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ARMORING OF SYNTHETIC-FIBER DEEP-SEA MOORING LINES AGAINST FISHBITE

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by

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Earl E Hays, Chairman
Department of Ocean Engineering

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Deep-sea mooring lines are susceptible to the biting attack of certain fishes. Many moorings have been damaged or parted by such attacks. Synthetic-fiber lines are most vulnerable, but extruded plastic jackets commonly used on wire ropes are also damaged.

Of the several biting species identified, sharks pose the most serious threat. Electrical, acoustic and chemical repellents have not produced encouraging results to date; only mechanical armor appears promising. It has been found that the mechanics of biting rules out armors composed of braided wires or ribbons, so attention has been focused on extruded plastics.

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Introduction

The deep-sea mooring program of the Woods Hole Oceanographic Institution was first reported by RICHARDSON et al (1963). During its first several years, the loss rate of moorings averaged about 40%. Of the indentified causes, cable failure accounted for the majority. It was soon established (STIMSON, 1965) that biting attack by marine organisms was responsible for all of the known mooring line failures. Several later papers (TURNER and PRINDLE, 1965, 1968; HAEDRICH, 1965; BANCHERO, 1966; SCHICK and MARSHALL, 1966) have discussed the geographical and depth distribution of the bites, and the indentification of species responsible.

To avoid losses due to fishbite, the trend since 1964 has been toward the use of wire ropes in the fishbite zone (0-2000 meters). A variety of mechanical and metallurgical problems prevented an immediate improvement in the recovery rate, but the lines were no longer severed by biting. Many of the non-biological problems have been solved, but the extruded high-density polyethylene jackets commonly used on such wires have been severely damaged by fishbite exposing the wires to corrosive attack. Moreover, many designers of deep-sea moorings favor synthetic-fiber mooring cables. Problems due to biting therefore remain an important consideration and a number of ways of protecting mooring lines in the deep-sea environment were studied.

Electric fields have been employed with some success in the protection of beaches (SMITH, 1966). Weak fields induce a temporary fright reaction; at higher field strengths an electrotaxis sets in, and fishes are caused to turn involuntarily toward the positive pole. A preliminary examination of the circuit constants indicates that the power requirements are beyond the capacity of buoy-mounted power supplies.

Acoustic fields are known to evoke a response from certain fishes, notably sharks (RICHARD and WISBY, 1968). Sharks have been attracted by low-audio and sub-audio frequencies, probably because they simulate the struggling of an injured fish. An Australian inventor, (ASSOCIATED PRESS, 1970) claims to have devised an acoustic shark repellent, effective at a range of seven miles, which emits a pulsed high-frequency sound. Recorded sounds of the killer whale have been played back in the presence of various fishes, without visible effect (CUMMINGS 1970). A 3.8 kHz acoustic beacon, installed at a depth of 500 m in a mooring, does not appear to have deterred the fishes. (The beacon was inoperative at the time of mooring recovery.) The attack was, if anything, more severe than usual; eight tooth fragments were imbedded in the cable jacket, in the depth range of 150 to 550 m.

Progress in this field is necessarily slow and uncertain. If the possibility of an effective acoustic repellent exists, its optimum characteristics will be difficult to establish, for positive conclusions must be drawn from negative results.

Chemical repellents seem to have negligible promise. Much military research has been conducted for the benefit of shipwrecked sailors and downed airmen, with uncertain results. The possibility of a chemical repellent effective for several months is remote; at best, it could be expected to deter only fishes approaching from the downstream side.

Armor appears to be the most promising protective method. In its first reported application (STIMSON, 1965), a jacket of polyvinyl chloride was extruded over a polypropylene rope The jacket proved to be too thin and and too soft to provide substantial protection. Later, SHICK and MARSHALL (1966) reported the application of polyethylene tubing (1 6 mm wall) over nylon rope. The polyethylene was punctured in numerous places, and it entrapped several tooth fragments. One tooth tip intruded through the inner wall and chafed the nylon. An unarmored mooring probably would not have survived such an attack.

Scope of the Problem

The world's oceans have not been comprehensively covered by deep-sea mooring programs; it is therefore not possible to draw many generalizations about the geographical distribution of the fishbite problem. The only region studied by W.H.O.I. which appears to be free of the problem is the Atlantic Ocean, north of the fortieth parallel. The same may be true of the higher latitudes in other oceans.

In a study of depth distribution, it is necessary to discuss two distinct classes of bites (STIMSON, 1965). At a typical mooring site in the Sargasso Sea, the rate of biting in the top 500 meters of a cable was observed to be, on the average, not less than one per week, but seldom more than one per day. Such bites are often severe, and many synthetic-fiber moorings have failed at a single, clean cut. (Figure 1) The wire in a jacketed wire rope can be laid bare by such a bite. (Figure 2)

At greater depths, bites are generally more frequent (several per day) but less severe. Often a sharp peak is seen at the depth of the permanent thermocline (700-800 meters) (TURNER and PRINDLE, 1968).

Of the species responsible for such bites, our evidence indicates that severe bites at relatively shallow depths are largely or entirely the work of sharks. Tooth marks on numerous cables have been matched against the dental geometry of the Atlantic white tip shark (*Carcharhinus longimanus*), with good agreement. The Atlantic white tip is the species most frequently observed at those Sargasso Sea sites where the incidence of biting has been highest; curiously, they are also abundant at sites in slope water north of

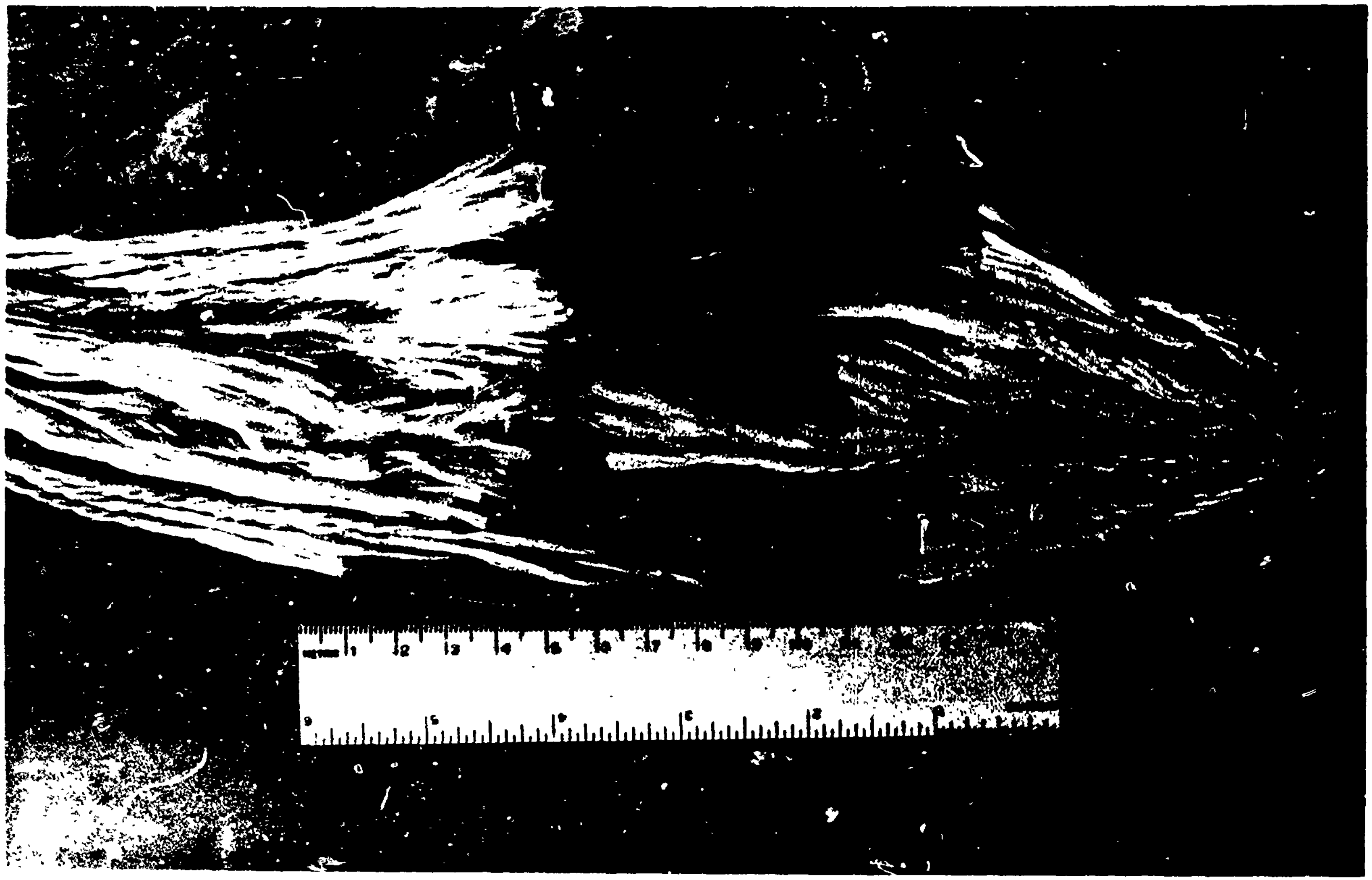

Figure 1. 13 mm. dia. Nylon Buoy Line Damaged by Fishbite and Subsequently Parted by Tensile Stress During Recovery.

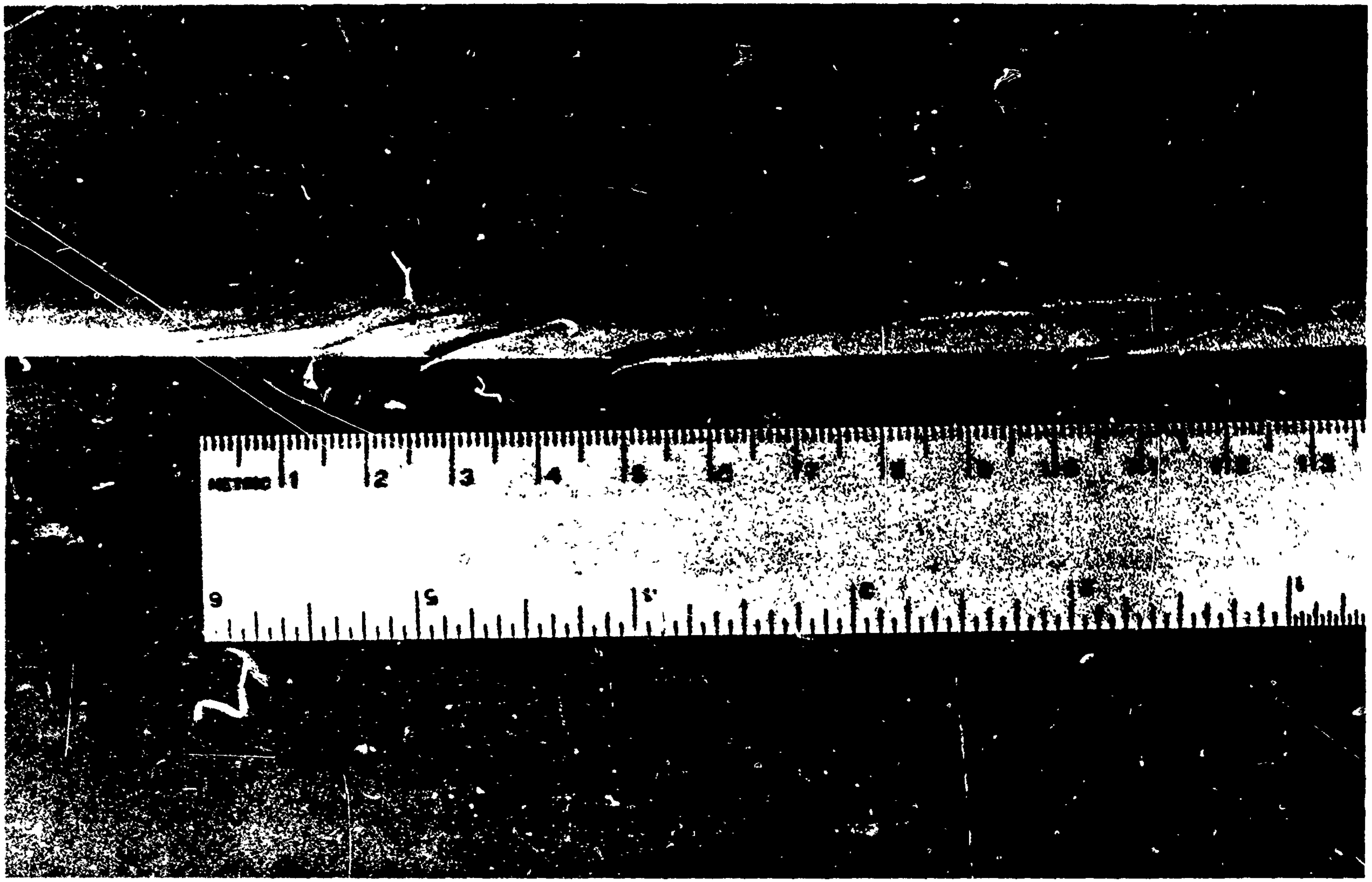

Figure 2. Fishbite on Plastic Jacket of Wire Mooring Line.

the Gulf Stream, where biting is not ordinarily a problem. No suspect species has been identified as present in the Sargasso Sea and absent in the slope water; therefore is must be tentatively concluded that the tendency of sharks to bite lines is influenced by environment.

BANCHERO (1966) reported bite damage to a mooring cable 644 km east of Miami, Florida, at a depth of 400 meters. Recovered tooth fragments were positively identified as those of a shark, species unknown. SCHICK and MARSHALL (1966) recovered teeth of a mako shark (Isurus) from a mooring line at 30° N, 140° W.

Recently, COLLIER (1972) has reported severe damage to a 5-cm diameter mooring line which had been attached to a buoy in 4300 meters of water eight (8) kilometers north of Ham's Bluff, St. Croix, Virgin Islands. The line failed at 340 meters depth. Photographs of the bitter end and of a section which was cut but did not part, show cleam cut strands typical of fishbite. The evidence indicates that the mooring line failed from fishbite. It occurred at a depth which suggests that the attacking organism was probably a shark.

The above, together with observations which have been made on 7.6 cm diameter lines attached to the XERB-1 (Monster) buoy, demonstrates that fishbite cannot be regarded as a problem limited to lines of small diameter.

