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KEVLAR COAXIAL CABLE DEVELOPMENT

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June [redacted]79

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NAVAL OCEAN RESEARCH AND DEVELOPMENT ACTIVITY
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FOREWORD

This report describes the design and testing of a light-weight, torque-free, Kevlar-reinforced, coaxial cable for severe mechanical bending applications. The development of this particular Kevlar cable is complete. Work is continuing on the development of other lightweight, torque-free, corrosion-resistant, electromechanical cables and will be the subject of future reports.

C. C. DARRELL, CAPTAIN, USN
COMMANDING OFFICER
NORDA

EXECUTIVE SUMMARY

The primary objective of this program is to develop a reliable 8.5 kilometer length of reinforced, torque-free coaxial cable with the ability to endure many thousands of bending cycles over small diameter sheaves. A braided, aramid fiber, Kevlar-reinforced, coaxial cable that had outstanding performance characteristics was developed for this specific application.

This report describes the two major areas of evolution necessary: optimization of the braid's mechanical behavior and the design of a compatible electrical coaxial core. Improvements in the mechanical performance ranged from an initial attempt that produced a cable capable of withstanding only a few hundred cycles of bending fatigue to the final cable which can endure many thousands of cycles. The greater stretch of aramid fiber versus steel necessitated an electrical conductor with the ability to withstand a three or four percent elongation, and also to survive the bending fatigue tests without severe degradation of its electrical characteristics. This improved coaxial conductor is also applicable to steel electromechanical cables that must experience severe bending.

The development of the aramid fiber cable has been completed; however, work is continuing with the design and testing of a low-torque, lightweight, plastic-encapsulated, caged armor steel cable. An additional area of investigation is being conducted to examine various methods of incorporating optical fibers into a coaxial cable. As with the previous requirements, the fibers must be capable of withstanding many thousands of bending cycles over small diameter sheaves.

ACKNOWLEDGEMENT

Successful completion of this project was made possible by the close cooperation and support given by Mr. Richard C. Swenson, Head of the Ocean Technology Division of NORDA.

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I. BACKGROUND

Coaxial electromechanical cables for oceanographic use are normally constructed with two layers of contrahelically laid galvanized steel wires as the load-bearing components. In some applications, this construction causes several problems. In long lengths the suspended weight results in small safety factors and requires robust winching machinery, is difficult to torque balance, and has a high corrosion potential. Additionally, cycling of this steel cable over small diameter sheaves has produced premature failures both mechanically and electrically.

The objective of this program is to develop and produce an improved 8.5 kilometer (km) length of coaxial electromechanical cable that is capable of withstanding many thousands of bending cycles over small diameter sheaves. The cable must also be lightweight, torque-free and corrosion resistant. In light of these requirements, a major test program was initiated to develop a braided, aramid-fiber-reinforced coaxial cable. Kevlar* was chosen for its unique properties of high strength-to-weight ratio, high fatigue life, compliance, and non-corrosive characteristics. A braided construction was chosen for ease of fabrication, self-limiting effects of strand damage, and natural torque-balance quality.

In recognition of the fact that the aramid fiber cable might not be able to meet the operational requirements to be imposed, a secondary effort was initiated to develop a relatively lightweight steel cable with low torque and corrosion protection. The result was a double-caged armor construction encapsulated in a plastic jacket. This cable is presently under development and appears promising.

II. REVIEW

Prior to construction of the Kevlar electromechanical cable, it was obvious that three areas existed which required intensive study:

Elastic Conductor Design (accommodate Kevlar's elongation)

Kevlar Strand Evaluation (abrasion, impregnation, environmental effects)

Braid Optimization (strength efficiency, bending, elongation)

At the same time these studies were being performed, pilot test cables were constructed and tested for problem definition. Then, utilizing the results of these tests, prototype cables were designed, fabricated, and tested. This process was reinforced along the way with input from mathematical modeling.

A. CONDUCTOR DESIGN

The conductor test series began by overbraiding a 15 meter (m) length of standard coaxial electrical cable, which is normally armored with steel, with two layers of Kevlar braid. Under axial tension cycling to 50% of ultimate break strength, conductor continuity was lost on the 20th cycle. Examination of the core revealed that the center conductor had kinked and broken; in addition, numerous kinks were observed in the return conductor (Fig. 1). The center conductor was

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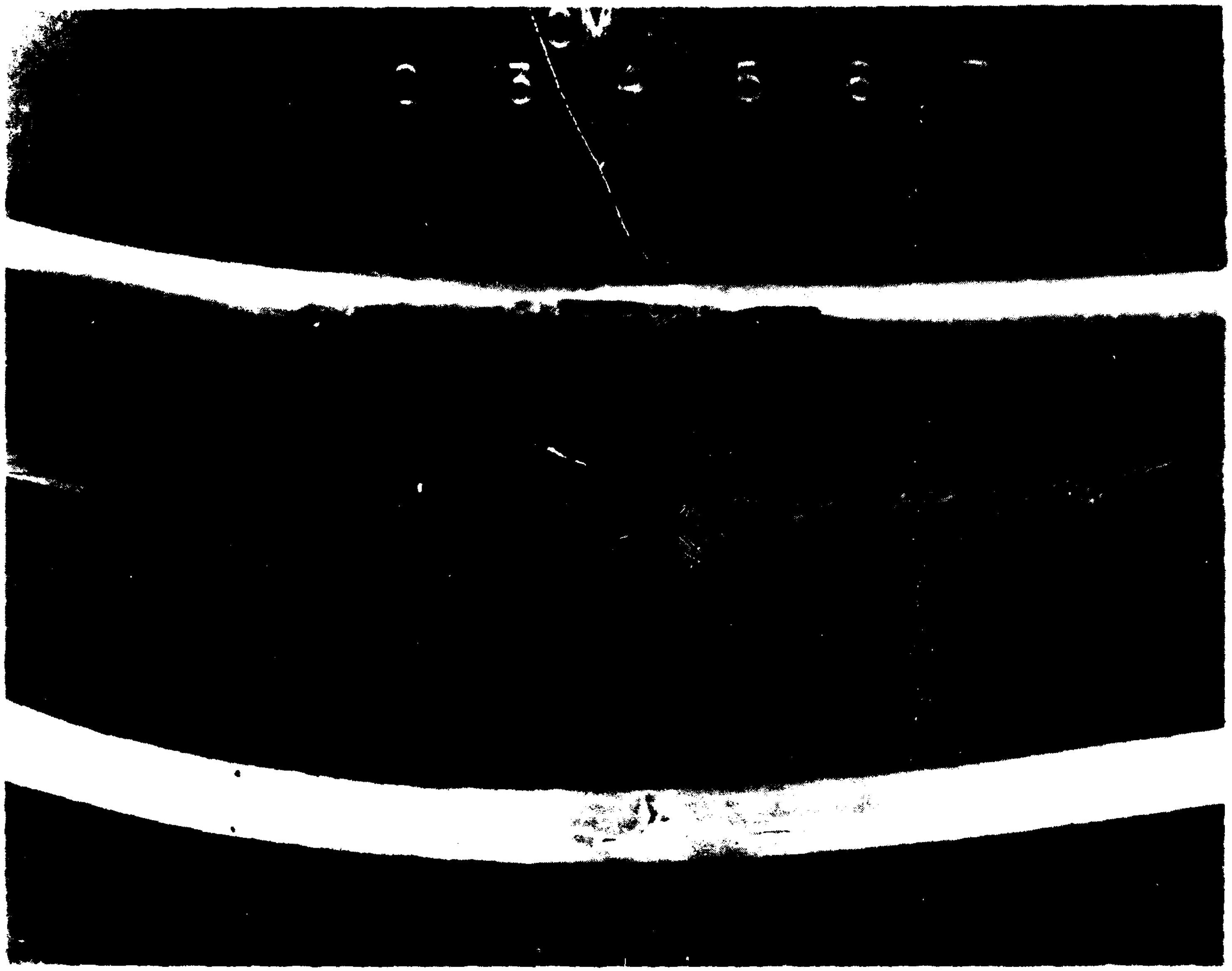

FIGURE 1 AXIAL TENSION FAILURE MODE OF STANDARD ELECTRICAL COAXIAL CABLE OVERBRAIDED WITH KEVLAR

constructed of No. 16 AWG annealed copper with a small (12^{o}) lay angle, and the outer conductor was a wrap of 42 copper wires with a 20^{o} lay angle. It was obvious that the greater stretch of Kevlar, as compared to steel, required a new, more elastic coaxial conductor design.

The design of the coaxial core benefited from a previous study to determine which combination of conductor configuration and conductor material would have elastic properties similar to those of the aramid fiber cable (Ferer and Swenson, 1979). The results of this study indicated that properly stranded, soft-annealed tinned copper exhibited sufficient flexure life to justify its use versus the more expensive alloyed copper. Additionally, the ideal center conductor configuration was determined to be 12 copper wires helixed with about a 36^{o} helix angle around an elastic filler rod. This became the core design.

Approximately 600 m of insulated center conductor was utilized to experiment with different techniques of applying the return conductor to the core and to observe the criticality of the helix on the center conductor by subsequent cyclic tension testing.

Five different candidate return samples were fabricated (Fig. 2). The principal candidate, which was based on the success of using flat Kevlar strands versus round strands in braids, was a flat ribbon copper with a width-to-thickness ratio of 10 to 1 in a braid for the return, as shown in sample A of Figure 2. This approach was to reduce notching at the crossovers by reducing the crimp angle and distributing the pressure. It would also be considerably easier to manufacture, particularly in long lengths. Specifically, the ribbons can easily be replenished on the bobbins of the braider as they individually run out. This is the same approach used in the Kevlar braiding process, and, by using this technique, the principal machinery required to fabricate the entire cable is the lower cost braiders. Additionally, the braiders provide much more flexibility in design changes and fabrication sources. The major question to be answered was: Would the braid survive bending under load?

The second sample, model "B", simply wrapped the core with one pass of ribbon. This approach was to reduce the number of small wires, but it still possessed the same types of length and control problems encountered in a single pass of round wire.

Model "C" used two passes of ribbon laid in opposite directions. This would place more copper and avoid the over and under crimp of the braid, if that proved to be a problem.

Model "D", the original design in which 120 small wires were helixed around the core, suffered severe wire crossover problems. Model "E" was constructed from two layers of the same small wires used in "D", but used two passes in opposite directions.

These cores were taped over with an aluminum-faced mylar tape and jacketed with the specified polyurethane jacket. One hundred feet of the two most promising candidates (A and B) were then overbraided with Phillystran for mechanical testing to prove out the core. A 22^{o} braid angle was used along with enough fiber to produce a 62.2 kilonewton (kN) breaking strength. Stress/strain, cyclic tension and bending tests were conducted on the prepilot cables.

