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TRAWL CABLE CORROSION

Robert D. Malloch
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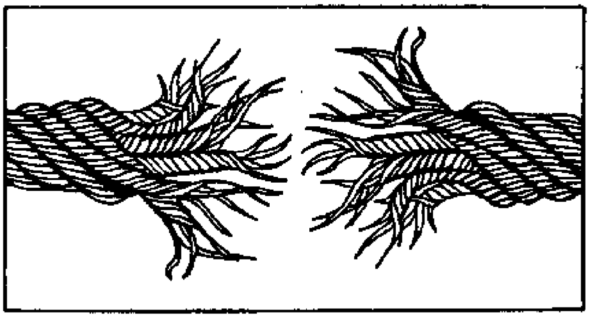

OREGON STATE UNIVERSITY
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AGRICULTURAL EXPERIMENT STATION
Special Report 520

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authors

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acknowledgment

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ABSTRACT

Pacific Northwest trawl fishermen spend an estimated $625,000 every year to replace corroded trawl cable. If the Pacific Northwest shrimp fleet is included, the yearly cost greatly exceeds one million dollars. Fishermen could save hundreds of thousands of dollars and increase the net return to the individual fisherman if they could extend the life of their trawl cables by 25 percent.

This project analyzed the nature of trawl cable corrosion on Oregon coastal trawlers to evaluate the feasibility of corrosion control. The analysis leads to a detailed discussion of possible future experiments designed to accurately determine the amount and type of protection needed. This report also provides a discussion of wire rope and general corrosion principles.

The corrosion analysis is based on a series of tests conducted on corroded trawl cable that Oregon trawl fishermen donated. Samples of used trawl cable were tested with regard to decreased breaking strength, weight loss and wire diameter reduction. These results, compared with results obtained from comparable new trawl cable, yielded the following conclusions:

1. Used wire rope is significantly lighter, has a significantly smaller wire diameter and has a significantly reduced breaking strength than new wire rope.

2. Trawl cable attached to bare steel trawl doors shows all of the above effects to a significantly greater extent near metal doors than 10 fathoms away.

These results lead to the hypothesis that galvanic corrosion decreases the trawl cable life and, in particular, that trawl cable galvanically protects metal trawl doors.

The report suggests that sacrificial metal protection and/or electrical isolation between trawl cable and metal doors will most likely protect the cable, and proposes a series of experiments to determine accurately the need and usefulness for each type of protection.

INTRODUCTION

About 250 trawlers from Washington, Oregon and Northern California drag the ocean bottom for soles and other commercially valuable bottom fish. These trawlers range from about 40 to 90 feet in length, with the vast majority between 50 and 80 feet. Yearly upkeep costs on such a boat may be considerable and are a large factor in determining the profit a fisherman earns. It is understandable, then, that fishermen investigate various ways of reducing yearly maintenance costs. Extending the life of trawl cables is one consideration.

Trawl cables are wire ropes (warps) that connect the boat with the trawl net being dragged across the bottom. On a typical run, fishermen deploy 100 to 150 fathoms of warp. A 50-foot dragger fishes approximately 120 days annually, while some larger draggers lengthen their seasons to 150 days a year. The maximum life expectancy of a warp is 18 months, and it is not uncommon to replace it every year. This comes to an annual cost for wire rope of $2,500 to $3,000 per boat. Some of the larger draggers estimate yearly costs of between $4,000 and $5,000. Using the conservative yearly cost of $2,500 and considering that the Pacific Northwest trawler fleet hosts 250 boats, then the industry spends $625,000 for wire rope alone in one year. If one also considers the 250 shrimp boats with similar deployment characteristics, Pacific Northwest fishermen spend well over one million dollars on wire rope annually.

Increasing the life of warps by 25 percent would save Northwest trawlers $300,000. This potential increase in warp life has been discussed among several fishermen in the area around Newport, Oregon, and has led to the involvement of Oregon State University as a research agency.

The pattern of warp wear is almost identical regardless of boat size, amount of warp deployed, or warp manufacturer. The 25 to 50 fathoms of warp closest to the trawl doors (Fig. 1) appears to corrode. Although trawlers generally use galvinized wire ropes in their warps to combat corrosion, for this area of apparent corrosion the galvanizing

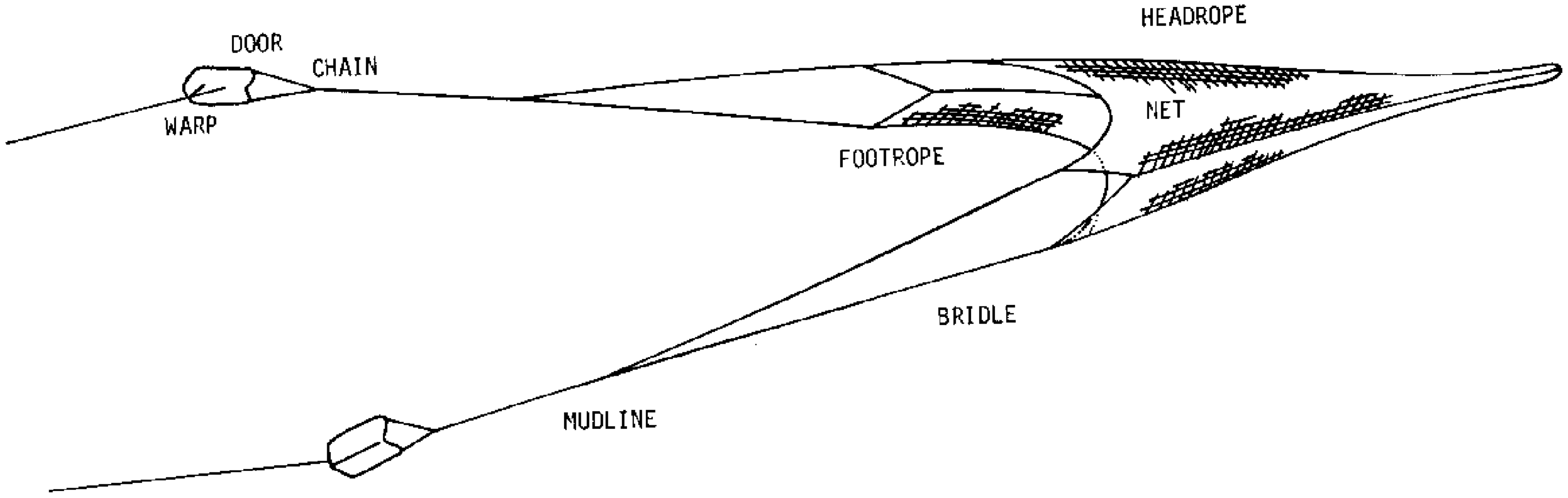

Fig. 1. Typical net deployment of an Oregon coast trawler.

is gone after only a few days of use. As fishermen continue to use the warp, its diameter decreases, its hemp core frays, the diameters of individual wires decreases, and it becomes much less flexible. These signs suggest that the warp has lost part of its strength. For this reason, fishermen remove a 25-fathom section of warp closest to the trawl doors whenever deterioration reaches an unacceptable level. Fishermen base this unacceptable level on past experience and observations, such as a decrease in total warp diameter, broken strands, excessive rust, and decrease in springiness. Cutting back 25 fathoms is convenient, since the fishermen mark their warps every 25 fathoms to help them determine how much cable has been deployed.

