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INVESTIGATION OF KEVLAR FIBER CABLES FOR USE IN ASW SONOBUOYS

John P. Brett, et al

Naval Air Development Center

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The initial phase of an investigation of kevlar fibers for application in ASW sonobuoy cables has been completed. The tensile and elongation properties of kevlar have been shown to be comparable to steel, and electro-mechanical cables constructed of kevlar have been shown to perform better than equivalent size steel cables. Further investigation to optimize the use of kevlar and to assure consistent results under rigorous testing is planned.

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SUMMARY

INTRODUCTION

The present interest in deep ocean sonobuoys has created the requirement for lightweight, high-strength cables. In shallow applications, copper-clad steel, brass-plated steel, or a combination of copper and steel is in general use; however, for deep applications, the high density of steel adds considerably to the sonobuoy weight and causes a significant portion of the cable strength to be employed in supporting the cable itself, resulting in either a loss of safety factor or an increase in cable diameter to maintain safety factor. In deep applications, torque-balancing and compact packaging problems arise because of the modulus of rigidity and modulus in bending of steel members.

Kevlar, a new organic fiber manufactured by E.I. duPont de Nemours and Company, shows promise as a strength member to replace steel in electromechanical cables. In addition to high tensile and low elongation properties comparable to those of steel, kevlar has a density and flexibility similar to that of nylon, dacron, and other fibers. To determine the applicability of kevlar to sonobuoy cables and to provide the sonobuoy industry with data and technical information on kevlar cables suitable for use in drifting and moored sonobuoys, an investigation was undertaken by this command.

RESULTS

1. The tensile strength of kevlar 29 has been observed to vary significantly with cable design and manufacturer processing, ranging from 330,000 to 383,000 psi with breaking elongations from 2.4 to 3.8 percent.

2. Elongation of helical lay design kevlar cables was observed to increase with increased lay angle, and helical lay kevlar designs were found to have significant torque under load.

3. Static fatigue of kevlar cable was observed when the loading was greater than 70 percent of ultimate tensile strength; however, no evidence of static fatigue was observed at loads less than 70 percent of ultimate tensile.

4. Of four ERAPS kevlar cables designed by different manufacturers, the Berk-Tek braid design was acceptable mechanically and electrically and performed successfully at sea; the South Bay design was unacceptable mechanically; both the Philadelphia Resins and Cortland designs did not have acceptable water integrity.

5. The Berk-Tek braid design exhibited a pop-through of the insulated conductor on rapid release of load because of the dissimilar elastic properties of kevlar and copper. The effect of this phenomenon in sonobuoy applications is not well defined.

6. After the initial elongation of kevlar cable under load, negligible creep due to static and dynamic loading was observed.

CONCLUSIONS

1. Kevlar fibers possess tensile and elongation properties comparable to those of high tensile steel, while maintaining the low density and flexibility of organic fibers, and they can be utilized in sonobuoy applications as the cable strength member in place of steel.

2. When properly designed, a kevlar cable is capable of providing improved mechanical properties and the same electrical properties as a steel cable. These can include: higher breakstrength, higher safety factor, lower cable weight, negligible torque, and easier packaging and handling.

3. A kevlar cable (the Berk-Tek braid design) has been tested in the laboratory and at sea, and it is considered to be suitable for inclusion in the ERAPS system and to be superior to the steel ERAPS cable.

4. Further investigation of kevlar cables is required, particularly in the following areas: use in smaller and larger sonobuoy cables, kevlar 49 cables compared to kevlar 29 cables, the effect of long term loading and ocean exposure on cables, the possible solutions to cable pop-through, and cable terminations.

BACKGROUND

There are two varieties of kevlar, kevlar 29 aramid and kevlar 49 aramid (formerly called fiber B and PRD-49, respectively). The principal differences between them are the lower elastic modulus, higher elongation, and lower cost of kevlar 29. The experimental data in this report refer to kevlar 29.

Kevlar is supplied as a continuous multifilament yarn in a number of standard deniers (fineness defined as weight in grams of 9000 meters of yarn) and is available in virtually unlimited lengths. With a density of 0.052 lb/in.^{3}, kevlar weighs less than 20 percent of an equivalent volume of steel, while exhibiting the strength of steel. A comparison of the mechanical properties of various strength member materials is shown in table I, where values have been generalized from a number of sources.[1-5] The problems with

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1. *Sturgeon, D.L., Wolffe, R.A., Miner, L.H., and Wagle, D.G.; PRD-49 Fiber and Composite Performance; E.I. duPont de Nemours and Co., Inc.*
2. *Moore. J.W.; A New Organic High Modulus Reinforcing Fiber; E.I. duPont de Nemours and Co., Inc.*
3. *Swenson, R.C. and Stoltz, R.A.; Design and Construction of Cables for Sensor Systems; Sea Technology, Oct and Nov 1973.*
4. *High Strength Lines and Cables; Cortland Line Company.*
5. *Hightower, J.D., Wilkins, G.A., and Rosencrantz, D.M.; Development of PRD-49 Composite Tensile Strength Members; ASME Paper No. 73-WA/OCT-14, Nov 1973.*

TABLE I

CHART OF GENERALIZED PROPERTIES OF CABLE STRENGTH MEMBER MATERIALS

Material	Density lb/in.^{3}	Tensile Strength 10^3 psi	Specific Tensile (in air) 10^3 ft	Specific Tensile (in sea) 10^3 ft	Elastic Modulus 10^6 psi	Breaking Elongation %	Specific Gravity	Cost $/lb
E-glass	0.092	450	408	682	10.5	2.4	2.5	0.5
S-glass	0.090	650	602	1023	12.6	> 3	2.5	1.0
Graphite	0.054	400	617	1965	30-50	1.3	1.49	500
Boron	0.095	400	351	575	55	0.8	2.63	200
Titanium	0.160	180	94	122	16.2	~ 1	4.42	?
Nylon	0.041	140	285	2944	0.7	19	1.14	1.0
High Tensile Steel	0.281	370	110	126	20-30	2	7.80	50
Kevlar 29	0.052	400	641	2228	9	3-4	1.44	7.5
Kevlar 49	0.052	400	641	2228	19	2.8	1.44	18

these materials are as follows:[5] Fiberglas has abrasion problems and is susceptible to static tensile fatigue, graphite and boron have poor abrasion resistance and an extremely high cost, titanium and steel have low strength-to-weight ratios (specific tensiles) and poor fatigue properties under flexure, and nylon has low tensile strength and very high elongation. Clearly, kevlar fibers are competitive with steel in providing the required strength at low cost. Moreover, the strength-to-weight ratio in sea water is one-seventeenth that of an equivalent volume of steel. Figure 1 shows a comparison of a brass-plated high tensile steel cable in a 1 x 7 construction and a kevlar cable constructed of six strands of fiber around a 1 x 7 copper core, where increase in weight in sea water and decrease in resistance are shown as functions of overall cable diameter. For a given diameter, the kevlar/copper cable weighs less and has less resistance. Using the same construction as in figure 1, figure 2 shows that the kevlar/copper cable has a breakstrength of approximately 75 percent of the same diameter steel cable; however, this value becomes greater than 86 percent when the cable self-weight (or amount of breakstrength wasted in supporting the cable itself) of 20,000 feet of cable is taken into account.

When steel is wound into a cable pack, the size of which is governed by overall sonobuoy volume, the cable is wound into a tight coil. Upon deployment, hockles, turns, and kinks develop due to load variations which allow the cable to coil upon itself (figure 3). These kinks result in areas of stress concentration where the cable may fail under high dynamic loads or after a reduced number of cycles of normal loading. Because of its flexibility, kevlar would be expected to practically eliminate this problem.

