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by

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APRIL 1970

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KINK FORMATION PROPERTIES AND OTHER MECHANICAL CHARACTERISTICS OF OCEANOGRAPHIC STRANDS AND WIRE ROPE

ABSTRACT

Tests were conducted ~~at the MIT Charles Stark Draper Laboratory~~ in order to measure the mechanical characteristics of a representative sampling of 1/4-inch diameter to 5/16-inch diameter oceanographic strands and wire ropes. Single-strand and three-strand wire rope were the only samples evaluated. The main purpose of the work was to compare the kink-formation properties, including both opening and tightening kinks, of each mooring line. In addition such mechanical characteristics as the torsional and linear spring constants and the degree of torque balance of given samples was measured.

It was found that the 3 x 19 wire ropes exhibited a markedly lower torsional spring constant than single strand samples. Therefore, they can absorb considerably more turns before developing excessive torque. The presence of high torque in a sample will, however, considerably reduce the ultimate breaking strength in tension. It was further found that at a tension of 4.5 pounds the average torque level required to produce kinks in samples is within a factor of two of each other. In addition, it is estimated that if a minimum tension of 10 pounds can be maintained in any sample under ideal conditions torques up to the breaking strength of the sample will not produce kinks. Under any conditions, though, a tension of greater than 100 pounds is felt to be sufficient to prevent kinks before a sample will break due to torsion. In light of these facts 3 x 19, 5/16-inch diameter wire rope was chosen as the best sample tested due to its low torsional spring constant and its superior torque balance properties.

The effects of the type of termination on the kink formation properties was measured. An open swaged socket and pin termination was found desirable in that it exhibited a torque level approximately twice that of large eye swaged terminations at the time of kink formation. A reduction in the degree of freedom of motion at terminations was further found to reduce the propensity for kink formation. Such can be affected by employing tightly-fitting shackles and stoppering hardware. In addition, the presence of prestrain or axial curvature in a rope due to being wound tightly on drums was found to contribute to kink formation. The amount of such contribution was, however, not measured.

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1. INTRODUCTION

Because of a desire for near-surface data on the part of the oceanographic community, at present most oceanographic sensors are buoy-mounted. With present trends it appears as though such will be the case for many years to come. Many problems are, however, inherent in such a sensor mounting scheme. Of necessity the sensors must be mounted in a moored array which contains an anchor rigidly fixed to the ocean floor for reference and a surface element. In most cases the surface element is a surface-following buoy which simultaneously serves as a base for measurement of meteorological data. In other cases the surface element is a sub-surface float which, although avoiding the violent excitation of surface waves, sacrifices much desirable oceanographic data. Mooring problems arise primarily in the surface-mounted buoys for two reasons:

(1) Fishbite problems, hazardous to non-metallic mooring lines, are generally more severe near the surface.

(2) The violent excitation introduced in a mooring line due to wave-driven buoy motion may contribute to mooring line failures.

For general applicability in all areas of the oceans, whether fishbite poses a problem or not, metalized or metallic mooring lines are most desirable. This work concerns itself specifically with the evaluation of the mechanical properties of steel strands and wire ropes which may contribute to failures in the presence of motions found in typical moored arrays. This work will compare the relative merits of specific samples tested and recommend on an absolute basis how each sample might be more effectively employed in a mooring. Data will be interpreted strictly in terms of static or very low frequency mooring loads. It is hoped that subsequent work will enable one to interpret the data generated here in terms of dynamic or resonant conditions within a mooring line.

1.1 Mooring Line Problems

At present most of the taut moorings employed by WHOI include a section of nylon line on the lower part of the mooring the length of which is approximately one-half of the full mooring length. The moorings of concern here are those for which the upper half is composed of many lengths of single strand mooring line or wire rope attached in series. All strands and wire ropes have been jacketed with polyethylene for corrosion protection.

In the process of deployment it is felt that two potential problems exist:

(1) Abrasion of the mooring line jacket by deck handling equipment.

(2) Kink formation in the mooring line which brings about a kink or backturn with an accompanying reduction in strength.

Problem (1) can be considerably alleviated by use of the proper equipment and sufficient care during deployment. Problem (2), however, is considerably more complex.

At present there are two popular methods of mooring deployment, both of which can cause the formation of kinks in mooring lines under the proper conditions.

(1) Anchor-first deployment.

(2) Anchor-last or free fall mooring implantment.

In the anchor-first deployment scheme the mooring anchor is the first item to be put over the side of the ship. It is usually lowered to the bottom by an on-board winch. As it is lowered measuring instruments may be attached. The tension in the mooring line at the deck level is therefore equal to the in-water weight of the anchor, the instruments, and the cable. Reasons for employing such a scheme of mooring deployment are the following:

(1) The ship may remain nominally stationary during deployment and subsequently implant the mooring in an accurately-known location.

(2) Given the proper deck-handling equipment and with the strand being paid vertically over the side, instruments may be readily attached.

(3) In calm seas and a fairly substantial mooring line tension maintained at all times, the chance of strand kink formation is reduced.

The points in disfavor of an anchor-first deployment scheme are the following:

(1) Strong, costly deck handling equipment is necessary for ease of and safety during deployment.

(2) Anchor-first deployment may only be affected with reliability in calm seas due to the fact that the dynamic motion of the vessel-anchor combination may impart excessively high or low tension for short periods of time during deployment. The high tension value could cause the strand to part in pure tension. At excessively low tension values stored torsional energy in the strand could be readily released in the form of a kink.

The anchor-last or free fall deployment scheme is described in Reference (1). In this scheme the buoy or surface element of the mooring is deployed first and the full mooring is assembled while being towed in a somewhat horizontal configuration behind the vessel. For example, for the case of a two-mile long mooring whose surface element is a toroidal float, the deployment vessel will proceed at a speed of approximately 1.5 knots. Such a situation will produce a mooring catenary from the stern of the vessel, for which the maximum catenary depth will be of the order of 800 meters when the mooring is fully deployed from the vessel stern. Subsequently, the anchor will be dropped from the vessel and the whole mooring will come to rest vertically while nominally in the desired location. Because the mooring components were cut to the proper length for the desired water depth the mooring will have a desired static tension with the anchor resting on the bottom. The desired static tension is readily created by employing nylon line in the bottom half of the mooring. The excessive stretch characteristic of nylon will alleviate problems caused by errors in cutting strands to the proper length. Furthermore, the nylon acting as an elastic is relied upon to allow the anchor to settle to the bottom, producing the desired amount of pretension.

Nylon line in the bottom portion of the mooring line also produces two other desirable effects:

(1) Nylon reduces the overall "stiffness" of a taut mooring such that the overall tension variation caused by lateral mooring motion or by the dynamics of wave action is reduced. At the same time the first natural frequency of the whole mooring is reduced. The merits of the latter point are yet to be established.

(2) Rotations introduced to the mooring line during anchor deployment should be absorbed by the nylon with no ensuing damage to the strand or wire rope portion of the mooring.

The problem with anchor last deployment schemes, as they now exist, is that the effect of anchor motion on the mooring line is unknown. It has been shown theoretically (see Reference 2) that for the case of anchor-last deployment with a spherical anchor a situation of zero tension exists for a short period shortly after the anchor is dropped from the vessel. If such were the case it is felt that kinks might be introduced into the cable. This is felt to be especially true for an anchor which could exhibit a certain amount of time-varying lift as in the case of a Stimson-type anchor.

The real problem to which this report addresses itself is not so much to methods of mooring deployment as to the choice of strands and wire rope to be employed in the mooring design. Specifically the mechanical properties of certain strands are measured and the implications of these properties on mooring design and deployment will be interpreted. The overall goal of such a study is to measure the mechanical properties of a few selected samples, choosing the "best" sample in light of these measurements, while establishing sufficient understanding of strand and wire rope parameters such that future samples may be more-simply evaluated. At the same time it is hoped that a knowledge of mechanical parameters will enable one to produce a workable analytical dynamic model of a mooring as an aid to future mooring designs. The purpose of this work is also described in Reference (1).

1.2 Evaluation of Mechanical Properties

The mechanical properties of the strand and wire rope samples are measured for the most part on new, unjacketed cables. Evaluation of fatigue failure properties of certain samples under various loading conditions have been covered in Reference (3). The effects of corrosion on various samples will not be covered in this writing.

The basic mechanical properties which a mooring designer needs are well-tabulated by reference to manufacturers' catalogs or by direct measurement. For example, wire size, type (i.e., torque balanced), material, wire configuration, and rated breaking strength (RBS) are numbers which are readily available. Such numbers are tabulated here in Tables 1 and 2. The actual breaking strength of numerous samples, as measured at the Woods Hole Oceanographic Institute (see Reference 4), are also tabulated for ready reference in Tables 1 and 2. This report further tabulates the measured torsional and linear spring contant, the amount of torque unbalance at a specified tension, and kink formation tendencies of each sample. Where applicable the parameters are tabulated for both positive and negative turns introduced to the strand or wire rope. In this report, positive turns are specified as those for which the outer layer of wires of a single strand are tightened (i.e., the pitch shortens) or the strand pitch of multi-strand wire ropes shortens as it tightens up. In such a case, if the tension in the strand were low enough a tightening kink might result. Similarly, for negative turns an opening kink might result.

The kink-formation tendencies in strands and wire ropes is of prime interest in this writing. Comparative measurements of the kink formation tendency of each sample were made and these numbers compared with both the measured and the calculated bending stiffness (EI) of each sample. All such numbers are tabulated in Tables 1 and 2.

1.3 Torque Balance in Strands and Wire Rope

Due to the helical windings of strands and wire ropes, when tension is applied longitudinally, the wires must support a transverse component of force which attempts to unlay the helix. This force develops a torque which is proportional to the helix angle of the individual wires (see Reference 5), the friction level between wires and strands, and the applied tension. For strands and wire rope samples in which all wires are wound with a helix in the same direction, considerable torque will develop as a function of tension. In most metallic mooring lines, however, an attempt is made at reducing this torque by winding different wire layers in opposite directions. This winding process produces a torque balanced strand or wire rope. Many of the samples tested for this writing were specified as torque balanced and are specified as such in Tables 1 and 2.

1.4 Samples Tested

From manufacturers' specifications and favorable reports, six samples of single strand and wire rope were selected as candidates for testing. In addition, samples of 1/4" dia., 1 x 19 strand which was often used in the past as a mooring line component was selected for tests as a standard or control against which to compare the other six samples. The additional samples tested, including four single strand samples and two three-strand samples, are listed in Tables 1 and 2. The strength of the samples was chosen to be between 7,690 and 13,000 pounds rated breaking strength. Such strengths represented a good safety margin over the average mooring tension. Simultaneously, the diameters of the samples were such that they were readily manageable with available deck-handling equipment.

The basic mechanical properties of the samples, including linear and torsional spring characteristics as well as certain failure modes, were measured with 100-foot long samples. All such tests were conducted with the samples in a horizontal position. In a second series of tests, samples approximately 17 feet long were tested in a vertical position in measuring relative kink-formation properties. All of the above lengths were terminated with swaged, large eye termination.

In a third test, 17 foot samples, terminated with open swage socket terminations, were tested in the vertical position. Such tests indicated the relative effects of the type of termination and associated hardware on the kink formation properties of samples.

2. TEST DESCRIPTION

The actual tests on mooring line strand and wire rope can be broken down into two types:

(1) Mechanical properties of samples measured with sample in horizontal configuration.

(2) Kink formation tests with short samples held vertically.

As already-mentioned, the former type of test was conducted with 100-foot samples. With such lengths the weight of the sample alone, while subtending a catenary, was sufficient to provide a level of tension necessary to prevent the formation of kinks at torque levels ranging up to 20 foot-pounds. In an attempt to relax tension to a low level, enabling kink formation, the sample catenary would come in contact with the ground, hindering kink formation. Thus it was deemed necessary to test kink-formation properties of strand and wire rope samples while held in a vertical position.

2.1 Measurement of Torque, Turns, Tension, and Stretch in Short Samples

The parameters of interest in the measurement of the mechanical properties of samples are torque, tension, rotation, and stretch. The apparatus for measuring such properties is schematically represented in Figure 1. The safety precautions inherent in such a test configuration are explained in Appendix A.

In Figure 1 it may be seen that the cable tension is sustained by two-fixed members - a tree and a trailer truck donkey. The tensioning member in the system is a 3-ton chain come-along which also allows sufficient flexibility to install new samples and account for small variations in the length of an untensioned sample. Large variations in sample length are

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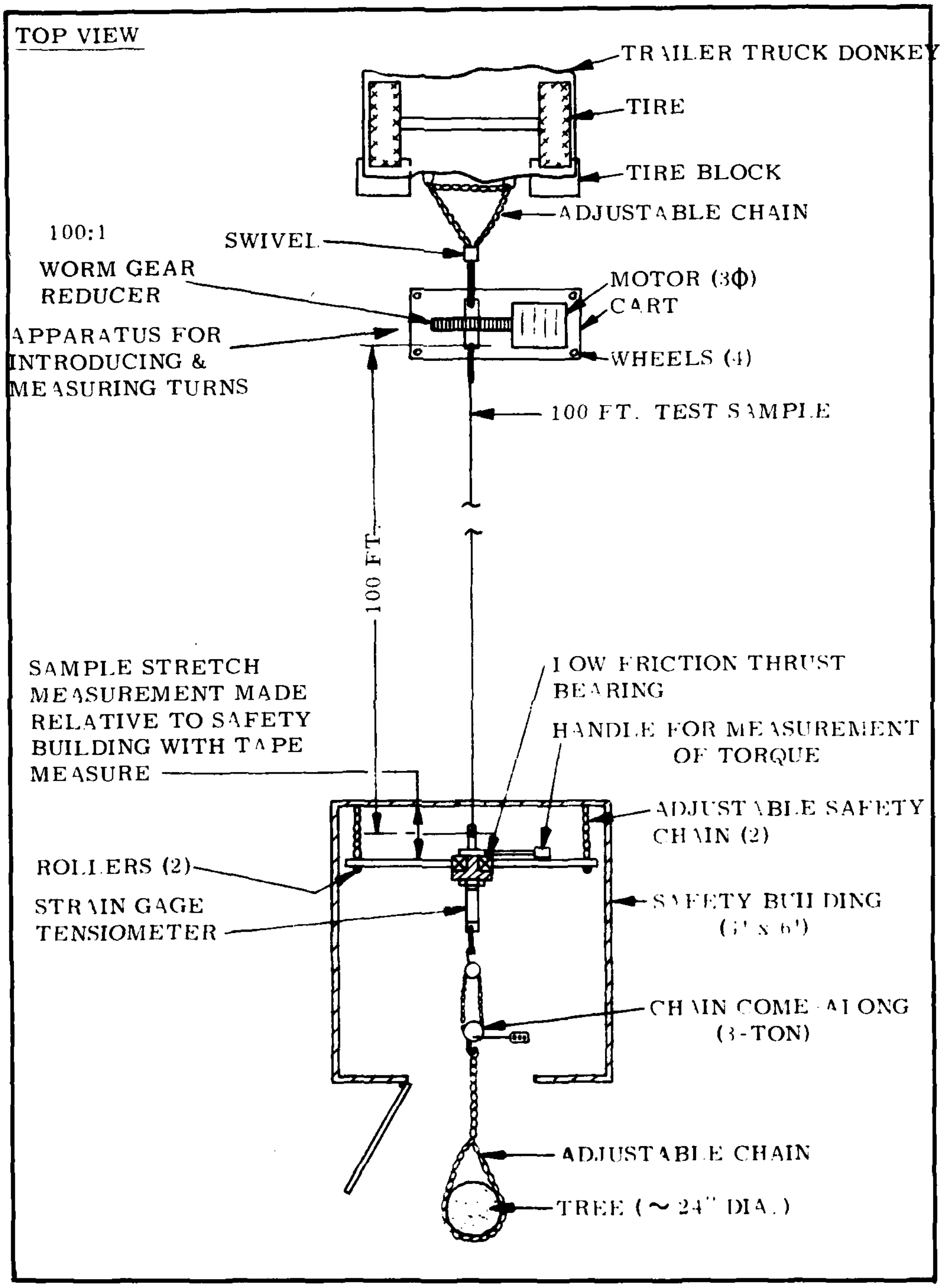

Fig. 1 Test Configuration for Measurement of Mechanical Properties

accounted for by a movable chain attached to the front of the truck. The attachment at the tree is also provided by a large chain. During all tests the truck brakes are fastened and the wheels are well blocked to help prevent truck motion. Furthermore, the actual compression of the truck tires against these blocks in the presence of tension is taken into account in the evaluation of sample stretch.

All measurement functions are read and controlled within the safety building. Two types of electrical power are provided to drive the apparatus: 220-volt, 3-phase, 60 cycle for the motor and 115-volt, 60 cycle, single phase for the tensiometer and its amplifier-readout circuitry. The 3-phase power passes through the building on the way to the motor. Within the building an on/off switch and a double pole, double throw switch for reversal of motor direction are installed. The motor, whose speed is 1750 RPM drives a 100-to-1 worm gear reducer which introduces relative turns in the sample at a rate of approximately 0.3 turns per second. The number of turns is measured by a battery-powered microswitch adjacent to the worm gear which flashes a light within the safety building with each turn of the worm gear. The whole motor and worm gear reducer are mounted on a rolling cart which freely moves axially as the sample is tensioned. Between the worm gear and the truck is an adjustable chain and a swivel to provide a tensioning member which will permit relative rotation between the chain and the sample.

The test sample passes into the safety building through a 5-inch diameter hole and attaches directly to a thrust bearing torque tester mounted on two wheels. This device houses a 5-inch O.D., angular contact ball bearing capable of axial loads up to 19,000 pounds.

A 15-inch handle, attached to the inner race of the ball bearing or the rotating member, permits easy measurement of the level of torque in the sample. In general a simple spring scale, mounted at a known radius on the handle, and pulled at a right angle to the arm, will provide the measurement of the torque.

Sample stretch is measured within the safety building as the relative distance between a reference point on the torque tester and the back wall of the building (see Figure 1). A retractable tape measure affixed to the building wall was employed for this purpose.

The level of tension in the sample is monitored by a 0-5000 pound Standard Controls strain gage load cell designed for ocean use. It was powered and its output signal read by a Sanborn Model 311A Transducer Amplifier. This compact piece of electronics permitted easy strain gage bridge balancing while enabling one to compensate for capacitance in the bridge. The strain gage tensiometer and readout device was calibrated, prior to its use, at the Instron Machine of the Metallurgy Department of M.I.T.

During actual tests the sample tension would be at 370 pounds just prior to the introduction of additional turns. The motor would then introduce a desired number of differential turns which would generally result in an increased torque and tension level. Then, keeping the level of turns constant, the come-along would be employed to reach specific and easily-read tension levels. At each level of tension both the sample stretch and the torque level would be measured and recorded in a log. In many cases the combination of torque and tension in the samples produced a failure either by completely breaking or by merely causing the outer layer of wires to break. Such failures are covered in Section 3.6.

2.2 Measurement of Kink-Formation Threshold

Prior to conducting the experiments described herein, it was felt that kinks could be induced in strands and wire rope samples held horizontally as described in Section 2.1. As the experiments proceeded it was found that such was not the case. The following two factors were found to prohibit kink formations when held as previously-described:

(1) When tension in the samples was reduced below approximately 150 pounds the samples would contact the ground, prohibiting kink formation at any lower tension.

(2) When excessive torque (15-20 foot-pounds) was introduced in the presence of moderate tension values (500-1500 pounds), the outer layer of wires or even the whole strand would fail before it would contain sufficient torque to form a kink.

Given the above competing factors it was decided to measure the kink-formation threshold in very short samples held vertically. The test configuration for this experimental phase is shown in Figure 2. A theoretical approach justifying the adequacy of the short samples is given in Appendix C.

The equipment shown in Figure 2 is largely self-explanatory. In all such tests a wooden block is inserted in both the upper and lower shackle in order to arrest any hardware motion in the presence of torque. In all initial kink-formation tests both ends of the mooring line samples were terminated with large eye (~ 2-inch diameter hole) swaged fittings. In later tests, measurements were made on the effects of the type of termination and hardware on kink-formation threshold.

The equipment in Figure 2 consists of a known weight of hardware which acts to give the sample a steady tension value. Turns are introduced into the sample by rotating the horizontal torquing arm. Such is done by manipulating it back and forth in order to avoid the wooden stand. At various intervals the turning process is stopped and the torquing arm allowed to come to rest against the wooden stand. At this point spring scales would be inserted at each end of the arm and the torque level measured, resulting in a plot of torque versus turns for each sample. When a kink would form in a sample the number of turns required would be known, thus enabling one to determine the torque level at kink formation. It is this torque level which is used as a comparative number in sample evaluations.

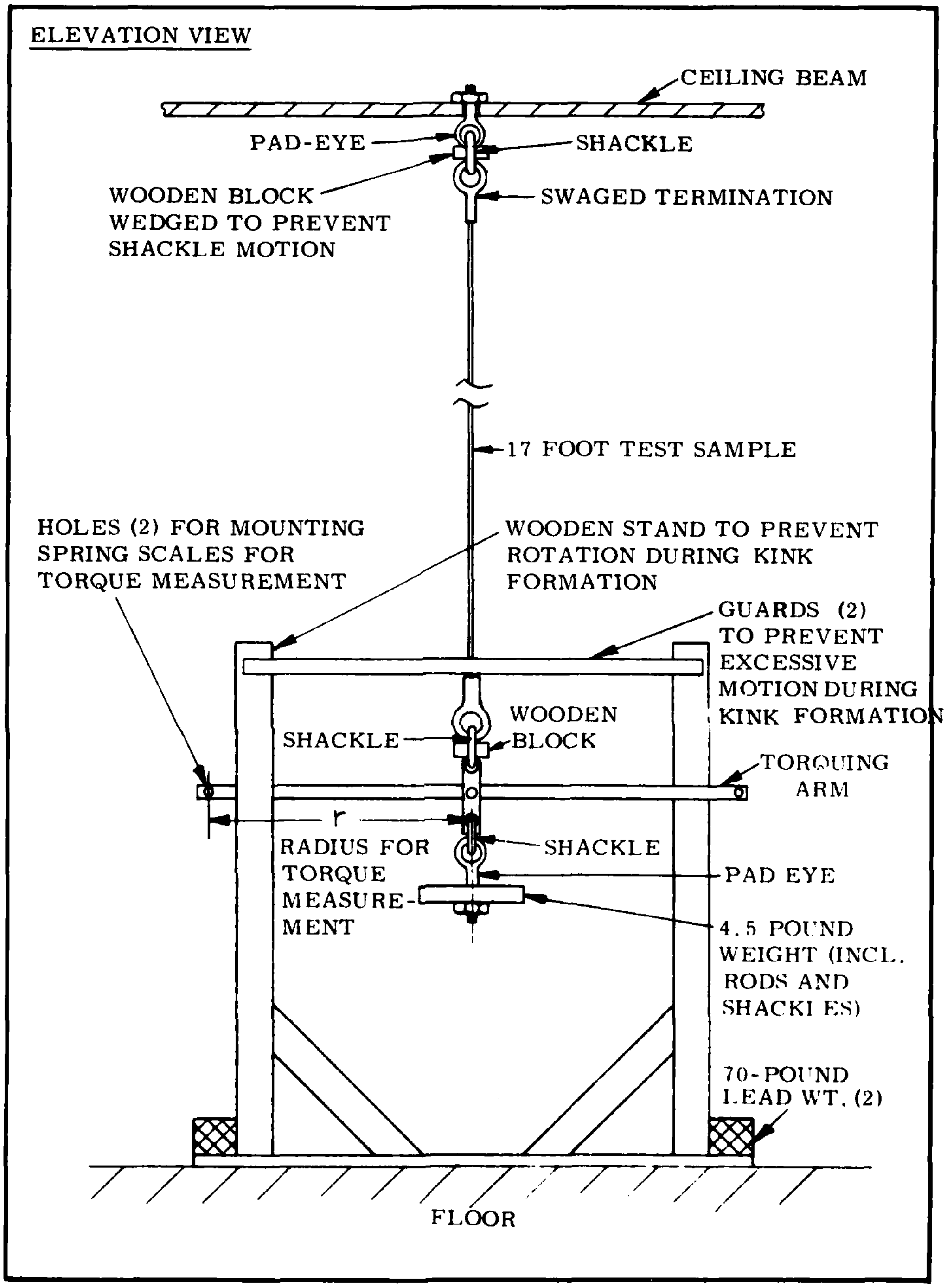

Fig. 2 Test Configuration for Measurement of Kink Formation Properties

Care was taken to insure that a very low value of spurious tension was introduced due to contact between the torquing arm and the wooden stand. This was accomplished by mounting well greased, smooth aluminum plates on the vertical members of the wooden stand. The coefficient of friction at this interface and its effect on the tension was measured but neglected in the data.

