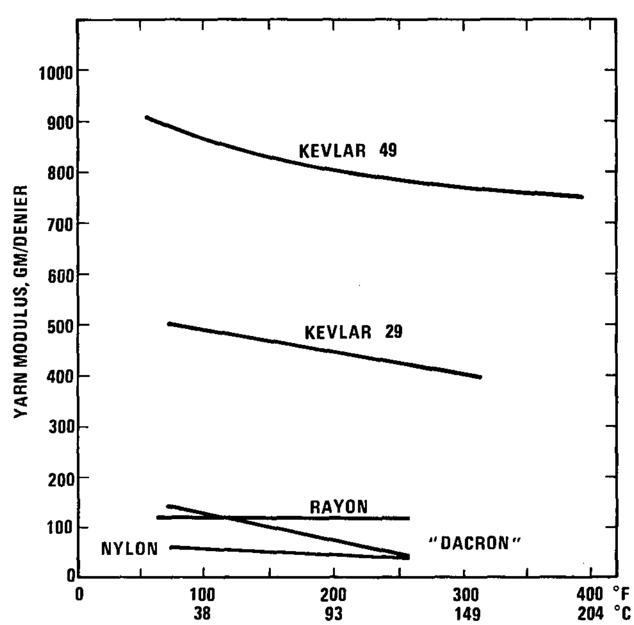

Fig. 8 — Effect of temperature on yarn tensile modulus tested at temperature after 5-min exposure in air (from E. I. du Pont, Wilmington, Del.)

The material is also inherently flame resistant, and self-extinguishing. Moreover, it does not have a melting point but chars and decomposes at 426°C (about 800°F). One climatic effect that must be noted is the aramid's sensitivity to ultraviolet radiation, a component of sunlight. This problem will be discussed later as it relates directly to ropes. It has been recommended that if this material is to be exposed to sunlight, it be shielded by a jacket of another material.

Finally, one must also take environmental pressure into account. In 1973, a number of Kevlar® 29 urethane-impregnated strands were coiled and pressure conditioned for one month at 68.95 MPa (about 10,000 psi) [5]. This was accomplished in four separate series of tests, the first three of which suffered some data reduction problems. The fourth and final test supplied a good control series which, when compared with all the other test samples, showed a 12.1% reduction in tensile strength. More testing is needed in this area before the results can be considered conclusive. A series of pressurization tests are scheduled to begin soon at NRL. The aramid fiber loaded at a percentage of its break strength is to be immersed in sea water and subjected to 55.16 MPa (about 8,000 psi) for a total period of three months. The results will be reported as soon as possible.

Table 5 — Tensile properties of Kevlar®* 29 at arctic temperature†

Property	40°C (about 75°F)	-10°C (about -50°F)
Tenacity, gpd	19.1	19.8
Tensile Strength, lb/in^2	351,700	364,600
GPa	2.425	2.513
Elongation, percent	4.1	3.9
Modulus, gpd	425	521
Modulus, $lb/in^2 \times 10^6$	7.82	9.59
GPa	53.91	66.12

*Twisted Kevlar® 29 Cord, 6.5 Twist Multiplier, 10%/Min. Elongation, 10 in. Gage Length, Tested At Temperature
†from E.I. du Pont, Wilmington, Del.

ARAMID FIBER MECHANICAL ROPES

Construction and Application

A strength member's reaction to tensile forces depends on the combination of the material and the construction chosen. Therefore, selection of a rope's structure is equally as important as selection of its fiber. The proper arrangement of yarns can enhance some desirable fiber properties that are already present and compensate for some that are lacking.

Synthetic materials, in the form of singles yarns, can be used to construct three basic types of rope: twisted, braided, and parallel lay. As can be expected, there are numerous variations in each category. Some of the more common types are listed below.

- Twisted
    1. Three-strand
    2. Four-strand
    3. Cable design
    4. Double helical lay
- Braided
    1. Solid braid
    2. Single braid
    3. Double braid
    4. Plaited
- Parallel
    1. Parallel strand
    2. Parallel yarn

Twisted Ropes

Before the development of today's continuous length synthetic fibers, ropes could only be constructed by twisting short lengths of natural fibers together. This intertwisting served two purposes; it held the rope structure together and allowed the structure to transfer a tensile load through interfilament friction. Then, as now, the yarns were twisted into plied yarns, the plied yarns into strands, and the strands into ropes. There are two distinct drawbacks to this approach: a torque is generated under tension, and the rope can have a low strength conversion efficiency.

As a tensile load is applied to a twisted rope, the individual components attempt to straighten, thereby inducing a torque. If one end of the loaded rope is free to turn, the lay of the rope lengthens as it revolves, reducing torque to zero. Upon sudden release of the load a torque is induced in a direction against the lay. With no tensile forces to keep the strands in place, they can immediately form kinks or hockles [6]. Therefore, caution is required when stranded, twisted ropes are to be used with a free end, such as in lowering anchors or in mooring buoys. Moreover, improper handling of a stranded rope can impart a twist opposite to the lay, which invariably causes hockles. For instance, care must be taken that turns are not wound onto a capstan or gypsy head opposite to the direction of rope lay.

The strength converison efficiency of any twisted rope is a function of its helix angle. The maximum strength of a continuous filament is obtained by laying all the fibers parallel, but since this imposes other restrictions which are unacceptable for some uses, a consequent reduction in strength can be a necessary design concession. This loss can be quantified by expressing it as the percent conversion efficiency of the rope. The conversion efficiency is equal to the rope tenacity divided by the yarn tenacity when multiplied by 100. The percent of tensile strength lost due to twist is determined largely by the magnitude of the helix angle of the strands. The lay of a strand follows a helical path around the rope, and the angle of this path with respect to the longitudinal axis of the rope is the helix angle (see Fig. 9).

Bare aramid fiber does not lend itself well to twisted rope because the fibers are easily abraded by each other and by any other object they might rub against. Impregnation or, to a lesser extent, the du Pont applied cordage finish, can reduce the internal self-abrasion tendency of the fibers, and the coating or a jacket can reduce external abrasion and mechanical damage.

The tensile strength of cable design Kevlar® aramid fiber ropes compares favorably with that of steel wire ropes, but as with all Kevlar® ropes, care must be taken with respect to abrasion and cutting resistance. If this is not a consideration in the selection process or if jackets can afford the needed protection, the more expensive aramid rope has the many advantages of low weight, long tension or fatigue life, ease of handling, and lack of corrosion problems.

The construction of the cable design rope is designated by two figures just as wire rope is. The first figure gives the number of strands in the rope; the second gives the number of yarns or ends in the strand. An example would be a 19 × 7 configuration which has 19 strands with seven ends in each strand. At equal diameter, the more strands in a rope, the more flexible it is. Table 6 lists the cable design aramid fiber ropes available from one company [7] along with each cable's minimum break strength and weight. Table 7 compares different cable materials of similar construction.

Braided Ropes

A braided rope is constructed by interlacing an equal number of yarns or strands. The rope is prevented from unlaying by the interlocking weave. The yarns twisted to the right are balanced by the same number of yarns twisted to the left, allowing the structure to be torque-free. Normally, braided rope has greater strength and lower elongation than an

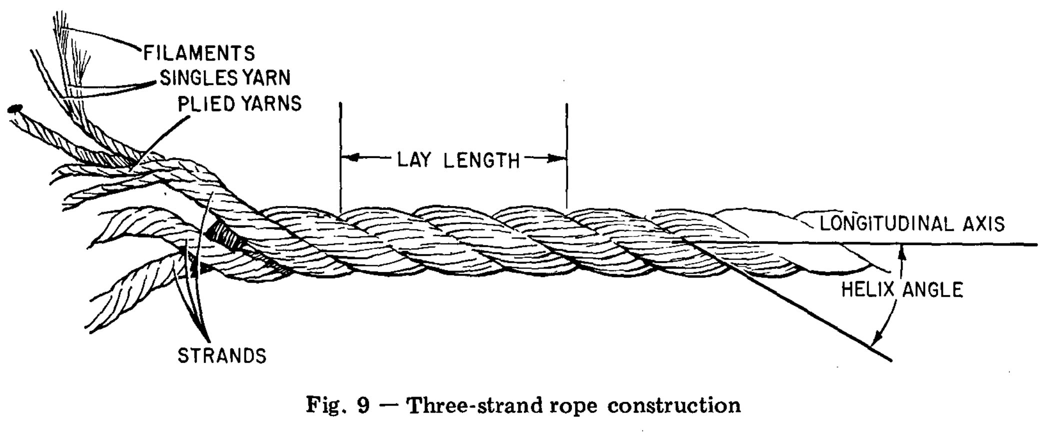

Fig. 9 — Three-strand rope construction

Table 6 — Average Values of Some Presently Available Cable* Design Twisted Aramid Fiber Ropes [7]

Design	Nominal Diameter cm (in.)	Minimum Tensile Strength MPa (psi)	Approx. Weight of Bare Rope kg(lb)/1000 ft
1 X 7	0.32 (0.127)	14.48 (2,100)	2.72 (6)
1 X 19	0.32 (0.127)	12.41 (1,800)	2.49 (5.5)
1 X 19	0.50 (0.196)	31.03 (4,500)	6.12 (13.5)
7 X 7	0.50 (0.195)	27.58 (4,000)	6.35 (14)
7 X 7	1.08 (0.425)	103.42 (15,000)	22.23 (49)
19 X 7	1.14 (0.45)	120.66 (17,500)	21.77 (48)
19 X 7	1.30 (0.51)	151.68 (22,000)	32.66 (72)
6 X 9-IPC	1.47 (0.58)	206.84 (30,000)	43.09 (95)

*from Philadelphia Resins Corporation, Montgomeryville, Pa.