Fishermen cut back trawl warp once or twice a fishing season. At the end of the season, they might switch the entire warp end-to-end. That is, they will attach the previously protected end of the warp, seldom wound off the winch, to the trawl doors. This practice utilizes the full length of the warp and extends its life. After the newly exposed end has been cut back once or twice, fishermen discard the entire warp.

Once installed on the boat, trawl warps receive very little maintenance. Fishermen periodically examine their warps to determine if the warps should be cut back. Other than that, they only grease the warp occasionally. Wire ropes used for trawl warps have fiber cores, which provide resiliency at times of shock loading. The most commonly used fiber, hemp, comes from the factory saturated with grease. The grease primarily lubricates, but also offers some protection against corrosion. During use, however, seawater displaces the grease in the hemp core and the grease becomes ineffective. For this reason, most fishermen periodically regrease the cores of their warps. They do this by soaking the warp with a petroleum product much like pinion grease cut with a solvent.

Steel trawl doors are commonly used on the Oregon coast. Some fishermen attach a zinc anode to decrease warp corrosion.

Most Oregon fishermen use Improved Plow Steel, 6 x 19, fiber core, galvanized wire rope (Appendix A). The 6 x 19 (which refers to the number of strands in the rope and the number of wires in the strand, respectively) has greater flexibility than does the less expensive 6 x 7 rope. Fiber core is almost a necessity, as the trawl doors drag along the bottom in a slow "skipping" motion and places a shock load on the wire rope. Each time the doors contact the bottom, a shock load results.

Fishermen today prefer either Korean or Japanese wire rope. Although slightly lower in quality than American wire rope, it costs appreciably less. Because American-made wire rope shows no substantial increase in life over foreign rope, fishermen generally feel it is not worth the extra cost. Table 1 presents a price comparison between foreign and domestic wire ropes based on local retail values.

Diameter (in.)	Galvanization	Country	Cost (¢/ft)
1/2	yes	U.S.A.	59
1/2	no	U.S.A.	45
1/2	no	Japan	30
9/16	yes	Korea	26
5/8	yes	Korea	29

Table 1. Typical retail cost of domestic and foreign made wire rope (Fall, 1977).

ANALYSIS AND NATURE OF TRAWL CABLE CORROSION ON THE OREGON COAST

According to La Que (1975), of the eight forms of corrosion discussed in Appendix B, four are likely found in seawater. These four are galvanic or two-metal corrosion, pitting, crevice corrosion, and stress corrosion. Table 2 compares the manifestations and favorable environments for these four forms.

The nature of trawl cable use on the Oregon coast would indicate that neither pitting nor crevice corrosion likely occurs. Because pitting requires stagnant conditions, it is not suspect. Crevice corrosion is unlikely due to boat speed (2 to 3 knots) and the subsequent flushing action.

Galvanic corrosion, on the other hand, likely exists. Warps made from wire ropes contain iron with various metals used as alloys. These metals have varying standard electrode potentials and continuously contact each other electrically. The only element missing is a conductive medium, and fishermen meet this requirement when they lower warps into the ocean. More importantly, many fishermen attach their warp directly to steel doors, which are most often galvanically unprotected. Thus, the lower lengths of a warp become anodic and galvanically protect the steel doors just as a sacrificial metal would.

The above analysis explains fishermen's observations quite well. Fishermen report the greatest corrosion in the 20 to 25 fathoms closest to the doors, even though they let out 100 to 150 fathoms on every tow. This is exactly what one would suspect if, in fact, the warp protects the doors.

Stress corrosion could be a factor in reducing the warp's strength. The two requirements for stress corrosion--a corrosive medium and tensile stress--both exist. If stress corrosion were present, it would tend to affect the warp along its entire exposed length. However, accelerated galvanic corrosion close to the doors could enhance stress corrosion, and compound the corrosion problem.

Corrosion	Manisfestation	Favorable Environment
Galvanic	General deposition of material on cathodic metal surface	Conductive solution
Pitting	Small, sometimes deep its over surface exposed metal	Stagnant water
Crevice	Localized corrosion at joints, gaskets, etc.	Localized stagnant water caused by geometry of objects
Stress	Fine cracks running through material	Simultaneous presence of tensile stress and corrosive medium

Table 2. Comparisons of kinds of corrosion likely to occur in seawater.

Experimental evidence

To determine if corrosion is a problem, and, if possible, the type of corrosion present, a series of experiments was conducted. The experimental design consisted of testing new and used wire rope samples for (1) breaking strength, (2) weight loss, and (3) wire diameter reduction.

One sample of cable was 1/2-inch 6 x 19 fiber core wire rope used for two years on an Oregon shrimp boat. Its total time in the water was estimated at about 3,000 hours, and it was attached to wooden trawl doors. The second sample was 7/16-inch diameter 6 x 7 fiber core wire rope that an Oregon trawler used for about 1,500 hours. This second sample was attached to bare steel trawl doors. These doors had small zinc anodes attached, but it was felt that the anodes were unimportant because of their small size. Both wire rope samples were galvenized. Tensile results are tabulated in Appendix C; weight data in Appendix D; and wire diameter data in Appendix E.

For the 1/2-inch 6 x 19 warp, used warp was taken at four different distances from the doors for testing: from the point of attachment to the wooden doors, 10 fathoms from the doors, 20 fathoms from the doors and 40 fathoms from the doors. Comparable new rope was used as a control.

Samples were taken from only two positions on the used 7/16-inch 6 x 7 warp because the warp was only 10 fathoms long. Samples were taken from the point of attachment to the metal doors, and from 10 fathoms away. Again, comparable new rope was used as a control.

Breaking tests were conducted at the Oregon State University Department of Civil Engineering. For each position on both of the used ropes, and for both pieces of new rope, three 3-foot long samples were tested. In preparation for tensile testing, each sample was unwound for a 6-inch length at each end. These ends were placed in a conical sleeve and secured with epoxy. The sample was then placed in a Baldwin-Tate-Emery tensile testing machine with the sleeves fitting into chucks at the top and bottom. The machine stressed the sample to failure while automatically noting the breaking strength. Data were then analyzed using standard analysis of variance techniques, followed by proper contrasts (Neter and Wasserman 1976).

Weight loss due to corrosion was determined by taking three 6-inch sections for each of the warp positions. The sections were immersed in 37 percent hydrochloric acid for one and one-half minutes to remove rust, and then briefly immersed in 15 normal sodium hydroxide to stop the acid's action. Then the samples were rinsed in water, dried for 24 hours at 105°C, and weighed.

