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FINAL REPORT

Wire Rope Improvement Program

September 1981

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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FINAL REPORT

WIRE ROPE IMPROVEMENT PROGRAM

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SUMMARY

In 1975, the Pacific Northwest Laboratory (PNL) began a study for the U.S. Bureau of Mines to determine ways of extending the service life of large-diameter wire rope used on draglines in the surface coal-mining industry. Authorization for the Wire Rope Improvement Program was based on the potential for eventual reduced costs and increased production at the mines.

Toward this program goal, activities in five major areas were undertaken during the WRIP. These included

- experiments using PNL-developed bend-over-sheave fatigue test machines to generate data on which to base a model for predicting large-diameter rope performance from that of small-diameter ropes
- bend-over-sheave fatigue testing to determine differences in rope failure rates at varying rope loads
- analyses to determine how wire ropes actually fail
- development of a load sensor to record and quantify operational loads on drag and hoist ropes
- technology transfer activities to disseminate useful program findings to coal mine operators.

Data obtained during the 6-year program support three primary conclusions. First, high loads on wire ropes are damaging. As an adjunct, however, potentially useful countermeasures to high loads were identified. Second, large-diameter rope bend-over-sheave performance can be predicted from small-diameter rope test behavior, over some ranges. Third, wire ropes fail as the result of individual wire failure(s). Program data corroborated important failure mechanisms and identified potentially useful countermeasures.

In addition, a load sensor concept was fully developed during the program. Sensors were used first on drag ropes. They proved sufficiently successful in accurately measuring impulse loads to warrant acquiring two more sensors for use on hoist rope loads as well.

In terms of technology transfer, the seminars on wire rope technology were apparently the more successful means of program findings dissemination. The first national wire rope symposium was also enthusiastically received by both researchers and coal industry representatives.

ACKNOWLEDGMENTS

Many individuals and organizations were actively involved in the Wire Rope Improvement Program over its 6-year lifetime. Earlier program publications have cited previous participants. For their contributions during Fiscal Year 1981, the following are gratefully acknowledged: H. Reese of the U.S. Department of Energy and W. I. Enderlin, Pacific Northwest Laboratory, who served as FY81 program managers; program consultants S. C. Gambrell, Jr., from the University of Alabama and L. T. Hansson of the Bucyrus-Erie Company; and the Washington Irrigation and Development Company, Centralia, Washington, for providing a load sensor field test facility.

The authors also wish to thank their colleagues at the Pacific Northwest Laboratory for their efforts in the laboratory and in the field: C. H. Allen, K. R. Ames, M. H. Morgenstern, D. A. Nelson, L. R. Shotwell, and E. V. Werry.

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WIRE ROPE IMPROVEMENT PROGRAM

INTRODUCTION

The work described in this report was performed by the Pacific Northwest Laboratory (PNL) and its subcontractor, Battelle Columbus Laboratories (BCL), as part of a continuing program begun in 1975 by the U.S. Bureau of Mines. On October 1, 1978, program sponsorship was transferred to the Division of Solid Fuels Mining and Preparation, U.S. Department of Energy.

When the Wire Rope Improvement Program (WRIP) was originally authorized in 1975, the overall goal was to determine ways to extend wire rope life, perhaps by improving wire rope itself. Program findings would ultimately be applied in the field to increase surface coal mine productivity and reduce costs to mine operators. Although the goal actually remained the same in subsequent contract years, tasks were adjusted to conform with progress and findings.

To the extent necessary, this report is intended to serve as a record of the entire 6-year program. The research procedures and findings related to tasks completed prior to Fiscal Year 1981 have already been reported in detail (Beeman 1977, 1978; Morgenstern et al. 1980). Nevertheless, the first main section of this report presents a brief overview of WRIP efforts from the program's inception up to FY81. The overview highlights the significant research efforts and results, providing necessary background for the overall program conclusions and recommendations that appear next.

The third major section describes the bend-over-sheave experiments conducted by BCL on small-diameter (1-1/2-inch) wire rope. The BCL single-wire experiments are also documented in this section. The correlation of the resulting laboratory data with field rope data is addressed here as well.

A BCL analysis of wire rope wear and failure modes comprises the fourth section. The fifth main section describes how the PNL-developed dragline load sensor system was used in the field to collect and analyze data describing actual hoist rope loads.

The sixth main section documents BCL efforts to disseminate program findings to the surface coal-mining industry.

The final section discusses key elements of wire rope performance as interpreted from WRIP research findings. The detailed information on wire rope construction and uses on surface mining equiment provides background for those readers outside the field who might want more basic explanations before perusing the technical aspects of this report.

PROGRAM OVERVIEW

This section reviews the program's significant research efforts and results from its inception up to FY81.

BACKGROUND

The Wire Rope Improvement Program for large-diameter rope (i.e., ropes measuring 2 to 5 in. in diameter) was originally authorized by the U.S. Bureau of Mines in June 1975. Authorization was based on potentials for increased surface coal mine productivity and reduced costs to mine operators.

The early program sought to determine ways of improving wire rope life; perhaps by improving wire rope itself. Modifications in rope construction techniques and wire composition and drawing practices were visualized as potential improvements. Correlation of low-cost small-diameter rope test results with large rope field performance might provide acceptable justification for such rope development. One candidate method would consist of validating an hypothesis that the Drucker-Tachau (D-T) ratio[a] correlates bend-over-sheave (BOS) fatigue lives for all practical wire rope sizes, sheave diameters and operating loads. The D-T ratio had already been used to correlate fatigue life data on fiber-core wire rope in sizes ranging from 1/2 in. to 1-7/16 in. and sheave diameters fifteen to thirty times the rope diameter, at loads covering the design factors[b] of interest, i.e., from 2 to 6.

If this hypothesis could be validated for large ropes, then rope development could be carried out on small-diameter ropes with some confidence that findings would apply to larger sizes. Hence, rope manufacturers would have the evidence needed before committing resources to production of improved larger rope sizes.

(a) The D-T ratio is the nominal bearing pressure, rope-upon-sheave, divided by representative wire strength.

(b) $\text{Design factor} = \dfrac{\text{Rated Rope Breaking Strength}}{\text{Operational or Test Load}}$

Testing the quantitative validity of Drucker-Tachau ratios for all reasonable rope sizes was not possible at the beginning of the program because no data describing bend-over-sheave (BOS) fatigue of large-diameter rope were available. Bend-over-sheave fatigue tests had never been conducted on large ropes other than on the draglines themselves. Thus, the first program effort was to build a BOS fatigue test machine for large-diameter wire rope and collect fatigue life data.

Data from BOS fatigue tests on large-diameter rope would provide opportunity to evaluate the D-T ratio hypothesis. In addition, development of rope damage in the test machine could be compared with damage observed in field ropes that had been retired, thereby providing insight to damage mechanisms. The fatigue test would closely simulate hoist rope field experiences; drag rope examinations would also be useful for comparison.

Preliminary information indicated that drag ropes wore out almost twice as fast as hoist ropes; comparative examinations might prove valuable for uncovering differences between hoist and drag wear-out mechanisms. Consequently, field rope samples were acquired.

Field trips to representative mines were also recognized as necessary for developing realistic perspectivies; 13 mine sites were visited early in the program. Data on rope life were obtained, and opportunities developed for viewing and photographing several operational procedures. Tour of a wire rope manufacturing plant provided further insight to other aspects of rope performance.

RESULTS FROM FISCAL YEARS 1976-1978

A fatigue test machine was designed and constructed at PNL for cycling 3-in. diameter rope around 90-in. diameter sheaves. Twenty-three ropes from two manufacturers, representing three rope designs, were tested in BOS fatigue at design factors from 1.9 to 2.9; fourteen of these produced comparative data. The others provided supplementary information as described in Beeman (1978).

Bend-over-sheave fatigue data from these fourteen tests of 3-in. wire rope did not correlate with available smaller rope data when compared by the

Drucker-Tachau ratio. However, almost all the smaller rope data were obtained from ropes with fiber cores. Because large dragline ropes have steel wire cores, the absence of correlation was not unexpected. The few data from comparable core small ropes were not sufficient to accept the D-T hypothesis; more tests with smaller ropes having comparable cores were needed.[a]

Field rope samples ranging in diameter from 2-7/8 in. to 4-1/2 in. were examined. They provided useful information about the degree of wear and notching that occurred at locations near the bucket, near the drum, and in the mid-region. Wear-out mechanisms appeared to consist of abrasive wear on outer wires plus notching and wear at strand-strand contacts, as well as at strand-IWRC contacts.

Three-inch diameter ropes tested on the BOS machine exhibited internal wear patterns strikingly similar to the field ropes. Test rope lives varied from 508 bending (or flex) cycles at a design factor of 1.9 to 84,712 flex cycles at a design factor of 2.9.

Meanwhile, compilation of results from field trips produced interesting data about rope life. Hoist ropes lasted about twice as long as drag ropes, but within each category was a five to one variation, apparently due to differences in overburden and in operational practice. The evidence seemed persuasive that real opportunities existed for extending rope life by encouraging favorable field practices. Useful dollar savings and less unscheduled down-time could reasonably be achieved without capital expenditures. Disseminating information to the operators suggested a technology transfer activity.

Field observations and 8-mm movies of operating draglines suggested that drag rope life might be seriously affected by the dynamic whipping and jerk loads the ropes can experience. Desirability for sensing and recording operational drag rope loads seemed clear.

(a) Steel wire core ropes are actually constructed with strands twisted about a central core consisting of a wire rope itself; hence, the term independent wire rope core (IWRC). The IWRC supports the strands so the rope does not collapse under service loads; it can also provide some margin of reserve strength in a new rope.

After the changeover to DOE sponsorship, planned activities were implemented for rope testing, technology transfer and load sensor development.

RESULTS FROM FISCAL YEARS 1979-1980

Small-diameter IWRC ropes, 3/4 in. and 1-1/2 in. in diameter, were obtained and tested in BOS fatigue. Most had the same number of outer wires in each strand as the 3-in. rope. This provided a first-order effect of geometric scaling. More tests with 3-in. rope were completed, extending data down to design factors of 5. The hypothesis of correlation over this range via Drucker-Tachau ratios was supported.

A principal difficulty lay in scaling damage accumulation processes and wire fracture properties. Quantitative understanding of controlling mechanisms was clearly lacking; influence of wear processes is a case in point. Qualitative hypotheses might be developed, but still missing are fatigue life data for large-diameter rope under different sheave-to-rope diameter ratios and with ropes of different constructions, together with mechanical properties data for individual wires comprising the rope.

During FY79, a load sensor link suitable for field use was defined in cooperation with selected mining companies; hardware, associated telemetry and recording apparatus for a dual load sensor system were completed and delivered for installation on a working dragline to collect preliminary field data. Field movies of professional quality were produced, showing certain types of operational practice and their effects on both drag and hoist rope motions. Related dynamic analyses of drag rope systems were conducted.

Instructive 1-day seminars, explaining fundamentals of wire rope construction and factors influencing its service life, were developed and presented at several mine sites around the nation. An interpretive review of the Wire Rope Improvement Program was presented at a COSMET[a] meeting in Kansas City, Missouri. Each of these activities produced positive feedback, encouraging more development and broader dissemination.

(a) Common Surface Mining Equipment Troubleshooting.

A national wire rope symposium was held in Denver, Colorado, and termed a success by attendees and cosponsors alike. Proceedings were published by Washington State University Engineering Extension Service.

TARGETS FOR FISCAL YEAR 1981

Principal thrusts for FY81 were directed at obtaining field data on drag rope loads with the load sensor, completing the BOS fatigue life tests on large and smaller ropes at high design factors, i.e., low loads, continuing wear and failure analysis studies, and expanding technology transfer efforts. Eight-strand rope and nylon sheaves were also tested. After early success with the drag rope sensors, it was decided to acquire two more sensors and test the hoist ropes as well. Additional field data were acquired; however, because of schedule disturbances due to the coal mine strike, activities on this aspect were too late for reporting here.

The specific activities conducted and results generated in each of these areas are documented fully in succeeding sections of this report.

CONCLUSIONS AND RECOMMENDATIONS

Three principal conclusions were drawn on the basis of Wire Rope Improvement Program Findings. This section lists these and other important conclusions, and then presents specific recommendations for future research.

CONCLUSIONS

First, the WRIP determined that high rope loads are damaging to wire ropes. Potentially useful countermeasures include the following:

- Mine management engineering and dragline operators can develop procedures that minimize need for digging up high and close to the house where large bucket position factors[a] are virtually unavoidable; this will help extend hoist rope life.
- Operators can practice fill and swing operations that minimize unnecessary movements involving bucket position factors much above 1.1 or so. This will keep hoist rope loads practically low and tend to improve productivity by shortening cycle time somewhat.
- Operators can practice smoother dump and return swings to minimize occurrences of rope whip.

The second major program finding was that, within specific ranges, large-diameter rope bend-over-sheave performance can be predicted from small rope tests. The correlation can be determined from flex cycles versus the term, load factor divided by sheave-to-rope diameter raio, D/d. The demonstrated limits appear to be D/d ratios of approximately 20 and above, and actual load factors below about 0.3.

Third, the WRIP concluded that wire rope failure develops from individual rope wire failures. Researchers found that most drag ropes on large draglines are retired as a result of wear and dynamic loads rather than bending fatigue. Cases in which bending fatigue dominates commonly indicate a sheave design or

(a) See Appendix A.

wear problem. Points of wire notching at cross wire contacts are not the usual sites of crack initiation as commonly believed; initiation often takes place between adjacent wires of a given strand.

Findings suggest that minor improvements in wire rope could result from modifications in wire composition and different thermomechanical treatments adjusted to accommodate phase transformation behavior in current or new alloys.

The BCL small-diameter wire rope and single-wire experiments led to four specific conclusions:

- The modified bearing pressure ratio provides a reasonable consolidation of bending fatigue data on ropes of different constructions.
- Filler-wire Seale and Warrington Seale wire ropes having the same number of outer wires per strand and made of the same wire strength have similar bending fatigue resistance.
- The number of outer wires per strand is directly related to bending fatigue resistance.
- Steel sheave groove hardness (in the absence of gross sheave wear) does not substantially influence rope life.

Load sensors installed on an operating dragline successfully transduced and telemetered the active loads on drag ropes. As a result, it was decided to obtain additional sensors for use on hoist ropes.

In terms of effective information dissemination, the most useful technology transfer activities were judged to be the seminars and the national wire rope symposium. The mining industry's demonstrated concern about good rope performance, coupled with miners' general receptivity to specific suggestions to extend rope life, suggest that continued technology transfer activities would be successful.

RECOMMENDATIONS

Recommendations based on BCL's small-diameter rope and single-wire experiments are numerous.

- Additional laboratory experiments should be performed to clarify the potential of 8-strand ropes for hoist rope usage.
- Nylon sheave groove experiments should be completed to evaluate fatigue life improvement potential.
- Additional strain-control, axial fatigue tests on rope wire should be completed to identify changes in material behavior and to characterize the wire rope service life potential of each wire.
- The influence of worn, hardened sheave grooves and fleet angles on rope life should be experimentally evaluated.
- Further multiple-load-level testing should be pursued to verify the usefulness of linear damage predictions of field rope service lives.
- Alternative lubricants and lubricating methods should be investigated as a means to enhance hoist rope service lives.
- An effort should be undertaken to acquire actual breaking strength data and information on the condition of each rope at retirement of a large number of dragline field ropes. These data could then be used to reevaluate the adequacy and consistency of current field rope retirement practices.
- A more rigorous model of wire rope fatigue damage accumulation should be pursued. The model would accommodate rope geometry cyclic wire material properties, sheave groove geometries and wire-to-wire plasticity effects.

The BCL wire wear and failure analyses also led to specific suggestions for additional research:

- Adhesion and dry fretting of wire rope internal contacts should be controlled by improved lubrication. Lubricants with good boundary lubrication properties, ability to penetrate contact zones and ability to inhibit corrosion of steel should be investigated. Fluid lubricants should be used in lieu of heavily waxed semi-solid lubricants with poor penetrating properties.

- Inclusion content in wire should be reduced to control delamination-type wear. Vacuum melted steel should be investigated.

- Wire microstructure should be altered from fine pearlite to spheroidizal structure or a lower bainite. These structures should reduce tendencies to form lamellar structures under heavy local deformation.

- Boron-containing steel should be considered to improve abrasion resistance of outer wires. The outer wires only need to be of this composition. This material has proven effective in snowplow blades where a combination of fracture toughness and resistance to abrasion by SiO_2 particles is required.

- Current methods for determining when a wire rope should be retired should be reviewed. Measurements of the width of abrasion scars on outer wires can be misleading owing to surface extrusion along the boundaries of the wear scars. Measurement of rope diameter does not take into account the contribution of internal fretting and notching and "bedding-in."

- The significance of white etching layer formation and cracking of this transformation phase on wire rope failure needs to be investigated further. Tests should be run on individual wires which have been treated to produce white etching phase (by abrasion). These wires should be compared with untreated wires for fatigue properties.

SMALL-DIAMETER WIRE ROPE AND ROPE WIRE EXPERIMENTS

R. R. Rice and R. L. Jentgen

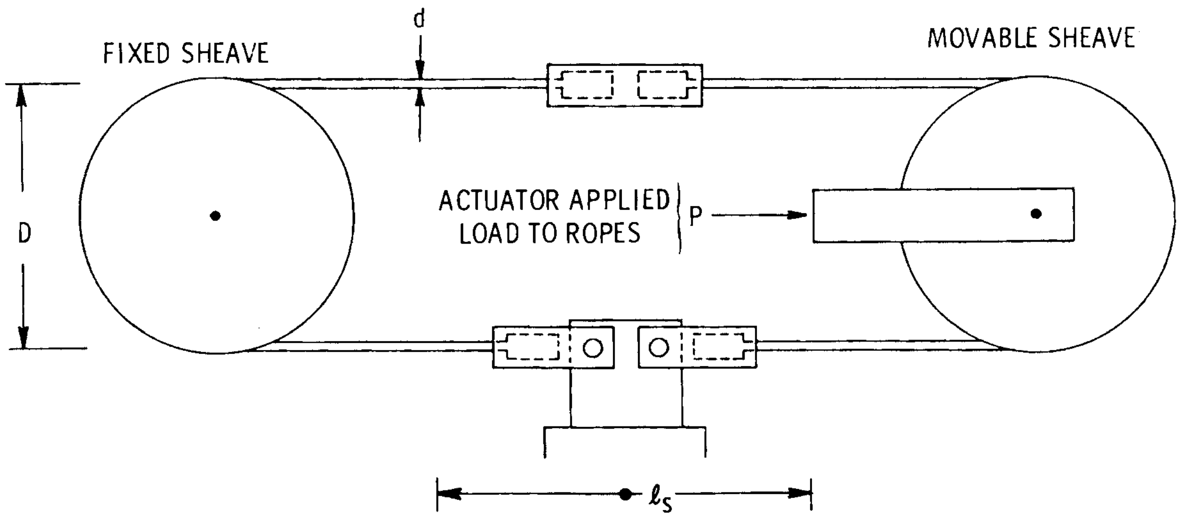
This section documents the experiments conducted at BCL on small-diameter wire rope and selected rope wires. Correlation of small rope results with field rope performance is attempted.

EXPERIMENTAL FACILITIES

Two bend-over-sheave fatigue machines are available at BCL. Both machines were used for the wire rope fatigue experiments conducted in this program. The larger machine is suitable for fatigue cycling of ropes up to 1-1/2 inches in diameter on sheaves up to about 75 inches in diameter. Cycling rates are adjustable up to linear speeds of 200 feet per minute while the amount of rope travel per half cycle can be adjusted from about 2 to 12 feet. The smaller machine is used to test ropes up to 3/4 inch in diameter on sheaves up to about 40 inches in diameter.

On each machine, one sheave is rigidly positioned on its axle and the other is mounted on a movable, rigid frame through which the tension is applied to a pair of rope specimens. This arrangement is shown schematically in Figure 1. In this program, the spacing of the sheaves and the stroke length were chosen so that, for all conditions tested, a critical section of each rope passed onto and off its sheave during each machine cycle. In other words, this primary test section received two bending cycles per machine cycle. The length of this critical section was always maintained at no less than four rope lay lengths or approximately 26 rope diameters. To each side of the critical or primary test section in the center of each rope sample were secondary test sections that were subjected to a single bending cycle during each machine cycle. The length of these secondary test sections was dictated by the sheave diameter as shown in Figure 2.

The sheaves were manufactured from 1045 steel plate, 3 inches thick for the 1-1/2-inch diameter rope and 1-1/2 inches thick for the 3/4-inch diameter rope. The sheave grooves were machined to 7 percent oversize in accordance



MECHANICALLY DRIVEN
ROPE CYCLING SYSTEM

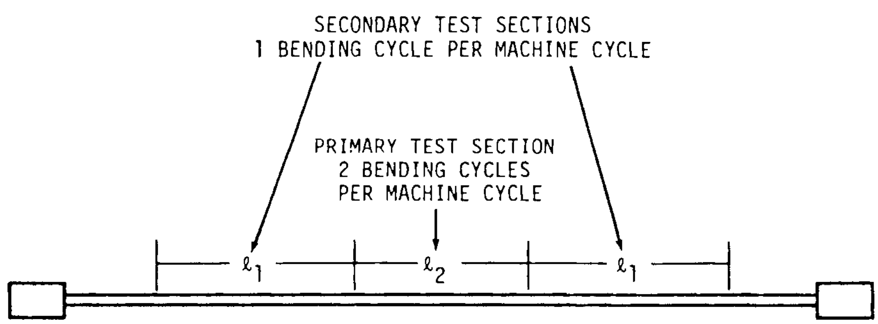
D = SHEAVE PITCH DIAMETER, in.

d = ROPE DIAMETER, in

ℓ_s = STROKE LENGTH, in.

P = ACTUATOR LOAD = 2 x ROPE TENSION (T)

FIGURE 1. Wire Rope Test Systems



ℓ_2 >4 ROPE LAY LENGTHS; $\simeq$ 26 x ROPE DIAMETER

$\ell_1 = \frac{\pi D}{2}$; D = SHEAVE DIAMETER

FIGURE 2. Test Sections Within Each Rope Sample

with the new ANSI standards for mining ropes. Sheave groove throat angles of 30 degrees were used on all sheave grooves and groove depths were set at the nominal rope diameter. After machining, all sheave grooves were flame-hardened to R_c = 55 to 60, so that no significant changes in sheave groove contour would occur during testing.

The selected rope tension was achieved and maintained through constant hydraulic pressure on the sheave load actuator. The load-pressure calibration of this actuator was determined before testing with a precision load cell traceable to the National Bureau of Standards. The linearity and stability of this calibration was within 2 percent.

STANDARD BEND-OVER-SHEAVE FATIGUE TESTS

Laboratory bend-over-sheave fatigue tests were performed on 3/4-inch and 1-1/2-inch diameter wire rope to develop baseline data for estimating the service lives of larger hoist ropes used in surface mining draglines and shovels.

An effort was made to procure 3/4-inch and 1-1/2-inch diameter ropes that were as similar as possible to the large hoist ropes that are typically used. The 3-inch diameter rope, B', tested at PNL, for example, is representative--it was a 6 x 57 filler-wire Seale, Lang-lay, IWRC rope. It was not possible to obtain exactly the same construction in the smaller diameters, but it was possible in most cases to obtain constructions having the same number of outer wires per strand. By maintaining similarity in the number of outer wires, it was possible to scale down the critical outer strand wires in direct proportion to the rope diameter.

The matrix of wire rope bend-over-sheave fatigue test parameters is shown in Table 1. Wire ropes were obtained from two different manufacturers for both the 3/4- and 1-1/2-inch diameter ropes. One manufacturer supplied filler-wire Seale (FWS) ropes while the other supplied Warrington Seale (WS). In this way, it was possible to examine the potential effects of modest differences in construction on bending fatigue resistance. Two sheave-to-rope diameter ratios (D/d ratios) and four design factors were considered so that the traditionally

TABLE 1. Matrix of Bend-Over-Sheave Fatigue Tests

Rope Diameter, in.	Rope Manufacturer	D/d 20 Design Factor 2	D/d 20 Design Factor 3	D/d 20 Design Factor 4	D/d 20 Design Factor 6	D/d 30 Design Factor 2	D/d 30 Design Factor 3	D/d 30 Design Factor 4	D/d 30 Design Factor 6	Rope Construction	Number of Outside Wires per Strand	Rope Breaking Strength, lbs Rated[d]	Rope Breaking Strength, lbs Actual
3/4	M		X	X			X	X		6 x 36 WS[b]	14	55,800	
	H		X	X	X	X	X	X	X	6 x 41 FWS[c]	16	55,800	65,900
1-1/2	M		X	X						6 x 41 WS	16	216,000	
	H		X	X			X	X	X	6 x 41 FWS	16	216,000	252,000
3[a]	B'					X	X	X		6 x 57 FWS	16	796,000	

(a) Tested at PNL.
(b) Warrington Seale.
(c) Filler-wire Seale.
(d) These rated strengths were established based on the Wire Rope Handbook (1966) Newer standards of the wire rope industry (Wire Rope Users Manual 1979) give approximately 5 percent higher breaking strengths.

used bearing pressure ratio value could be examined for a range of test conditions. Rated and actual (where available) breaking strength for each rope construction are also tabulated. Note that actual strengths exceed rating by over 15 percent. This has been observed previously (Gibson et al. 1974) and is considered typical.

The bearing pressure ratio value or Drucker-Tachau factor (Drucker and Tachau 1944) was first proposed in 1944 as an empirical factor or design criterion which could be used to correlate wire rope bending fatigue data (for a particular construction) generated at different combinations of wire strength, rope diameter, sheave diameter, and rope tension. It is expressed as:

$$B = \frac{2T}{UDd} , \tag{1}$$

where T = rope tension, lb.

U = wire ultimate strength, psi

D = sheave diameter, in.

d = rope diameter, in.