Much damage to plastic covers of cables is in the form of long scratches and gouges, parallel to the axis. (Figure 3) Sharks teeth are raked aft and are rather flexibly mounted, so such damage could not be effected by a shark in forward motion along the cable. Sharks have no significant ability to exert reverse thrust. The process which caused damage remained a puzzle until WALDEN (1969) offered a plausible explanation: the relative motion

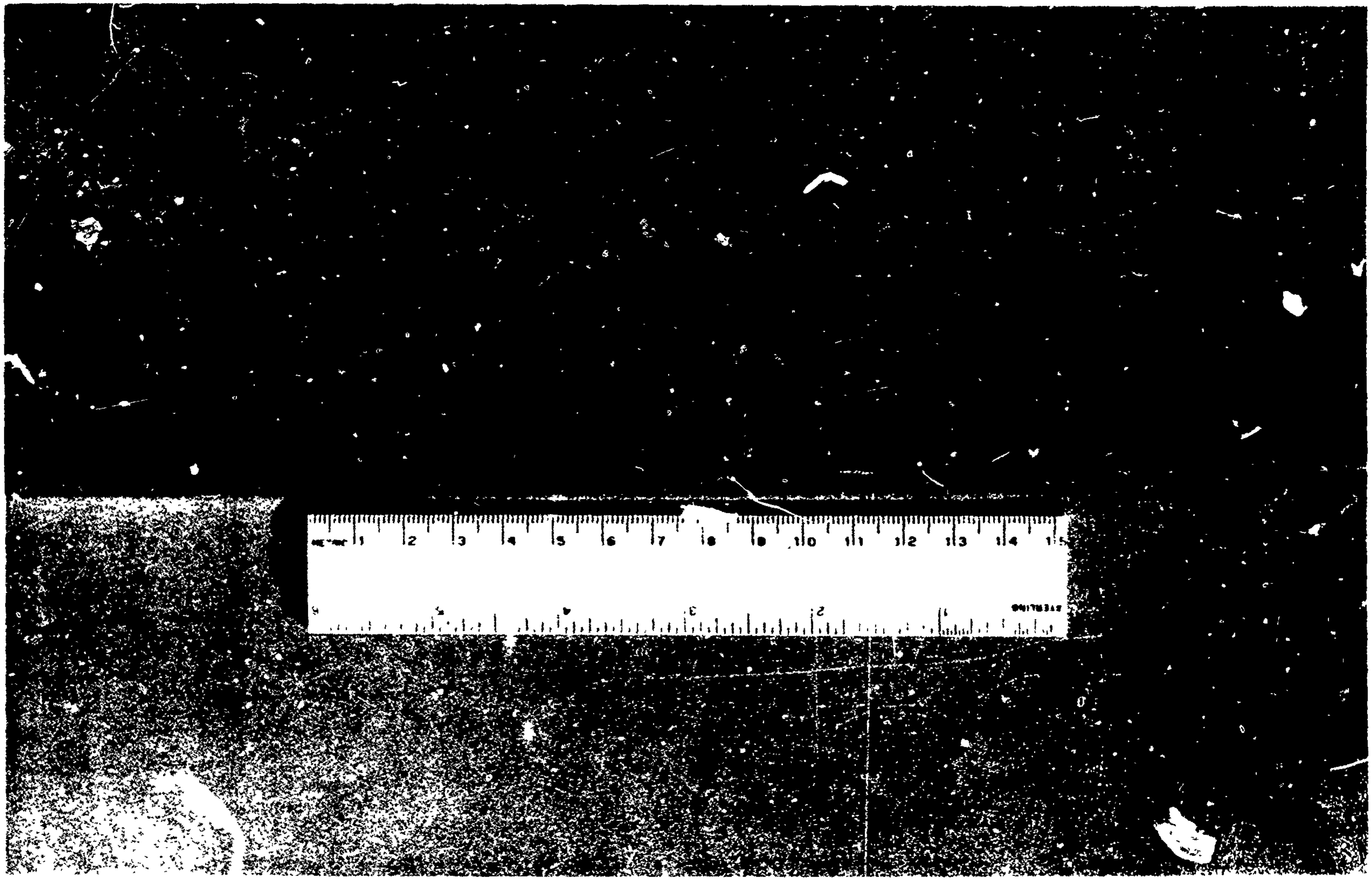

Figure 3. Tooth Scratches on Polyethylene Cover of Steel Mooring Line.

might be supplied by the buoy heaving in a seaway. He has dubbed the phenomenon the "dental floss effect".

It is evident from the work of SNODGRASS and GILBERT (1967) that sharks do not exert their full biting capability on cables. Mooring line damage must be the result of testing for edibility, rather then concerted attack. The severe damage due to the dental floss effect is probably inadvertent and involuntary.

Bites at greater depths are principally caused by *Sudis hyalina* and *Alepisaurus ferox*. Both species have been positively indentified from recovered tooth fragments (HAEDRICH, 1965). It appears certain that an armor resistant to sharks will withstand the lesser bites of these two species.

Armor Design Requirements

Because of the dental floss effect, the use of braided metallic armor was ruled out. It contains many interstices in which teeth may snag. Recent efforts have therefore been focused upon extruded plastic tubing.

Early in the laboratory tests, it was established that resistance to cutting diminishes with increasing tensile stress in the armor. Since synthetic-fiber rope stretches appreciably under load, some means of decoupling the load from the armor is essential. If there are to be no instruments in the fishbite zone, and if the upper 2000 m of the mooring line can be manufactured and deployed in one piece, there is no problem: the armor can be affixed to the upper terminal and left free at the bottom. For moorings which must be terminated at closer intervals, the telescoping configuration shown in Figure 4 has been designed, and has been successfully tested

A practical armor must be sufficiently flexible to spool on a reel of reasonable dimensions A maximum core diameter of 0.61 m was arbitrarily chosen All candidate materials reported herein were able to meet thie requirement

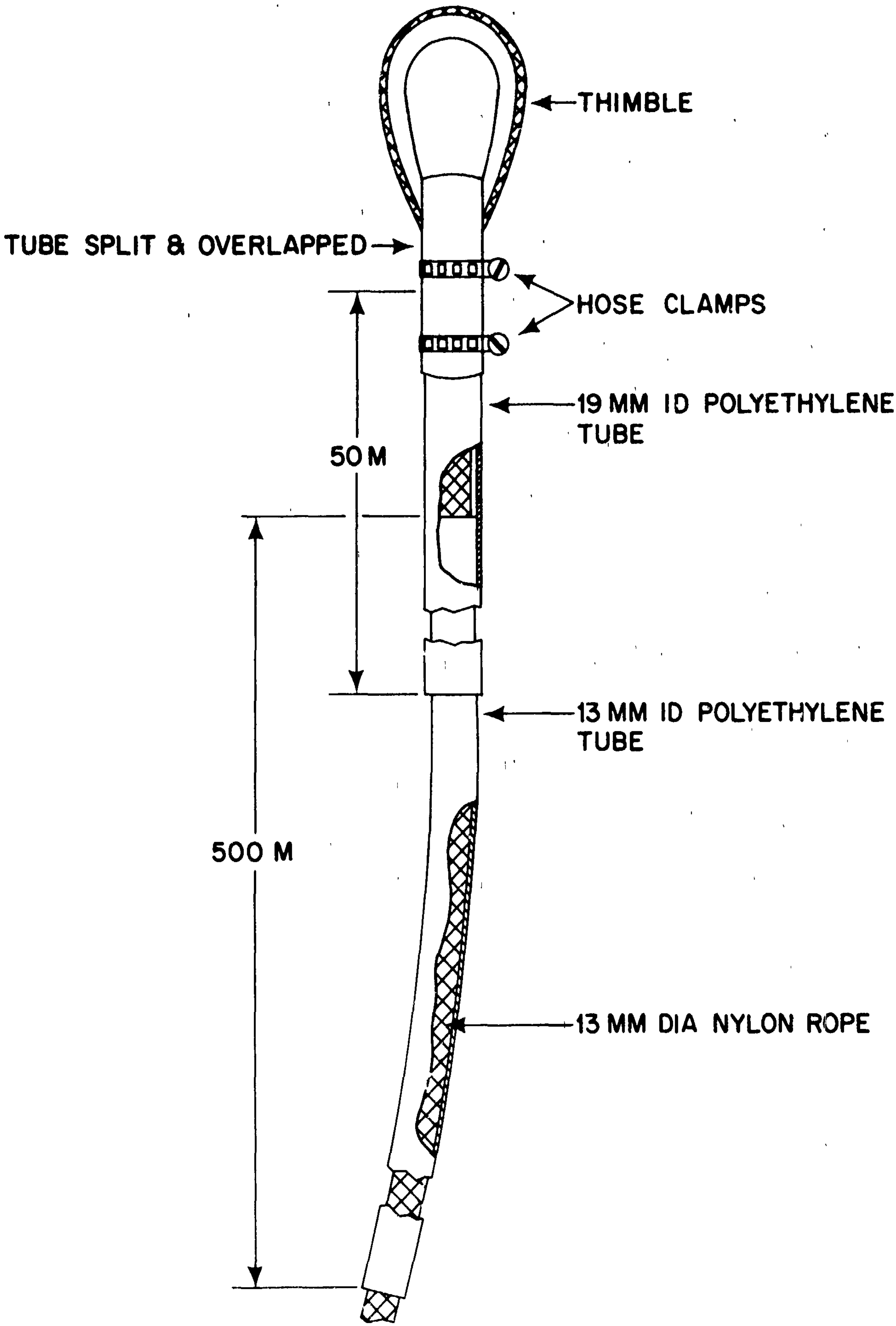

Figure 4. Mooring Line Armor-Telescoping Method.

Laboratory Screening Tests

Several laboratory tests have been developed for use in screening materials which appeared potentially useful for mooring line armor. One type of test measures the susceptibility of materials to piercing by sharp edges. Another simulates the gashes, scrapes and punctures which were found in coverings of mooring lines.

Resistance to Cutting

The purpose of this kind of test was to measure resistance to simple cutting as indicated by the force needed to move a sharp edge through the material. According to BARKAS et al (1932), the force required to move a blade through a cross section of material depends upon the factors illustrated in Figure 5. The force is large when edge radius and sharpness angle are large. It is also increased by depth of cut and coefficient of friction if the material closes behind the edge and binds the blade. If, on the other hand, the material has a tendency to split or move away from the sides of the blade, cutting force will be less. Fiber tension reduces blade binding and lessens resistance to cutting.

The cutting tools available to various marine organisms which might be involved in cutting mooring lines were studied. Teeth of Sudis hyalina and sharks, and the beaks of sea turtles, and squid, were observed and measured for hardness. Results indicated that the teeth of carcharinid sharks are probably the most efficient cutting instruments of all. It was decided to concentrate further efforts on these and to design a cutting test with reference to them.

Because the effectiveness of a cutting edge is a function of hardness, the teeth of two species of carcharinid sharks were tested using the Moh scale of hardness commonly employed by geologists.

Hardness of sharks' teeth from several sources as noted below was found to

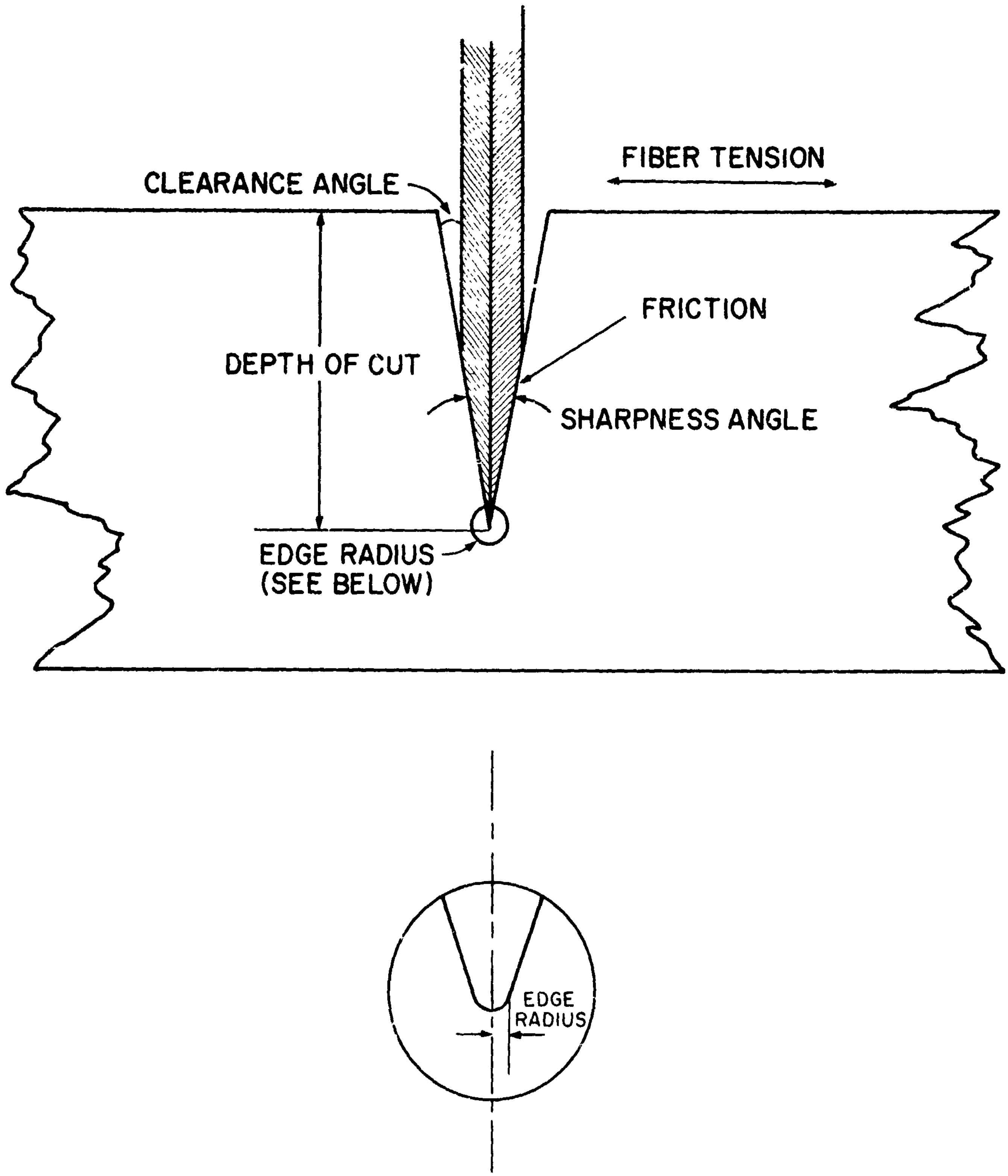

Figure 5. Mechanics of Cutting.

be as follows:

White tip sharks -

Carcharinus longimanus (Museum of Comparative Zoology, Harvard) MCZ #35516 - Moh #6

Carcharinus commersonii (Museum of Comparative Zoology, Harvard) MCZ #236259 - Moh #6
MCZ #35517 - Moh #6

Carcharinus longimanus (caught at Site D, August 16, 1970. Teeth tested after being frozen) - Moh #4-5

Blue sharks -

Prionace glauca (caught off No Mans Land, August 5, 1970. Test made on freshly caught specimen) - Moh #5-6

The Moh hardness of carcharinid sharks' teeth appears to be in the range of 4 to 6, or about the same hardness as a tempered steel knife blade. The data suggests that drying of shark teeth causes them to become harder.