Following the weight reduction test, diameter reduction data were collected from the same samples. Thirty diameter readings were taken for each sample. Diameter measurements were taken randomly along the lengths of three different wires of three different strands. In this way, it was hoped that any oversight due to not measuring wire near the core would be eliminated.

Conclusions

As expected, there were highly significant differences between new and used rope in weight and wire diameter regardless of whether rope was attached to wooden or metal doors. This indicates that highly significant weight losses and wire diameter reductions occurred during the 1,500 hours that 7/16-inch rope was in the water while attached to metal doors, and during the approximately 3,000 hours the 1/2-inch rope was used attached to wooden doors. Corrosion was present, but the tests tell nothing about the nature of that corrosion.

According to the analysis, no significant difference existed for either weight loss or wire diameter reduction between the positions along the 1/2-inch rope attached to wooden doors. That is, corrosion tended to be uniform. However, for the 7/16-inch wire rope attached to metal doors, there was a highly significant difference for both weight loss and wire diameter reduction between the door end and 10 fathoms from the door. Corrosion tended to be greater near the door. These findings indicate a difference in corrosion patterns depending on whether wooden or metal doors were attached to the wire rope. When metal doors were used, it seems reasonable at this time to postulate that galvanic corrosion was present, and that the wire rope became anodic and cathodically protected the metal doors.

Tensile tests were conducted in conjunction with weight loss and diameter reduction tests in order to further clarify the form and extent of corrosion. These tests were important, since a reduction in tensile strength is the ultimate manifestation of corrosion. For the 1/2-inch rope attached to wooden doors, three samples were tested for each of the four warp positions. Three samples of new rope were also tested. Unfortunately, preparation of the samples was not consistent and the results are therefore suspect.

Unlike the weight loss and diameter reduction results, the tests indicated no significant difference in tensile strength between new and used samples, or among samples taken at different positions along the warp. This is due primarily to inconsistencies in the tensile test method. It could be assumed that proper results would have shown significant reduction in breaking strength between new and used rope but with no difference along the length of the warp. However, such an assumption cannot be verified or rejected with the data at hand.

Fortunately, when the 7/16-inch rope that had been attached to metal doors was tested, the tests were valid because the method of sample preparation had been clarified. Three samples of new rope and three samples of used warp from the door end, and three samples from 10 fathoms back from the doors were tested. Results indicated a statistically significant difference between new and used rope, no statistically significant difference between samples taken from the door end and samples 10 fathoms back from the door. It should be noted, though, that a difference between the door end and 10 fathoms back was observed. The mean breaking strength of warp taken from the door end was 15,387 pounds, as compared to a mean of 16,000 pounds ten fathoms back. These are significantly lower than new rope, which averaged 20,053 pounds. If more samples had been tested, a significant difference would have been likely observed between the door end samples and those taken 10 fathoms back. This statement is based on the observed differences between the samples, and on the closeness of the results to showing such a significant difference.

The reliable tensile tests tended to support the hypothesis that a greater rate of corrosion existed closer to the doors than farther back along the warp. This is even more conclusive when considering the results from the weight loss and strand diameter reduction tests as well.

It should be noted that no indications of stress corrosion were observed. There were broken strands on both warps, but the breaks tended to be random and infrequent. It is conceivable that this was due to factors other than stress corrosion, as a random visual examination turned up no signs of wire cracks. Future tests that could possibly be conducted for stress corrosion will be discussed in the next section.

A visual core examination discovered very little difference between core from used rope and core from new rope. There was a tendency for used core to have impressions in it from adjacent strands, but little compacting and no breaks, cuts or fraying were observed.

SUGGESTIONS FOR FUTURE WORK

There is little doubt that the wire rope used for trawl lines on the Oregon coast corrodes to a significant extent. Whether this corrosion causes a significant reduction in strength is still unclear and should be further investigated. The could best be done in a manner similar to the method described in this report. Cooperating fishermen could donate discarded warp and appropriate sections could then be tensile tested. The results would be statistically compared to unused samples of the same wire rope to analyze strength reduction.

It is of course desirable to use as large a sample as possible. In statistical terms this increases the degrees of freedom for error and reduces variance. A large sample size would minimize differences found within the same treatment (i.e., position on the warp), which caused some problems with the analysis reported in the last section. Rather than using only three samples at each position, four, or even better, five would increase the precision of the experiments. Also, increasing the number of warps subjected to this testing would serve the same purpose.

It seems likely that the warp closest to the metal doors corrodes at a higher rate than along the rest of its length. Fishermen's observations strongly indicate this as do the experiments reported earlier. This suggests that galvanic corrosion is at work, but more importantly, that the warp galvanically protects the metal doors.

The tensile test experiment previously described would give a good statistical indication of the hypothesis' soundness. A further, more controlled experiment, would involve immersing the samples with and without comparable attached metal doors into seawater. If samples were immersed in a tidal zone, perhaps at OSU Marine Science Center in Newport, tidal movement would be comparable to towing velocities although salinity would be lower. A continual immersion test such as this could last for 60 to 70 days, thus matching the number of hours that fishermen use a typical section of warp located near metal doors. Two 12-foot lengths of rope attached to simulated metal doors and two 12-foot lengths of rope not attached to metal should be sufficient. For comparison, it would also be desirable to have an equivalent amount of unused rope. This would yield six 3-foot samples for each treatment for tensile testing as well as two 3-foot samples for each treatment for other tests, such as weight loss and diameter reduction.

Stress corrosion, a possible form of corrosion, was not adequately considered in the experiments performed for this report. The suggested continuous immersion test could be used, or modified, to determine if stress corrosion exists. La Que (1975) and Compton (1970) suggested a dead weight test and emphasized the importance of testing in seawater, if seawater is the relevant medium. Continuous immersion tests meet both of these criteria. If lengths of rope used in these tests attach weights comparable to the tensile stress encountered under towing, a careful examination for cracks would indicate the presence or absence of stress corrosion.

Tensile tests are costly. A ballpark figure for each test would be about $15. It immediately becomes apparent that extensive testing of fishermen's warp as well as samples from a dead weight immersion test could become expensive. As with all studies a decision must be made balancing economy with data.

One thought should be kept in mind at all times with regard to this report and future studies, though. The ultimate function of trawl warp is to transmit without breaking the force necessary to move a net along the ocean bottom. Other tests are important and necessary, but they eventually must relate to maintaining the tensile strength of wire rope used as trawl warp for as long a time as possible. Tensile tests are probably the single most important means of evaluating performance.

Once the mode of corrosion has been established, it becomes necessary to determine the practicality of protection. With all evidence indicating that galvanic corrosion exists, and, in particular, that the warp galvanically protects the metal doors, the remainder of this report will consider the galvanic testing and various protection strategies.

GALVANIC CORROSION, TESTING AND PROTECTION

The intensity of galvanic corrosion is perhaps the first useful information desired. This information in critical when considering sacrificial metal or impressed current protection.