D I S C U S S I O N

KEVLAR STRAND TESTING

As produced by duPont, kevlar yarn has a tensile strength of 400,000 psi. Impregnation of and construction of cables from kevlar may cause variations in the tensile strength of kevlar fiber in a useful form. Philadelphia Resins Corporation markets several sizes of epoxy-impregnated kevlar 29. An impregnated 1500 denier kevlar and a construction of six parallel strands of 1500 denier kevlar, also impregnated, were tested. Tensile measurements yielded a value of 342,000 psi with average breaking elongations of 3.55 percent for the single strand and 2.85 percent for the six-strand construction. This was in excess of the advertised 320,000 psi, but considerably lower than the 400,000 psi duPont value. Figure 4 illustrates the distribution of the breaks.

Short term creep tests conducted over a period of 24 hours at loads to 50 percent of rated breakstrength indicated that after the initial elongation of the material there was negligible creep. This is substantiated by the advertised data (figure 5). Philadelphia Resins Corporation has also subjected kevlar to loads up to 50 percent of ultimate tensile for a period in excess of 400 days without significant creep.

Samples loaded for creep testing have been observed to fail suddenly after a short period of time. When the samples were subjected to loads less

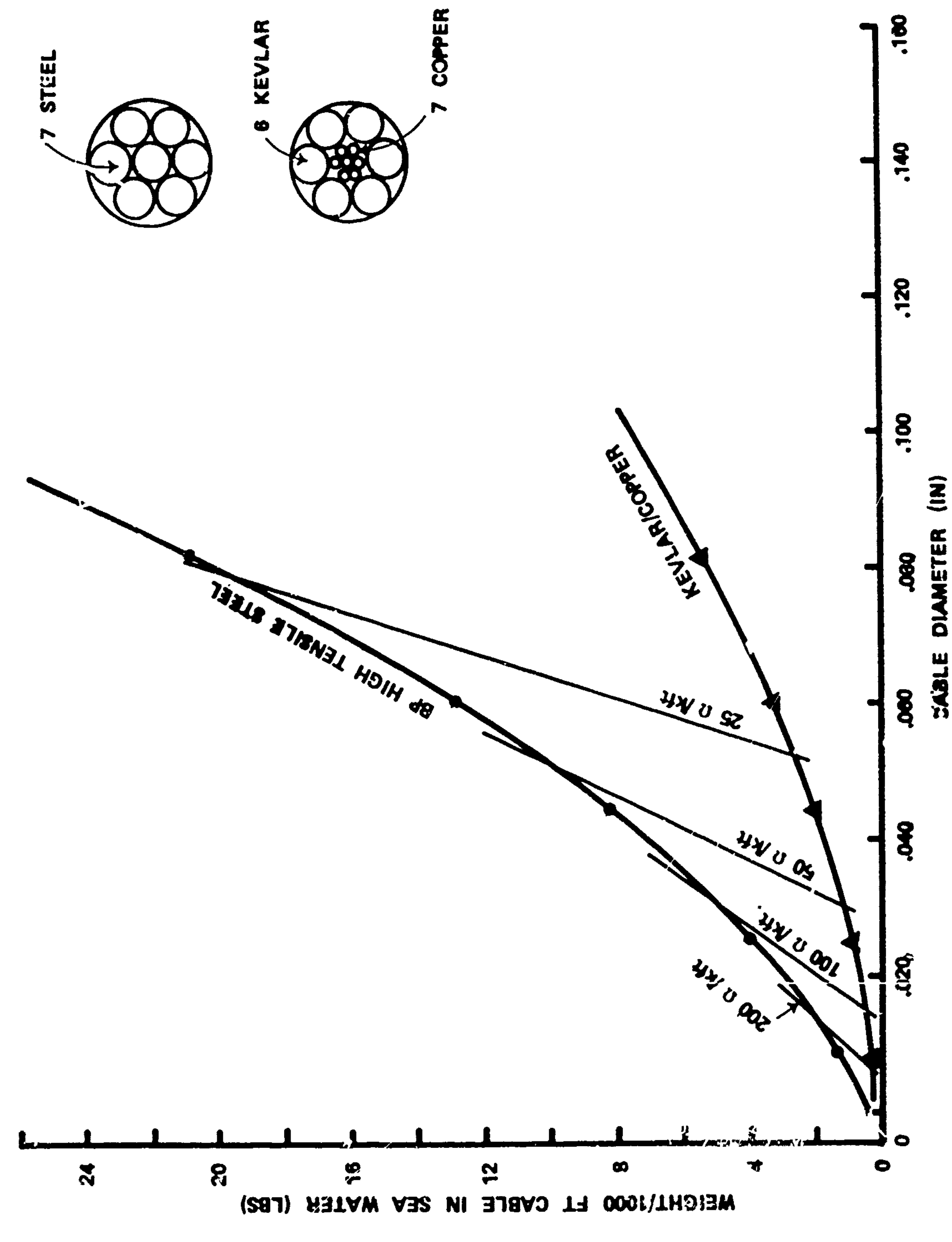

Figure 1. Comparison of Kevlar vs. Brass Plated Steel.