Because the wire rope fatigue test machines are designed to test two ropes simultaneously, two test results were obtained for each combination of rope diameter and sheave diameter. Both ropes rarely fail at exactly the same time, so the standard procedure was to cycle them both until one rope specimen failed, and then replace the failed rope with a dummy rope of the same construction. The test was then restarted and continued until the second rope also failed. The primary criterion for rope failure was failure of one strand, although some data on accumulated wire breaks were also taken, and in most cases it was possible to identify failure according to common field practice and ANSI MII recommendations, i.e., when either 6 broken wires in one lay length or 2 broken wires in one strand of one lay were broken.

The baseline bend-over-sheave fatigue data generated on the 3/4-inch diameter ropes are listed in Tables 2 and 3 for the 6 x 36 WS and 6 x 41 FWS,

TABLE 2. Bend-Over-Sheave Fatigue Test Results for 3/4-Inch Diameter, 6 x 36 WS, Lang Lay, IWRC Wire Rope

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
20	3.00	7N	--	33756	11.2	6.27
		7S	--	32796		
	4.00	6N	--	50944	8.41	4.71
		6S	--	54850		
30	3.00	2N	58278	80118	7.47	4.18
		2S	53772	69226		
	4.00	1N	84236	106906	5.60	3.14
		1S	81406	108544		

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

TABLE 3. Bend-Over-Sheave Fatigue Test Results for 3/4-Inch Diameter, 6 x 41 FWS, Lang Lay, IWRC Wire Rope

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
20	3.11	10N	--	45786	15.4	7.98
		10S	--	44008		
	3.00	9N	72810	78520	10.8	5.62
		9S	66708	72810		
	4.00	8N	--	109534	8.12	4.22
		8S	74242	94436		
	6.00	11N	85402	125050	5.41	2.81
		11S	103390	125164		
30	3.00	4N	88344	120358	7.21	3.75
		4S	91822	125954		
	4.0	3N	138024	179642	5.41	2.81
		3S	142820	186762		
	6.0	12N	129480	352868	3.61	1.88
		12S	330468			

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

Lang Lay, IWRC wire rope constructions. The data for the two ropes are compared in terms of bearing pressure ratio and cycles to one strand failure in Figure 3. Distinct logarithmic linear trends are evident for the two rope constructions. The only substantial deviation from linear trends is evident for the D/d = 20, design factor = 6 test data on the 6 x 41 FWS rope. It appears that the bearing pressure ratio tends to overestimate life for low D/d levels and design factors above 4 or 5. The bearing pressure ratio trends remain logarithmic linear for a D/d of 30 at all design factors tested.

In an attempt to reconcile the different rope trends for the two rope constructions, a modification of the bearing pressure ratio was considered. The modified bearing pressure ratio is simply the standard expression given in Equation (1) multiplied by the ratio of the outer wire diameter to the rope diameter as follows:

$$B^1 = \frac{2T\ d_w}{UDd^2} \tag{2}$$

where dw = outer wire diameter, inch.

The 3/4-inch diameter wire rope data are replotted in Figure 4 in terms of the modified bearing pressure ratio. Some layering of the data still remains, although a best-fit logarithmic linear regression of the pooled data gave a correlation coefficient of over 90 percent, and no single data point deviates from the mean by more than a factor of 1.5. Considering that deviations as large as a factor of 1.4 existed for the individual rope regression analyses, the modified bearing pressure ratio will be taken as an adequate parameter for the representation of the 3/4-inch diameter wire rope bending fatigue data.

The baseline bend-over-sheave fatigue data generated on the 1-1/2-inch diameter ropes are listed in Table 4 for both the 6 x 41 WS and 6 x 41 FWS, Lang Lay, IWRC wire rope construction. A plot of these data in terms of the modified bearing pressure ratio is given in Figure 5. The resultant best fit logarithmic linear trend line was virtually parallel to the 3/4-inch rope trend

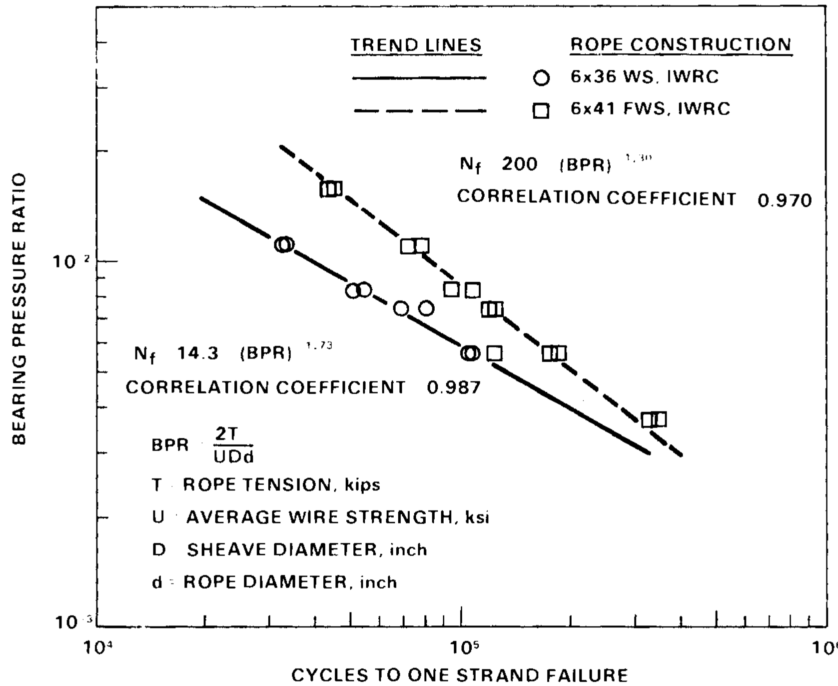


FIGURE 3. Cycles to Failure as a Function of Bearing Pressure Ratio for Two 3/4-Inch Diameter Rope Constructions

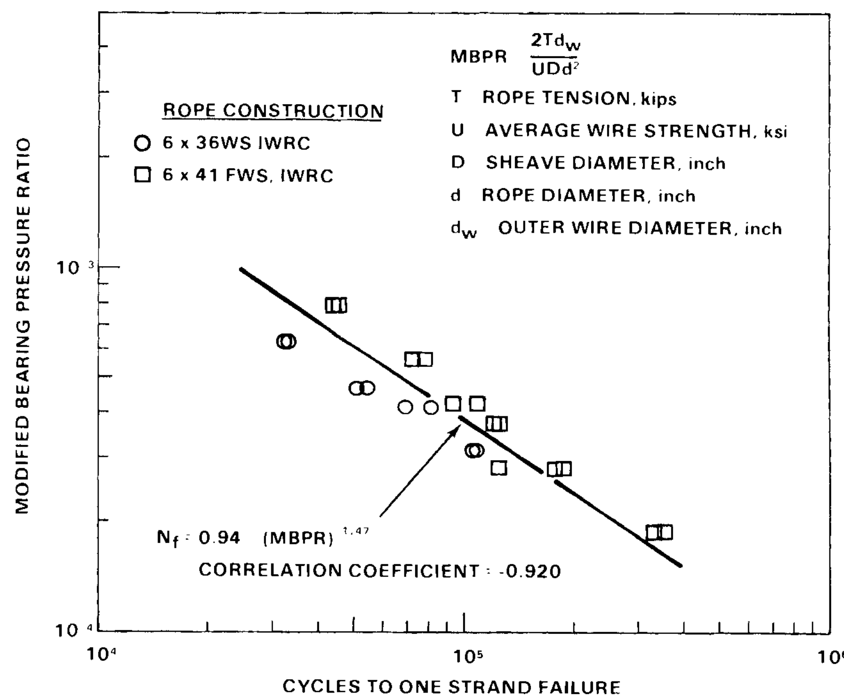


FIGURE 4. Cycles to Failure as a Function of the Modified Bearing Pressure Ratio for Two 3/4-Inch Diameter Rope Constructions

TABLE 4. Bend-Over-Sheave Fatigue Test Results for Two 1-1/2-Inch Diameter, 6 x 41, Lang Lay, IWRC Wire Ropes

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
			6 x 41 WS			
20	3.05	2N	36480	47598	10.9	5.53
		2S	36480	43090		
	4.00	1N	56800	69360	8.33	4.22
		1S	45590	57542		
20	3.63	4N	47284	59354	9.12	4.68
		4S	51414	57988		
	4.00	3N	60880	66498	8.27	4.25
		3S	56780	64976		
			6 x 41 FWS			
30	3.05	6N	75616	99082	7.23	3.71
		6S	75616	91940		
	4.00	5N	101806	137030	5.52	2.83
		5S	87230	125648		
	6.00	7N	153832	213988	3.68	1.89
		7S	163526	226494		

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

line and it was displaced by about a factor of 1.30 in life below the smaller rope trend line. This shift might be construed as a rope size effect although this conclusion cannot reliably be drawn since the 1-1/2-inch diameter rope data fall on top of the 3/4-inch diameter, 6 x 36 WS wire rope data and it may simply be that the 3/4-inch diameter 6 x 41 FWS wire rope displayed abnormally high fatigue resistance. (In this context it should be noted that virtually identical rope trends were observed in an earlier study on the basis of the modified bearing pressure ratio for ropes of the same diameter that differed in the number of exterior wires per strand.)

The trends established in Figures 4 and 5 for cycles to failure of one strand should be viewed in comparison to Figure 6, where the cycles to attainment of the "6 and 2" wire break retirement criterion are plotted as a function of the modified bearing pressure ratio for all four rope constructions. There is more variability in these data although a logarithmic linear trend line provides a reasonable representation of the data. The slope of the line is steeper, which indicates that the difference between cycles to attainment of the broken wire criterion and cycles to one strand failure becomes greater for decreased loads and increased D/d values. Above a modified bearing pressure ratio of about 6×10^{-3}, strand failure develops very shortly after the development of a concentration of broken wires in the rope.

EXPLORATORY BEND-OVER-SHEAVE FATIGUE TESTS

Five different exploratory experiments were conducted. The first was conucted to investigate the impact of sheave hardness on wire rope bending fatigue life. The second study was completed on a prototype 8 x 25 FW, IWRC wire rope to evaluate its potential as a dragline or shovel hoist rope. The third investigation was conducted to examine the influence of a modified rope lubricant on the fatigue properties of the 6 x 41 FWS construction.

The fourth experiment was done to examine the influence of alternating high and low rope tensions on bending fatigue life. The last study was initiated to determine whether nylon sheaves would enhance wire rope bending

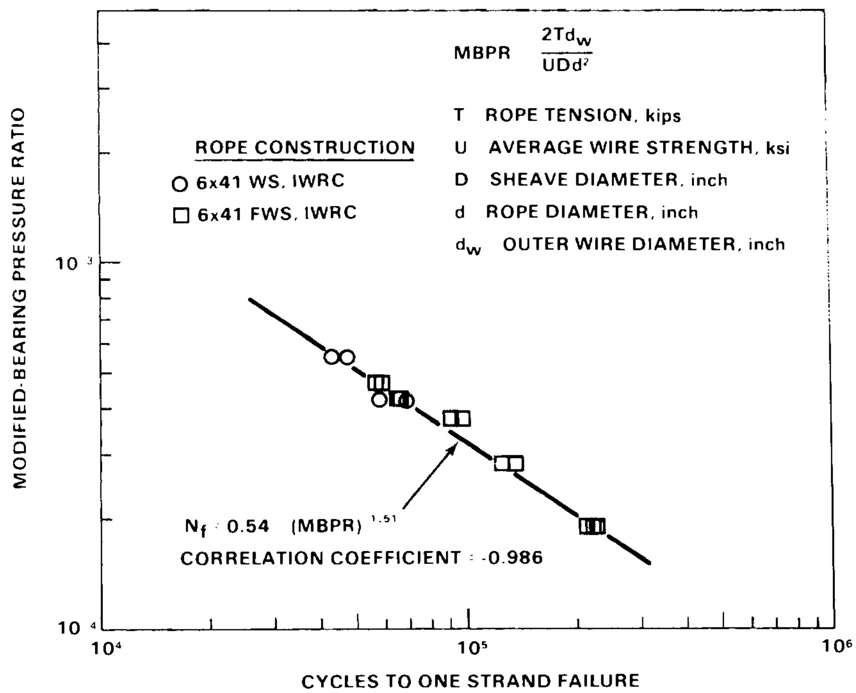


FIGURE 5. Cycles to Failure as a Function of the Modified Bearing Pressure Ratio for Two 1-1/2-Inch Diameter Rope Constructions

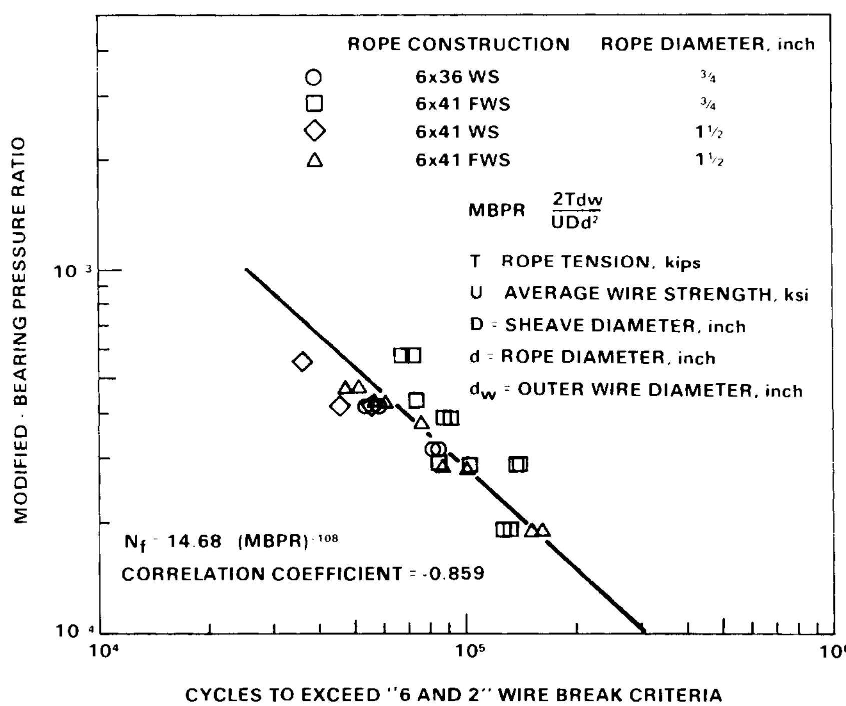


FIGURE 6. Cycles to Retirement Criteria as a Function of the Modified Bearing Pressure Ratio for Four Rope Constructions

fatigue resistance beyond that observed on standard steel sheaves. The experimental procedure and the results are reviewed in the following paragraphs.

<u>Sheave Hardness Effects</u>

To examine the influence of sheave hardness on wire rope bend-over-sheave fatigue resistance, a series of experiments was performed on unhardened, no initial oversize sheaves. The sheaves were manufactured from hot rolled steel plate--R_c hardness of about 20. The sheave groove geometry was the same as used for the standard tests except that the sheave groove radius was machined to 0.375 inch (no oversize) rather than 0.401 inch (7 percent oversize).

The test results for the no initial oversize, unhardened sheave tests are presented in Table 5. These results are presented graphically in Figure 7. Again a logarithmic linear trend is evident. The results, in comparison to Figure 6, were surprising, in that there was little effect on bending fatigue resistance due to the unhardened, no initial oversize sheaves. The trend line for the 6 x 41 FWS rope tested on unhardened sheaves does fall slightly below the 6 x 41 FWS rope data generated on hardened sheaves and the difference increases with decreasing values of the modified bearing pressure ratio, but the trend lines are very similar when both 3/4-inch ropes tested on hardened sheaves are included in the comparison. Under the controlled laboratory conditions of this study it must be said that the hardness of the sheaves had little impact on wire rope bending fatigue resistance.

It was noted in these experiments that the sheave groove diameter increased rapidly during the first rope test, but that it soon stabilized at about 3 to 4 percent over the nominal rope diameter, which, of course, matches the oversize seen commonly in new ropes. The sheave groove did continue to wear into the sheave, however, and the surface of the groove became heavily scarred as shown in Figure 8. After 280,000 bending cycles on the D/d = 20 sheaves, the sheave grooves had worn an average of 0.012 inch. Similarly, after 500,000 bending cycles on the D/d = 30 sheaves, the sheave grooves had worn an average of 0.021 inch. This corresponds to a wear rate of about 0.042 inch per million cycles. Eventually, this wear would make the sheave unsatisfactory for service, especially in a field situation involving occasional significant fleet

TABLE 5. Bend-Over-Sheave Fatigue Test Results for a 3/4-Inch Diameter, 6 x 41 FWS Wire Rope Tested on Unhardened, No Initial Oversize Sheaves

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
20	3.0	4N	48078	57252	10.8	5.62
		4S	48078	56590		
	3.0	5N	43816	58724	10.8	5.62
		5S	48916	59972		
	4.0	6N	66354	94404	8.12	4.22
		6S	73930	79966		
30	2.0	9N	50944	66452	10.8	5.62
		9S	--	65812		
	2.4	8N	59706	76612	9.01	4.69
		8S	70234	83080		
	3.0	1N	37404	97834	7.21	3.75
		1S	55448	81974		
	3.0	2N	73566	108512	7.21	3.75
		2S	65356	101090		
	4.0	3N	48028	144432	5.41	2.81
		3S	75722	149966		

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{d_w}{d}$, where d_w = outer wire diameter.

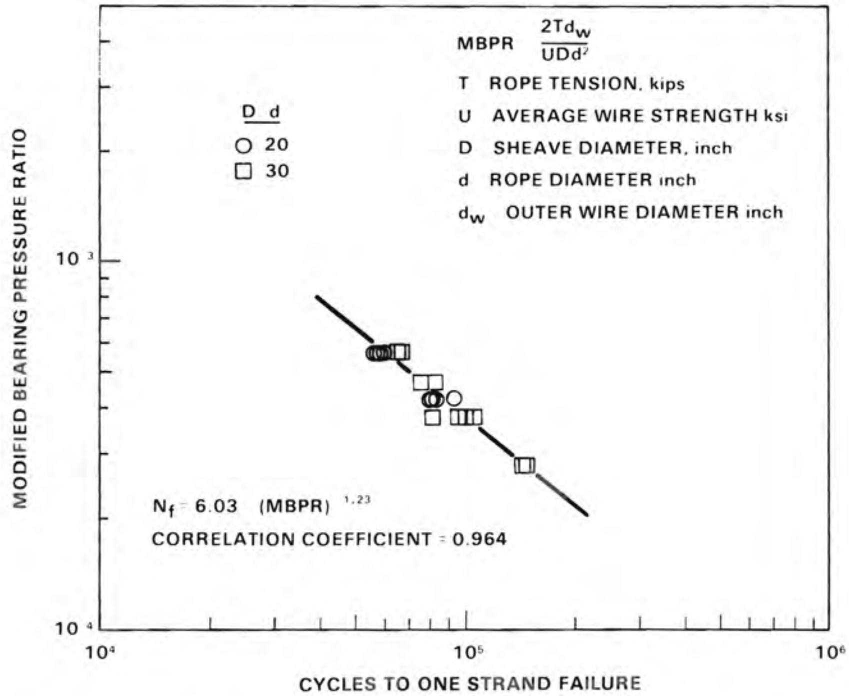


FIGURE 7. Cycles to Failure as a Function of the Modified Bearing Pressure Ratio for 3/4-Inch Rope on Unhardened, No Initial-Oversize Sheaves

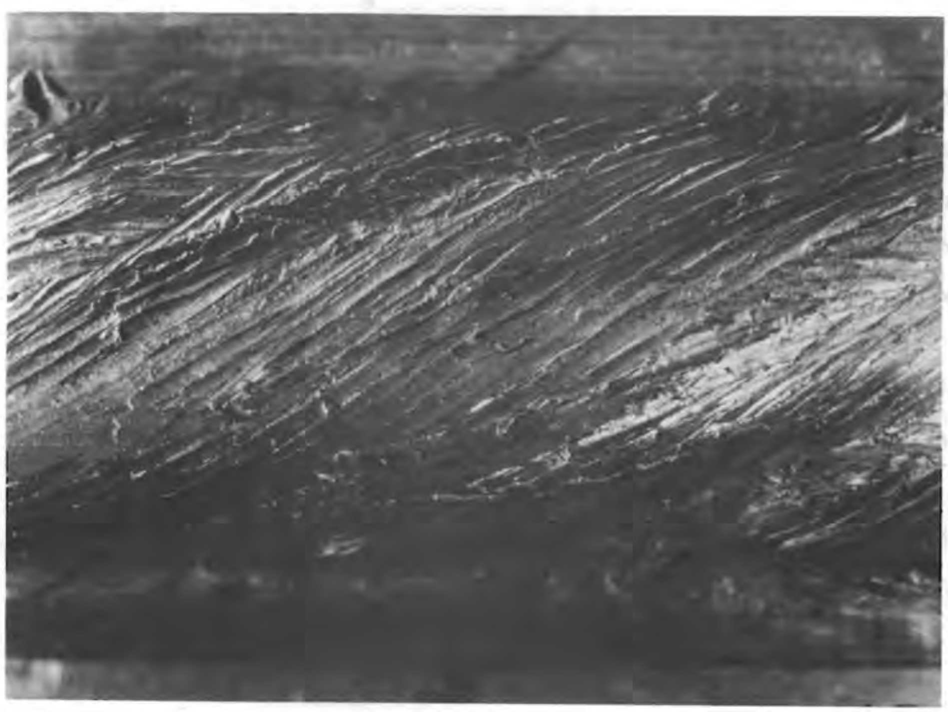


FIGURE 8. Groove of Unhardened D/d = 20 Sheave After 250,000 Bending Cycles

angles, because the throat angle of the sheave groove effectively changes with groove wear from 30 degress to 0. This leaves a U-shaped sheave groove that would be very damaging to the wire rope if any fleet angle developed.

It is important to note that the results found in this experiment probably do not relate particularly well to the field situation where a surface-hardened sheave groove has worn. In the field, the geometry of the sheave groove would not change so readily to accommodate the rope as it wears. Instead, the sheave groove diameter is likely to reduce to below the nominal rope diameter and induce high compressive forces on the rope which could be very damaging and cause very short bending fatigue lives.

Alternative Construction Study

Improved bending fatigue resistance is an important goal in designing new rope constructions for hoist rope usage in large draglines and shovels. Recent work at BCL has demonstrated this usefulness of the modified bearing pressure ratio in approximately correlating the bending fatigue resistance of 6-strand wire ropes having different numbers of outer wires per strand. This consolidation works because there is a consistent trend of improved fatigue resistance with an increased number of smaller outside wires per strand. (Of course, wear resistance diminishes, but this discussion centers on bending fatigue resistance.) A logical extension of this idea was to prepare the construction of a wire rope with small outside wires relative to the rope diameter. Ropes wider than 2 inches in diameter are typically not available with more than 16 outer wires per strand. The 6 x 41 FWS wire rope obtained for this study has 16 outer wires, for example. Since an 18-outer-wire-per-strand, 6-strand rope could not be obtained in the desired diameter, an 8-strand rope construction was considered. With an 8-strand rope, given the same number of outside wires per strand, the outside wires are approximately 16 percent smaller. Subsequently, an effort was made to obtain a 1-1/2-inch diameter, 8 x 41 FWS wire rope. The only rope manufacturer found willing to build a special rope construction offered an 8 x 25 FW, Lang Lay, IWRC rope rather than the 8 x 41 FWS. The 8 x 25 FW rope is a 12-outer-wire-per-strand construction, so it was not considered optimal for purposes of this study, but it was still of sufficient interest to warrant a limited experimental evaluation.

Two bend-over-sheave fatigue tests on standard hardness D/d = 30 sheaves were completed on the 8 x 25 FW wire rope. The results are compiled in Table 6. Comparison of these test results on the basis of the modified bearing pressure ratio with 6 x 41 FWS data on 1-1/2-inch diameter rope (Figure 7) shows very similar trends. This is another way of saying that, for the same rope tensions and D/d ratios, the 8 x 25 FW rope gave slightly lower fatigue resistance. This was predicted since the outer wire diameter of the eight-strand rope was 8 percent larger than the outer wires of the six-strand rope. On the average then, it would be expected that an 8-strand, 16-outer-wire-per-strand rope construction would exhibit longer bending fatigue lives for the same rope tensions and D/d ratios because such a rope would have smaller outer wires.

These comments regarding the benefits of small outer wires should be tempered with consideration for practical field usage situations. Drag ropes on draglines are generally more prone to damage by wear than bending fatigue. These ropes must have relatively large outer wires to resist wear. Even some hoist ropes experience enough scrubbing and sliding on sheaves and drums that wear effects cannot be discounted. The apparent recommendation is to use wire ropes in hoist rope applications with as many outer wires per strand as can be obtained and used successfully without introducing significant wear-related problems. In surface mining wire ropes of 3 inches in diameter and greater, this means that some low-wear hoist rope applications could probably be best served with 18-outer-wire-per-strand constructions (such as 6 x 55 WS and 6 x 61 FWS).

Modified Rope Lubricant Testing

It has been demonstrated elsewhere (VDI 1968; Lex 1954) that lubricants placed in a rope during manufacture and/or applied afterward during usage can substantially increase wire rope bending fatigue life. The specific issue to be addressed in this study was whether a low-viscosity, maintenance-type lubricant could be used to advantage over a conventional asphaltic lubricant as an internal lubricant applied during rope manufacture. The question arises from the fact that the asphaltic lubricants are believed to be less effective as

TABLE 6. Bend-Over-Sheave Fatigue Test Results for a 1-1/2-Inch Diameter 8 x 25 FWS, Lang Lay, IWRC Wire Rope

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[a]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[b] Ratio	Modified Bearing Pressure[c] Ratio x 10^{-3}
20	3.05	2N	136480	147598	10.9	5.53
30	3.00	1N	71624	>76638[d]	7.36	4.07
		1S	66174	76638	7.36	4.07
	4.00	2N	100204	120620[d]	5.52	3.05
		2S	85264	>120620	5.52	3.05

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

(d) Rope removed somewhat before one strand failure to facilitate examination and identification of initial sites and causes of wire failures.

boundary lubricants than specific low-viscosity maintenance lubricants. Effective boundary lubrication is necessary at wire-to-wire contact points in a rope to reduce friction and wear which can lead to fatigue damage. The asphaltic lubricants are also frequently incompatible with lubricants applied during rope maintenance and are more inclined to pick up dirt.