Several methods exist to determine intenwity of corrosion. The most direct would be determining the weight loss of corroded specimens. An expanded dead weight immersion test described earlier in this section would yield this data. This data can be compared to data from a control experiment and the actual currents and current densities approximated.

LaQue (1975) describes a control experiment in a section entitled "Galvanic Corrosion Testing." In consists of immersing several specimens in seawater for several days. Each specimen receives a fixed and constant amount of current over the duration of the test. This technique shows relationships between applied current, potential, and corrosion as measured by weight loss. Weight losses noted for specimens with no applied current but attached to simulated metal doors can be compared to weight losses from the control experiment. The magnitude of the current flow between warp and doors can be accurately made.

A second method of determining current flow is actually measuring the current in a laboratory. A wire rope sample could be connected to a small metal door by means of a milliameter and immersed in a seawater bath. Current between the two can be directly measured. If time and finances permit, it would be desirable to use both methods and correlate the results.

Protection against corrosion now becomes of prime importance. Metal can be protected from galvanic corrosion in one of five basic ways: Modification of environment, modification of material, impressed current protection, sacrificial metal protection, and electrical isolation. Only three of these are realistic in this case.

It is unlikely that either environment or material modification would be fruitful for Oregon fishermen. The environment--the ocean--is well established and does not lend itself to large scale changes, and though better materials are available, they cost appreciably more than any benefits derived. The task, therefore, seems to be protecting the warp, either galvanically or by isolation.

Impressed current protection, described in the corrosion section, is probably impractical. It would require forcing an electric current along the entire length of deployed warp or establishing a remote underwater impressed current device. The amount of current needed would already be determined, had current flow been established by the previously mentioned tests. Supplying this current, however, would probably require more effort and expense than would be worthwhile.

The most appropriate form of protection seems to be sacrificial metal protection. The concept of using a sacrificial metal is described in Appendix B under the section on corrosion. The three metals most commonly used as the mode are aluminum, magnesium, and zinc, with zinc used most frequently. Table 3 summarizes the relative performances of these metals. Again with a known

Anode material	Ampere-hours per pound		Actual consumption	Anode efficiency
	Theoretical	Actual	(lb/A-year)	(%)
Aluminum	1352	675	12	50[a]
Magnesium	997	600	14	60
Zinc	372	335	25	95[b]

[a] Can be increased to 90 percent by alloying with mercury.

[b] In seawater.

Table 3. Current outputs per pound of galvanic anodes (La Que 1975).

magnitude of current flow derived from previous experiments, the amount of zinc per surface area of warp can be calculated. Properly sized pieces of zinc can then be placed in contact with wire rope specimens in a laboratory set-up and weight loss of both zinc and rope noted when the rope attaches to metal. Several tests with varying amounts of zinc should yield useful information on the quantity of zinc necessary to protect a given length of warp. This information should serve as a check on the above calculation. It should be kept in mind that velocity increases corrosion rates (Nachman and Duffy 1974). Therefore, if possible, such laboratory tests should be conducted in seawater moving with a velocity of 2 to 3 knots.

Placing the zinc anodes on the warp is a problem to consider. It is quite important that the anodes do not interfere with the warp's movement over pulleys and the like. As the warp bends while moving over a pulley, and while stored on a circular drum, the anode cannot be attached to the warp in a way that renders the warp inflexible. Perhaps a zinc anode could be cast onto a wire, and this wire woven into the rope.

Adequately protecting metal doors with zinc anodes might be sufficient to reduce warp corrosion. If, in fact, the warp galvanically protects these doors, it stands to reason that already protected doors would draw less current from the warp. This could be tested in two ways. In the first way, wire rope samples attached to metal protected with zinc anodes could be added to the dead weight immersion test. Second, test samples of wire rope could be subjected to the same conditions as described above in the laboratory, except that attached zinc would adequately protect the metal. Measured currents and weight losses would indicate the adequacy of the treatments.

Electrical isolation is the final means of protecting the warp closest to the metal doors. This would simply break the electrical contact between warp and doors. The major prerequisite of insulator would be that it is as strong as the warp, and able to handle periodic shock loading. Ceramic isolators, that utility companies use, might be considered as well as synthetic rope and certain plastics. Isolator effectiveness could be measured in the same way as protecting the metal doors. Samples isolated from their metal weights could be added to the dead weight immersion test and/or specimens in the laboratory tests could be similarly isolated from metal objects.

A valuable and long term effectiveness test of various protection strategies would require the assistance of cooperating fishermen. Various strategies would be employed under actual fishing conditions and evaluations made over several months to years. This might not be possible, however, as a fisherman must protect his interests and would be apprehensive concerning the well-being of his gear. This does not mean that experiments should not be investigated. On the contrary, the information would be the ultimate test of a protection strategy's usefulness.

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APPENDIX A
WIRE ROPE

Strands of wire wrapped in various ways around a core make up wire rope. Fisherment can buy both wire strands and core in several different forms, which provide varying strengths, durabilities, and flexibilities.

A basic material used in constructing wire rope is plow steel. Plow steel, a low carbon steel, is acceptable primarily for applications where corrosion and abrasion conditions are not severe. It tends to be relatively soft and of less strength and greater ductility than higher carbon steel. One higher carbon steel is commonly known as improved plow steel. As would be expected, improved plow steel is tougher and has greater tensile strength than normal plow steel, and is the most commonly used material in constructing wire strands. Extra improved plow steel, generally the highest grade of straight carbon steel, has a high carbon content, which gives it low ductility, greater toughness, and approximately 15 percent greater tensile strength than improved plow steel. Though it is recommended for severe conditions, its corrosion resistance differs little from either plow steel or improved plow steel.

In general, plow steel grade ropes are made from steel wire in the AISI 1050-1060 range, while higher strength ropes are in the AISI 1070-1090 range (Goodwin 1977). Table A-1 lists the basic composition of these steels.

Various other ferrous wires are available for more specialized applications. Traction steel is designed specifically for hoisting ropes on traction-type elevators. Iron with very low levels of carbon is used for sash cords, serving strands, and iron tiller ropes. Stainless steels are available for applications that require improved corrosion resistance. The most common stainless steel has 18 percent chromium and 8 percent nickel alloy. It pocesses similar mechanical properties to improved plow steel.

SAE #	AISI #	Carbon (% wt)	Manganese (% wt)	Phosphorus (% wt)	Sulfur (% wt)
1050	C1050	.48-.55	.60-.90	.040	.050
1052	C1052	.47-.55	1.20-1.50	.040	.050
1055	C1055	.50-.60	.60-.90	.040	.050
1060	C1060	.55-.65	.60-.90	.040	.050
1070	C1070	.65-.75	.60-.90	.040	.050
1074	C1074	.70-.80	.50-.80	.040	.050
1078	C1078	.72-.85	.30-.60	.040	.050
1080	C1080	.75-.88	.60-.90	.040	.050
1085	C1085	.80-.93	.70-1.00	.040	.050
1086	C0186	.86-.95	.30-.50	.040	.050
1090	C1090	.85-.98	.60-.90	.040	.050

Table A-1. Composition of AISI 1050-1090 steels. (Oberg and Jones 1972).