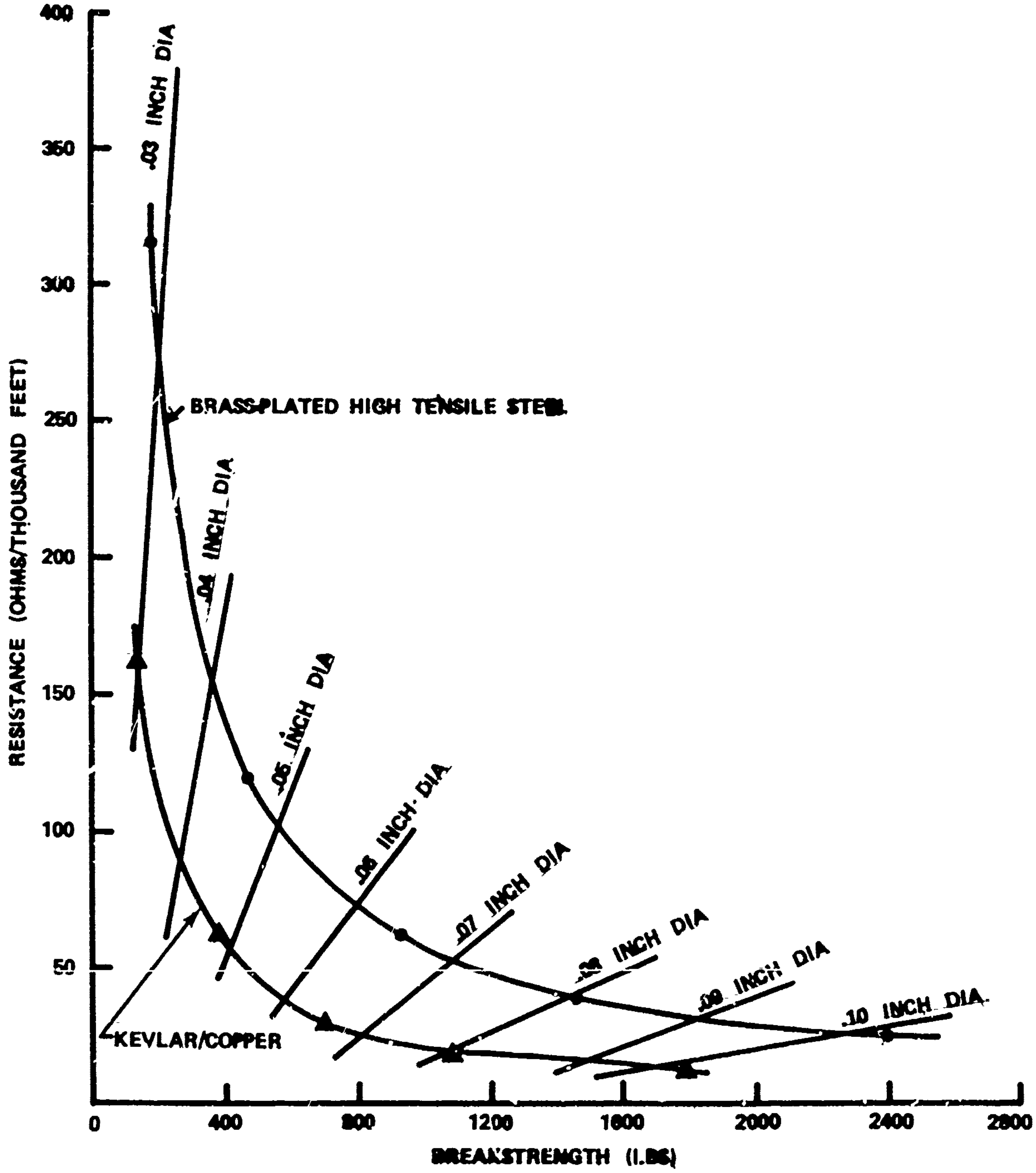

Figure 2. Comparison of Kevlar vs. Brass Plated Steel.

Figure 3. Typical Cable Snarl Problem.

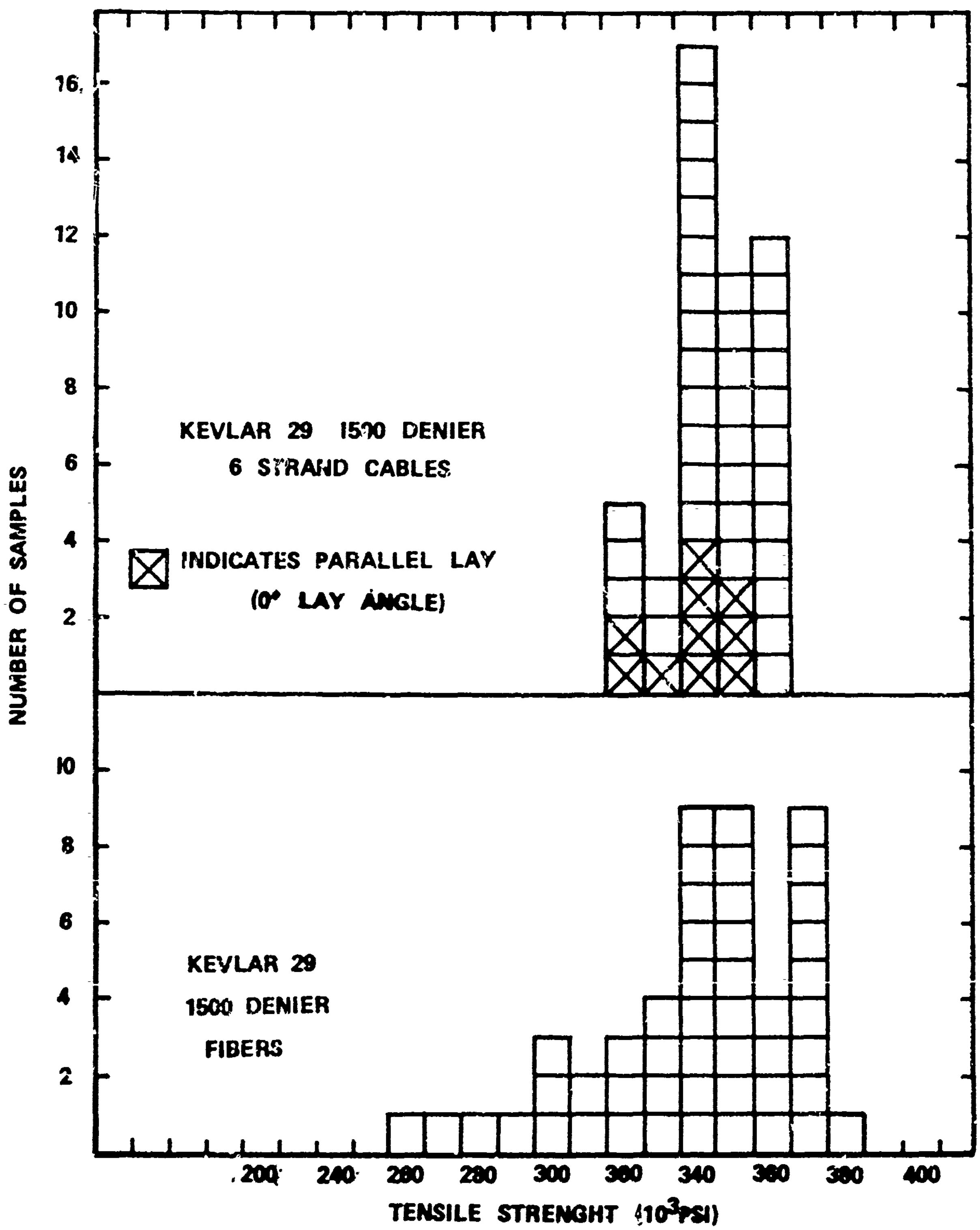

Figure 4. Break Strength Distribution of Epoxy Impregnated Kevlar Strands.