A low-viscosity maintenance lubricant was chosen from among the best lubricants examined in another BCL program (Jentgen 1978). An arrangement was made with a rope manufacturer to introduce this lubricant into a 3/4-inch diameter, 6 x 41 FWS wire rope during manufacture. A series of bend-over-sheave fatigue tests was planned to examine the fatigue resistance of the modified lubricant rope in comparison to the standard asphaltic-base-lubricated, 6 x 41 FWS rope. Testing was curtailed because of funding restrictions but two sets of ropes were successfully tested in bending fatigue before the effort was terminated. The results of those tests are presented in Table 7. The fatigue lives obtained at the high load fell slightly above baseline fatigue trends shown in Figure 6, while the fatigue lives obtained at the low load fell somewhat below baseline trends.

The mediocre results may be attributable to the very modest quantity of lubricant that was applied during manufacture. Visually, and to the touch, the ropes were essentially dry. Before any definite conclusions can be made regarding the suitability of the low viscosity lubricant for use as manufacturing lubricant, some additional study is needed. Tests similar to those already completed should be done using a more liberally lubricated test rope. In addition, comparative tests should be performed in which the maintenance lubricant is added periodically during cycling to regular asphalt-base lubricant ropes and modified lubricant ropes.

Combined High-Low Load Tests

Most laboratory wire rope bending fatigue data are generated at constant rope tensions, even though almost no field rope experiences constant rope tension throughout its service cycle or its lifetime. In order to examine whether constant amplitude data could be used in a meaningful way to estimate the

TABLE 7. Bend-Over-Sheave Fatigue Test Results for a 3/4-Inch Diameter, 6 x 41 FWS, Lang Lay, IWRC Wire Rope Manufactured with a Low-Viscosity, Maintenance-Type Lubricant

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure		Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
			6 and 2 Criteria	One Strand Broken		
20	3.00	1N	55,618	61,210	10.8	5.62
		1S	69,548	>69,548	10.8	5.62
	4.00	2N	72,202	75,272	8.12	4.22
		2S	79,940	84,888	8.12	4.22

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

fatigue life of a wire rope subjected to variable loads, such as are seen in the field, a series of combined high-low load tests was planned. Only one test was completed within the curtailed program period but it is worthy of a brief discussion.

The experiment which was conducted involved the 3/4-inch diameter 6 x 41 FWS wire rope on D/d = 30 sheaves. The rope tension history involved repeated blocks of 4,000 cycles at a design factor of 3.00, followed by 4,000 cycles at a design factor of 6.00. These rope design factors were chosen to simulate the "full-bucket" and "empty-bucket" portions of the dragline hoist rope operating cycle. To allow ready comparison with the other wire rope fatigue data, the results are presented in Table 8. It is not readily apparent from this table whether the fatigue lives obtained would have been expected based on previous constant load test results. Based on simple linear damage calculations, predictions of bending fatigue life were made as presented in Table 9. Calculations were made for both failure criteria, and it is apparent that both predictions were quite good. The actual number of bending cycles to the "6 and 2" criterion exceeded the prediction by 4.2 percent, while the actual number of bending cycles to one-strand failure fell below the prediction by only 0.7 percent.

Additional experiments should be performed to verify these results, but the indication is that the fatigue life of a wire rope subjected to two distinct load levels (such as are seen by most field ropes) can be reasonably estimated by using baseline fatigue data. When predicting the fatigue life of hoist ropes used in surface mining machines it is apparent that the baseline fatigue data representing cycles to exceedance of the "6 and 2" wire break criterion should be used, since that criterion most closely represents the retirement criterion used in the field.

<u>Nylon Sheave Experiments</u>

Several recent studies (Chen and Gage 1979; Chen and Ursel 1979) have concluded that the bending fatigue life of wire ropes can be extended significantly through the use of elastomeric sheave materials in place of

TABLE 8. Bend-Over-Sheave Fatigue Test Results for a 3/4-Inch Diameter, 6 x 41 FWS, Lang Lay, IWRC Wire Rope Tested at Alternating High-Low Rope Design Factors

Sheave to Rope Diameter Ratio, D/d	Design Factor d.f[(a)]	Specimen Identification	Cycles to Failure: 6 and 2 Criteria	Cycles to Failure: One Strand Broken	Bearing Pressure[(b)] Ratio	Modified Bearing Pressure[(c)] Ratio x 10^{-3}
30	3.00/6.00(d)	1N	95,882	147,672	7.21	3.75
		1S	111,982	149,844	3.61	1.88

(a) d.f. = rated rope strength/rope tension.

(b) $B = \frac{2T}{UDd}$, where U = outer wire strength and T = rope tension.

(c) $B' = B \cdot \frac{dw}{d}$, where d_w = outer wire diameter.

(d) Repeated blocks of 4,000 cycles at design factor of 3.00, followed by the same number of cycles at design factor of 6.00

TABLE 9. Fatigue Life Predictions for Two-Load Level, Bend-Over-Sheave Fatigue Test

Design Factor	Cycles/Block	Predicted Damage Fraction/Block Base On 6 and 2 Failure Criterion[(a)]	One-Strand Failure Criterion[(b)]
3.00	4,000	0.0543	0.0392
6.00	4,000	0.0258	0.0142
	Predicted Damage/ Block	0.0801	0.0534
	Predicted Blocks to Failure Criterion	12.48	18.73
	Actual Average Blocks to Failure Criterion	13.00	18.59
	Present Error Predicted to Actual	+4.2%	-0.7%

(a) Based on best fit line for 6 x 36 WS and 6 x 41 FWS combined data shown in Figure 6.

(b) Based on best fit line for 6 x 36 WS and 6 x 41 FWS combined data shown in Figure 4.

traditionally used steel sheaves. This study was undertaken to investigate this claim for rope constructions and sheave D/d ratios representative of hoist rope service in large surface mining machines.

Nylon sheaves, 45-inch pitch diameter and 3 inches thick, were obtained for fatigue testing 1-1/2-inch diameter, 6 x 41 FWS Lang Lay, IWRC rope. A design factor of 4.0 was chosen for testing. Unfortunately, the sheaves deformed substantially when operated under full rope tension. Sheaves of this size made entirely from nylon have never been evaluated before and the "dishing" of the sheaves resulting from cold-flow of the nylon was not anticipated. In less than 1,000 bending cycles the "dishing" had become so severe that the alignment of the sheave in the fixture was lost and the sheave containment bolts were broken. Attempts to constrain the outside edge of the sheave from warping did not remedy the problem. Additional attempts to stiffen the sheave with steel plates around the hub were also unsuccessful. Within the available time period, it was not possible to operate the sheave successfully because of dimensional instability and low stiffness. No useful bending fatigue data were obtained. Nylon used as a sheave groove liner in large sheaves might well be a more practical alternative. Nylon used in this way may be useful in improving wire rope bending fatigue resistance, but this conclusion awaits laboratory and field verification.

SINGLE WIRE EXPERIMENTS

Experiments on individual wires taken from wire ropes used in this program were completed to 1) document the monotonic tensile properties and 2) attempt to identify the cyclic behavior of the wires under conditions involving cyclic plasticity, such as a wire experiences at a cross-wire contact point in a rope.

Monotonic Stress-Strain Experiments

Tensile tests were performed on wires taken from the 3/4-inch, 1-1/2-inch and 3-inch diameter wire ropes so that a comparison in static tensile properties of the wire materials could be made. Only the outer wires in each rope construction were tested. The wires were tested in displacement control in an electrohydraulic test system. At least a 10-inch gage length was used in each experiment. The resulting data are given in Table 10. This table includes information on the rope construction and diameter from which the wires were taken as well as a range of experimental measurements and computations including proportional limit stress, yield strength, ultimate tensile strength, apparent elastic modules, reduction in area, the Ramberg-Osgood shape parameter, and the plastic strain coefficient. These data are based on an average of two tensile tests per wire size for each rope size/construction. Table 11 shows an example of stress records for one wire size and rope construction.

In summary, the 3/4- and 1-1/2-inch diameter rope wires exhibited little difference in tensile strength or reduction in area. The values found corresponded favorably with AISI standards for extra-improved plow steel wire. The 3-inch rope wire material was substantially lower in strength and corresponded more closely to improved plow steel strength standards. The yield strengths and proportional limit stresses were quite variable, because of differences in strain hardening behavior; this is reflected in the substantial difference in Ramberg-Osgood shape parameters.

Cyclic Stress-Strain Experiments

To induce controlled strain conditions in rope wires it was necessary to devise means for performing fully reversed, strain-controlled axial fatigue cycling experiments. To the authors' knowledge, this had never been done before. To avoid buckling of the wires during compressive loading, a very short gage length specimen fixture was considered as shown in Figure 9. A 0.153-inch diameter wire is shown, although tests were attempted on wires as small as 0.040 inch. Initially, the ends of the wires were gripped with split, conical wedges that were compressed around the wire into mating conical housings as described in Rungta and Rice (1981).

This arrangement worked well for determination of cyclic material properties of the wire, but it resulted in nearly 50 percent end failures for the experiments continued to cyclic failure. End failures were reduced by using a hardenable epoxy to "socket" the wire ends in the conical housing. The lower

TABLE 10. Individual Wire Tensile Properties[a]

Rope Diameter, inch	Rope Construction	Wire Diameter, d , inch	Proportional Limit P.L., ksi	Yield Strength,[c] y, ksi	Tensile Strength, u ksi	Apparent Elastic Modulus,[d] E.X. 10^3 ksi	Reduction in Area, R.A., %	Ramberg-Osgood Value, n	Plastic Strain Coefficient, K
3/4	6 x 36 WS	.042	138.	235.	295.	32.0	38.	5.60	1.05×10^{-14}
3/4	6 x 41 FWS	.039	111.	213.	285.	30.8	52.	4.53	5.75×10^{-12}
1-1/2	6 x 41 WS	.076	95.	212.	288.	27.5	51.	3.71	4.65×10^{-16}
1-1/2	6 x 41 FWS	.077	137.	230.	286.	26.5	49.	5.83	3.41×10^{-15}
3	6 x 57 FWS	.149	129.	190.	221.	25.6	55.	7.75	4.52×10^{-19}

(a) Based on an average of 2 tensile tests per wire size for each rope/size construction.

(b) Based on plastic strain level of 0.01%

(c) Based on plastic strain level of 0.20%

(d) Listed as "apparent" because not established from precision modulus experiment, a likely value for these wire materials would be 29 x 10^3 ksi.

TABLE 11. Stress-Strain Data for 3/4-Inch Diameter Rope 6 x 36 WS, 0.42-Inch Diameter Wire

Stress, σ ksi	Spec. No. 1 Total Strain ε_t %	Spec. No. 2 Total Strain ε_t %	Elastic Strain[(a)] ε_e %	Average Plastic Strain[(b)] ε_{pavg} %
20	0.64	0.58	.062	----
40	.132	.120	.125	.001
60	.196	.177	.187	----
80	.263	.238	.250	.0005
100	.328	.297	.312	.0005
120	.400	.359	.375	.0045
140	.469	.423	.437	.009
160	.555	.499	.500	.027
180	.643	.577	.562	.048
200	.749	.674	.652	.086
220	.871	.791	.687	.144
240	1.03	.934	.750	.232
260	1.24	1.13	.812	.373
280	1.47	1.36	.875	.540
290	1.66	1.54	.906	.694

(a) Based on a value of $E = \sigma/\varepsilon_{tavg}$ at σ = 80 ksi

(b) $\varepsilon_{pavg} = \dfrac{\varepsilon_{t_1} + \varepsilon_{t_2}}{2} - \varepsilon_e \quad , \quad \varepsilon_e > 0.0$

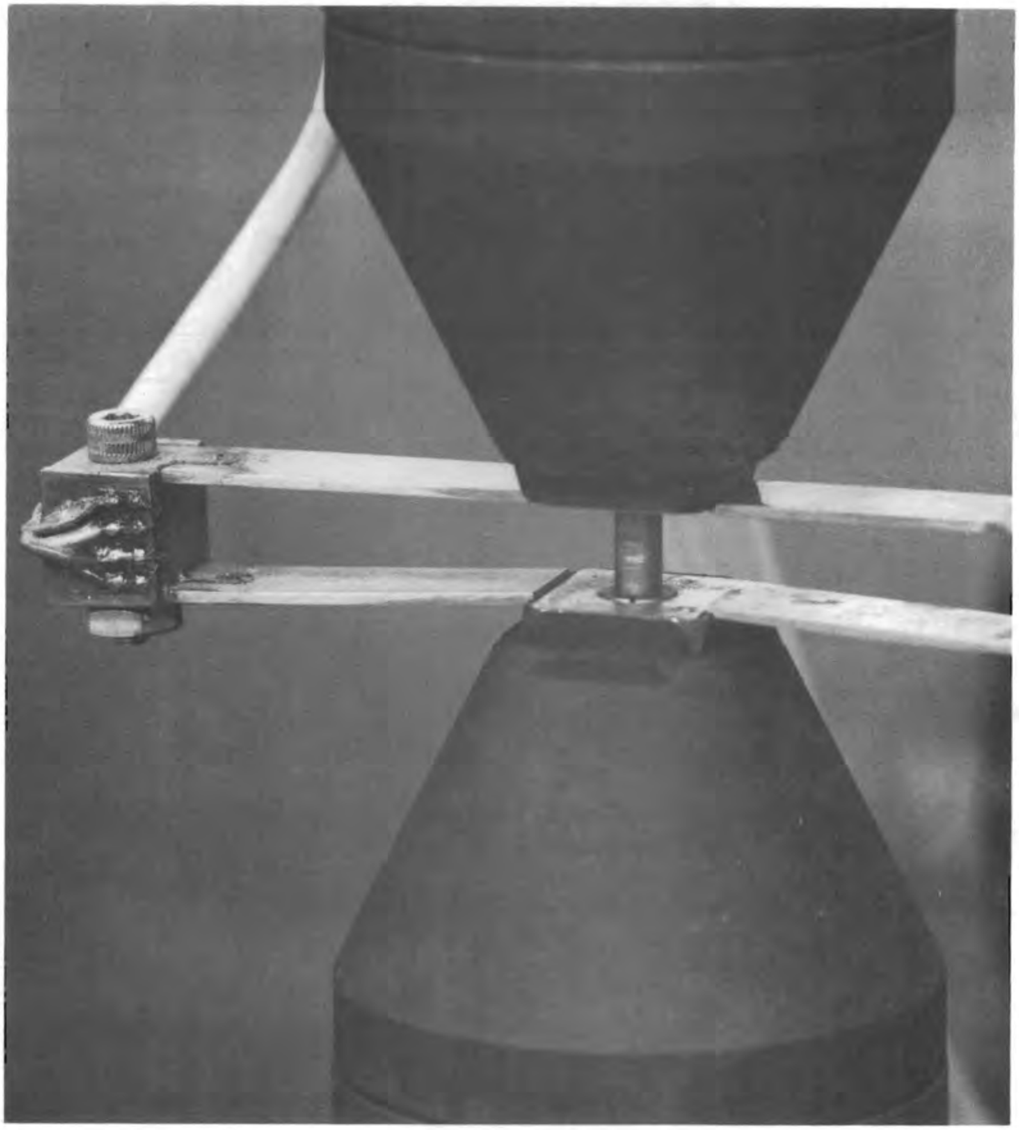


FIGURE 9. Initial Axial-Strain Controlled Fatigue Setup For Single Rope Wires

modulus epoxy aggravated another problem, however--a slight wire movement into and out of the grip during cycling. This movement biased the indicated strains produced by compliance gages mounted between the fixtures. Movements were less than 0.0020 inch, but they were nearly as large as the displacements required to induce a 1 percent strain in a 0.075-inch diameter wire sample 0.150 inch long. The net result was a false indication of strain in the wire.

A solution to the problem of false wire strain readings was found by using cylindrical buckling guides with machined openings large enough to attach longitudinal extensometry directly on the wire sample. A longer wire sample could be used with the buckling guides and the slight movement of the wires in the epoxy grips ceased to be a problem. Using this approach, a limited quantity of data was generated before the single-wire efforts were terminated.

The only fatigue data obtained were on a 0.153-inch diameter wire typical of the wire used in a 3-inch diameter, 16-outer-wire-per-strand rope construction. Using the direct longitudinal strain measurement device, it was possible to identify significant cyclic softening of the wire when subjected to large strain amplitudes (of 0.5 percent and above). The monotonic and cyclic stress-strain curves are shown in Figure 10 for the 0.153-inch diameter wire.

The observed softening occurred very rapidly, and nearly stable behavior was seen after less than 50 cycles. Typical hysteresis loops for the beginning of an experiment are shown in Figure 11. The strain softening is quite evident. The stability of the stress response after initial softening is evident in Figure 12, where the tensile stress amplitude versus cycles is plotted for several experiments. The two experiments shown in Figure 11, which were run at lower strain amplitudes, showed essentially stable response throughout the test until failure.

These experiments imply that the highly worked, hardened wires used in a wire rope can be expected to cyclicly soften at cross-wire contact points in a rope where repeated plastic deformation takes place. A secondary implication is that any analysis directed toward the quantitative prediction of wire rope fatigue behavior, that relies on a knowledge of local stresses and strains, will not be accurate unless the cyclic response of the rope wire material is well characterized. Only limited data are available to date, but it is not unreasonable to expect that strain control fatigue tests on wires from several different ropes would offer a good indication of the relative fatigue resistance of each rope.

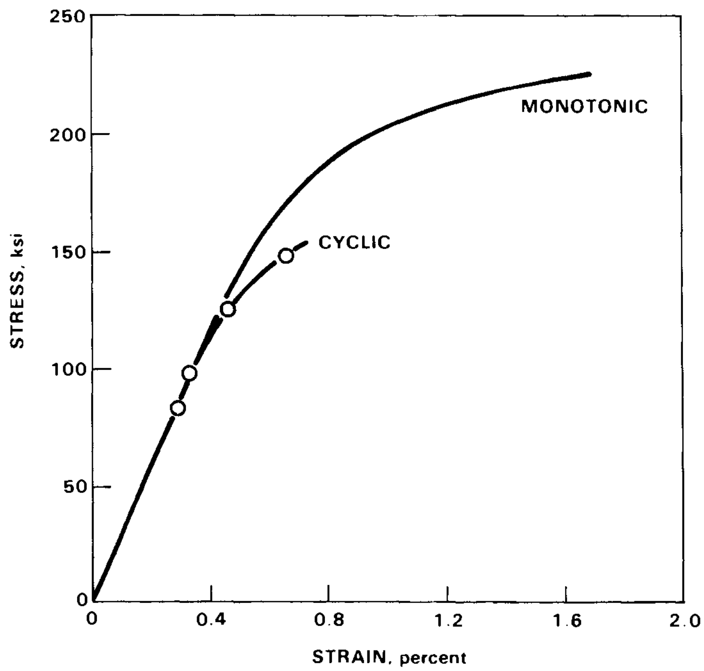


FIGURE 10. Cyclic and Monotonic Stress-Strain Curves for a 0.153-Inch Diameter Wire, Manufacturer H

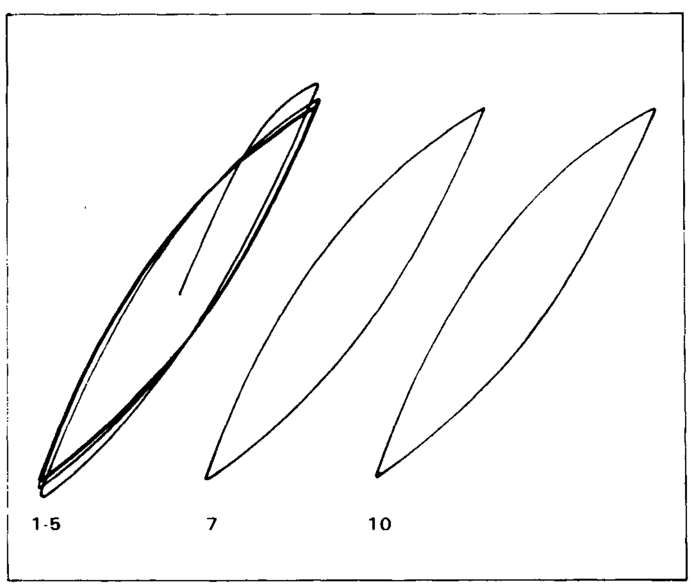


FIGURE 11. Cyclic Stress-Strain Hysteresis Loops for a 0.153-Inch Diameter Wire, Manufacturer H

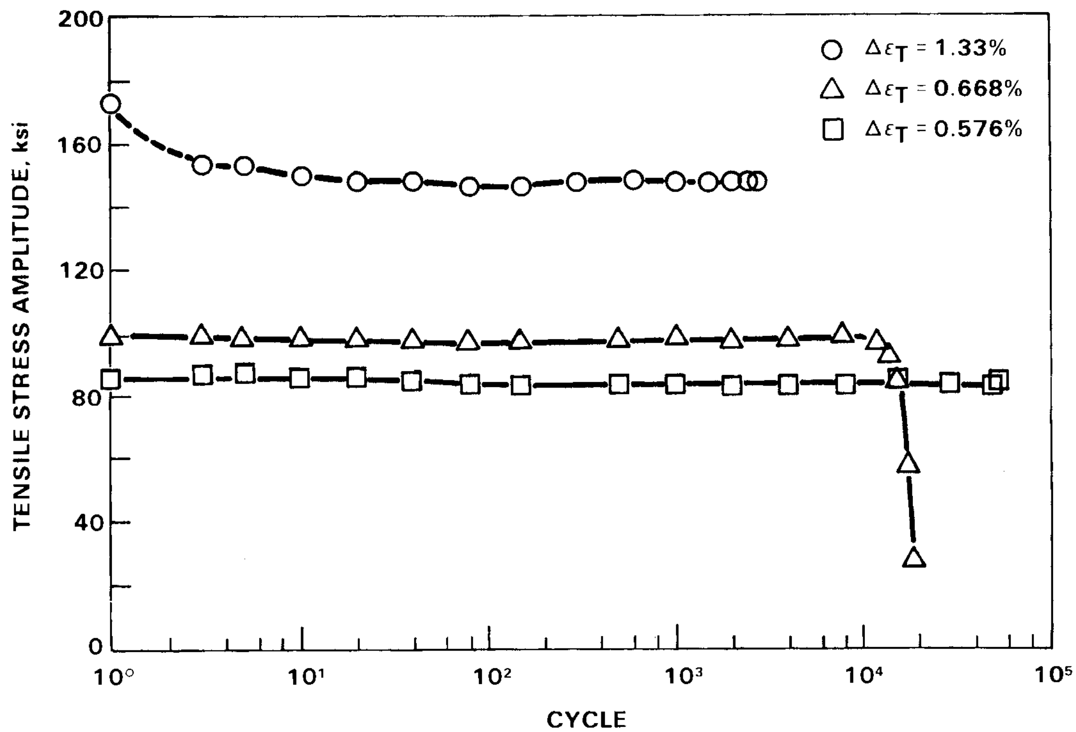


FIGURE 12. Tensile Stress Amplitude Versus Cycles for a 0.153-Inch Diameter Wire, Manufacturer H

CORRELATION OF LABORATORY AND FIELD ROPE FATIGUE LIVES

An obvious and very important consideration in this program was the relationship between laboratory test results and actual field rope service performance. Fortunately, a limited number of carefully documented field data on hoist ropes were obtained by PNL and these data were transmitted to BCL for review. These data are presented in Table 12. The raw data include the bucket size and weight, point sheave diameter, rope diameter, and average yardage of overburden removed before rope retirement. With a few reasonable assumptions, it was possible to convert these data into a form that was directly comparable to the laboratory developed data. The results of that analysis of the field data are presented in Table 13.

First, a D/d ratio was computed to identify the severity of bending over the point sheave. Second, the number of machine operating cycles before rope retirement was computed as the yardage removed before retirement divided by the bucket size. Rehandle was not considered in the computation of machine

TABLE 12. Field Data on Hoist Rope Fatigue Performance

Mine	Bucket Size, yd^3	Bucket Weight, pounds	Point Sheave Diameter, inches	Hoist Rope Diameter inches	Overburden Removed Before Rope Retirement, yd^3
11	58	116,000	120	3	4,094,000[a]
3	60	140,000	120	3	4,876,000[a]
8	100	200,000	144	4 1/2	3,258,000[a]
6	41	80,000	85 1/4	2 7/8	3,598,000[a]
5	70	140,000	110	3 1/2	4,424,000[b]

(a) An average value based on a series of ropes over a period of time.

(b) A single rope retirement yardage.

TABLE 13. Analysis of Field Rope Data

Mine	Sheave to Rope Ratio D/d	Machine Operating Cycles[a]	Estimated Bucket Load When Full,[b] lbs.	Approximate Design Factor[c] Bucket Full	Bucket Empty	Rope Outer Wire Diameter, in.	Approximate Modified Bearing Pressure Ratio[d] x 10^{-4} Bucket Full	Bucket Empty	Equivalent Value
11	40	70,600	272,600	4.40	10.3	.153	2.11	0.89	1.58
3	40	81.250	302,000	3.97	8.57	.153	2.33	1.09	1.72
8	32	32,575	470,000	5.48	12.9	.230	2.02	0.87	1.53
6	29.6	87,775	190,700	5.82	13.9	.147	2.17	0.92	1.61
5	31.4	63,205	329,000	4.90	11.5	.178	2.37	1.01	1.77

(a) Bending Cycles = $\frac{\text{Yardage Removed}}{\text{Bucket Size}}$ x 2 (2 bending cycles/operating cycle).