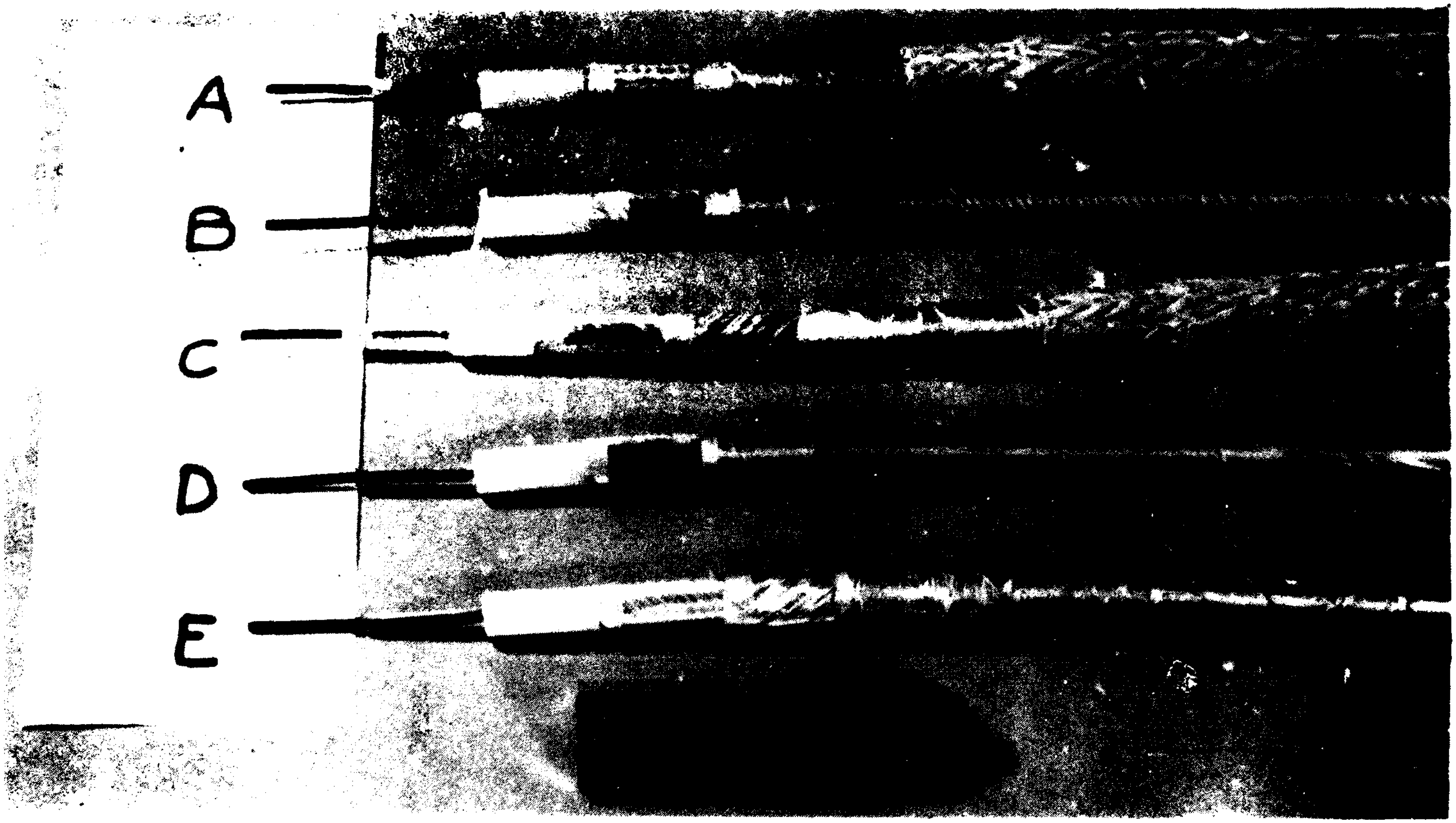

FIGURE 2 FIVE EXPERIMENTAL COAXIAL CABLE DESIGNS

Cable "A" was tension loaded from 0 to 12.5 kN (20% of breaking strength) for 1105 cycles. The characteristic impedance of 45 ohms was unchanged by the testing. Time Domain Reflectometer measurements also revealed no variation. The cable was then cycled an additional 10,882 cycles at 0-18.7 kN, which produced a 1% elastic stretch without apparent degradation. However, upon subsequent dissection of the core, the predicted buckling of the center conductor was observed. This validated the requirement for built-in constructional stretch of the center conductor. The braided return survived this phase of testing without damage.

The prepilot cable "A" was then subjected to cyclic bending under load, a more critical test of the braided return. The cable was tensioned to 12.5 kN (20% of breaking strength, approximately 0.5% elongation) and bent over a 20:1 sheave-to-cable diameter ratio for approximately 1000 cycles, at which time the Kevlar braid failed (Table 1). This, in turn, parted the electrical conductor. Measurements during cycling showed negligible change (less than 5%) in the characteristic impedance and capacitance. Again, dissection of the cable showed no damage to the braided conductor return prior to cable rupture. Several lubricants were applied to the Kevlar braid in an attempt to improve performance. The only one that showed significant improvement was the DuPont wax, which was under development at the time.

This phase of the program validated the necessity for careful center conductor design, and proved that a copper ribbon braid could be used as a return. This, in turn, renders the cable relatively easy and less expensive to produce.

B. KEVLAR STRAND EVALUATION

Early tests of the aramid fiber ascribed low bending fatigue values to the bare yarn; however, the real culprit was abrasion (Ferer and Swenson, 1976). Each filament within the yarn has a hard surface that is easily removed as the yarn is worked. Several manufacturer-applied surface finishes are available, but they only help to a small extent. One particular company has developed a process to impregnate the yarn with a urethane compound, extending its abrasion lifetime by an order of magnitude. Therefore, the first series of cables were constructed from this material. Subsequent braided cable bending tests showed, however, that the failure mode was still interstrand abrasion. Upon further discussion, the contractor managed to formulate an improved resin impregnation, and instituted the use of a water-resistant surface lubricant, providing much superior strand abrasion protection. This is the material used in the present design. Work is still being carried on by DuPont and others to improve the fibers' wearing properties; hopefully, future developments may further extend the material's abrasion-related fatigue lifetime.

Prior to the initiation of the cable development program, an investigation was conducted to determine the suitability of Kevlar for use in oceanographic ropes and cables. Tests were conducted on the mechanical performance of this fiber in both air and water with no significant strength loss observed (Swenson, 1975). However, two reports issued during the early phases of the cable program implied that the aramid fiber lost a significant amount of strength when used as mooring lines in the ocean (Walden, 1976; Bourgault, 1976). This precipitated further experimentation under more controlled laboratory conditions in order to isolate each of the potential problem areas. Tests conducted by the Naval Ocean Research and Development Activity and other facilities agree that: the creep properties of Kevlar are load-dependent and result is less than 0.2% elongation per

TABLE 1

INITIAL CYCLIC BEND-OVER-SHEAVE COAXIAL CABLE TESTS

SAMPLE NO.	NO. OF CYCLES TO FAILURE	TENSION kN	TENSION lbf	% OF BREAK STRENGTH	BRAID LUBRICATION
I 1	1640	12.5	(2800)	(20)	Dry
I 2	4168	12.5	(2800)	(20)	Grease
I 3	1270	12.5	(2800)	(20)	Grease
I 4	1000	12.5	(2800)	(20)	Grease
I 5	186	18.7	(4200)	(30)	Grease
I 6	132	18.7	(4200)	(30)	Grease
I 7	524	18.7	(4200)	(30)	Molylube
I 8	756	18.7	(4200)	(30)	Molylube
I 9	3076	18.7	(4200)	(30)	Dupont Wax
I 10	2048	18.7	(4200)	(30)	Dupont Wax

Phillystran K-29 open weave unjacketed 22° braid

Sheave diameter = 38 cm

year in the usable load range; stress fatigue is only a problem at levels of material stress greater than 70% of the fibers' break strength; and, there is no evidence of environmental effects due to pressure and sea water on slack or tensioned aramid fibers (Ferer, 1977). The apparent reduced break strength observed on samples taken from several long-term moorings may have been caused by intra-strand abrasion related to cable strumming.

A modification in strand configuration not only increased the strands' wear characteri^tics, but reduced the fibers' crimp angle (in braids, the angle at which fibers must deflect from the axis of the weave to cross over each other). The initial strand was twisted and impregnated through a round die, causing a round cross-sectional area. In braiding the strands over each other, the round shape made each fiber travel around a bend equal to its own diameter - a very poor practice. By reducing the amount of twist in the yarn and by flattening the strand after impregnation to produce a more oval cross sectional area, a number of improvements were effected. It increased the area over which the strand-on-strand bearing forces could be spread, thus accommodating the poorer transverse properties of Kevlar fibers. In addition, because a bent strand cannot allow proper load sharing among the individual fibers within the strand, the larger bend radius allows a greater strength efficiency. Finally, the reduced strand-on-strand bearing pressure reduces the frictional forces and thus, abrasion, as the fibers move.

Concurrent with this effort, Philadelphia Resin Corporation developed a silicone-based lubricant which was applied after impregnation. The lubricant significantly improved the fiber's abrasion properties.

Kevlar 29 was used for the construction of the first test cable series because Kevlar 49, as produced at the tim^, had poorer statistical break strength. Subsequent advancements in the manufacturing process improved the material's behavior, causing a reevaluation of the initial choice. Because Kevlar 49's elongation to break was approximately 2.5% versus 29's 3.5%, it was determined that its use would transfer less stress to the electrical core. Although this was shown to be true in axial tension, the lower stretch proved to be detrimental in bending. The fiber could not accommodate itself in the tight weave braid, and despite the urethane impregnation and lubrication, Kevlar 49's abrasion resistance proved to be much less than that of Kevlar 29. Therefore, the final test cable series were constructed of Kevlar 29.

C. BRAID OPTIMIZATION

Prior to the initiation of the Kevlar cable development program, it was not intuitively clear that the construction of braided ropes would be a good application for aramid fiber. The anticipated problems of self-abrasion, low transverse modulus and constructional elongation would appear to limit the use of this fiber. However, test samples which accommodated those weaknesses by means of the impregnated flat strand discussed earlier produced surprisingly good results in strength conversion efficiency, elastic elongation, and tension fatigue.

The principal merits of braided aramid are:

1. Ease of fabrication, which requires considerably less precision and risk than alternative construction, i.e., accommodates the no-yield and high modulus problems which otherwise would require precise tension control in serves and parallel construction.

2. Self-limitation of the effects of strand damage and elimination of the requirement for continuous strand length. Local imperfections and individual strand damage are averaged over a short length of the cable.

3. Accommodation of a wide variety of core sizes.

4. Wide range of strengths though choice of strand sizing, braid design and number of layers.

5. Excellent axial cyclic-tension fatigue life at high stress levels.

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

7. Flexibility and small bending radii.

8. Torque-free cables.

9. A large industrial capability to produce braids in existing equipment.

The early test results, along with the many desirable features of braids, lead to a more concentrated effort in analytical modeling (Phoenix, 1974) and experimental validation in which the principal braid parameters were studied. As seen from Figure 3, there are many braid parameters to consider. Among these are the type of braid, the type and size of strand and whether it is impregnated and/or lubricated, the number of passes, etc. Obviously, all these cannot be evaluated in a modest effort. Thus, the effects of braid angle and crimp angle on elongation, strength, cyclic tension fatigue, and bending fatigue were the principal parameters considered in a test series utilizing polyurethane-impregnated, non-twisted strand.