In later tests the equipment in Figure 2 was employed to compare the effects of the following termination conditions at the lower end of the sample on the kink formation properties:

(1) Large eye swaged terminations with unblocked shackle.

(2) Open swaged socket and pin.

(3) Open swaged socket and pin with sling link and unblocked shackle (i.e., rod and clevis).

The results of such tests are described in Section 3.4.

Prior to the construction of the kink formation test equipment shown in Figure 2, kink formation tests were conducted in the vertical position but at tension values ranging from 12 to 72 pounds. This equipment included a 5-gallon can of water suspended by the 17-foot sample. A specified level of torque would be put into the sample and then water slowly released from the can. It was hoped that a kink would form when the tension, acting as a stabilizing influence, reached a low enough value to no longer contain the stored torsional energy. It was found that basically this test method was extremely dangerous and not a good scheme for deriving comparative data. In some cases the weight of the hardware alone after the bucket was empty of water was sufficient to prevent the formation of kinks. Such was true with torque levels up to 15 foot pounds. Similarly, in some cases samples would fail in combined loading (torsion and tension) without forming a kink. In another case a sample formed a kink in an almost explosive manner at a torque of approximately 15 foot-pounds and at a tension of 44 pounds. Such data was non-repeatable and a difficult base on which to compare the relative merits of the samples tested. This type of test was abandoned in favor of that previously-described. It is, however, described here in order to amplify the problem. A description of additional data findings from these tests will be found in Appendix E.

The kink formation tests were complicated by residual strains and curvature found in strands and wire rope as a result of being wound on small diameter drums and reels during shipment and storage. Such a curvature was to a large degree removed for the following reasons:

(1) The tests reported herein were primarily to compare the merits of each sample on a relative, not an absolute basis.

(2) Due to its manufacturing method and its position and time on a cable reel, it is felt that the residual curvature from one sample to another can differ widely enough to contaminate the relative measurements.

(3) Due to the low tension values the importance of residual curvature as a driving force for kink formation is increased relative to the torque driving force which is of interest here.

The residual curvature was found to be considerably reduced by either laying the 17-foot long, terminated samples in a straight configuration on the floor or by hanging them vertically with a small weight on the end. Both such methods were done for a period of days, allowing creep to remove almost all of the easily-observed residual strain.

An attempt was made in this work to correlate the bending stiffness, EI, of each sample to its kink formation propensity. It was also hoped that by correlating the measured and calculated values of EI one might later merely calculate the value and ascertain information on its kink-formation properties. Reference 6 outlines a theoretical approach which suggests the correlation between bending stiffness and the formation of kinks as well as how EI is both measured and calculated. For easy reference Appendix B in this writing again describes how EI is measured and calculated.

3. RESULTS

The results of all of the mechanical tests performed by the MIT/IL are found in this section. These data are plotted in three graphs for each sample. Also these data are numerically tabulated along with other pertinent data from the manufacturer. It is hoped that a concise compilation so displayed will enable one to more readily compare the properties of strands and wire ropes.

3.1 Mechanical Properties

The mechanical properties of samples, derived in the manner described in Section 2.1, are summarized in Tables 1 and 2. The plots of the actual data from which many of the constants were derived are shown in Figures 3 to 23.

From the tension characteristics one obtains the torque at zero turns as a function of the applied tension, P. This factor is a measure of the lack of torque balance in a strand or wire rope in the as-received condition. A linearized approximation of this torque balance (TB) characteristic may be given by:

$$TB = \left[\frac{\partial T}{\partial P}\right]_{\Theta = \text{Turns} = \text{Zero}} \qquad (3.1)$$

where: T = Torque

P = Tension or Pull on cable.

The torque balance of a cable is a function of the geometry of the wires within the strand or rope and the friction level between them. It is not a function of the sample length. Such a quantity can be looked on as one figure of merit for a strand or wire rope in applications where torque or rotation must be minimized. The smaller the absolute value of this quantity the more desirable the sample.

TABLE 1

Property \ Cable Type		1 x 19 GAC 1/4" Dia. Jacketed	1 x 42 UHS 1/4" Dia. Torque Bal.	1 x 42 G 1. IPS 1/4" Dia. Torque Bal.	1 x 50 Gal. IPS 1/4" Dia. Torque Bal.
Rated Breaking Strength		8,200 lbs	13,000 lbs	9,000 lbs	7,690 lbs.
Meas. Avg. Break. Strength		10,700 lbs*	N.A.	10,880 lbs*	10,100 lbs*
Meas. Tot. Cable Area		.0404 in^2	.0381 in^2	.0368 in^2	.0438 in^2
Arrangement of wires in Strands & Lay from Center Outward		1-6R-12L	1-6R-(6+6F) R+23L	1-6R-(6+5F) R+23L	1-5L-(5+5F) L-10L 24R
K_T = Torsional Spring Constant/ Unit length(Θ=0) (P=2,000lb) [ft^2-lb/Turn]	Pos. Turns	14	30	20	50
	Neg. Turns	20	16	20	50
K_L =Linear Spring Constant/ Unit Length(Θ=0) [lbs]		8.4×10^5	10.9×10^5	8.3×10^5	13.2×10^5
TB=Torque Balance at Zero Turns [ft-lb/lb]		4.75×10^{-4}	3.75×10^{-4}	10.5×10^{-4}	3.75×10^{-4}
Bending Stiffness (EI) Unjacketed (lbf-in^2)	Meas.	216 jacketed	96	96	118
	Calc.	206 unjacketed	103	93	119.4
Relative Kink Formation Properties for Length = 17 ft. Tension = 4.5lbs	+ Turns	-	-	5.2 Turns	3.4 Turns
	+ Torque	-	-	2.5 ft-lbs	9.0 ft-lbs
	- Turns	-	-	-14.75turns	- 5.9 turns
	- Torque	-	-	-4.3 ft-lbs	-3.9 ft-lbs
Core Wire	Dia.	.052 in.	.044 in.	.044 in	0.024 in.
	Area	.00053 in^2	.00152 in^2	.00152 in^2	.00045 in^2
Wire Properties Layer 1.	Dia.	.052 in.	.042 in.	.044 in.	0.024 in.
	Pitch	2.0 in.	2.3 in.	2.8 in.	1.8 in.
Wire Properties Layer 2.	Dia.	.052 in.	.032(6).044(6)	.028(6).042(6)	.024(6).032(5)
	Pitch	2.2 in.	2.3 in.	2.5 in.	1.9 in.
Wire Properties Layer 3.	Dia.	X	.028 in.	.028 in.	0.050 in.
	Pitch	X	2.6 in.	3.2 in.	1.8 in.
Wire Properties Layer 4.	Dia.	X	X	X	0.028 in.
	Pitch	X	X	X	2.0 in.

* Data Derived from W.H.O.I. Technical Memorandum No. 20-68.

TABLE 2

Property \ Cable Type		1 x 41 Gal. IPS 9/32" Dia. Torque Bal.	3 x 19 Aluminized, swaged 9/32" Dia.	3 x 19 Gal. IPS 5/16" Dia. Torque Bal.
Rated Breaking Strength		9,000 lbs	9,900 lbs	10,300 lbs
Meas. Avg. Break. Strength		9,900 lbs*	9,900 lbs*	10,500 lbs*
Meas. Total Cable Area		.0426 in^2	.0417 in^2	.0432 in^2
Arrangement of Wires in Strands and Lay from Center Outward		1-6R-12R-22L	1-9L-9L	1-9L-9L
K_T=Torsional Spring Const./Unit Lgth. (θ=0)(P=2,000lb) [ft^2 - lb/turn]	Pos. Turns	40	5	7.9
	Neg. Turns	25	5.8	7
K_L Linear Spring Constant/Unit Length (θ=0) [lbs]		11.3×10^5	11.5×10^5	8.8×10^5
TB=Torque Balance at Zero Turns [ft-lb/lb]		4.25×10^{-4}	24.5×10^{-4}	Approx. Zero
Bending Stiffness (EI) Unjacketed (lbf - in^2)	Meas.	98	95	96
	Calc.	112	81.6	94.5
Relative Kink Formation Properties for Length = 17 ft. Tension= 4.5 lbs.	+ Turns	3.7 Turns	26 Turns	24.2 Turns
	+ Torque	3.8 ft-lbs	5.4 ft-lbs	4.4 ft-lbs
	-Turns	-13.25 Turns	-13.2 Turns	-24.2 Turns
	-Torque	-3.15 ft-lbs	-1.82 ft-lbs	-8.25 ft-lbs.
Core Wire Properties	Dia.	.046 in	.046 in	.046 in
	Area	.0017 in^2	.0017 in^2	.0017 in^2
Wire Properties, Layer 1.	Dia.	.041 in	.024 in	.022 in
	Pitch	1.8 in	.9 in	1.0 in
Wire Properties, Layer 2	Dia.	.041 in	.034 in	.036 in
	Pitch	3.0 in	.7 in	1.3 in
Wire Properties, Layer 3.	Dia.	.031 in		
	Pitch	2.1 in		
Strand Properties	Area (tot.		.0139 in^2	.0144 in^2
	Lay		Right	Right
	Pitch		1.3 in	5.6 in