(b) Based on overburden weight of 2700 lb./yd^3, could actually vary from 2100 lb./yd^3 to 3200 lb./yd^3 depending on type of overburden.

(c) Based on 6 x 61, IWRC, Lang Lay, Ips Wire Rope, and Bucket suspended at 20 degrees from vertical with drag rope at 15° below horizontal (i.e. load magnification factor of 1.20)

(d) $B' = \frac{2 \cdot \text{Individual Rope Tension} \cdot \text{Rope Wire Diameter}}{\text{UTS} \cdot \text{Sheave Diameter} \cdot \text{Rope Diameter Squared}}$, where UTS = 220,000 psi.

cycles, since exact values were unknown. It is not unlikely that 10 to 20 percent rehandle did occur in some cases, which, of course, would have increased actual rope bending cycles beyond those computed. This factor is probably at least partially compensated for, however, by the fact that the bucket is not always full during every dump cycle.

Third, the full bucket weight was estimated based on an overburden density of 2,700 pounds per cubic yard. This density of overburden would correspond to dry clay and gravel. Densities as low as 2,050 pounds per cubic yard are found for loose, dry earth, while densities as high as 3,400 pounds per cubic yard are found for wet sand and gravel. Acknowledging this potential spread in overburden density, a density of 2,700 pounds per cubic yard was chosen as a reasonable average. Fourth, the approximate design factors for the bucket, both full and empty, were computed based on a pair of 6 x 61 class, IRWC, Lang Lay wire ropes of improved plow steel grade. The design factors were computed based on a bucket position factor (or load magnification factor) of 1.20. This factor is required to account for the angle from vertical in which the bucket is held during a dumping cycle. This consideration is discussed more completely in Appendix A. Fifth, the outer wire diameters of each pair of ropes were computed based on 16 outer wires per strand (which most 6 x 61-class ropes have).

Finally, different MBPR values were computed based on a full bucket and an empty bucket. These calculations were straightforward, once a wire strength level was assumed. An ultimate strength value of 220 ksi was chosen as typical of IPS grade wire rope in the 3- to 5-inch diameter range.

Using the above estimates of modified bearing pressure ratio and a "6 and 2" wire break retirement criterion, the number of rope bending cycles to retirement were predicted as shown in Table 14. Using this approach, the predicted operating life before retirement was overestimated in four out of five cases, and rope lives were overestimated by 27 percent on the average. There are probably several reasons for this significant overestimation of fatigue lives. Rehandle, as already mentioned, could account for much of this discrepancy. Crown wire wear in the laboratory was not appreciable, whereas in the

TABLE 14. Fatigue Life Predictions for Field Hoist Ropes

Mine	Bending Cycle	Approximate MBPR, $\times 10^{-4}$,	Predicted Damage Fraction/Machine Cycle[(a)] $\times 10^{-6}$	Predicted Machine Cycles to Retirement Criteria	Actual Machine Cycles to Retirement Criteria	Percent Error Predicted to Actual
11	Full Bucket	2.11	7.30			
	Empty Bucket	0.89	2.87			
			10.17	98,330	70,600	-28.
3	Full Bucket	2.33	8.13			
	Empty Bucket	1.09	3.58			
			12.71	78,680	81,250	+3.3
8	Full Bucket	2.02	6.97			
	Empty Bucket	0.87	2.81			
			9.78	102,250	32,575	-68.
6	Full Bucket	2.17	7.53			
	Empty Bucket	0.92	2.98			
			10.51	95,150	87,755	-7.8
5	Full Bucket	2.37	8.28			
	Empty Bucket	1.01	3.30			
			11.58	86,360	63,205	-27.
			Average	92,150	67,080	-27.

(a) Based on 6 and 2 wire break retirement criteria, i.e., $N_i = 14.68 \cdot (\text{MBPR})^{-1.08}$, Damage = $1/N_i$.

field it can be, and somewhat shorter lives might be expected as a result. Related to this, sheave groove geometry and fleet angles are potential field problems that can reduce life. Dynamic loads were not considered in this analysis, and recent work at PNL indicated that dynamic loads can be significant. Most of these factors are very hard to quantify accurately unless considerable effort is exerted during rope usage. Therefore, it appears most practical at this time to recommend the analysis procedure described here along with a safety factor of about 1.3 on laboratory rope lives to put estimated field rope lives into a realistic range.

WIRE ROPE WEAR AND FAILURE ANALYSIS

W. A. Glaeser, R. Erickson, and R. L. Jentgen

Wear and failure analyses conducted at BCL are documented in this section.

ROPE EXAMINATION PROCEDURES

A number of samples were obtained from ropes retired from operating coal mine draglines. An additional three rope samples were obtained from PNL. One sample was of a new rope; the other two were from ropes tested on the bend-over-sheave machine at PNL.

The field samples were obtained when a machine was being reroped. The site was visited at this time and samples of the drag ropes were selected. Four- to six-foot sections were cut with a torch from the bucket end, the fair-lead traverse section and the section nearest the drum when the bucket is at the bottom of the pit.

Rope sections were then transported to BCL and their condition recorded by photography in the as-received condition.

Dirt was removed from the exterior of the rope so that the condition of the outer wires could be examined and photographs taken. An example of a cleaned rope sample is shown in Figure 13.

A strand was then removed from the rope section and the condition of the lubricant, notching of strand-to-strand contacts, IWRC notches or wire breaks and valley breaks were investigated.

The rope with a strand removed was photographed for the record. An example of the conditions found is shown in Figure 14. The features mentioned above were examined by hand magnifier and the general condition of the interior of the rope assessed.

Several wires were removed from the strand and cleaned in solvent. Segments were cut out of the wires for microscopy. Segments containing notches and wire-to-wire contact scars were examined by light microscopy and by scanning electron microscopy (SEM). Both light microscopy and SEM are considered

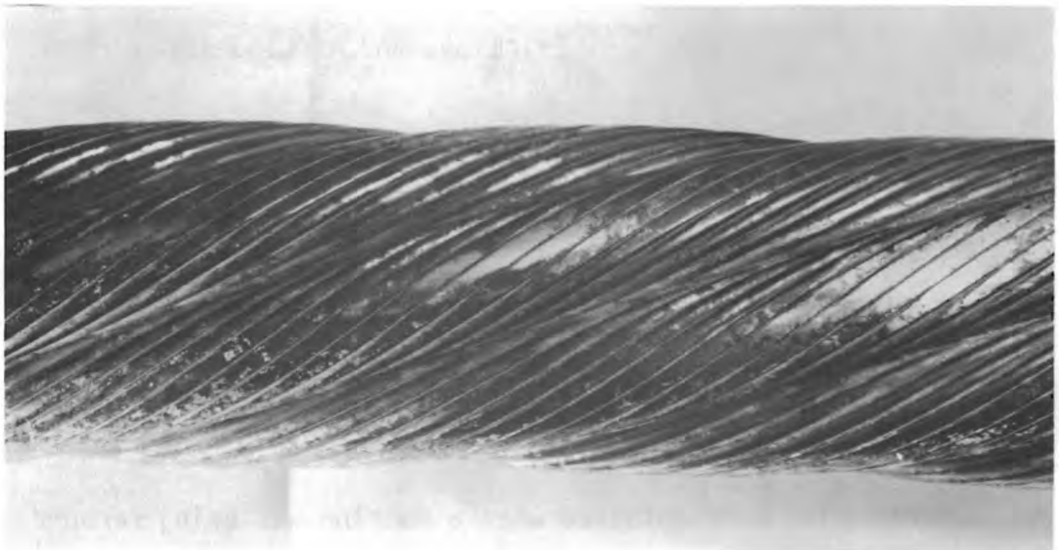


FIGURE 13. Field Sample After Cleaning Showing Outer Wire Wear

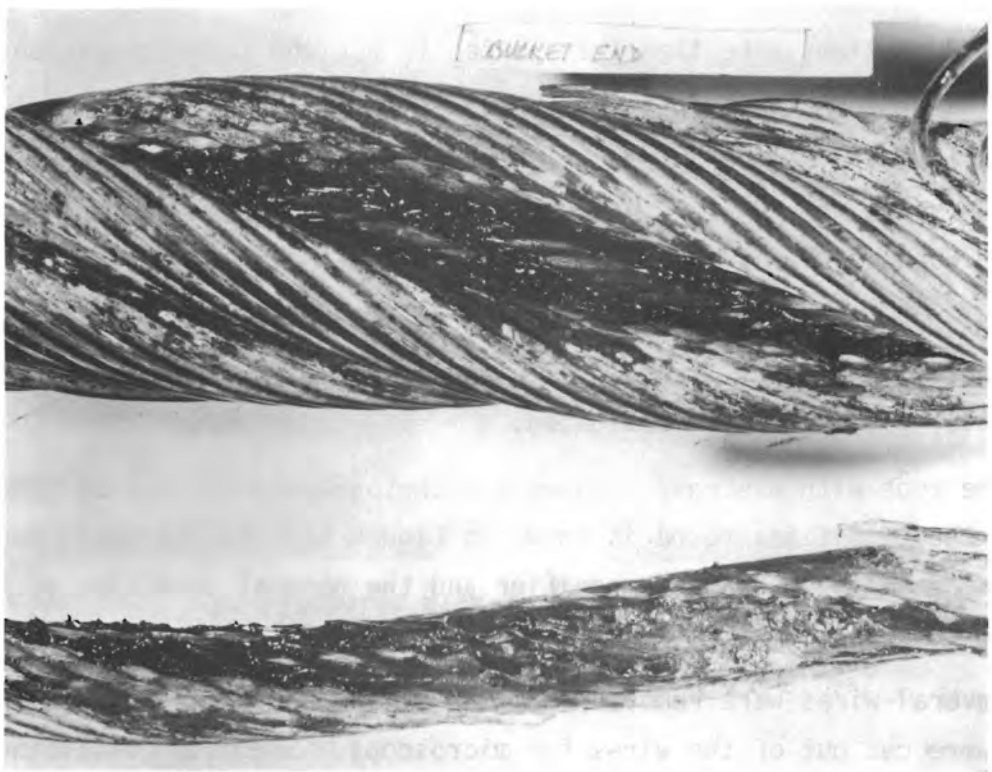


FIGURE 14. Field Sample with Strand Removed to Show Condition of Lubricant

important because each is capable of revealing specific features of the surface morphology. Further discussion of nondestructive examination techniques is presented in Appendix C.

Metallographic sections were made through selected areas of wires removed from the sample rope sections. The metallographic sections were examined in both the as-polished and etched conditions. The as-polished examinations were used to determine the extent of nonmetallic inclusions in certain samples and to analyze for subsurface cracking. Etched samples were examined principally to determine the extent of subsurface deformation and to detect transformed (white etching) layers. Deformation was assessed by observing the extent of grain boundry tilt at near-surface locations and the drawing out of ferrite grains into thin lathes. Sectioning was done through notches at strand-to-strand contact zones with the metallographic section plane oriented to the direction of surface flow. Abraded outer wires were also sectioned and the section lane was oriented parallel to the abrasion striations. Sections were also made in the vicinity of wire fractures. Right sections were made through selected wires to check and compare the overall microstructure.

Selected wire samples were also subjected to chemical analysis by emission spectroscopy. Quantitative analysis was performed for alloying elements and trace elements. Trace elements were included to determine the uniformity of the steel in a given rope.

INITIAL ROPE ANALYSIS

Initial rope inspections consisted of qualitative characterizations of the condition of each rope sample. Visual inspections of the extent and type of wire breakage, wear, contamination, corrosion, and lubricant condition were performed on the rope strands and IWRCs from each specimen. A summary of these observations is provided in tabular form in Appendix B.

To provide a more quantitative indication of the outside wire wear experienced by several rope samples, typical wear regions were measured and the reduction in outside wire cross-sectional area was computed. The results of these measurements are summarized in Table 15. Because these types of ropes are known to support approximately 47% of the applied load with the outside strand wires, the resultant loss of the rope's breaking strength was also computed. These losses are expressed as percent reductions in strength in Table 15.

TABLE 15. Typical Cross-Sectional Area and Strength Reductions Due to Wear of Outside Wires

Sample Identification	% Worn From Outside Wires Range	% Worn From Outside Wires Average	Average Loss of Ropes Load Capacity due to Outside Wire Wear %
Fairlead End	20-22	21	10
Bucket End	18-64	44	21
Bucket End	4-7	5	2
Original Bucket End	31-50	40	19
Final Bucket End	5-25	13	6
Load Cell Drag Line			
Drum End	4-13	11	5
Center	31-37	34	16
Bucket End	15-22	18	8

From the data in Table 15, note that, for the drag ropes examined, the center portion of the rope experiences more outside wire wear than either the bucket ends or the drum ends.[a] Apparently, this is the result of sampling the "most used" section of the rope. That section traversing the fairlead sheaves tends to be in contact with the sheaves during the rope's entire working life, while abrasion at the bucket end is removed by cutoffs and/or reversing rope ends during service. As would be expected, the bucket ends of ropes tended to exhibit greater wear than did the drum ends observed.

(a) "Drum end" samples were those taken from the section of the rope nearest the drum when the bucket is at the bottom of the pit.

The chemical compositions of several wire samples were analyzed using spectrographic techniques. The results of these analyses are listed in Table B.2, Appendix B.

DETAILED ANALYSIS

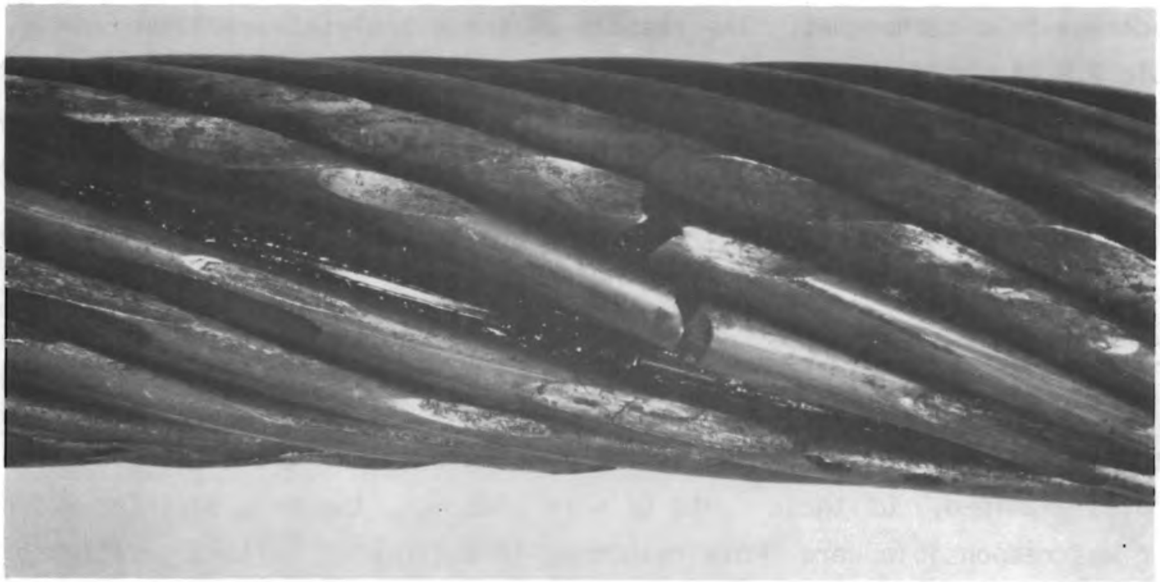
Rope samples were examined in depth for fracturing, notching, and signs of outer wire wear, as well as IWRC deformation and inclusion content.

Wire Fractures

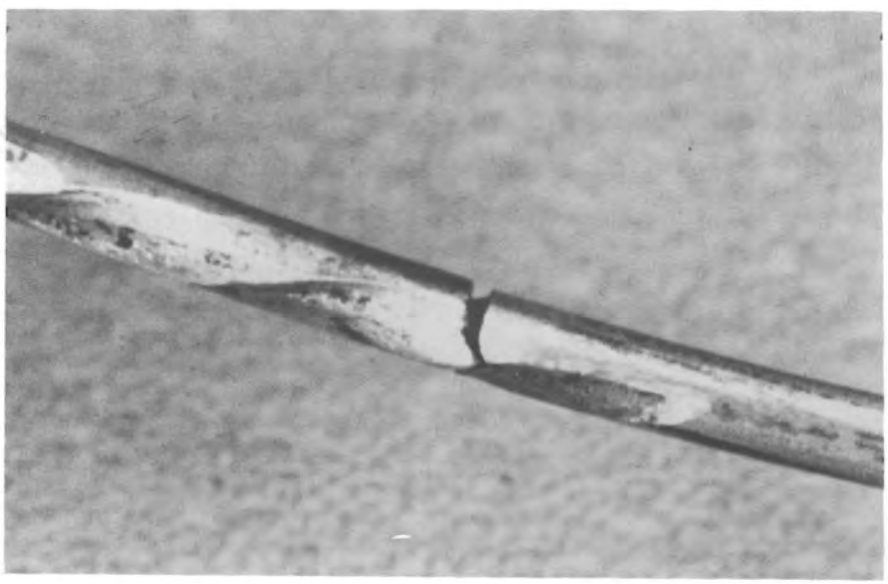
Wire breaks from strand-to-strand contacts (valley breaks), tensile failure of outer wires and crushing of the IWRC were found in a number of the field samples examined. Of these types of wire breakage, the only ones for which wear was responsible were those resulting in outer wire failure. Valley breaks were exclusively fatigue failures.

A typical valley break wire fracture found is shown in Figure 15. Note that one fracture goes through a notch. Fracture analysis revealed that the origin was not in the notch but remote from it. The fracture surface is shown in Figure 16. Note that the typical thumbnail feature characteristic of fatigue indicates fracture origin away from the notch surface. Note also the secondary fractures traveling in the axial direction. This effect was noted for most valley fractures and suggests an axial weakening from inclusions strung out in the axial texture developed by cold drawing. Details of the origin of the fracture are shown in Figure 17. Apparently, the crack started in a nick or indentation in the wire surface.

When the orientation of the fracture origin was established in the strand from which the wire was removed, it coincided closely with the location of the maximum reversing bending stresses expected during flexing of the rope. It can therefore be concluded that the valley breaks found in this particular strand resulted primarily from fatigue and that reduction in section by notching had little to do with the failure. Of the field samples analyzed, no valley breaks were found that could have been generated by the strand-to-strand notching process.



a. Valley Break Fractures in a Strand



b. Fractured Wire Removed from Strand

FIGURE 15. Typical Valley Break Wire Fracture

FIGURE 16. Fracture Surface of Wire Shown in Figure 15

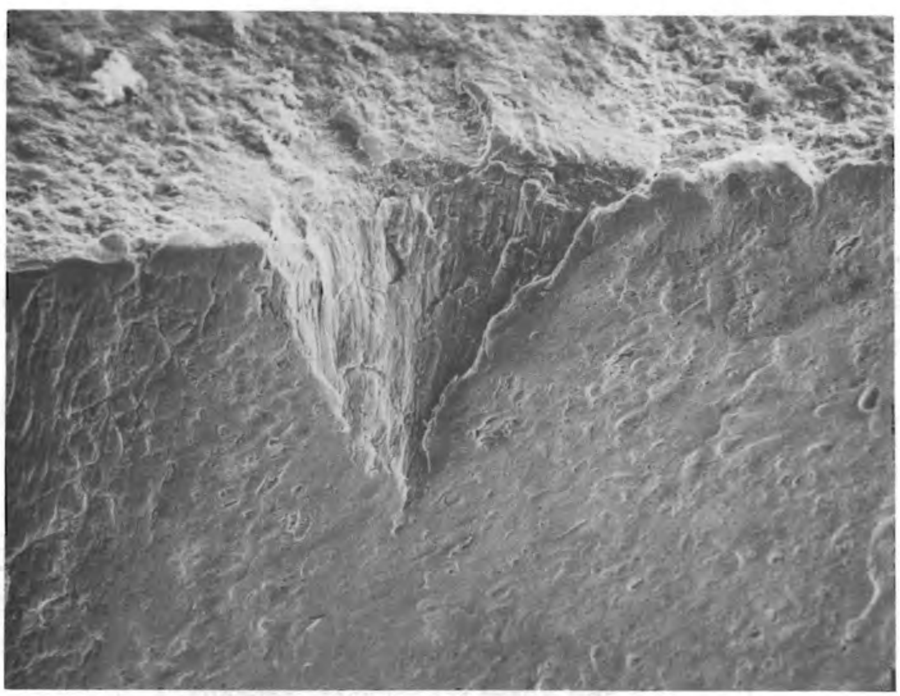


FIGURE 17. Detail of Origin at Defect in Wire Surface

Wire Notching

The internal condition of the rope samples analyzed was modified considerably by notching of wires. Two types of notchings were common in all samples:

- strand-to-strand notching - usually appear in groups of three or four elliptical notches oriented at an oblique angle to the individual wire axis. Matching notches are found on the contacting strand.
- strand-to-IWRC notching - elongated notches on both the IWRC and the strand wires where both come into contact. Quite often the strand wire has two notches with a ridge between them.

Examples of the types of notches described above are found in Figure 18. Note the high visibility of the notches once the rope is opened. The extent of notching seen in used rope was not found in new rope. Notches are present in new rope from the manufacturing process; however, they are much smaller and less noticeable than used rope notches.

Details of a strand-to-strand notch are shown in a composite of three SEM micrographs in Figure 19. The dark flake-like material seen on the surface of the notch is a thin coating made up of a mixture of lubricant remnants and fine debris (oxide, silt, wear particles). This condition is indicative of lubricant starvation.

Although much of the surface of the notch appears bright and shiny to the naked eye, the SEM micrograph shows roughened areas. Gouges can be seen where adhesion and galling have taken place in the contact zone. This further indicates complete lubricant starvation.

The boundary of the notch is ridged--the result of metal flow. Considerable plastic flow of metal can be seen both laterally and axially. The lateral flow is from contact stress yielding. The axial flow is from relative motion between the two surfaces. The axial flow and galling indicate high tangential forces, which would inhibit relative motion between the surfaces. This action, plus the "keying" of the two wires with conforming notches, will tend to reduce rope flexibility and increase stress concentration during bending over sheaves.

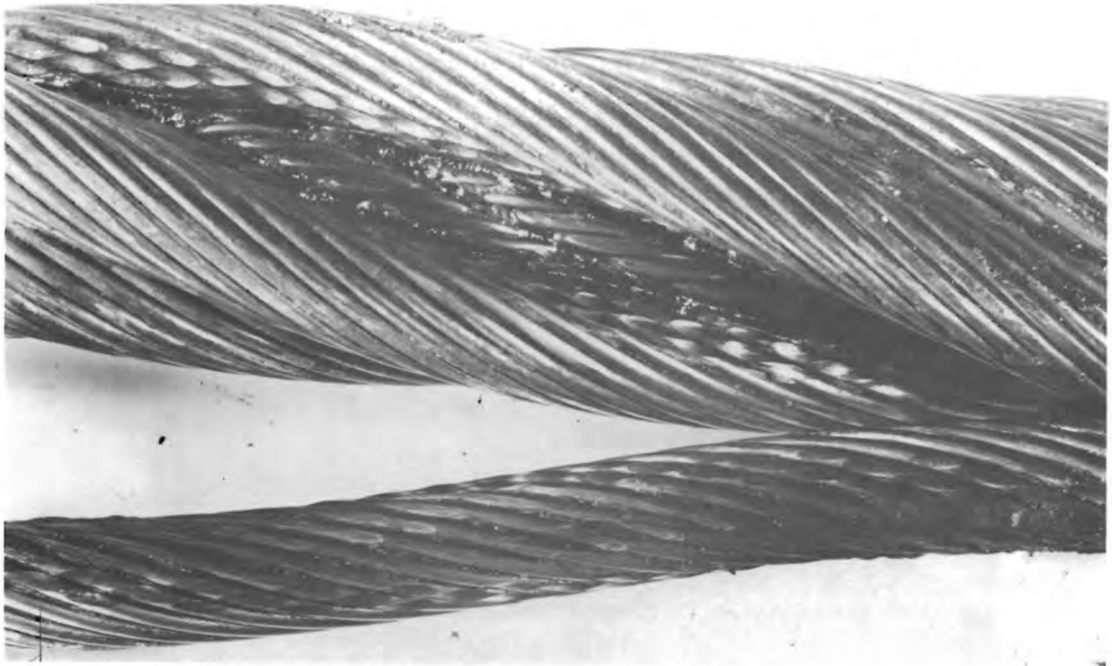


FIGURE 18. Example of Wire Rope Internal Notching

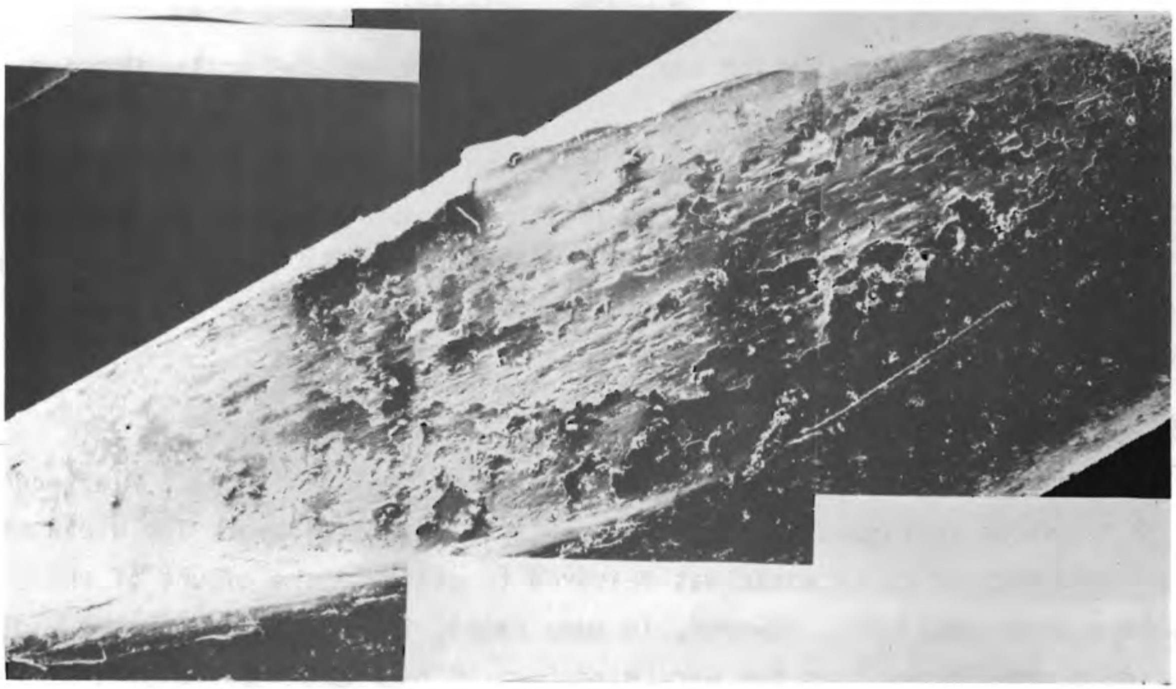


FIGURE 19. Detail Surface Micrograph of Typical Wire Notch from Strand-to-Strand Contact

The size of notches produced by strand-to-strand contact is caused partly by wear. However, a significant part of the notch is the result of plastic deformation. Metallographic sections taken through notches show extensive plastic flow including formation of extruded lips at the boundaries of the notches. A typical section through a notch is shown in Figure 20.