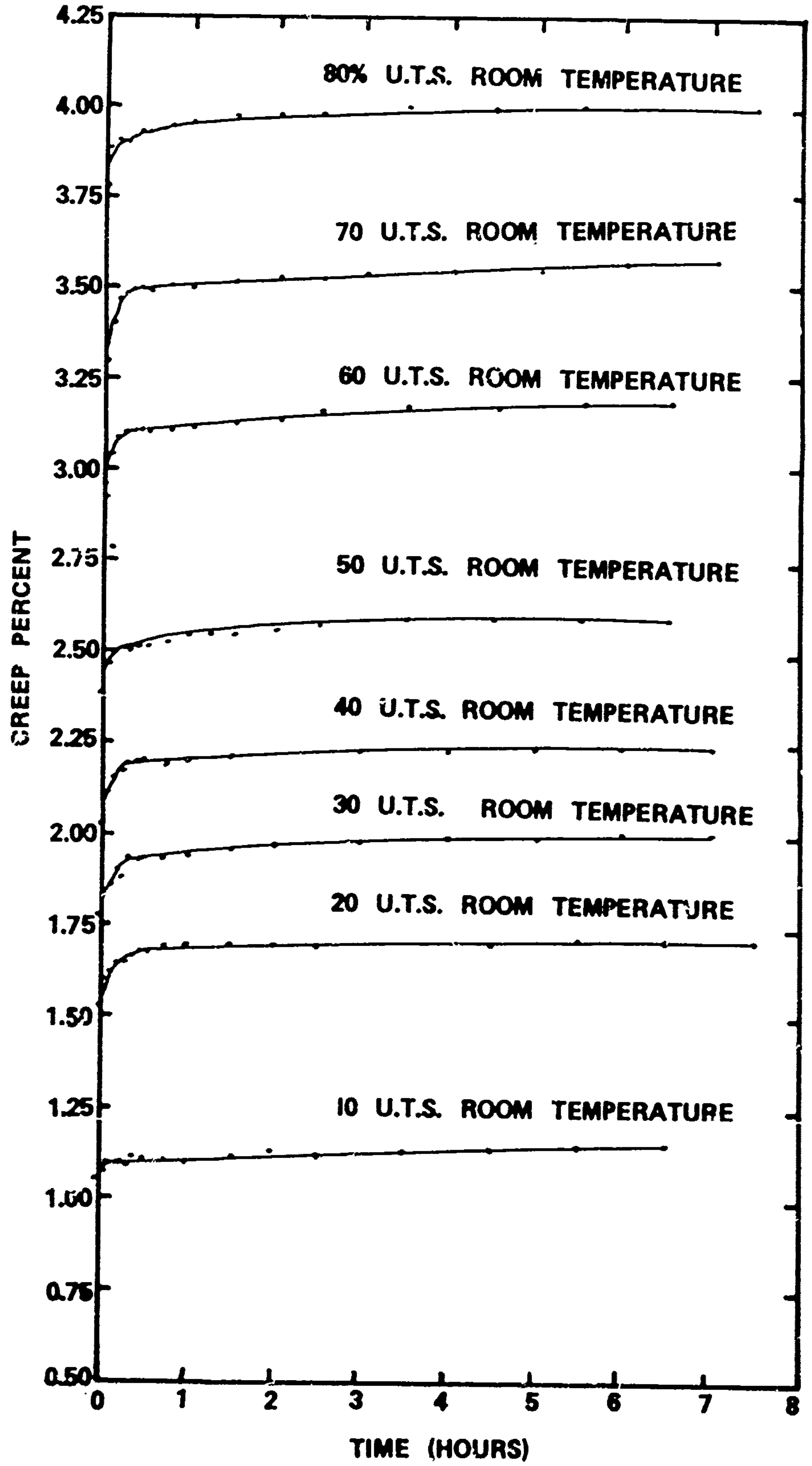

Figure 5. Creep of Kevlar 29.

than 70 percent of ultimate, these breaks occurred only at locations of stress concentrations, such as termination fittings or kinks in the cable. At loads above 70 percent of ultimate tensile, cable failures, which occurred after anywhere from a few seconds to several days (figure 6) were no longer restricted to terminations but were observed at midspan. Several failures were of the cascading type (rapid succession of strands breaking) indicating the possibility of unequal load distribution amongst the strands. Samples loaded below 70 percent of breakstrength have been suspended for two weeks and then tested with no reduction in breakstrength, indicating that the problem of static fatigue is a problem only at the upper load limit. Further investigation of the effect of long term loading is warranted.

Dynamic testing consisted of an oscillatory load superimposed on a static load (figure 7). The combination of these two provided the necessary loading variations. The oscillatory load was suspended by a length of bungee chord in order to minimize shock loading. The initial loading was chosen to be 30% of ultimate with an oscillatory load of 10 percent of ultimate cycling at a frequency of 1.3 Hz. After a test period of approximately 7 hours, or 32,000 cycles, samples were tensile tested. Average breakstrength of the samples was 5 to 10 percent below the average strength of the control samples; however, wide variations in results indicated that the effect of dynamic fatigue on kevlar was not well defined. Rather, dynamic loading only served to increase the already wide dispersion in cable properties. Further testing at longer periods and higher loadings is presently being conducted.

SONOBUOY CABLE CONSTRUCTIONS

To assess the effects of standard construction techniques on breakstrength and elongation of kevlar cables, a variety of cable constructions were purchased for testing. Because these cables were being considered for use in the ERAPS (Expendable Reliable Acoustic Path Sonobuoy) system which is under development, all cables were specified to be electrically and mechanically compatible with that sonobuoy, leaving the design details to the discretion of the manufacturers. The cables were required to have a 0.058-inch outside diameter and a nominal breakstrength of approximately 360 lb, a figure based upon system weight and the safety factor desired.

The cable designed by Philadelphia Resins Corporation consisted of 7 strands (1 x 7) of number 36AWG copper wire surrounded with a helical wrap of six strands of epoxy-impregnated 1500 denier kevlar 29, with a 7-mil extruded nylon jacket. The cable obtained from Cortland Advanced Products had a core of 7 strands (1 x 7) of No. 36AWG enameled copper sheathed by 5 strands of 1500 denier kevlar 29, oriented parallel to the core (lay angle = 0 degrees). The fibers were impregnated with urethane and a braided nylon jacket applied over the impregnated kevlar. Berk-Tek, Incorporated designed a cable which differed from the others in that a 10 mil thickness of surlyn insulation was applied directly to the stranded copper core (1 x 7 construction of No. 36 AWG). Eight strands of 1000 denier kevlar 29 were wrapped in a long lay braid around this core. The braid strands were coated with urethane to prevent unravelling, but no

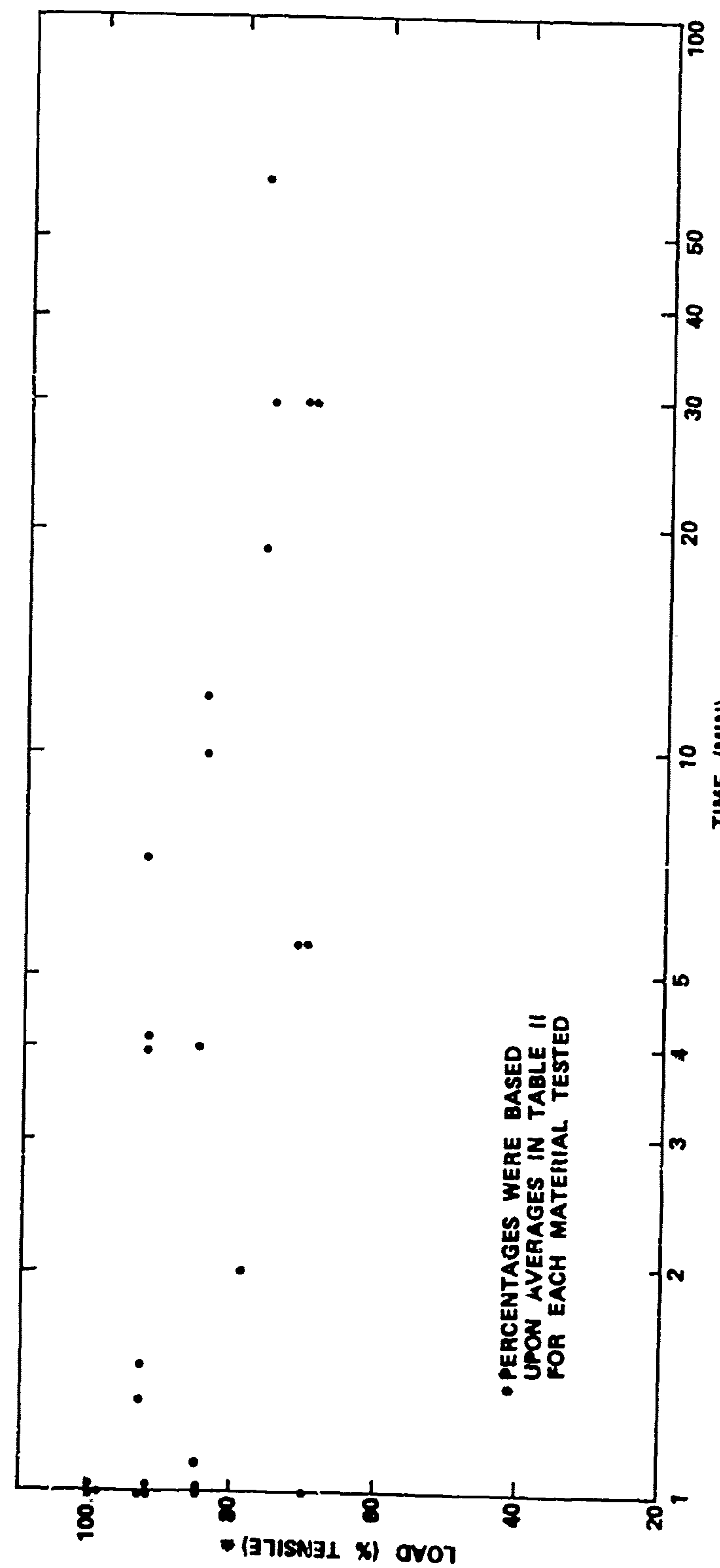

Figure 6. Static Fatigue Failure.