The mathematical analysis of Kevlar braid made certain pertinent assumptions which should be reviewed before describing the verification experiments.

1. Each N braid end travels in a helical path with helix radius R and helix angle θ. N/2 ends form left traveling helices, and N/2 ends form right traveling helices.

2. The braid core elastically resists radial contraction. The core does not carry any axial load.

3. The untwisted strands compress or squash transversely at crossover points. The strands cross at some angle, called the crimp angle.

4. The data are equally adaptable from 1/1 diamond braid to both 2/2 regular and 3/3 Hercules braids.

Sixteen different models of braided electromechanical cable were manufactured for this series of tests. The basic strength member of all the cables was urethane-impregnated, Kevlar 29, aramid fiber strands. It had an equivalent diameter of 0.1 cm with a break strength of 1.3 kN. Thirty-two of these strands were braided over lengths of each of four cores into a 2/2 regular braid. The only variations in the braiding process were the construction angles. The cores

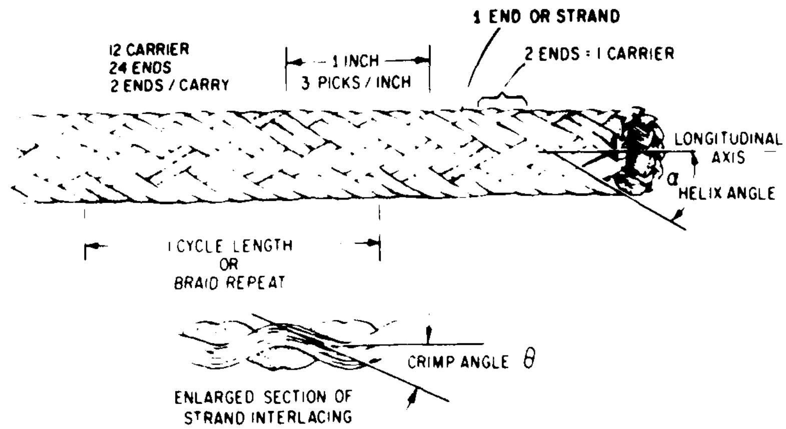

FIGURE 3 TUBULAR DIAMOND BRAID CONSTRUCTION

consisted of four different grades of thermoplastic rubber (TPR: TPR 1600, TPR 1900 and TPR 2800, and a blend of TPR 2800 and TPR 1600. All the cores were extruded to a diameter of 0.89 cm.

Each of the 32 ends in the cable had a break strength of 1.33 kN. This means that the ideal ultimate strength of a parallel fiber rope, so constructed, would be 42.56 kN. However, the magnitude of the braid construction angles determines the relative cable break strength.

The resultant test data points were plotted on the theoretical curves taken from the study on mathematical modeling and were in good agreement (Fig. 4). Just as the mathematical modeling predicted, the cable strengths decreased as the braid and crimp angles increased. Comparison of the experimental data and the curves indicates a slightly lower actual tensile strength. However, the difference in the two values is consistent (14%) throughout, proving it to be an accurate method of prediction.

The differences in core hardnesses over the range selected had no effect whatsoever on the test data. It appears that the core elongated proportionally to the braid due to its high elasticity. There were no ridges pressed into the core by the braid, therefore, the core must have been experiencing a reduction in cross sectional area along with the braid.

Clearly, the key parameters affecting a rope's strength translation efficiency are the crimp angle θ and the braid angle. An increase in either results in a reduction in strength. One 3 m sample was selected from each of the 16 cable constructions to obtain load-elongation characteristics. The test procedure for establishing a stress/strain relationship entailed cycling each cable 10 times from zero to 50% of break strength. On the first and the tenth loading cycle, several measurements were obtained and recorded. Again, as in the tensile tests, the core hardness made no observable difference in the results.

Stress-strain information provided the ropes' modulus of elasticity (E_r) which, when divided by the modulus of the ends (E_s), produced a figure of comparison. These empirical outputs were grouped by braid and crimp angle, then averaged. The actual and calculated data are compared in Figure 5. As can be seen on the graph, the tests do an excellent job of confirming the predictions.

As in the strength translation efficiency loss, a rope's modulus is reduced with any increase in crimp angle and/or braid angle. In addition, because the construction angles were determined in part by the cross sectional area A and the number of strands N, any attempt to increase the strength by increasing these factors will cause a marked decrease in modulus.

III. CABLE TEST PROGRAM

A. PRE-PILOT CABLE

The conductor design effort outlined in Section I.A, validated the need for the aramid strand improvements described in Section I.B. A second test cable was then constructed utilizing the improved lubricant-coated, resin-impregnated strand. This braid was applied over a residual electrical core in two layers using a 25° helix angle on one length and a 30° helix angle on a second length. Jacketing consisted of a thin nylon braid which was bonded to the aramid. A rope

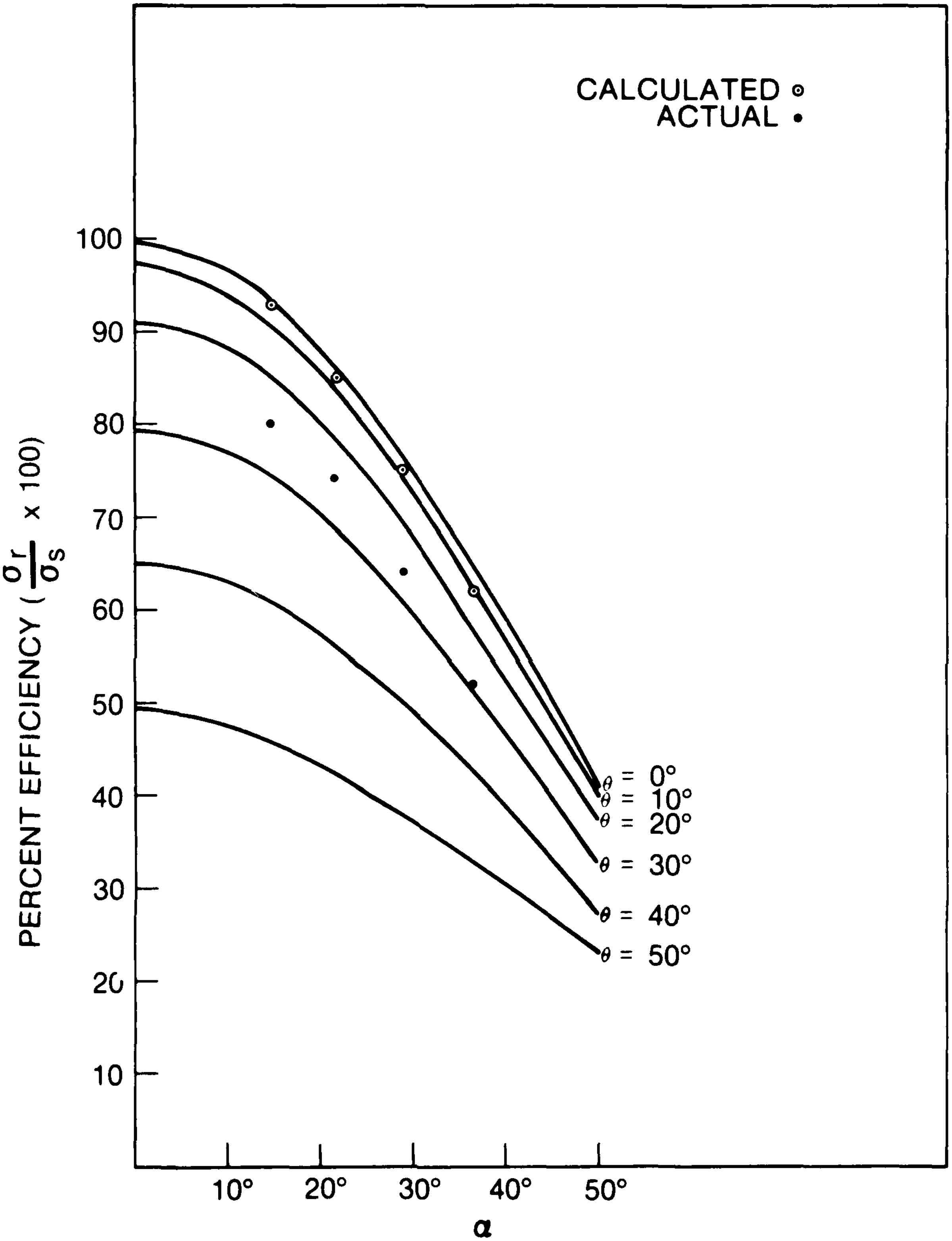

FIGURE 4 PERCENT BREAK STRENGTH EFFICIENCY VERSUS BRAID ANGLE (α) FOR SEVERAL CRIMP ANGLES (θ)