* Data Derived from W.H.O.I. Technical Memorandum No. 20-68

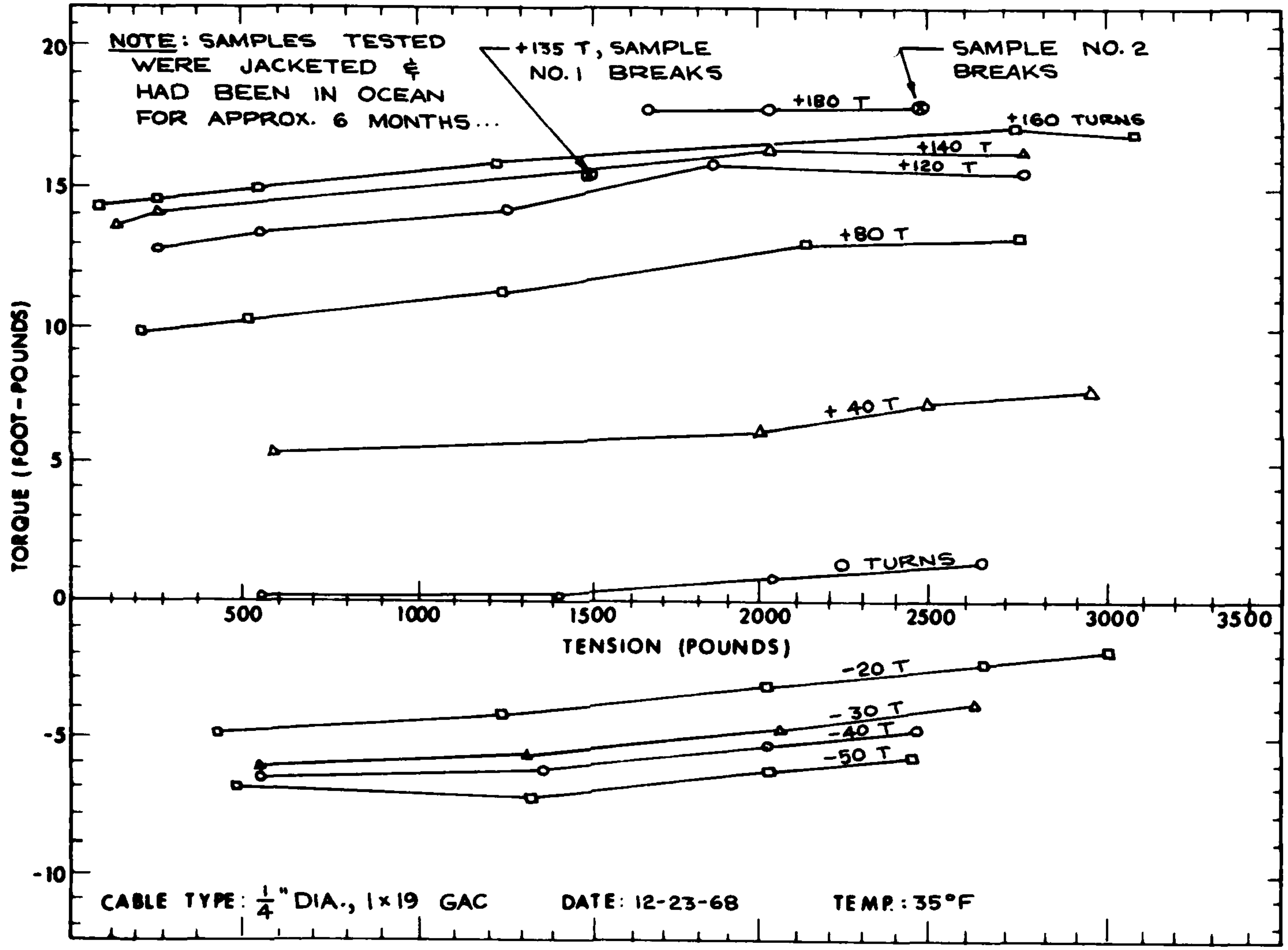

Fig. 3 Strand Tension Characteristics, 1 × 19

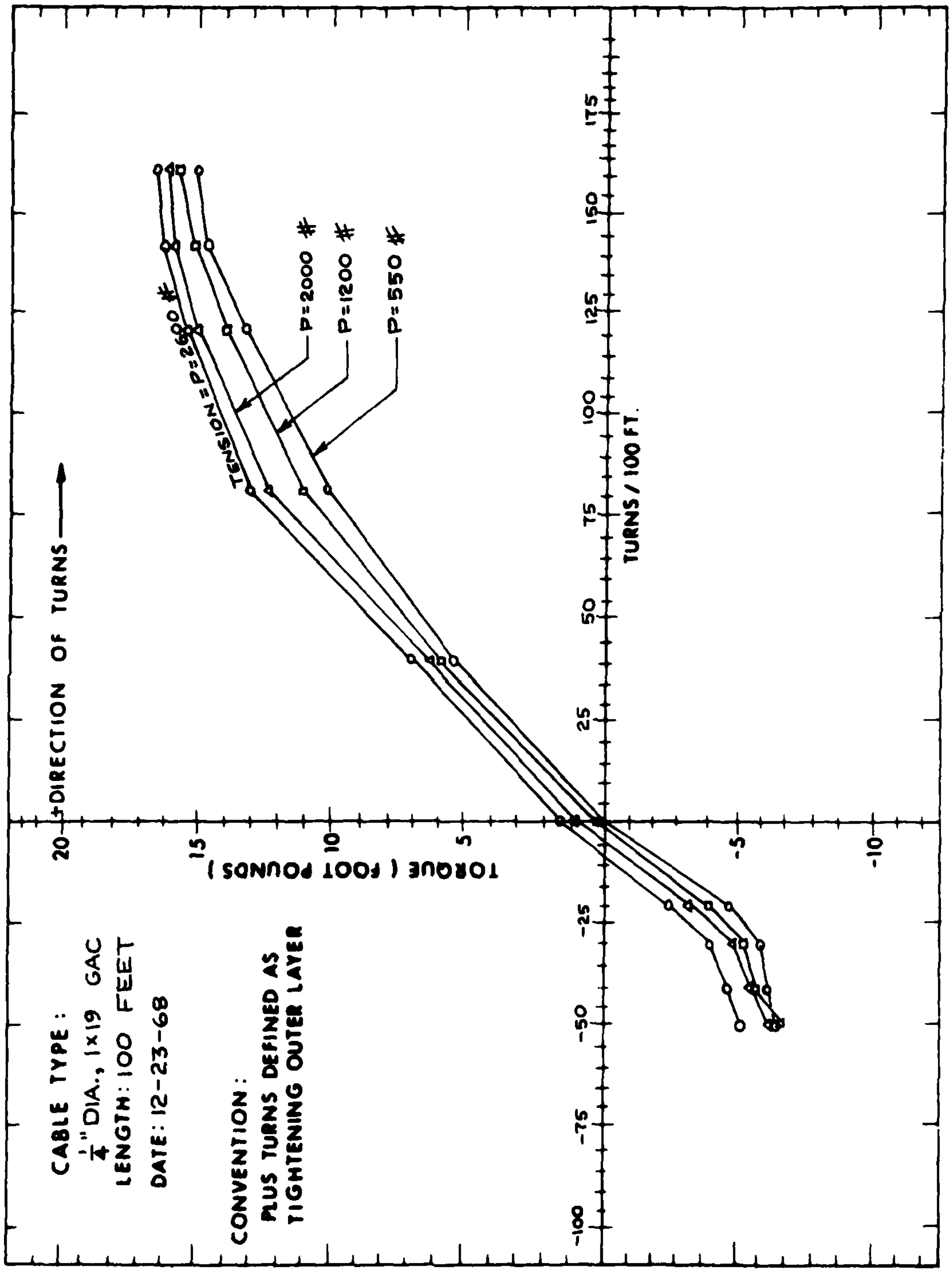

Fig. 4 Strand Torque Characteristics, 1 × 19

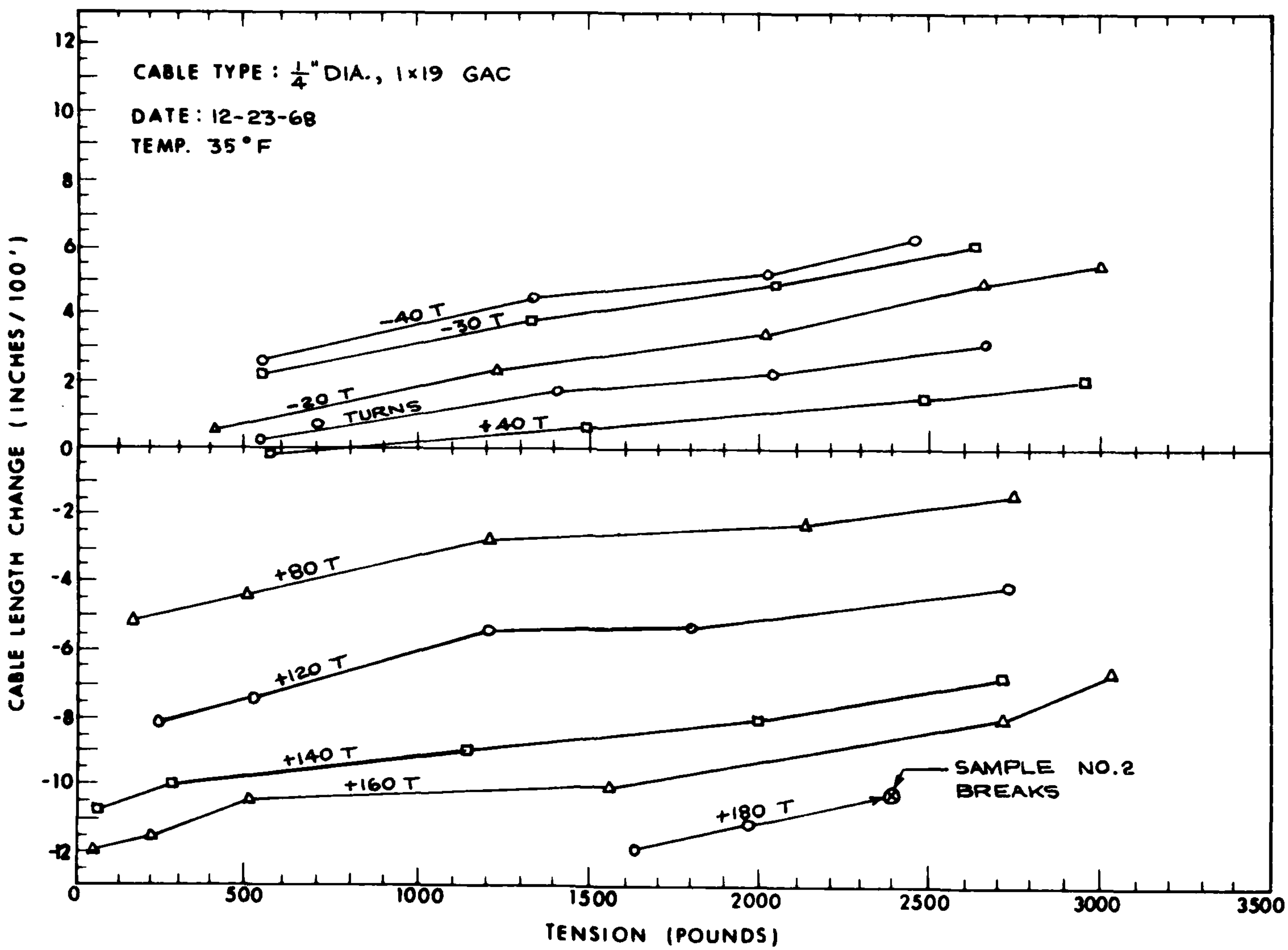

Fig. 5 Strand Stretch Characteristics, 1 × 19

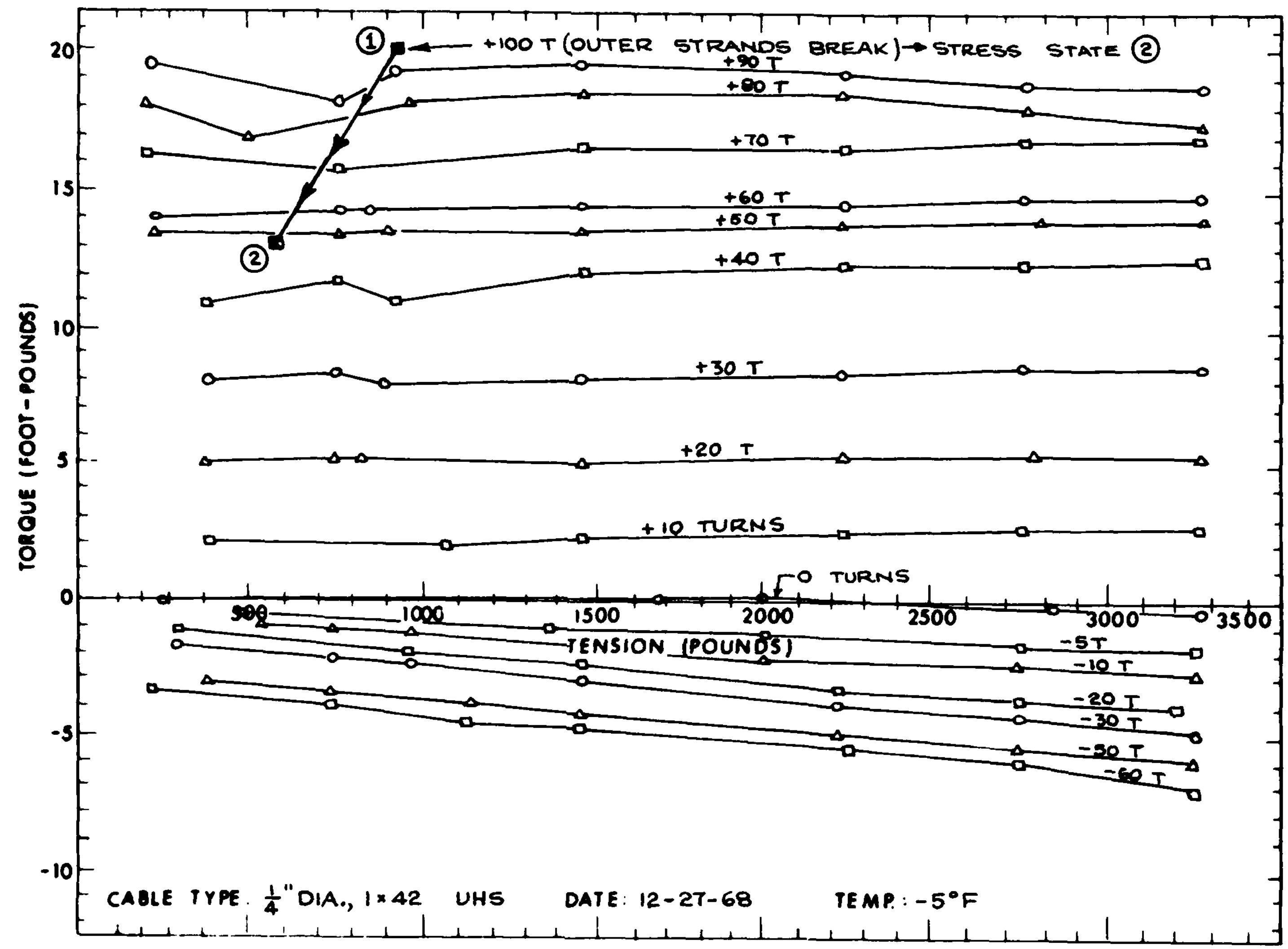

Fig. 6 Strand Tension Characteristics, 1 × 42 UHS

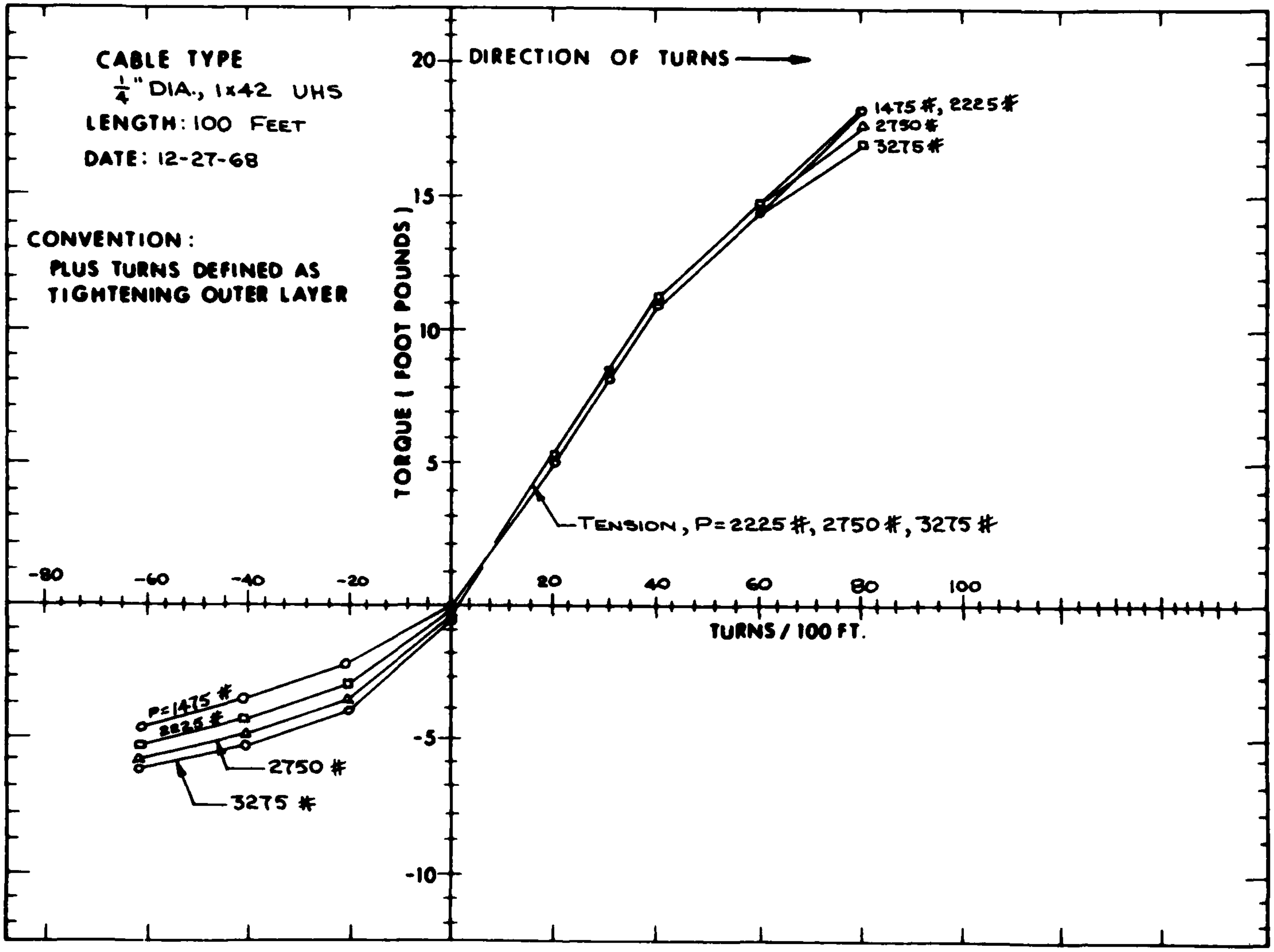

Fig. 7 Strand Torque Characteristics, 1 × 42 UHS

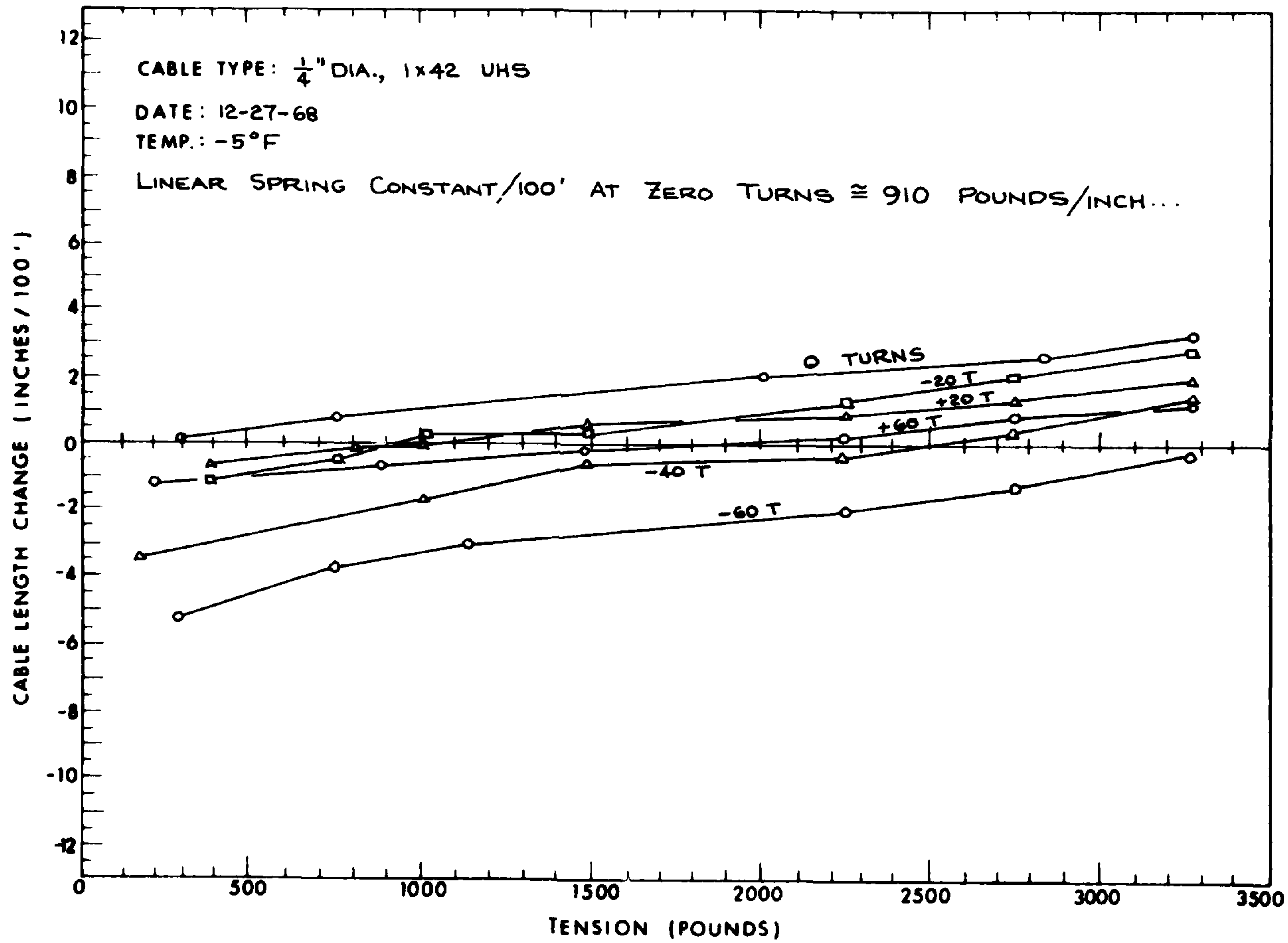

Fig. 8 Strand Stretch Characteristics, 1 × 42 UHS

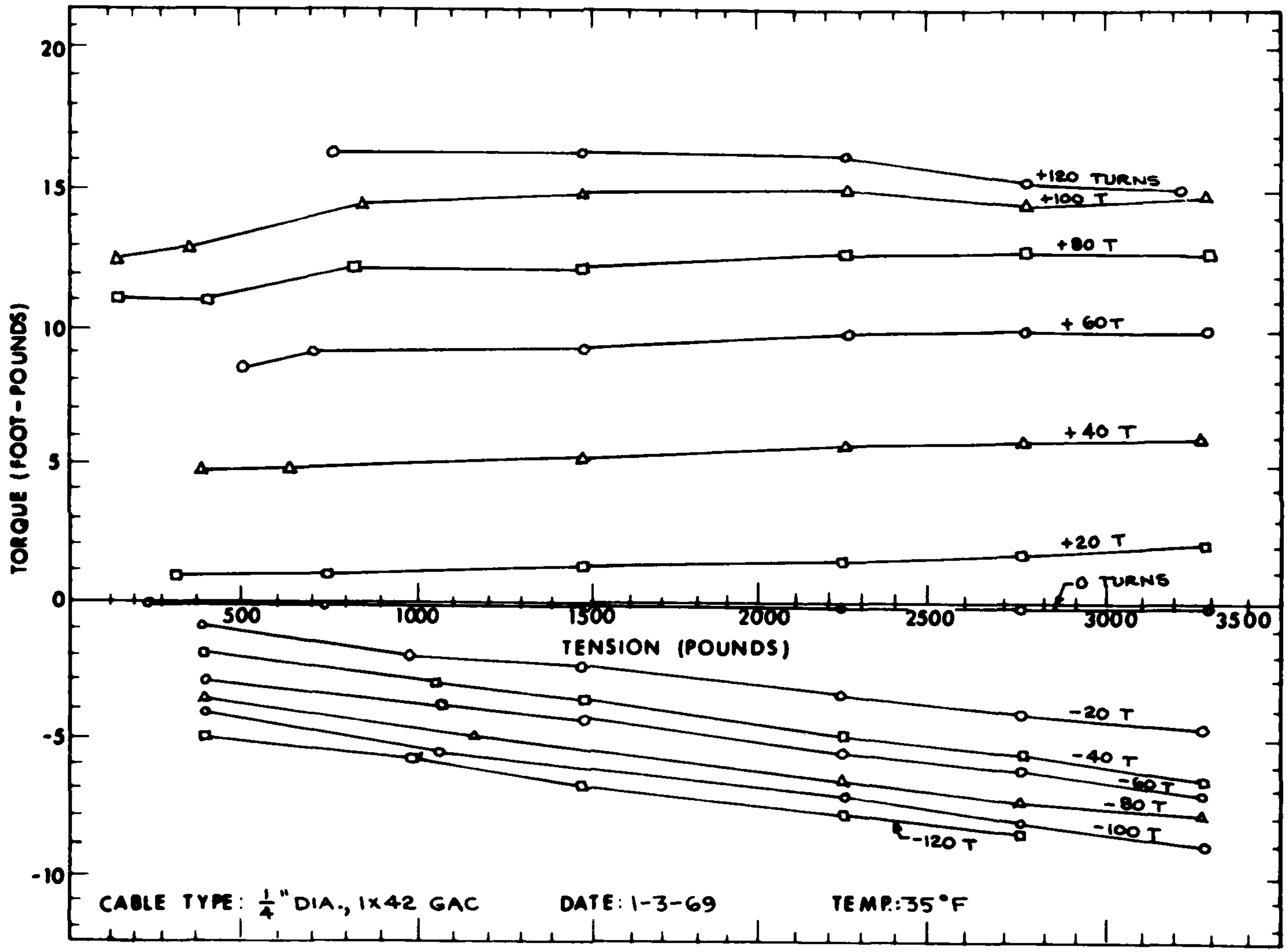

Fig. 9 Strand Tension Characteristics, 1 × 42 GAC