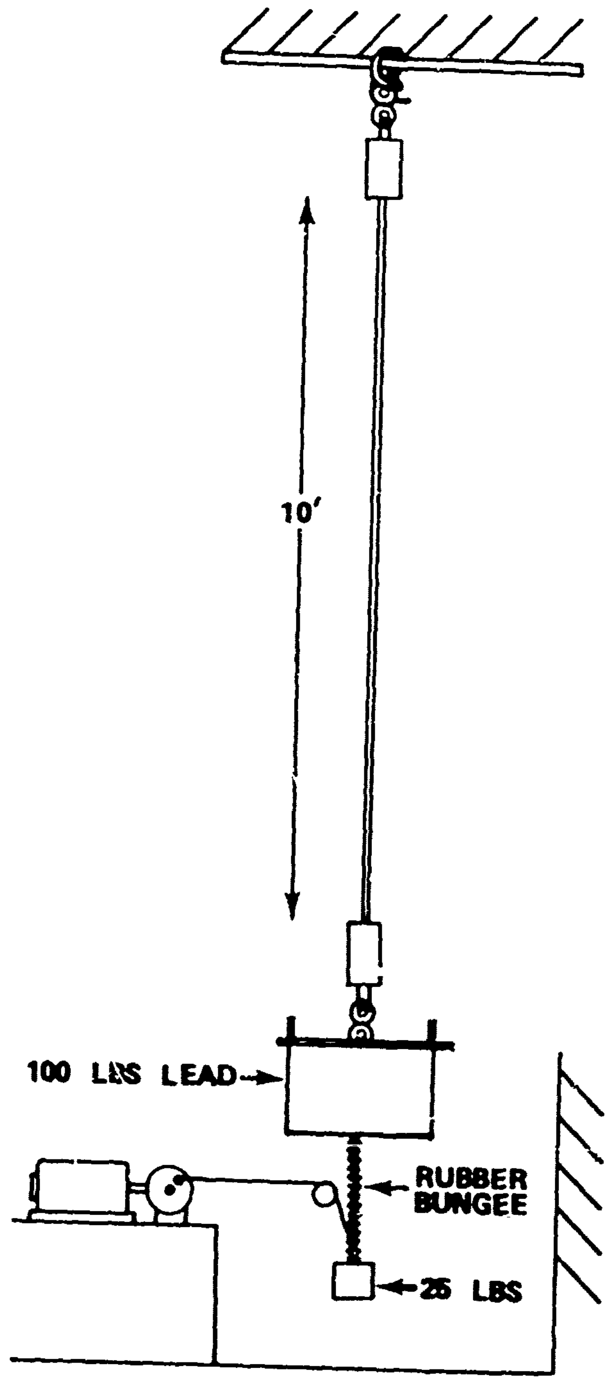

Figure 7. Test Fixture Dynamic Fatigue.

exterior jacket was applied. The cable manufactured by South Bay Cable Corporation used the same 1 x 7 core of No. 36AWG copper insulated with 10 mils of TPX. Three untreated strands of 1500 denier kevlar 29 were laid parallel to the core and two strands were wrapped helically around the exterior of the cable. No jacket was applied. The four constructions are illustrated in figure 8.

Testing of the kevlar cables to date consisted of tensile testing to determine stress-strain relationships, static loading for long term load effects and torque measurements, and dynamic loading for fatigue. Tensile testing and some dynamic testing was performed on an Instron tensile machine with a 20,000 lb capacity and an extensometer which provided simultaneous stress-strain data. Static effects were obtained by suspending lead weights on a 10-ft length of cable.

Three of the four cable constructions had comparable breakstrengths. A total of 103 breaks gave average values of breakstrength as follows: The Philadelphia Resins cable, 363 lb; the Cortland cable, 340 lb; the Berk-Tek cable, 350 lb; and the South Bay cable, 242 lb. It was immediately obvious that the South Bay cable was not well designed. The three strands placed parallel to the core bore a disproportionately large percentage of the load rather than sharing this load with the two other strands so that all five would be equally stressed. The kevlar tensile strength in this construction (based on all five strands) was determined to be 273,000 psi. Tensile strength was 330,000 psi for the Philadelphia Resins helical lay, 368,000 psi for the Berk-Tek braid, and 383,000 psi for the Cortland straight lay construction. The distributions of data for the four cables are shown in figure 9. Rather large variations of breaking tensile occur for each construction; however, the general trend of the data is easily discernible. The reason for the differences in average tensile strengths among the Philadelphia Resins cable, the Berk-Tek cable, and the Cortland cable is not immediately obvious.

As part of the investigation of kevlar constructions, a number of mechanical cables were purchased from Philadelphia Resins Corporation, each consisting of six strands of epoxy-impregnated 1500 denier kevlar 29 served around a strand of monofilament nylon with lay angles from 2.3 to 14.9 degrees. The results of the tensile tests on these cables, summarized in figure 4, showed no distinct pattern of tensile strength with lay angle, and yielded results not appreciably different from six parallel strands. These cables showed considerably more consistency in tensile strength than individual strands. The average tensile strength for both the individual strands and six-strand mechanical cables was somewhat greater than the Philadelphia Resins electromechanical cable, although the same type of kevlar components were used. Again, this is not a well understood area; however, the relative weakness of all the kevlar cables and component strands compared to the Cortland cable indicates a basic difference in the kevlar or epoxy impregnation which affected the strength of the Philadelphia Resins cable adversely.