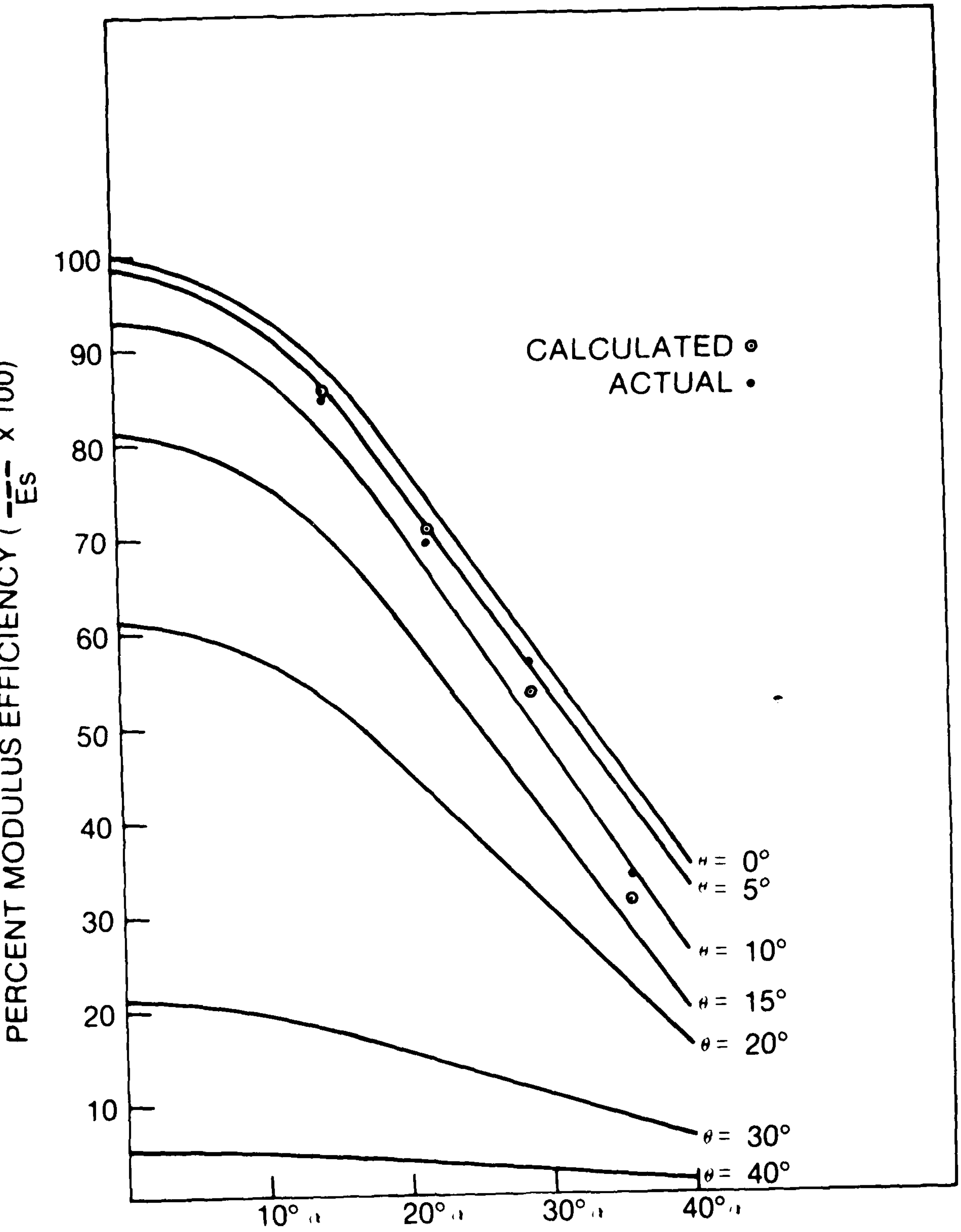

FIGURE 5 PERCENT MODULUS EFFICIENCY VERSUS BRAID ANGLE (α) FOR SEVERAL CRIMP ANGLES (θ)

cyclic-fatigue testing machine obtained from another Navy laboratory was used in this series and termed the "prepilot cable tests". The data scatter was very large (Table 2), traceable partially to inexperience in terminating techniques and partially to the machine itself. Cables tested on the right side of the machine consistently abraded and failed much earlier than those cycled on the left side. There appeared to be either sheave alignment problems or an unbalanced tensioning device.

Concerning the cable, the following general observations were made after failure:

1. The nylon cover was worn on the underside where it was in contact with the sheave; however, it was not worn through.

2. The outer surface of the outer Kevlar braid was also slightly worn where it was against the sheave, but was in excellent condition elsewhere. The adhesive bonding the Kevlar to the nylon was not visible in the area of the breaks.

3. There was some indication of wear between the outer surface of the inner braid and the inner surface of the outer braid. Apparently, the two layers move in relation to each other. None of the adhesives had penetrated through to this area.

4. The inside surface of the inner braid was clean and smooth. It showed no signs of rubbing between the braid and the polyurethane-jacketed electrical core.

Although the condition of the electrical cores was not important to this series of tests, they were examined and provided the expected results. The polyurethane jacket and the polyethylene dielectric were both in good condition. Except for being firmly pressed against the outer conductor, the metallized foil ha no rips or holes. The inner conductor survived the bending with no kinks or buck sections, and the outer round wire conductors failed as they had in previous tests.

In conclusion, the only apparent damage to the cable appears to have been caused by the two layers of Kevlar rubbing against each other.

B. LAYER ISOLATION TESTS

The next iteration was to fabricate and test cables to determine the best method of isolating the layers of Kevlar braid. Philadelphia Resins Corporation overbraided three 30 m lengths of electrical core for Kevlar interlayer abrasion tests. Each cable was constructed of the same Kevlar strand braid angle (25°), and each was protected by a bonded nylon jacket. One length consisted of two layers of Kevlar with a wrap of 0.1 mm thick Mylar tape in between. A second length had a coating of latex compound interposed. A third length had only a single layer of Kevlar braid. Upon completion, these cables were shipped to Tension Member Technology to evaluate bend-over-sheave performance over a 36.8 cm sheave (20:1). Test conditions were the same as those imposed for the first series of tests, except for the single layer; the load at 20% of break strength for this cable was 6.8 kN. In addition, all three samples were cycled at two speeds to evaluate this effect on the cable (600 cycles/hr and 1800 cycles/hr) (Table 3).

TABLE 2

PREPILOT KEVLAR CABLE BEND-OVER-SHEAVE TESTS

SAMPLE NO.	NO. OF BENDS TO FAILURE	TENSION	
	30° Braid (121D)	kN	lbf
PP1	18,640	18.7	(4200)
PP2	12,068	18.7	(4200)
PP3	2,564	18.7	(4200)
PP4	1,746	18.5	(4150)
PP5	5,306	18.7	(4200)
PP6	2,496	18.2	(4100)
PP7	2,900	18.2	(4100)
	25° Braid (121CN)		
PP8	13,098	18.7	(4200)
PP9	9,000	18.7	(4200)
PP10	8,064	18.7	(4200)
PP11	12,064	18.7	(4200)

1) Phillystran Kevlar Braid PS49S - with nylon jacket.
2) All samples tested on left sheave of machine.
3) Tension was approximately 30% of break strength.
4) Sheave diameter = 38 cm

TABLE 3

LAYER ISOLATION CYCLIC BEND-OVER-SHEAVE TESTS

Cable Diameter = 1.8 cm
Sheave Diameter = 38 cm
Cycling Stroke = 66 cm
Test Tension = 18.7 kN
Braid Angle (Deg.) = 25°
Nylon Jacket on all Samples

Two Layers of Kevlar 29

Sample No.	Layer Isolation Material		Bending Cycles/Hr.	Cycles to Failure
M-1	Mylar	Air	1800	4,264
M-2	"	"	1800	3,826
M-3	"	"	600	9,014
M-4	"	"	600	7,424
M-5	"	"	600	9,998
M-6	"	Water	600	11,154
L 1	Latex	Air	1800	5,136
L 2	"	"	1800	3,094
L 3	"	"	600	1,452
L 4	"	"	600	1,778

Single Layer Kevlar 29

Sample No.	Layer Isolation Material		Bending Cycles/Hr.	Cycles to Failure
S 1	-	Air	600	92,804
S 2	-	"	600	110,342
S 3	-	"	1800	55,914
S 4	-	"	1800	110,764

For the Mylar cables, the test speed seemed to have a significant impact on the bending fatigue life, with the slower speed providing approximately double the fatigue life of the higher speed. The one specimen which was tested in water had the longest fatigue life of all Mylar cable samples. Average number of cycles to failure at the slower speed was again about 10,000.

Tests of the latex cable showed just the opposite results, in that the higher test speed provided the longer cable life. However, even the best sample performance indicated that the latex offered no improvement.

The single-layer cable had a fatigue life of approximately one order of magnitude greater than that of the other samples. No definite conclusions can be drawn regarding the influence of test speed on these cables. Both speeds had samples that survived 110,000 cycles.

The dramatic difference in fatigue life between the single-layer and two-layer braided cable suggests that the bearing pressure of the cable on the sheave is much more significant than the tensile load in each filter bundle in determining the cable fatigue life.

From these results, it appeared that the Mylar isolation tape provided only minimal bending fatigue life advantage for the two-layer braided Kevlar cable, but it did help. Therefore, it was incorporated into the design. It was thought possible to utilize a copper-coated Mylar tape at some future time if the cable required a shield.

The results of this second series of tests, coupled with the results of the first series, gave sufficient evidence that a Kevlar cable could be built that would survive 10,000 cycles at 18.7 kN load over small (20:1) diameter sheaves. At this point, the decision was made to advance to the braid angle studies.

Based on the conductor elongation studies discussed previously, a length of the specially designed coaxial cable was fabricated for use in the layer isolation tests and all future cable designs. The center conductor consisted of twelve strands of 0.6 mm soft annealed copper helixed at a 36° angle around a semi-conductive polyethylene core. The return conductor was constructed of thin, flat, soft copper strips, braided over the low density polyethylene dielectric core. Jacketing was provided by a 0.25 cm thick polyurethane extrusion.

Initial tests on this core under load and cycled, both in straight axial tension and bend-over-sheaves, produced excellent results. Ten thousand axial tension cycles from 0 to 30% of load did no damage to the electrical core. In the bend-over-sheave tests conducted at 20% of load, examination of the conductors at about 4,500 cycles again showed no mechanical or electrical change in the conductors.

As the ability of the Kevlar strand to withstand sheave cycling improved, it became possible to test the core at a higher number of cycles. Near 8000 cycles, the braided strips began to break up. However, determination of this mechanical damage is possible only by dissection of the cable. There is no indication of any electrical change during the tests as indicated by a Time Domain Reflectometer, and only slight changes in the conductor resistance. It should be pointed out, however, that only D.C. electrical properties were being measured.

TABLE 4

PILOT CABLE BEND-OVER-SHEAVE TESTS

Cable	Braid Angle	Environment	Cycles to Failure
A_4	16°	Air	216
A_5	16°	Air	248
A_6	16°	Air	284
A_7	16°	Ice Water	186
B_4	24°	Air	658
B_5	24°	Ice Water	298
C_4	33°	Air	1,622
C_5	33°	Ice Water	9,150
C_6	33°	Air	1,142
C_7	33°	Ice Water	5,000

600 cycles per hour

18.7 kN Tension

D/d=20/1

C. PILOT CABLE

Fabrication of the pilot cables was completed during the third quarter of FY 77. They were constructed from three different Kevlar braid angles (A-16°, B-24°, C-33°) over the newly designed electrical core. Each included a thin wrap of Mylar tape between the Kevlar braid layers to alleviate possible interlayer abrasion.

The object of this series was to determine an optimum point of operation under specified conditions by comparing the opposing factors of decreasing cable strength with increasing braid angle, and an increasing number of cycles to failure in bend-over-sheave tests with increasing braid angle.

Four samples of each cable were prepared and terminated, two for bend-over-sheave tests and two for tensile break tests. The initial tensile specimens indicated a problem in that they parted near the terminations at 75.6 kN, or approximately 15% below the expected break strength. The first pair of cyclic sheave tests conducted on Cable A at 18.7 kN load and 600 cycles per hour survived only a few hundred bends before failure (Table 4). Examinations of the broken cable seemed to indicate that the braided strands had severed each other in intralayer abrasion. Two samples of Cable C were then mounted and tested with slightly better results, but still nowhere near what was expected. A second check on the strand size and break strength showed that the material met the required specifications. Two lengths of Cable B provided the same results as Cable A.