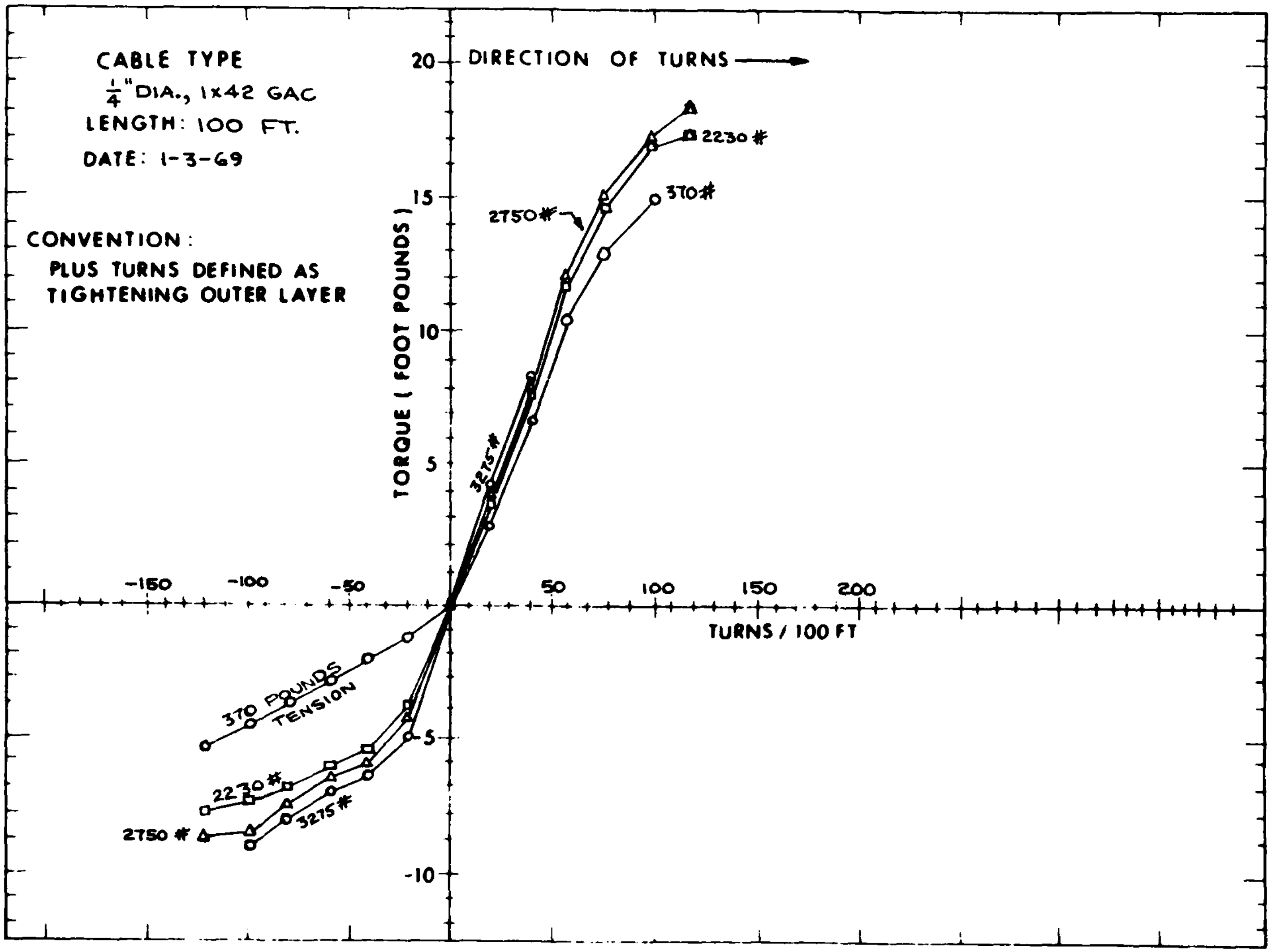

Fig. 10 Strand Torque Characteristics, 1 × 42 GAC

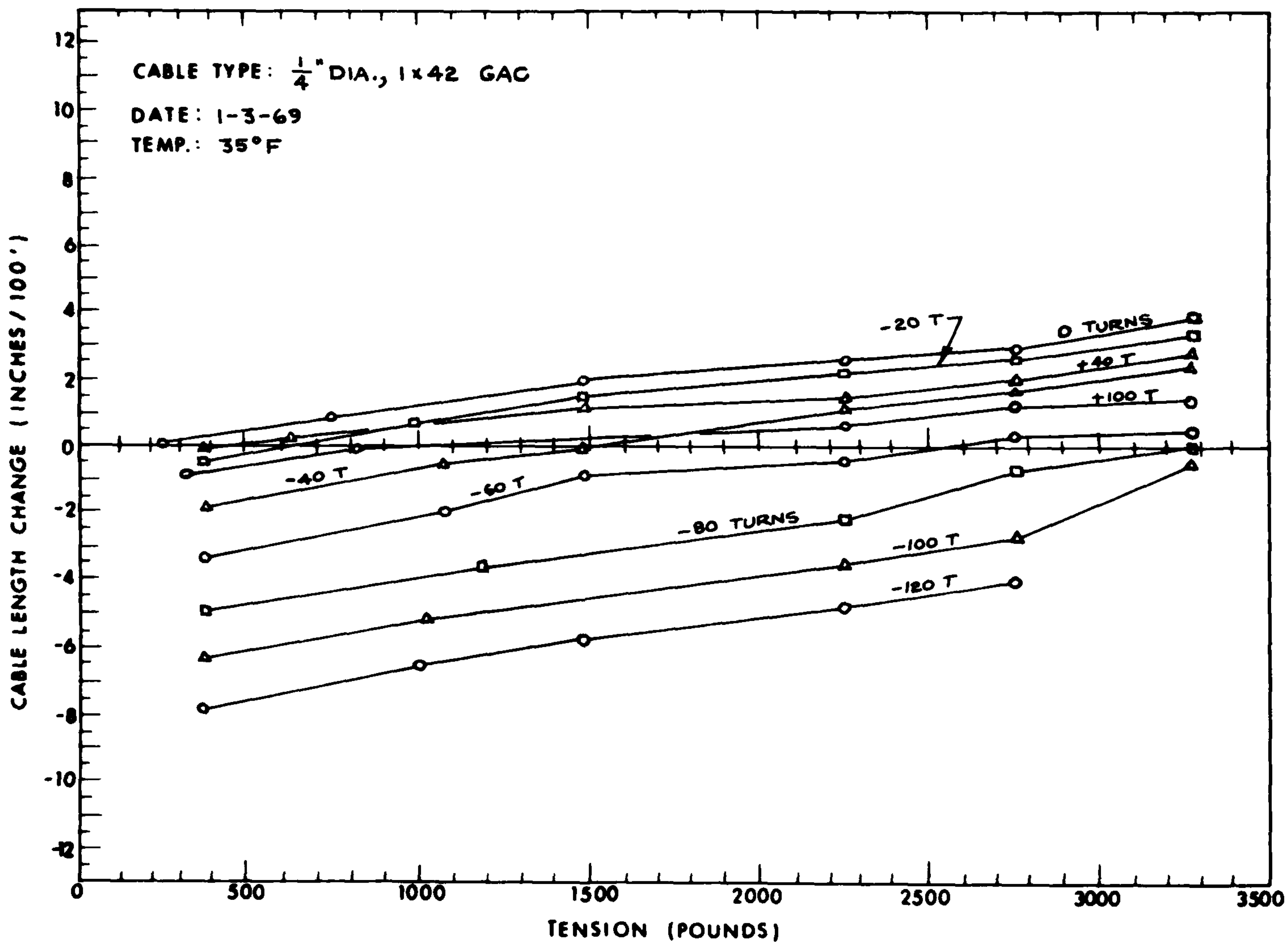

Fig. 11 Strand Stretch Characteristics, 1 × 42 GAC

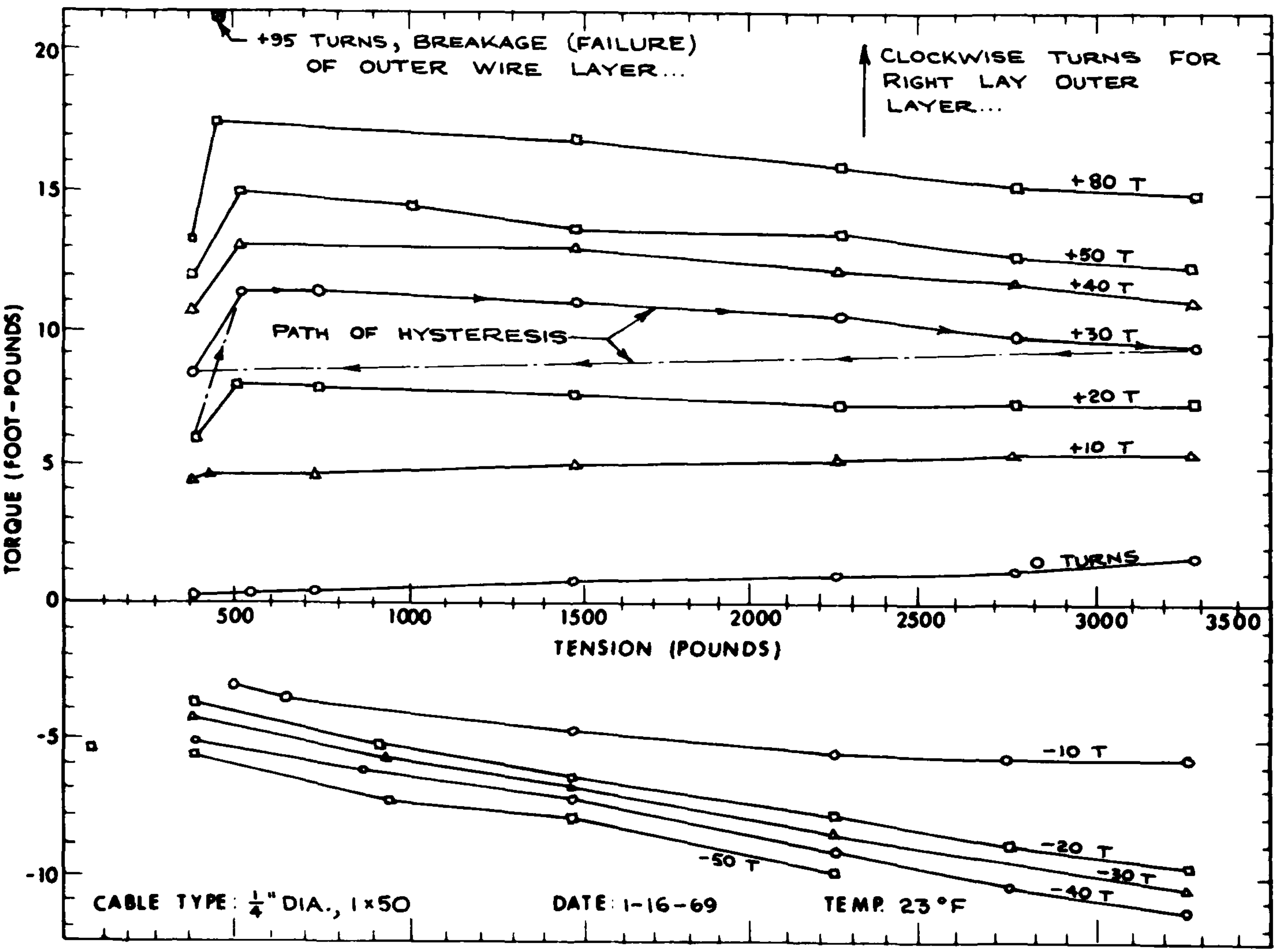

Fig. 12 Strand Tension Characteristics, 1 × 50

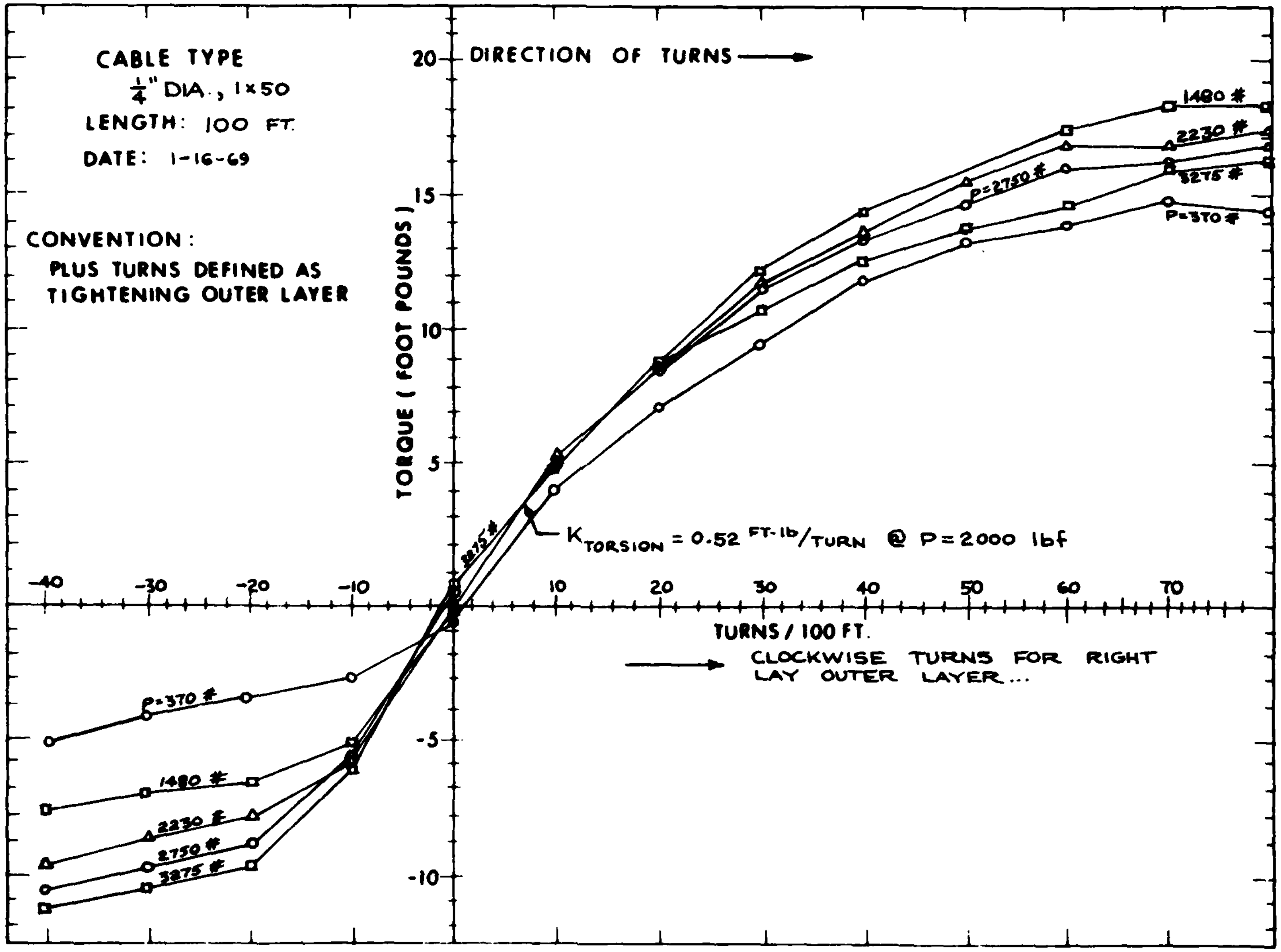

Fig. 13 Strand Torque Characteristics, 1 × 50

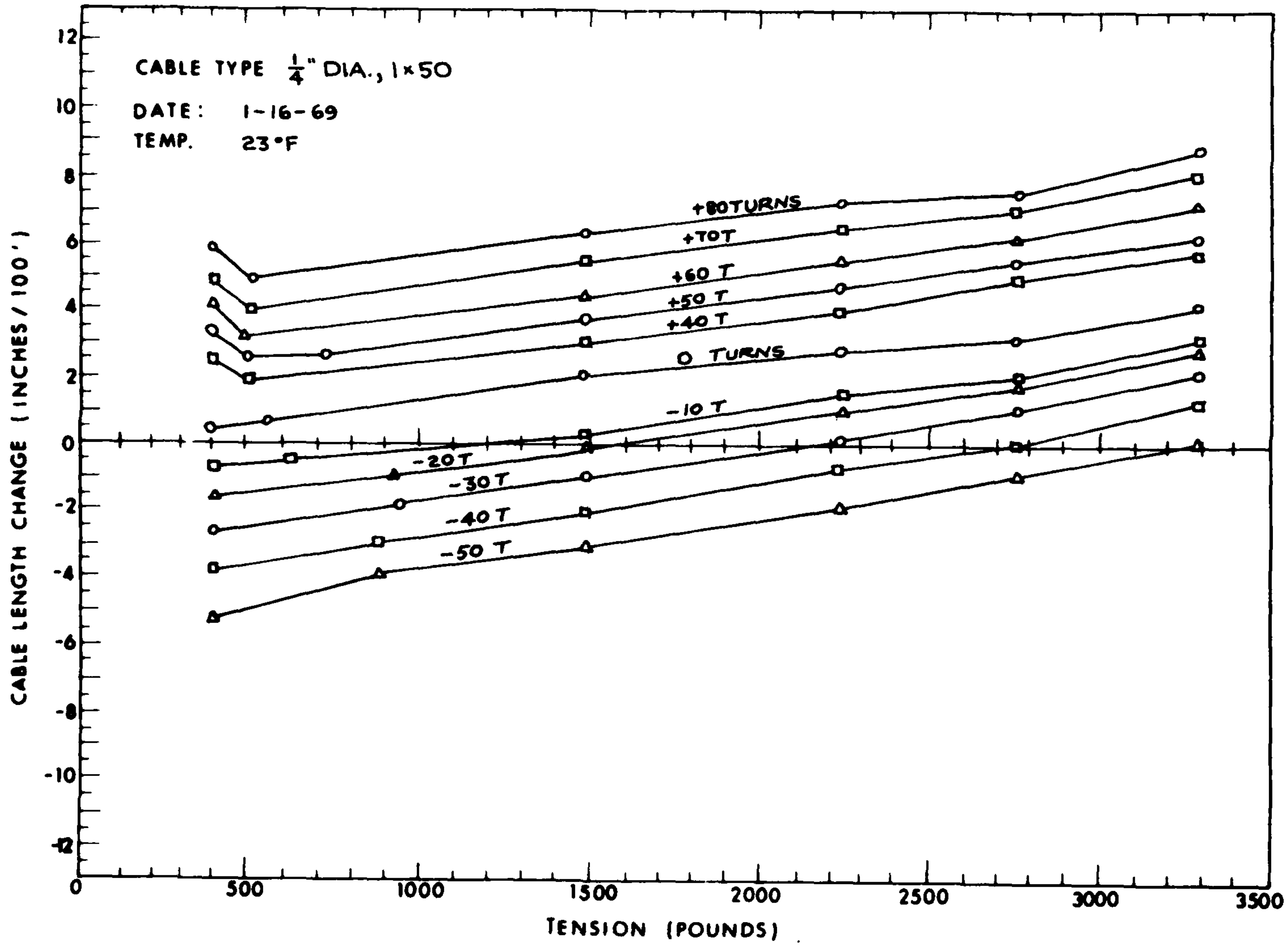

Fig. 14 Strand Stretch Characteristics, 1 × 50

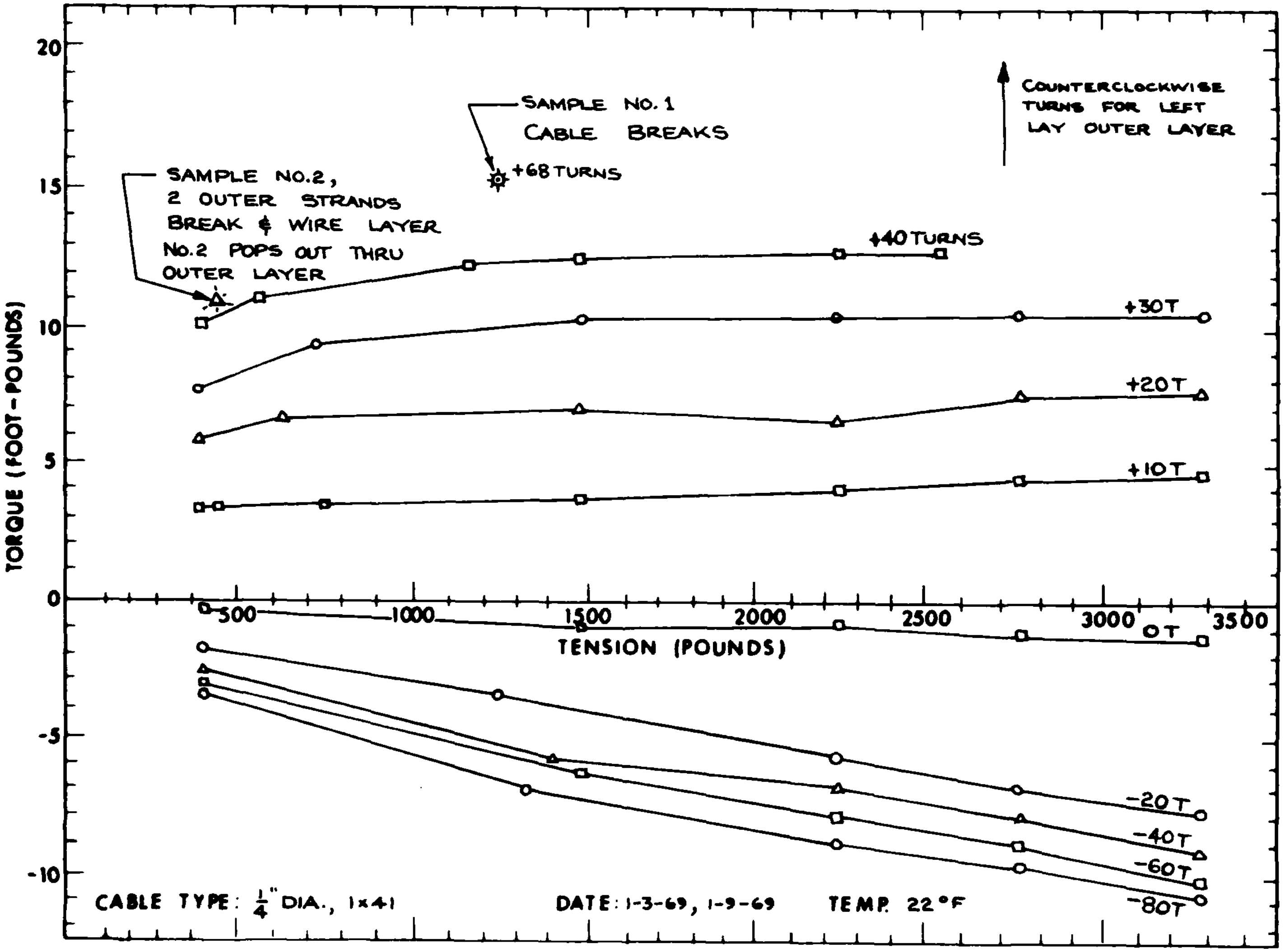

Fig. 15 Strand Tension Characteristics, 1 × 41

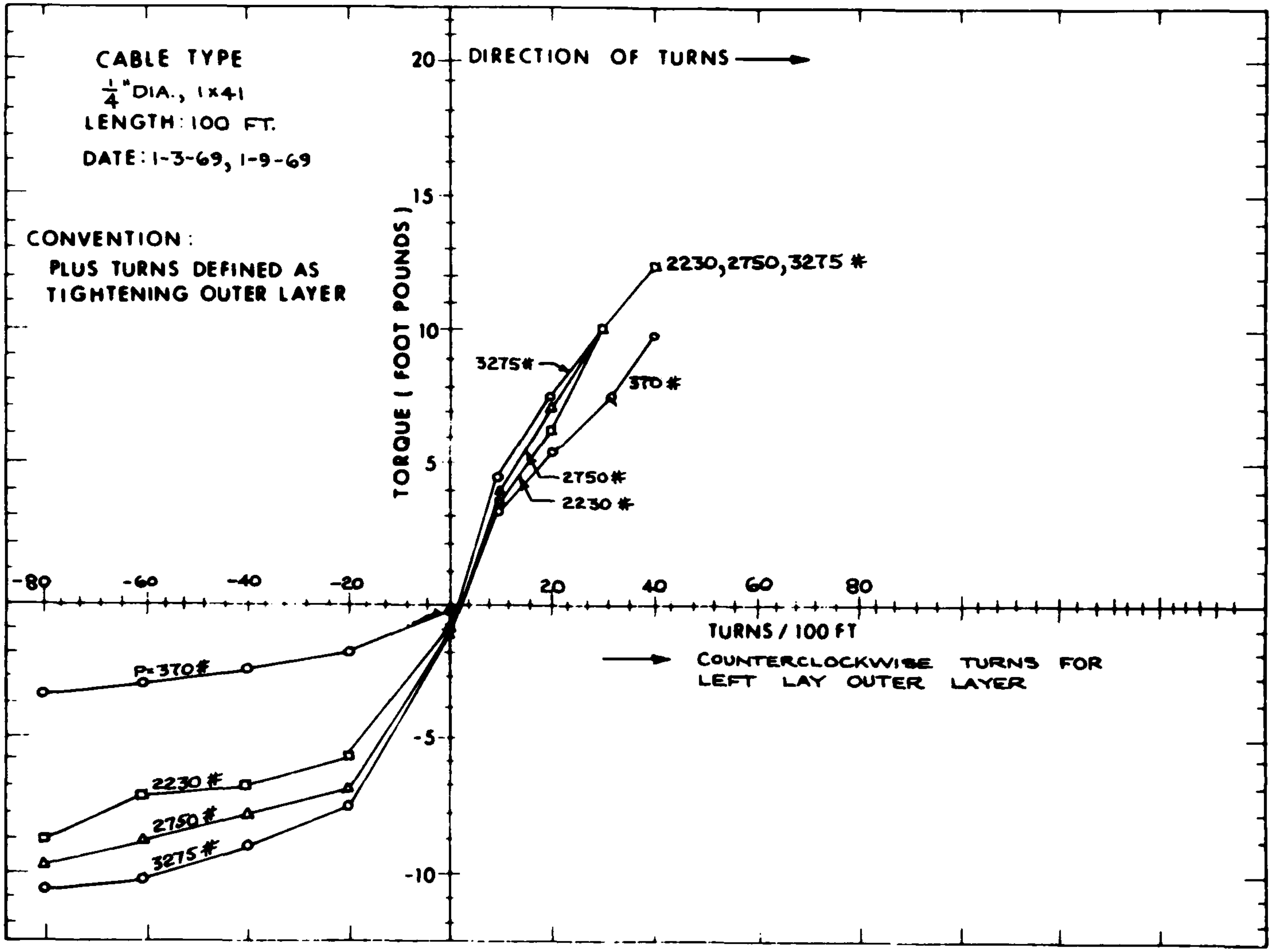

Fig. 16 Strand Torque Characteristics, 1 × 41

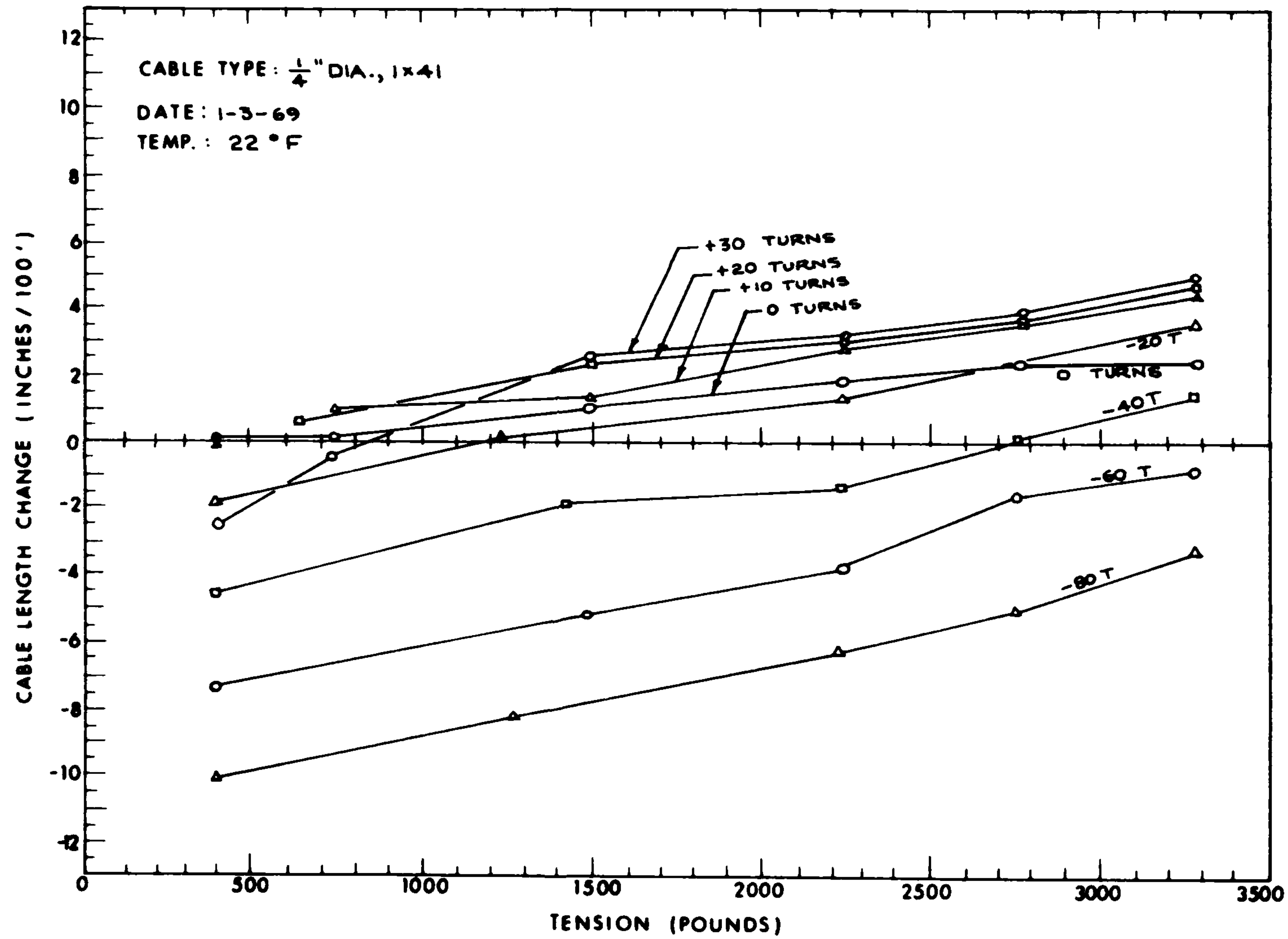