Nonferrous wire ropes are primarily used for severe corrosion problems. Bronze and monel are the most commonly used nonferrous materials. However, it should be noted that ropes made of these materials should not be used for heavy loads in or the presence of abrasive forces.

The core of a wire rope is the central support structure. It supports the outer strands and maintains their proper position under applied loads. Three basic core types are used today: independent wire rope core, wire strand core and fiber core. Materials used for cores are the same as those used for the wire, with one exception--the fiber core. It is usually a synthetic fiber, but often sisal, jute, hemp or cotton is used.

Independent wire rope cores are just as the name implies: a wire rope, complete with its own core, used as a core for a larger rope. An independent core increases the overall tensile strength of a wire rope. It does not readily yield to the compressive action of the outside strands and provides long-lasting support under heavy loads.

A wire strand core uses a separate strand of wire for its core. Possessing almost identical properties as independent wire rope core, wire strand cores are typically used for smaller diameter ropes. Independent wire rope cores are used for larger ones.

Fiber cores, made of synthetic or natural fibers, are more flexible than metal cores and lend themselves to applications where the wire rope must conform to a small radius of curvature. They are resilient and therefore effective when anticipating shock loads. Fiber core soaking in a pinion-type grease cut with solvent to lubricate the core offers another advantage. This decreases abrasive wear on the outer strands and may also increase overall corrosion resistance. Table A-2 compares fiber core, independent wire rope and wire strand cores.

The individual wires are the basic component of any wire rope (Fig. 2). Thus, the first step in constructing a wire rope is preforming the wires that will eventually compose the rope. A preformed wire has been preshaped into a proper configuration before assembling. This removes the tendency to straighten under loads and leaves wires relaxed in their proper positions.

A certain number of preformed wires are then wound into a strand. Anywhere from

	Property	FC	IWRC	WSC
1)	Strength	poor	good	good
2)	Flexibility	good	poor	poor
3)	Compression due to outer strands	possibly substantial	neglegible	neglegible
4)	Resilience	good	poor	poor
5)	Heat resistance	poor	good	good
6)	Use	Light duty, shock loading	Heavy duty	Small diameter duty

Table A-2. Comparison of fiber core (FC), independent wire rope core (IWRC) and wire strand core (WSC).

three to 47 wires, and in certain special cases more than 47, may be wound into a single strand. A strand may either be complete as a wire rope, make up the core of a wire strand core, or be preformed and wound about a core to form a large wire rope.

A more complete discussion of wire rope construction, including diagrams may be found in most product information literature available from companies manufacturing wire rope. Broderick & Bascom's Wire Rope Handbook (1966) and U.S. Steel's Tiger Brand Wire Rope Handbook (1975) are examples.

For a given number of strands and a specific core, there are a variety of ways of wrapping them together to form a wire rope. Twisting wires in one direction to form strands, and twisting the strands in the other direction to form rope, constructs a regular lay rope. In regular lay wire rope, the accepted standard for wire ropes, the outer wires lay essentially parallel to the longitudinal axis.

In contrast to regular lay is lang lay rope. Both wires in the strands and strands in the rope twist in the same direction. The outer wires run diagonally across the rope and are exposed for longer lengths than in a comparable regular lay. Lang lay ropes untwist more easily than regular lay ropes, as well as crush and distort. However, they show greater flexibility and have greater resistance to fatigue and abrasion than regular lay ropes.

Combining regular lay and lang lay is known as alternate lay. An alternate lay wire rope has strands that are alternately regular and lang lay. It is sometimes used in compromise situations where certain aspects of each are desired.

Right and left lays are available for both regular and lang lay. Right lay is standard, but under certain applications, left lay may be specified. The determining factor in choosing a lay is whether strands rotate from right to left while unwinding from the drum.

Under certain high stress conditions individual wires composing a strand may move in relation to each other. This undesirable situation generally reduces flexibility and tensile strength. Using filler wires minimizes this movement. Filler wires, small non-load-bearing wires, space and position wires in a strand.

Two very important mechanical properties that must be considered in selecting wire ropes are flexibility and tensile strength. Flexibility is required in varying degrees

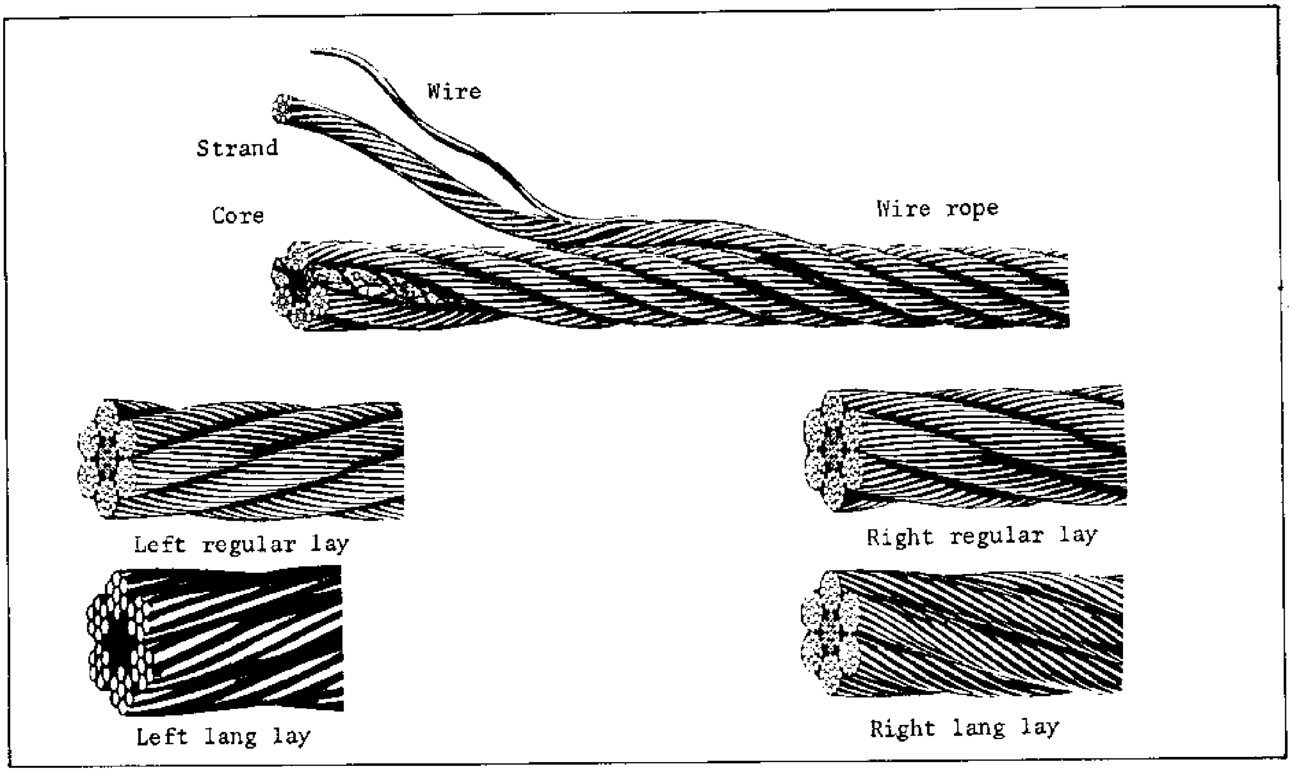

Fig. 2. Composition of wire rope (U.S. Steel Supply, 1975).