Several lengths of the braid were again examined and no flaws could be observed. The interlayer Mylar tape was well applied, the braid angles on both the inner and outer layers corresponded within a few tenths of a degree, and there were no cuts or lumps on the braid. However, it was noticed that the latex compound applied to bond the nylon jacket to the Kevlar had permeated the inner Kevlar layer at several points. This resulted in bonding the inner Kevlar layer to the electrical conductor at those points. In previous tests where latex was purposely applied between the Kevlar layers, the cable performance had suffered, but not to this extent. The intralayer abrasion appeared as severe as in previous cables that had failed at about 8000 cycles. These results were extremely perplexing and necessitated further testing to determine the cause of these early failures.

D. PRE-PROTOTYPE CABLE

Three new cables were designed and manufactured (P,Q,R series) in such a manner as to determine if the problems encountered in the pilot cable test series were caused by:

1. The strands being packed too tightly caused intralayer abrasion and compression failure.

2. A latex compound on the inner layer of Kevlar caused it to lock, thereby allowing the load to be carried on only the outer layer.

3. The abrasion resistance of Kevlar 49 was unacceptable.

Tests were conducted on several specimens of three different constructions: a 48-carrier, K-29 cable (P); a 48-carrier, K-49 cable (Q); and a 32-carrier, K-49 cable (R). The results, although enlightening, did present another problem. The cable constructed of Kevlar 49 apparently outperformed the Kevlar 29 cable in bend-over-sheave tests. This information was in conflict with previously reported data. Subsequently, strands were removed from each cable, coded, and returned to the factory for confirmation of material specifications. As suspected, there had been a mix-up in the construction process and the cable marked 49 was, in reality, 29, and vice versa. A second series of coded strands was returned to substantiate the first, with positive results. This finding then raised doubts about the material in each of the previous cables. Table 5 lists the actual performance of the cables corrected as to material and cycles.

Strands were then removed from the remaining specimens of the initial Kevlar coaxial cable which had been so successful in the sheave cycling tests. These strands were also returned to the factory for testing, and were also shown to be constructed of Kevlar 29. This explained the reduction in number of cycles to failure observed in the successive cables, which definitely were structured of Kevlar 49.

It should be pointed out that the simplest method of making a positive identification of strand composition is by performing a load elongation test. Both Kevlar 29 and 49 have the same break strength for equal strand size; however, the material elongation near the ultimate strength is sufficiently different (2.5% versus 3.5%) to distinguish between the two. This has been discussed with DuPont and they are presently considering various methods of enabling visual identification of strand type.

Upon analysis of the P,Q,R series, and reexamination of the A,B,C series, including the manufacturing process for both, several conclusions concerning the failure modes were possible.

1. The premature failure of the A,B,C series was caused by uneven sharing of the load between the two layers. This was not because of latex binding the inner layer as originally suspected, but rather, due to a faulty manufacturing process. A review of the production log showed a change in the braider sp tension, conceivably causing the outer layer to be relatively loose as compared to the inner layer. This was not discernible when the cable was jacketed with a tight nylon braid. By observing a reconstruction of the pilot cable, however, the reasons for its perplexing behavior became quite clear. The inner layer was applied under a fixed tension over the polyurethane jacketed core and immediately wrapped with Mylar tape. The outer layer was applied under tension, but over the slippery tape. There were many times during the takeup reeling process that the cable slackened, allowing the outer layer to readjust itself, loosening the weave. Thus, the inner layer carried most, if not all, of the load. This problem can be alleviated by maintaining a constant takeup tension.

2. Kevlar 29 out-performs Kevlar 49 in this particular application. The superior abrasion resistance of K-29 is well-documented. Kevlar 49 had been originally chosen for this cable because its elongation is approximately 30% less than that of K-29. In order to avoid applying additional stress on the coax, inherent to the greater stretch, a lesser abrasion resistance had been considered a reasonable trade-off. Tests have shown, however, that the coax can survive the greater elongation and provide a longer sheave cycling life with the use of K-29.

TABLE 5

CYCLIC BENDING TESTS COMPARING KEVLAR 49 WITH KEVLAR 29

Cable Designation	Kevlar Type	No. of Ends Per Layer	TENSION kN	(lbs)	Cycles to Failure
P1	29	48	18.7	(4200)	6,830
P2	29	48	18.7	(4200)	8,884
Q1	49	48	18.7	(4200)	3,014
Q2	49	48	18.7	(4200)	5,082
R1	49	32	18.7	(4200)	1,456
R2	49	32	18.7	(4200)	3,676
R3	49	32	12.5	(2800)	10,054
R4	49	32	12.5	(2800)	15,154

D/d =2-/1
1) Sheave Diameter = 38 cm
2) Braid Angle 24°

The 29 (P) outperformed the 49 (Q) by almost a factor of two. All of the cable samples maintained electrical continuity until rupture. From this information, coupled with the fact that the previous most successful cable was also 29, it can be concluded that 29 is the proper choice for this application.

3. Strand packing is not a problem under axial load; results under bending are inconclusive at this time. As an axial load is applied to an unsupported tubular braid, it collapses to a locked position. When this condition exists, the edges of the strands are in contact with each other, causing a compressive transverse loading and high abrasive forces. However, in the cable-under test, the braid is supported on the core. The reduction in the diameter of the cable under axial load is on the order of 0.15 cm. When the core is removed and the braid tensioned, the reduction is on the order of 0.38 cm, showing that the "locked" condition has not been achieved under axial tension loading. The possibility remains, however, that locking is occurring under bending conditions.

4. The braid angles of the two layers of Kevlar should remain similar to each other. A review of the mathematical equations on helix angle versus bending radius shows the relationship between the two layers (Lily, 1974). With similar braid angles, the outer layer is required to stretch about 0.1% more than the inner layer over the same bending radius. This represents about a 5% increase in stress on the outer layer. To compensate, the braid angle of the outer layer should be increased by a few degrees.

In order to ascertain if the effects of straight axial tension were adding to or canceling the increased stress, a review of the braid's mechanical behavior was also initiated. The calculations show that to achieve ideal load sharing characteristics, the braid angle of the outer layer should be less than the inner layer. Figure 6 is a curve of the theoretical strength efficiency for a 22° braid angle cable with a constant crimp angle versus the braid angle in degrees. With the same angle on both layers, the inner layer has a strength efficiency of 0.78 (Point A). The outer layer has an efficiency of about 0.69 (Point B). If the outer layer braid angle is reduced to 18°, its efficiency is also raised to approximately 0.78 (Point C). This represents about a 6% difference in the stress levels on the two layers (Tucchio, 1977).

Consequently, with the two opposing requirements of increasing the outer layer braid angle to improve bending performance and decreasing the outer layer braid angle to improve break strength efficiency, it was decided that the braid angle on the two layers should remain the same.

E. PROTOTYPE CABLE

All of the pilot series cables were constructed with an outside diameter (O.D.) of 1.83 cm. When loaded to 18.7 kN, the O.D. of the cable was reduced to about 1.68 cm, causing the cable to be undersized for the designed sheave groove radius (1.75 cm). To avoid this, and to also insure that the inner layer strands were not approaching the locked position in bending, both the inner and outer layer of aramid braid were redesigned. The original inner layer was constructed of 48 strands with four ends of aramid in each strand (48 X 4 = 192 ends). It was changed to a 32 strand braid with 6 ends in each strand (6 X 32 = 192 ends). On the positive side, this maintained the same total number of strength members, but reduced the number of times they had to cross each other. It displaced the material, allowing more breathing room in the weave, and made the layer thicker. On the negative side, it increased the crimp angle by a few percent. The only change

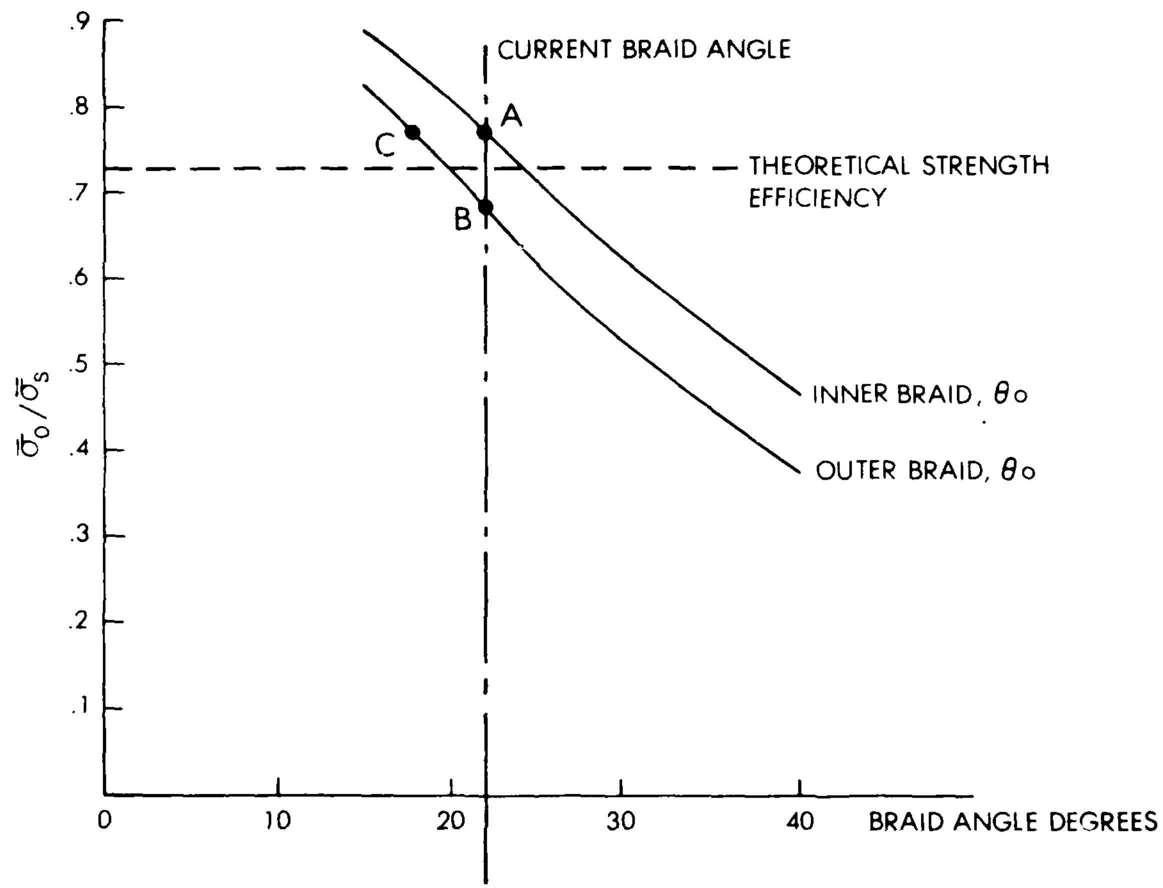

FIGURE 6 STRENGTH EFFICIENCY VERSUS BRAID ANGLE FOR INNER AND OUTER LAYERS

in the outer layer was the removal of one end from each of the 48 strands - from 48 strands/seven ends per strand to 48 strands/six ends per strand. This reconfiguration reduced the break strength by about 10%, increased the cable's O.D. under working load to the desired size, and increased the cable's bending fatigue life. Figure 7 shows the cable construction details.