Fig. 17 Strand Stretch Characteristics, 1 × 41

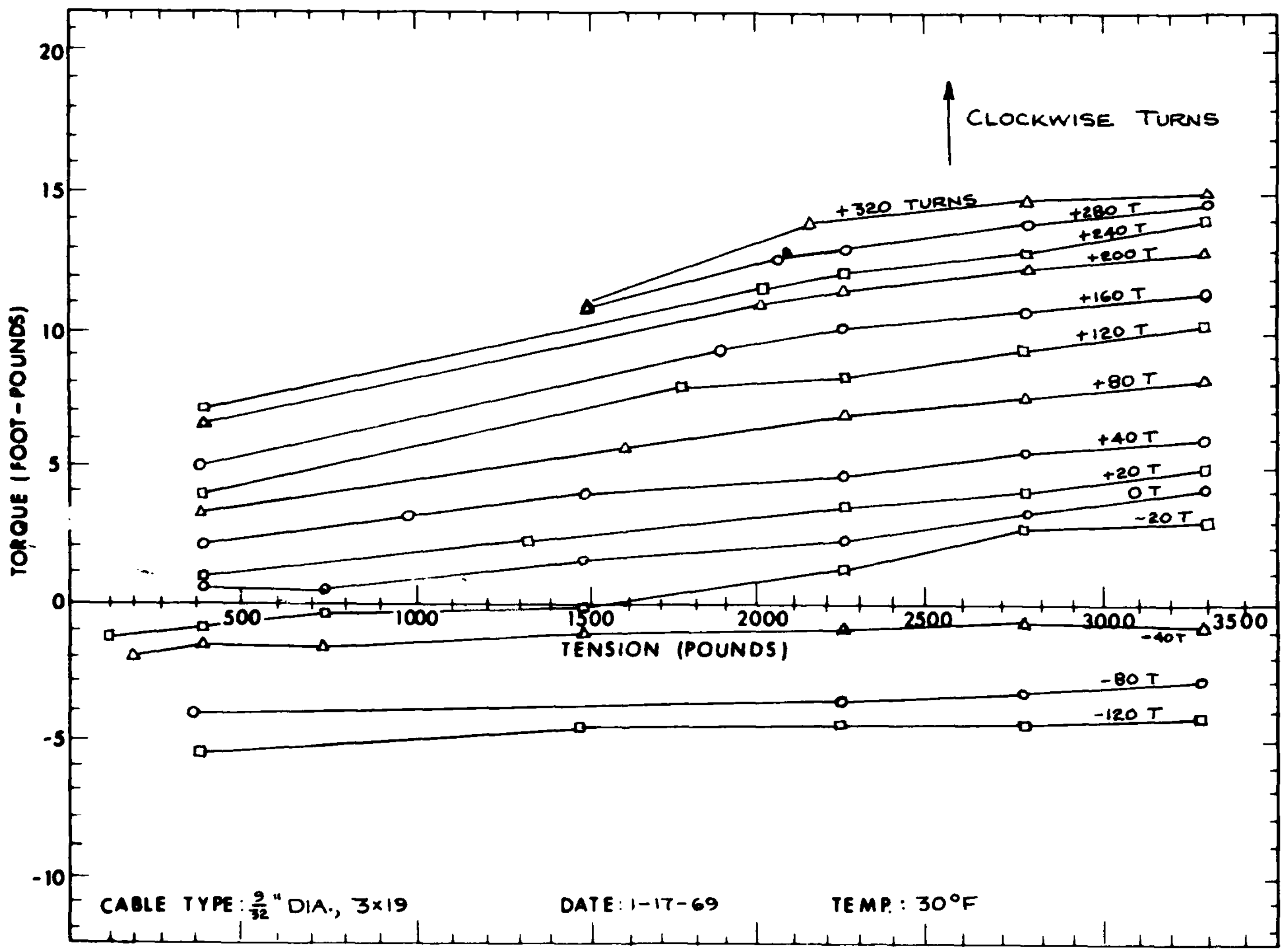

Fig. 18 Wire Rope Tension Characteristics, 3 × 19, 9/32" Dia.

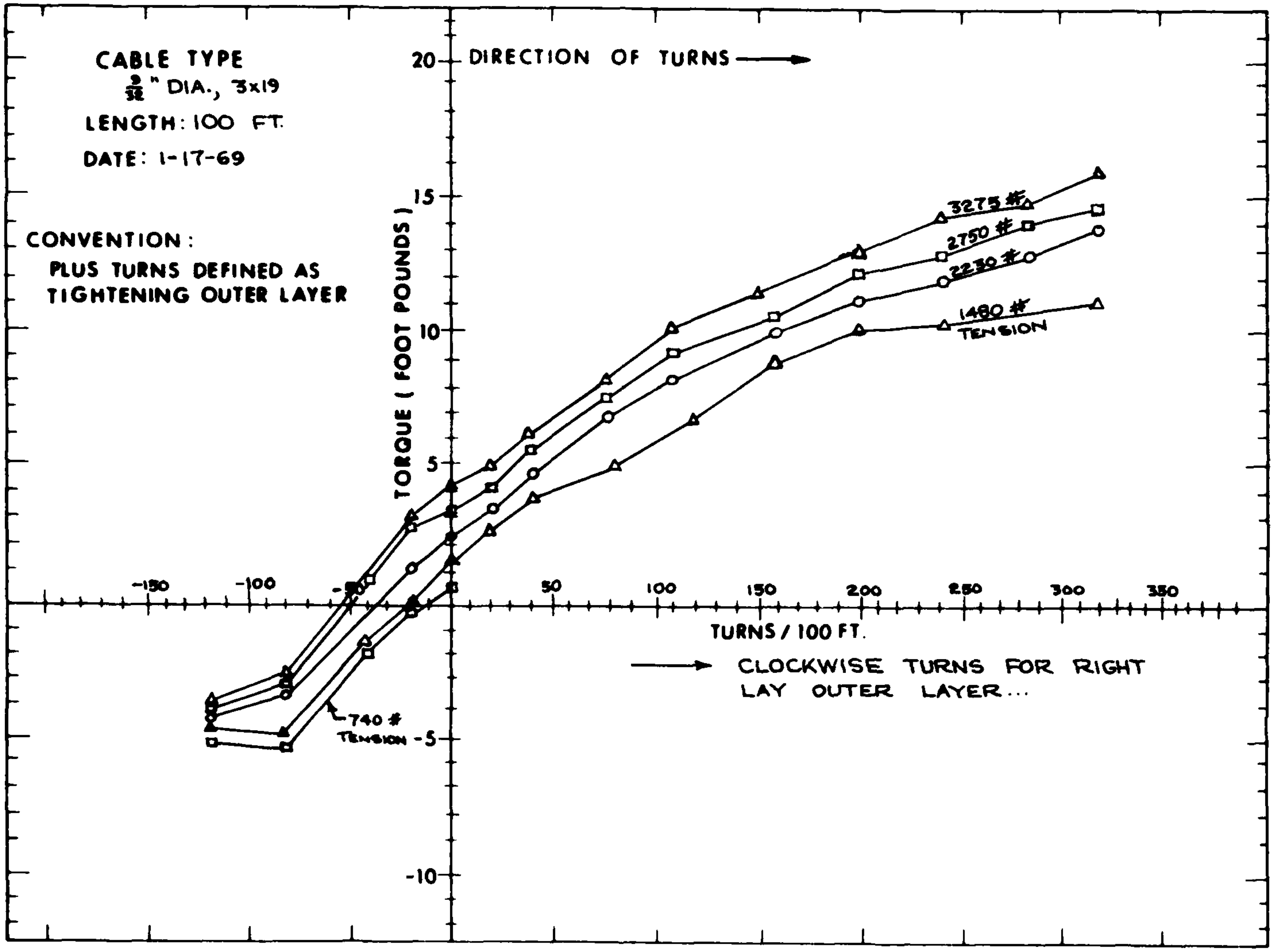

Fig. 19 Wire Rope Torque Characteristics, 3 × 19, 9/32" Dia.

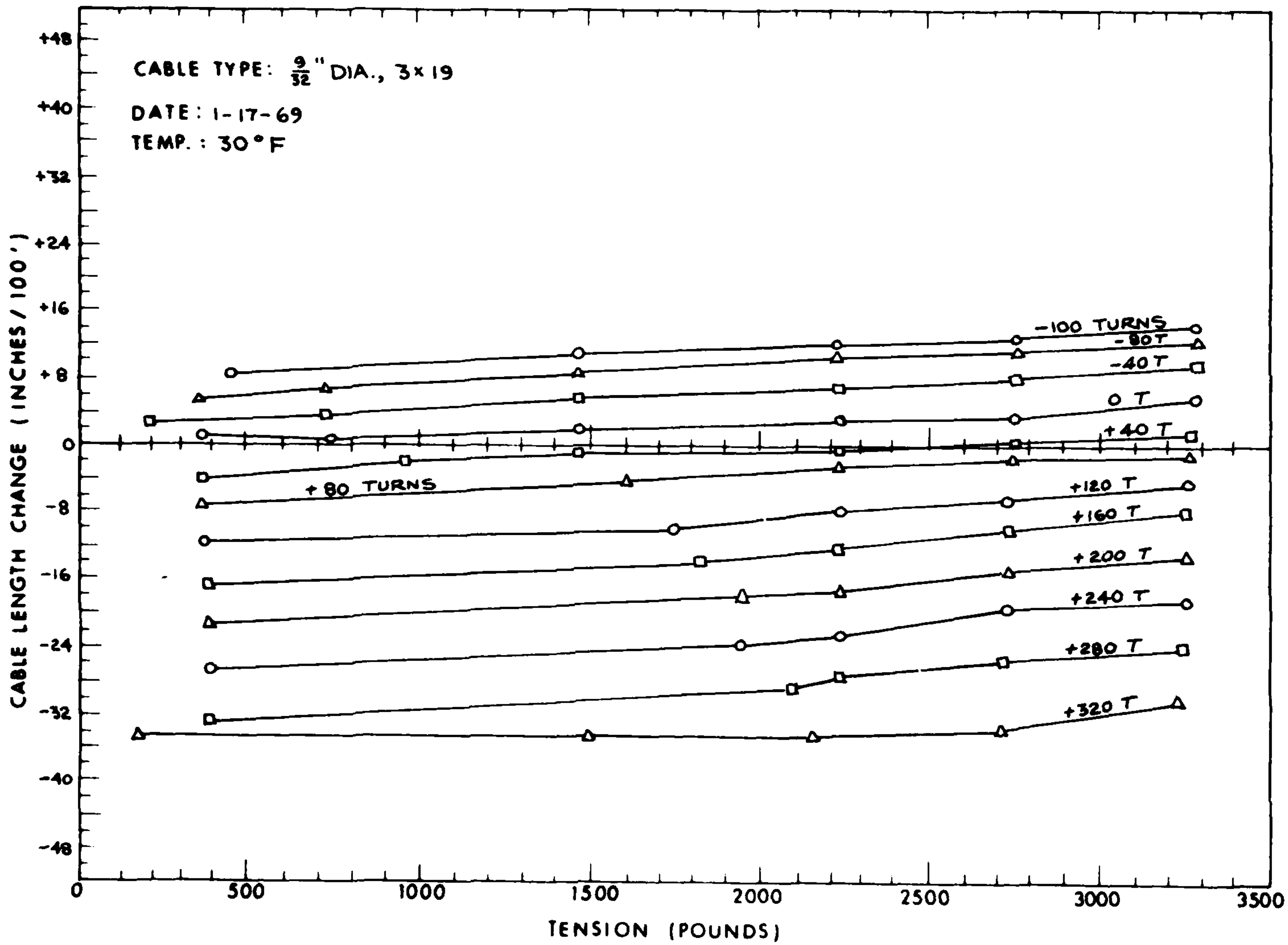

Fig. 20 Wire Rope Stretch Characteristics, 3 × 19, 9/32" Dia.

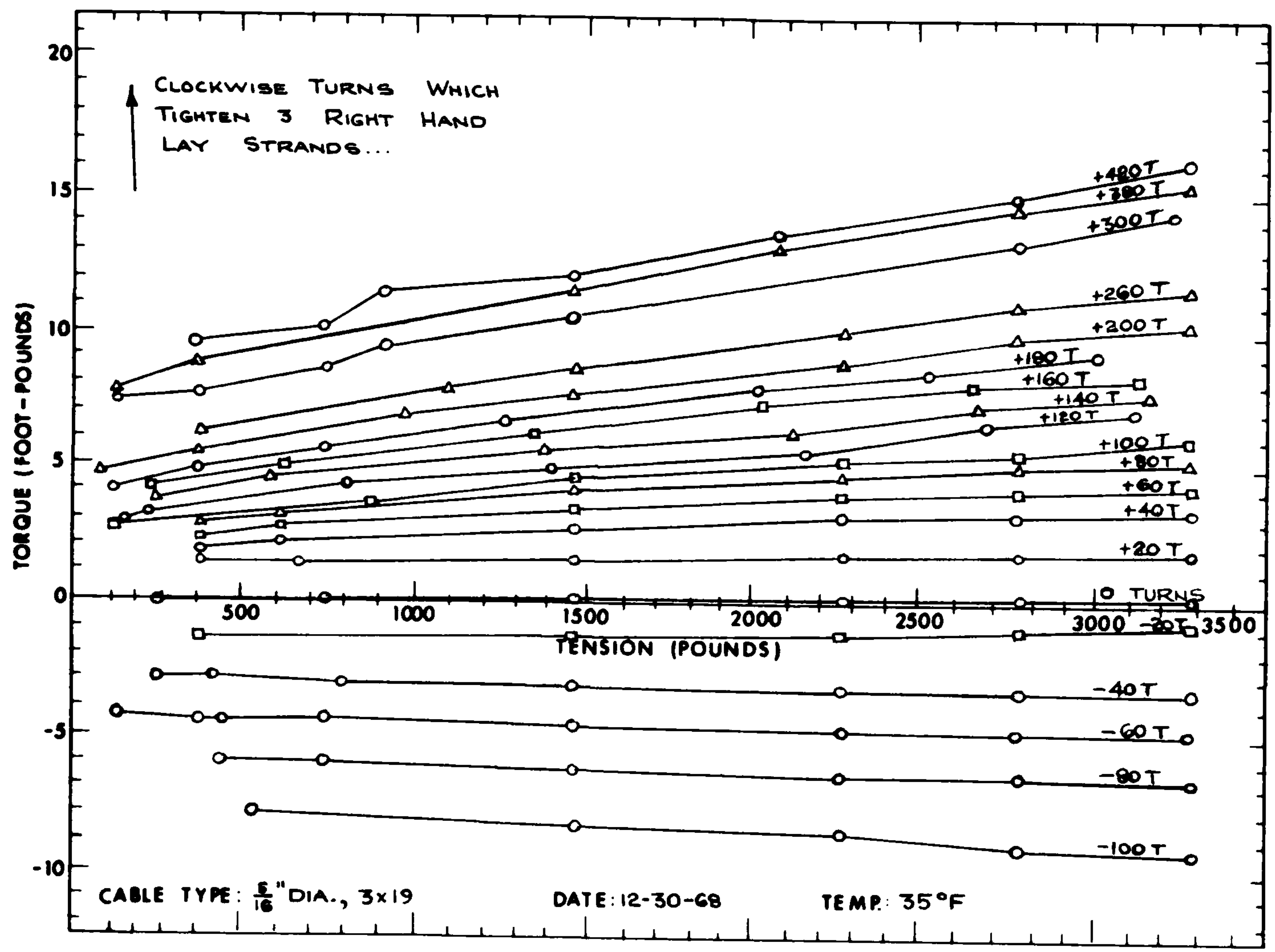

Fig. 21 Wire Rope Tension Characteristics, 3 × 19, 5/16" Dia.

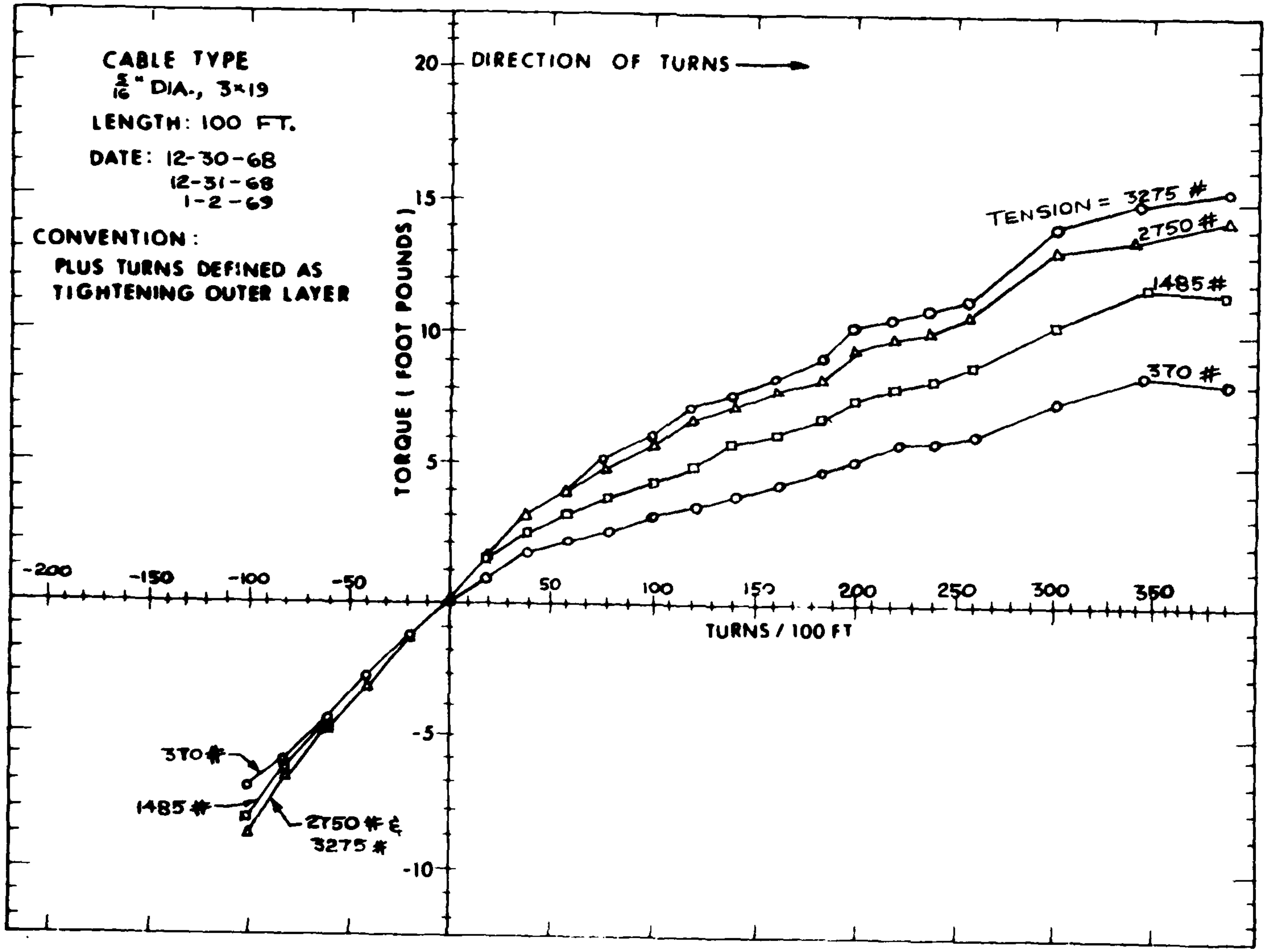

Fig. 22 Wire Rope Torque Characteristics, 3 × 19, 5/16" Dia.

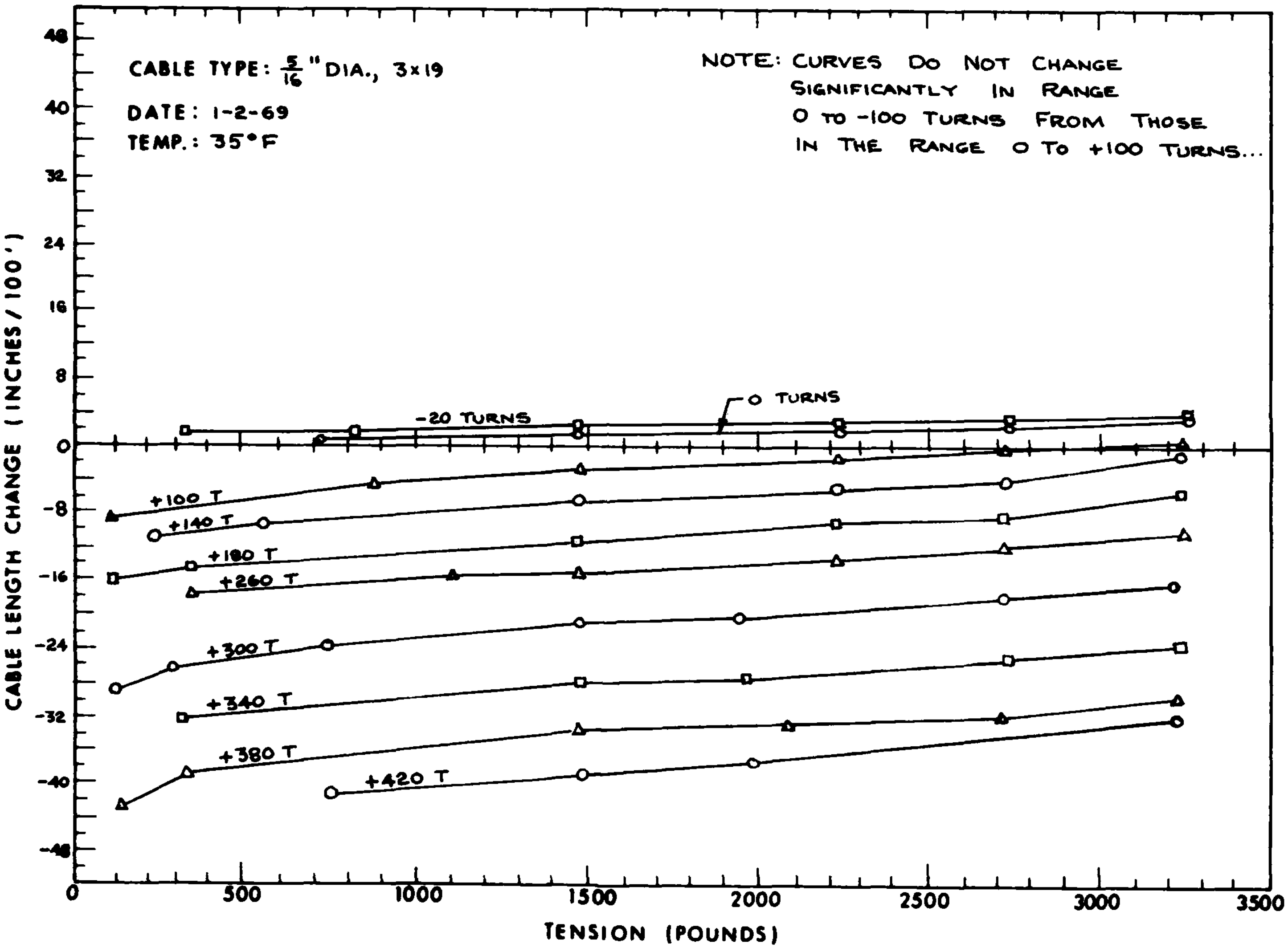

Fig. 23 Wire Rope Stretch Characteristics, 3 × 19, 5/16" Dia.