depending on the radii of curvatures encountered in normal applications. Flexibility properties may be adjusted by rope lay, size of rope, core and wire material. Generally, as the flexibility of a wire rope increases, tensile strength decreases. Tensile strength is perhaps the single most important property of a wire rope. Very high tensile strengths may be attained by adding wires to the strands, strands to the rope, and improving the core's strength. However, this decreases the rope's flexibility and, to a degree, its resistance to shock loading.

To provide corrosion protection, galvanizing wire ropes is quite common. Each wire is individually galvanized, then formed into strands and ropes. As a rule of thumb, galvanized wire rope has only 90 percent of the tensile strength of bright, nongalvanized rope. This, of course, must be accounted for in selecting a proper rope.

APPENDIX B
CORROSION

Corrosion is a broad term used to describe any destruction of material due to its interaction with the environment. Seawater forms a highly corrosive environment that destroys most metals. Not only does seawater contain every element, but it contains ample organic compounds as well, which often form complexes, or ligands, with metal ions. This process corrodes metals.

Both seawater corrosion and non-seawater corrosion can be classified into various forms. For convenience, each form should be distinctive with regard to appearance, cause and corrective or preventive procedures. Valuable information about preventing one type of corrosion can result and be compared with typical manifestations of a given form.

Classifying types of corrosion, although, somewhat arbitrary, varies from text to text. Fontana and Green (1967) provided the format used in this discussion. They define eight forms of corrosion: (1) uniform attack; (2) galvanic or two-metal corrosion; (3) crevice corrosion; (4) pitting; (5) intergranular corrosion; (6) selective leaching; (7) erosion corrosion; and (8) stress corrosion.

Uniform attack

Uniform attack, the most common form of corrosion, causes the greatest weight loss of metal. It uniformly destroys material over the entire exposed surface of an object by chemical and electrochemical means. The proper material and/or coating selection, inhibitors, and cathodic protection typically reduce uniform attack.

Galvanic or two-metal corrosion

Galvanic or two-metal corrosion, quite common in aqueous solutions including seawater, results from the chemical potential difference between two dissimilar metals in electric contact with each other. Submerged in a suitable aqueous solution one of these electrically connected metals will corrode, while the other remains unaffected. Determinating which metal of a two-metal couple will corrode is based on their respecitve standard electrode potentials. The actual theory and determination of these potentials is beyond the scope of this paper, but several references dealing with this topic are listed in the bibliography (Gatty and Spooner 1938; Tomashov 1966; and Butler and Ison 1966).

Basically these potentials are referenced against the hydrogen electrode (H_2/H^+), which is defined as zero. The more positive an ion's standard electrode potential, the greater its tendency to accept electrons, while the more negative its potential, the greater its tendency to donate electrons. Thus the direction of electron flow between two metals that are electrically connected in an aqueous solution can be determined when their standard electrode potentials are known. For example, when zinc (Zn) contacts iron (Fe), the electron flow direction is easily determined. Zinc has a standard electrode potential of -0.763, while iron's is -0.440. Although both metals have negative potentials, zinc, the more negative, tends to donate electrons while iron accepts them. Overall electrons flow from zinc to iron:

$$Fe^{+2} + Zn \rightleftarrows Fe + Zn^{+2}$$

where zinc is said to be anodic and iron cathodic.

This concept, and in particular this example, is very important in corrosion engineering. As one might expect, the process of losing electrons steadily over a long period of time might reduce the quantity of metal an appreciable extent. This metal (zinc in the above example) corrodes while the other less negative metal (iron) is protected by acquiring electrons. In general, the more negative metal--that one which donates electrons--is called the anode and corrodes. The less negative, or more positive, metal, called the cathode, typically does not corrode.

The above discussion briefly overviews galvanic corrosion. To what extent it occurs depends on many factors in addition to the standard electrode potentials. Some factors include the concentrations of the two metals in solution; exposed surface of each metal; and the pH, temperature, and ionic strength of the environment.

An important consideration in galvanic corrosion is that the dissimilar metals need not be pure. Many of today's engineering materials are metal alloys that contain one or more specific metal ions in a matrix of a primary metal, usually iron. Both primary metal and alloyed ions are in electrical contact, and it is likely that their potentials differ. Therefore, corrosion likely occurs under suitable conditions such as in a seawater environment.

Crevice corrosion

Crevice corrosion, localized form of corrosion, occurs in shielded or protected areas that form stagnant solutions of corrosive materials. Gaskets, holes, cap joints, bolt and rivet heads, as well as dirt and other corrosion products, all can lead to crevice corrosion.

In crevice corrosion the reaction in the crevice and on the exposed outside surface is initially the same. Oxygen acts as the electron acceptor while the metal (M) acts as the electron donor:

oxidation $M \rightarrow M^+ + e^-$

reduction $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

However, in the crevice, restricted flow leads to depletion. Therefore, oxygen reduction no longer occurs. Dissolution of the metal continues, though, which eventually leads to a buildup of a positive charge in the crevice. Chloride ions now migrate into the crevice (hydroxyl ions also migrate, but at a slower rate), increasing the metal-chloride concentration. The metal-chloride then hydrolyzes, which increases hydrogen and chloride ion concentrations:

$$MCl + H_2O \rightleftarrows MOH + H^+ + Cl^-$$

Both of these ions tend to accelerate the dissolution rates of most metals. Due to this effect, crevice corrosion becomes autocatalytic, or self-accelerating.

As crevice corrosion proceeds, an interesting reaction takes place. The rate of oxygen reduction on adjacent exposed surfaces (i.e., outside the crevice) increases as the rate of crevice corrosion increases. This tends to protect the exposed surface cathodically, in much the same way that zinc protected iron in the galvanic corrosion example.

Fontana and Green (1967) note another form of crevice corrosion called filiform corrosion. It usually appears under protective coatings as a network of rust-colored tails. Water being supplied to an actively corroding "head" by osmosis is thought to be the cause, owing to the high concentration of ferrous salts that supply osmotic pressure. The actual corrosion process is similar to that described for crevice corrosion. As ferrous hydroxide (rust) precipitates, the active head moves on, and only the rust-colored tail remains behind.