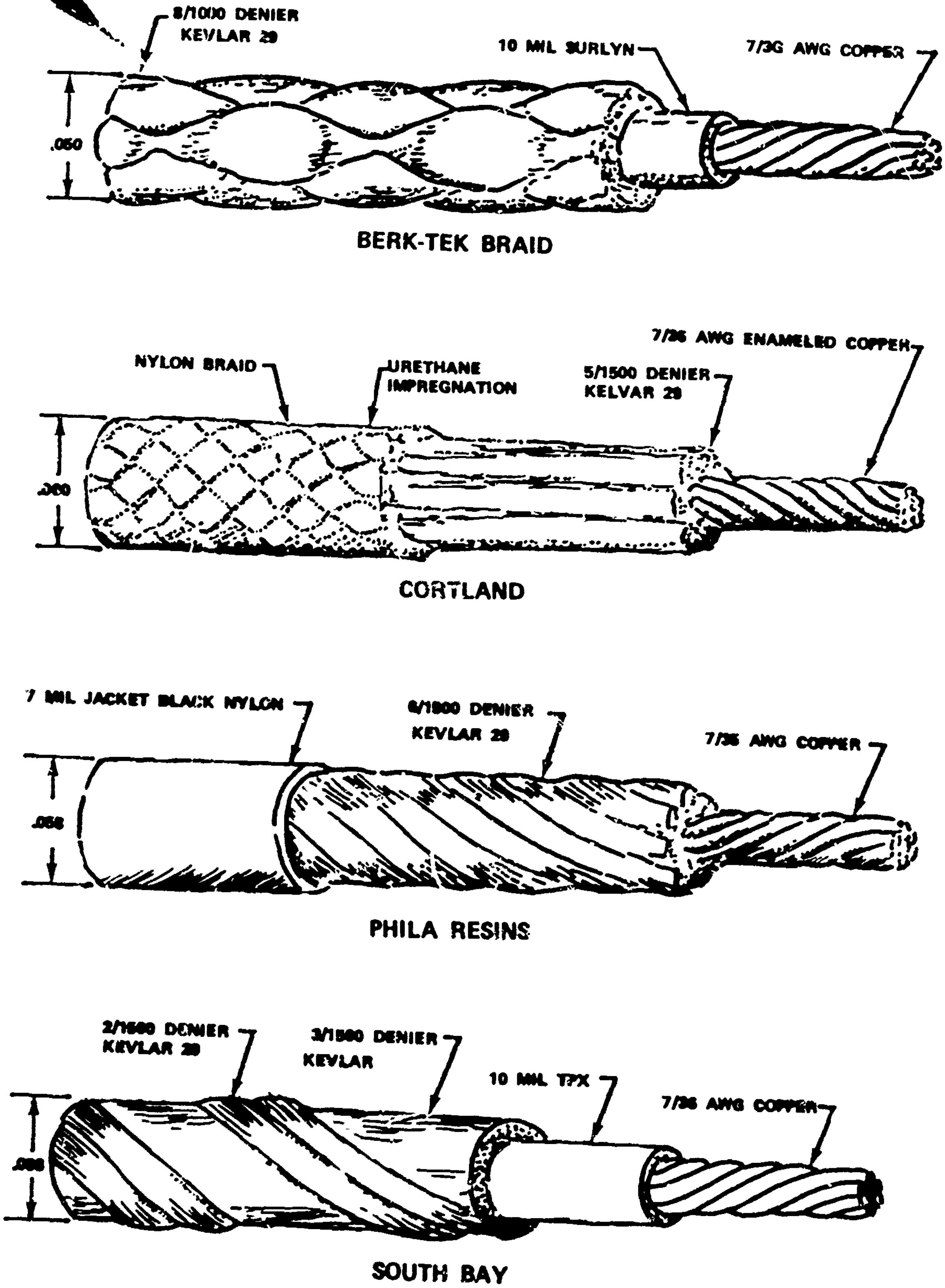

Figure 8. Cable Samples.

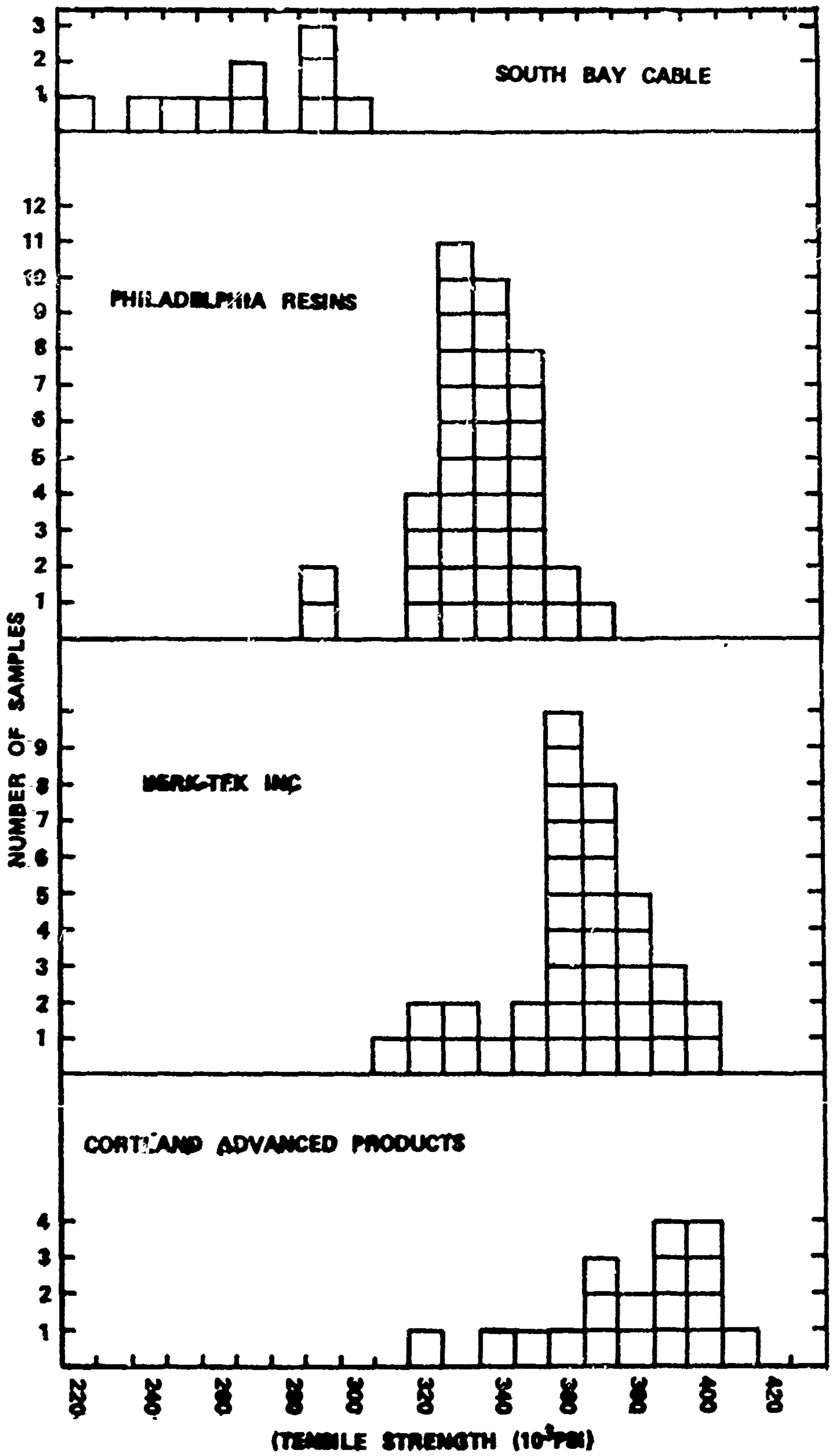

Figure 9. Distribution of Breaks.

Another result of testing the various lay angles of kevlar stranded cable yielded a definite trend. The breaking elongation of the cables increases with increased angle of lay, as shown in figure 10. As lay angle increases from 0 to 15 degrees, the elongation at break is increased by about 1 percent. This is reflected further in the Philadelphia Resins cable which has a breaking elongation of 3.8 percent, whereas the Cortland cable has a breaking elongation of 3.0 percent. Surprisingly, the Berk-Tek braid elongated only to 2.6 percent at break and the Southbay cable elongated to 2.4 percent. No explanation for the Berk-Tek and Southbay cable elongations can be proffered at this time; however, greater consideration of the source and treatment (impregnation, handling, etc.) of kevlar must be given in future comparisons of kevlar cables. Table II summarizes the average tensile strengths and elongations for all samples tested.