It may be observed in the tension characteristics that the slope of some of the torque versus tension curves varies in proportion to the number of relative turns introduced between different ends of the strands or wire rope. This effect may be seen, for example, in Figure 21 for 5/16" dia., 3 x 19 wire rope. Such an effect can be understood when one realizes that the introduction of relative turns changes the helix angles of the various wires within single strand mooring line or the helix angle of the strands in multi-strand wire rope. Thus, if a strand or wire rope is torque balanced (i.e., torque is not a function of tension), to keep it as such the number of relative turns per unit length in a strand or rope should be held very close to zero. Such might be accomplished by the use of reliable low-friction swivels. The effect of the helix angles of individual wires and strands is well documented in the literature (see Reference 5).

Another effect which is readily observable in the tension characteristics is shown in Figure 12 for the case of 1 x 50, 1/4" diameter strand. In this graph it may be seen that as more and more positive turns are put into the strand it appears to become negatively torque balanced. That is, for constant turns, as the tension is increased the measured torque appears to decrease. It is also seen that the initial portion of the curve appears to rise steeply over a very low tension range. Both of these effects are caused by what is here called mechanical hysteresis and will be discussed in the next section.

The strand and wire rope torque characteristics, plotted in Figures 4, 7, 10, etc., can be viewed as constant tension sections through a three-dimensional plot of torque, turns, and tension. Such plots usually show four or five sections taken at tensions of 370, 1480, 2230, 2750, and 3275 pounds. Such values were chosen because they represented easily-achieved tension values measured with a strain gage readout device. The data shown in these plots can also be derived from the tension characteristics by proceeding vertically along a constant tension line whose value is equal to one of those mentioned above. In so doing we may define the torsional spring constant at a constant, specified tension level in the region of zero turns in the following manner:

$$K_T = \left(\frac{\partial T}{\partial \Theta}\right)_{\substack{P = \text{constant} \\ \Theta = \text{zero}}} \qquad (3.2)$$

where Θ is the number of relative turns in the sample per foot of sample length. The value of Θ is merely the total number of relative turns introduced to the full sample divided by the sample length (100 feet):

$$\Theta = \frac{\text{turns}}{100} = \left[\text{turns}/_{\text{foot}}\right] \qquad (3.3)$$

The torsional spring constants listed in Tables 1 and 2 are derived from the plots of torque characteristics. The spring constant is listed as the measured slope of an estimated 2000-pound tension curve through the origin. In order to convert the given constant to apply to strands whose length is greater or less than one foot one should divide the given torsional spring constant by the new length measured in feet. For example, if one had a 100 foot length of 1 x 19, GAC strand as described in Table 1 it would have a torsional spring constant of .14 ft-lb/turn. It should be observed in some of the plots of torque characteristics and in Tables 1 and 2 that in the region of zero turns the value of K_T is not the same for both positive and negative turns. Such is the case because the value of K_T is merely an approximation to the linearized plot between adjacent data points in the torque characteristics plot. It should be pointed out, however, that the value of K_T is a smooth curve through the origin of the torque characteristics. It would be seen as such if many data points were taken in that region of the curve.

The stretch characteristics of samples are plotted in Figures 5, 8, 11, etc. The raw data thus plotted serves to specify the linear spring constant at zero turns per unit length, K_L, of each strand or wire rope. Because the stretch characteristics of a sample are a function of its length, for most generality the linear spring constant will be defined in the following manner:

$$K_L = \left(\frac{\Delta P}{\Delta L / L} \right)_{\Theta = O} \qquad (3.4)$$

Thus K_L is the change of tension per unit of axial strain in the sample when no relative turns have been introduced (i.e., $\Theta = O$). Thus the units of K_L will be merely pounds. The measured values of K_L are tabulated in Tables 1 and 2.

In the same manner as for the torsional spring constant, the linear spring constant for long samples may be derived by dividing the tabulated value by the new sample length. Thus a 100-foot sample of 1 x 19, GAC would have a linear spring constant of 8,400 pounds per foot of stretch.

The data on the torsional and linear spring constants in addition to the torque balance properties were measured for the following reasons:

(1) A knowledge of mechanical constants will enable one to choose a sample of strand or wire rope which displays desired torsional or tension responses in the presence of fixed geometry, applied rotations, or linear translations. For example, if one had a taut mooring of 1/4" Dia. 1 x 19, GAC strand, 10,000 feet long, the following information is immediately derived:

K_L = 84 pounds per foot of stretch

K_T = 1.4×10^{-3} ft-lb/turn

These values neglect friction introduced by the presence of water. If one wished the undamped natural frequency of axial vibration for such a system it could be approximated by the relation:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{K_L}{M}} \qquad (3.5)$$

where M is the lumped mass of the mooring assumed to reside at the upper end. If the value of M were 2000 pounds, including the virtual mass of elements in the water, f_n would be 0.185 cycles per second, or approximately the wave-driving frequency. It is felt that if such were the case one should re-design the mooring such that the natural frequency would be well below the wave frequency and as a result make the mooring much less dynamically responsive to motions whose frequency is well above the mooring natural frequency. Such might be accomplished by inserting a piece of nylon line or mooring line with a lower value of K_L in place of the 1 x 19 strand.

The above is a very simplified example, but it shows the immediate applicability of the data. Similar simple design uses may be made of the torsional and torque balanced properties of samples.

(2) Values of the constants shown in Tables 1 and 2 may be employed as real data in future analytical models of static and dynamic loadings on specific moorings. For example, one might pick a given mooring containing current meters and other instruments at known locations in the mooring line. If these instruments are very heavy compared to the weight of the mooring line it may be possible to model this situation by assuming that the instruments are fixed in space and that the mooring line oscillates transversely, thus producing a dynamic loading. The magnitude of the motion, the accompanying tension variations, the frequency, and the torque are all highly dependent on the parameters reported in Tables 1 and 2.

(3) The last and most important reason for deriving the given data is that it enables one to directly compare the mechanical properties of each of the samples measured and on this basis alone select what appears to be the most desirable sample.

On the basis of the values of K_T, K_L, and TB the 5/16" Dia., 3 x 19 wire rope is the most desirable as a mooring element. While having nominally the same linear spring constant as other samples tested its low value of torsional spring constant, along with that of 9/32" Dia., 3 x 19 aluminized wire rope, makes it desirable. The 9/32" Dia., 3 x 19 samples fall short of the 5/16" Dia., 3 x 19 samples in their poor torque balance properties.

It is desirable to have a low value of torsional spring constant in order to minimize torque build-up within a mooring line due to the introduction of turns by a rotating buoy or anchor. Similarly it is desirable to have a low value for TB, the torque balance figure of merit, in order to minimize instrument motion and cable rotation upon the application of tension. If, for example, tension is applied to a poorly torque-balanced sample and one end is allowed to rotate freely it will do so in order to relieve the torque thus developed. When the applied tension is released or lowered as due to wave motion on a buoy there will be a level of torque of opposite sign to that originally applied present in the sample. If the end restraint cannot respond to this new torque by rapidly and freely rotating, which for a large buoy is impossible, a kink might develop in the mooring line. It can be seen that such would not be the case if a sample were perfectly torque balanced at all tension values. Thus the choice of 5/16" Dia., 3 x 19 wire rope is made because it is almost perfectly torque balanced for the case of zero turns.

It might be instructive to follow the above description of what happens to a non-torque-balanced sample when alternate values of tension are imposed on it by referring to the curve of tension characteristics for 1/4" Dia., 1 x 19 strand (Figure 3). As tension is applied to a relaxed sample the state of torque and tension will proceed up the zero turns curve because the turns have not had a chance to relieve themselves initially. With an end free to rotate the torque thus developed will be relieved by the sample unwinding somewhat in the negative turns direction. Such will proceed until all of the torque is released by rotation while at the elevated tension level. Now, if the applied tension is rapidly released to a lower value the state of torque and tension will travel down the new constant turns curve until it reaches the new value of applied tension. It may be seen that, due to the finite slope of the constant turns curves, due to poor torque balance properties, there is now a negative value of torque present in the sample. If the remaining tension is sufficiently near zero and the torque value high enough, an opening kink might thus result.

Another undesirable property of non-torque-balanced samples is that in the presence of cyclic tension and the accompanying cyclic rotation of non-torque-balanced mooring lines, there is considerable rubbing and possible abrasion between wires within the wire rope or strand. Over a long period of time such wear could produce a mooring failure.

It was found that the values of strand or wire rope bending stiffness, EI, derived by both calculation and measurement schemes outlined in Appendix B, produced values which agree closely. The values are shown in Tables 1 and 2 for unjacketed line except for the measurement on 1 x 19 strand. This sample contained a jacket which increased its measured stiffness by approximately ten percent. An estimate of the effect of a jacket on the bending stiffness is found in Appendix D.

It was also found that six of the samples exhibited values of bending stiffness which were nearly the same while the seventh sample, 1 x 19 strand, was both measured and calculated to be approximately twice as stiff in flexure while still nominally of the same outer diameter. Such a fact can be understood when one looks at what governs the bending stiffness EI of a sample.

In Appendix B it is found that E, Young's Modulus, is approximately the same for each sample and I, the transverse area moment of inertia of a sample is given by the relation:

$$I = \frac{1}{2} I_\rho = \frac{1}{2} \int r^2 dA \qquad (3.6)$$

where I_p is the polar moment of inertia. It was found (reference 6) that I_p can be calculated by independently summing the I_p's of each wire within the strand as if each wire were acting independent of every other wire. Thus one gets the relation:

$$I = \frac{1}{2} \sum_{i=1}^{N} \frac{\pi D_i^4}{32} \qquad (3.7)$$

where: D_i = Wire Diameter

N = Total Number of wires/sample.

A simplifying assumption of a uniform wire diameter per strand for illustration purposes produces the relation:

$$I = \frac{N \pi D^4}{64} \qquad (3.8)$$

It can be shown that, N, the number of wires per sample is inversely proportional to the wire cross-sectional area (i.e. $N \propto \frac{1}{D^2}$). Thus one can rewrite (3.8) in the proportional form:

$$I \propto \left(\frac{1}{D^2}\right)\left(\frac{\pi D^4}{64}\right) = \frac{\pi D^2}{64} \qquad (3.9)$$

Therefore as the diameter of each individual wire, D, increases, I will increase proportional to D^2. As a result the 1 x 19 strand with a larger D, has a value of EI which is approximately twice that of the other samples.

Of prime concern in the investigation herein reported are the kink-formation properties of each sample. Employing the apparatus described in Section 2.2 the kink formation threshold of the majority of samples was measured and tabulated in Tables 1 and 2. For each sample tested, numbers were measured for both positive and negative torque and turns. A detailed description of the kink formation results is found in Section 3.3.

In addition to the measured mechanical properties, Tables 1 and 2 contain a compilation of physical characteristics of each sample. The arrangement of strands and wires within the sample is given for easy reference and comparison. Similarly, the wire sizes and approximate pitch (i.e., the distance between nodes within the wire or strand helix) are listed. Such data were derived by actual measurements on samples. The compilation of all such data is felt to be an aid in evaluating samples as well as assisting in future calculations. For example, given a certain tension, strand length, and number of differential turns between ends of a strand, one could employ the listed data to derive an approximate state of stress within each wire of the strand (see Reference 5).

3.2 Torque Hysteresis in Presence of Tension

As mentioned earlier there is a hysteresis-type of effect occurring with the torque and tension in some of the samples. The most pronounced case showing this effect is with the 1 x 50 strand as shown in Figure 12. In this figure one particular hysteresis path is pointed out in order to demonstrate the manner in which the data was taken. With the lowest value of tension (370 pounds) for +20 turns in the sample, +10 turns were added to the sample. This produced an increase in tension and a drastic increase in the torque level. Subsequently the tension was increased and data measured at predetermined tension values up to 3275 pounds. In so doing, the torque level was linearly decreasing with the increase of tension. When the tension was then lowered to its lowest value the torque, however, decreased again, reaching a value considerably lower than that measured just after the introduction of the +10 turns.

It is evident that the above effect is caused by internal friction between the wires within the strand. The introduction of additional relative turns in the sample distributes most of the turns near the end of the sample which was rotated. Because the turns are confined to only a limited portion of the sample length, the resulting torque is considerably higher than if they were uniformly distributed over the sample length. As the tension is increased, though, the previously-hindered relative motion between wires is overcome by axial motion, relieving the torque. In the process it is felt that considerable rubbing takes place between the wires which might result in damaging wear over a long period of time. Such would be true only if full hysteresis cycles of turns and tension were allowed.

3.3 Kink Formation

The data which strictly apply to relative kink formation properties for the case of blocked, ring eye, swaged terminations are shown in Tables 1 and 2. In some cases the kink-formation properties differ markedly in both the positive and negative directions. Furthermore, it is felt that a mooring line might receive either type of rotation with equal probability.

Thus a figure of merit on a sample's kink-formation propensity can be obtained by averaging the absolute values of the kinking torques in each direction. In addition it is illustrative to average the absolute values of the number of positive and negative turns. Table 3 is created in order to tabulate such quantities for the tested samples:

TABLE 3

Sample (Length = 17 feet)	Average Kink Formation Torque (Tension = 4.5 lbs.) $\frac{1}{2}\left[\lvert T_+\rvert + \lvert T_-\rvert\right]$	Average Number of Turns for Kink $\frac{1}{2}\left[\lvert \Theta_+\rvert + \lvert \Theta_-\rvert\right]$
1/4" Dia., 1x42, GAC	3.4 foot-pounds	10
1/4" Dia., 1x50, IPS	6.45 foot-pounds	4.7
9/32" Dia., 1x41, IPS	3.5 foot-pounds	8.5
9/32" Dia., 3x19, Aluminized	3.6 foot-pounds	19.9
5/16" Dia., 3x19, IPS	6.3 foot-pounds	24.2

The 1 x 50 strand and the 3 x 19, 5/16" Dia. wire rope appear to be almost a factor of two better than the three other samples tested. Another factor of importance is the fact that the multi-strand samples (3 x 19 wire rope) absorb between three and five times as many average turns as single strand samples before forming a kink. For negative turns all samples except the 3 x 19, aluminized, swaged sample absorbed more turns than in the positive direction before kinking. On the basis of greater absorption of rotational energy, multi-strand or wire rope samples are recommended. Of the two multi-strand samples tested the 5/16" Dia, 3 x 19 again appears to be superior in terms of kinking properties.

The most important fact which is derived from the outlined tests is that the only time kink formation poses a problem in strands or wire rope samples is when the tension is very nearly zero. The level to which tension must fall in all samples in order to produce a kink, no matter how high the torque level may be, is so near zero that it is academic to choose one sample over another on this basis. It is felt that if one had ideal conditions imposed on a mooring and one could always maintain a tension of greater than approximately 10-pounds in a mooring line it is felt that kink formation would not be a problem. By ideal conditions the following is meant:

(1) Terminations such as swaged ring eye and swaged rolled eye, in addition to those created by Crosby Safety Clips, and preformed terminations, be prohibited unless their motion at a termination condition is restrained by blocks (see Section 3.4).

(2) Swaged ring eye fittings which are blocked, as above, should be properly swaged to give no transverse preferential offset at a termination. Swaged eyes which are bent in the termination process contribute to kinking (see Section 3.4).

(3) Strand and wire rope should be free of residual axial curvature due to being tightly wound on small diameter drums and reels during storage and shipment. It is felt that such a common condition produces a predilection to kink formation at low tension values. The magnitude of this effect and its relation to drum radius was not measured.

The above ideal conditions are difficult to obtain in practice. Therefore, in light of the above, and calculations found in Appendix E, it appears that under non-ideal conditions a tension of close to 100 pounds may be necessary to inhibit kink formation with torque values up to those which cause the sample to fail in combined loading.

As mentioned earlier, it was hoped that a relative correlation might be derived between the bending stiffness (EI) of samples and their relative kink formation properties. For the five samples for whom kink formation tests were conducted their measured bending stiffnesses are approximately of the same value while, as mentioned earlier, their average absolute values of kinking torques differ by almost a factor of two (see Table 3). Thus, it appears as though there is no correlation between measured (or calculated) bending stiffness and the kinking tendency. It is still felt that under the proper conditions of strand choice and tests a correlation might be eventually found between EI and the kinking propensity. The bending stiffness data, although of limited application here, is still included in order to amplify the problem.

3.4 Effects of Terminations on Kink Formation

In the course of conducting the kink-formation tests some subtleties were observed. It was found that the swaging method on a given termination, the type of termination, and the hardware (shackles, sling links, etc.) associated with a termination all influence the kink-formation threshold.

It is possible that due to poor dies or their improper use, swaged fittings end up both ovaled in cross-section and curved in profile. The ovaling might mean that the termination will not develop the full breaking strength of the mooring line. It is further felt that the curved or banana-like swagings will, however, present a slight predisposition to kink formation. Such can be seen by the following line of thought.

When a sample which is free of most of its residual curvature contains a low value of tension and a large number of relative turns, it will buckle to visibly form a helix with the number of nodes equal to twice the number of relative turns imparted. In the static case torque within the sample is uniform in the axial direction. The sample, however, is not purely axially aligned but in a helix. Therefore, there is a torque component normal to the main axis of the sample as shown below in Figure 24.

It is this transverse component of torque which produces the kinks. The greater the angle between the main axis of the sample and the centerline of the sample (angle α), the greater will be the transverse torque. It is felt that the curved swagings produce a greater helix angle adjacent to

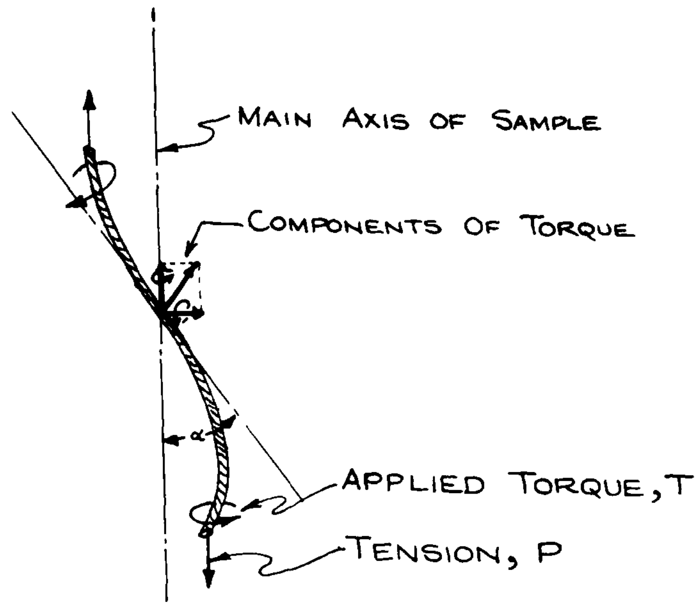

Figure 24
Configuration of Buckled Strand

the swaged termination, thus enhancing the formation of a kink.

The kink-formation results described in Section 3.3 are all given for the case of blocked shackles at the large ring eye swaged terminations (see Figure 2). Tests were conducted wherein the effect of blocking the shackles was measured with a 1 x 41 strand. The results are shown in Table 4 along with the results for the blocked case. It may be seen, by comparing cases (1) and (2), that it takes considerably less torque to form a kink when the shackle is free to move. In such a case the round portion of a 1/2" anchor shackle was mounted inside of a standard round ring eye termination which contains approximately a 2-inch I.D. In the presence of torque the shackle works its way vertically up inside the termination, while having two points of contact against the sloping walls of the termination. When the torque level is sufficient the shackle will flip around to the top side of the termination raising the weight of the hardware below. In the process the shackle allows the ring eye termination to rotate by almost 90 degrees with respect to the shackle, thus freeing a measure of the torque stored in the strand. This results in an increased helix angle at the termination which produces a kink at lower torque levels than normal. It was found that after the shackle rotated around the termination, the torque level dropped somewhat due to strand unwinding and that additional torque was required to actually bring about a kink.

TABLE 4

Effects of End Conditions on Kink Formation

(1 x 41 Strand, Length = 17 Feet, Tension = 4.5 Pounds)		
Case	Type of End	Kinking Torque
(1)	Ring Eye Swaged, Blocked	3.8 ft-lbs.
(2)	Ring Eye Swaged, Unblocked	2.35 ft-lbs.
(3)	Open Swaged Socket & Pin (Clevis)	4.8 ft-lbs.
(4)	Open Swaged Socket & Pin (Clevis) with Sling Link & Anchor Shackle (Unblocked)	3.2 ft-lbs.

Open swaged socket or clevis and pin terminations were tested and compared to cases (1) and (2). In addition, a sling link and anchor shackle was added to the open swaged socket and the results measured. The results are also found in Table 4.

The open swaged socket alone was found to give the best results because it permits only one degree of freedom of rotation at the point of attachment. It is suspected that it performed better than the large eye blocked swaged termination because in the latter case some motion occurred within the termination in spite of the blocking. The addition of a shackle and sling link below the open swaged socket termination gave poor results for the same reason as case (2). From these results it is recommended that open swaged socket and closed swaged socket or rod and clevis terminations and stoppering attachments be employed wherever possible.

3.5 Effect of Jacketing on Measured Properties

Almost all of the tests conducted for this writing were on unjacketed samples. Only the 1 x 19 strand contained a polyethylene jacket which had been at sea for approximately six months. It is expected that all metallized mooring lines will contain a jacket when in use so its anticipated effect should be mentioned.

By reference to Appendix D it can be seen that a jacket increases the overall bending stiffness by less than 10%. In most cases it only increases the measured and calculated value for the metallic element by only approximately 6%. It is therefore felt that jacketing has a minimal effect on the kink-formation properties when it is intact. It was observed, however, that when samples contained sufficient torsional energy to pose a kink-formation problem, the jacket would split in shear, thus reducing its effect even more.

Other mechanical properties are felt to be only slightly effected by the presence of a jacket. By reference to Appendix D, the low values for tensile and shear strength indicates the level of the effect of the jacketing. Such an effect will be felt for all values of tension with no torsion up to the breaking strength of the sample. In torsion, however, the metallic component of the mooring line can absorb more relative turns than the jacket because wires can roll or slide over each other at the same time the jacket being cast around specific wires and strands in manufacture will be compelled to follow these elements in their large rotational excursions. Thus the jacket will fail in torsion or combined torsion and tension before the metallic component will.

For single strand samples, in which negative turns are introduced, the outer layer of wires will expand to a larger helical radius. Such a situation produces a combined loading of torsion and internal stress which causes the jacket to fail sooner than in torsion in the positive or tightening direction. Thus it is advisable that large numbers of turns, especially negative turns, be kept out of a mooring line in an attempt to preserve the integrity of the jacket. Further, it is recommended that from a purely mechanical point of view the most flexible jacketing material be employed to prevent torsional stress cracks, where such can occur. This fact, however, competes with jacket toughness desired for abrasion resistance.