The edges of both blue and white tip sharks' teeth are serrated. The triangular shape of the teeth together with the round cross section of mooring lines and the fibers from which they are made result in a skew or drawing cut which reduces the force necessary to push a cutting edge through the material. One measurement of the edge radius of a tooth from a white tip shark indicated an approximate radius of 0.005 mm and a cutting angle of about 10°.

All things considered, sharks' teeth are very effective instruments for cutting materials of a fibrous nature, especially if the fibers are under tension

In designing a standard laboratory cutting tool, one might circumvent the the whole problem by using sharks' teeth *per se*, but such an approach is difficult because of the limited and uncertain supply of sharks' teeth and because there is considerable variability in size, shape and maturity among the teeth on any one jaw. Hence, it was decided to use a straight edge of hardness, cutting angle and edge radius as near to those of sharks' teeth as could be readily obtained in a mass produced item. The blade chosen for use was a Heavy Duty Utility Knife blade, #1992-5, made by Stanley Tools, New Britain, Connecticut. It had the following characteristics:

Hardness - Moh 5 to 6

Cutting angle - Approximately 17°

Thickness - 0.61 mm

Edge radius - Approximately 0.0025 mm

Results of preliminary tests indicated that blades lost sharpness progressively when used for a series of cuts. To eliminate this variable, all cutting tests reported herein were made using a new blade for each cut.

Cutting tests were run on a Baldwin Universal Testing Machine, Mark CS.

Knife blades were mounted so that the axis of the test specimen would be perpendicular to the side of the blade. Specimens were fastened for cutting in two ways. Those which were to be cut without tension were laid or clamped in a V-shaped support so that the knife blade which was fastened to the moving head of the testing machine would be brought against the side of the specimen. (Figure 6) In order to let the blade pass through the specimen, a slot was provided in the specimen holder as shown. Blade binding was alleviated by using a minimum size slot for the knife blade. A slot width of 3.2 mm was used in all tests. The highest speed of the machine, 0.51 m per minute, was used whenever specimens were tested without tensile stress.

In cases where specimens were tested under tension, it was not possible to standardize closely the rate of movement of the cutting edge, but an attempt was made to use a moderate and constant rate of speed. Specimens were secured to the

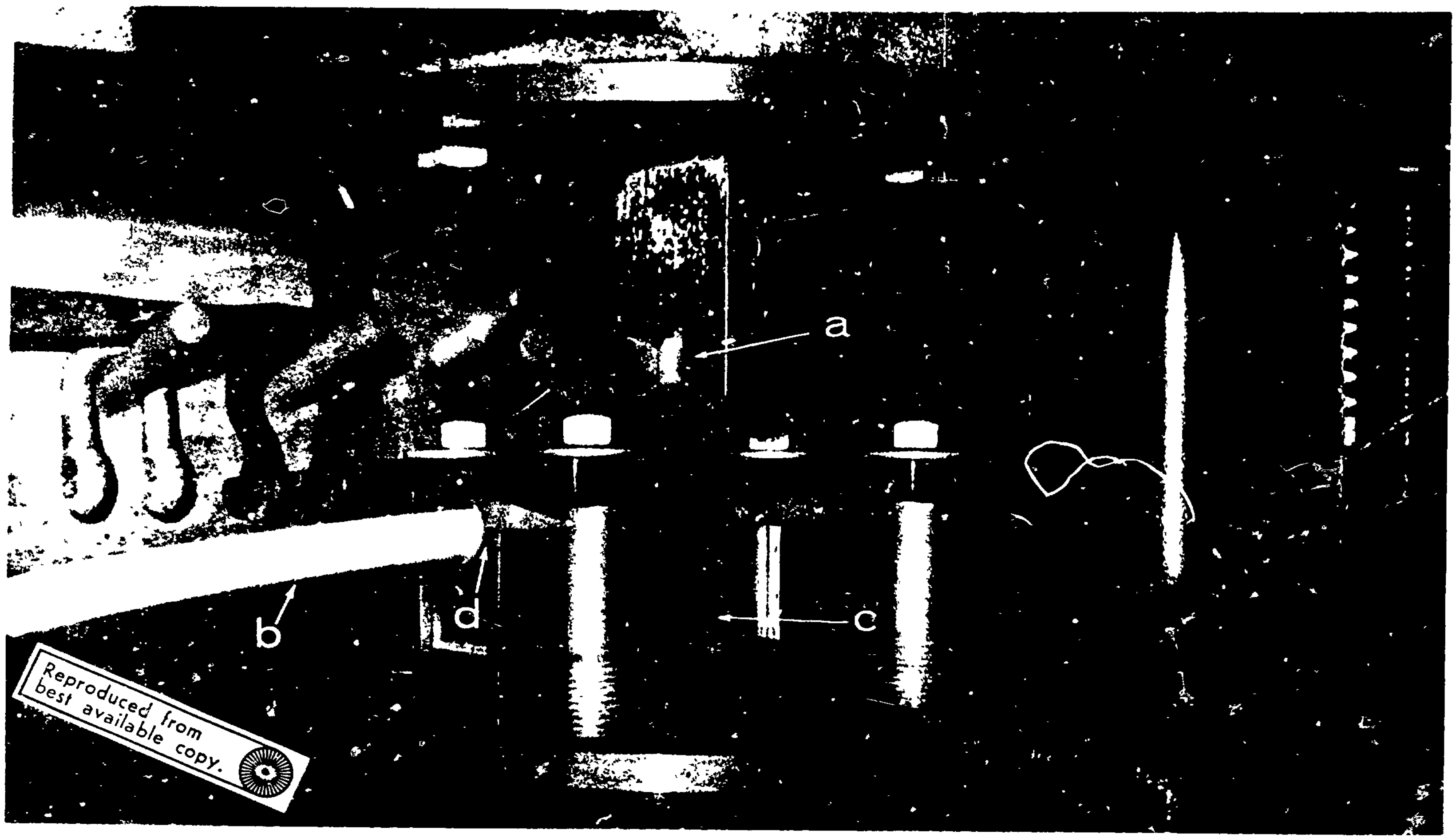

Figure 6. Cutting Test Without Tension

(a) Knife blade
(b) Test specimen
(c) 1/8" gap
(d) Tube supporting specimen

heads of the testing machines and the knife blade was mounted in a U-shaped stirrup so that is could be pulled across the specimen. Cutting force was then applied by hand and measured by means of a spring balance, as shown in Figure 7, which illustrates the same technique using sharks' teeth instead of a knife blade for cutting.

Results

Cut Tests on Ropes

Measurements of the force required to cut 1.43 cm diameter plaited nylon ropes at various tensions are presented in Figure 8. It is clear that there was an inverse relationship between cutting force and tension.

The force required to cut a polypropylene rope, of a type which has been used as a mooring line, was 22.2 newtons at 4,450 newtons tension. The cutting resistance of a glass rope was much higher, being more than 222 newtons at the same tension.

Cut Tests on Rope Armor Candidate Materials

Results obtained from cutting nine armor materials without tension are plotted in Figure 9.

To test the possibility that water might have a significant lubricating effect, the same samples of plastics were tested wet. A comparison with data obtained from dry tests is also presented in Figure 9. In two cases, polyethylene and polyurethane, the presence of water lowered cut strength 20 to 25%. In all other cases, there was no indication that the force required to cut wet materials was significantly less than that required to cut the same material dry

To determine the effect of tension upon the cut resistance of armor materials, tests were carried out on polyethylene tubes. It is evident that increasing tension produced a drop in the ability of polyethylene

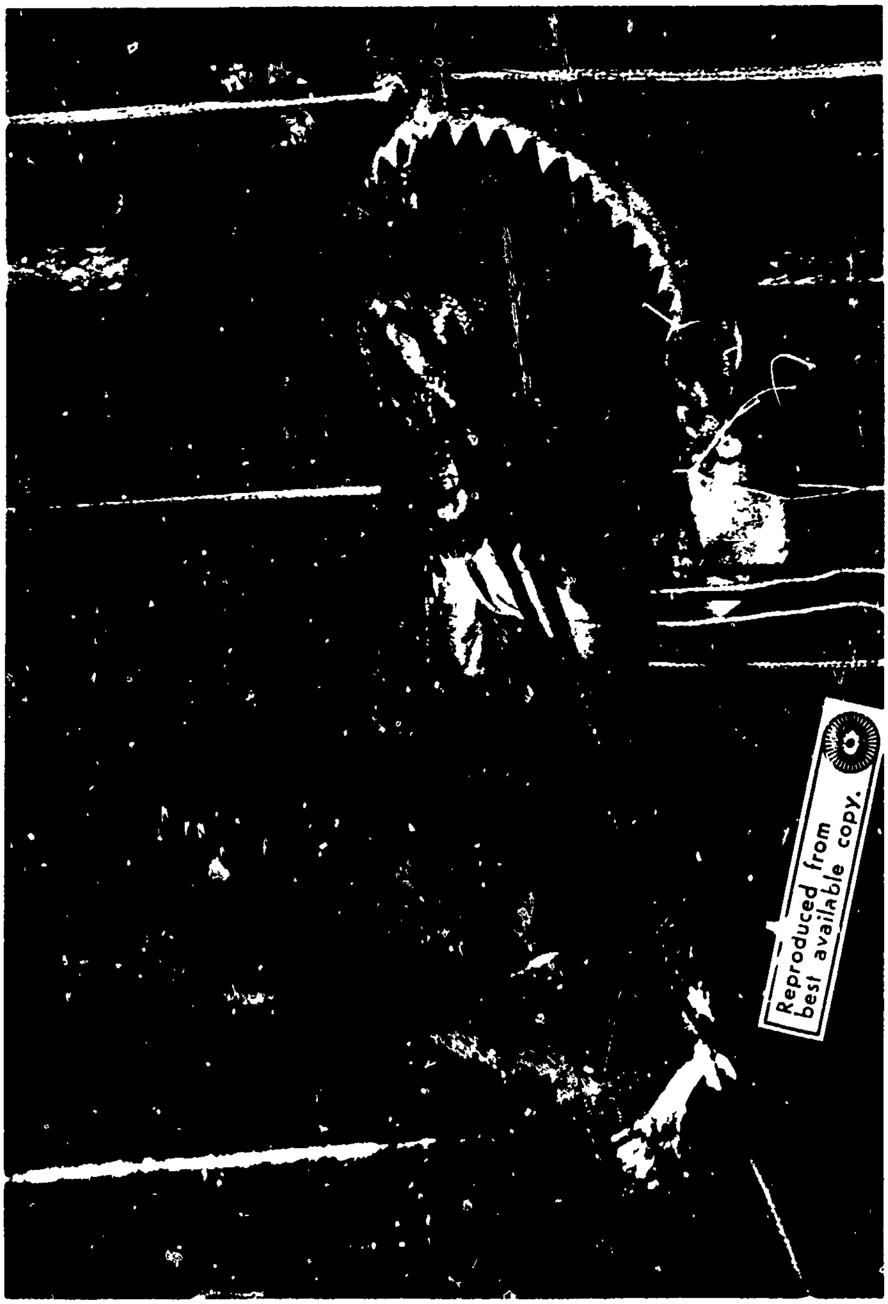

Figure 7. Measurement of Cutting Force with Specimen Under Tension.

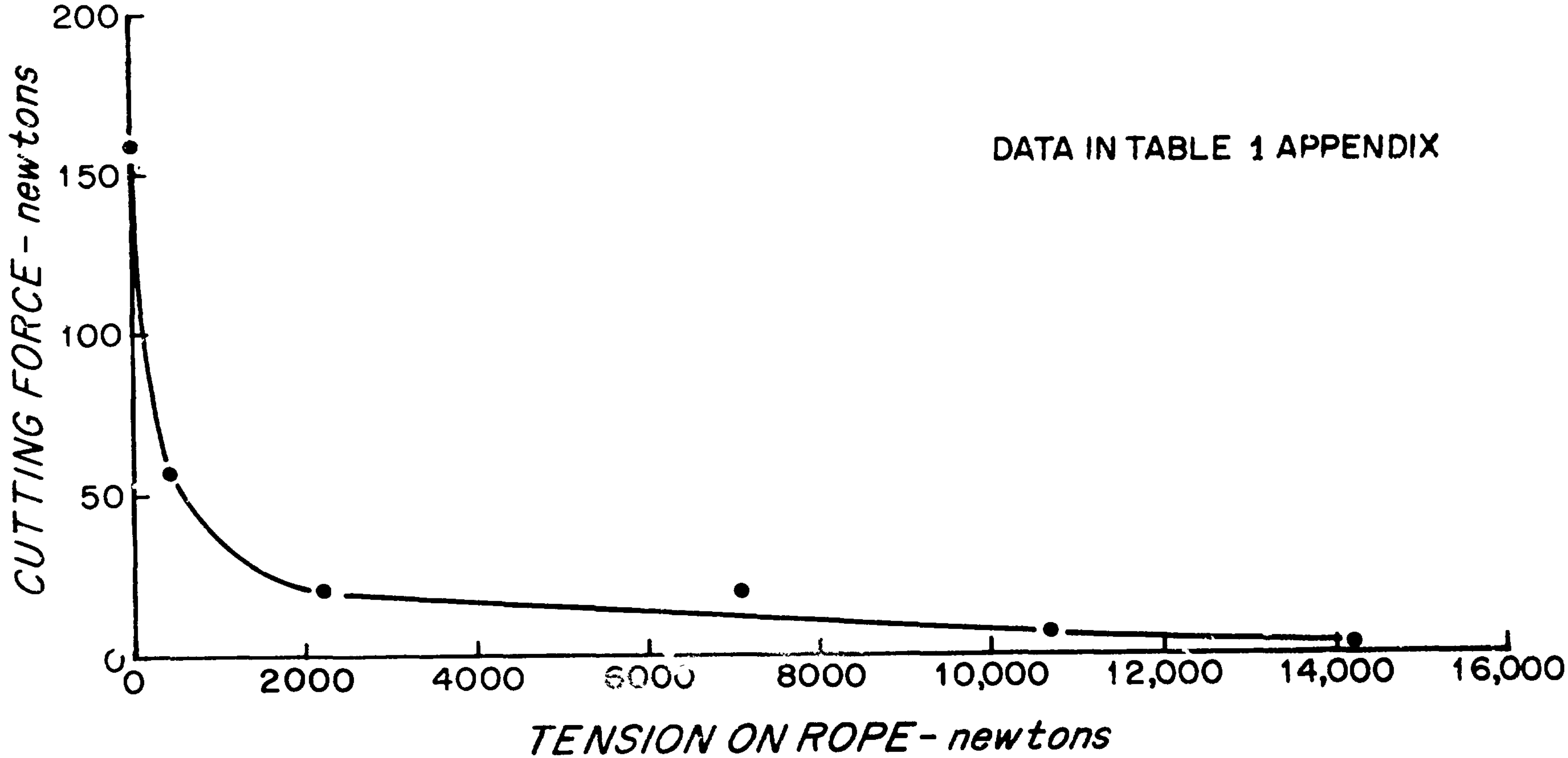

Figure 3. Effect of Tension on Cut Strength of Nylon Rope.