Static testing yielded information on torque and long term steady-state cable characteristics. The Philadelphia Resins nylon core cables tended to unlay during testing with a measured torque of from 0.00082 oz-in./lb of static load to 0.00325 oz-in./lb. The copper core Philadelphia Resins cable had a torque of 0.00394 oz-in./lb. The Cortland and Berk-Tek cables exhibited no torque. One aspect of torque rotation of the Philadelphis Resins cable was the effect on the cable jacket. After coming to a rest, it was found that the cable had elongated 8.125 percent, and the jacket had been twisted and stretched until there were numerous barespots in the insulation. Upon release of the load, these cables coiled back upon themselves. Any reapplication of load produced kinks in the cable.

Dynamic load testing of kevlar cables has shown little effect on breakstrength. Loads of 35 percent of break were chosen for the test. There was a slight (5 percent) reduction in breakstrength, but this is not felt to be entirely dependent on loading. Some samples were actually stronger after oscillation than they were before testing. Elongation of the cable due to the oscillations was minimal, being less than 0.5 percent.

In electromechanical cables, a problem occurred because of the dissimilar elastic properties of kevlar and copper. Kevlar is elastic, elongates up to 3 percent under load, and returns to its original length after load release. The copper conductor, however, yields at less than 0.5 percent elongation, although it will elongate up to 19 percent before breaking. In an electromechanical construction, therefore, when load was applied and released, the kevlar relaxed and the copper, having been permanently elongated, was forced to bunch up inside the contracting cable. In the Philadelphia Resins cable, this phenomenon can cause the copper to push through both the surrounding kevlar and the thin external nylon jacket (figure 11). In the Berk-Tek cable, the insulated copper pushed through the kevlar braid with no observable damage to the insulation. In the case of the Berk-Tek cable, the danger which must be considered is the possibility of the pushed-through (or popped-through) conductor being fatigued by cyclic stresses (from ocean wave dynamics). This has by no means been shown to occur; however, the need for further testing is definitely indicated.

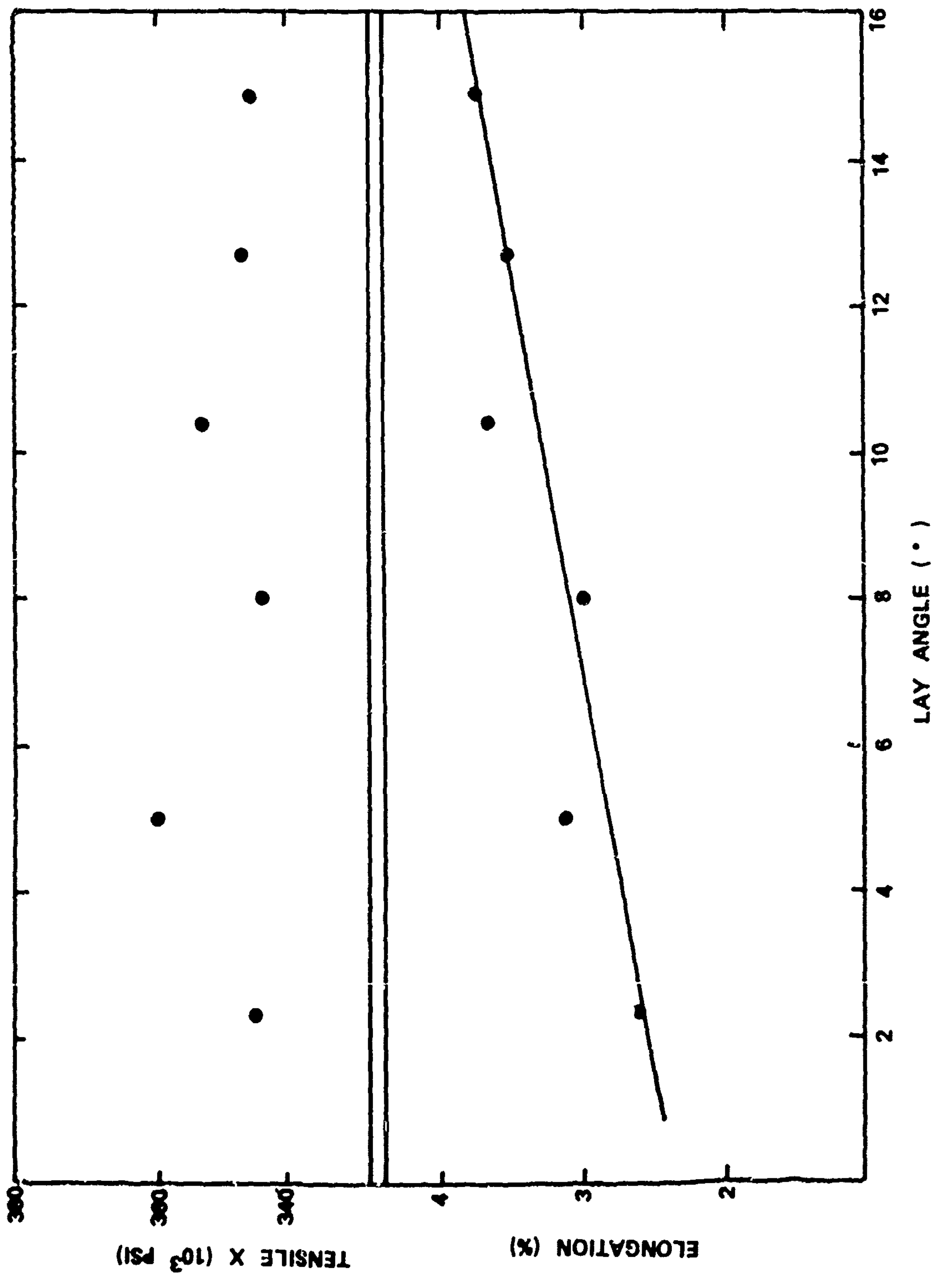

Figure 10. Effect of Lay Angle.

TABLE II

SUMMARY OF DATA

	Avg. Tensile 10^3 psi	Avg. Elongation to break %
Epoxy-impregnated 1500 denier kevlar 29	342	3.55
6 strands of epoxy impregnated 1500 denier kevlar 29		
a. parallel lay	342	2.85
b. lay angle = 2.3 degrees	346	2.6
c. lay angle = 5.0 degrees	360	3.1
d. lay angle = 8.0 degrees	345	3.0
3. lay angle = 10.4 degrees	353	3.68
f. lay angle = 12.7 degrees	348	3.55
g. lay angle = 14.9 degrees	347	3.75
ERAPS cable constructions		
a. Berk-Tek	368	2.6
b. Philadelphia Resins	330	3.8
c. Cortland	383	3.0
d. Southbay	273	2.4

PHILA RESINS

BERK-TEK

Figure 11. Conductor Pop-through.

Testing of the Berk-Tek cable has determined that this effect is a function of load and release rate. At a constant load of 100 lb (about 28 percent of break), the number of cycles needed to form a kink (a bunching up of the conductor) ranged from 10 at a release rate of 5 in./min to 1 at 20 in./min. At 300 lb (85 percent of break) these figures were reduced to 3 cycles at 5 in./min to 1 cycle for anything greater than a 10 in./min release rate (figure 12). An instantaneous relaxation of load, such as occurs upon cable failure, will produce numerous conductor pop-throughs.

In an effort to eliminate this problem, the copper core was pulled out of the braid so that the copper would not be a part of the termination. It was thought that this would allow the copper to feed into the braid as the braid stretched, reducing the amount of elongation of the copper, and when the load was released, the slack in the copper would be taken up at the loose end. What occurred, however, was that the braid acted like a "chinese finger" and gripped the copper as it elongated, stretching the conductor along with the braid, rather than feeding extra copper in.