3.6 Sample Failures During Tests

In the test phase wherein the mechanical characteristics were measured with 100-foot samples held horizontally, numerous mechanical failures resulted. Photographs of such failures are shown in Figures 25 to 32. A detailed examination of the broken ends showed that in all cases the failure resulted from a combined loading of torsion and tension resulting in ductile fracture. Such is evident by the cup and cone effect combined with a helical edge of the cone of each wire which carried the load.

The applied loads which produced the failures are shown in the plots of tension characteristics (Figures, 3, 6, 9, etc.). Two mooring lines, 1 x 19, and 1 x 41 failed by completely breaking into two pieces. This effect was seen in two samples for each line (see Figures 25, 26, 30, and 31). In the case of the 1 x 19 strand, positive turns had shifted much of the torsional and tensile load to the outer wires while the inner wires were lengthening their pitch and trying to push out through the outer layer. This situation produced a complex state of stress which brought about a failure of the outer layer at a very low tension value (approx. 1500 pounds). Subsequently, the load was shifted to the inner layer of wires which, in-turn,failed.

Direct observations of any of the failure processes were not made. It is, however, felt that the 1 x 19 strand ultimately failed while it was wrapping itself around some remaining wires during the failure process. Such a situation is conjected because of the appearance of the failed samples in Figures 25 and 26. It is, therefore, felt that in some failures which return from the sea appearing to be the result of the formation of a kink may be

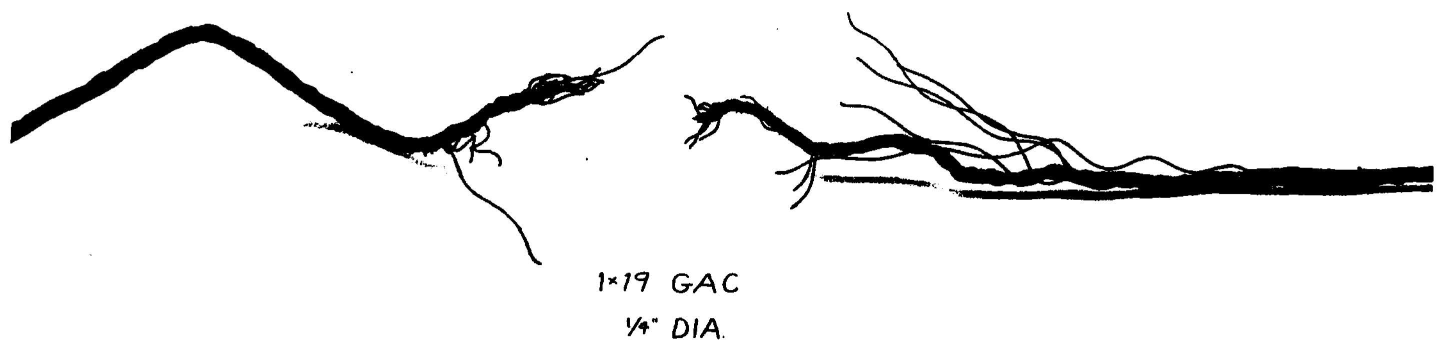

Fig. 25 Failed Sample No. 1, 1 × 19 Strand

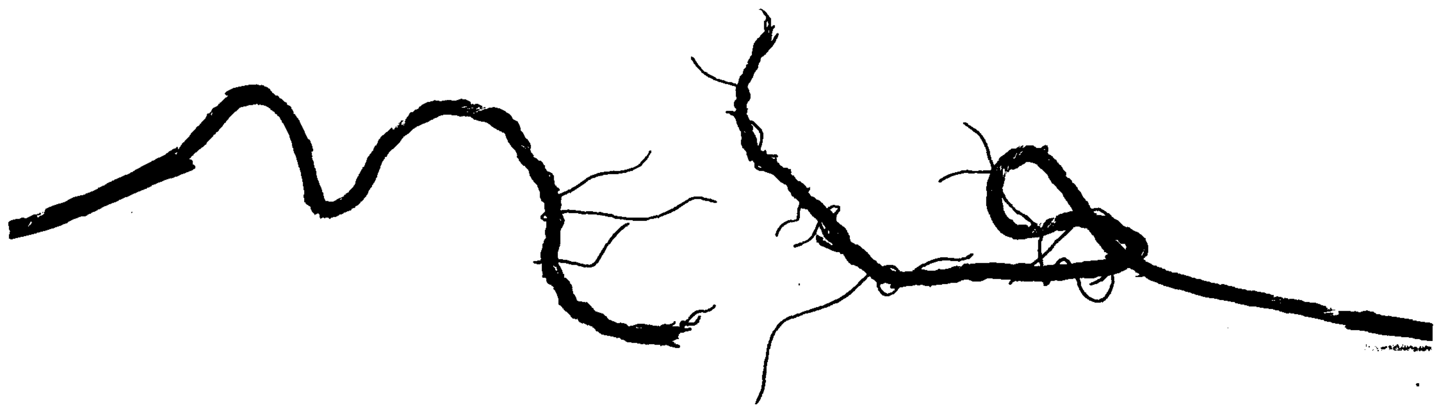

Fig. 26 Failed Sample No. 2, 1 × 19 Strand

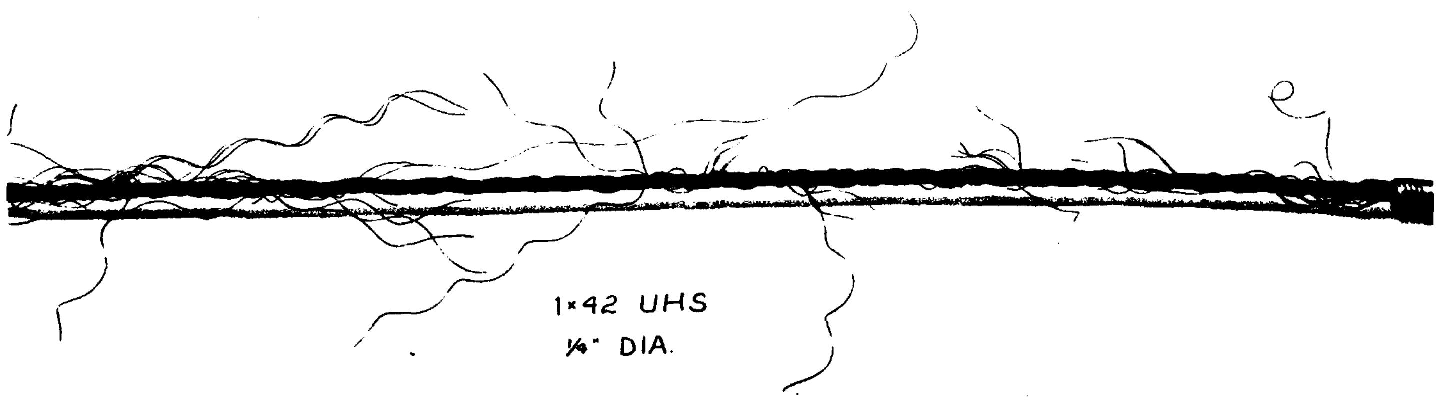

Fig. 27 Failed Sample, 1 × 42 UHS

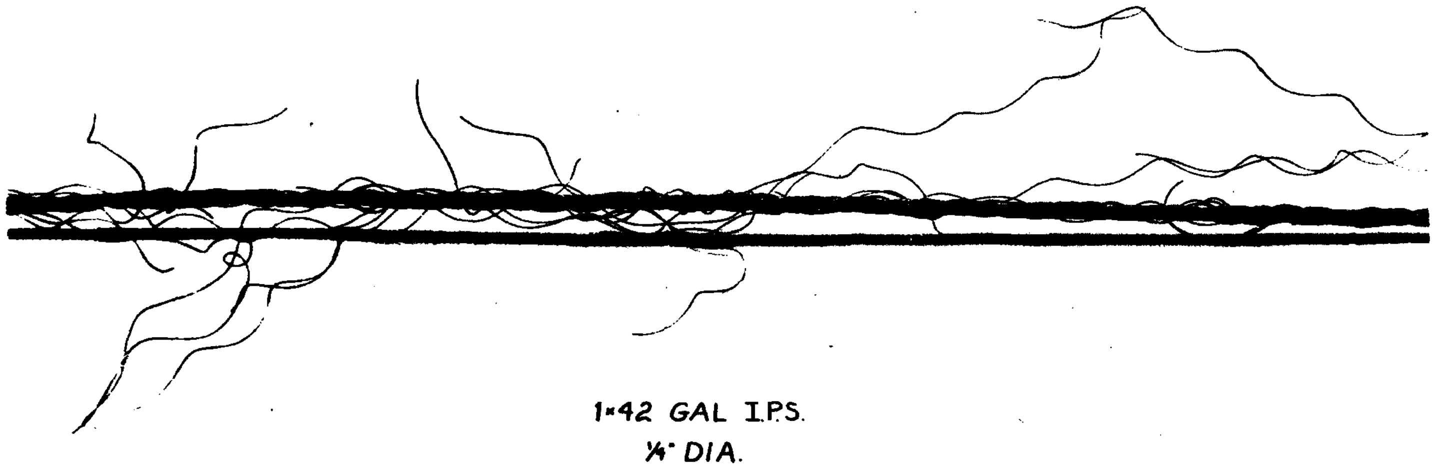

Fig. 28 Failed Sample, 1 × 42 GAC

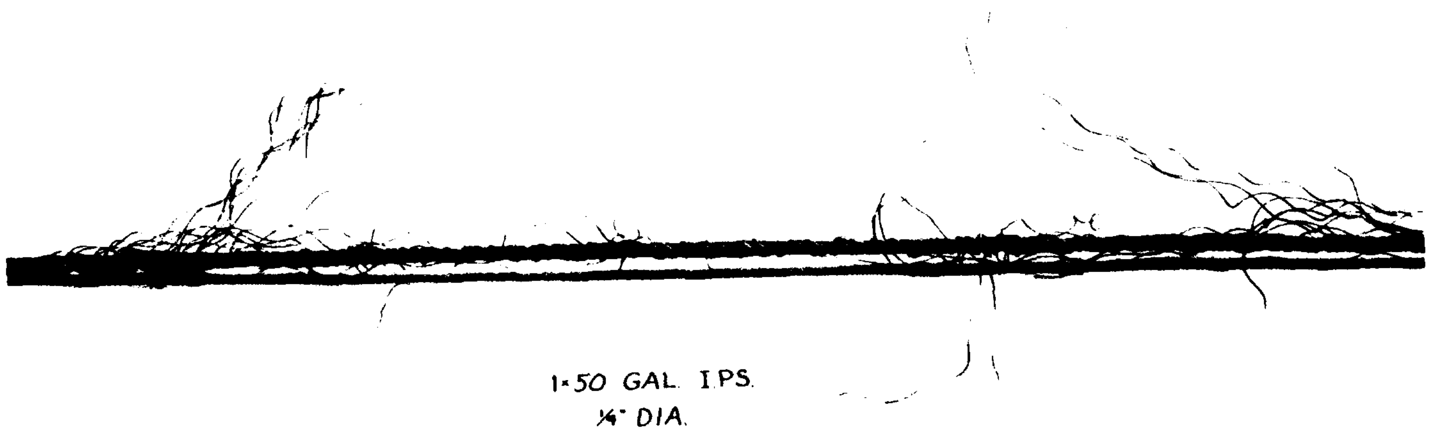

Fig. 29 Failed Sample, 1 × 50 Gal. I. P. S.

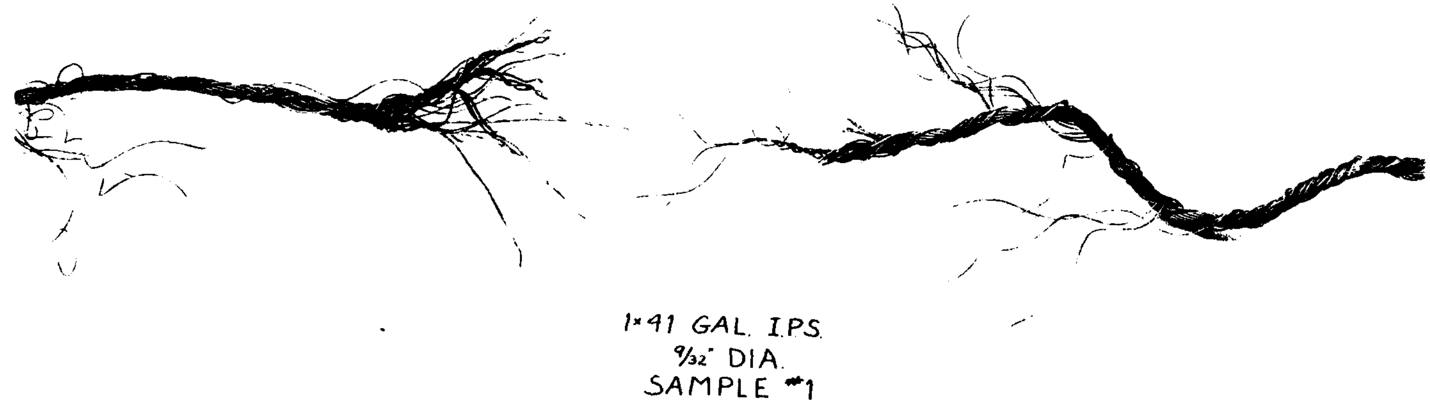

Fig. 30 Failed Sample No. 1, 1 × 41 Gal. I.P.S.

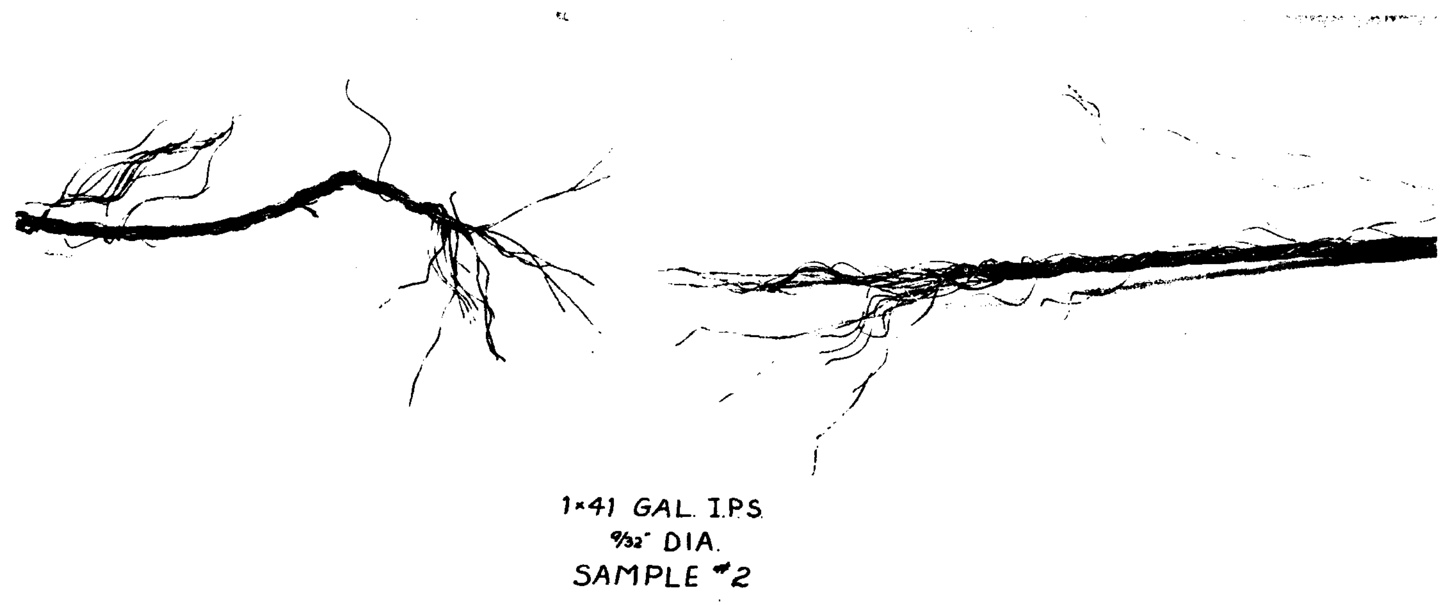

Fig. 31 Failed Sample No. 2, 1 × 41 Gal. I. P. S.

Fig. 32 Failure Mechanism of 1 × 41 Strand in Presence of Torque and Tension

caused by torsion and tension alone. When the combined loading produces a failure in only a few of the wires in the outer layer, the stored torque will cause the failed wires to rotate about the remaining wires. They will continue as such until they absorb the torsional energy or fail themselves. In so doing, the wires which broke originally may whip out radially as shown by a few of the wires in Figures 25 and 26. At the same time, they may bring about a permanent deformation in both themselves and the main strand. It is felt that such a mechanism happens so rapidly that only a very high speed camera could capture the action.

The 1 x 41 strand failure is better documented. Figure 32 is a photograph of 1 x 41 sample number 2 prior to its complete failure which is shown in Figure 31. In this case the inner layer of wires, in the presence of positive turns, popped out through the outer layer, forming a fan-like array. In so doing it may be seen in Figure 32 that the outer layer of wires was put through a tight radius which must sustain all of the torsion as well as the tension. This tight radius adds a shearing mode to the shearing mode caused by the torque. The net result, upon increasing the torque or tension, is the failure shown in Figure 31. The applied load, for each failure of the 1 x 41 strand, is pointed out in the 1 x 41 tension characteristics, Figure 15.

The other failures, which produced only a failure of the outer layer of wires, are shown in Figures 27, 28, and 29. Again, these failures were caused by a high state of stress primarily caused by torque. In these cases it appears as though more of the stored energy resided in the outer layer of wires. Upon their failure, there was evidently insufficient energy to produce a failure of the inner wire layers as well. As shown in Figure 6, after the outer layer of wires failed at approximately 1000 pounds of tension and 20 foot-pounds of torque the remaining state of stress was approximately 600 pounds of tension at 13 foot-pounds of torque.

4. CONCLUSIONS

(1) The test apparatus for measuring torque, turns, and tension was adequate for measuring mechanical properties of samples. The total accuracy of an individual measurement is estimated to be approximately 10%.

(2) So-called "torque-balanced" strands or wire rope (i.e., samples which exhibit no torque in the presence of applied tension) are subject to question and clarification in the following areas:

(a) The best torque-balanced samples, in the presence of no rotation, still exhibit a small level of torque over certain ranges of tension. Such was found to be true even for 5/16" Dia., 3 x 19 wire rope.

(b) Many "torque-balanced" samples, in the presence of no rotation, exhibit torque over-all ranges of tension.

(c) A samples' torque-balanced characteristics may change in proportion to the differential number of turns introduced between its ends. Thus if turns are introduced to a sample which was originally well torque-balanced, it will subsequently exhibit the undesirable qualities of a non torque-balanced sample as described in Section 3.1. It may thus be more susceptible to kinks and wear in the presence of varying tension. In light of this fact swivels are especially desirable in conjunction with well torque-balanced samples in order to maintain their torque balance.

(d) Torque-balanced strands or wire rope samples can potentially absorb as many differential turns as a non-torque-balanced sample before developing excessive torque. That is to say they are not torsionally stiffer than non-torque-balanced samples.

(3) Multi-strand mooring lines, such as 3 x 19, can absorb more differential turns than single strand lines before developing excessive torque. Such a conclusion, arrived at for the case of unjacketed samples, is based on the fact that the multi-strands when given negative turns can more freely unlay and when given positive turns can more freely shorten the strand pitch and therefore the overall sample length. In standard

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single strand torque-balanced samples, positive turns (i.e., tightening the outer wire layer) will unlay inner wire layers which are being constrained by the tightening outer layers thus resulting in a higher torsional spring constant. Negative turns in a single strand sample may more freely unlay than positive turns by the same type of phenomenon only with opposite rotation. The introduction of either positive or negative relative turns can seriously reduce the ultimate breaking strength of a sample as shown by numerous failures. High torque values can produce failures at tension values of less than 10% of the RBS (see Appendix E).

(4) Multi-strand mooring line is further desirable because broken wires in the outer layer of a strand become locally trapped due to the presence of other strands overlaying the strand containing the broken wire. For example, in 3 x 19 wire rope if a wire break should develop in the outer layer of one of the three strands, contact with the other two helically-wound strands would prohibit the single broken wire from unravelling. It is expected that the outer wires in each strand are more vulnerable to both mechanical and corrosion damage and that a weakness brought about by such a failure remains local. Such would not be the case for single strand mooring line. It is felt that the weakness caused by such a failure would be felt over a much greater length of the sample even with a jacket present. Given no jacketing, the weakness could in time propagate over the whole sample length.

(5) The measured linear spring constant of mooring lines, which primarily incorporates Hooke's Law strain in addition to compression and sliding of wires, varies somewhat from one sample to another. Single strand and multi-strand samples both exhibit individual differences in this property. Both types of samples did, however, exhibit approximately the same average value for K_L. The measured values for the modulus of elasticity varied from 22 to 30 x 10^6 psi.

(6) Hysteresis was observed in the torque-turns curve for constant tension. That is to say that at a given level of tension if a given number of turns were placed in a sample, resulting in a level of torque, one would achieve a zero torque condition again by the removal of a fewer number of turns. Such a situation results from friction between wires and strands within the sample and indicates that in the presence of turns relative motion between wires is opposed by friction forces which produce mechanical wear of the wires and strands. The presence of momentarily higher tension or cyclic tension reduces the hysteresis effect by assisting the wires and strands in seating themselves in a new position relative to each other. In so doing, torque built up due to friction between wires is reduced.

(7) In the presence of constant tension each sample tested kinks at approximately the same average torque level. The average is measured as the average of the absolute values of the torques necessary to form kinks in both the positive and negative direction.

(8) At moderately high torque levels (5-10 foot-pounds) the level of tension required to prevent kink formation under ideal conditions is so near zero that it is academic to on this basis only choose one sample over another at constant torque. Under non-ideal conditions wherein sample prestrain from being wound on drums and poor termination conditions exist the tension required to prevent kink formation at moderate and high torque values is appreciable. Due to the dangers and difficulties in carrying out kink formation tests in the presence of high torque and appreciable tension, under non-ideal conditions, no comparative, quantitative results are given. It is felt that the conditions under which a sample is tested do, however, greatly influence the kink-formation characteristics of a sample.

(9) Given that torque exists in a mooring line either via differential turns introduced via a driving force at one end or via rotation of one end in response to torque introduced in non-torque-balanced samples as a

result of tension, kinks will result if a zero tension exists anywhere in the sample. There is felt to be a low threshold of torque below which kinks will not form in the zero tension condition, but such a torque level was not measured because a true zero tension condition could not be obtained in static tests.

(10) When differential turns are applied between the ends of a sample the following seems true. If the turns are such as to tighten the outer layer of wires in a single-strand sample or to tighten the strands of a multi-stranded rope (i.e., positive turns as defined in this writing) the various wires are held more as a single unit than individual wires and thus the bending stiffness (EI) of the cable should increase slightly. The converse of this statement is also true.

(11) When the torque in a sample finally produces a kink, some or all of the torsional energy is released through friction, permanent deformation of the cable, and a temporary increase of tension which does work on that which is restraining the sample. (see Appendix E.) Depending on the type of strand, end restraints, and direction of relative turns the resulting kinks may produce drastically different results. For simplicity assume that the end restraint is a small mass with weight equal to approximately 5 pounds. The following conclusions are based on the assumption that the compound loading situation of torsion and tension in the sample will not produce a failure by breakage in any portion of the cable.