Table 7 — Comparison of Various Cable Materials With Similar Constructions

Construction and Nominal Diameter cm (in.)	Material	Break Strength kg(lb)	Approx. Wt. of Bare Rope, kg (lb)/1000 ft		Approx. Cost (per 1000 ft)
			In Air	In Water	
1 X 7	Aramid*	952.6 (2,100)	2.72 (6)	0.91 (2)	$150
	—	—	—	—	—
0.32 (1/8)	Galvanized (Extra High Strength)	830.1 (1,830)	14.52 (32)	12.70 (28)	60
1 X 19	Aramid*	2041.2 (4,500)	6.12 (13.5)	1.81 (4)	$350
	Stainless Steel	2131.9 (4,700)	34.93 (77)	30.39 (67)	380
0.48 (3/16)	Carbon Steel Aircraft	2131.9 (4,700)	34.93 (77)	30.39 (67)	80
7 X 7	Aramid*	2721.6 (6,000)	9.53 (21)	3.18 (7)	$650
	Stainless Steel	2767.0 (6,100)	48.08 (106)	42.18 (93)	750
0.64 (1/4)	Galvanized	2767.0 (6,100)	48.08 (106)	42.18 (93)	250
6 X 19	Aramid* (IPC)†	13,608 (30,000)	43.09 (95)	13.15 (29)	$2,250
	Stainless Steel	10,342 (22,800)	208.66 (460)	181.44 (400)	
1.27 (1/2)	Galvanized Extra Improved Plow Steel (IWRC)‡	12,065 (26,600)	208.66 (460)	181.44 (400)	400

*Kevlar® Fiber Phillystran
†IPC — Independent aramid fiber core
‡IWRC — Independent wire rope core

equal diameter three-strand rope. However, because the impregnated Kevlar® is stiff it requires a reduced helix angle and a more open weave. Thus, the fibers are more nearly parallel and suffer less transverse stress. An additional advantage is the fact that braided ropes have a round, smooth exterior which tends to flatten out on a bearing surface. The wear is distributed over a large area, hence the rope's abrasion resistance is increased.

Braided rope construction can be designated by a large number of interrelated specifications, some of which are illustrated in Fig. 10. By increasing either the braid angle α or the crimp angle θ, both the rope modulus and the rope strength are reduced. For example, a braided rope with an α of 30° and a θ of 20° has a calculated 68% of the strength of a rope with the same strands laid parallel, and only 30% of the parallel strand modulus [8]. The use of more strands or ends per carrier has some definite advantages; namely, (a) smaller strands can be used, (b) core pop-out is minimized, and (c) a slightly better modulus and strength can be realized for the same angles [8].

Braided ropes come in a number of constructions. The single or hollow braid is not really hollow when under tension. However, it does have a tendency to flatten out as the number of strands increase.

Double braids are constructed of two hollow braid ropes, one inside the other. The inner is called the core; the outer is called the cover. Properly fabricated, they share the load equally. Although the inner and outer ropes are usually of similar material, they can be made up of two different materials. By balancing the various braid geometry factors, a rope could utilize the optimum properties of each fiber. For example, the core could be an impregnated aramid fiber for maximum strength, and the cover nylon or polyester for maximum abrasion resistance.

Again, as in the case of the twisted ropes, impregnation of the aramid yarns with a low modulus material such as polyurethane can reduce abrasion and increase the life of the rope. Where cyclic loading over a sheave is not a problem, the unimpregnated fibers can be used at lower cost. Many types of aramid fiber braids are currently available: tubular, solid, plaited, braid over a core, single braid, and double braid. One particular combination consists of an aramid stranded cable-design rope over which additional layers of aramid yarn are braided. The number of braided layers added depends on the required break strength. A final jacketing of black polyurethane is extruded over the rope to improve external abrasion resistance.

As the tension on a braided rope increases, the braid spacing becomes closer, exerting a compressive force directed toward the center of the rope. As the diameter of the rope increases, at some point, depending on the braid geometry, the internal compression forces of a series of braids over braids could exceed the transverse strength of the material. The radial pressure generated on the core is given by the equation

$$P_R = \frac{F\,M \sin^2 \alpha}{2\,\pi\,R^2 \cos \alpha}$$

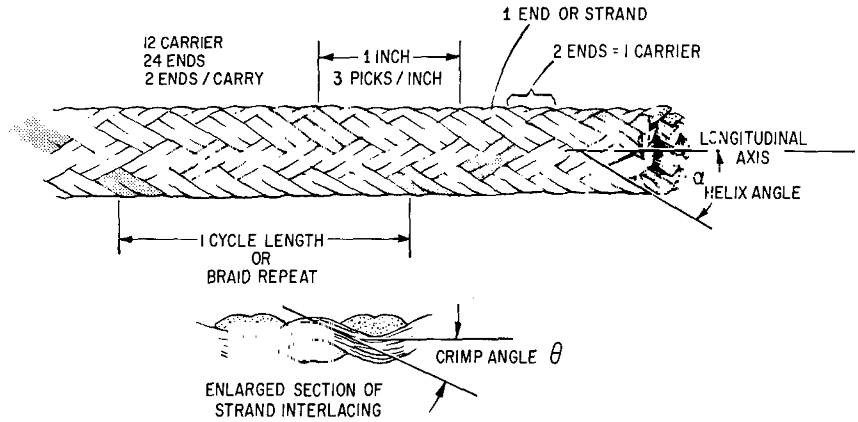

Fig. 10 — Tubular diamond braid construction

where P_R = radial pressure, F = effective tension in a given strand, M = number of strands, R = radius, and α = helix angle [8]. Braided ropes have been designated with elastic cores to minimize the problem.

The principal merits of braid are

1. Self-limitation of the effects of strand damage. Local imperfections and individual strand damage are averaged over a short length of the cable. Even if each strand is cut many times along the length of the cable, only a slight decrease in cable strength will result as long as the cuts are separated by several feet.

2. Ease of end-fitting with eye splices, epoxy-potted conical sockets, or braided grips

3. A wide range of strengths through choice of strand sizing, braid design, and number of layers

4. Excellent cyclic-tension fatigue life at high stress levels

5. Low elastic stretch

6. Flexibility and small bending radii

7. Excellent cost effectiveness, within certain ranges, in relationship to alternative materials and strength requirements

8. Ease of fabrication, which requires considerably less precision than alternative constructions

9. Completely torque-balanced

The aramid braid's principal fault is that it is susceptible to failure by abrasion when cycled over pulleys, both by interfiber and surface abrasion. Advances by du Pont described in an earlier section should alleviate this problem considerably. Table 8 lists some typical break strengths of small braided ropes.

Table 8 — Strength of Small Tubular Braided Kevlar® 29 Ropes*

Number of Ends In Rope	Denier of Ends	Diameter of Rope cm (in.)	Break Strength of Rope kg(lb)	Weight Per 1000 ft kg(lb)
8	200	0.06 (0.025)	22 (50)	0.06 (0.13)
8	400	0.06 (0.025)	45 (100)	0.12 (0.27)
8	1000	0.08 (0.030)	135 (300)	0.27 (0.6)
10	1000	0.09 (0.035)	180 (400)	0.36 (0.8)
4	1500	0.11 (0.042)	90 (200)	0.23 (0.5)
8	1500	0.15 (0.060)	180 (400)	0.45 (1.0)
12	1500	0.15 (0.060)	270 (600)	0.64 (1.4)

*from Cortland Advanced Product Division, Cortland, N.Y.

Parallel Fiber Ropes

With the introduction of the continuous filament synthetic fiber, a new design in rope structure was made possible. The yarns could be laid parallel to each other, allowing an increase in break strength by orienting all fiber in the direction of the rope axis. For a given diameter rope cycled in tension-tension, the parallel lay construction offers maximum strength and minimum elongation. If properly constructed, the strength of this rope is close to the aggregate strength of all the individual yarns. There is minimum constructional elongational; the stretch of the rope is primarily due to the material stretch. Moreover, internal abrasion is reduced.

To obtain the maximum benefit from all these advantages, care must be exercised in the manufacturing process. Because the material's modulus is so high and because there is no material yielding before rupture, an aramid parallel fiber rope must be constructed so that all individual strands share the load equally. Uniform pretensioning and careful alignment of the strands are two major factors in accomplishing this. Otherwise, the shortest yarn or strand will be the first to take up the load. It ruptures, passing the load to another, then another, until the rope has failed at a load lower than the theoretical strength.

Because there is no interlocking structure the rope must be jacketed. This reduces the strength-to-weight ratio in air but, if the jacket material has positive buoyancy, it could increase the ratio in water. The jacket is also an asset where abrasion resistance is a concern. As with the braided ropes, there is no torque, and therefore no problem with kinks or hockles due to tension relaxation.

However, as with other structures, there are design tradeoffs. First, depending on the jacketing material and the fiber impregnation, the parallel lay can be more rigid than other constructions, but this need not necessarily be so. Proper material selection can produce a flexible rope. Secondly, parallel lay rope is not recommended for use as working or running rigging over small bending diameters. In twisted or braided ropes the yarn's helical path insures equal fiber stressing as the rope rounds a sheave or capstan. When parallel lay ropes are bent, the center fibers are stressed at a median load level. While the fibers on the inner side of the curve, against the sheave or drum, are stressed at a lower than median level (maybe even in compression), the fibers on the outer side of the bend are carrying most of the load. Recommended bending radii for ordinary applications is roughly 24 times the rope diameter [9] (i.e., sheave diameters should be 48 times the rope diameter). If the rope is to be cycled, higher ratios should be used; for low loads or cycles the ratio can be reduced.

Kevlar® is well suited to the parallel lay rope. The internal abrasion problem inherent with the aramid fiber is minimized. The jacketing material, necessary to the structure, provides external abrasion resistance, but in this respect it is still a fiber and cannot match the abrasion resistance of steel. Lastly, this construction makes maximum use of the fiber's great tensile strength and its low elongation, which are the two outstanding characteristics of the material. Used in standing rigging such as guy wires or mooring lines, its life and service should be excellent.

Aramid Fiber Rope Mechanical Properties

Static Properties

Most rope selection begins with values taken from a load-elongation curve. However, other static tests include creep and stress rupture data. The following paragraphs contain a discussion of those static mechanical properties pertinent to the designer.