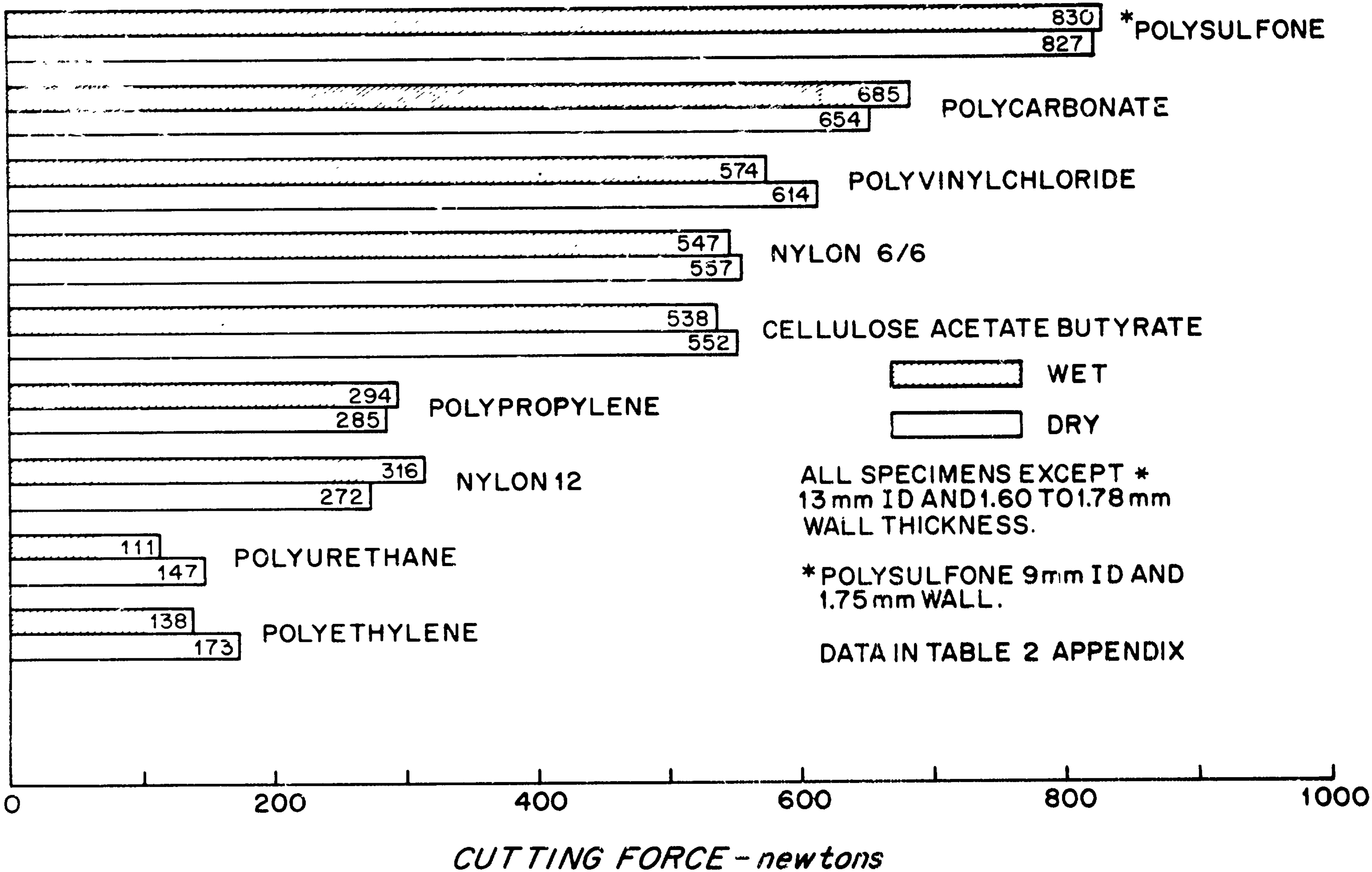

Figure 9. Cut Strength of Unstressed Armor

pipe to resist cutting as shown in Figure 10.

Armored Line

Results of cut tests on armored ropes under tension are presented in Figure 11. It is apparent that increased tension did not reduce the resistance of nylon rope armored with polyethylene, but there was a marked drop in cut resistance of armored dacron rope as tension increased. The difference was due to bonding between the rope and the armor. In the case of dacron, polyurethane armor was extruded directly onto, and was bonded to, the dacron rope. As a result, the armor was stressed when a load was applied to the rope, and there was a loss of resistance to cutting. Nylon rope, on the other hand, was not bonded to its polyethylene armor. The latter was not stressed as load was applied to the rope, and there was no drop in resistance to cutting. Clearly, this is an important design consideration in applying armor.

Cutting Test with Sharks' Teeth

To test the theory that sharks' teeth have the capability of cutting mooring lines, a few tests were made using the teeth of a white tip shark *in situ* on a jaw which had been preserved by drying. An upper jaw was used. 1.3 cm standard, long-pick, plaited nylon rope under 13,350 newtons tension was cleanly severed at a cutting force of 102 newtons. The technique used in making the test has been shown previously in Figure 6.

The same test was repeated with a 1.3-cm diameter rope of the same kind armored with 1.3 cm ID polyethylene pipe. Again, the rope was under 13,350 newtons tension, but the armor was not stressed. At the maximum available cutting force of 223 newtons, neither the rope nor the armor was parted. However, it was found upon inspection that the armor had been pierced by

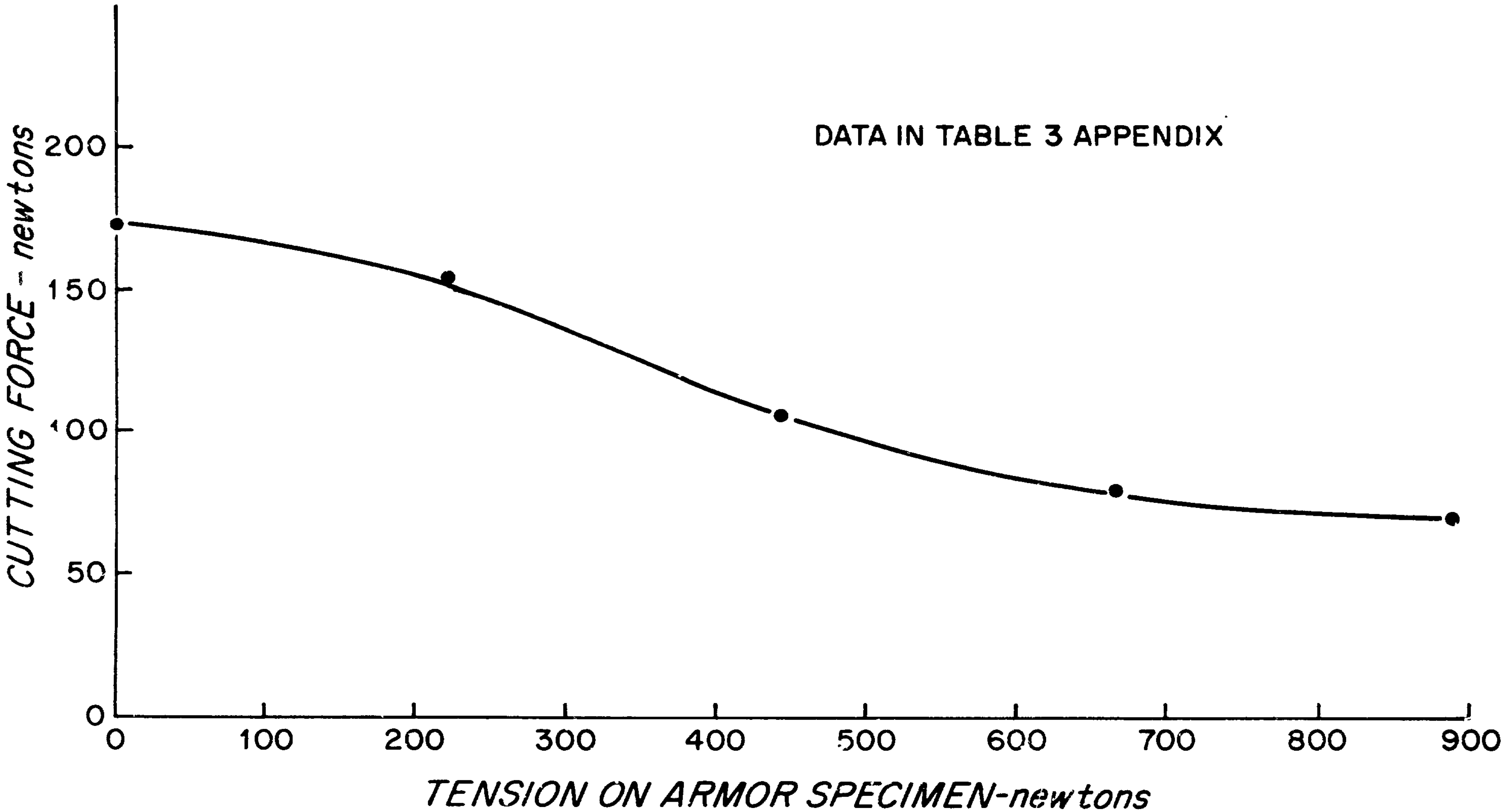

Figure 10. Effect of Tension on Force Required to Cut Polyethylene Pipe.

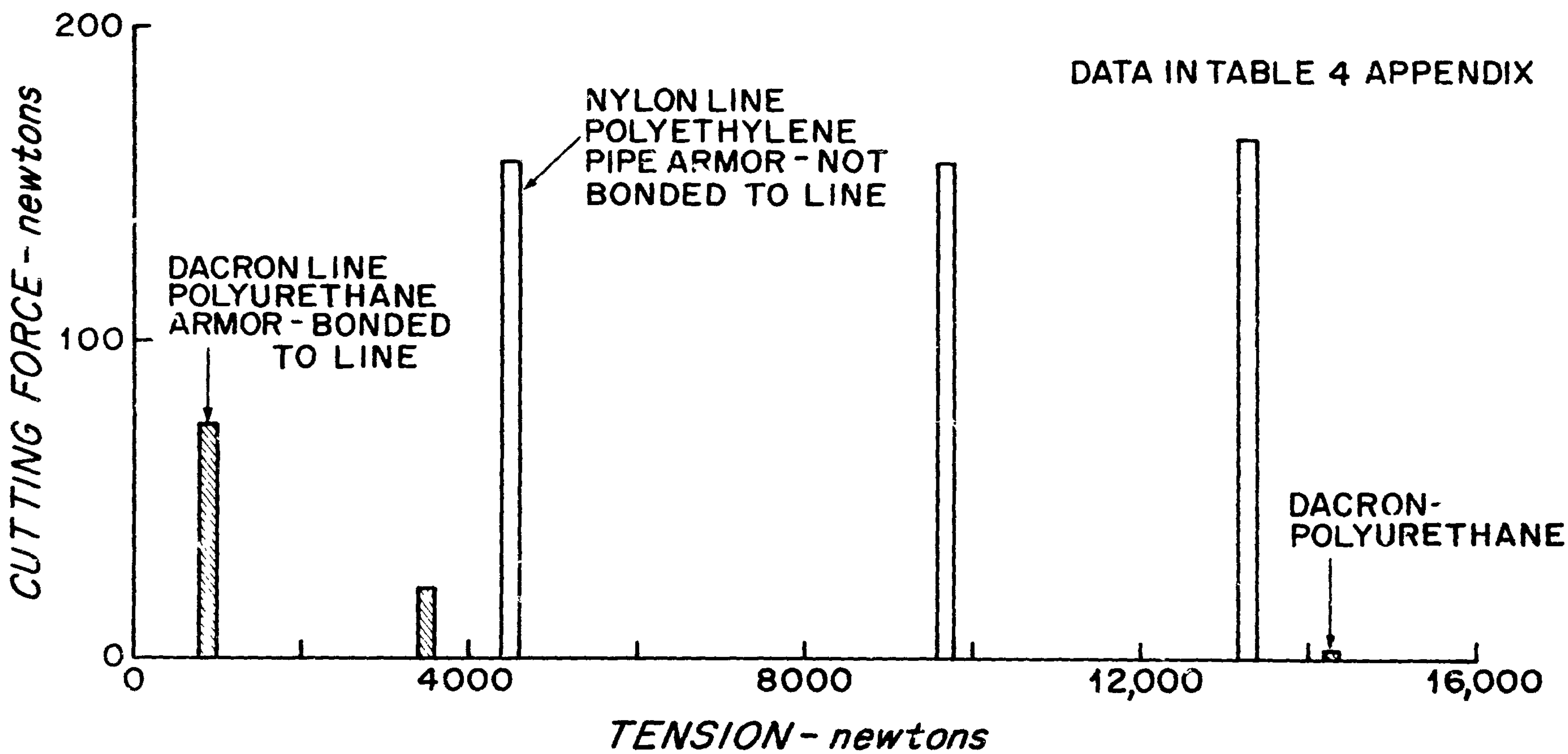

Figure 11. Effect of Tension on Cut Strength of Armored Lines.

the tooth points and the underlying rope was severely damaged.

The above test confirmed the ability of sharks' teeth to cut nylon lines at forces which appear to be well within the biting capabilities of sharks. Data obtained by SNODGRASS and GILBERT (1967) indicate that some sharks can close their jaws with a force as great as 1450 newtons or about 6.5 times the force used in the laboratory to produce significant damage to a rope armored with polyethylene pipe.

Stab Test

A second type of test was devised to simulate the cutting which might occur with sharp-pointed tools, such as shark teeth, and also to provide a test which could be applied to a wide range of materials without the necessity for bringing them into the laboratory.

The test instrument consisted of a modified tubing cutter with a dial indicator attached and calibrated so that readings could be translated into terms of force required to penetrate through the wall of a test specimen. The instrument will accomodate either a shark tooth or a steel replica. It is shown in Figure 12.