CASE I Single Strand Samples, Positive Turns

Due to the increased bending stiffness resulting from positive turns a "figure 8"-type tightening kink will form normal to the axis of the cable. A sketch of such a kink is shown here in Figure 33. The only sample for which this is not the case is 9/32" dia., 1 x 41 torque-balanced strand. For this sample, wire layer number 2 pops out through the outer wire layer (see Figure 32) resulting in a greatly-weakened strand.

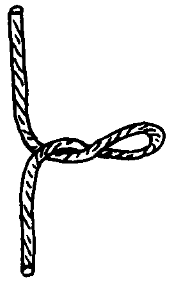

Figure 33

Large "Figure 8" Kink

CASE II Single Strand Samples, Negative Turns

Due to a reduced bending stiffness caused by the loosening of the outer wires either a "figure 8"-type of opening kink or what will be called a rolling kink (i.e., small "figure 8") may develop. Such a kink is sketched in Figure 34. For moderate torque levels (1-4 foot-pounds) the case of nearly zero tension will tend to produce a large "figure 8" kink which when retensioned will pull through

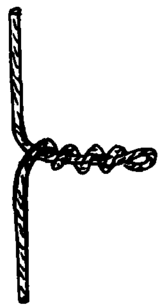

Figure 34

Rolling or Tight "Figure 8" Kink

to form a kink sometimes called a backturn. For higher torque levels, however, and slightly higher values of tension a tight "figure 8" or rolling kink might develop in unjacketed cables. Such a kink results in one portion of the full strand rolling over and deforming around an adjacent portion much like a cable winding around a small pulley or drum whose diameter is that of the strand. The release of stored torsional energy in this way will momentarily produce rather high tension values higher than when a standard "figure 8" loop forms. For example, a 1/4" dia., 17-foot long cable containing a torque of 5 foot-pounds can, when throwing a rolling kink, develop tensions in excess of 100 pounds. Appendix E describes this phenomenon in more detail.

CASE III Multi-Strand Sample, Positive Turns

CASE IV Multi-Strand Sample, Negative Turns

In Cases III and IV the resulting kinks appear much the same. Because it is felt that samples buckle in looping or backturning as a function of the applied torque and tension rather than the stored energy, such cables buckle at approximately the same torque levels as single strand samples. The stored elastic energy of twist is, however, so much greater in wire ropes that when they buckle (tightening or opening kinks) they will produce a tight "figure 8"-type of kink as described in Case II. It is felt that once the buckling begins the vast amount of stored torsional energy is suddenly released, permanently deforming the rope into tight loops or backturns. Momentarily during the initial phase of the buckling process tensions well in excess of 100- pounds have been observed (see Appendix E).

(12) Standard swaged eye terminations, shackles, and sling links which are found where shots of cable are joined or where instruments are mounted enhance cable kinking propensity in the presence of torque. More generally, it appears as though any mooring line discontinuity such as that which provides one or two degrees of freedom in flexure or twist aids in releasing torsional energy via a kink. A reduction in the freedom of motion allowed at such discontinuities should help reduce the chances of mooring line kink formation. Open swaged socket (rod and clevis) terminations are found to be better than ring eye swaged terminations. Furthermore, pin-type cylindrical stopper hardware is recommended for use with open swaged socket terminations over shackles and pear-shaped sling links.

(13) For the samples tested, it is felt that under ideal conditions if a tension greater than 10 pounds can be maintained, any torque up to the sample failure point will not produce a kink. Under non ideal conditions, however, it is felt that sample prestrained axial curvature and loose-fitting terminations will produce kinks before failing in combined loading with tension values up to 50 or 75 pounds. Therefore it is felt that tensions greater than approximately 100-pounds should prevent kinks in the samples tested under almost any type of condition.

The work reported herein has shed light on the magnitude of the kink formation problem. It has further listed much data which could be used in future dynamic modeling and testing of mooring lines. Such work is outlined under Recommendations.

5. RECOMMENDATIONS

It is felt that due to lack of time insufficient data and understanding is available on the effects of an extreme number of negative turns on the tension characteristics. More specifically, the states of stress which produced failures as shown in Figures, 3, 6, 12, and 15 were all for the case of positive turns introduced to the sample. For better understanding it is recommended that similar failures be incurred by the introduction of negative turns.

It is further recommended that the actual states of stress which produced failures be calculated in terms of the stress states in the individual wire layers. Such calculations would necessitate an estimate of the reapportionment of wire loading as a function of the number of relative turns introduced and the resulting change of pitch length for each wire layer. In this manner it is hoped that a yielding criteria such as the Maximum Shear Stress or Von Mises criteria could be applied to mathematically demonstrate the observed effects.

The kink formation tests are deficient in two areas. As shown in Table 1 there is no kink formation data tabulated for either 1 x 19 or 1 x 42 UHS strand. For a complete comparison of all samples such information is desirable. Secondly, it is felt that kink formation tests with 200 meter horizontal samples would be an interesting and meaningful comparison with the 100-foot samples. Kinks could not be formed in the shorter samples due to the catenary contacting the ground. It is felt that by vertically supporting the longer samples at 100-foot intervals might produce interesting results. Such a possibility is mentioned in light of the observed fact that once a kink begins to form all of the stored energy is seemingly channeled to the kink-formation area. Thus, it is felt that a greater level of total stored energy might locally bring on kink formation more easily.

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Because it is felt that a multi-strand mooring line is desirable more research and testing on such samples is needed. It is recommended that the merits of a swaged wire rope be evaluated on the following points:

(1) Swaging produces more material cross-section per rope diameter.

(2) Swaging produces a smoother rope finish which should be less abrasive when the rope is wound in layers on a drum.

(3) It is felt that swaging should produce a rope of higher bending stiffness which may be undesirable when the sample is subjected to multiple passages over a small diameter sheave or pulley.

As pointed out earlier and in Appendix E, kink-formation tests and data is difficult to obtain under all conditions except the very ideal situations already outlined. It is recommended that tests be conducted to ascertain the effects of sample prestrain on kink-formation conditions. It is felt that such tests might show that mooring line storage drums and reels should have a diameter considerably greater than is presently found in order to reduce kink-formation propensity.

Considerable time and effort was put into both measuring, calculating, and correlating sample bending stiffness, EI, with the kink-formation tendency. No meaningful correlation resulted for the samples tested. It is felt that such an approach still looks appealing and that kink formation tests on samples with greatly differing values of bending stiffness would be meaningful for correlation purposes.

Because the static breaking strength of oceanographic strands and wire rope samples exceeds the static loading by a factor of at least three, it is felt that many failures are a result of the dynamic nature of the environment. Whether the dynamics produces kinks and subsequent failures or merely failures in pure tension is not known. It is, therefore, recommended that suitable mathematical dynamic modelling and parallel dynamic testing be undertaken to gain a better understanding of the failure mechanisms. It is forseen that the dynamic testing might be done in a water environment in order to include damping effects found in the ocean.

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APPENDIX A

SAFETY PRECAUTIONS

Because of the relatively high tensions (3300 pounds, max.) that the cables would experience in addition to their unknown properties, considerable safety precautions were necessary in order to protect the life and limb of the test personnel. The possibility of cable breakage and subsequent release of stored energy loomed as the biggest safety consideration. Further, safety precautions were necessary to assure that in the presence of high torque the hazards of certain rotating elements were minimized. Other problems such as safety in the presence of kink formation and proper electrical grounding were considered.

As already-mentioned in Section 2, a small building was employed at one end of the test cable in order to house instruments and personnel, thus affording safety should the cable break at a distance from the building and lash back at the building. In the event of cable breakage anywhere between the torque tester and the opposite end of the cable (see Figure 1.) test personnel, who are stationed between the torque tester and the tree, would further be protected against the dangers of motion of components internal to the building. Such is afforded by a variable chain linkage which ties the torque tester to the end of the safety building opposite that at which personnel are stationed. In this manner elastic energy stored in the tree-chain, come-along, and tensiometer would be absorbed by safety chains in the event of a cable breakage. A variable chain linkage is necessary here because as the tension is increased the cable stretch which is realized within the building must also be accommodated by the safety chains.

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There is a finite possibility of cable breakage between the torque tester and the tree but components in this segment of the linkage are chosen such that their rated load-carrying ability is a factor of two or more greater than the loads which they would experience. Furthermore, such components would experience merely pure tension loading rather than both torque and tension experienced by the cable.

The dangers posed by the introduction and measurement of torque in the cable were overcome in the following way:

(1) Turns were mechanically introduced to the cable via a 1 hp., 3-phase motor through a 100:1 worm gear drive at the opposite end of the cable from the safety building. By employing a worm gear drive one is assured that when no power is applied to the motor the stored torsional energy in the cable will be unable to rotate the motor. The motor power cable led through the safety building wherein power and direction-reversing switches were located. The number of turns in the cable is measured at the drive motor by a micro-switch the output of which is displayed in the safety building.

(2) Because the tests are conducted under a static loading situation, the torque is constant along the cable. Therefore torque introduced by the motor is most easily and safely measured within the building. This end of the cable is mechanically well-restrained from rotation such that a dangerous propellor-like rotation by the torque-measuring arm (see Figure 1.) is eliminated. A spring scale or Dillon force gage is then applied to this arm for torque measurement without fear of rotation.

The electrical power driving the motor was a 3-phase, 208-volt, Y-wired system. The motor, however, was wired for 3-phase, 220-volt power which is delta-wired. It was feared that the lower driving voltage might possibly cause the motor to overheat. Such was not the case because the loads imposed on the motor were low relative to its power and also the motor was open to freely convect its heat away to the atmosphere. A fourth wire was, however, needed in this system to commonly ground all metal cases.

In the kink-formation tests a simply-constructed yoke encompassing the lower end of the cable insured that where a kink formed the ensuing release of energy did not allow the lower end of the cable and its associated hardware to whip about (see Figure 2).

Appendix B

Measurement and Calculation of Bending Stiffness (EI) of Strands and Wire Rope

In Section 3.1 it was mentioned that the bending stiffness (EI) of samples was both measured and calculated. In this section both techniques are described.

The bending stiffness (EI) is the product of Young's Modulus, E, and the transverse area moment of inertia, I. Where the flexural modulus of elasticity is given, it should be used in place of E. The theoretical value for I is derived as one-half the polar moment of inertia of a round section such as a strand or wire rope. This fact can be seen as follows:

$$I = \int_0^{r_{max}} x^2 \, dA = \int_0^{r_{max}} y^2 \, dA \qquad \text{(B1)}$$

$$I_{polar} = \int_0^{r_{max}} r^2 \, dA = \int_0^{r_{max}} (x^2 + y^2) \, dA$$

therefore:

$$I = I_{xx} = I_{yy} = 1/2 \, I_p = 1/2 \int_0^{r_{max}} r^2 dA \qquad \text{(B2)}$$

For the case of strands or wire rope, in which area voids exist, the theoretical value for I can be given as:

$$I = 1/2 \sum_{i=1}^{n} r_i^2 \, dA_i \qquad \text{(B3)}$$

where: n = Total number of wires in strand or wire rope

r = Radius of individual wire from center of strand or wire

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A = Cross-sectional area of a given wire

Two possibilities exist for the calculation of I in strands or wire ropes:

(1) The individual wires all adhere to each other and act as one large unit in which case one would apply the parallel axis theorem about the central wire to derive I.

(2) The wires act independently in which case one should sum only the individual I's of each wire about its own center. This case neglects friction between wires in the bending process.

It was found in reference (6) that the latter means of calculating I is the truest representation. In this case one merely sums the I's of the individual wires as shown in the following example:

$$I = I_{r_o} + 6I_{r_1} + 12I_{r_2} + 23I_{r_3} \quad \text{(B4)}$$

Equation (B4) is written for a 1 x 42 strand as shown in Table 1 where the I of the core wire is added to that of the six wires in the first layer and so on. The radii of the individual wires are given by R_o, R_1, R_2; and R_3. For the case of circular wire of radius R, the individual area moment of inertia is given by:

$$I_{r_i} = 1/2\ AR_i^2 \quad \text{(B5)}$$

where A is the cross-sectional area of the wire. This relationship holds true for each wire in equation (B4). By combination with equation (B3) it results in the following general relation for the transverse area moment of inertia:

$$I_{xx} = 1/2 \sum_i n_i \frac{A_i R_i^2}{2} \qquad \text{(B6)}$$

where n_i is the number of wires in the layer i.

The value of I derived in equation (B6) is then multiplied by the Young's Modulus of the material, usually steel, to give the calculated values of EI listed in Tables 1 and 2.

A simple but effective means of measuring the bending stiffness of a strand or wire rope is to measure the first mode buckling load of a sample in axial compression. It does not give the variation of EI with tension, which is thought to produce an effect, but it provides a meaningful point from which to start.

The critical load for which continued buckling will occur for no increase in load is a function of the boundary conditions imposed on the column. The experiments conducted for this writing employed the configuration shown in Figure B1.

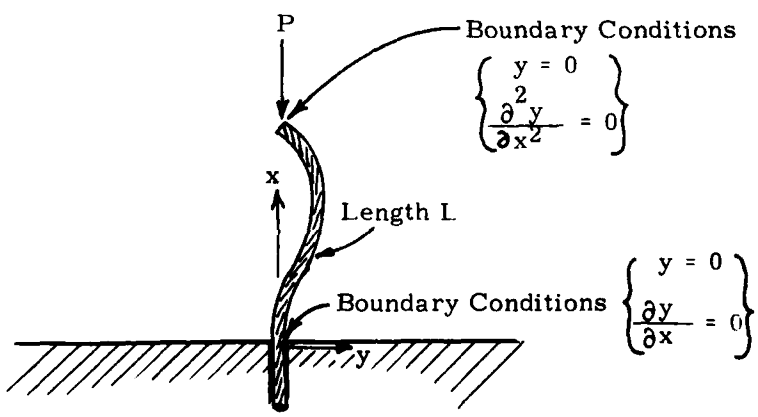

Figure B1

For this case the critical load is given by:

$$P_{CRIT} = 20.2 \frac{EI}{L^2} \qquad (B7)$$

In the laboratory the length of each sample was varied within the limits of 10 to 23 inches and the average value of P_{CRIT} measured with a spring scale. This then enabled the easy calculation of EI. It was felt that an inability to accurately control the upper boundary conditions on the sample accounted for dispersion in the data. The results of EI given by equation (B6) and the average measured value given by equation (B7) do, however, agree within approximately 10 percent.

Appendix C

Adequacy of Short Samples in Kink-Formation Tests

In Section 2.3 a method is described wherein the kink-formation threshold of mooring line samples is measured. The length of the samples tested was only 17-feet, which seems short relative to the mooring line lengths for which the data applies. This section theoretically just. ies the applicability of short sample lengths in studying the kink-formation phenomenon.

It is shown in reference (6) that when a long, slender shaft is loaded both in torsion and tension it will buckle, forming a helix, before it will fail in torsion. The conditions under which such a situation holds are the following:

$$YS = \text{Yield Strength} \geq E/1,000 \qquad (C1)$$

where E is Young's Modulus of Elasticity. At the same time the relationship between the bar length, L, and the radius is given by:

$$L/r \geq 2,000\,\pi \qquad (C2)$$

Equation (C2) is derived by knowing that a circular shaft loaded in pure torsion will buckle when the torque reaches the critical level given by:

$$T_{CRIT} = \frac{2\pi EI}{L} \qquad (C3)$$

This value is then equated to the torque applied to a circular shaft when the shear yield strength (YS) of the material is just reached in it's outer fibers. This value is given as:

$$T_{YIELD} = \frac{\pi}{2} (YS) \; R^3 \qquad (C4)$$

Assuming the relation given in equation (C1) for the yield stress, and that the transverse I of a circular shaft is given by:

$$I_{xx} = \frac{\pi R^4}{2} \qquad (C5)$$

one equates the torques of equation (C3) and (C4) to arrive at the relation given in equation (C2).

For the material employed in mooring lines a good assumption for the yield stress is 180,000 psi while the value of $E = 30 \times 10^6$ psi. Plugging these values into the above relations gives the criteria that a long, slender bar will buckle before it fails in torsion if:

$$\frac{L}{R} \geq 334\pi = 1,050 \qquad (C6)$$

For the largest-diameter sample (5/16" Dia., 3 x 19 wire rope) the 17-foot sample has a ratio of $L/_R$ = 1,260. Thus, the approximate theory states that which was observed.

The implications of the previous analysis are that samples will buckle into a helical setting before failing in torsion. Beyond this, references (6) and (7) go on to show that this buckled state is the first step towards the formation of a kink. The tension within the sample will, however, dictate whether this kink will actually form. With only a minimum of tension ($>$ 10 pounds) it was found that under ideal conditions the buckled state would still be stable enough to cause failure in combined torsion and tension loading before a kink formed.

Appendix D

Effect of Jacket on Mooring Line Bending Stiffness

The effect of a 0.035-inch polyethylene jacket on the calculated bending stiffness (EI) of 1/4-inch diameter strand will be calculated. It will be assumed that the EI of the jacket alone can be linearly added to that of the metallic portion of the mooring line.

Before actually making the calculation the following approximate mechanical properties of polyethylene are given:

Flexural Mod. of Elas. $= E = 2.2 \times 10^4$ psi

Tensile Strength $\approx$ 1,600 psi

Shear Strength $\approx$ 1,400 psi

The transverse area moment of inertia is again given by the relation

$$I_{xx} = 1/2\, I_{polar} = \int_{r_i}^{r_o} r^2 \, dA \qquad \text{(D1)}$$

where: $r_i = 0.125$ inches

$r_o = 0.160$ inches

Therefore:

$$I_{xx} = 1/2 \left[2\pi \int_{r_i}^{r_o} r^3 \, dr \right] = \frac{\pi}{4} \left(r_o^4 - r_i^4 \right) \qquad \text{(D2)}$$

$$I_{xx} = 3.24 \times 10^{-4} \text{ in.}^4$$

Employing the given value for the flexural modulus of elasticity, the following value for the bending stiffness of mooring line jacket is given:

$$EI = 6.9 \text{ lbf} \cdot \text{in}^2$$

By comparing this contribution to the calculated and measured value for the EI of the metallic member alone it is seen that a jacket increases the bending stiffness by less than 10%.

Appendix E

Non-Correlatable Kink Formation Tests

As described earlier, kink-formation tests were initially conducted with 17-foot sample lengths held vertically wherein the sample tension was created and varied by water in a 5-gallon can suspended by the sample. The experimental sequence was to tension each sample to approximately 55 pounds by filling the can with water. Then, each sample would be twisted to create the same torque level, irrespective of the number of turns required. Subsequently, the water would be slowly released from the can by opening a solenoid valve and the tension would decrease until a kink formed. The weight of water removed from the can would be subtracted from the original tension and result in a comparative number for each sample. The number derived would be the amount of tension required in a sample to inhibit kink-formation wherein all samples contained the same level of torque. The lower the value of tension required, the better the kink-formation properties of a sample.

The above types of tests were conducted with varying degrees of success. By initial tests it was found that the weight of the empty bucket and hardware alone, approximately 12 pounds, was sufficient to prevent kinks at moderate torque levels. Therefore, a relatively high torque level of approximately 15 foot-pounds was chosen as the value at which samples would be compared.

It may be seen in Table E1 that for the four different samples tested for which all are positive turns the results are drastically different. I will comment on each test on an individual basis.

Table E1

Non-Correlatable Kinking Results				
Test	Sample	Torque	Tensions	Results
(1)	1 x 42, UHS	+15.1 ft-lbs	45 lbs	Catastrophic failure by kinking. Bucket clamp straightened
(2)	1 x 42, GAC Sample 1	+15.4 ft-lbs	12 lbs	No kink
(3)	1 x 42, GAC Sample 2	+20.4 ft-lbs	72 lbs	Catastrophic failure. Outer wires failed then kink formed. Bucket clamp straightened
(4)	1 x 41, IPS	+4.0 ft-lbs	55 lbs	Wire Layer No. 2 pops out through outer layer
(5)	1 x 50, IPS	+14.8 ft-lbs	Approx. 5 lbs	Kink formed at very low tension

TEST (1)

Prior to this test it was observed that the swaged termination was bent slightly like a banana. It is felt that this fact combined with a level of prestrained axial curvature led to a kink. Due to the amount of torsional energy stored in the sample prior to the kink formation, the kinking took place in a very explosive manner, releasing all of the energy. In so doing a 3/16" thick circular ring, supporting the water can, was straightened out thus dropping the can to the floor. Simultaneously the lower end of the sample shot rapidly towards the ceiling. A later test showed that it took 250 pounds of tension to straighten the ring out in the manner observed. In order to see how such a tension could be created a simple energy balance can be argued.

The amount of torsional energy imparted to the sample in winding it up is given by:

$$E_T = \frac{1}{2} K_T N^2 \tag{E1}$$

where K_T is the *linearized torsional* spring constant and N is the number of turns introduced. Plugging in values found in Table 1 and correcting for a 17-foot long sample gives a value

$$E_T = 50 \text{ ft-lb.}$$

When a sample kinks, the amount of cable required to form a *single* loop must come from a shortening of the overall sample length. In the process the weight of the bottom restrai· ι (water can) must be moved through such a distance. If a constant force is assumed during this process then the energy expended in lifting the end restraint is merely:

$$E = P \Delta l \tag{E2}$$

Where P is the tension and Δl is the amount of strand required to form a single loop. If it is assumed that Δl is 3 inches and the energy of torsion is equated to the energy in equation (E2), one may solve for P. For the assumptions made a value of P = 200 pounds is derived. During the initial phases of kink formation the value could be much greater and not a constant as assumed here. Thus, the ring failure may be somewhat understood by this energy argument.

TEST (2)

In this case for the nominal value of 15 foot-pounds of torque placed in the sample the tension in the sample could not be reduced to a level low enough to permit a kink to form. This is true because the water can and the associated hardware weighed approximately 12 pounds by itself.

TEST (3)

This test is a rerun of test (2) but at a higher value of initial torque. In addition to the weight of the full water can the sample tension included 17 pounds of additional weights placed on the top of the water can. Such was originally done for safety sake during the process of winding the torque into the sample.

Prior to the observed catastrophic failure which produced the same results as test (1), three wires in the outer layer of the strand failed in combined loading. By far the greatest stress on these wires was in shearing due to the high torque level. Immediately the sample failed by kinking in the vicinity of the wire breakage. In so doing the supporting circular ring was again bent straight and the water can and weights dropped to the floor. It is felt that the localized reduction of torsional rigidity and bending stiffness due to the wire failures led to the kink formation.

TEST 4

In this test the same results as shown in Figure 32 were observed. No further torque was imparted to the sample following the failure.

TEST 5

In this test the nominal 15 foot-pounds of torque was imparted to the sample and all the water released from the bucket. No kink was formed. In a desire for a real value of tension which would enable a kink to form, a portion of the weight of the water can was supported. A kink was thus formed at a tension of approximately 5 pounds.

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