A total of 38 samples of the prototype cable were subjected to three types of mechanical tests to determine the physical and electrical characteristics. First, elongation versus tension was measured on three specimens as they were pulled to failure. Second, a total of 27 specimens were subjected to a series of cyclic bend-over-sheave fatigue tests using two sheave diameters and five tension loads. Finally, eight specimens were tested in cyclic-axial-tension fatigue at two tension loads.

1. Tension Elongation

Three specimens were subjected to elongation versus static-straight-tension and then broken (Nos. 13,14,15). Each specimen was 15.25 m (50 ft) long. One end was wrapped 2-1/2 times around a flat-surfaced drum grip, with the free end terminated in a clamp. The other end of the specimen was wrapped 180° around a sheave that had a pitch diameter of 73 cm (29 in); the free end was wrapped 2-1/2 times around the drum grip and also terminated with a clamp. The ends of the cable were prepared to allow measurement of conductor resistance and insulation resistance, as well as electrical continuity during the pull to break test. An extensiometer was attached to one straight section of the specimen using a 127 cm gauge length. The attachment points were located some distance away from the sheave and drum grip tangent points to avoid end effects.

Specimen 13 was tension-cycled 10 times to 22.5 kN (5000 lbf) and then pulled to failure. Specimens 14 and 15 were tension-cycled 10 times to 35 kN (7870 lbf) before being pulled to failure. Electrical measurements were made on the specimens before and after the first 10 load cycles, as well as while the specimens were held under tension on the ninth load cycle. These measurements include resistance of the core conductor and the shield conductor, as well as the insulation resistance between them with an applied potential of 4500 Vdc. Electrical continuity of the center conductor and shield was measured during the pull-to-break test and was continuous in all specimens up to the point of complete cable failure. The results of the pull-to-break tests appear in Table 6.

2. Cyclic-Bend-Over-Sheave Fatigue Tests

A total of 27 specimens were subjected to cyclic bending fatigue tests at various cable tensions. Two sheave diameters were used providing D/d (sheave diameter/cable diameters) ratios of 20 and 40. All the specimens were terminated using Philadelphia Resins A-14 epoxy in 3/4-inch open sockets.

a. D/d = 20

The D/d = 20 tests were performed on a vertical test machine. Each specimen had an electrical length of 305 cm (120 in) and a mechanical length of 239 cm (94 in) nose-to-nose.

Two cable specimens were tested simultaneously, one wrapped over each of two test sheaves. The sheaves had a tread diameter of 37 cm and a groove

KEVLAR COAXIAL CABLE

CABLE CHARACTERISTICS

Imped: 500 kHz to 1 mHz = 40 ± 8 Ω
Cap: 39 ± 7 pf/ft.
Atten: Max at 500 kHz = 1.5db/1000 ft.
Cent. Cond = 1.67 Ω/1000 ft.
Out. Cond = 1.31 Ω/1000 ft.

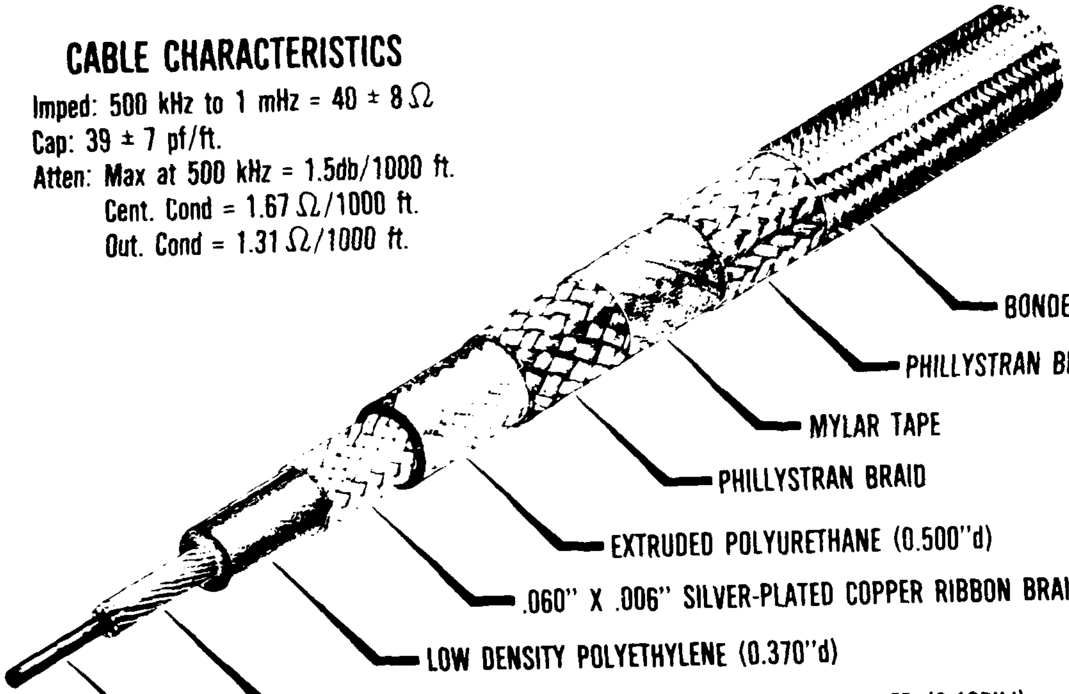

FIGURE 7 PROTOTYPE CABLE CONSTRUCTION DETAILS

TABLE 6

AXIAL TENSION TESTS

SPEC. NO.	TENSION kN (lbf)	CYCLES	RESISTANCE OF CORE CONDUCTOR (mΩ)	RESISTANCE OF SHIELD CONDUCTOR (mΩ)	LEAKAGE CURRENT AT 4500 VDC (μA)	INSULATION RESISTANCE AT 4500 VDC (mΩ)	ELECTRICAL CONTINUITY CONTINUOUS UNTIL BREAK	BREAKING STRENGTH lbf	POINT OF FAILURE
PR 13	0	0	60.3	64.9	<.01	>450,000			
PR 13	22.2 (5000)	9.5	59.8	61.3	<.01	>450,000			
PR 13	0	10	60.2	64.8	<.01	>450,000			Drum Grip
PR 13	-	-	-	-	-	-	Not monitored	15,060	Tangent Point
PR 14	0	0	59.6	65.3	<.01	>450,000			
PR 14	34.7 (7800)	9.5	60.3	59.7	<.01	>450,000			
PR 14	0	10	60.6	64.4	.1	>450,000			Drum Grip
PR 14	-	-	-	-	-	-	Yes	15,500	Tangent Point
PR 15	0	0	60.2	65.5	<.01	>450,000			
PR 15	34.7 (7800)	9.5	60.5	65.5	<.01	>450,000			
PR 15	0	10	60.8	64.5	<.01	>450,000			Sheave
PR 15	-	-	-	-	-	-	Yes	15,500	Tangent Point
PR 16	35.5 (8000)	9	-	-	-	-	Not monitored		
PR 16		10						17,800	Center Break

NOTES: Specimen electrical length is 1524 cm (50 ft).
Distance between drum and sheave tangent points is 213 cm (7 ft).
Diameter of drum grip is 63.5 cm (25 in) - flat surface.
Diameter of sheave is 73 cm (28.7 in) - groove diameter = 1.83 cm (0.72 in).
No. 16 had epoxy potted end fittings installed at factory.

diameter of 1.83 cm. A 104 cm cycling stroke allowed a 46 cm test section of the cable to pass onto, around, and off the test sheave during each stroke of the machine. Thus, each machine cycle produced two straight-bend-straight cable bending cycles. The tests were conducted at a cycle rate of 1200 cable bending cycles per hour (600 machine cycles per hour) at 18.7 kN load.

Cycling continued until a specimen failed, at which time it was replaced with a "dummy", and the test continued until failure of the second specimen occurred. If a specimen achieved 75,000 cable bend cycles, the test was terminated and the remaining breaking strength of the cable was measured. Measurements of core conductor resistance, shield conductor resistance, and leakage current between the shield and core with an applied voltage of 4500 Vdc were made periodically during the tests.

The results of the mechanical tests for D/d = 20 appear in Table 7. All of the D/d = 20 test specimens failed before completing 75,000 bend cycles; therefore, no remaining breaking strength tests were performed. The resistance of the shield conductor increased as the specimens were cycled, with Specimen 4 exhibiting the largest increase (+28%). Core conductor resistance also increased, with Specimen 29 exhibiting the largest change (+9%). No significant changes occurred in the electrical insulation resistance during the tests.

b. D/d = 40

The D/d = 40 tests were performed on the same vertical test machine. These test sheaves had a tread diameter of 71 cm (28 in) and a groove diameter of 1.83 cm (0.72 in). The specimens had a nose-to-nose electrical length of 427 cm (168 in) and a mechanical length of 361 cm (142 in). The specimens were cycled at a rate of 1200 bending cycles per hour at various tension loads. Electrical measurements of conductor and insulation resistance were made periodically during the tests.

The results of the mechanical tests for D/d = 40 appear in Table 8. Four of these specimens survived 75,000 cycles without failure and were subjected to remaining breaking strength tests. Conductor electrical resistance increased as the specimens were cycled, with Specimen 17 exhibiting the greatest shield resistance increase (+10%) and Specimen 21 exhibiting the greatest core resistance increase (+9%). No significant changes occurred in the electrical insulation resistance during the tests.

3. Performance Of Cables As A Function Of Various Parameters

There are three methods of improving the performance of a braided cable in the cycling fatigue mode:

(a) Increase the braid helix angle.

(b) Decrease the operating load.

(c) Increase the D/d ratio.

Strength-member braid angle has a large effect on a cable's cycling fatigue behavior, as can be seen in Figure 8. The data plotted on this graph are for cables with similar construction; however, the two curves are for two different

TABLE 7

PROTOTYPE CABLE CYCLIC BEND-OVER-SHEAVE FATIGUE TESTS (D/d=20)

Sheave diameter = 37 cm (14.56 in).
Sheave groove diameter = 1.84 cm (0.724 in)
Cycling stroke = 104 cm (41 in)
Length of test section = 46 cm (18 in)
Cycle rate = 1,200 CPH

SPECIMEN NUMBER	CABLE TENSION kN	(lbf)	ULTIMATE BREAK STRENGTH	BENDING CYCLES TO FAILURE
PR 5	13.35	(3,000)	17	36,382
PR 6	13.35	(3,000)	17	35,622
PR 7	13.35	(3,000)	17	41,718
PR 8	13.35	(3,000)	17	32,664
PR 1	18.7	(4,200)	23	21,038
PR 2	18.7	(4,200)	23	12,240
PR 3	18.7	(4,200)	23	18,124
PR 4	18.7	(4,200)	23	28,696
PR 9	24.5	(5,500)	31	5,400
PR 10	24.5	(5,500)	31	8,644
PR 11	24.5	(5,500)	31	7,640
PR 12	24.5	(5,500)	31	5,380
PR 29	31.1	(7,000)	39	1,404
PR 30	31.1	(7,000)	39	528
PR 37	31.1	(7,000)	39	1,900
PR 38	31.1	(7,000)	39	2,470

1) Cable-bending cycles per hour (one machine cycle=two straight-bent-straight cable bending cycles).