Stab tests were performed by placing a specimen in the V-shaped holder and advancing the tooth until it pierces the wall of the test item. force needed for penetration was proportional to the deflection of the frame of the instrument as measured by the dial indicator. Force measured was found to be a function of speed of movement of the penetrating point. Within the range of speeds which one would naturally use, however, the indicated variation was within 10% of measured values and therefore the variability did not interefere with the purpose of the instrument, which was to provide a quick and portable means for discerning differences between materials as a preliminary to more complete evaluation.

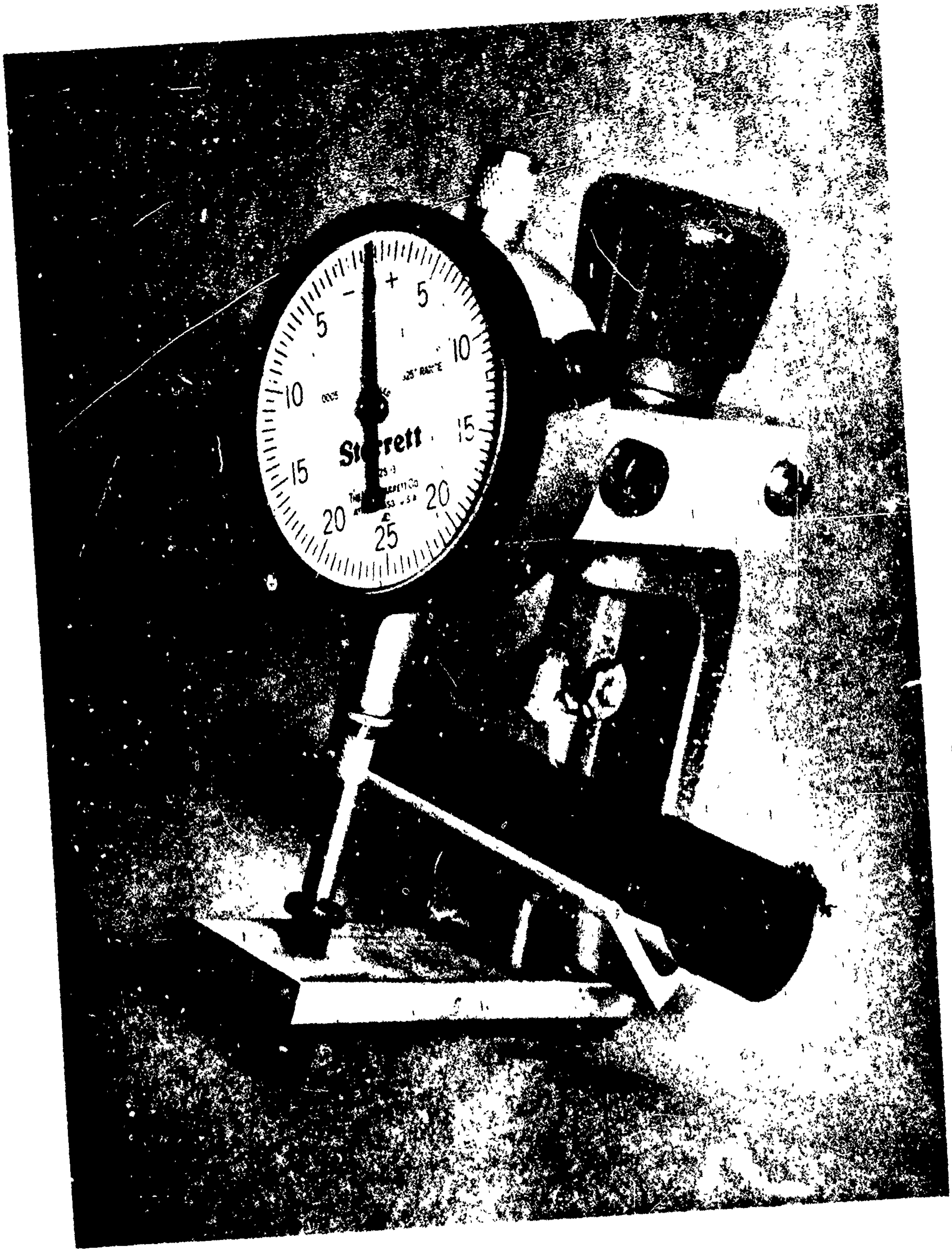

Figure 12. Stab Test Instrument.

Results of stab tests on a group of nine (9) plastics are given in Table 5.

Polyethylene is known from experience with deep-sea mooring lines to be on the low side in stab resistance. The present data indicate that polyurethane of Durometer Shore 65A would be even less satisfactory. In fact, there is reason to believe that such a material might give rise to a false sense of security when used on mooring lines because it was observed that cuts in polyurethane tubing had tendency to close after the passage of a sharp edge and then become very difficult to see, especially if the material were opaque.

The sample of nylon 12 was no better than polyethylene. Cellulose acetate-butyrate and polypropylene occupy an intermediate position as they did in the cut test. Unless they have other properties which make them specially suited to the job, this would seem to indicate that other materials should receive priority in development of mooring line armor.

Nylon 6/6 occupied an intermediate position in the stab test, as it did in the cut test. Because of its other properties such as resistance to impact, and low temperature of brittle transition, however, it should receive further consideration.

The materials which showed highest resistance to puncture were polyvinyl chloride, polycarbonate, and polysulfone. Inasmuch as they were also at the top of the list in terms of cut resistance, they appear to be worthy of special attention

In general, there was good correlation between the results of the cut test and the stab test

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Tooth Snagging Tests

To obtain a measure of the resistance of materials to snagging and piercing by sharp-pointed teeth, an apparatus was devised so that specimens of armor could be drawn under pointed tools, which would simulate the action of sharks teeth scraping the surface of a buoy line. Provision was made for the application of a constant load to the tool as it rested on the surface of a specimen and for measuring the force necessary to start the specimen moving under the tool. A picture of the apparatus is shown in Figure 13.

Tests were performed by placing a tooth in the tool holder, setting the tooth at a desired angle to the axis of the specimen, hanging a known weight on the axis of the tooth holder and then measuring the force needed to start the specimen moving under the tooth.

Two types of tests were performed. In one, teeth were placed in the apparatus with their broad sides across the axis of the test specimen. This would correspond to a situation where a buoy line might be drawn between the teeth on the side of a shark's jaw. In tests of this kind, the points of two adjacent teeth were brought to bear equally upon the surface of the specimen.

A second type of test involved used of a single tooth which was brought to bear upon the test specimen with its broad side in a vertical plane which passed through the axis of the test specimen.

Tooth angles were measured with reference to a horizontal plane which coincided with the axis of each test specimen as shown in Figures 14 and 15 The attack angle was measured between the leading side or edge of a tooth and the direction of the force applied to pull the specimen beneath

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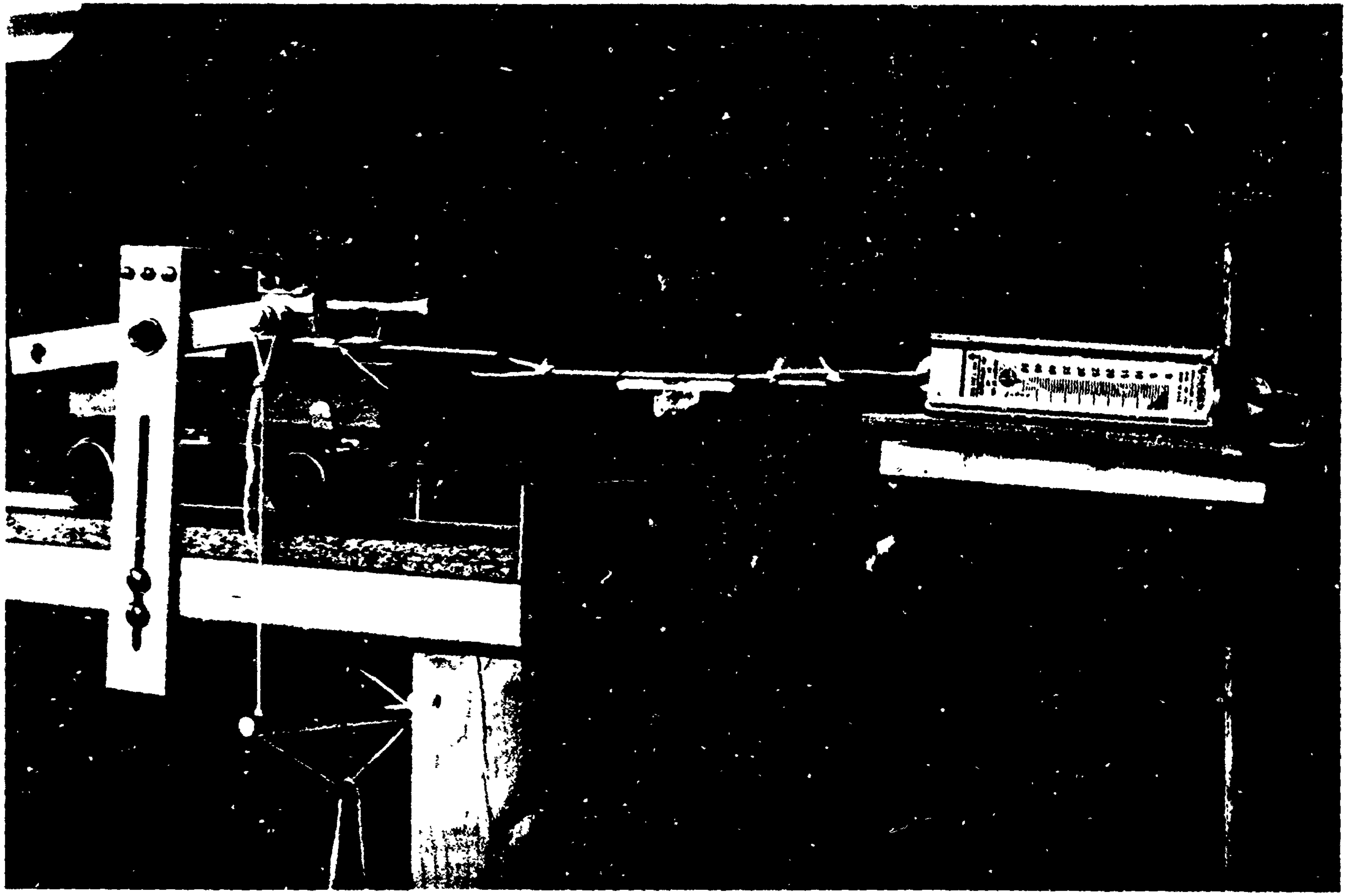

Figure 13. Snag Tester

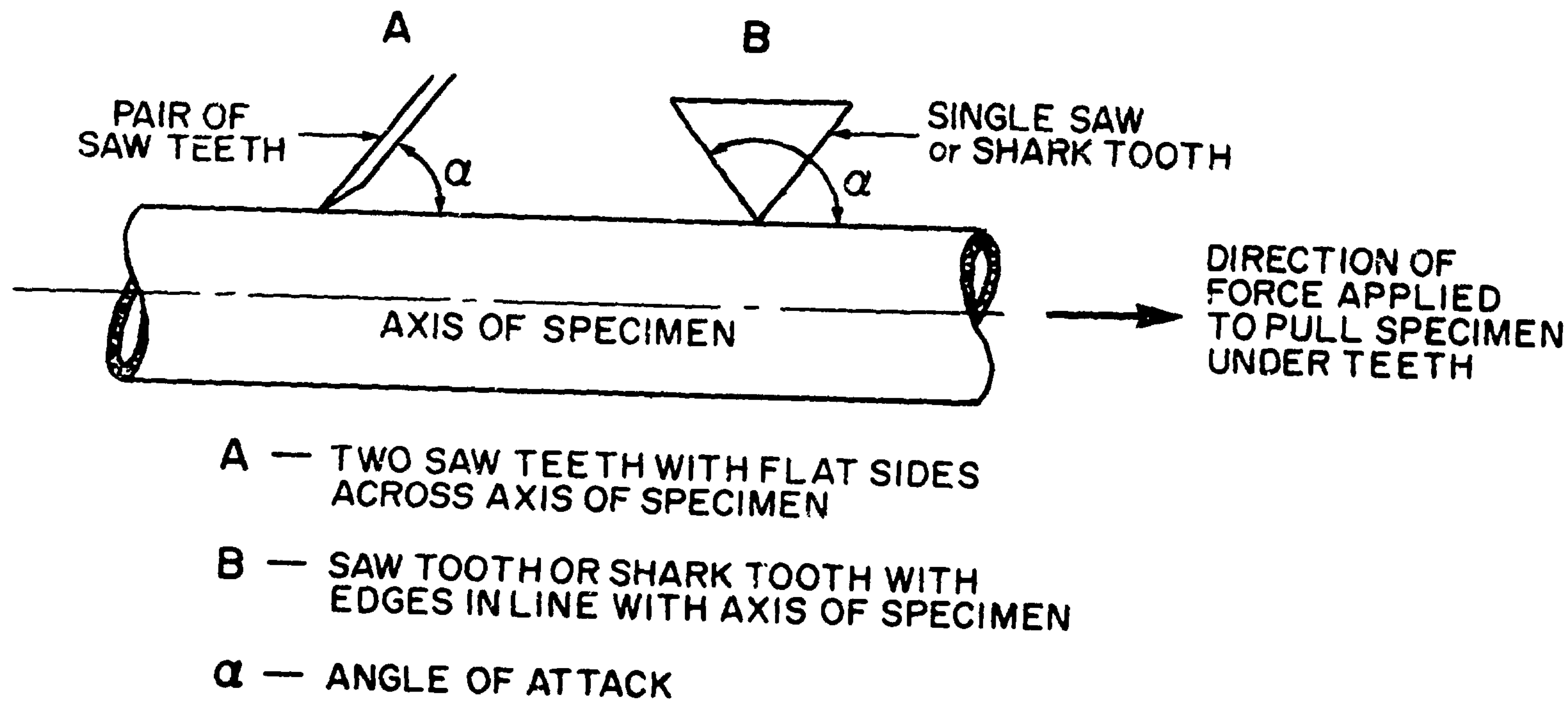

Figure 14. Measu.ement of Tooth Angles in Snag Tester.