Load-Elongation

Information on the break strength and the elongation at rupture of Kevlar® aramid fiber ropes is readily available from a number of manufacturers. Due to the many variables of rope design and construction techniques, it is best to obtain the information directly from the companies concerned.

Figure 11 shows typical load-elongation curves of aramid braided rope with a diameter of 0.279 cm (0.110 in.) and a tensile strength of 340.1kg (about 750 lb) [10]. The curve shows the first cycle loading to 50% of break strength. The rope elongates about 3%, of which 0.75% is constructional stretch. On the 10th cycle the elastic elongation is only about 2.3%, but at this point the constructional stretch has been reduced to roughly 0.3%.

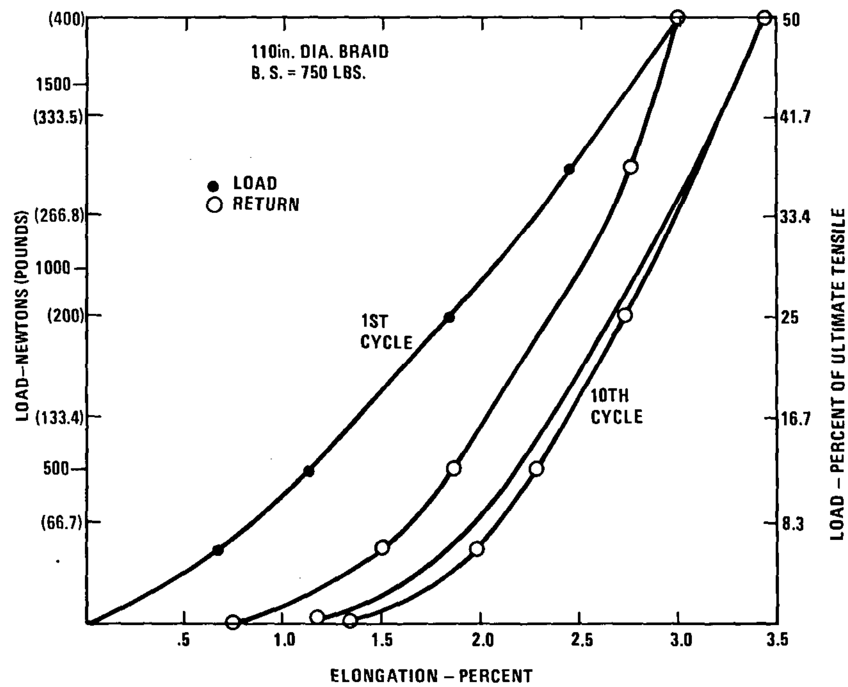

Fig. 11 — Typical load-elongation curve of a braided rope (from Philadelphia Resins Corporation, Montgomeryville, Pa.)

Figure 12 again shows load elongation curves, but this time of a 3 X 7 cable design rope [10]. The first cycle loading has 2.95% total elongation of which about 1.30% is constructional. By the 10th cycle constructional elongation is almost eliminated. As previously mentioned, both the constructional and elastic elongation will depend to a large extent on the constructional parameters of the rope.

Figure 13 contains two load-elongation curves for a parallel lay rope [11]. The first is the initial loading; the second, many cycles later. During normal usage the load-elongation record of a parallel lay rope would lie between the two lines. Infrequent use and/or low loads should place the curve near the left slope; frequent use and/or high loads would tend to move the curve to the right. The constructional stretch found in twisted and braided ropes is almost nonexistent in the parallel lay. Also note that the elastic stretch is the smallest of the three types of rope at the start, and it does not drop off as rapidly after prolonged use. Figures 14 and 15 compare the elongations of various synthetic materials and different constructions [12]. All the tests mentioned in this section have been conducted in air [12].

Creep

Creep is the name given to the nonrecoverable elongation of a material which is held under sustained loading. Its magnitude is a function of the load and the length of time the load is maintained. After removal of the stress the material usually exhibits some elastic recoverable stretch and some permanent deformation.

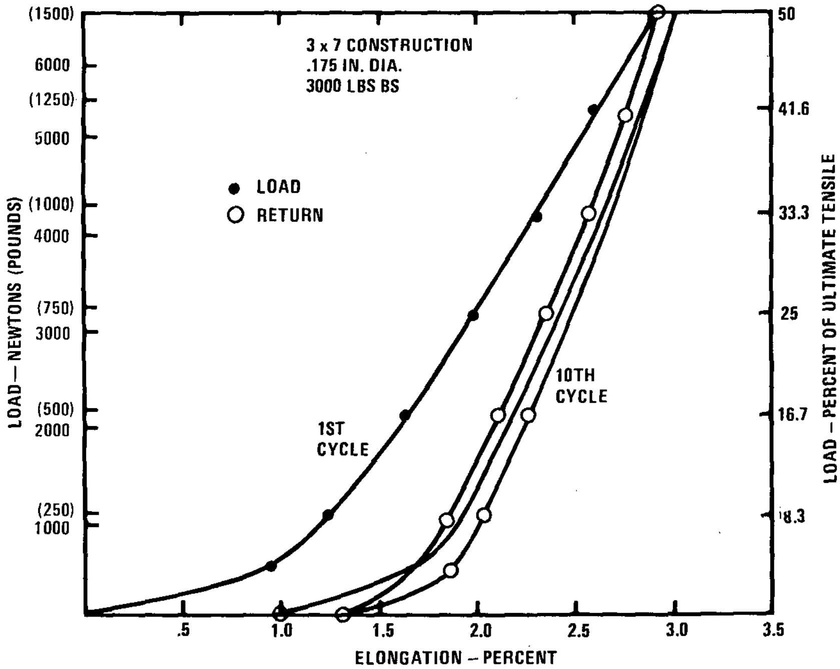

Fig. 12 — Typical load-elongation curve of a cable design rope (from Philadelphia Resins Corporation, Montgomeryville, Pa.)

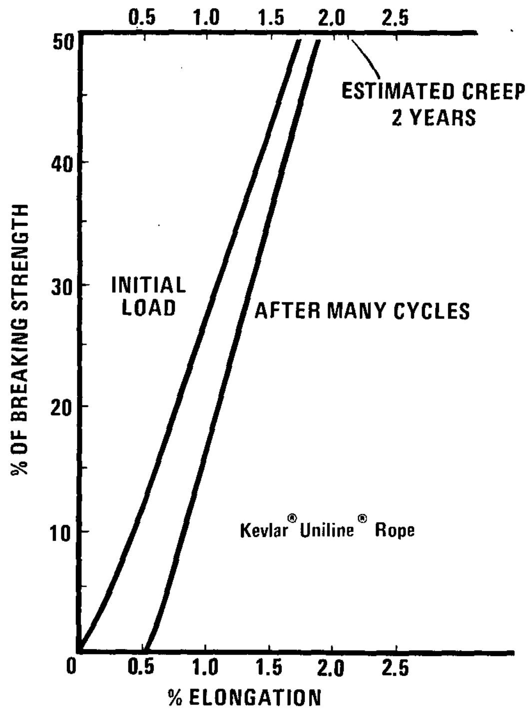

Fig. 13 — Typical load-elongation curves of parallel lay rope (from Wall Rope Works, Beverly, N.J.)

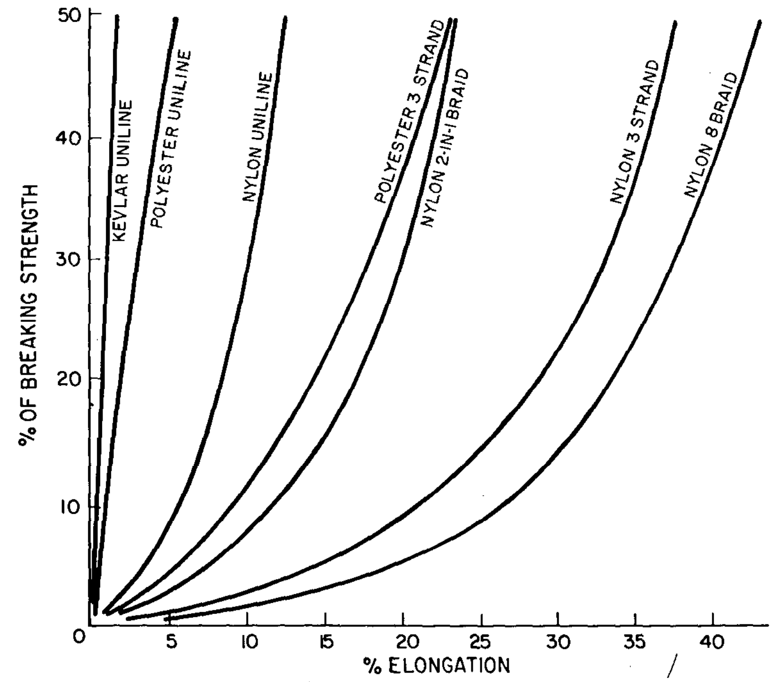

Fig. 14 — Comparative first load-elongation curves (from Wall Rope Works, Beverly, N.J.)

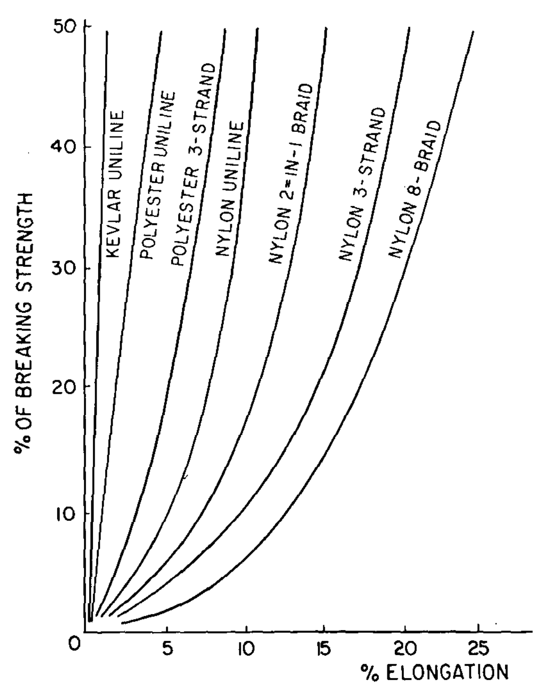

Fig. 15 — Comparative load-elongation curves after cycle loading (from Wall Rope Works, Beverly, N.J.)