As another attempt at reducing the magnitude of the problem, a nylon strand was substituted for the central wire of the conductor. It was felt that the exterior wires, being wound in a helix, would tend to unlay before undergoing stress yielding. The nylon would stretch and upon load relaxation would return the copper to its original length. This method has not been thoroughly tested, but initial tests indicated a reduction of the magnitude of this proplem by about half. Alternate solutions to the pop-through problem have yet to be undertaken include the use of kevlar 49 which has less elongation than kevlar 29 and the process of "hot stretching" the kevlar to reduce its elongation.

According to duPont, kevlar has a dielectric constant of 3.36 at 10^{10} Hz. The Philadelphia Resins and Cortland cables attempted to utilize kevlar as a dielectric; however, because of inadequate water integrity in the nylon jackets, the conductors were shorted to sea water. The Berk-Tek and Southbay cables were watertight and performed well at sea, but kevlar was not used as a dielectric in these cables. Capitalizing upon the dielectric properties of kevlar appears attractive where sufficient insulation can be provided and should be pursued further.

Until the successful utilization of kevlar for its dielectric properties, the most desirable method of cable construction for sonobuoy application is the braid. This method provides a flexible, torque-free cable, high in tensile strength and low in elongation. It also permits the most effective insulation of the conductor for water integrity. In comparison to the ERAPS steel cable, the kevlar braid design provided 80 percent higher tensile strength and twice the safety factor based on static load, while reducing the weight in air of the sonobuoy by nearly 20 lb.

Cable size is principally dependent upon the quantity of copper required to transmit the signal and the thickness of insulation required to insure sufficient isolation from sea water. If brass-plated high-tensile steel could provide, by itself, sufficient conductivity to meet the sonobuoy cable electrical requirements, the steel cable would be stronger than kevlar for a

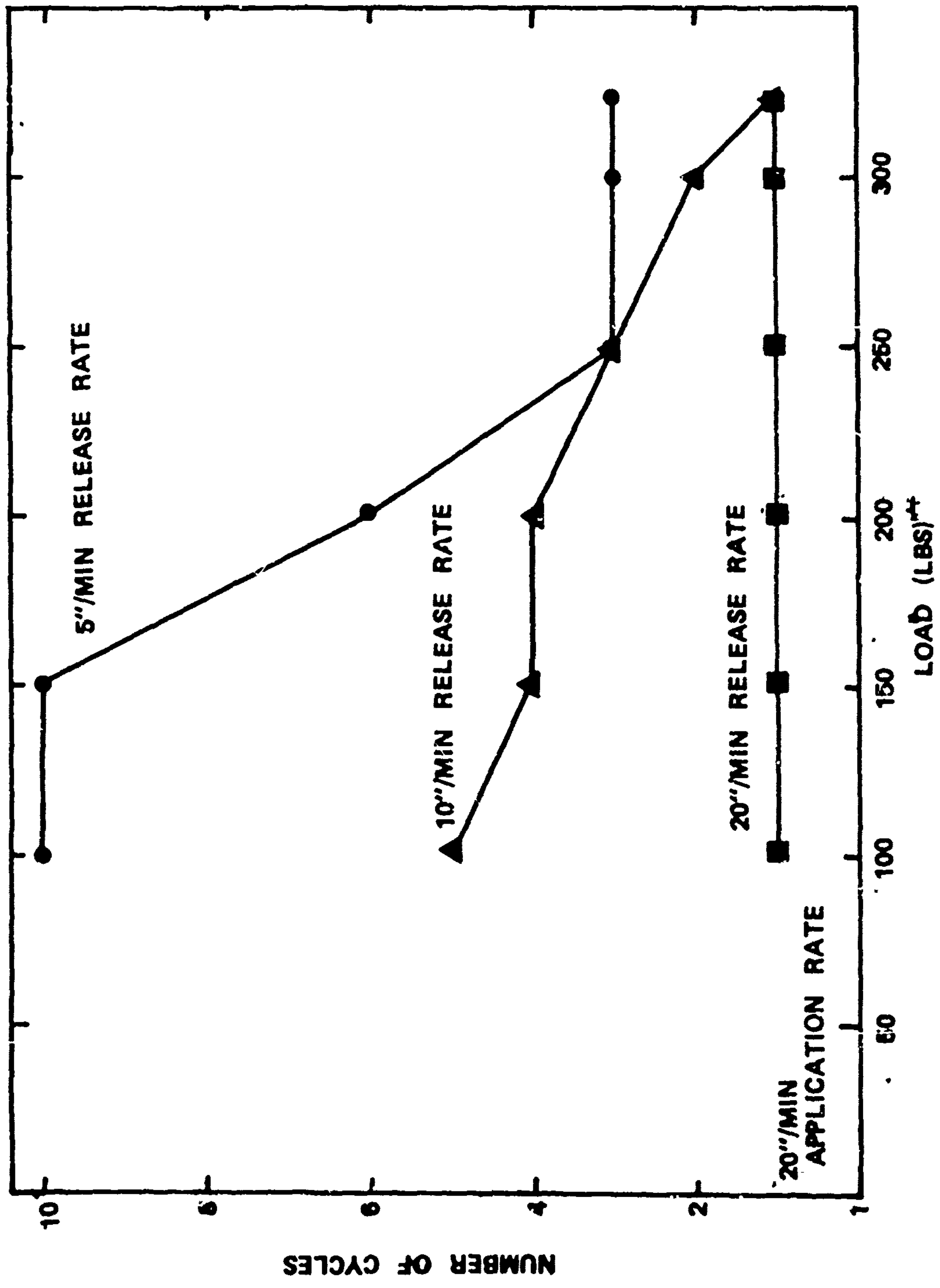

Figure 12. Cable-Pop-through.

given diameter, as figure 2 indicates. However, it is the case with most sonobuoy cables, as illustrated in the ERAPS design, that the maximum allowable d-c resistance is considerably less than that attainable using brass-plated steel alone, and copper strands must be added at the sacrifice of some of the steel. Since kevlar is multistranded and pliable, it can be applied so as to fill in the interstices that usually result in cable construction and, therefore, can be more efficiently utilized than steel. By applying the kevlar in the form of a braid around the insulated copper, more of the cable cross-sectional area is employed for the strength member and less for the insulation than in the construction which places the strength member in the center and has an extruded insulator on the outside. Braided steel is not an impossible construction; however, in a braid, fine hairs of the braided material are unavoidably broken, and experience has shown that these steel hairs will penetrate the insulation. A mylar tape would normally be applied to the insulated conductor to reduce the possibility of puncture from the steel hairs, but this also reduces cable flexibility and does not guarantee that such penetration would not occur. A steel braid or a helical lay of steel external to the insulated conductor obviates any advantage derived from using the steel as part of the conductor, and the helical lay requires torque balancing.

A kevlar cable has considerably less weight than a steel cable, and since most sonobuoy systems use the cable to support a massive body, the effective breakstrength of the steel cable is more dramatically reduced because of cable self-weight than that of the kevlar cable. Therefore, an advantage in breakstrength and in factor of safety is realized in a kevlar cable. This advantage is most significant in long cables, where the body being supported is heavy and the size of the cable is restricted, and where a simple brass-plated or copper-clad steel cannot provide sufficient conductivity. The flexibility and the elimination of torque are significant additional factors in the packaging, payout, and performance of the cable in sonobuoy applications.