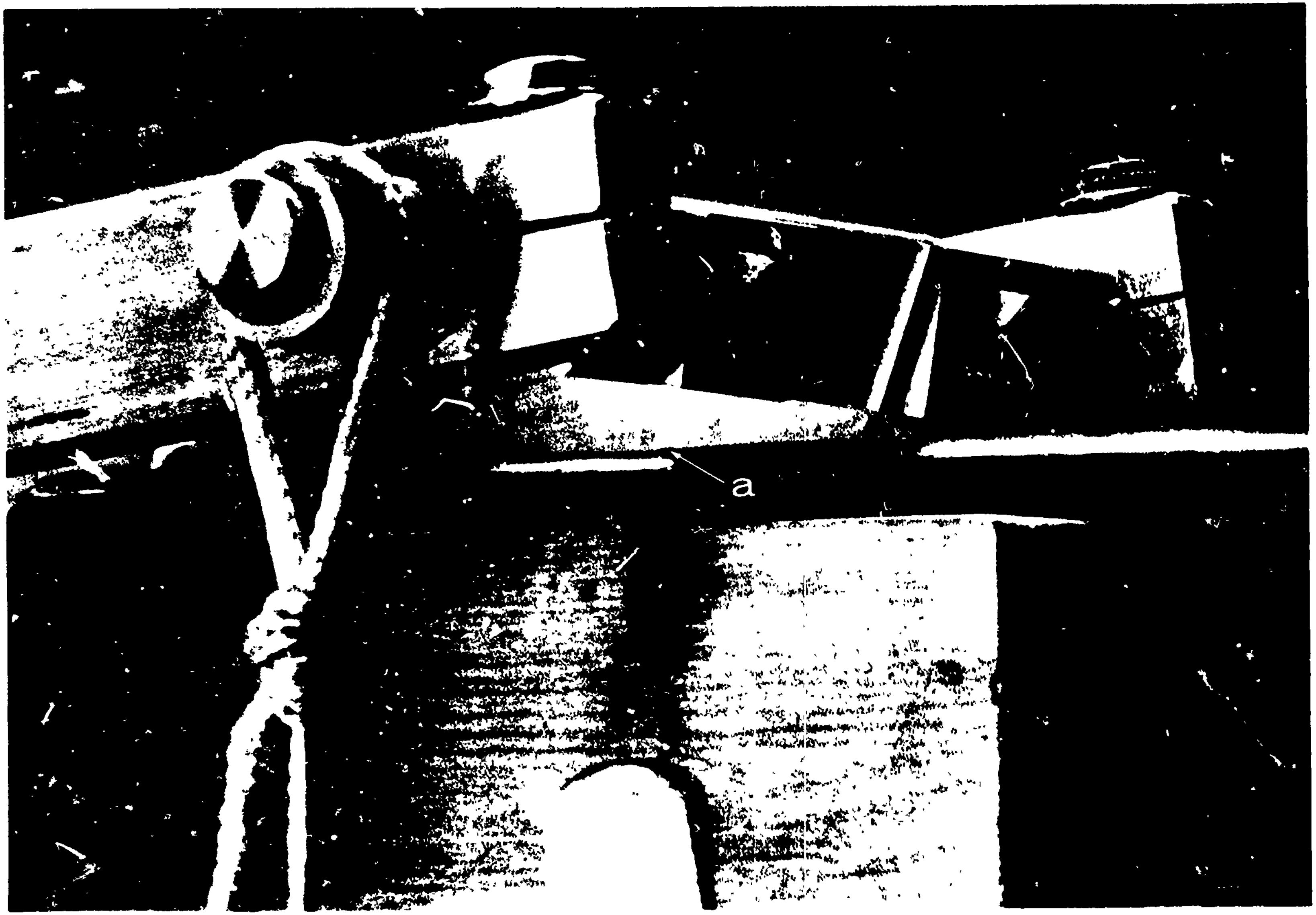

Figure 15. Shark Tooth in Position on Snag Tester

(a) Shark tooth

the teeth as shown. When pairs of saw teeth were used for snagging tests, angles were less than 90°, usually 60°. When a single tooth was used with its edges in line with the axis of the test specimen, angles were greater than 90°, usually 115°. Both steel saw teeth and sharks' teeth were used in testing.

However, it soon became apparent that sharks' teeth would not stand sufficient force laterally to allow testing highly resistant materials. Therefore, subsequent tests of this kind were done with steel saw teeth. The saw teeth were as manufactured by Snow and Neally Co. in their bow saw blade #102. The blade has a thickness of 0.56 mm. Each tooth was 5 mm wide at the base and 6 mm high. They were triangular and symmetrical with a hardness of 5 to 6 Moh. In these characteristics the saw teeth resembled those of white tip sharks. In other ways, however, they differed. Shark teeth are rounded on one side and flat on the other. The saw teeth were flat on both sides and had a smaller radius at the tip than did either the teeth of white tip or blue sharks. For testing purposes, the saw teeth were filed until they resembled sharks' teeth in the latter two characteristics.

Preliminary test results indicated that the modified saw teeth produced marks on polyethylene pipe which were similar to those seen on a length of the same material which had been exposed in the sea.

In the first tests made, two saw teeth were brought to bear upon the surface of armor test specimens as it was thought that this was the most likely course of events if sharks' teeth were involved <u>in vivo</u>. It was found that angle of attack had a critical effect upon the force required to pierce the wall of a test specimen. The results are shown graphically in Figure 16. It is evident that tooth angle had a marked influence upon the force at which piercing of the wall took place. A minimum occurred at an angle between 55° and 60°.

As a result of the above observations, it was decided that in order to make the screening test severe and critical an angle of 60° would be used wherever possible.

Similar tests were then run on the group of nine (9) plastic armor materials which had been tested for resistance to cutting. Results are given in Table 7 in terms of the maximum force which could be applied to the teeth without piercing each specimen and the ratio of vertical force on teeth divided by the force required to move the specimen horizontally. The ratio might be regarded as a "Snag Coefficient"; low values indicating a low tendency for catching and penetration of a tooth point. A second series of snag tests was run in which teeth were used with their edges in line with the axis of the test specimens. This would put them in the same relationship to a mooring line as the front teeth of a shark attacking a vertical line while himself being horizontal in the water. In such a position, there would be much more chance that relative movement of line and teeth would produce serious cuts and punctures.

In setting up the test technique, it was necessary to choose an angle between the axis of test specimens and the cutting edges of teeth Shark teeth are asymmetrical and their configuration varies with position in the jaw. The best one can do in choosing an angle for test purposes is to pick one which is likely to be common within the range of teeth and their angles of attack The final choice was 115°

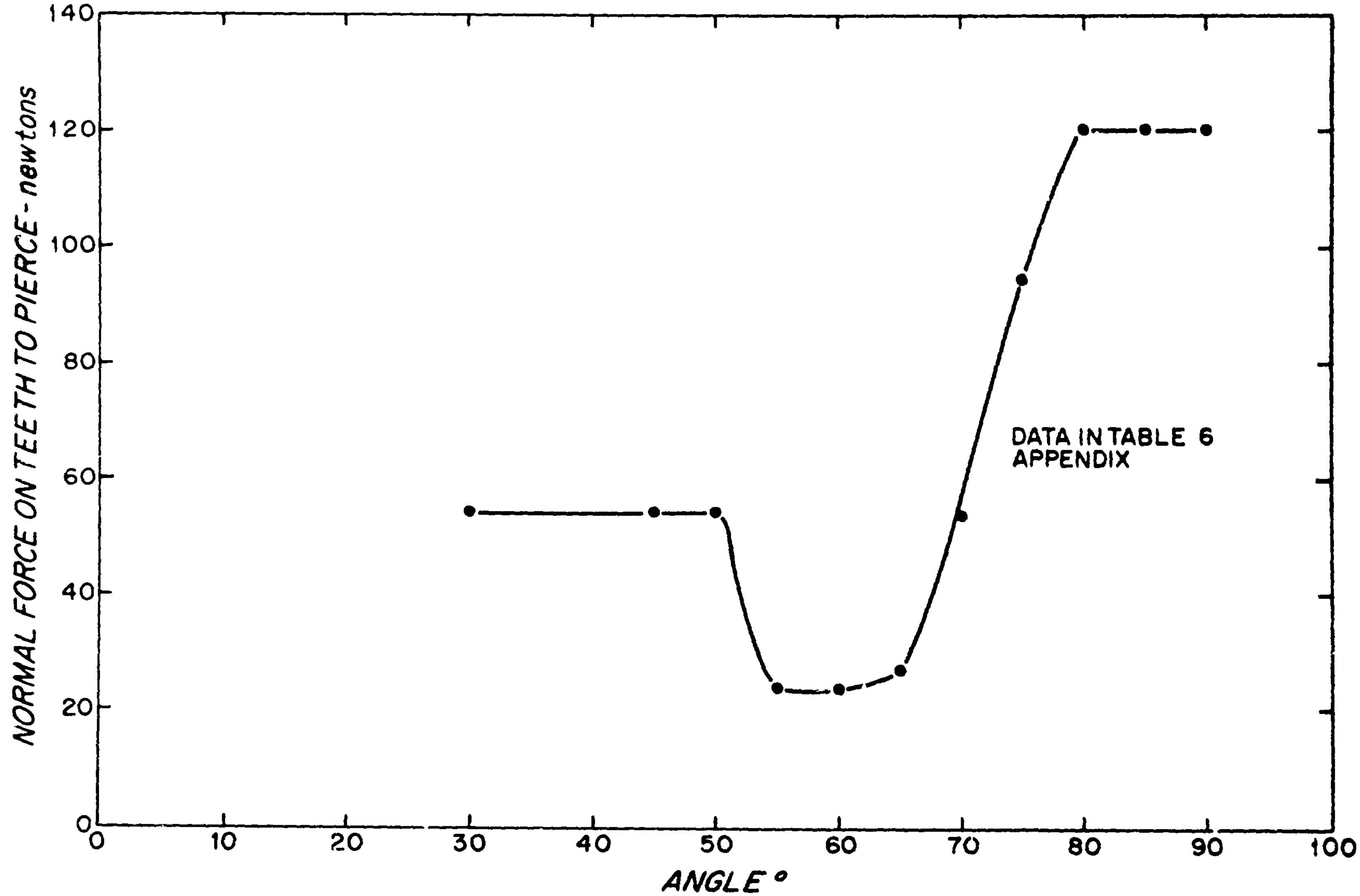

Figure 16. Snag Test on Polyethylene Pipe--Effect of Changing Tooth Angle.

Again, the nine test samples were run using both steel saw teeth and a white tip shark tooth. Data are presented in Table 8.

From the results of this test it is possible to rate the various materials in order of their ability to resist digging with a sharp point.

It is also evident that the shark tooth penetrated plastics at lower forces than required with the steel tooth. However, the ranking of materials in resistance to scratching and perforation was the same using either kind of tooth. Apparently the steel tooth and the shark's tooth were similar in the mechanism by which damage to various materials was produced. It is proposed that in the future steel saw teeth be used as they are more durable than sharks' teeth which break when materials which are tough enough to serve as effective armor are tested.

Full-scale Tests on Armored Mooring Cables

In the recent armor test program there have been five full-scale test moorings.

Two moored stations, #298 and #300 were set at 39° N Lat, 70° W Long (Site D). The top 1500 meters of each of these lines was steel wire rope covered with high density polethylene. The duration of the stations and the numbers of bites observed on the retrieved lines are shown graphically in Figures 17 and 18.

An effort was made to distinguish between the type of bite previously attributed to Sudis hyalina and the more severe bites and slashes thought to be the work of sharks. Such a distinction is difficult to make and the results of the effort should not be taken too seriously. Its usefulness lines in establishing a basis for estimating the frequency of bites ("other") which are apparently caused by sharks

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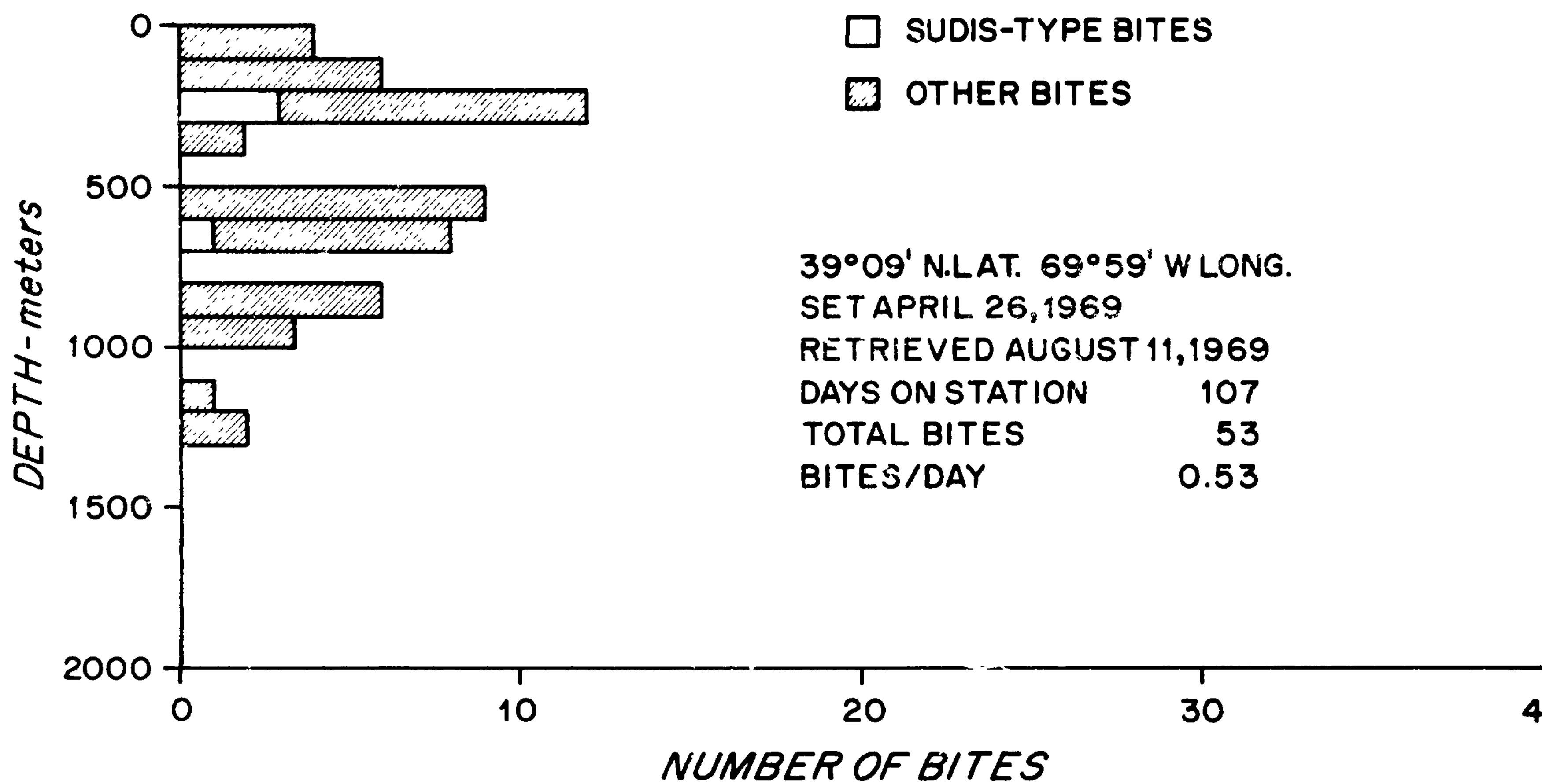