Aramid fibers possess very low creep after a small initial elongation. This was shown previously in Fig. 4. Figure 16 shows the results of creep tests on polyurethane-impregnated Kevlar® 29 aramid fibers (1500-denier yarn) [13]. Two sets of tests were performed, one in air and one in water. Variations between the two sets are probably due to test procedures and apparatus, and not to actual material differences. However, they do show that creep is not a significant problem; it is load-dependent (within tested range), and results in less than 0.2% elongation per year for the first year. Figure 17 compares the various synthetic ropes for which data are available. The curves on nylon came from Flessner's report on creep [14], and the polyester information was taken from a French paper [15].

Static Fatigue

As creep is related to elongation under load, static fatigue is related to creep. Static fatigue or stress rupture tests are conducted in much the same way as the long-time creep tests discussed previously. A constant load is applied to a specimen at a constant temperature. However, because the load is now a very high percentage of the break strength, the time required to break the specimen is recorded rather than the elongation.

Tests conducted at various laboratories have shown that many specimens of aramid fiber stressed under relatively high loads (> 70%) have failed suddenly after varying time periods. Data points taken by the Naval Air Development Center [16] show that at loads above 70% of break strength, failures occurred at midspan within a time range of a few seconds to several days. Only samples without overstressed points, loaded below 70%, have been suspended for long periods without failure. However, Fig. 4, published by du Pont, and a paper on the stress rupture behavior of Kevlar® 49 aramid fiber indicate that Kevlar® on the average is not as unstable above 70% as it might first appear, but that considerable scatter exists in time-to-failure at high load [17]. In addition, any nonuniformities in rope construction can lead to localized overloading and early failure at high loads. The conclusion can be drawn that static fatigue is only a problem near the upper load limit. The higher the applied load, the shorter the fiber life.

Dynamic Properties

Dynamic stresses can be induced in a rope by a number of forces: imposed and self-excited vibration, passage over sheaves, impulse loading, and tension cycling. The simple action of lowering a weight from a pitching, heaving, rolling ship can produce enough combined stresses to fatigue a rope beyond its break strength. Preliminary measurements indicate Kevlar® aramid fiber has excellent fatigue life.

Cyclic-Tension Fatigue

Tension-tension cycling induces fatigue in a rope by the continual tensile loading and unloading. If an aramid rope were to be chosen for this task only, the parallel fiber rope would minimize the possibility of internal abrasion. Since ropes are chosen for other purposes and only incidently suffer cyclic loading, other types of ropes are covered.

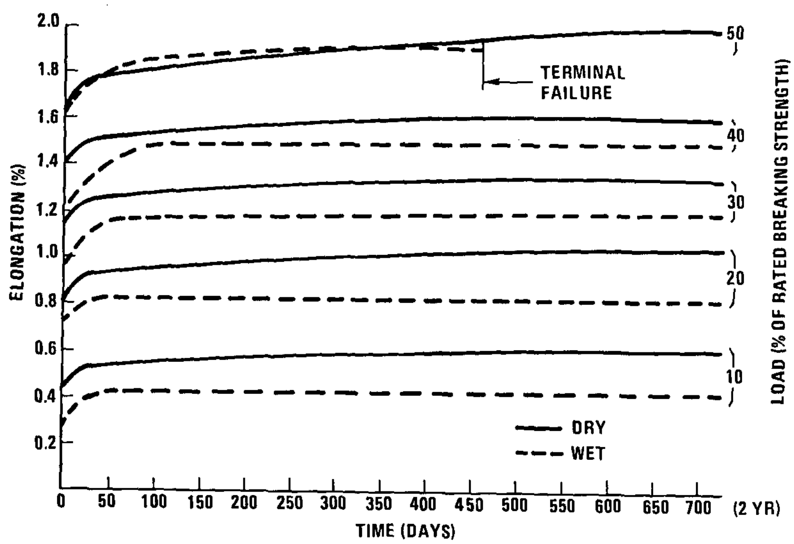

Fig. 16 — Results of creep measurements for Kevlar® fiber (1500 denier yarn)

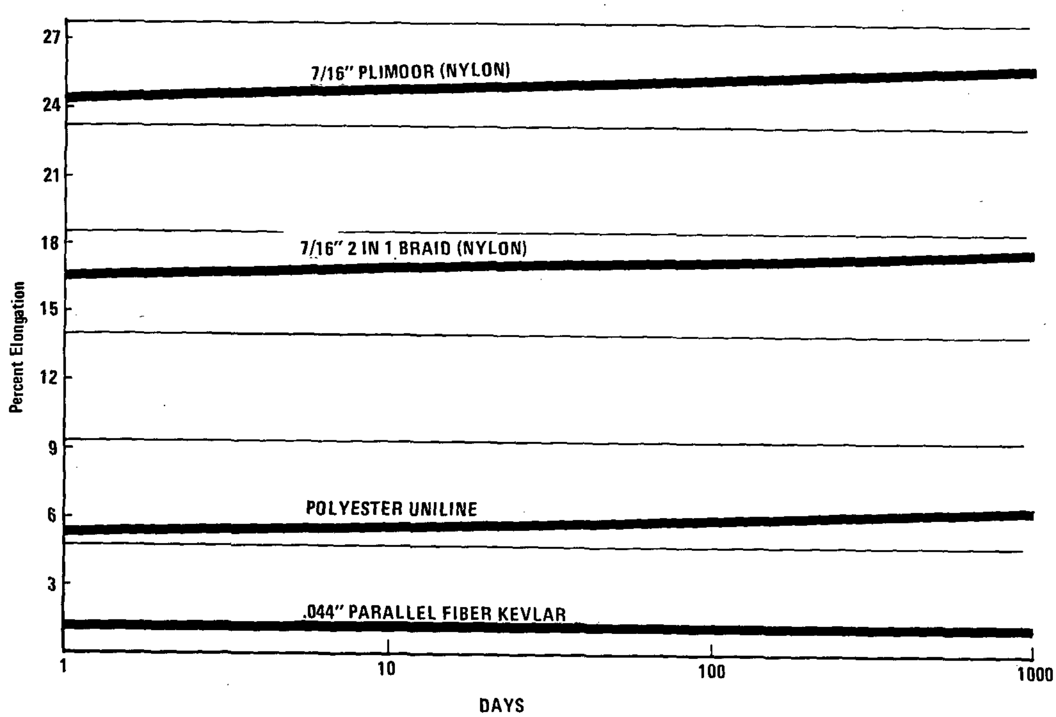

Fig. 17 — Creep of various ropes loaded to 30% of break strength

A series of tests were performed on braided ropes of 871.8 kg (about 2000 lb) break strength. The samples included two types of braid; one of each type was impregnated with urethane, the other made with cordage finish yarn. All the specimens were cycled to 362.9 kg (about 800 lb) 20, 2449, 7503, and 15,000 times. The conclusions were that after 15,000 cycles, the impregnated braid properly constructed loses little or no strength [18]. Tests have just been completed on a 19 X 7 0.584 cm (0.23 in.) aramid fiber rope with a rated break strength of 2721.5 kg (about 6000 lb). It has been cycled to 50% of its break strength over seven million times with no reduction in strength [19]. There is still more testing to be done but at the present time it appears that tension-tension cycling has little effect on most Kevlar® ropes.

Bending Fatigue

Cyclic fatigue testing of ropes over sheaves is a realistic method of predicting the life of running lines. Again, internal and external abrasion are the major problems, but they are solvable ones. The internal or self-abrasion problem can be reduced by impregnation, especially with the addition of wax overlays or by imbibing soft cordage with waxes or resin-bonded solid lubricants as described earlier. Jacketing the exterior of the rope with polyester, nylon, dacron, or ployurethane increases the external abrasion resistance, thereby increasing the bending fatigue life. The most obvious method of improving bending fatigue life is to maintain as large a sheave diameter to rope diameter ratio (D/d) as possible. Data supplied by du Pont on the reverse bend cycling of various ropes over pulleys (Table 9 and Fig. 18) indicate that Kevlar® ropes of wire rope construction are particularly effective in cyclic lifetime and that jacketing material can have an appreciable effect on lifetime. For instance, a 19 X 7 urethane impregnated Kevlar® 29 rope cycled at 20% of ultimate over pulleys of D/d = 24/1 went 40,000 cycles to failure with no jacket, 100,000 cycles with an extruded urethane jacket, and 183,000 cycles to failure with a braided Type 77 Dacron® polyester jacket. A lubricated 19 X 7 steel cable under the same conditions went 50,000 cycles and failed in fatigue, while the Kevlar® 29 cables failed via abrasion, including abrasion between the Kevlar® and the sheave or between the Kevlar® and the inside of the jacket.

Unimpregnated and impregnated braids and ropes of Uniline® construction gave poorer cyclic lifetime, but performance of impregnated braids showed a strong improvement with increasing braid angle, albeit with a small decrease in ultimate break strength.

Table 9 also shows that a wax overlay on impregnated strands in braided and wire rope constructions and a wax imbibing of soft cordage braids yield improvements in cyclic lifetime over sheaves of 10-40X.

Cyclic Impact Tests

Cyclic impact tests determine how many times a rope will absorb a large amount of energy before it fatigues; it also is a good check on the durability of the rope's end fittings. Preformed Line Products ran such a test on an aramid Uniline®* rope and a 0.95-cm (3/8-in.) 3 X 19 galvanized improved plow steel cable [20]. The 0.95-cm (3/8-in.) aramid

*Registered trademark of Wall Rope Works.