2) Electrical continuity and insulation resistance remained within acceptable limits during all tests.

TABLE 8

PROTOTYPE CABLE CYCLIC BEND-OVER-SHEAVE FATIGUE TESTS (D/d=40)

Sheave diameter = 71 cm (28 in)
Sheave groove diameter = 1.83 cm (0.720 in)
Cycling stroke = 158 cm (62 in)
Length of test section = 46 cm (18 in)
Cycle rate (1) = 1,200 CPH

Specimen Number	Cable Tension kN	(lbf)	Bending Cycles To Failure (2)	Measured Remaining Breaking Strength kN	(lbf)(4)
PR 17	24.5	(5,500)	75,000(3)	66.0	(14,840)
PR 18	24.5	(5,500)	75,000(3)	61.0	(13,710)
PR 19	24.5	(5,500)	75,000(3)	61.5	(13,830)
PR 20	24.5	(5,500)	75,000(3)	59.0	(13,260)
PR 21	31.1	(7,000)	56,568	--	
PR 22	31.1	(7,000)	8,328	--	
PR 23	31.1	(7,000)	34,802	--	
PR 24	31.1	(7,000)	40,970	--	
PR 25	53.4	(12,000)	8	--	
PR 27	53.4	(12,000)	6		
PR 28	53.4	(12,000)	10		

1) Cable-bending-cycles per hour (one machine cycle=two straight-ben - straight cable bending cycles

2) Electrical continuity and insulation resistance remained within acceptable limits during all tests.

3) Cycling was halted after a maximum of 75,000 cycles were completed.

4) During the breaking strength tests, all specimens failed at sockets and not in the test section.

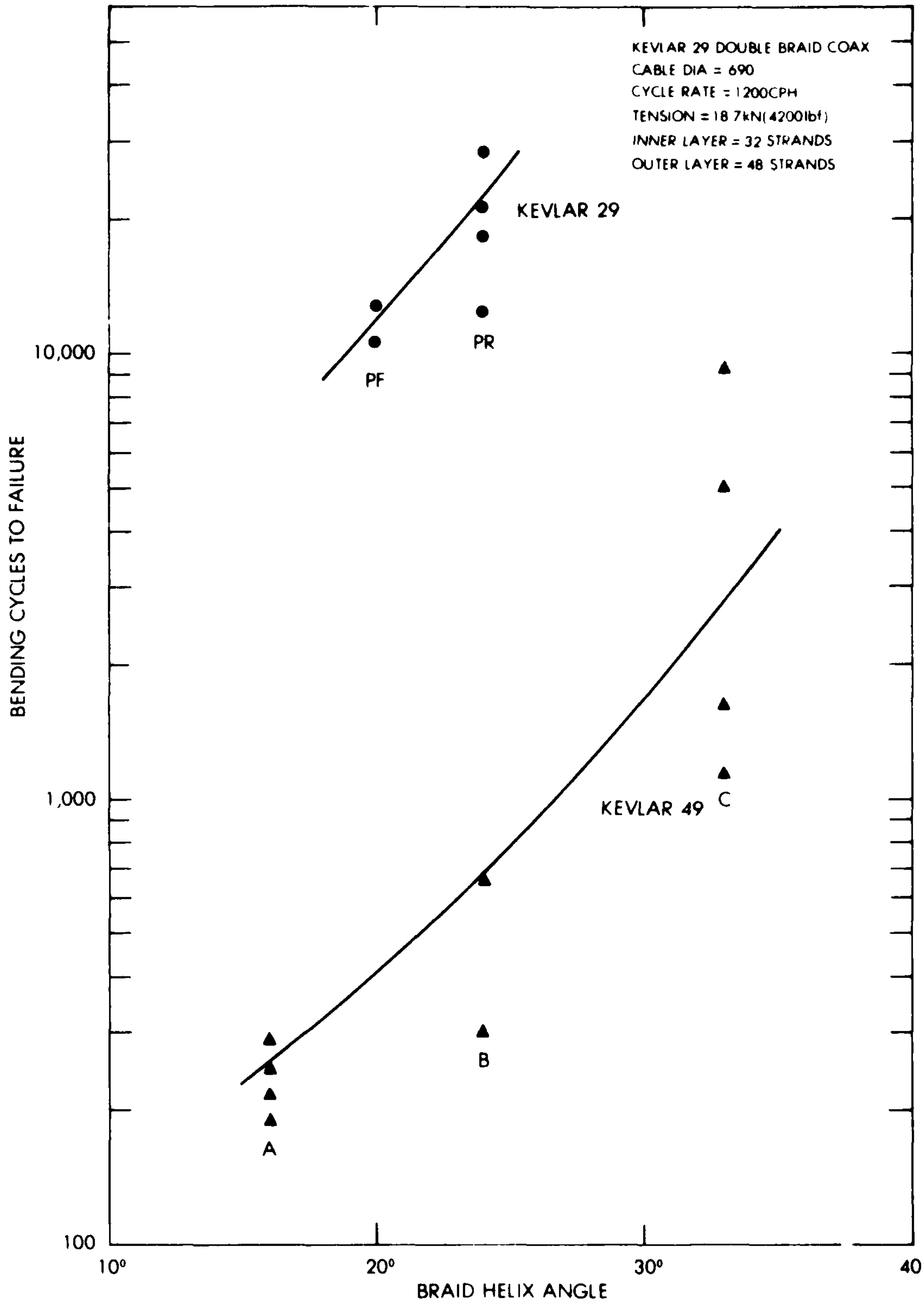

FIGURE 8 CYCLES TO FAILURE AS A FUNCTION OF BRAID HELIX ANGLE

TABLE 9

CABLE STRENGTH AS A FUNCTION OF BRAID ANGLE

Cable Test Series No.	Cable Type	Avg. Axial Breaking Strength(1) kN	(lbf)	Avg. Breaking Strength Over 71 cm. Sheave(2) kN	(lbf)	Percent Braid Strength Efficiency(3)
A	K49-16°	77.8	(17,500)	75.4	(16,900)	60
B	K49-24°	65.8	(14,800)	53.4	(12,000)	48
C	K49-33°	45.8	(10,300)	40.5	(9,100)	34
PF	K29-20°	84.5	(19,000)	----	-----	65
PR	K29-24°	73.4	(16,500)	68.9	(15,500)	63

1) Most ruptures occurred at cable termination.

2) Most ruptures occurred at sheave tangent point.

3) $\left(\frac{\text{Axial Break Strength of Cable}}{\text{Aggregate Strength of All Strands in Cable}} \right) \times 100$

TABLE 10

CABLE ELONGATION AS A FUNCTION OF BRAID ANGLE

Cable Test Series No.	Kevlar Type	Braid Angle Degrees	Percent Total Elongation at 18.7 kN(1)	Percent Stabilized Elastic Elongation After Cycling at 18.7 kN	Percent Elongation Per 1 kN(2)
A	49	16	-	-	
B	49	24	2.0	85	0.28
C	49	33	4.4	1.95	0.12
PF	29	20	2.3	0.6	0.039
PR	29	24	2.6	0.75	0.14

1) Total elongation includes effect of constructional elastic stretch.

2) Average stabilized elongation divided by tension in linear region.

3) All cables have identical cores.

materials - Kevlar 49 and Kevlar 29. As can be observed, Kevlar 29 outperforms Kevlar 49 in this application, and this information is supported by all previous work. If the angle is increased as the load remains constant, the stress on each strand is increased as a function of the cosine of the angle. At higher stress levels, the time or cycles to rupture have more scatter. This has also been observed in all the tests. Additionally, the cable's maximum strength and its elongation characteristics are affected. Table 9 shows the decrease in break strength with increasing braid angle. Table 10 lists the various stretch properties of each cable.

Figure 9 summarizes the data on one cable construction at various tensions and two D/d ratios. As expected, tension has a significant effect on cable lifetime. Again as the load is increased, data scatter increases.

4. Cyclic-Straight-Tension (CST) Fatigue Tests

Eight specimens were tested in CST fatigue at both 25% and 50% of break strength. Specimen 33 was tested, using 12 in diameter flat drum grips, but failed after less than 5,000 cycles. As a result of this test, all other CST specimens were terminated using Philadelphia Resins A14C epoxy in 3/4-inch open sockets. A cable breaking strength of 72 kN (16,200 lbf) was assumed for test purposes. Two specimens were tested simultaneously, and cycling continued until both specimens failed or 100,000 axial cycles were completed.

Measurements of core and shield conductor resistance and leakage current between the shield and core at 4500 Vdc were made periodically during the tests. Note that the insulation resistance may be calculated from the leakage current measurements. The results of the mechanical tests appear in Table 11. Following the axial fatigue tests, all specimens were reterminated using Kellums grips and their breaking strengths measured. This test data is also summarized in Table 11.

Dissection of fatigue Specimen 40 (100,000 cycles at 25% breaking strength) revealed no damage to the cable conductors or insulation. Dissection of fatigue Specimen 41 (100,000 cycles at 50% breaking strength) revealed that the flat braid wires of the shield conductor were broken at the crimp angles throughout the length of the specimen. This damage is reflected in the increased electrical resistance of the shield conductor measured on Specimen 41. Specimen 40 exhibited virtually no change in shield conductor electrical resistance during the 100,000 cycle test at 25% breaking strength. Specimen 41, on the other hand, suffered resistance increase of +7% at the low tension and +20% at the high tension.

Both the axial and bending fatigue performance of the cable were more than satisfactory; however, the break strength was about 20% below that which was needed. This necessitated a final attempt at rearranging the mechanical components within the existing size limitation. Each strand of the 32 part braid was increased by one 1500 denier end, from six ends per strand to seven ends per strand. In addition, the braid helix angle was reduced from 24° to 20° on both layers. Tests showed an increase in average break strength of only about 10% (73.4 kN to 82.3 kN), coinciding with the expected decrease in the average number of bending cycles to failure on the order of 40%.