FIGURE 20. Deformation and Extrusion in the Notch-Forming Process

Metal flow is delineated by the texturing of the white ferrite in the structure. Comparing the flow lines in the wear surface with the ferrite grains in the bulk shows that this is a severe deformation process. Presumably, this plastic strain accumulates during service and does not occur all at once, i.e., with the first load application.

Wear of Outer Wires

Outer wire wear was prevalent on all field samples of rope. Flattened wires as shown in Figure 18 could be seen with the naked eye. The width of the flats worn on outer wires was measured to estimate the amount of reduction in wire cross sections. However, in some cases, it was found that the widths measured were larger than the wire diameter. Closer examination of individual outer wires revealed that plastic flow and extrusion of surface material on outer wires tended to produce a flat area wider than a right section through the wire at the given location.

The surfaces of worn outer wires were examined by microscopy and ample evidence was found for abrasive wear. Gouging wear, typical of the wear process associated with hard mineral abrasives, was detected. Abrasion marks were oriented in one direction at a constant angle to the axis of each wire. The surface topography of the worn wires differed substantially from that of the wire-to-wire contact scars. (These scars are always polished and often very bright when viewed at low-power magnification.)

A typical outer wire wear scar is shown in Figure 21. Large abrasion gouging marks can be seen where sharp mineral surfaces have contacted and plowed across the wire surface as the rope was dragged through spoil. Evidence of surface flow and extrusion is seen along the edges of the wear scar. Details of gouging wear can be seen in Figure 22. The rounded debris particles on the surface are corrosion products.

FIGURE 21. Wire Section Flattening and Surface Extrusion in Outer Wire Wear

FIGURE 22. Gouging Abrasion Wear Pattern on Outer Wire

Ropes from bend-over-sheave tests do not have the outer wire wear condition seen in the field ropes. The wires show very little evidence of wear flats. Presumably, the wear associated with sheave contact during testing is insignificant because there is little relative sliding between the rope and the sheave on a test machine. However, sheave overspin effects in a dragline produce considerable rope wear (and sheave wear).

Metallographic sections made of outer wires from field ropes revealed considerable cold working of the surface layers from the abrasion process. Figure 23 exemplifies the extent of subsurface plastic flow resulting from abrasion. A mineral particle can be seen imbedded in the surface. The flow patterns surrounding the imbedded particle indicate that it was gouging the surface before it became immobilized and partly covered by metal extrusion. This is typical of the gouging abrasion mode.

Areas of white etching at the surface of abraded outer wires were often found during metallographic analysis of wire samples. An example of this condition is shown in Figure 24. A two-phase structure can be seen. A layer at the surface shows no structure and, therefore, remains white after

FIGURE 23. Section of Outer Wire from Rope Exhibiting Abrasive Wear

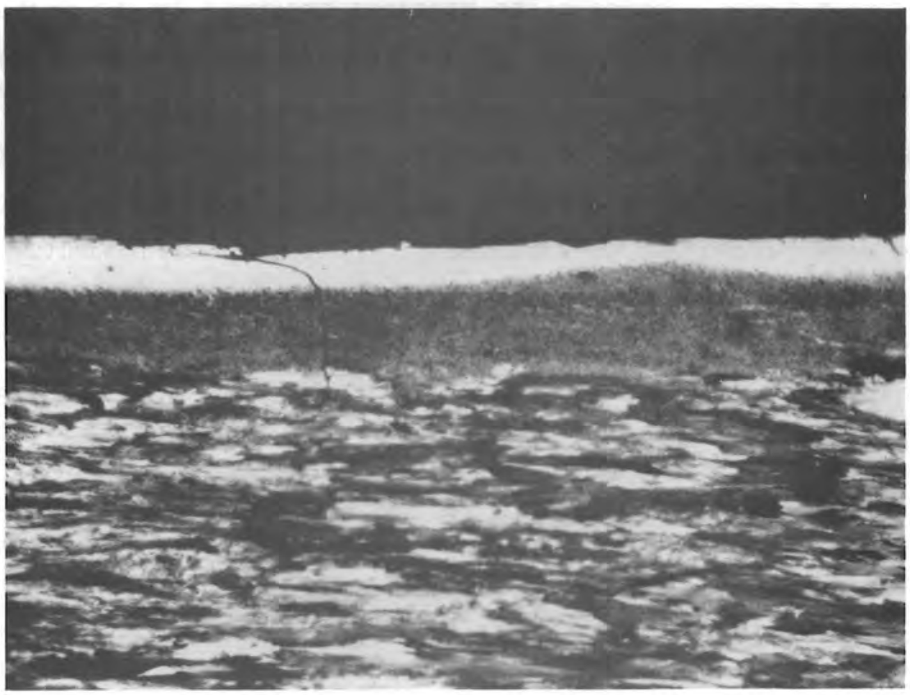


FIGURE 24. Metallographic Section Through Worn Outer Wire Showing White Layer (Rc 64), Intermediate Phase (Rc 48) and Crack

etching. A transition phase between the white layer and the bulk of the undisturbed material shows some structure and is not as hard as the white layer. Microhardness measurements taken in these phases were:

- white layer - 800 Knoop (Rc 64)
- intermediate phase - 500 Knoop (Rc 48)
- undisturbed wire material - 400 Knoop (Rc 40).

The white layer and intermediate phase are presumed to be a zone of very heavy deformation (larger total strain than the textured zones shown in Figure 20). The intermediate zone is presumed to be composed of decomposed carbides imbedded in a high-dislocation matrix possibly arranged in a cell structure. Strain-hardening raises the hardness of this zone above that of the undisturbed wire material. The white layer is presumed to be transformed material, probably untempered martensite. The transformation is not caused by heating to the austenitic transformation level and quenching, but is the result of a large-strain shear process. The hardness measured in the white layer is the maximum hardness that one might expect for untempered martensite formed from steel having the carbon level found in the wire (approximately 0.8 %). Hardness measurements were made on white etching areas found in several of the rope samples analyzed. The hardness levels ranged from 700 Knoop (probably large-strain work hardening) to 1050 Knoop. Hardness measurements for undisturbed wire materials were remarkably consistent. Average microhardness readings for five samples of undisturbed wire materials ranged from 419 to 466 Knoop. Specially etched specimens were examined by SEM to determine whether a fine structure could be detected in the white layer. The tongue area in Figure 25 is shown at high magnification in the SEM micrograph shown in Figure 26. Some structure is resolved in the white etching zone, apparently lathe-like structure presumed to be martensite. Full verification would require selected area diffraction analysis on thin-foil transmission electron microscopy.

IWRC Deformation

The carbon content of IWRC wires is generally lower than that for strand wires in the ropes analyzed. The IWRC wires are softer as a consequence. Notching and wire-to-wire fretting are more severe in this rope component. An example of the extent of notching and wire-to-wire fretting is shown in

FIGURE 25. White Etching Layer on Worn Wire from Field Rope

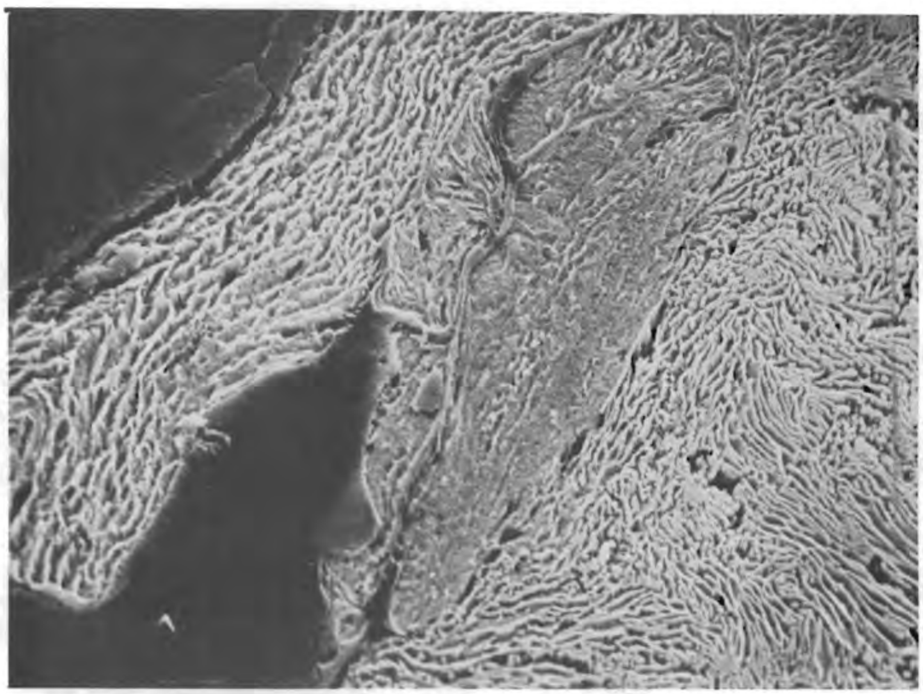


FIGURE 26. SEM Micrograph of Tongue Area, Figure 25

Figure 27. The heavy surface roughening and production of extrusion and fibrous debris can be seen. The depth of the strand-to-IWRC notch is much greater than was found in notches from strand-to-strand contact in the same rope.

Failure of the lubricant to inhibit adhesion and galling in the wire contact area (notch area) is evident from examination of the contact surfaces.

Inclusion Content of Wire

Metallographic sections of wire samples revealed a distribution of fine inclusions. The presence of inclusions was also indicated from the silicon content found in the chemical analyses of selected wires.

Although inclusions appear to be relatively small, their tendency to distribute at ferrite grain boundaries provides a mechanism for development of a delamination type of wear. In the notch areas, where large strains occur near

FIGURE 27. Notching and Wire-to-Wire Contact Fretting in IWRC Wires from 5-Inch Rope

the surface, ferrite grains are deformed into thin plates layered between deformed layers of pearlite. The orientation of the layered structure is parallel to the surface and the inclusions tend to line up along the layer boundaries. This reduces the fracture toughness of the deformed layer and flake-like debris can be generated. An example of delamination wear observed is shown in Figure 28. Note that the fracture separating the wear flake from the bulk material follows the flow lines of the heavily deformed layer. This type of wear mechanism can produce heavy wear because wear-flake thickness can be as much as the thickness of the deformed layer.

SUMMARY

Among the field samples analyzed, a general pattern of wear was found. Severe deformation to depths of 0.001 inch was common at all wear sites including outer wires, strand-to-strand contacts and wire-to wire contacts. Outer wire wear was clearly caused by abrasion. The abrasion action was generally ploughing by hard particles accompanied by surface flow in the direction of sliding. Surface flow produced extrusion of metal at the boundaries of the wear scars on outer wires. The resultant flattening of the outer wires produced a ledge-shaped scar that was often wider than the diameter of the wire.

FIGURE 28. Delamination Wear in a Strand-to-Strand Notch

Estimating the percentage of wire diameter as wear taken place by measuring the widths of outer wire scars can be misleading because of the extrusion of the edges of the wear flats.

The abrasion wear of outer wires was also accompanied by formation of hard white-etching areas and a delamination type of wear. Although some white etching areas were found in strand-to-strand contact notches, this phenomenon was found most often in abraded outer wires. The white etching areas are presumed to be mechanically transformed material--presumably untempered martensite. This material was determined to have the maximum hardness for carbon steel, given the carbon content analyzed. Some light etching areas were presumed to be the result of large-strain work-hardening and probably were composed of a subgrain or cell structure. The untempered martensite often contained radial cracks. The cracks did not extend beyond the white-etching layer and no wire fractures were found that could be associated with white-etching areas.

The heavy deformation associated with abrasive wear produced a texturing of the ferrite-pearlite structure producing very thin plates of ferrite sandwiched between plates of deformed pearlite. Nonmetallic inclusions distributed along the layer boundaries can produce voids during heavy plastic strain, weakening the laminar structure and leading to a delamination type of wear. This process is expected to result in a higher wear rate than might be expected for lower-deformation wear processes.

Notching in the strand wires did not proceed far enough in the samples examined to reduce the load-carrying capacity of the wires involved to a point where tensile fracture might occur. However, notch surfaces were devoid of lubricant and ample evidence of adhesion and galling between the two surfaces was found. It is highly probably that partial immobilization of strand-to-strand, strand-to-IWRC and wire-to-wire contacts occurred in these ropes and the flexibility of the rope was impaired during bending over sheaves. Although all valley breaks examined showed fracture origins remote from notch areas, the freezing of wires at notches might contribute to a stress condition in the rope that would accelerate fatigue failures.

Wire rope samples from bend-over-sheave tests showed very little wear of outer wires. The abrasive wear so prevalent on the field samples was not there. Notching and wire-to-wire fretting was similar to field samples. Thus, failure of tested ropes was more likely associated with fatigue and not wear.

LOAD SENSOR DATA COLLECTION AND ANALYSIS

J. M. Alzheimer, G. H. Beeman, and L. A. Strope

A major effort in the Wire Rope Improvement Program at PNL was the conceptualization and development of a sensing device to accurately measure loads on operating draglines. Such a device, the load sensor was successfully designed and constructed by the summer of 1980. Complete details of the concept's development were fully documented in Morgenstern et al. (1980, Sec. 6.0). This section will describe the collection and analysis of field data obtained with the load sensor. Analysis results and implications are also presented.

DATA COLLECTION

One of the two available load sensors was connected to an operating dragline at a field site near Centralia, Washington, provided by the Washington Irrigation and Development Company. The dragline, equipped with 3-1/4-inch diameter drag ropes and a 60-cubic year bucket, was conducting a benching operation as shown in Figure 29.

DATA DESCRIPTION

The data consited of a load/time history for both drag ropes from the dragline. Four hours of data were collected for subsequent analysis. The reader must recognize here that the data obtained by PNL represent the operation of a particular dragline benching in a particular type of overburden. Hence, the following analysis should not be construed as representative of all dragline operations.

A typical load/time history is shown in Figure 30. During the four hours of data taken, 171 cycles were recorded for the left rope (as viewed from the cab) and 179 cycles were recorded for the right rope. The difference in the number of cycles was due to time spent initially calibrating the incoming signal. Data obtained for each rope are summarized in Table 16. Accuracy of the loads is better than $\pm 10\%$ of recorded values.

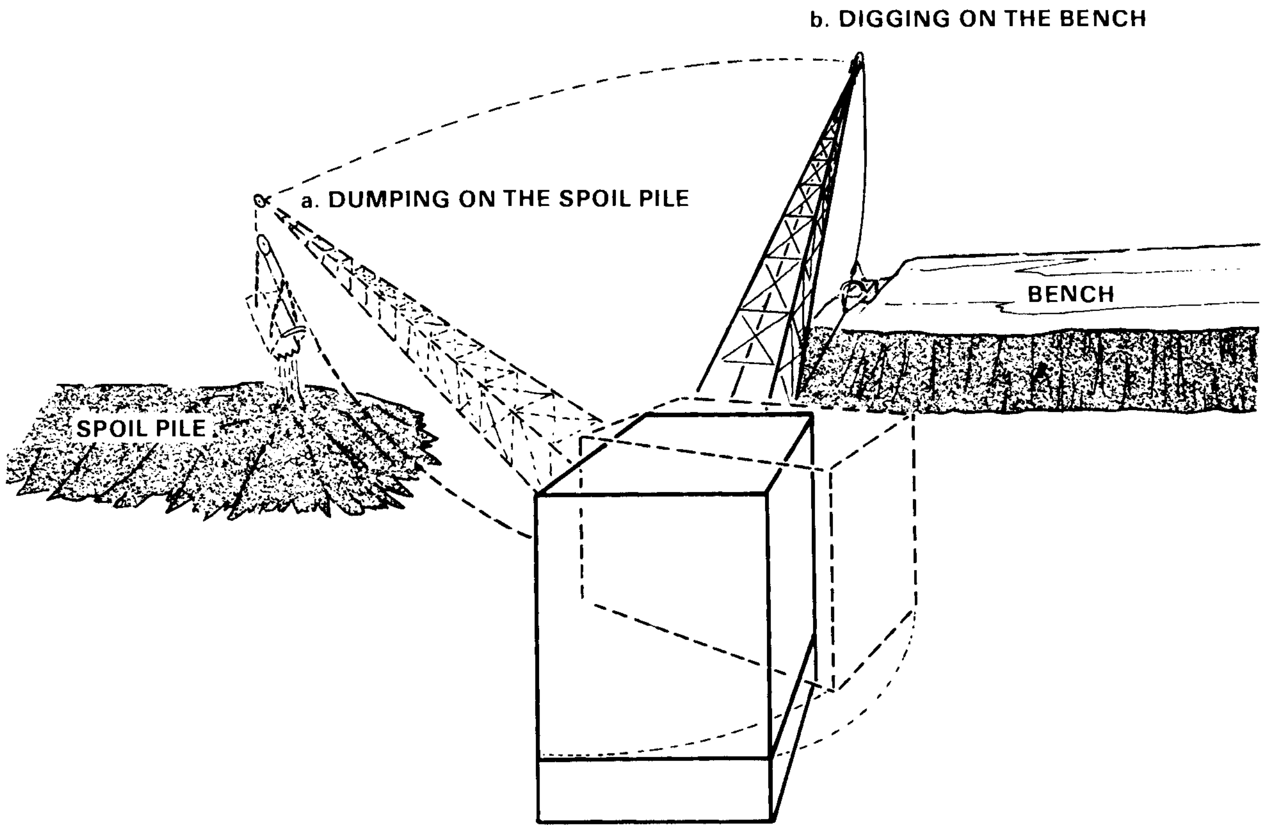


FIGURE 29. Digging and Dumping Features Employed During Load Sensor Operation

The average load for both ropes taken together is 364.85 kips. The rated breaking strength for this particular rope is 1,000 kips. The average load in the rope is therefore 26.5 percent of the rated strength of the rope, or a design factor of 2.74.[a] This average load level is significant in that it had previously been assumed by PNL that the stall setting of the drag motors would limit rope loads to ∿35 percent of rated strength, or a design factor of 2.86. In fact, dynamic loads as high as 66 percent of the ropes' rated strength (d.F. = 1.52) were observed.

(a) Design factor is defined as $\frac{\text{Rated Rope Breaking Strength}}{\text{Working Load}}$.

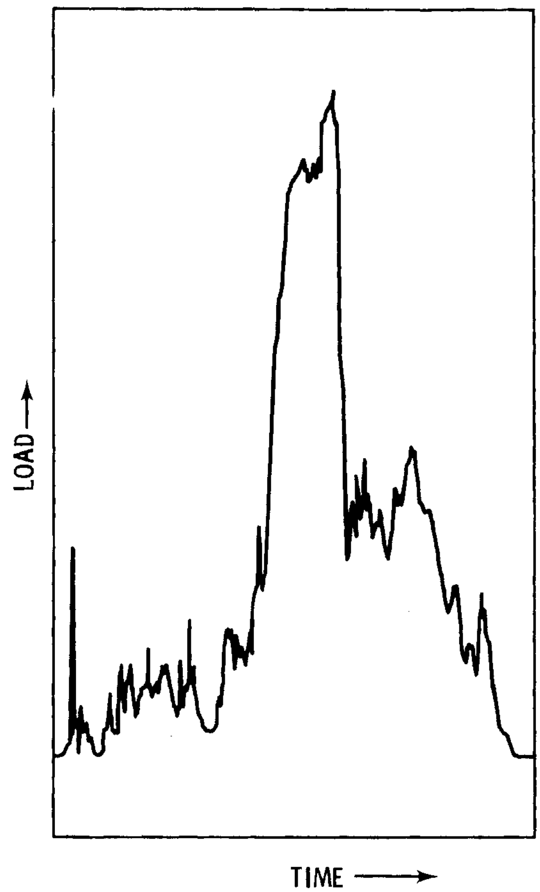


FIGURE 30. Sample Trace of Load/Time Signal from Drag Rope Load Sensors

TABLE 16. Load Sensor Data Summary[a]

	Right Rope	Left Rope
Number of Cycles	179	171
Maximum Load (kips)	540	660
Minimum Load (kips)	170	145
Average Load (kips)	361.2	368.5
Standard Deviation (kips)	67.4	76.6

(a) This analysis and the data reported here use only the peak load for each digging cycle.

Figure 31 presents occurrence diagrams of loads in each rope as a percentage of rated strength. These diagrams show that loads in the range of 30 percent to 50 percent[a] of the ropes' rated strength are not uncommon.

Figure 32 presents corresponding exceedance diagrams. These show that ∿60% of the loads are greater than 35 percent of the ropes' ultimate tensile strength (d.F. = 2.86).

Fatigue data generated in the testing phases of the WRIP were also used in load sensor data analysis. Figure 33 shows the S-N diagram used in the fatigue evaluation. For this analysis β is defined as

$$\beta = \frac{2T}{UDdN},$$

where T = tensile load in the rope (pound)

U = ultimate strength of the outer wires (psi)

D = diameter of the sheave (inch)

d = diameter of the rope (inch)

N = number of wires per strand.

DATA ANALYSIS

Using Figure 33 and Miner's Rule for cumulative fatigue damage, the data obtained from the load sensor were evaluated. The cumulative usage factor is 0.0023 for the four hours of data. This corresponds to an estimated life of 1,750 hours for the ropes under these loading conditions, which compares favorably with the actual life of drag ropes in the field. Drag ropes typically last 1,000 to 2,000 hours. It should also be noted that the estimate of 1,750 hours is for total failure. In the field, drag ropes are seldom allowed to fail completely but are nearly always retired with some remaining life.

Figure 34 shows the relative amount of damage done by the indicated loads. Over 80 percent of the damage to the rope, as determined from the cumulative usage factor, is done by loads greater than 35 percent of the ropes' UTS.

(a) Design factor of 3.33 to 2.0.