Table 9 — Reverse Bend Cycling Test Results for Impregnated Braids and Wire Rope Constructions*†

Cable	Helix Angle	Load kg(lb)	D/d	Jacket Yes or No	Other Conditions	Cycles To Failure
Impregnated Braids	14.6°	703.0 (1550)	24	Yes		870
	14.6°	510.3 (1125)	24	Yes		1284
	21.8°	657.7 (1450)	24	Yes		1461
	21.8°	657.7 (1450)	24	No		1686
	21.8°	657.7 (1450)	24	No	11.4% Wax Overlay	66,375
	28.9°	589.7 (1300)	24	Yes		5442
	28.9°	589.7 (1300)	24	No	10.9% Wax Overlay	117,750
	36.6°	510.3 (1125)	24	Yes		33,560
Unimpregnated Braids	~12°	20% UTS‡	24	No		396
	~12°	20% UTS	24	Yes		1320
	~34°	20% UTS	24	No		1296
	~12°	20% UTS	24	No	10-12% Wax Impreg.	13,000
Wire Rope Construction (19X7) Impregnated	15°	526.2 (1160)	24	No		40,000
	15°	526.2 (1160)	24	Yes		100,000
	15°	526.2 (1160)	24	No	10-12% Wax Overlay	>400,000
Steel Wire Rope (19X7)	15°	544.3 (1200)	24	No	Lubricated	50,000

*Load = 20% Ultimate.
†from E.I. du Pont, Wilmington, Del.
‡Ultimate tensile strength.

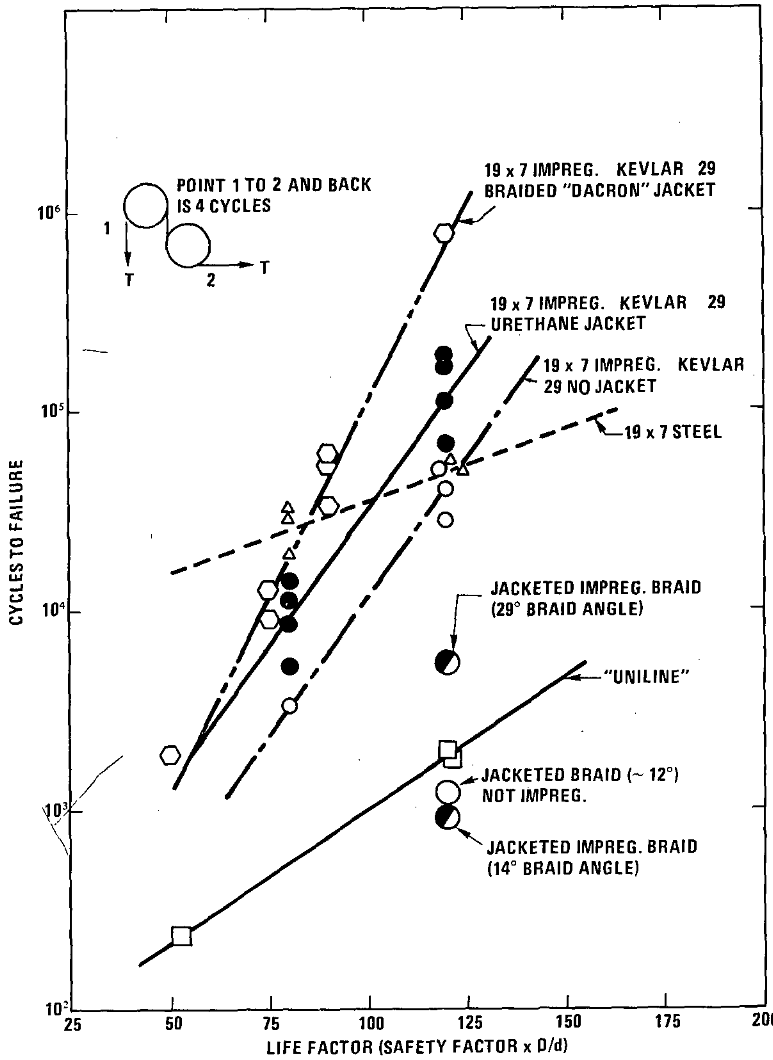

Fig. 18 — Reverse bending performance of ropes (from E. I. du Pont, Wilmington, Del.)

parallel fiber rope with a break strength of 6350 kg (about 14,000 lbs) survived 100,000 impacts or a total of 400,000 tension oscillations where the maximum load was 2268 kg (about 5000 lbs) (Fig. 19). This represented 42% of the aramid rope's break strength and 34% of the steel rope's ultimate load. Testing of the rope after shock loading indicated that it had lost only 13% of its original strength.

Conclusions of the tests were that the parallel fiber rope stored 75% more energy than a comparable steel cable for the same load and stretched 33% more for the same energy stored. Figures 20 and 21 show this in graph form, where the area under the curves is equivalent to energy stored. The aramid rope had 48% more damping capacity than a similar steel cable.

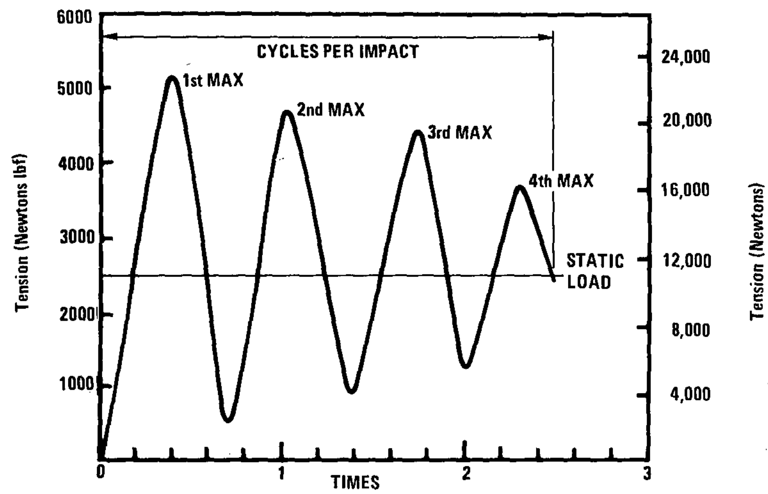

Fig. 19 — Cable Stress During Cyclic Impact Testing of Kevlar® Mooring Line (14,000 lbs)

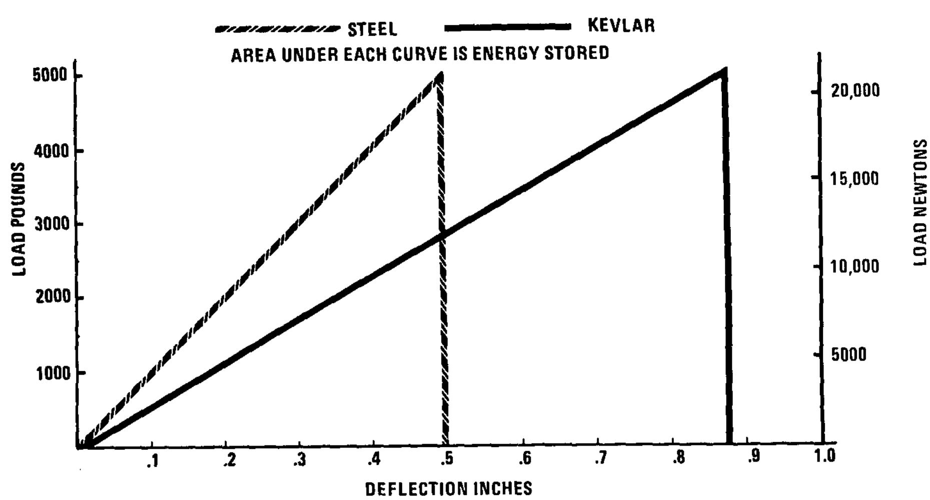

Fig. 20 — Kevlar® and steel energy stored at equal load (from Preformed Line Products Company, Cleveland, Ohio)

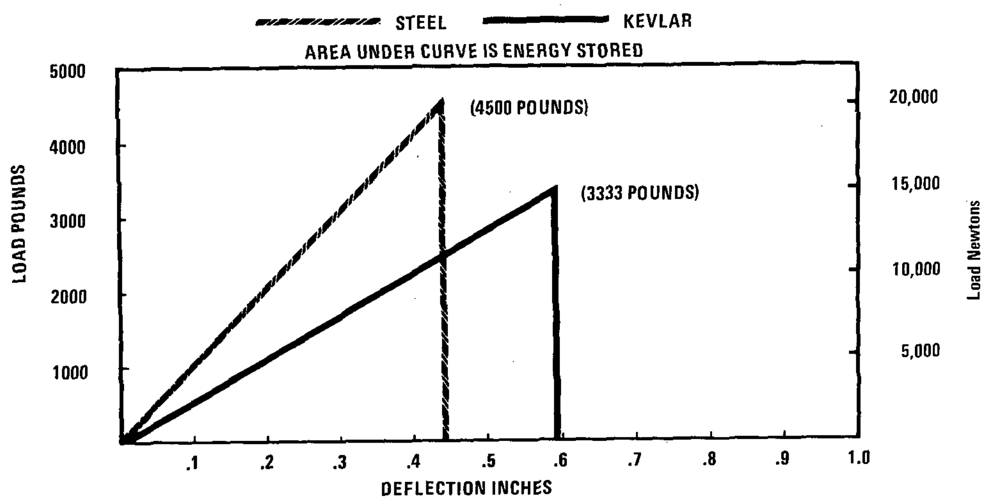

Fig. 21 — Kevlar® and steel displacement at equal energy stored (from Preformed Line Products Company, Cleveland, Ohio)

Mechanical Termination

Termination of aramid fiber ropes requires special attention. Since the material has so little elongation and no yield, each element of the strength member must be proportionately loaded. If the strands or yarns are unevenly stressed, the one under the greatest strain will break first, then the next to take up the load will break, with the remaining strands or yarns cascading until the last end gives. Rope termination must be carefully considered to obtain the maximum break strength of each rope.