Figure 17. Fishbite vs. Depth
WHOI Moored Station #298

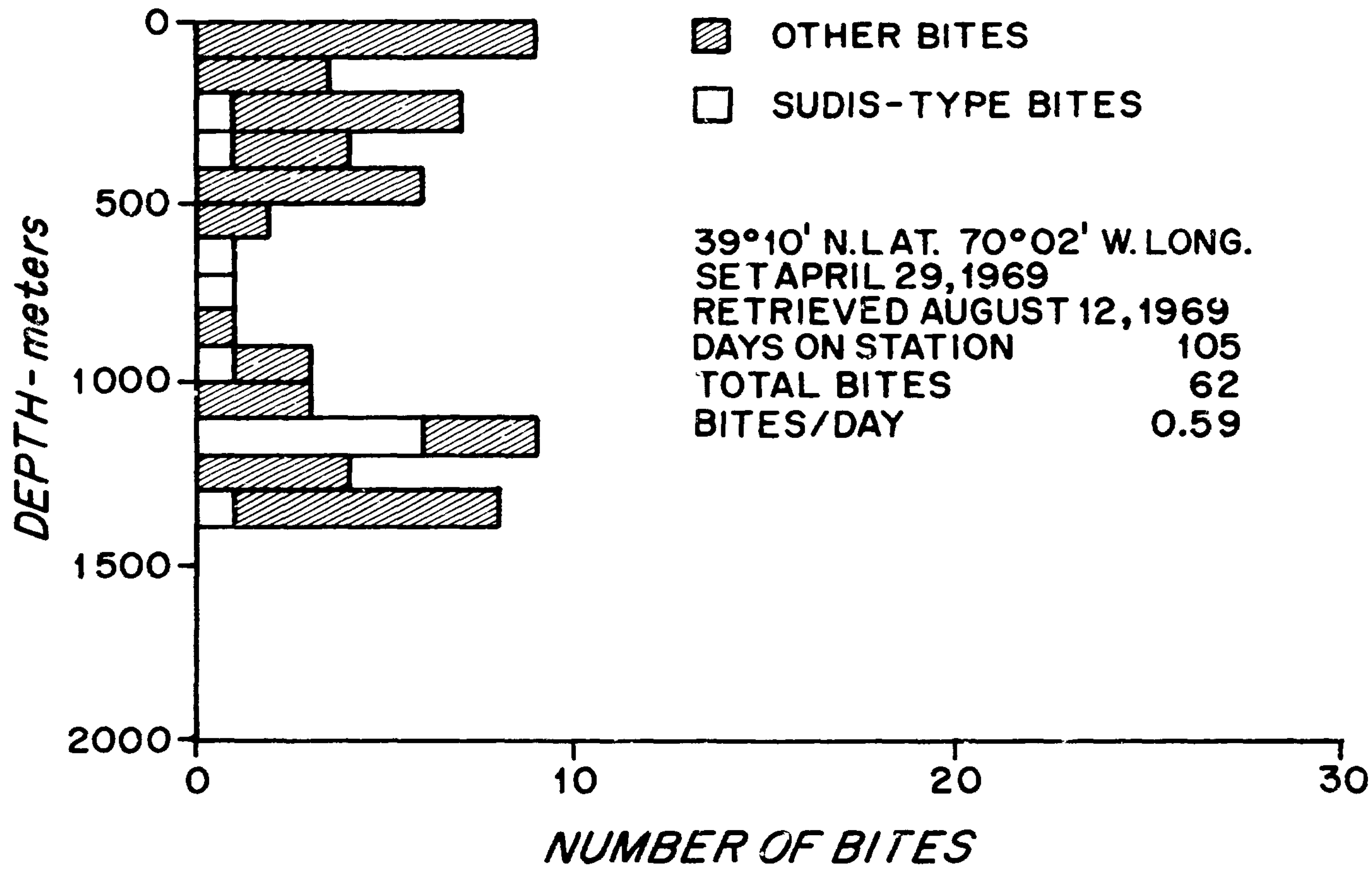

Figure 18. Fishbite vs. Depth
WHOI Moored Station #300

and the prevention of which may be regarded as the prime target in developing protective armor. The overall average rate of such bites at the two stations was 0.47 bites per mooring line day. Most of the bites were superficial but because they are the kind attributed to sharks, a potential for serious damage is indicated. In fact, four (4) gashes in the polyethylene jacket of mooring #298 laid bare the underlying steel wire. At moored station #300, there was one such incident.

Another moored station (#315) was set to test the effectiveness of armor on nylon rope. Because it was cheap and readily available, polyethylene water pipe of nominal 13 mm I.D. was used. 30 m lengths were laboriously snaked onto a mooring cable, and coupled together by short lengths of the same 19 mm I.D. pipe used in the telescoping section of each 250-m shot. The armored portion of the mooring extended to a depth of 1500 meters.

The mooring was set at Site "L" (34° 00'N, 70° 00'W) in August 1969. Two months later the buoy was not on station. The lower portion of the mooring line was retrieved by means of a secondary recovery system, and was found to have been severed at a depth of 720 meters. The sharp, planar cut was totally unlike any fishbite previously observed; because another mooring 500 km away had been molested at about the same time, piracy was suspected.

Fifty-nine bites were found on the recoverd portion of the armor, all of which were below the zone of most severe attack (Figure 19). None of these penetrated the wall of the pipe, but many were severe enough to have done substantial damage to an unarmored rope. Not all of the couplings between lengths of pipe held, so the performance of the

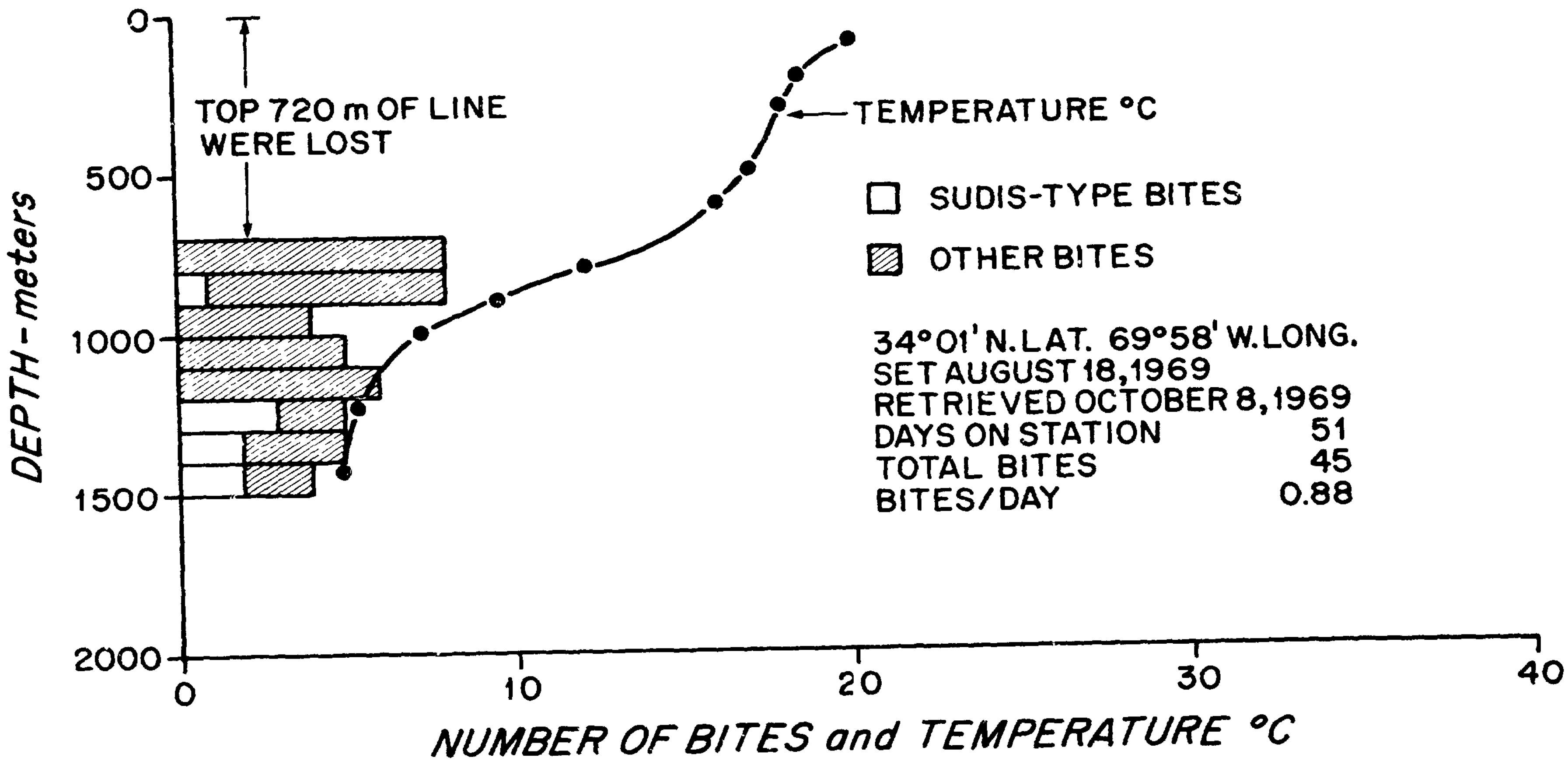

Figure 19. Fishbite vs. Depth
WHOI Moored Station #315

telescoping section was not clearly established.

A more effective armor material and a better method of application were sought. It was learned that rope could be passed through the center of a crosshead extruding die, and that thermoplastic armor could be "tubed" on, so that its inner wall remained smooth, and did not stick to the rope. After a preliminary screening of several candidate materials, polycarbonate resin was chosen for the next trial. Four 500 m lengths were manufactured, and installed in W.H.O.I. moored Station #341 at Site "L" (34° N Lat., 70° W Long.) in June 1970.

Before the mooring was launched, it was observed that a large number of fine cracks had formed on the inside wall of the polycarbonate armor. At the time of recovery two months later, the armor was severely crazed, but intact except for one break near the top of the first shot. During hauling over the sheaves and onto the winch drum it shattered into small pieces. Later, it was established in laboratory tests that crazing of the polycarbonate occurred whenever it was in close contact with the polyester rope. Presumably, some yarn treatment or lubricant is responsible. It must be isolated and eliminated before it will be feasible to use polycarbonate armor on synthetic-fiber rope.

In spite of its deteriorated condition, the polycarbonate armor withstood fishbite very well. In all, 178 bites were recorded (Figure 20). None penetrated the 1.3 mm wall.

Pending a solution to the problem of polyester-polycarbonate interaction, an armor of rigid polyvinyl chloride (PVC) was specified, and four 500-m shots were installed in W.H.O.I. moored Station #355, also at Site "L" in October 1970 (Figure 21). The PVC withstood