Because the bending tests are wrapped 180° around such a small diameter sheave (37 cm) and cycled over the same portion of the cable, they are much

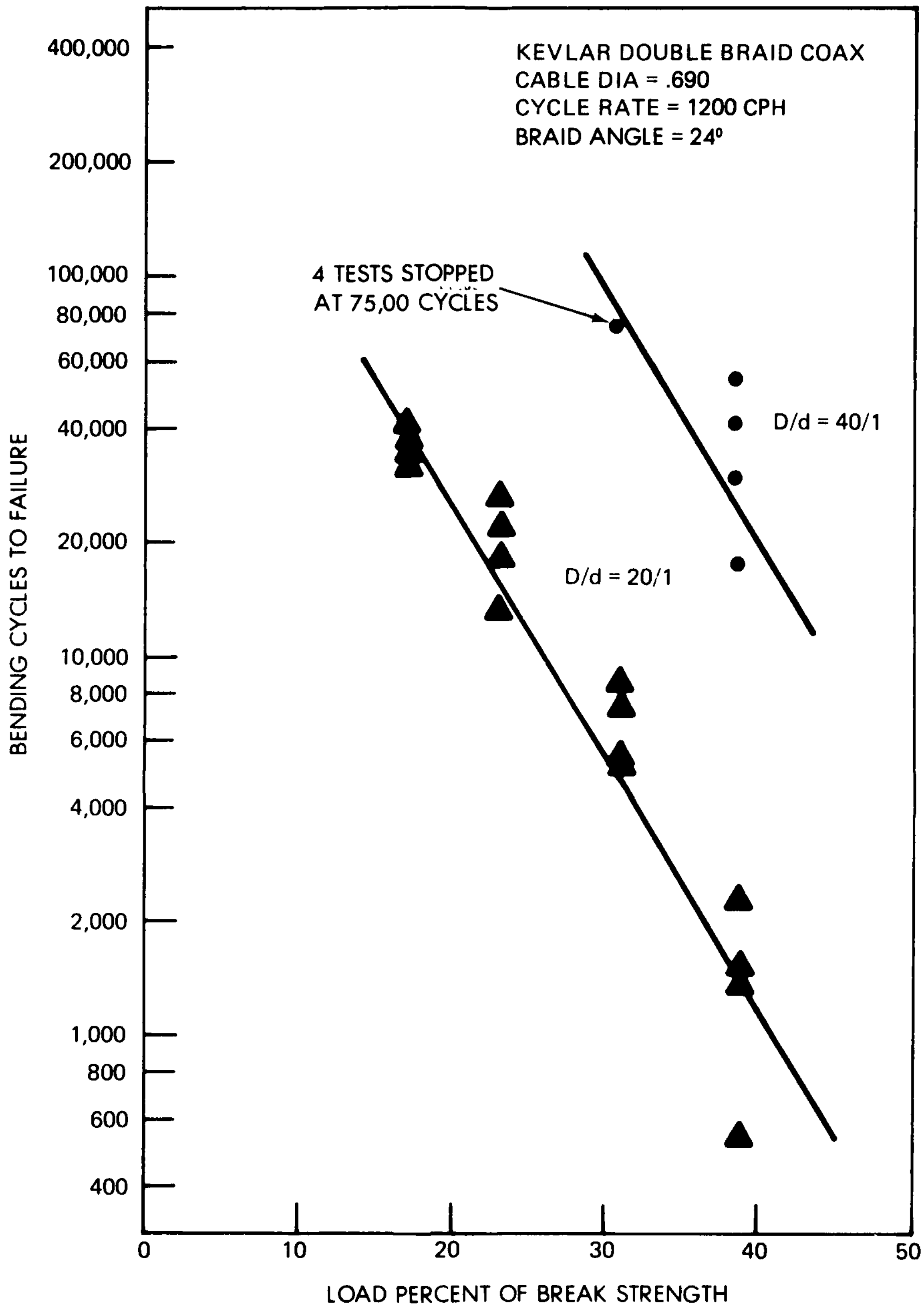

FIGURE 9 CYCLES TO FAILURE AS A FUNCTION OF CABLE TENSION

TABLE 11

PROTOTYPE CABLE CYCLIC STRAIGHT-TENSION TESTS AT 25 AND 50 PERCENT OF CABLE BREAKING STRENGTH

25% of breaking strength = 18 kN (4050 lbf)
50% of breaking strength = 36 kN (8100 lbf)
CST cycling rate = 0.1 Hz (360 CPH)

Specimen Number	Percent of Breaking Strength	CST Cycles to Failure	Remaining Breaking Strength (5)
34	25(3)	100,000(2)	75,500 kN (16,970 lbf)
35	25(3)	100,000(2)	70,500 kN (15,850 lbf)
39	25(3)	100,000(2)	75,200 kN (16,900 lbf)
40	25(3)	100,000(2)	71,500 kN (16,070 lbf)
31	50(4)	39,540(1)	70,500 kN (15,950 lbf)
32	50(4)	67,419(1)	64,500 kN (14,500 lbf)
41	50(4)	100,000(2)	74,200 kN (16,680 lbf)
42	50(4)	54,415(1)	67,700 kN (15,220 lbf)

1) Failure occurred at nose of socket.

2) Stopped test at 100,000 cycles.

3) 25% of breaking strength test=2.5 kN (550 lbf) minimum tension to 18 kN (4050 lbf) maximum tension.

4) 50% of breaking strength test = 5 kN (1100 lbf) minimum tension to 36 kN (8100 lbf) maximum tension.

5) Cable specimens were terminated with Kellums grips for the remaining breaking strength tests.

more severe than would be seen under normal operating conditions. The lowest figure of 11,000 cycles at 25% of break strength over a 20:1 ratio bend can be considered outstanding performance for this synthetic fiber electromechanical cable.

IV. ADDITIONAL RELATED DEVELOPMENTS

A. TERMINATIONS

Several different types of terminations were used in the test program: Newco thimble clamp combinations, both spelter sockets and Reliable potting heads with Epoxy; Kellums grips; Philly net, a urethane-coated, braided Kevlar strand; and a back-braided splice.

The hard massive type end fittings usually produced break strengths during static loading on the order of 10% below those that spread the load over several feet of cable. In addition, the breaks usually occurred near the sockets. They allowed little readjustment of the layers for proper load sharing over the relatively short sample lengths. This may prove not to be a problem over long lengths of cable. In dynamic tests, the cables were apparently more severely damaged near the sockets, and always failed at that point when tested for residual break strength.

With this aramid reinforced cable, as with almost all fiber ropes and cables, the softer, more flexible end fitting performs better. The transition from a compliant structure to a hard heavy mass is eased. The load transfer region changes from an area of a few square inches to a square foot or more. Finally, because the end splice or grip is always designed with a break strength greater than that of the cable, the system becomes stronger at what was its weakest point.

B. SINGLE BRAIDED LAYER

In order to pinpoint the modes of failure in cyclic bending, several types of cable were tested under the layer isolation work discussed in Section III.C. One suspected bit of information obtained from these tests was the outstanding bending fatigue performance of the single braided layer of aramid fiber. The actual D/d ratio was 24:1 for a 1.6 cm diameter cable. Loaded at [illegible].7 kN (1[illegible] lbf), this cable survived approximately 100,000 cycles before failing. The single layer eliminated the problems experienced in load sharing among multiple layers, and halved the bearing pressure per layer. This suggests that for bending applications, the single layer is the more efficient design, providing, of course, that the circumference of the core allows for sufficient fiber to achieve the desired strength in one layer.

C. MINILINE* COAXIAL CABLE

Late in 1977 DuPont introduced waxed Kevlar strand, which Wall Rope Works used to develop their Miniline series of ropes. Long-term axial creep and break strength tests showed this cable to be a very efficient application of aramid fiber. Wall Rope overbraided a 60 m length of surplus coaxial core for testing.

*Trademark of Wall Industries, Inc.

The rope is constructed of eight strands of waxed Kevlar 29 woven into a long pick braid.

The first series of bend cycling tests were run on a 1.25 cm Miniline rope with no core. Its breaking strength was approximately 111.2 kN. The results of the bending tests were excellent at large D/d ratios, but not very promising at a load of 20% of breaking strength over a 20:1 D/d ratio (Table 12, Part A). The second series consisted of the same rope construction over a R.G. 58/U coax and results were similar to the first series (Table 12, Part B).

The third series had the specially designed coax as a core. This 1.25 cm diameter electrical cable increased the rope's diameter to about 1.9 cm, increased the braid's helix angle, and reduced its tensile strength to about 88.96 kN. Table 12, Part C, lists the two samples tested. The results indicated that this design would not be as reliable over small sheave-to-rope diameters as the impregnated two-layer construction presently employed. The one conclusion that can be drawn is that increasing the D/d ratio helps far more than reducing load.

D. MANUFACTURING PROBLEMS

During construction of the different iterations of pilot and prototype cables, several problems appeared in the manufacturing process. Each defect found in the cable was correctable through careful quality control, but first had to be identified.

When the change was made in strand configuration from a round cross-sectional area to an oval shape, more care had to be taken in winding the bobbins. In the first cable produced with this flattened shape, the strands had several twists and turns per meter, weakening the entire braid. The bobbin's winding process was then improved by feeding the strand evenly and smoothly to avoid crimps and twists.

A second, more serious problem and one that plagued the entire series of test cables was the changing of the cable take-up-tension during the braiding process. Relaxing or increasing the spooling tension of the braided cable changed the rate of cable feed to the extent that the lay angle of the braid was varied by a few degrees over several meters of cable. This probably would not seriously affect the performance of long lengths of single-layer braid other than to cause much scatter in test specimen data. However, it can be very detrimental in multilayer cables. The cable's performance depends on proper load sharing; if one layer is applied more loosely than another, there will be unequal division of the burden. Specimens from one poorly constructed length consistently ruptured at the break strength of the inner layer, then passed the load to the outer layer, which immediately ruptured at the same load. The construction problem in this case was more pronounced because the inner layer was braided and immediately wrapped with Mylar tape prior to spooling. The outer layer, however, had no constraint after braiding, and with each slack period in the erratic take-up process, it loosened. This difficulty was also corrected.

A final, completely unexpected error occurred in the mixup of the fiber material at the manufacturer's plant. The appearance of Kevlar 49 and Kevlar 29 are identical; only load elongation curves can distinguish between the two. Although they were labeled by DuPont, somehow one was substituted for the other. If this happened on just a few strands of the cable, its performance would obviously be

TABLE 12

WAXED KEVLAR "MINILINE" BENDING FATIGUE TESTS

D/d	% of Breaking Strength	Bend Cycles	% of Residual Breaking Strength
20/1	30	226	Failed
46/1	30	12,000	64
36/1	20	12,000	68
46/1	20	12,000	80
20/1	20	734	Failed
20/1	10	5,882	Failed
	B. Rope with RG -- 58		
46/1	20	6,000	81
20/1	10	5,880	Failed
	C. Rope with Special Design Coax		
40/1	20	120,000	65
24/1	10	13,652	Failed

degraded. This has been discussed with DuPont, and the suggestion made that at least one of the types ought to contain a single-colored filament for identification purposes.

V. SUMMARY

The objective of this program was to develop a lightweight, torque-free, coaxial, electromechanical cable for oceanographic use. Because there was little precedence upon which to base the expected optimum performance of a Kevlar braided cable, several iterations of design, construction and testing were necessary. This work yielded several end products: First, a newly designed electrical coaxial cable capable of maintaining its D.C. electrical characteristics despite the many stretching and bending cycles required; second, a braided, torque-free, lightweight mechanical cable with the ability to withstand many thousands of bending cycles over small diameter sheaves, and, finally, the ability of industry to now produce a potentially successful cable with a more comprehensive knowledge of braided rope construction.

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