Although filiform corrosion is not important in seawater, crevice corrosion is. Preventing and modifying crevice corrosion will be discussed later in this section.

Pitting

Pitting is another form of localized corrosion. An affected surface will be characterized by a multitude of small pits whose surface diameter typically equal to or less than pit depth. This highly destructive form of corrosion is not easily detected because of the small size of the pits and their tendency to be concealed under corrosion products. The penetrating nature of pitting, with little total weight loss, may result in failure.

The corrosion mechanism for pitting is similar to crevice corrosion. The major difference is in its initiation. While crevice corrosion occurs only on protected areas under stagnant conditions, pitting is often found on open areas of exposed surface. Evans (1951) postulated that pit initiation could start at any point where the rate of metal dissolution is temporarily higher than in the surrounding area. Chloride ions will migrate toward this area, and if not swept away, will initiate the pitting process. Pitting might also start at a slight imperfection, such as a scratch or surface dislocation.

Once initiated, pitting is autocatalytic. That is, once begun, it will continue. The pit tends to proceed in the direction of gravity due to the dense nature of the corroding solution. In seawater, pitting is a problem only under stagnant conditions.

Intergranular corrosion

Fontana and Green (1967) described intergranular corrosion as a localized attack at and adjacent to grain boundaries in which there is little corrosion of grains. Grains typically fall out, with a corresponding decrease in strength. Impurities can cause intergranular corrosion as well as alloy depletion or alloy enrichment at grain boundaries.

Intergranular corrosion is most prevalent when a metal has been heated to a temperature sufficiently high to allow precipitation of an alloying element at grain boundaries. This leaves the area immediately adjacent to the boundary seriously depleted with respect to this alloy. If the alloy, such as chromium in steel, significantly resists corrosion, the depleted area is susceptible to corrosion.

Weld decay is a good example of intergranular corrosion. The heated areas alongside the weld deteriorate due to intergranular corrosion and weaken the weld. This form of corrosion is not prevalent in seawater applications.

Selective leaching

Selective leaching is a form of corrosion in which one element is removed from an alloy. Perhaps the most common form of selective leaching is dezincification of brass. Under corrosive conditions, brass dissolves in localized areas. Copper then plates back onto the remaining metal while zinc remains in solution. Corrosion of zinc by cathodic reduction of water into hydrogen gas can accelerate this. Because zinc is more negative than copper, this reaction likely occurs. However, selective leaching is not considered a major problem with iron alloys in a seawater environment.

Erosion corrosion

Erosion corrosion is the increased rate of deterioration of a material due to the relative movement of a corrosive fluid across it. It is highly velocity-dependent. Increased velocities increase the rate of corrosion considerably if the corrosive fluid also contains solid particles. Mechanical wear, when coupled with erosion corrosion, especially devastates materials.

Stress corrosion

Stress corrosion refers to cracking due to the simultaneous presence of tensile stress and a corrosive medium. Tips of cracks or notches act as stress concentrators. Under relatively low tensile stresses, corrosion has been observed to start in these areas. Once started, corrosion spreads like a crack, either along grain boundaries or across grains. The tip of the crack has a very small radius, which concentrates the stress even more. For this reason, material subject to stress and in a corrosive environment--such as seawater--may experience relatively swift crack propagation.

Stress corrosion is often found under the same conditions as pitting. Therefore, it is likely that a common crack initiation point would be at a pit tip. Perhaps the most deleterious effect of stress corrosion is reduction of fatigue strength. Thus materials subjected to cyclic loadings would be greatly affected.

Protection against corrosion

Selecting the proper materials is the most basic way to prevent corrosion. Several authors (Wilde 1972; Nachman and Duffy 1974; Baghadasarian and Ravitz 1975) stress material selection in combating seawater corrosion. Because each environment corrodes certain materials to a greater extent than others, it is preferable to conduct corrosion tests in the actual environment if possible. Compton (1970) stresses this point when discussing seawater corrosion.

Seawater possesses unique corroding capabilities, and acts as a severe corrosive medium for specific materials. Nachman and Duffy (1974) found that 10 to 14 percent aluminum and four percent molybdenum significantly increased the corrosion resistance of steel, while such elements as chromium, nickel, and copper offered a negligible increase in corrosion resistance.

To troubleshoot or solve corrosion problems, the corrosion engineer carefully analyzes the material composition of the object being corroded after identifying the form of corrosion and the relevant parameters of the corrosive medium. Often the material being used is not optimum for the environment. When this is the case, substituting a more appropriate material may be worthwhile. Many times, though, using a substitute is impractical owing to cost or availability, and, as is often the case, even the best available materials will corrode to an unacceptable extent. Under these circumstances, further means of corrosion control should be investigated.

Applying organic or inorganic coatings is one popular and successful way of protecting objects susceptible to corrosion. Generally, coatings maintain a physical barrier between a corrodible material and a corrosive environment.

Inorganic coatings are thin layers of metal or ceramic material. Metallic coatings are applied by electrodeposition, flame spraying, cladding, hot dipping or vapor deposition, and do not provide electric insulation. Ceramic coatings are applied by various forms of diffusion and chemical conversion, are brittle and often electrically insulate the material.

Organic coatings are more common than inorganic coatings, and when properly applied, often provide the least expensive means of corrosion protection. Organic coatings include paints, varnishes, lacquers, and similar substances, usually applied over organic primers. As with organic coatings, they maintain a physical barrier between the material and the environment. Organic coatings tend to wear off, scratch, and chip quicker than inorganic coatings, but are easily repaired. A good touchup program will greatly increase the protective life of a paint job, while a scratch in a hot-dipped coat can be a significant problem.

Under some corrosive conditions, it is possible and practical to modify the corrosive environment instead of, or as well as, the corroding material. The addition, or deletion of an oxidizer or inhibitor might greatly reduce the corrosion rate. An oxidizer or inhibitor is a substance which, when added in small concentrations to an environment, decreases the corrosion rate (Fontana and Green 1967). Lowering the temperature will decrease corrosion rates in some instances, as will decreasing the relative velocity between the medium and a corrodible material. It should be obvious, however, that modifying the seawater environment is impractical.

Galvanic protection is an increasingly popular form of corrosion control in both seawater and fresh water. Galvanic protection can be broken down into two main forms: (1) sacrificial protection, and (2) impressed current protection.

Galvanic protection uses the principles discussed earlier regarding galvanic or two-metal corrosion. The following half-reactions model galvanic corrosion of a metal (m).

$$m \rightarrow m^{+n} + ne^-$$

$$2H^+ + 2e^- \rightarrow H_2$$

where e^- denotes an electron.

Supplying electrons to the metal surface protects the metal.

Sacrificial metal protection uses another metal with a more negative standard electrical potential than the protected metal. When the two metals electrically contact each other, the more negative of the two gives up, or sacrifices, electrons to the other and protects the more positive metal from corrosion.