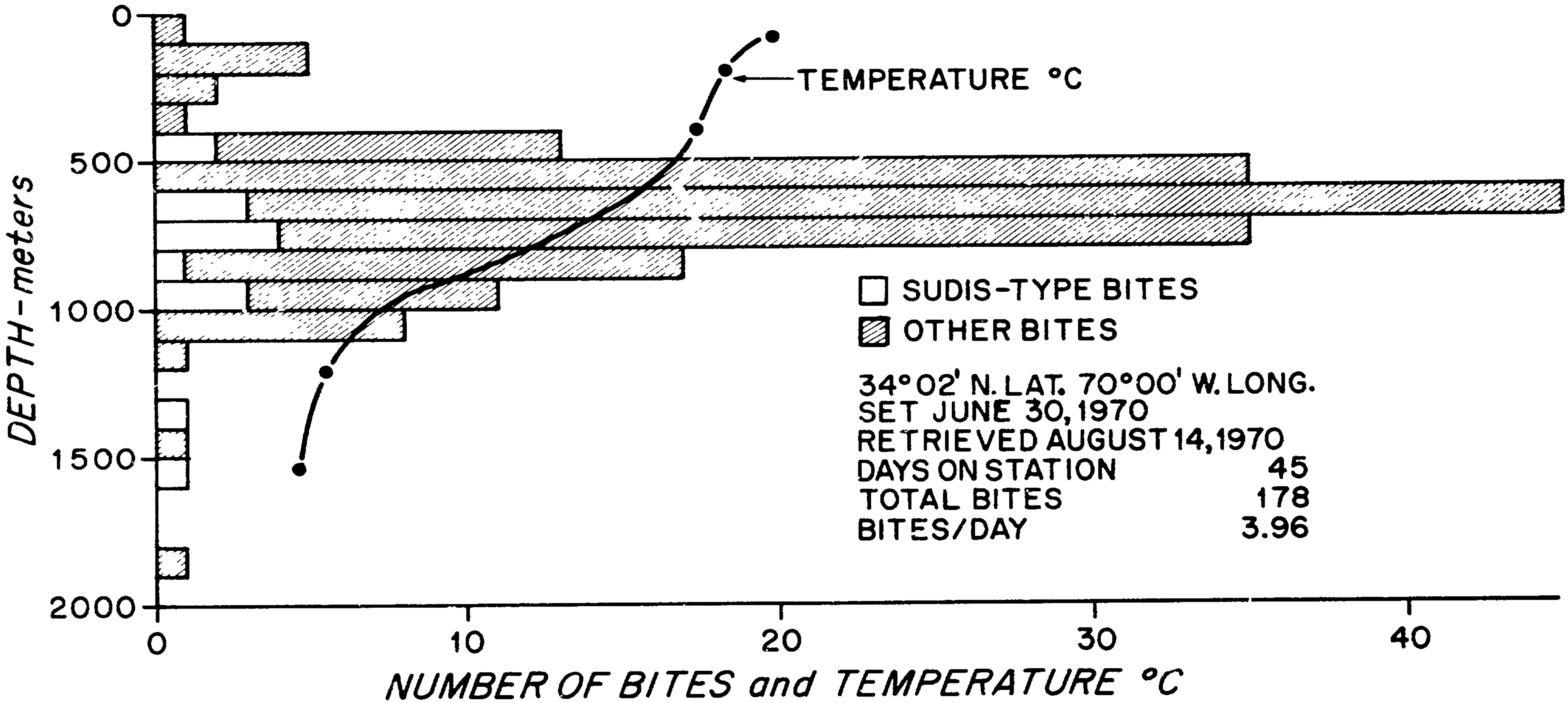

Figure 20. Fishbite vs. Depth
WHOI Moored Station #341

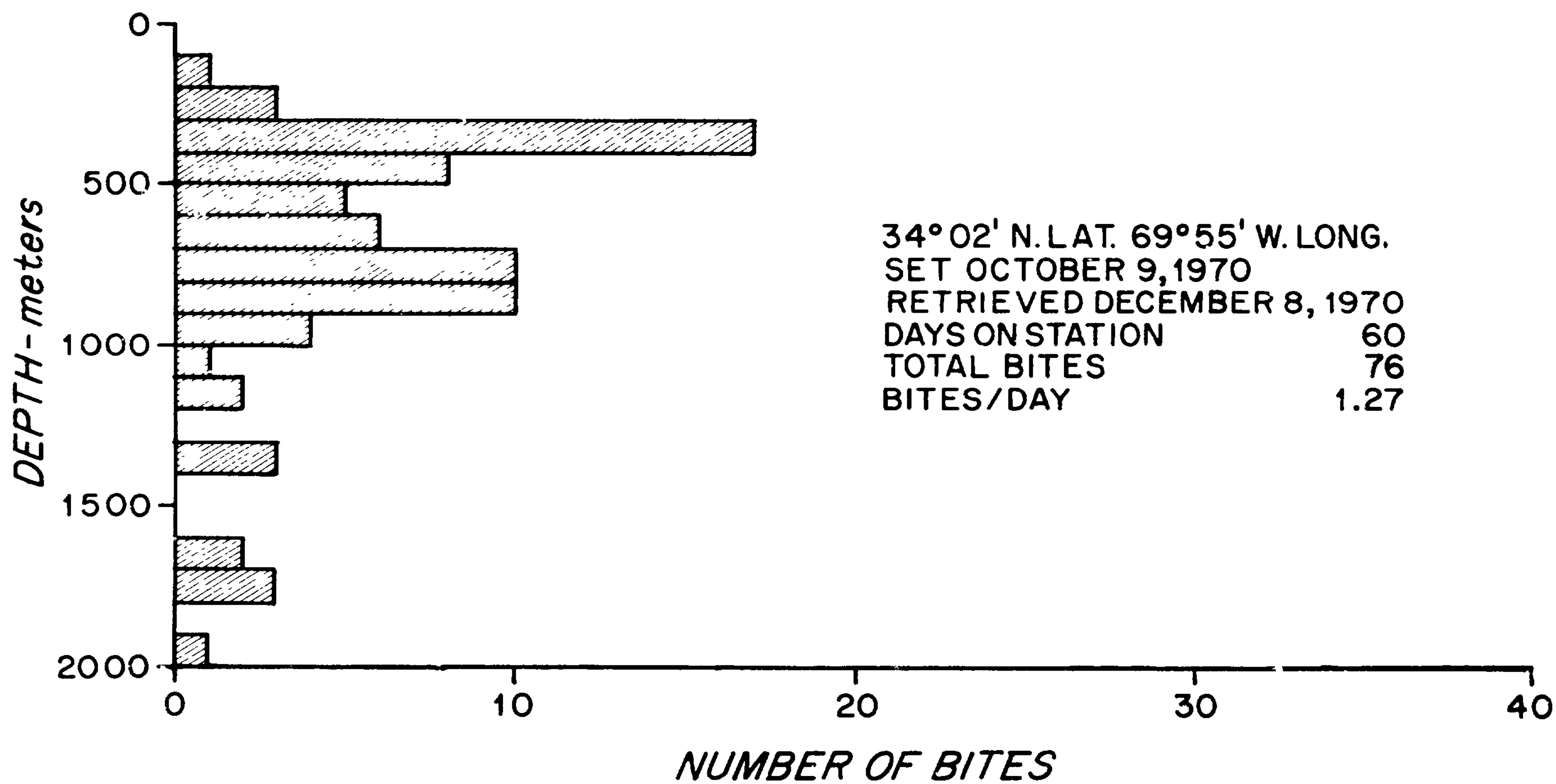

Figure 21. Fis' ite vs. Depth
WHOI Moored Station #355

fishbite, but cracked severely. The cracking appears to have been due to brittle transition at low temperature, rather than chemical interaction.

Because of the continuing need for improved protection of wire ropes as well as synthetic-fiber ropes, a polycarbonate jacket was applied to four 500-m shots of 8 mm 3x19 wire rope, and deployed in W.H.O.I. moored Station #401, again at Site "L", in August 1971. The jacket did not crack in laboratory tests, or in storage on reels before use, but upon recovery of the mooring in October 1971, this jacket too, was found to be severely cracked.

Field Trails

In an attempt to bridge the gap between laboratory tests and deep-sea exposures, armor samples were exposed to live sharks under a variety of observable conditions. The specimens were shrouded in fish or meat, much as SNODGRASS and GILBERT (1967) baited their gnathodynamometer.

Two sharp-nosed sharks (Isurius oxyrhincus) off San Juan, Puerto Rico, circled baited samples in a tensile frame(Figure 22) for hours without touching them, yet one of them took a baited hook as soon as it was offered. Two captive lemon sharks (Negaprion brevirostris) at La Parguera, Puerto Rico, were totally indifferent to all offerings. A small tiger shark (Galeocerdo cuvieri), caught on a hand line off La Parguera, was induced to bite a few samples while struggling alongside the boat. The results were spectacular, but difficult to interpret.

Several blue sharks (Prionace glauca) off the southern coast of Massachusetts proved more cooperative, voluntarily biting a number of baited specimens. Polyethylene samples were severely damaged; even the polycarbonate

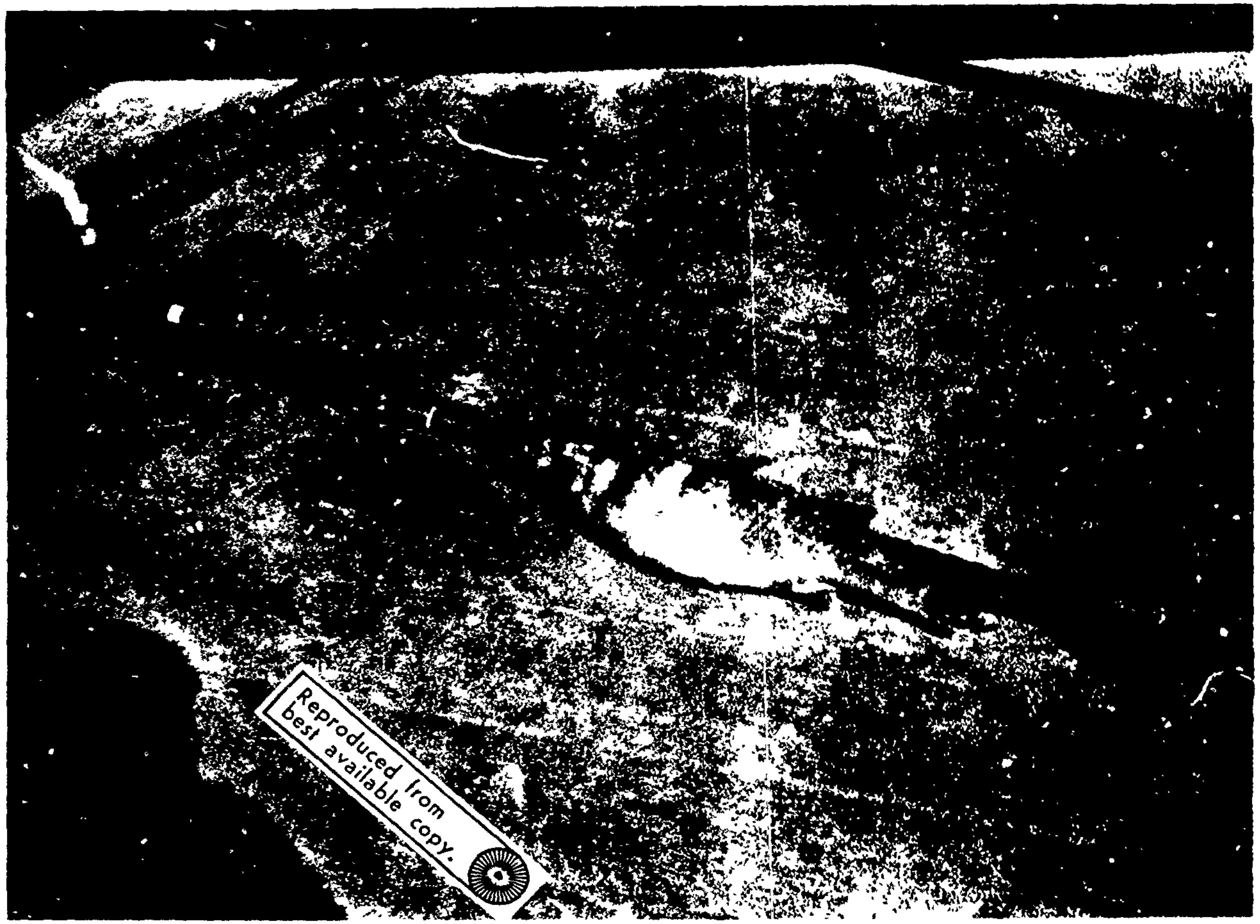

Figure 22. Baited Rope Specimen in Tensile Frame.

tubing, which withstood all attacks in the deep-sea trials of armored mooring lines, was readily punctured. These results supported our earlier hypothesis that sharks, attacking a tasteless object such as a mooring line, do not exert their full biting capability.

Conclusions

1. A study of the biting capabilities and behavior patterns of marine organisms led to the conclusion that attention should be centered upon sharks as the organisms most likely to be involved in bite damage to mooring lines.

2. Most of the marks left by the teeth of marine organisms on mooring line covers were superficial, indicating a light attack. However, such attacks could represent a serious hazard to unprotected lines under tension.

3. Laboratory test methods have been developed for preliminiary evaluation of materials for use as mooring line armor against fishbite.

4. Results of screening tests indicate that, when all properties are considered, the most suitable fishbite armor material will be a thermoplastic.

5. With reference to their resistance to cutting, stabbing, and snagging tests, thermoplastics tested fell into three categories:

   a. Materials which were flexible but were penetrated rather easily (polyethylene, polypropylene, polyurethane, nylon 12).

   b. Materials which had high resistance to cutting and stabbing but which were stiff and had a tendency to fracture (polycarbonate, polyvinyl chloride, polysulfone).

   c. An intermediate group, less rigid, less susceptible to cracking, intermediate in cut and stab resistance, (Nylon 6/6, cellulose acetate-butyrate)

6. Tension greatly reduces the resistance of materials to cutting, therefore, in designing armored moorings it is essential that the protective cover be isolated from tensile stress.

7. Data from moored stations indicate that biting is a common occurrence in warm water and, on the average, should be expected to occur every day or two.

8. Results from moored buoy stations indicate that plastic armor such as polycarbonate or polyvinyl chloride with a wall thickness of 1.7 mm will provide adequate fishbite protection for a 13 mm diameter nylon line, if brittle fractures can be eliminated.

Acknowledgements

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APPENDIX

TABLE 1 thru TABLE 8

Table 1

Effect of Tension on Force Required
to Cut Plaited Nylon Rope, 14.5 mm diameter.

Tension on Specimen Newtons	Cutting Force - Newtons Ave.
0	160
445	57
2220	22
7120	20
10680	5.6
14220	2.8

Table 2

Cut Resistance of Armor Materials -
Dry vs Wet Test

Material	ID cm	Wall mm	Force to Cut		
			Newtons-Ave.		% of Dry
			Dry	Wet	
Polyethylene	1.3	1.65	173	138	80
*Polyurethane	1.3	1.60	147	111	75
Nylon 12	1.3	1.78	272	316	116
Polypropylene	1.3	1.71	285	294	104
Cellulose acetate-butyrate	1.3	1.50	552	538	98
Nylon 6/6	1.3	1.78	557	547	98
Polyvinyl chloride	1.3	1.70	614	574	94
Polycarbonate	1.3	1.65	654	685	105
**Polysulfone	0.9	1.75	827	830	100

* Shore 65A
**9.5 mm ID

Table 3

Effect of Tension on Force Required
to Cut Polyethylene Pipe, 13 mm ID, 1.65 mm Wall

Tension Newtons	Cutting Force Newtons
0	174
222	156
445	102
668	80
890	58

Table 4

Effect of Tension on Cut Strength
of Armored Lines

Sample	Tension on Line Newtons	Cutting Force Newtons
13-mm braided nylon	4450	156
rope, polyethylene armor	8900	156
not bonded to line.	13350	165
Dacron "Nolaro",	890	84
approx. 13-mm dia.,	3560	22
polyurethane	14202	3.6
bonded to line.		

Table 5

Force Required to Pierce Various
Plastic Materials Using a Single
Steel Saw Tooth or Shark's Tooth

Material 13 mm ID Tube	Wall Thickness mm	Force to Pierce, Newtons	
		Saw Tooth	Shark Tooth
* Polyurethane	1.60	-	27
Polyethylene	1.65	85	58
Nylon 12	1.55	89	58
Cellulose acetate-butyrate	1.78	125	76
Polypropylene	1.70	147	94
Nylon 6/6	1.78	214	134
Polyvinyl chloride	1.70	209	147
Polycarbonate	1.65	236	192
**Polysulfone	1.75	348	227

* 65 Shore A
** 9.5 mm I.D.

Table 6

Force on **Teeth Required to Pierce
Polyethylene Pipe *vs Angle
of Teeth in Snag Test

Tooth Angle °	Force to Pierce Newtons
30	54
45	54
50	54
55	24
60	24
65	29
70	54
75	90
80	121
85	121
90	121

*Polyethylene pipe 13 mm ID.
1.65 mm wall thickness
**Two steel saw teeth

Table 7

Snag Tests on Armor Materials
Using Two Steel Saw Teeth

Material 1.3 cm ID Tubes	Wall Thickness mm	Force - Newtons Vertical on Tooth F_V	Horizontal to Move F_M	Ratio FM/FV
Polyethylene	1.65	10.7	98	9.2
*Polyurethane	1.60	10.7	45	4.2
Nylon 12		10.7	26	2.4
Polypropylene	1.70	36	200	5.6
Cellulose acetate-butyrate	1.78	36	192	5.3
Polycarbonate	1.65	63	178	2.8
Polyvinylchloride	1.70	55	147	2.7
**Polysulfone	1.75	80	209	2.6

*65 Shore A
** 9.5 mm ID

Table 8

Snag Tests Using Single Tooth Parallel to Specimen Axis

Armor Material 13 mm ID Tube	Wall Thickness - mm	Maximum Force on Tooth Without Piercing - Newtons	
		Saw Tooth	Shark Tooth
*Polyurethane	1.60	24	11
Nylon 12	1.55	36	36
Polyethylene	1.65	45	36
Polypropylene	1.70	63	54
Cellulose acetate-butyrate	1.78	63	54
Nylon 6/6	1.78	120	80
Polyvinylchloride	1.70	120	X
Polycarbonate	1.65	187+	X
**Polysulfone	1.75	187+	X

X-Shark tooth broke under forces needed to pierce these specimens.

*65 Shore A
**9.5 mm ID