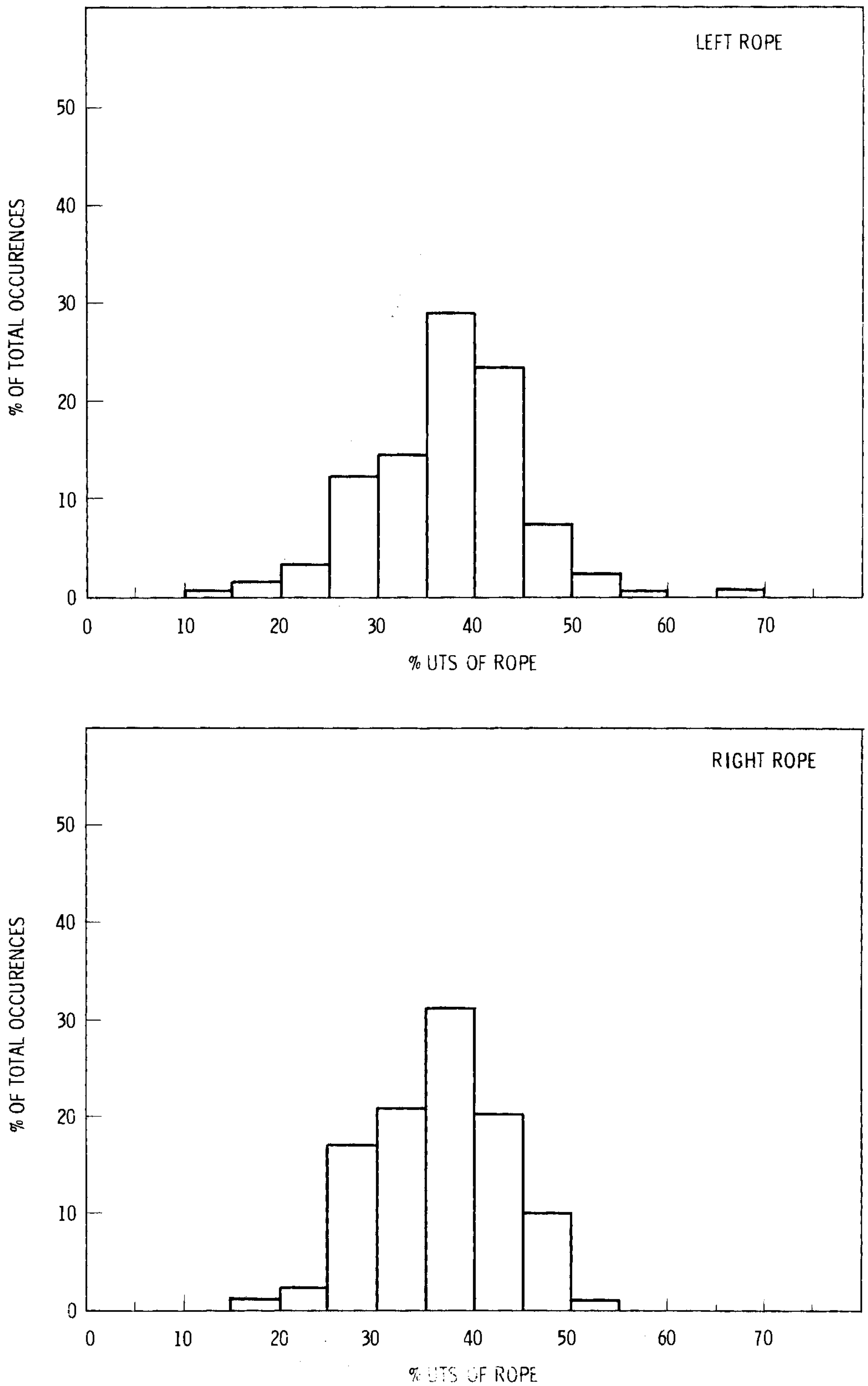
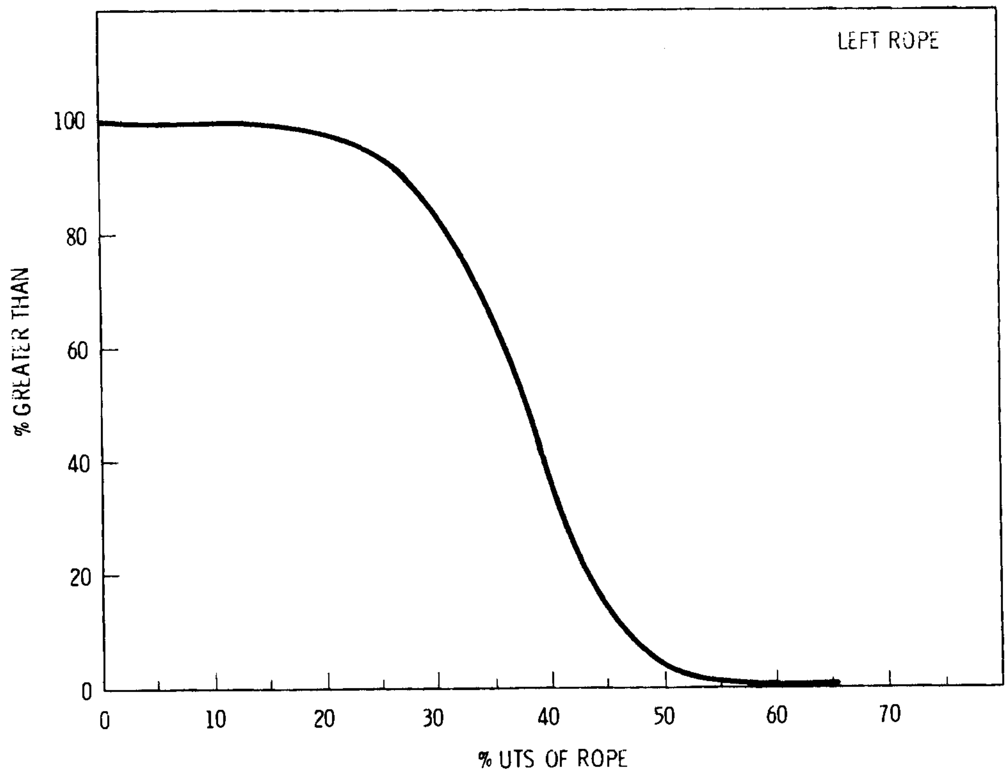


FIGURE 31. Occurrence Diagrams for the Subject Drag Ropes



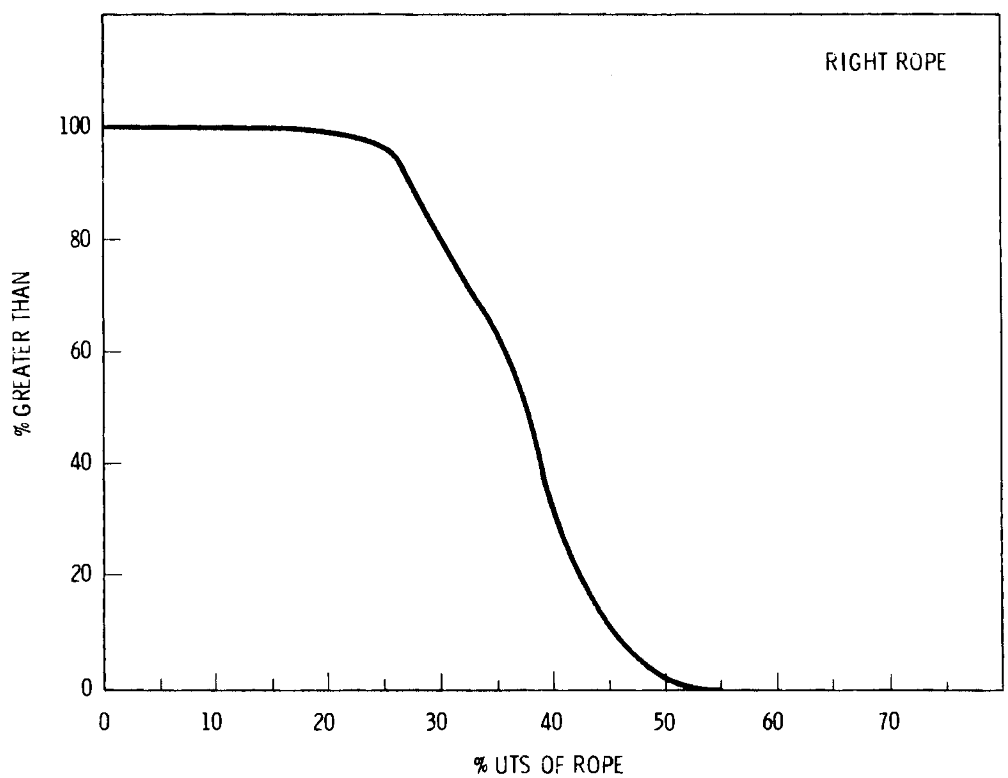


FIGURE 32. Exceedance Diagrams for the Subject Drag Ropes

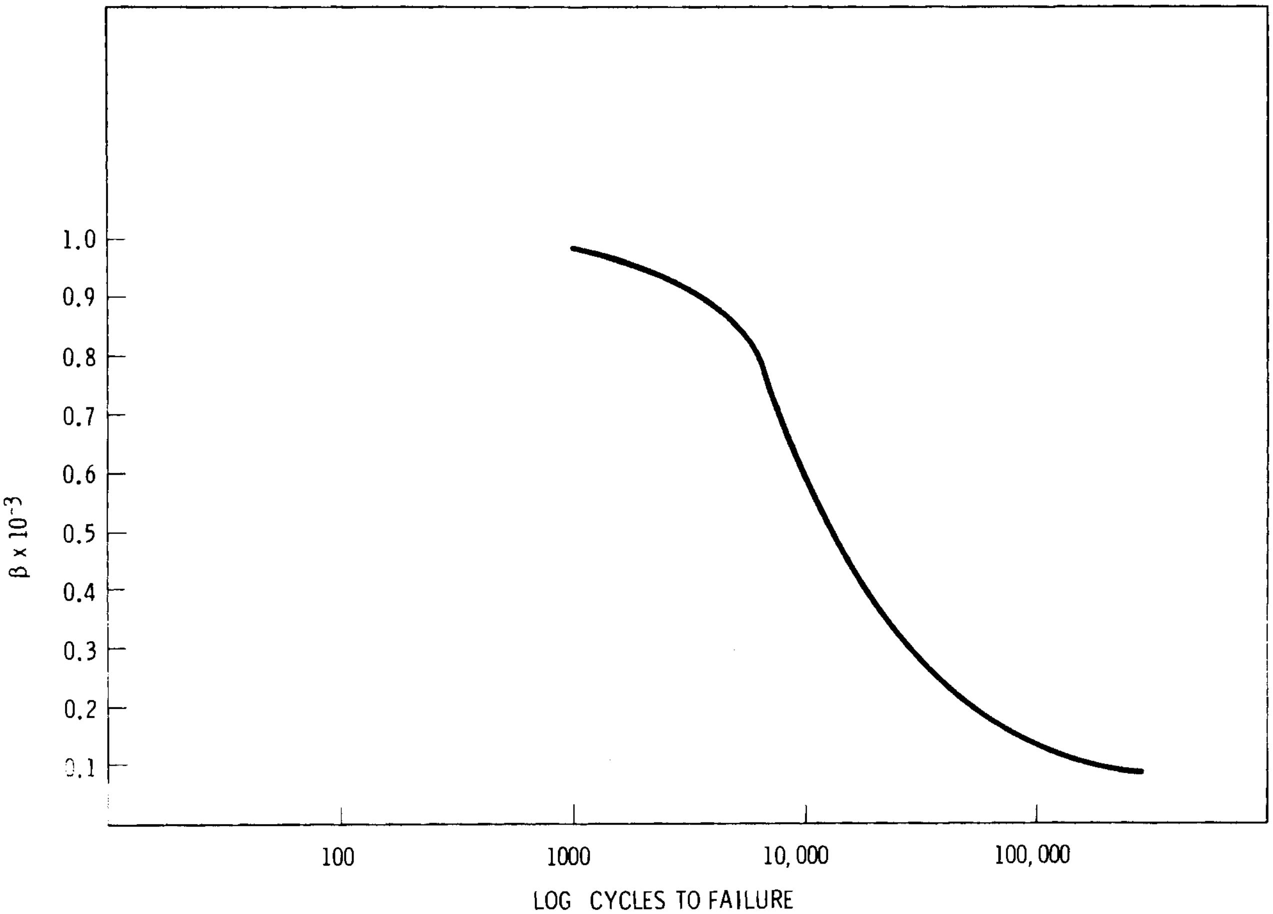


FIGURE 33. Fatigue Life Curve Used in Analyzing Cumulative Rope Damage

The same analysis technique can be used to determine the effect of increasing or decreasing overall loads in the rope by 10 percent. For this evaluation it was assumed that the dragline operated 20 hours per day, 365 days per year and had a cycle time of 60 seconds. It was also assumed that a rope change resulted in 5 hours of downtime.

A 10 percent decrease in rope loads results in a 20 percent increase in rope life. The 10 percent decrease in loads is assumed to be the result of a 10 percent decrease in bucket size. The 20 percent increase in rope life is accompanied by a 10 percent decrease in overburden removed. Assuming that:

- both drag ropes are changed at the same time
- each is 350 feet long
- rope cost is $20/foot

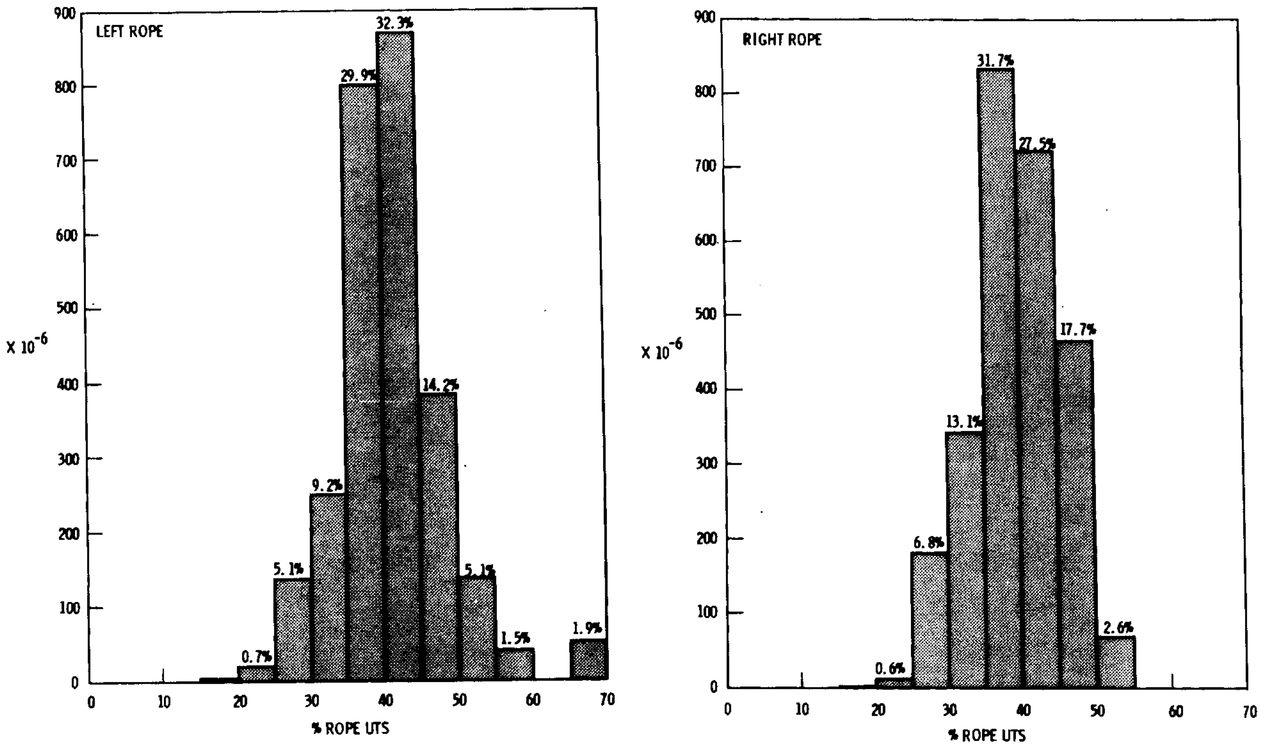


FIGURE 34. Plots of Relative Damage Factor Calculated From Fatigue Curve by Employing Miner's Rule

- overburden is worth $0.20/cubic yard
- no change in cycle time occurs,

the 20 percent increase in rope life results in a savings of ∿$9,700/year in rope costs. The 10 percent decrease in overburden removed is an additional cost of $522,000, resulting in a net loss of $512,300.

A net gain of the same magnitude can be computed if the bucket used carries 10 percent more overburden for the 10 percent increase in rope loads, even though rope life is shortened. However, this result must be tempered by considering specific mine site and equipment costs, including likely increases in maintenance. Nevertheless, operating a larger bucket through the lowest practical range of bucket position factors is virtually certain to promote increased total productivity.

TECHNOLOGY TRANSFER

R. L. Jentgen

The major technology transfer activity during FY81 was conducting seminars at mine sites. Other efforts included technology commercialization, collection of field rope samples and planning for a national wire rope symposium. Technology transfer activities prior to FY81 were documented in detail in Morgenstern et al. (1980).

WIRE ROPE SEMINARS

Seven seminars entitled "The Use of Large Diameter Wire Rope in Surface Mining Machinery" were presented in Illinois, Ohio, Indiana, and Tennessee. Attendees were primarily mining company operators and their field personnel.

Seminar Scope

The scope of the seminars presented earlier in the WRIP was broadened to address not only the fundamental construction and applications engineering features of wire ropes in general, but the practical selection, use, damage, inspection and retirement of large-diameter wire ropes used in surface mining machinery.

Seminar Materials

Considerable effort was expended in modifying the material used in the earlier seminars. After the seminar in Jasper, Alabama on January 30, 1980, it became apparent that the mining personnel attending were most interested in hands-on wire rope problems and solutions based on the rope constructions they use (or should be using), and the dragline/shovel riggings of the machines that they operate. As a result, the 35-mm slide materials were almost completely revamped to encompass a more practical, dragline/shovel rope applied educational format. These efforts resulted in a slide presentation that explain the rationale and development of current wire rope practices in surface mining, as well as the potential advances in the state-of-the-art that might be achieved as a result of WRIP findings. The final edition of the slide materials contains approximately 125 slides.

At the same time, the motion picture portion of the presentation was revamped and improved to include selected footage from the 16-mm movies taken under the direction of Dr. Gambrell, WRIP consultant. These efforts resulted in an approximately 30-min. video tape showing machine- and operator-induced dynamic effects, as well as some particularly undesirable rope handling practices.

Seminar Format

A typical 2-day seminar consisted of one day in the field observing rope practices at the host mine(s). On the second day a 4-hour presentation was made using the slide and movie (video tape) materials. In the presentation of the second day during the introduction, the scope of the WRIP was explained and slides were presented illustrating shovel and dragline designs, rope applications and sizes for thse machines, a dragline census, annual rope utilization requirements for these machines and the costs associated with rope changeouts at retirement. Then, the sessions on rope constructions, selection considerations, storage, handling, installation, operation and maintenance were presented. Following a short break, the video tape on dynamic and operational effects was shown. After a short discussion of the foregoing, the sessions that deal with damage, deterioration, inspection, and retirement were presented.

After a short discussion of all of the topics presented thus far, a summary of the "state-of-the-art" of wire ropes for the machines used by the audience in its particular mines was offered.

At this point, the research and development carried out on the WRIP was presented in perspective with the state-of-the-art as the mine personnel knew it from their experience and in the new light of the seminar information. The research and development session also included a description of the work of others; therefore, all of the new known ideas that promise to increase rope life were discussed. Finally, as a product of the field trip taken the previous day to their machines and the discussions with personnel in the field and at the seminar, a list of specific recommendations was offered that was intended to improve rope life at the individual mine(s).

Seminar Evaluation

Evaluation of the usefulness and effectiveness of the seminars was attempted using an audience response form. As a result of an indicated lack of understanding of some topics by the attendees after they experienced the seminar, those topics that appeared to be confusing and those that were concluded to need more information were simplified and/or elaborated on, and clearer slides were prepared and substituted.

The potential benefits of the seminar might be assessed more accurately by citing the significant interest shown by attendees. Requests for copies of the slides and/or presentations of the seminar were numerous.

In evaluating these requests, coal mining companies in the U.S. were deemed to be the only candidates that could be justified to receive the seminar on WRIP funding. Those U.S. coal mining companies who requested, but to whom we were unable to give, the seminar were sent the seminar materials.

In addition, four U.S. coal companies wanted copies of the seminar, although they had not requested seminar presentation at their mine site.

TECHNOLOGY COMMERCIALIZATION

Work on this task was initiated by the consideration and gathering of reference materials for a topical publication on lubrication of wire rope for surface mining machinery with the objective of formulating a tentative specification for maintenance lubricants. Unfortunately, the program termination at the end of FY81 required a decision to stop work on this activity.

FIELD ROPE SAMPLE COLLECTION

This activity began with collection of drag ropes retired from a dragline. These ropes were to be subjected to a wear and failure analysis at BCL to determine the failure mode at retirement.

After considerable study, it was decided to obtain the bulk of the drag ropes intended for wear and failure analysis from a common dragline model that has consistent design features (e.g., rope diameter, fairlead arrangement, bucket capacity, boom length). Such a dragline model was identified. Owners were contacted and arrangements were made to obtain retired drag rope samples as they were changed out.

One set of drag rope sales was delivered to BCL before the Phasedown caused cancellation of the rope acquisition activity. Immediately prior to the Phase-down announcement, a common data sheet and a standard questionnaire were formulated to obtain accurate rope history and retirement information.

SYMPOSIUM PLANNING

A meeting between BCL and PNL was held on December 18 to formulate plans for a second National Wire Rope Symposium. St. Louis in October 1981 was the target location and time period. At this planning meeting, a suggested format for the symposium was presented that was designd to attract participation in the program and attendance of the surface coal mining industry. As a followup to that meeting, BCL sent two letters to PNL suggesting:

- a 3-day format featuring one day of papers and panels specifically involving surface mining personnel and/or their interests
- a list of potential Symposium Advisory Board members
- keynote speaker possibilities
- mailing lists that would assure appropriate contact with local surface mining companies.

Unfortunately, plans for the Symposium had to be cancelled when the Phase-down was announced.

KEY ELEMENTS OF WIRE ROPE PERFORMANCE ON SURFACE COAL-MINING DRAGLINES

W. E. Anderson

This section will describe how large-diameter wire rope is used on walking draglines, as well as interpret the mechanisms involved with relevant rope performance and durability. The interpretation is based on pertinent information obtained during field trips to mines and rope manufacturers, relevant seminars and symposia, discussions with WRIP staff, and study of data generated during the project or available from open literature or other sources. This is not an exhaustive rendition of the technology and practices related to use of large-diameter running ropes. However, it should be helpful to mine operators and their staff.

SURFACE COAL-MINING DRAGLINE RUNNING ROPE SYSTEMS

As background to the description of dragline rope systems, some explanation of the dragline itself is presented next.

Dragline Performance/Function

Surface coal-mining draglines are principally used to move overburden from coal seams of interest. Their size and manner of locomotion are unique. Size is often referenced simply in terms of the bucket capacity, expressed in cubic yards. Draglines move themselves from place to place by means of external feet mounted on rotating eccentrics that literally lift the system and drag it forward in a cyclic mode; hence the term "walking dragline." Walking draglines typically range in capacity from 35 yd^3 (approximately 3.5 million lb) to 150 yd^3 (approximately 15 million lb) with an average near 70 yd^3 (1981). Their efficient operation means lower cost for delivered coal.

The dragline includes a primary structural frame containing the counterweight, motors, drums, and electrical equipment (Figure 35). Its long boom extends opposite the counterweight. The entire structure rotates on a large base and houses an operator's cab. The cab is positioned for viewing the bucket system, which is lifted and lowered by hoist ropes and pulled by drag ropes.

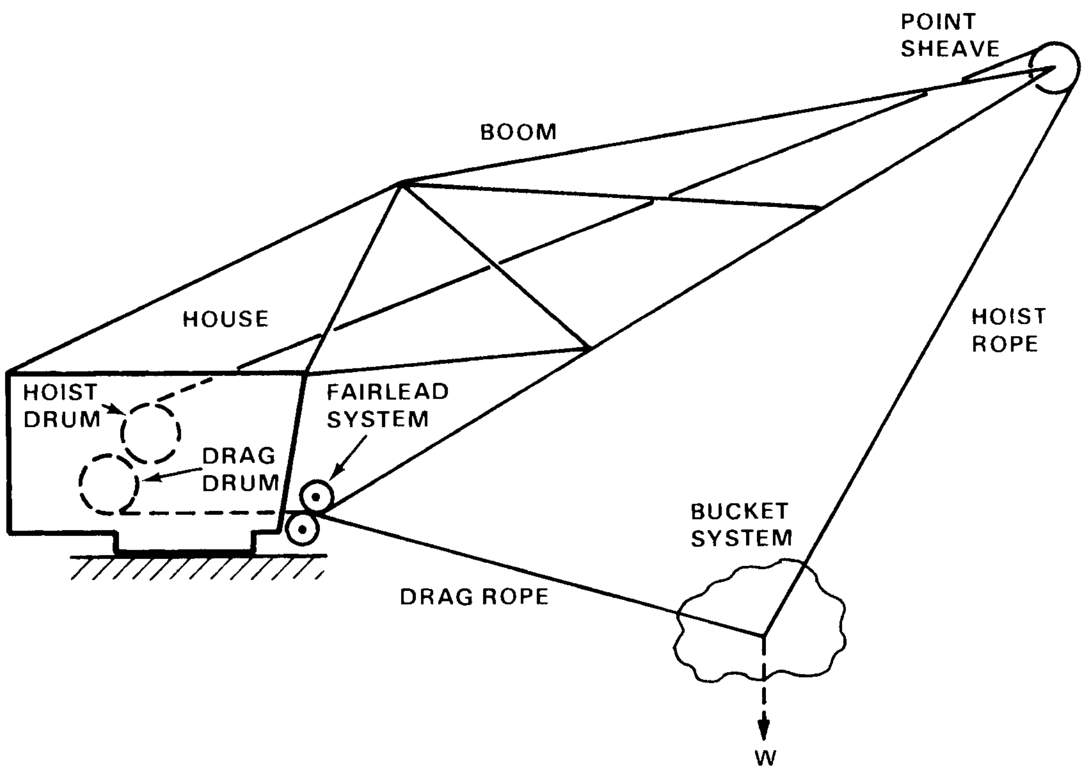


FIGURE 35. Schematic Arrangement of Walking Dragline

Most draglines have a pair of ropes for each function; some larger ones have two pair for a function, as shown in Figure 36. Each rope system has its own drums to wind up and pay out its respective ropes. On walking draglines these ropes measure 2 to 5 in. in diameter; they are the principal topic of this report.

Walking draglines have large, pod-like feet on each side of the structural frame, operated by an eccentric mechanism such that the entire system can be advanced in steps. When retracted, the feet turn with the housing and boom (see Figure 37).

Walking draglines are field-assembled because of their huge size. Components are fabricated at manufacturers' shops in pieces small enough to be shipped; assembly may take 1-1/2 to 2-1/2 years. All walking draglines of these larger sizes are electrically driven, using power from a nearby source. The dragline pulls its power cable with it when moving from place to place in the mine, as shown in Figure 37.

FIGURE 36. Four-Rope Hoisting System on Walking Dragline

Total weight of walking draglines runs surprisingly close to 100,000 lb/ft^3 of nominal bucket capacity, although variations arise from different boom lengths and bucket sizes. For example, two otherwise identical draglines may have somewhat different-sized buckets because of differences in overburden density that each machine moves. In some cases the same machine may employ different sized buckets as it works its way through overburden of different densities.

The dragline operator lowers the bucket onto the ground or into the pit, pulls on the drag ropes to fill the bucket, then lifts the bucket with hoist ropes, swinging the dragline and bucket to dump the contents on a pile (Figure 38). In addition to drag and hoist ropes, an auxiliary system employs dump ropes that, with special tensioning or releasing of hoist and drag ropes, controls whether the bucket tips up to contain the load of overburden (Figure 39) or drops the open end to dump it.

FIGURE 37. Dragline in Process of Walking

FIGURE 38. Bucket Dumping Overburden on Pile

FIGURE 39. Bucket with Bale and Single Dump Rope System

Wire ropes in hoist, drag or dump functions continually move and bend over pulleys, called sheaves (usually pronounced "shiv"). Bend-over-sheave (BOS) actions cause rope wear and degradation, so that rope replacement is frequently necessary. One characteristic aspect of wire rope usage on walking draglines is the large loads on these ropes compared with their ultimate strength. Wire ropes for underground mining might experience maximum loads at one-tenth, one-eighth, or, at most, one-sixth of their breaking strength. However, ropes on walking draglines typically work at one-fourth to one-third of their ultimate strength. Differences in rope life between the two situations are understandably large.