The type of rope (parallel, braid, or twisted) should be an influence on the type of end fitting to be used. Those available include epoxy potting terminals, splices, and some wire rope terminating hardware. At this point it must be remembered that Kevlar® is a fiber; thus methods that have been used to terminate fiber ropes should generally be used to terminate the aramid. Usually the best one to use is the one tested and recommended by the rope's manufacturer. Wall Rope Works has developed a method of splicing their parallel fiber rope (Uniline). This system employs the Chinese finger grip principle which effectively doubles the amount of fiber at the end fitting and will hold to 100% of the rope's break strength. It is easy to learn, can be accomplished in less than an hour, and will survive almost any type of loading.

The process is easily accomplished by simply removing several feet of the jacket on the end of the cable, separating the parallel strands or braids into four equal groups, forming an eye around a thimble, and then back braiding over the standing part of the cable. The thimble used should be the largest one feasible to accommodate the fibers high strength and to avoid small bending radii. The length of braid, number of crossings, and spacing have been carefully worked out to maximize the strength, and the resulting splice is normally served with yarn for protection.

In effect, this type of end fitting doubles the number of strength members before the end fitting and produces a tapered, more rugged section at the eye. Therefore, near the eye, the stress per fiber should be about half that in the cable. A potted conical-socket end fitting, on the other hand, would impose the full load at the socket, plus the additional sore point produced by transferring from a low moment of inertia to a high moment of inertia at the end fitting. Furthermore, very precise strand length control is required during the application of the socket because little load sharing can be expected along the length of a properly made parallel cable.

This spliced end fitting is very practical and consistently results in test cables being broken at midspan at very high stress levels; their endurance of 100,000 impact cycles to 36% of the test cable breaking strength is ample testimony of their sturdiness. They are inexpensive and involve very little weight increase.

Philadelphia Resins Corporation utilizes an epoxy end fitting on their ropes. The rope is inserted into a cone-shaped potting fixture, broomed out, then cleaned. Epoxy resin is poured into the cone and cured, thus securing the rope into the fitting. These terminations will also develop 100% of the rope's break strength if proper care has been taken.

The potted end fitting is utilized on both braided and twisted aramid fiber ropes. Imperfections and minor length variations of the strands in the end fitting are easily adjusted to and accommodated by the multiple crossings in the braid or strands.

Sampson Cordage Works presents an eye splice suitable for 2-in-1 braided rope. This relatively simple splice will develop 90% of the rope's break strength. A number of mechanical terminations which were originally developed for wire rope have also been used on fiber ropes with some success. However, it is recommended that the working load of ropes so terminated not exceed 20% of its breaking strength.

Work is presently being done at the Naval Research Laboratory on rope accessories such as end fittings, stoppers and grips. A very good cable grip is easily formed from strands of impregnated Kevlar® by forming an eye around a thimble with a group of parallel strands and dividing the strands into four equal bundles extending from the base of the eye. These can then be braided to the end of or along the length of any type of Kevlar® cable or rope in much the same fashion as the end fitting is accomplished for parallel construction. Therefore, the grip can be used as an end fitting or as a stopper; its strength can be made much greater than that of the line to be held, and it can be applied in a few minutes.

This type of grip has been used with the Moored Acoustic Buoy System (MABS) array at sea to attach the anchor at any location along the array without interrupting the cable. For example, where part of the array is to be vertical and part on the bottom, two grips are used — one leading the cable in each direction (for deployment considerations).

Speculation still persists that Kevlar® cables are difficult to terminate or end-fit, but this has not been found to be the case with either braids or parallel construction. Obviously, the right fitting must be chosen, and various percentages of breaking strength can be achieved with different choices of end fitting for applications that warrant a lower strength level. The various tests of breaking strength, long term cyclic impact, and tension fatigue have shown that Kevlar® cable and appropriate fittings perform very well.

Service Consideration

Environmental

Kevlar® 29 and 49 ropes have the features regarding environmental stability already covered. The fibers have excellent resistance to a wide range of chemicals; however, as shown in Table 4, strong mineral acids and, to a lesser extent, concentrated bases will degrade the material. Prolonged exposure of aramid ropes to direct sunlight should be avoided because the aramids are sensitive to ultraviolet radiation, as are many other synthetic fibers. A Kevlar® three-strand rope shows percentage strength losses similar to those of nylon for equal size ropes [21]. The weakening effect of ultraviolet is not as pronounced in larger ropes because the outer layers of material screen the inner fibers. However, an exposed rope should have a jacketing material of some sort which will also help protect against abrasion and mechanical damage.

Thermal stability of the aramid fiber is excellent for a temperature range of -10 to 204°C (about -50° to 400°F). Nevertheless, long term service at temperatures above 150°C (about 300°F) if not recommended, for oxidation effects weaken the material [22]. Figures 6 and 7 show the resulting decrease in strength and modulus with increasing temperature. In contrast to other organics, Kevlar® fibers have near zero shrinkage on heating. Moreover, cryogenic temperatures do not have adverse effects of any significance on the fiber. Table 5 lists the small change in properties with a 50.0°C (about 125°F) change in temperature.

Abrasion Resistance-Fishbite

Because Kevlar® is a fiber, the relative ease with which the fibers are cut and/or abraded in a transverse direction as compared to metal must be kept in mind. Its abrasion resistance is equivalent to that of nylon or polyester under wet conditions but at least ten times worse under dry conditions. Table 10 lists the cycles to failure for ropes of three different synthetic materials when oscillated back and forth over an octogonal steel bar [22].

Naturally all ropes should be kept away from sharp and abrasive surfaces. Sheaves, drums, chocks, and bits can become scratched and gouged from previous use. If any synthetic fiber rope is to rub against a surface, the area should be carefully inspected and dressed down if necessary. Fixtures to be inserted into a rope, such as terminations and thimbles, should be examined for cutting edges.

Another possible mode of rope failure by cutting and/or abrasion is fishbite. There has been considerable discussion and speculation on this subject. Ten years ago a number of deep-sea mooring systems that had gone adrift were recovered with portions of the mooring lines intact. Several of the ropes were studied and it was concluded that the failures

Table 10 — External Abrasion Resistance of 1/4-in.-Diameter Ropes*†

Item	Construction	Cycles to Failure	
		Dry	Wet
Kevlar® 29‡	Single Braid (16 picks/ft)	225	315
Kevlar® 29‡	Single Braid (30 picks/ft)	195	270
Dacron®	2-in-1 Braid	1150	180
Nylon	2-in-1 Braid	--	135
Dacron®	3-Strand	2380	570
Nylon	3-Strand	2900	690

*Octagonal steel bar — 25-lb load, 30 cpm
†from E. I. du Pont, Wilmington, Del.
‡Kevlar® 29 without lubricants

were due to fishbite [23]. Since then, several papers have been published covering the various types of sea creatures involved in the bites and their depth distribution [24, 25].

On the other hand, the authors have never observed indications of fishbite on acoustic measurement arrays deployed in various parts of the Pacific, Atlantic, Mediterranean, and Carribean ocean areas. The differing observations are not necessarily contradictory, however because of distinctive difference exists in the mooring systems involved. One supports hydrophones, and is therefore designed to remain motionless and quiet, whereas the other system, on which most fishbite has occurred, consists of unfaired mooring lines for surface follower buoys. It appears, therefore, that fish do not tend to bite cables which do not strum. During the past three years particular attention has been paid to fishbite by carefully examining the various arrays and mooring lines during recovery, yet not a single bite has been observed. Most of the arrays have been subsurface buoy systems in deep water with the buoy placed less than 300m (about 1000 ft) below the surface; several systems have been surface supported, but considerable care was taken to decouple the surface motion. All have utilized some type of cable fairing.

This is not conclusive evidence, however, and a good deal of conflicting information exists. Explicit experiments will be required to determine whether or not fish bite motionless cables, and until then one should proceed with caution in utilizing synthetic cables through the fishbite zone.

Finally, the construction of the rope must be included as an important factor in its resistance to wear and cuts. When comparing the various ropes of equal size and material, for example, the eight-ply will concentrate its weight on the knuckles of the weave; however, a braid or a twisted rope of many strands will distribute the load, and therefore, the abrasion, over more of the surface area.

Biodegradation

An additional problem that might be encountered, especially near shore, is encrustation of the exposed fiber with marine life. A number of samples of aramid fiber rope were exposed at a depth of 5.5 m (about 18 ft) in a Hawaiian bay [26]. After six months, they exhibited a calcareous growth which was easily removed. The tensile strength and modulus of the exposed samples remained uneffected.

However, after a 20-month exposure of similar samples, the rope became heavily encrusted, and the filament helix was disrupted where larger barnacles had attached themselves. Testing revealed a 40% reduction in tensile strength. It must be emphasized here that these samples were not jacketed, and were exposed in coastal waters.

Handling and Safety Factors

It is impossible at this time to set exact safety factors for aramid fiber ropes, not even the wire rope industries with their years of experience have been able do it. The proper factor not only depends on the rope, its construction, and its material, but also on the loads applied, speed of operation, end fittings used, acceleration and deceleration, length of rope, number and size of sheaves and drums, duration of rope usage, the abuse it has had during that time, and most important, the possible loss of life and property should that rope fail. At this point some guide lines can be provided, but as experience is gained, changes may be required. The basic recommendation for ordinary usage of an aramid fiber rope is a safety factor of 5:1; i.e., that breaking strength of the rope should be five times as great as the largest expected load on the rope.

As previously mentioned in this report, the ratio of sheave diameter to rope diameter is very important. To prolong a working rope's lifetime, the sheave diameter should be as large as possible. Braids and twisted aramid fiber ropes should have a ratio of about 25:1. Parallel strand ropes require a much larger diameter; here, a ratio approaching 50:1 is recommended. These proportions must be varied according to the aforementioned variable factors, and would also apply to capstan drums and various types of cable-tensioning machinery.