Zinc, magnesium, and aluminum are the most likely metals to be used as the anode, or electron donor. They all have relatively negative standard electrode potentials, but differ in weight and cost. Both aluminum and magnesium are lightweight, a desirable feature, but zinc costs considerably less. In addition, zinc has a more suitable activity while magnesium is usually too active. For this reason zinc is the most commonly used sacrificial metal, especially in protecting iron, and iron alloys.

Impressed current protection works on exactly the same principles as sacrificial metal protection, but an externally supplied current donates electrons to the metalic surface. The metal object to be protected is connected to an external DC power supply. The protected object acts as the cathode (negative terminal) while the positive terminal connects to an inert anode, such as graphite. Electrons then pass from the inert anode to the metal surface, and supply the electrons necessary for corrosion prevention. The amount of current depends on the environment, conditions within the environment, and the protected structure. As an example, pilings exposed to tidal motion in seawater require a current density of 608 milliamps per square foot.

APPENDIX C

TENSILE TEST DATA

Position	Sample	Breaking strength (lbs)
Door End	1	17,140
	2	17,240
	3	18,100
10 Fathoms	1	16,840
	2	17,150
	3	15,730
20 Fathoms	1	18,300
	2	17,900
	3	17,750
40 Fathoms	1	16,400
	2	18,000
	3	17,650
New	1	15,920
	2	18,760
	3	14,300

Table C-1. Tensile test data - 1/2-inch 6 x 19 wire rope.

Position	Sample	Breaking strength (lbs)
Door end	1	14,800
	2	15,860
	3	15,500
10 Fathoms	1	16,160
	2	15,840
	3	16,000
New	1	20,060
	2	20,060
	3	20,040

Table C-2. Tensile test data - 7/16-inch 6 x 7 wire rope.

APPENDIX D

WEIGHT DATA

Position	Sample	Weight (gm/cm)
Door end	1	5.5297
	2	5.5141
	3	5.5328
10 Fathoms	1	5.4733
	2	5.5490
	3	5.4887
20 Fathoms	1	5.4380
	2	5.4674
	3	5.4523
40 Fathoms	1	5.3837
	2	5.4039
	3	5.4227
New	1	5.5112
	2	5.5245
	3	5.4908

Table D-1. Weight data - 1/2-inch 6 x 19 wire rope.

Position	Sample	Weight (gm/cm)
Door end	1	3.9052
	2	3.8839
	3	3.8949
10 Fathoms	1	3.9525
	2	3.9405
	3	3.9414
New	1	3.9504
	2	3.9828
	3	3.9844

Table D-2. Weight data - 7/16-inch 6 x 7 wire rope.

APPENDIX E

WIRE DIAMETER DATA

Sample	Diameter (in.)	Sample	Diameter (in.)	Sample	Diameter (in.)
Door End					
1	.0322	11	.0330	21	.0331
2	.0324	12	.0341	22	.0329
3	.0307	13	.0324	23	.0307
4	.0327	14	.0341	24	.0329
5	.0329	15	.0340	25	.0336
6	.0330	16	.0341	26	.0333
7	.0333	17	.0336	27	.0329
8	.0328	18	.0339	28	.0341
9	.0334	19	.0342	29	.0337
10	.0326	20	.0325	30	.0320
10 Fathoms					
1	.0335	11	.0343	21	.0329
2	.0332	12	.0329	22	.0345
3	.0341	13	.0340	23	.0330
4	.0330	14	.0334	24	.0326
5	.0332	15	.0326	25	.0338
6	.0340	16	.0330	26	.0322
7	.0323	17	.0337	27	.0326
8	.0325	18	.0328	28	.0341
9	.0327	19	.0317	29	.0303
10	.0326	20	.0325	30	.0323
20 Fathoms					
1	.0332	11	.0322	21	.0329
2	.0322	12	.0330	22	.0340
3	.0329	13	.0345	23	.0328
4	.0327	14	.0327	24	.0327
5	.0339	15	.0340	25	.0337
6	.0334	16	.0330	26	.0339
7	.0334	17	.0339	27	.0322
8	.0336	18	.0329	28	.0325
9	.0342	19	.0337	29	.0335
10	.0330	20	.0337	30	.0340

Table E-1. Wire diameter data - 1/2-inch 6 x 7 wire rope.

Sample	Diameter (in.)	Sample	Diameter (in.)	Sample	Diameter (in.)
40 Fathoms					
1	.0338	11	.0328	21	.0314
2	.0327	12	.0328	22	.0337
3	.0331	13	.0319	23	.0331
4	.0332	14	.0329	24	.0333
5	.0329	15	.0318	25	.0318
6	.0331	16	.0332	26	.0330
7	.0334	17	.0323	27	.0319
8	.0337	18	.0310	28	.0333
9	.0332	19	.0333	29	.0319
10	.0338	20	.0332	30	.0322
New					
1	.0391	11	.0378	21	.0381
2	.0408	12	.0381	22	.0385
3	.0398	13	.0386	23	.0383
4	.0397	14	.0384	24	.0381
5	.0380	15	.0359	25	.0390
6	.0375	16	.0385	26	.0387
7	.0380	17	.0384	27	.0389
8	.0381	18	.0381	28	.0377
9	.0384	19	.0384	29	.0387
10	.0382	20	.0386	30	.0381

Table E-1. (Continued)

Sample	Diameter (in.)	Sample	Diameter (in.)	Sample	Diameter (in.)
		Door End			
1	.0463	11	.0456	21	.0453
2	.0464	12	.0459	22	.0457
3	.0471	13	.0459	23	.0466
4	.0469	14	.0461	24	.0454
5	.0456	15	.0468	25	.0460
6	.0467	16	.0462	26	.0452
7	.0463	17	.0465	27	.0460
8	.0451	18	.0462	28	.0467
9	.0470	19	.0455	29	.0461
10	.0460	20	.0476	30	.0465
		10 Fathoms			
1	.0468	11	.0454	21	.0468
2	.0469	12	.0475	22	.0465
3	.0472	13	.0452	23	.0474
4	.0453	14	.0467	24	.0467
5	.0451	15	.0455	25	.0467
6	.0465	16	.0480	26	.0466
7	.0462	17	.0479	27	.0461
8	.0466	18	.1478	28	.0466
9	.0472	19	.0460	29	.0470
10	.0475	20	.0460	30	.0471
		New			
1	.0497	11	.0488	21	.0495
2	.0493	12	.0490	22	.0494
3	.0493	13	.0495	23	.0492
4	.0489	14	.0493	24	.0492
5	.0488	15	.0493	25	.0496
6	.0490	16	.0489	26	.0494
7	.0491	17	.0492	27	.0494
8	.0488	18	.0490	28	.0497
9	.0493	19	.0489	29	.0494
10	.0492	20	.0489	30	.0493

Table E-2. Wire diameter data - 7/16-inch 6 x 7 wire rope.