Actual rope life on large draglines varies from a few weeks to several months; drag ropes typically last only half as long as hoist ropes (Anderson and Brady 1979). Every time a rope is judged to be threateningly worn, or becomes damaged in service, expedited replacement is necessary to restart operations. Costs for medium-sized (60- to 70-yd^3 capacity) draglines run about \$2500/hr; a pair of drag ropes costs about \$15,000. Even with as little as four hours downtime for changeout, the total bill can be \$25,000, which does not include the costs of lost time and amount of overburden not moved. Because of these substantial costs, just modest improvements in rope life can be worthwhile.

Hoist, Drag, and Dump Rope Systems; Sockets

Modern draglines almost universally employ the Page System of bucket control. Originally started in 1903 on a stiff-legged derrick, the concept eventually developed into a system that permitted much improved production performance on modern draglines, under the hands of a reasonably skilled operator. The basic idea consists of rigging the bucket as shown in Figure 40. When all the components are properly adjusted, the bucket fills by pulling on the drag rope while the hoist rope remains effectively slack.

When the hoist rope is tensioned enough to begin lifting the bucket and its load, and proper tension is maintained on the drag rope, the bucket "cocks", holding most of the filled material inside it. This step is pictured in Figure 41. The pictured dump sheave motion due to tension of the hoist rope should help clarify how the cocking action comes about.

As drag rope tension is slackened, the bucket swings more under the point sheave and the open end of the bucket begins to rotate down. Properly adjusted, a bucket will quickly empty and be ready for swinging back to the digging location. It is the combination of bucket cocking and quick dumping which makes the system so effective in skilled hands. However, the several factors just mentioned do not treat all the important aspects of bucket and dump rope system design; location of the bridle pivot on the bucket, location of the drag rope attach point, angle of tooth bite and bucket geometry are some of the other critical aspects involved in productive dragline performance. (One recent study of these buckets is available in Stillwell et al. 1979.)

Hoist Rope Systems

A simplified sketch of dragline rope systems (Figure 35) shows the hoist rope coming directly over the point sheave into the cab and onto the hoist drum. In some designs, additional sheaves are located between the point and

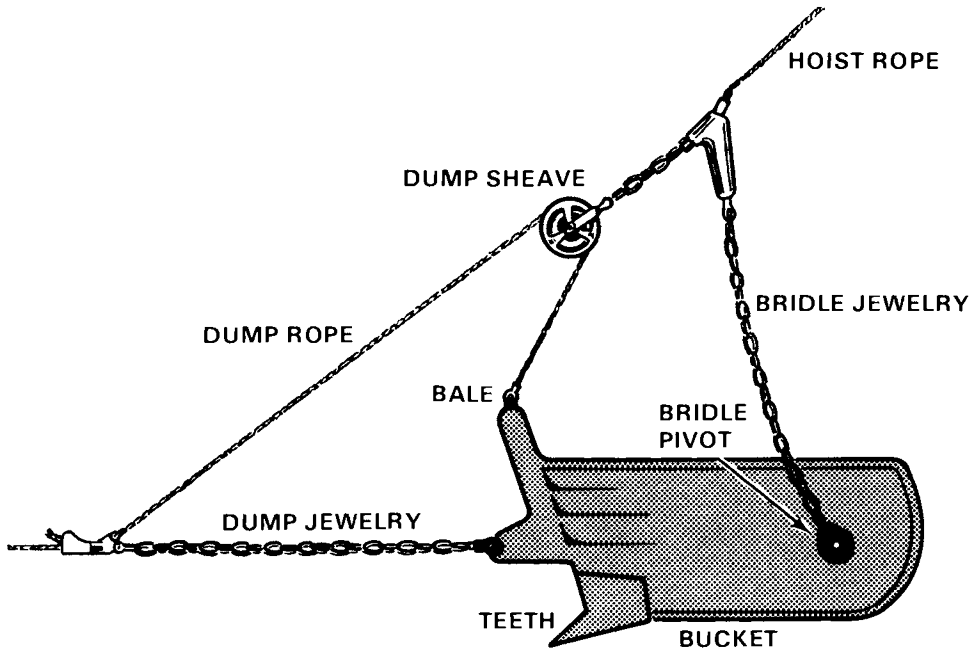


FIGURE 40. Basic Rigging Arrangement of the Page System (digging position, hoist rope just slack)

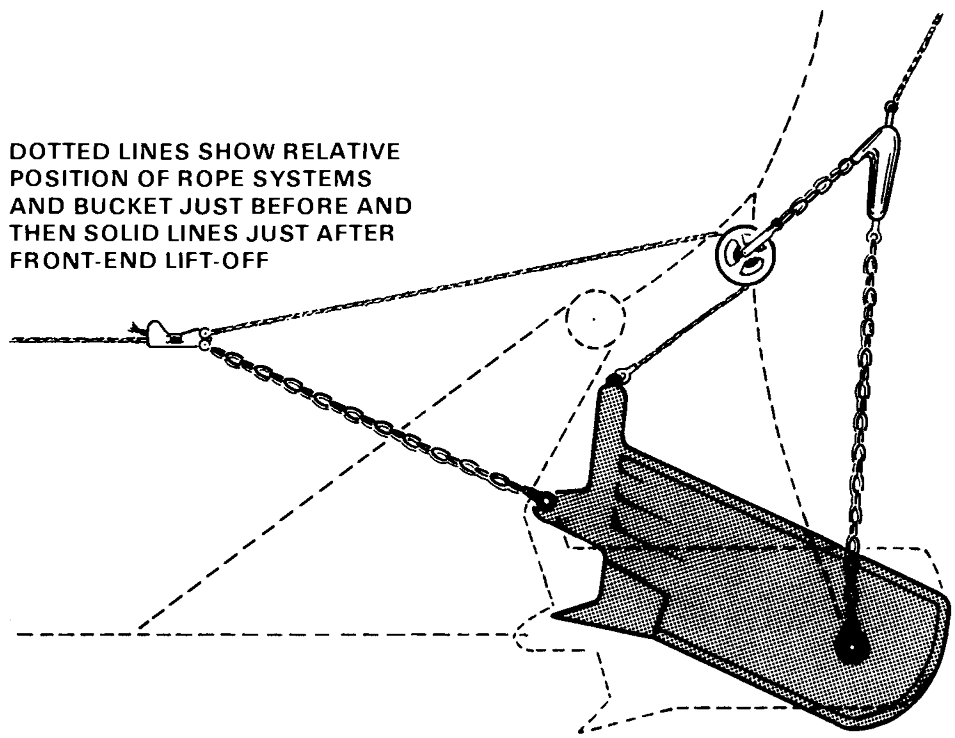


FIGURE 41. Simultaneous Tension of Both Hoist and Dump Ropes Holds Open End of Bucket Up

the drum; e.g., a large one near the house redirects the rope onto the drum, or several smaller sheaves along the boom guide the hoist rope between the house and the point sheave.

Beyond the point sheave, hoist ropes hang down to their sockets, which are connected to an "evener" (equivalent to a singletree) and thence to the bucket jewelry and bucket via bridle pivot attach points. This arrangement is shown in Figures 36, 38, and 39. Once connected, hoist ropes are essentially always under some load because the hoist jewelry alone may run several percent of the total bucket system weight. When unloaded and hanging statically from hoist ropes, a total bucket system weighs approximately 2000 lb/yd^3 of bucket capacity. Although overburden weighs roughly 2100 to 3100 lb/yd^3 in the bucket, deadweight loads on the hoist ropes are an appreciable fraction of a nominally-full bucket.

Peak hoist rope loads occur after digging, during lift and swing-to-dump portions of the cycle. Related and consequential effects of these weight and sheave arrangement factors associated with the hoist rope system are discussed in Appendix A.

Drag Rope System

Drag ropes function differently from hoist ropes; consequently, the load history for a typical cycle is also quite different. Peak loads occur during pulling to fill the bucket. Then only moderate loads are necessary to hold the bucket cocked; after dumping, loads are small until digging again, except when any substantial dynamic actions occur. Frequently while returning to the dig location, a bucket can easily swing rather wildly if not controlled, and excite the drag system jewelry into violent motions, slapping sockets and chain together. This action then generates significant jerk loads on the drag ropes, particularly flexing them at their sockets.

Fairlead designs may differ considerably among draglines, but all utilize sheaves in one way or another. Because the bucket may swing out of alignment with the vertical boom plane, fairlead assemblies must tolerate sidewise loadings, so they are arranged to accommodate some of that motion. Principal loads, however, arise in the vertical boom plane (sometimes with little reverse bending, and sometimes through substantial reverse bends) and sheaves are always suitably located to accommodate that function.

After reeving through the fairlead assembly, drag ropes pass into the house, often over floor rollers or other devices to support them, on their way to the drag drum. There, as with hoist drums, each rope is attached to one side of its respective drum and wound up into a drum groove so that the ropes neither touch laterally nor wind over themselves (as on most smaller-rope drums). Drums are large, not only to accommodate hundreds of feet of rope without overwinding, but also to provide a reasonably large ratio of drum diameter to rope diameter, 25 or 30 to 1, for example. Both right- and left-hand drums are connected by a single axle/motor system so that they turn together. As a consequence, the full available pulling power could be applied to just one drag rope, if the other one is askew for some reason, because the drag rope system has no evener as does the hoist (Figures 36, 38, and 39).

Drag drums are often quite far from the fairlead so that fleet angles at the drum are not much of a problem. Nevertheless, at the fairlead assembly horizontal guides or sheaves ensure that ropes enter the vertical sheaves cleanly and do not ride up on the sheave rim when ropes are feeding out. Thus, because the vertical sheaves may swing from side to side, rope wear in the fairlead region is virtually unavoidable.

Dump Rope Systems

Although the dump rope system appears simple, some mines have reported more downtime for dump rope change-out than for drag rope (Anderson and Brady 1979). A properly rigged dump rope system is important to efficient dragline performance; together with the bridle pivot location on the bucket, the dump ropes establish the amount of effort required to carry the bucket to dump position and quickly spill the load.

One end of the dump rope connects to the drag chain; the other end connects to the front of the bucket, or a bucket bale, after passing through its sheave, suspended from the hoist jewelry. Figures 40 and 41 show the essence, while Figures 38 and 39 display actual conditions. Dump sheaves are relatively smaller than other sheaves in comparison to the diameter of the ropes used on them. Note the guards on the dump sheaves to prevent the ropes from falling off to the side. Guards are needed because the dump sheaves may swing about when the hoist is slack and shed unguarded rope. Generally, dump rope systems suffer much abuse from slackened hoist ropes. Some operators are able to keep the hoist just taut enough to suppress dump system flopping about, yet not interfere with bucket digging; such craftsmen are a joy to watch.

Sockets

Nearly all hoist, drag and dump ropes are terminated with wedge sockets. These sockets can take more than three-quarters of the rope breaking load without suffering serious damage. A rope is socketed by pulling the bitter end through the socket hole, forming a bight and putting that end back through the socket hole with a rounded wedge in the bight. The bight is then pulled snug, driving the wedge into the socket hole, and jamming the rope into the hole sides, thereby securing rope to socket, A simplified sequence is shown in Figure 42. Getting the wedge and rope out so another can be made up is often difficult.

Socketing a rope requires power equipment. In the field a cat-tractor is generally used to pull the bitter end by tying onto it with smaller rope chokers. To pull the bight snug and drive in the wedge the socket must be

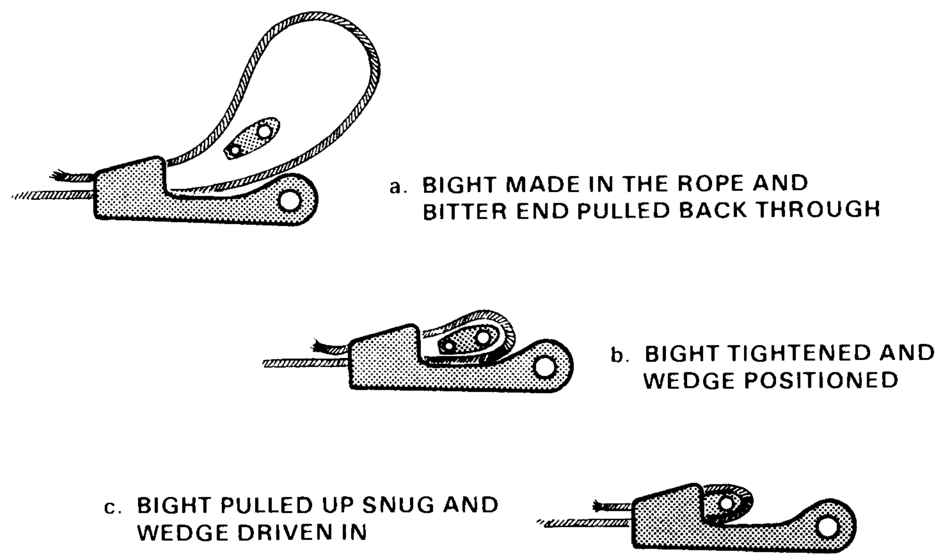


FIGURE 42. Schematic of Rope Socketing Sequence

delayed while pulling on the running end of the rope with a choker. As the bight tightens, the rope accommodates to the very small radius of the wedge by extensive relative sliding of the strands near the bend; hence, it might be considered a controlled kink.

KEY ELEMENTS OF RUNNING WIRE ROPES

This section is intended as a subjective interpretation of the WRIP experience concerning large-diameter wire rope. It should reflect the findings reported elsewhere, but it is biased by the author's limitations and perhaps by the mode of presentation. The plan is to present research results in terms of mechanisms that operatively affect rope durability. First, the rope itself is described. Reasons why ropes are the way they are include proprietary designs and trade secrets, none of which are known by the author from first-hand accounts. On the other hand, if deductive reasoning unintentionally touches upon some of these aspects, no confidences have been betrayed.

Rope Design/Manufacture

Wire rope is constructed somewhat like the more familiar hempen rope, but a key difference may not be obvious, namely that wire rope is composed of strands that wrap about a central core. Typically, the core is approximately the same diameter as the six strands twisted about it, and the assembly may be visualized as six solid but flexible rods wrapped tightly together around a central core of the same size.

General Features and Lay

Core material may be nonmetallic. However, the one of interest is metallic, and appears to be another rope itself, but with a different construction and a different twisting pattern; this is the independent wire rope core (IWRC). The primary reason for metallic construction is to resist the tremendous bearing loads from the outer strands as the rope bends over the system's sheaves.

Many variations of rope construction have been fashioned, but the type generally utilized for walking draglines consists of six outer strands composed of several dozen wires and the IWRC. Outer wires of each strand will be of the same diameter, but inner wires may be of differing diameters, according to the designed pattern, which takes on various names, often involving "Warrington" or "Seale" in some manner. This historical aspect carries through into description of the rope by class, wherein a 6 x 37 class rope may not have 37 wires in each of the six strands, but some other number. The actual number would be used in a technical specification, like 6 x 55 IWRC RLL. Sayenga (1980) is a particularly interesting historical account.

Because the six strands are uniformly wrapped around a core, any one strand will twist around and return to an equivalent orientation in one turn along the rope. This distance of one turn is called the lay length. The twist is called the lay; it can turn clockwise down the length, that is, to the right, or to the left. Furthermore, because the strand is itself a specially twisted bundle of wires, its twist can be either right or left, as well. When a left-hand twisted strand is wrapped onto a core by twisting the strand to the right, the pattern is termed Right Regular Lay (RRL). Had the two twists been the same, that is, both to the left, the rope would be Left Lang Lay, or LLL.

Regular Lay construction produces a rope that is more resistant to unwinding under tension loads than a Lang Lay rope. Nevertheless, Lang Lay construction is preferred in large ropes used for running over sheaves at high loads, because the Lang pattern presents the outer strand wires differently to the sheave as well as to the overburden spoil (in the case of drag ropes), tending to produce more even wear on the rope outer wires than does Regular Lay construction. The interested reader can pursue the many other considerations in rope design and application in Sayenga (1980).

Lay Length Matching

Starting at one and counting down the rope length by strands to the seventh will identify the same strand as the starting one; measuring this lay length and the rope diameter will produce evidence that the lay length is about six or seven rope diameters. Now, if a Lang Lay rope is laid open by twisting off the strands, it will be seen that the IWRC is of Regular Lay construction. Although the core lay direction is seen to be the same as the strands, its regular construction causes the outer strand wires to contact the outer core wires at a rather shallow angle as may be seen in Figure 43. Hence, the contacts between strands make one characteristic deformation shape and the strand/core contact areas a different shape, as seen in Figure 44. These contact areas are more clearly delineated in Figures 45 and 46.

Lay length is one important factor governing rope modulus or axial stiffness; that is, how much stretch it will exhibit for a given amount of added load. If all the strands were parallel, it can be visualized that the stretch behavior would be very nearly that of a solid bar of the same total sectional area. Because the strands are twisted about a core, axial pull on the rope tends to slide the strands over the core in an unwrapping mode, thereby reducing stiffness from that of an equal area solid bar. A shorter lay length should have a lower modulus than a longer lay length.

The IWRC (core rope) itself must be made to about the same lay length in terms of its diameter as the total rope; otherwise the IWRC stiffness modulus will differ from the total rope and thus carry too much or too little of its share of the load. This leads to the question of the core of the core rope; if the core of the core is a single solid wire, then it must suffer the damage accumulation resulting from its higher modulus. In a typical large-diameter rope, the effective modulus is roughly 12,000,000 in. lb/cu in. (or lb/sq. in.). On the same basis, a solid steel wire will exhibit roughly a 30,000,000 modulus. For a given stretch of the total rope, the IWRC-core wire will experience approximately 2-1/2 times the stress of an average wire in the strands. Early failure of the central core wire in such rope designs would not be surprising. Nor would it be surprising to find that some rope designs utilized variations of the IWRC with regard to the central core construction or the relative hardness of the core wires. In short, rope designs to minimize the potential problems discussed here should be expected in the marketplace. A sample rope section is shown in Figure 47.

Wire Properties/Quality

One feature of wire rope is that its wires have been thoroughly tested for gross defects by the very process of wire drawing from an initial rod dimension to the diameter utilized. Microstructure resulting from drawing and annealing,