Storage of synthetic fiber ropes under tension on a drum or reel is not a good practice; various types of cable tensioning machinery are available to relieve any stresses in the rope prior to spooling. If however, it is necessary to wind onto a drum under tension, the ideal situation would be to have no more than one layer, but for oceanographic purposes. This is impractical. Assuming a need to spool many layers of rope under tension, several red flags must be raised. The fleet angle should be as small as possible to avoid excessive chafing of the rope. In the case of twisted fiber rope, it is important to wind the rope onto the drum in the proper direction of lay; otherwise, the rope will tend to unlay and kink if tension is temporarily removed. This does not pertain, however, to parallel lay or braided ropes. Finally, it is important to avoid spooling too many layers under to much tension, since the radially directed force will become greater than the compression strength of the material, thereby crushing the innermost layers.

A unique method of deploying and retrieving aramid fiber arrays has been developed and used by the Systems Engineering Staff of the Acoustics Division at the Naval Research Laboratory. The braided Kevlar® rope, which includes electrical wires, hydrophones and fairing, is stored in a wooden box. The line is fed by hand from the box to a large diameter V-grooved sheave which is fixed to a capstan. The sheave groove provides sufficient tension on the rope to lower or raise the array, and the box provides the necessary storage area and protection. There is no complicated deck machinery needed.

The decision as to the proper time for removal of a rope from service is a difficult one. Presently there is no definite answer. Tensile tests of worn ropes from various installations would be the only way of accumulating enough data to allow reasonably close estimates to be made.

ARAMID FIBER ELECTROMECHANICAL CABLES

Construction and Application

Primarily, it is the fact that both Kevlar® 29 and Kevlar® 49 have very low elongation under load which has enabled this fiber to succeed as a strength member in electromechanical cable. The elongation of the aramid fibers at break strength is 4% for Kevlar® 29 and 2.4% for Kevlar® 49. This relatively small amount of stretch makes it possible to include properly designed electrical conductors within the synthetic fiber cable.

Second on the list of merits must be the material's very high tensile strength. It is because this aramid has an ultimate load of 2.75 GPa (about 400,000 $lb/in.^2$) that it is in contention with steel, whose ultimate strength is in the order of 2.07GPa (about 300,000 $lb/in.^2$). Of course, as with all the various fibers and wires used to make rope, the ultimate strength of the cable will depend on the conversion efficiency of the construction chosen. Nevertheless, for similar construction and equal size, the tensile strength of the aramid fiber compares very favorably with other cable strength members.

If we now merge the fiber's great tensile strength and high modulus with its light weight it becomes readily apparent that, at this time, Kevlar® has the best strength-to-weight ratio of all conventional cable materials (see Fig. 5). With a density of only 1.44g/cm^3 (0.052 $lb/in.^3$), this ratio is seven times greater than steel in air and twenty times greater than steel in water.

Due to the fiber's low specific gravity, aramid cables can be made neutrally buoyant just by the prudent choice of materials used in conductor insulation and/or cable filler and jacketing. Hence, there may be no need for the flotation modules sometimes necessary in systems utilizing steel electromechanical cables. The obvious benefits include reduction of handling and storage problems, avoidance of additional drag, and elimination of any implosion hazards sometimes caused by buoyance modules.

The Kevlar® electromechanical cable possesses numerous possibilities for design variation: type of strength member, sensor location, size and number of electrical wires, conductor insulation, position of conductors relative to strength members, and jacketing material. Properties of the aramid fiber rope have already been covered in preceding sections; hence, the following sections will discuss the features of the aramid fiber that relate to electromechanical cable (for a more comprehensive coverage of the development of aramid fiber electromechanical cable, see [27].)

Helically Wrapped Strength Member Cable

A Kevlar® 49 twisted strand, electromechanical cable has been developed by the Naval Undersea Center [28]. After a number of tests on the prototype cable, several suggestions concerning the fiber and its handling were put forth [29].

1. Very tight quality control procedures must be followed in the production state. Each change of technique or material should be accompanied by tests.

2. To assemble this type of cable, most U.S. companies utilize machines designed for use with steel wire. Several modifications are necessary before they are suitable for use with aramid fiber.

3. Cables will possess some degree of torque.

Braided Strength Member Cables

Braided strength member electromechanical cable appears to have some outstanding characteristics both in and out of the ocean. Its principal merits include those of braided mechanical ropes with a few additional ones:

1. Ease of fabrication, which requires considerably less precision than alternative constructions

2. Completely torque-balanced

3. Self-limitation of the effects of yarn damage. Local imperfections and individual yarn damage are averaged over a short length of the cable. Even if each yarn is cut many times along the length of the cable, only a slight decrease in cable strength will result as long as the cuts are separated by several feet.

4. Ease of end-fitting by eye-splicing or with epoxy-potted conical sockets

5. Accommodation of a wide variety of core sizes

6. A wide range of strengths through choice of yarn sizing, braid design, and number of layers

7. Excellent cyclic-tension fatigue life at high stress levels

8. Low elastic stretch that can be easily accommodated by properly designed conductors

9. Flexibility and small bending radii

10. Excellent cost effectiveness, within certain ranges, in relationship to alternative materials and strength requirements

11. New sensor mounting designs, making it possible to insert sensors into a braided electromechanical cable without cutting or end-fitting the cable

Yarn failure due to abrasion and compression has been alleviated by the use of untwisted* impregnated yarn. The untwisted yarns tend to flatten out at the crossovers, thereby reducing the crimp angle and distributing the compressive load. Aramid cables of this type have sustained a million tension cycles at loads up to 1.24 GPa (about 180,000 lbs/in.^{2}) without strength reduction.

The abrasion resistance of the fibers due to cycling over sheaves has been the more serious problem to date. A slight twist and impregnation with urethane initially improved the yarn's self-abrasion problem, but did not eliminate it. Recent results published by du Pont indicate a large increase in the wear life of the fiber by using wax overlays (previous sections). However, some additional testing will be necessary before results are conclusive.

The electromechanical cables are constructed by weaving one or more layers of braid over one or more electrical conductors. The mechanical break strength of the cable then depends on the braid helix angle, crimp angle, ends per carrier, etc. (see previous section), and on the layers of braid added. Final options include incorporating fairing into the last weave, substituting a jacket of a more abrasive-resistant fabric on the last weave, or extruding a polyurethane jacket over the entire assembly.

An example of a braided electromechanical cable that has performed well is one currently in use in oceanographic acoustic systems. It is a 36-conductor electrically tapered hydrophone array cable with a break strength of 8709 kg (about 19,200 lbs). Data from load elongation curves indicate that the linear elongation is 1.26% at 3629 kg (about 8,000 lbs) and that at working load, it is only 0.3%.

Basically, the cable consists of four braided cables with nine electrical conductors in each cable. The four cables were assembled and overbraided, incorporating an antistrumming fairing into the jacket. Upon completion, the outside diameter was 2.22 cm (7/8 in). The finished product along with its inline hydrophone cage is shown in Fig. 22.

Because the instrumentation is uniformly spaced along the cable, it is possible to taper the electrical conductors along the 1829-m (about 6000-ft) length. This tapering reduces both the cost and the weight of the array. A thermoplastic rubber filler rod is used in place of the absent conductors to prevent deforming and weakening the braid (see Fig. 23).

*This does not refer to the slight amount of yarn twist necessary to improve the yarn's strength and abrasion resistance, but rather to the yarns which have twists an order of magnitude higher.

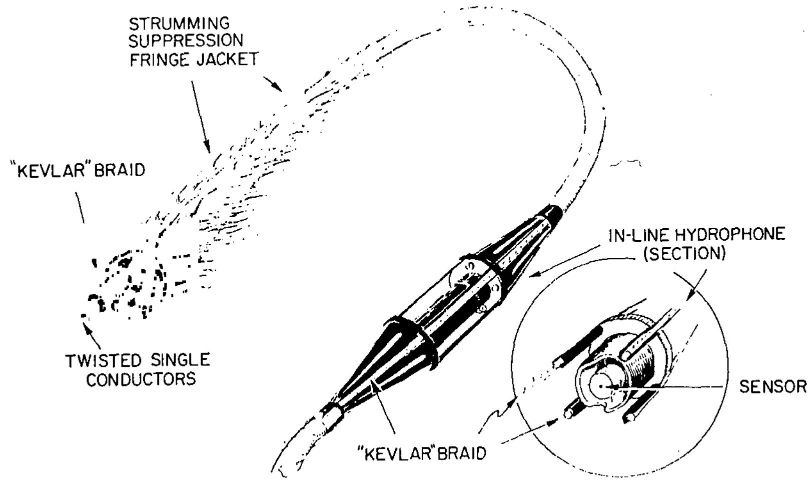

Fig. 22 — Four-strand Kevlar® hydrophone cable

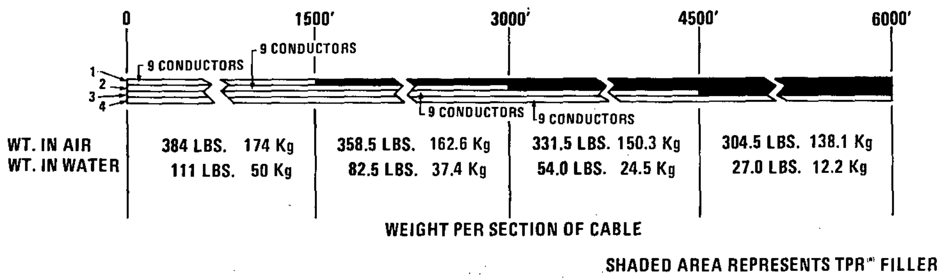

Fig. 23 — Braided four-strand Kevlar® cable

From our testing and experience, it appears that aramid braid provides excellent strength member construction for electromechanical cable.

Parallel Strength Member Cables

The parallel-strand electromechanical cables tested and used to date have performed exceptionally well and represent a significant step forward in ease of sensor array fabrication and operation. However, caution must be exercised that they are not used for other than the intended design application. Again, as in the parallel-strand mechanical ropes, considerable care is required in fabrication to establish equal loading on all strands and to produce a good, firm, well-bodied cable with good handling characteristics.

With this parallel-strand approach it becomes fairly easy to bring out the conductors at any point along the cable for attachment of instrumentation. In addition, as in the case of specially designed sensors, the cable can be opened, the instrument inserted into the center of the cable, and the strength members run alongside the instrument case. Either method eliminates the problems associated with cutting and end-fitting the cable at each sensor location.

A typical parallel aramid fiber electromechanical cable is the 1402-m (about 4,600-ft) six-element Uniline®, which was designed and fabricated for a MABS system. Three conductors were twisted together to form each triad and six triads were cabled around a 0.419-cm (0.165-in.) diameter thermo-plastic rubber (TPR®*) core. The assembly was then covered with two layers of 1-mil mylar tape, resulting in a 1.06-cm (0.42-in.) diameter electrical core.

The strength members consisted of thirty-four 12,000-denier latex rubber-impregnated Kevlar® 29 strands parallel with and around the electrical core. This assembly was wrapped with two layers of neoprene tape and then braided over with a polyester jacket which included tufts of polypropylene fringe fairing at 2.54-cm (1-in.) intervals. The cable had a diameter of 1.9 cm (0.75 in.), a weight of 0.10 kg (0.22 lb)/ft in air and 0.03 kg (0.066 lb)/ft in water, and a measured breaking strength of 14,130 lb/ft (see Fig. 24).

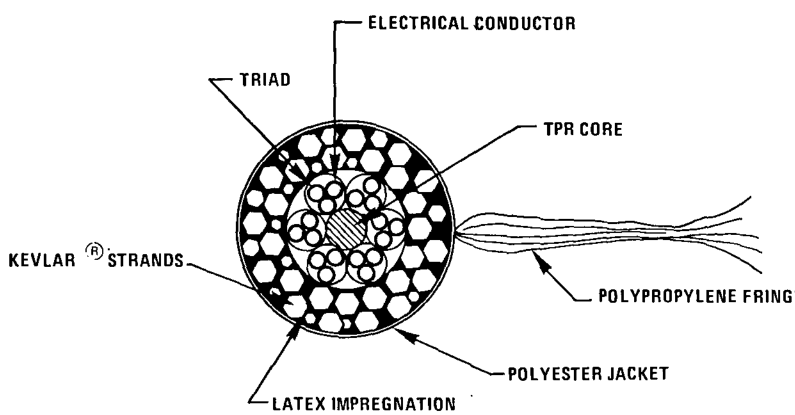

Fig. 24 — Parallel strand electromechanical cable

The in-line hydrophones were inserted into this cable while it was being coiled into a pressure tank; three hours were required to mount each hydrophone. Single-pin, slip-on connectors were used to seal the conductors to the hydrophones. The array was then pressure tested, found to be free of faults, coiled in a crib, and shipped for loading on board ship.

During the subsequent deployments, the array was coiled on deck and snaked off the deck during anchor free fall, payed out directly from the crib, and spooled onto a deck winch. Multiple handling produced no indications of weakness in the design for this application. After final recovery, the array was coiled back into its crib with one end available for buoy attachment and the other for anchor attachment if another deployment was required. Payout speeds from 30.48 to 60.96-m (about 100 to 200 ft)/min have been used. Performance, both mechanical and acoustical, has been excellent.

*Registered trademark of Uniroyal Corporation.

After six months aboard ship the array was in excellent condition. No deterioration nor corrosion was evident. It was then cut in half; the lower section was coiled in a 1.22-m (about 4-ft) cube box and air-freighted to Australia, while the upper section was placed in storage. The array can be rejoined, operated as two individual six-element arrays with addition of more hydrophones, or operated as a single 12-element array.

The array section shipped to Australia was reconfigured as a six-element array (by the addition of three hydrophones) and used for a surface-supported sensor system. It was deployed and recovered three times by hand, without the use of any deck machinery in conditions of 20 to 35 knots steady wind. Acoustic performance of the system in these adverse conditions was excellent, and logistic expense of the operation was minimal.

A sample of this cable was subjected to the same laboratory testing as previously described. Both the breaking strength and sheave life were significantly less than for the previous cables, but the proportionately larger electrical core, along with the use of ordinary conductors, undoubtedly contributed to that result. However, the actual 6350.0 kg (about 14,000 lb) breaking strength provides a static safety factor of greater than 10, and 794 bending cycles at 1134 kg (about 2,500 lb) tension far exceeds the envisioned life requirements for the service intended.

Woods Hole also purchased a 4572-m (about 15,000-ft) continuous length of this cable and used it in conjunction with their Acoustic Data Acquisition Capsule (ACODAC) system [31]. A 4570-m (about 15,000-ft), six-element array cable was formed by opening the cable jacket, separating (without cutting) the strength members, extracting the appropriate color-coded triad, and installing slip-on connectors. The hydrophones were attached and removed during deployment and recovery, respectively, by clamping them to the cable. The location of hydrophone placement is easily found since the cable is permanently marked at 30.48-m (about 100-ft) intervals by colored tufts in the fringe fairing while the cable is under tension during the cabling process. The cable was wound on a large winch.

Cost Considerations

In designing a cable for suspended-array applications, one must consider array fabrication, testing, calibration, handling, deployment, reliability, and performance in terms of overall system cost. Considerable final system cost savings can be realized if the optimum fit can be found between the materials available and the performance required. The costs are much harder to identify than simply being the bare cost-per-foot of cable. For example, in comparing two 3048-m (about 10,000-ft) six-element arrays for the MABS, one of round wire armor steel and the other of Kevlar® 29, one finds that the steel cable costs $1.00 per foot while the Kevlar® cable costs $2.00 per foot. However, the costs of the same two cables faired and rendered neutrally buoyant by the addition of syntactic foam floats are $5.50 per foot and $2.74 per foot, respectively. Also, because of the ease of making the Kevlar® array and because negligible additional buoyancy is required to compensate for the weight associated with sensor attachments, the final, finished array costs are $75,000 for steel and $31,400 for Kevlar®. Furthermore, for the Kevlar® array, the lead time required is less than half that for steel, the performance and versatility are much greater, and the maintenance and replacement costs are considerably lower.

Over and above these basic costs, one must compare the operational costs of requirements for the two systems. It appears from experience that this is where Kevlar® cables produce major savings. Some of these considerations are the number of personnel required (including the number of berths on the deployment vessel), the winching requirements, deck and storage space requirements, total weight, weather dependence, and array life (for example, the steel MABS array failed during its first season of use, although it was repaired as a result of dynamic loading, but after one season of usage the Kevlar® array appears to be in new condition with no signs of deterioration or damage).

SUMMARY

Kevlar® is an outstanding fiber; its use will allow new oceanographic engineering designs. However, indiscriminate replacement of ropes and cables constructed of other materials must be avoided. In order to make maximum use of the fiber's strong points, its more vulnerable ones must also be considered.

This report has summarized the known properties of aramid fiber, both strong and weak, as determined by du Pont, various rope manufacturers, and the authors. Moreover, it has pointed out areas where information is lacking and more testing must be done.

The Naval Research Laboratory is now engaged in studies of various aspects of cable technology. In addition, several environmental and mechanical experiments are now being conducted on aramid fiber and on the ropes produced from it.

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GLOSSARY

(Terms As Used In This Report)

Array	An assembly of instruments, such as hydrophones or thermistors, distributed along, supported by, and communicated with by means of an electromechanical cable.
Catenary	1. The curve assumed by a negatively buoyant cable in equilibrium under gravitational forces. 2. A term used in cordage technology to describe slack or unequal lengths of yarns in a strand or rope.
Compliance	The degree to which a cable can elastically elongate to reduce the effects of dynamic loading.
Creep	Permanent time-dependent elongation of a cable under load (as distinct from, and in addition to, elastic elongation).
Denier	Weight in grams of a 9000-m length of fiber yarn or filament.
Dog Leg	Term used in cable technology to describe a buckling of conductors within the cable as a result of permanent elongation followed by compression loading.
Elastic Modulus	Ratio of unit stress to unit strain within the elastic limit of the material.
End	Similar to strand.
Fiberglass	Occasionally used as a rope fiber, where total fire resistance is required. It has very low elongation and very high strength, but has poor resistance to flexing, is susceptable to fatigue, and exhibits fiber deterioration in water.
Filament	A fiber of extreme length, manufactured by an extrusion process. Many filaments contained in one bundle out of one extrusion process are called multifilaments. A filament which has a diameter over 0.1 mm or 4 mils is called monofilament.
Kevlar	Du Pont trademark for a new high strength, low stretch aramid fiber (formerly called PRD 49 and Fiber B).
Kink	A knot, back turn, or loop drawn tight in a cable, generally caused by the release of stored torsional energy during tension relaxation.
Lay	The length of a complete turn of a strand in a rope or cable.
Nylon	High tensile strength, high elasticity. Energy absorption and impact resistance are excellent. Abrasion resistant. Immersion in water lowers strength and increases elongation.

Polyester	Generic term for a family of fibers manufactured under various trade names: "Dacron" (Du Pont), "Fortrel" (Celenese), "Kodel" (Eastman). High tensile strength, low elastic elongation, and excellent abrasion resistance.
Polypropylene	A fiber made in either monofilament or multifilament form. Strength is approximately 60% to 75% that of nylon and polyester. A light weight fiber with high positive buoyancy. Not as abrasion resistant as polyethylene. Poor working line.
Polyethylene	About 5% less strength than Polypropylene and 5% heavier. Light weight, high buoyancy.
Serving	Helically wrapped strands or yarns around a cable core (as for armored steel cable or for protection at fittings).
Strand	Fibers or yarns twisted and/or impregnated to form a strength-member building block for ropes or cables.
Tenacity	The breaking strength of a yarn in grams of force divided by the denier of the yarn.
Twist	The number of turns per inch in a yarn.
Yarn	A longitudinal group of fibers with or without twist.
Yarn Diameter	$\frac{\text{filament diameter} \times \sqrt{\text{no. of filaments}}}{0.91}$ (0.91 is the packing factor.)