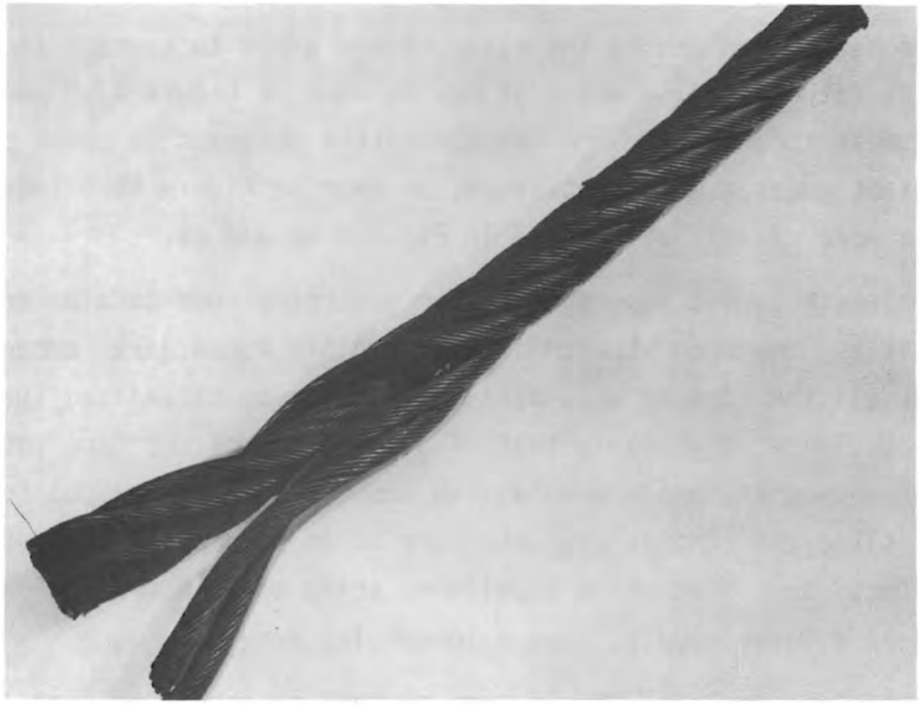


FIGURE 43. General View of IWRC Rope with Two Strands Twisted Out

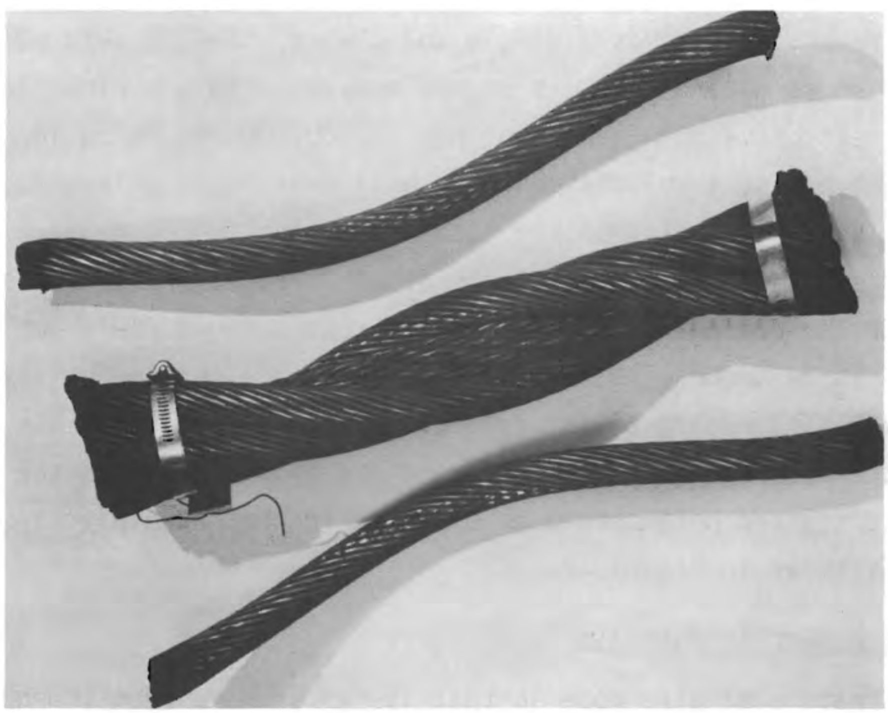


FIGURE 44. Another Rope with Strands Twisted Out to Show Contact Areas

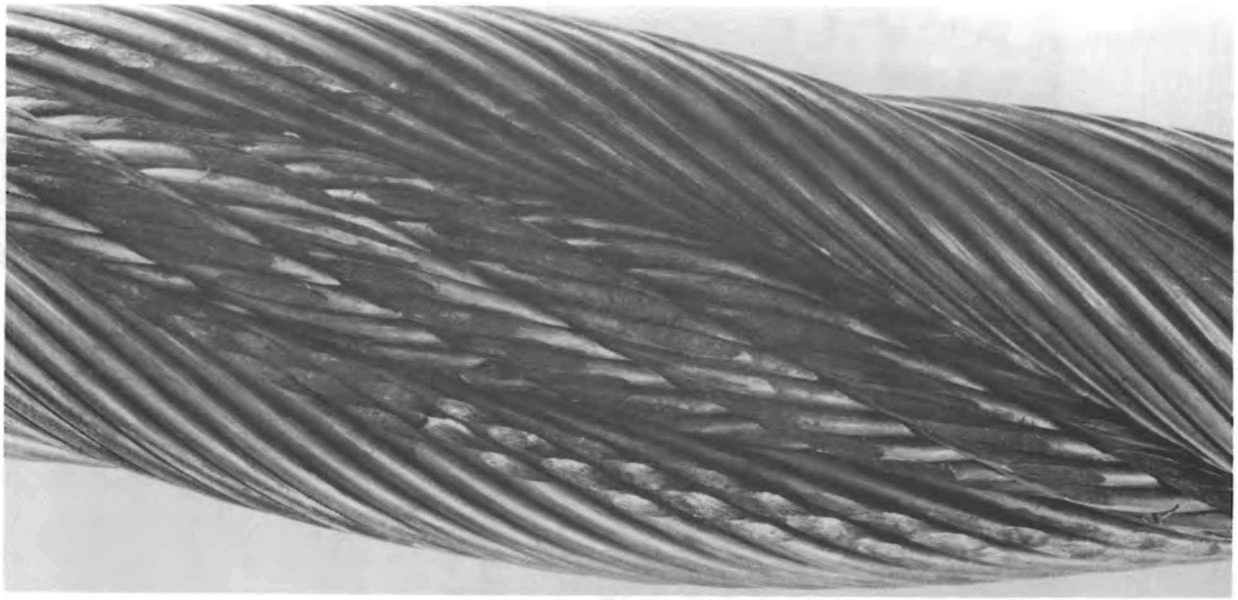


FIGURE 45. Closeup of IWRC and Strands in Figure 44

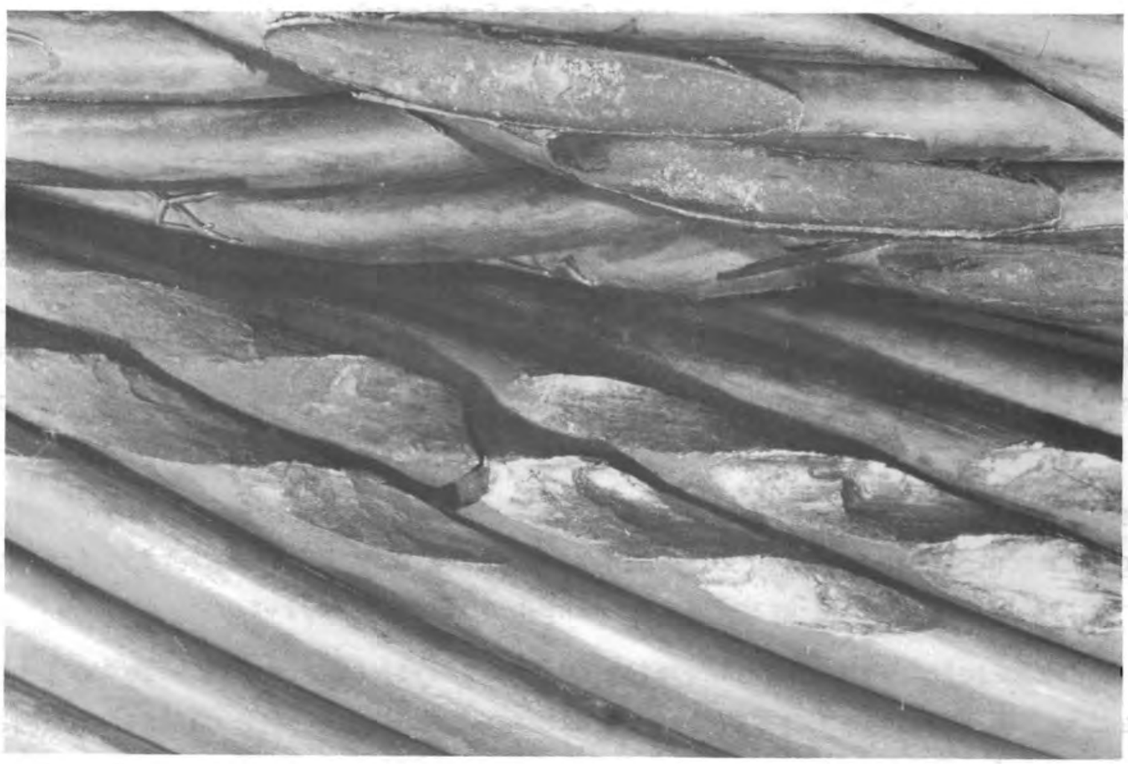


FIGURE 46. Detail of Wear Patterns and Wire Fracture Seen in Figure 45

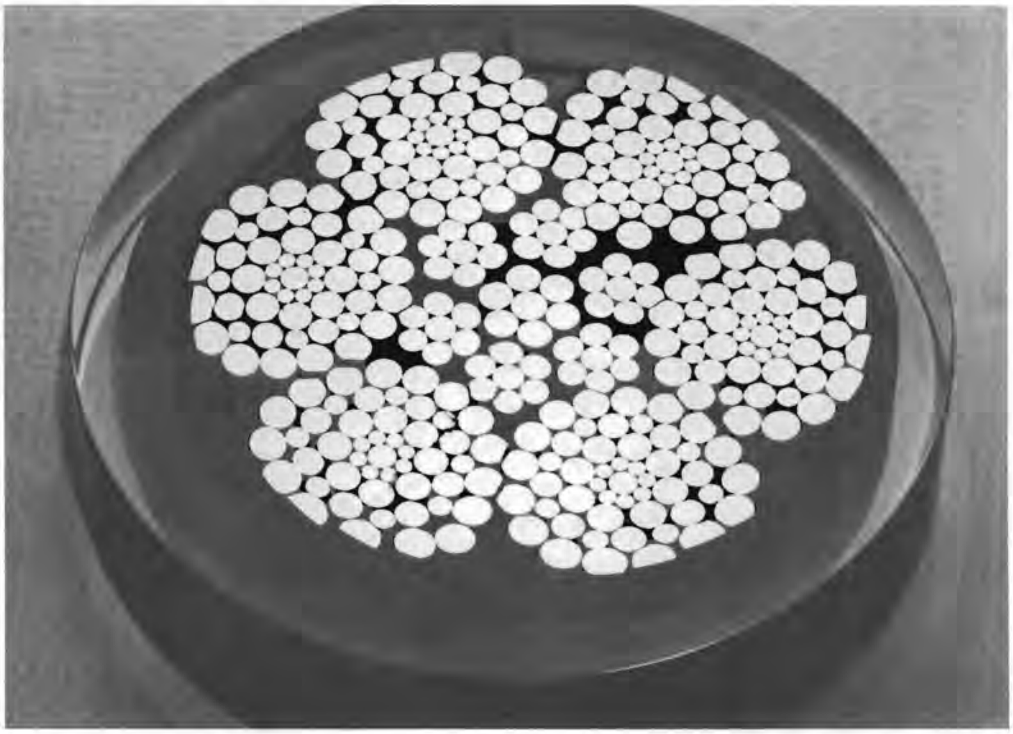


FIGURE 47. Sample Rope Cross Section from Used Drag Rope

or patenting (Sayenga 1980) the different size wires produces an amazing combination of strength and toughness; therein lies the practicality of wire rope. All the different diameter wires are typically drawn down from the same starting rod size, about 3/8 in. diameter. Thus, the larger wires receive less working/texturing than the smaller wires; normal thermal treatments do not completely "recondition" the drawn product to a "zero" baseline metallurgical level prior to the subsequent reductions. The end result is neatly summarized in Figure 48.

Simple carbon steels of commercial purity seem to have just about the right amount of impurities to accentuate microstructural texturing from the wire-drawing. Several examples are shown in Figure 49.

From a manufacturing viewpoint, wire drawing to a final size must be carried out in some specified draw-patent-draw sequence, with just-appropriate combinations of diametral reduction and tempering. Because so many sizes are

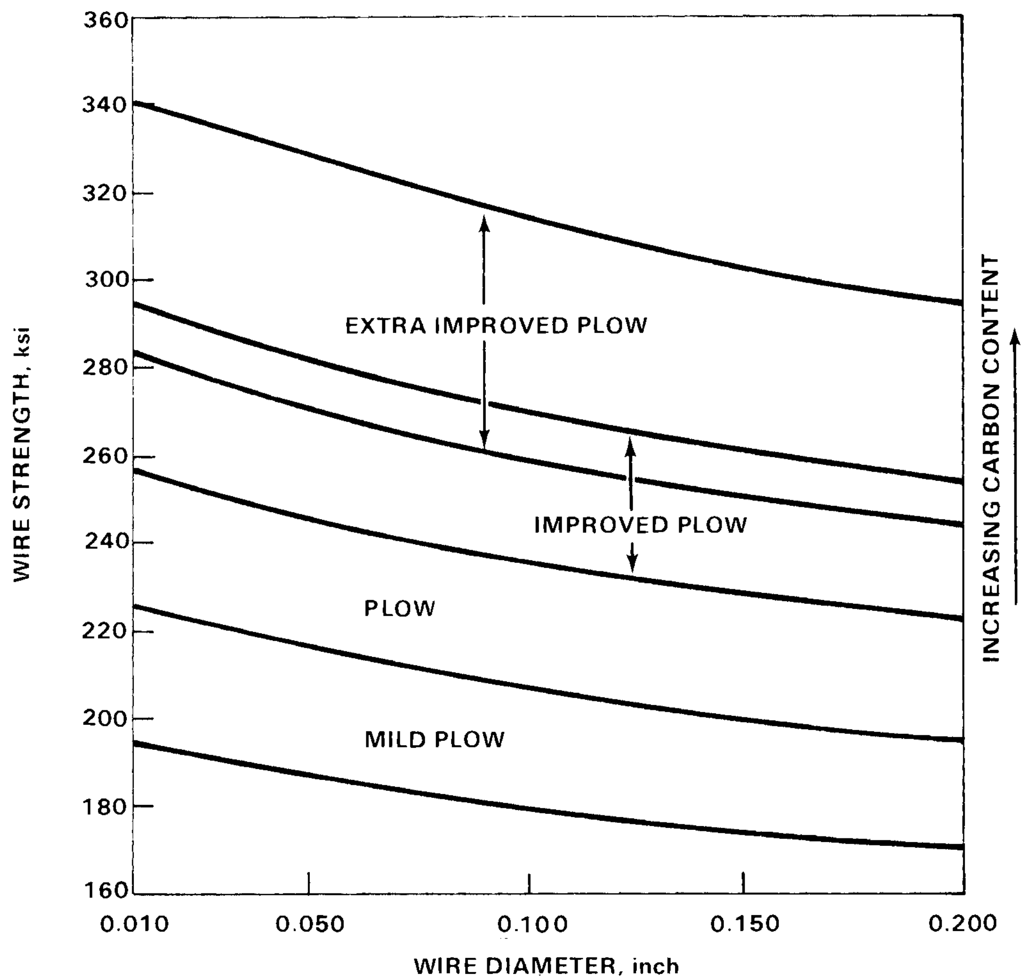
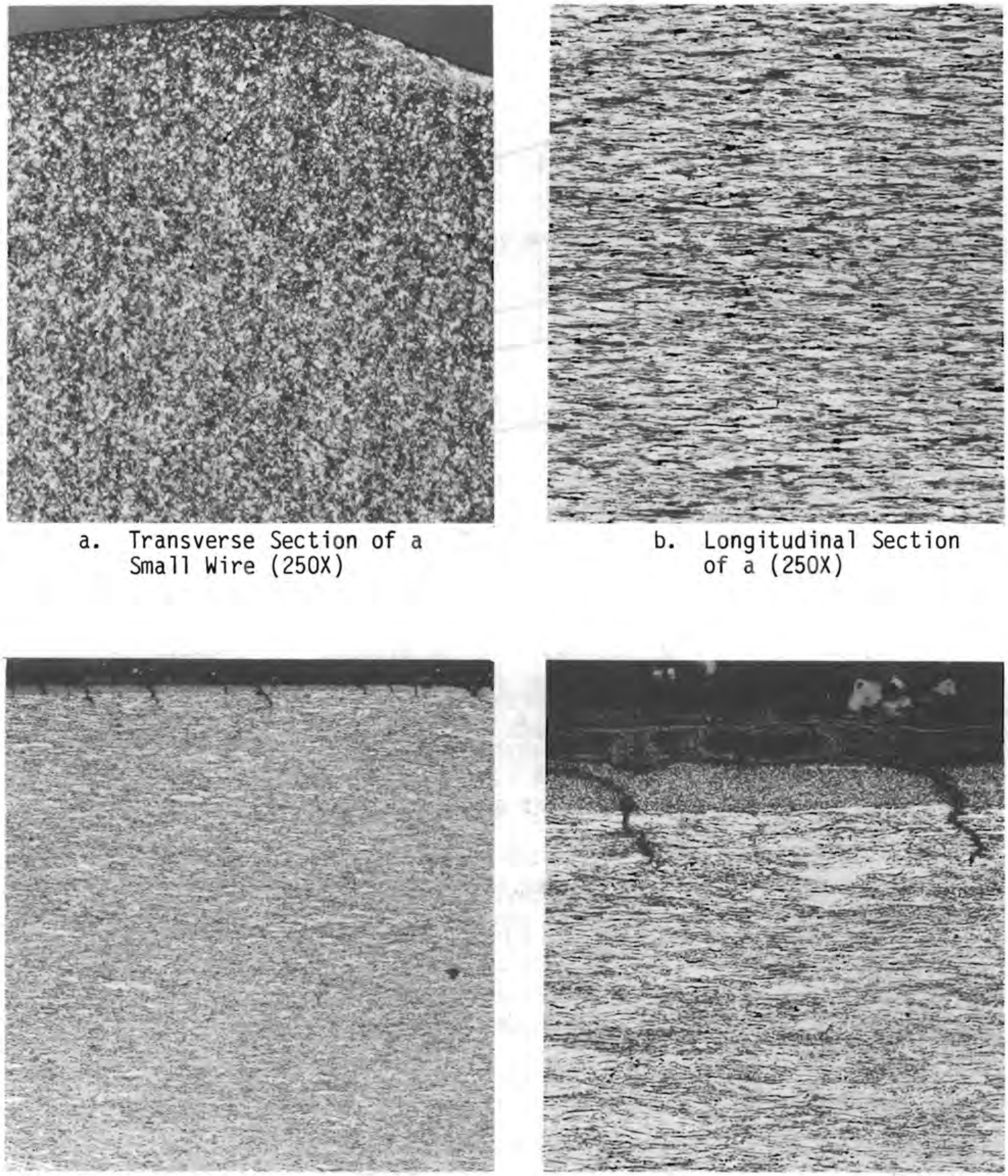


FIGURE 48. Carbon Steel Wire Strengths for Various Grades and Diameters

needed to supply needs for even modest ranges in rope diameter, too much or too little rope of one diameter and strength for completing a particular rope order could easily be produced. In any given rope, then, one or two wires might be of the proper diameter but a different strength than their nominally identical companions. Their effect on total rope performance is doubtless minimal when they occur internally, and some care is no doubt exercised to ensure that large differences are not found in the outer strand wires. But, occasional substitute wires in a given rope might be expected.

Considering the self-inspecting characteristics of wire drawing and desirability for strongly textured microstructure, it is difficult to imagine dramatic changes that might be employed in manufacture of wires for wire rope.



a. Transverse Section of a Small Wire (250X)

b. Longitudinal Section of a (250X)

c. Longitudinal Wire Section Along Minor Contact Area (50X)

d. Longitudinal Wire Section Along Minor Contact Area (250X)

FIGURE 49. Sample Wire Microstructure

Minor additions of special elements might be proposed to enhance the preferential properties after drawing, but a full range of patenting experiments would likely be required and it would seem unlikely that the gain could be worth the cost to a practicing manufacturer. Failure and wear studies just do not seem to point to wire quality as a place for substantive improvement in rope life. Properties selected for a particular rope design, however, may practically influence rope life in a given situation, and manufacturers of large rope would be expected to capitalize on this point in developing their product lines.

Compaction Factor/Preforming

Two characteristics of large-diameter ropes deserve consideration. Compaction factor describes how closely to theoretical or ideal packing a particular rope is designed. Ideally, one can describe specific wire sizes so that they would fit together exactly, with no looseness and with no crowding. Of course, in practice this would require amazing accuracy of wire diameter control, to say nothing of requirements in forming the core and the strands together. Even normal drawing die wear produces slight changes of wire diameter, making idealism impractical. However, some looseness must be intentionally designed into the rope system to accommodate the "shrinking" as the wires become worn and deformed at the contact points (Figure 50). Each manufacturer coud be expected to arrive at his own compaction factor, best suited to his practices in wire diameter control and other manufacturing and rope design experiences.

In Figure 43, the preformed effect on strand geometry may be seen. Early difficulties with wire rope included its propensity to unwind under load if the ends were not restrained. This led to rope designs with cross-lay, or other features to counteract this tendency (Sayenga 1980). Also, prior to preforming, it can be imagined that a suddenly slackened rope might readily "birdcage," splaying the strands and core into a real mess at some local spot or spots along the rope length. Preforming was the important development to compensate for both problems to a great extent, according to Sayenga (1980).

Forming up a rope involves making strands and IWRC from their own combination of wire sizes and strengths, and rolling up the appropriate lengths onto

a. Intentional "Looseness" of As-Fabricated Rope

b. Snug Fit After Some Accommodating Wear/ Deformation

FIGURE 50. Conceptual Requirement for Compaction Factor

individual bobbins, one for each strand and one for the IWRC. All the bobbins are mounted in a rotatable cage with a seven-hole die-head on the front. Around the die-head are adjustable roller-cams that can be set to kink each strand as it feeds through the head. This kinking preforms the rope so it can be twisted together more easily and thereafter behave better with respect to unwinding or birdcaging. It is likely that all large-diameter running ropes are preformed; any slight detrimental effects caused by the residual stresses left in wires after kinking at the die-head are more than compensated for by the overall beneficial effects.

It is unlikely that substantive improvements in rope life might be found by introducing changes in preforming practices. However, insofar as compaction factors are concerned, it is tempting to speculate that modest improvements in some wire rope products might be achieved by closer attention to the blend of wire properties and initial "looseness" of the strand compaction.

Corrosion Protection/Lubrication

Rope manufacturers universally apply some form of viscid compound to their large ropes during the fabrication process; its principal function seems to be corrosion protection for the rope during shipping and storage. Other compounds or fluids intended to function as lubricants may be introduced into the rope;

whether or not seems a manufacturer's prerogative. In the field, some operators diligently apply favored lubricants, while others occasionally apply old crankcase oils; both approaches seem not to shorten rope life.[a] Considering the weather extremes under which draglines work, lubrication and corrosion protection seem at once both mandatory and impossible.

Lubrication requirements for the hoist ropes and the drag ropes apparently constitute two different categories. Upon installation, the hoist ropes are essentially free of contact with the overburden, while the drag ropes are continually exposed and pulled through loosened material. The hoist ropes always have some load on them; the weight of rope hanging down from the point sheave plus the bridle jewelry and dump system is substantial. Hence, the hoist ropes are always kept "closed" in addition to being exempt from dragging in the dirt. Some form of internal lubrication, either built-in or introduced as a penetrating fluid, might be designed to extend hoist rope life. Of course, suitable corrosion protection would also be needed.

Studies indicate that drag ropes are very likely to experience complete unloading, if not rebound compression forces. If the ropes fall in the overburden without being tensioned, dirt/stone particles are most likely to be jammed into the rope interior; that is, between the strands while they are loose. It is difficult to imagine what kind of lubricant might work under those circumstances. Even if the drag ropes were kept somewhat tensioned, they will often be dragged through the overburden and pick up dirt which can then work down between the strands when the ropes are unloaded during unsymmetrical digging/jerking, or when slackened to dump the bucket. Sticky lubricants or corrosion-protection compounds appear counterproductive in these circumstances.

Because different mine sites may have very different types of overburden and chemical species contacting the drag ropes, a universal solution is not expected. Protection against acidic conditions is surely desirable, and

(a) One reported test approximating dump rope usage on a very large dragline compared no lubrication (except as-fabricated) with continuous bathing in good, penetrating oil; the lubricated rope lasted 50% longer (Gibson 1980).

probably obvious to mine operators in those situations, but an "all-purpose" lubricant for drag ropes does not seem easily achievable.

Summary

The key elements of rope design and manufacture may be summarized as follows. Six strands preformed around an independent wire rope core of contrasting lay constitutes a time-proven basic design for large-diameter rope; that construction holds up well under the high tension and bending loads experienced by running rope systems on walking draglines. Carbon steel compositions and qualities provide useful combinations of cost, strength and toughness for this application of drawn wire.

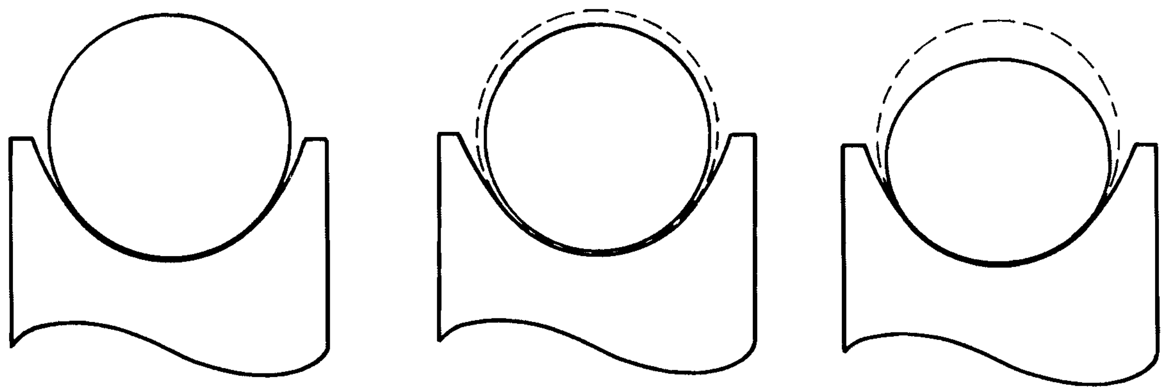
Proprietary rope designs stem from select combinations of wire properties and sizes, combined with appropriate compaction factors. Modest improvements in rope life may be realized by adjusting these aspects to fit a particular service function, and by providing built-in corrosion protection and lubrication.

MACROSCOPIC ASPECTS OF ROPE DURABILITY

After a rope is laid up it must fit certain dimensional criteria, particularly with respect to diameter. Rope made to a specified diameter may be a little larger, but never smaller, than the named dimension. In a broad sense this may be readily seen as reasonable, since the rope would be expected to lie looser without load than with load. Furthermore, the intentional introduction of looseness as a compaction factor in design implies that the rope will be smaller in diameter after a bit of working than when first rigged. Surely this must influence the design of sheave groove geometry.

Sheave Groove Dimensions and Quality

Sheaves are approximately as much larger than the nominal rope size as the upper tolerance on the rope itself. Thus, the unloaded or slightly loaded new rope will just snugly fit a new sheave groove for that size rope. After the rope has been used for a while, it will clearly fit rather sloppily into the sheave groove. Under dragline working loads the rope will thus be flattened to some extent as it deforms to fill the oversize groove. This sequence is pictured in Figure 51.



a. Snug Fit of Unloaded Rope

b. Loose Fit of Axially Loaded Rope

c. Flattened Fit of Loaded and Bent Rope

FIGURE 51. Rope Fit in Standard Size Sheave Groove

A more satisfying consideration of the flattened rope effect can be developed by considering the rope as a seven-circle section; that is, with IWRC and strands of the same diameter, composing a rope of three circle diameters, fitting into a sheave groove somewhat larger than the rope size. The rope is viewed in Section A-A, Figure 52, at a position shortly after it has begun a wrap around the sheave. That section view is imaginarily kept in the same place while the rope, under practical loading, feeds onto the sheave and passes by the viewed position. This activity is shown as a schematic rendition of a Left Lay rope moving onto a sheave.

Because the sheave groove is larger than the rope diameter, and the rope is under appreciable load, two competing situations occur. The strands tend to be pulled against the sheave groove, while their twist tends to keep them tight around the core. Some accommodation takes place; the sequence is diagrammed in Figure 53.

The slipping-off relative motion between strands and core, shown in Figure 53, is probably not as deleterious to rope life as the lengthwise relative motion of strand/core or strand/strand caused by the bending itself. Furthermore, considerable differential axial movement occurs between components just

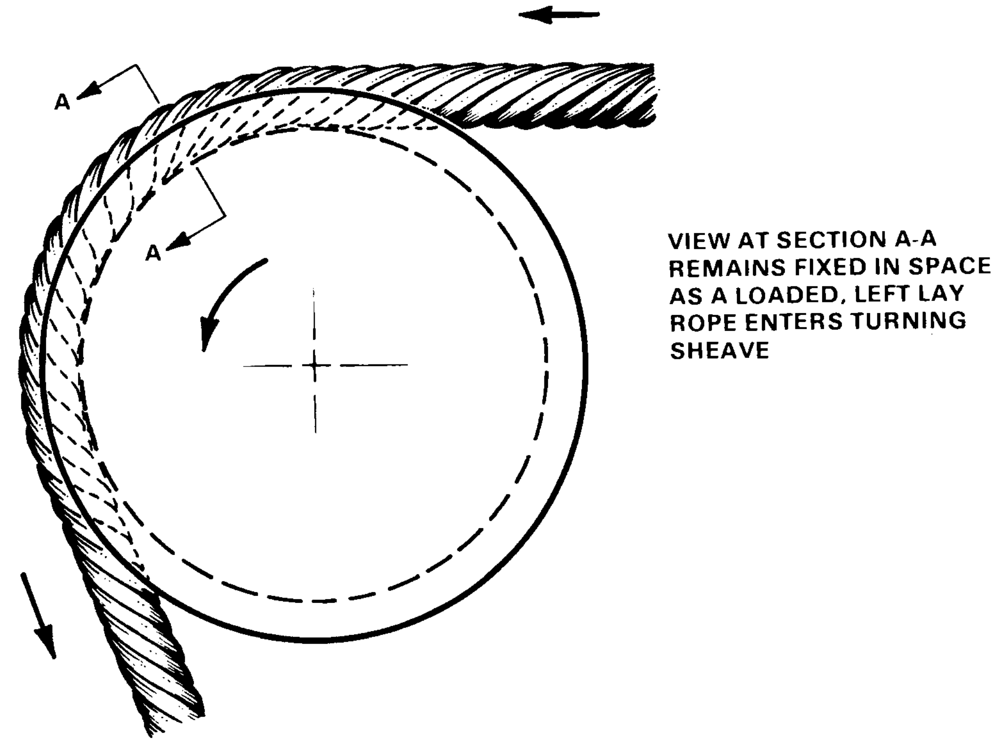
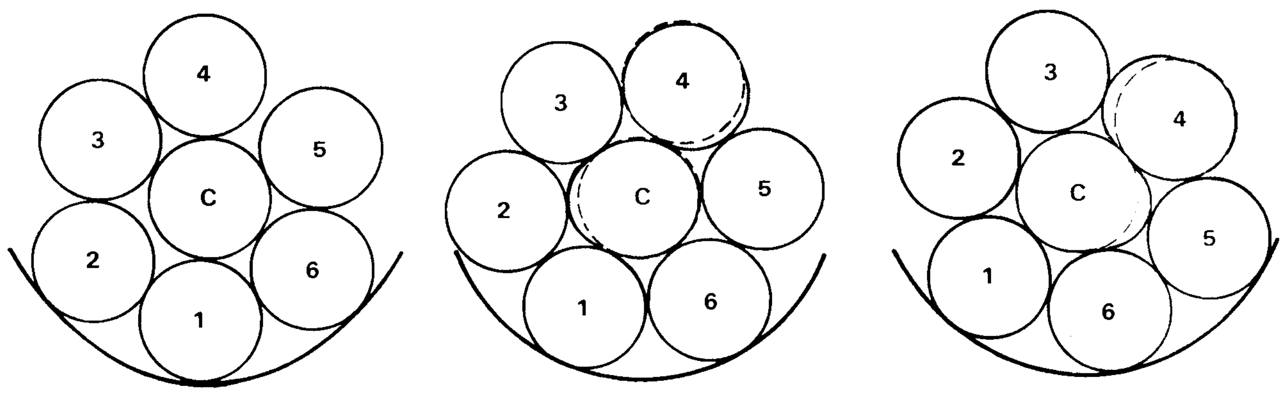


FIGURE 52. Schematic of Rope/Sheave Condition for Assessing Strand/Rope Motion via Seven-Circle Model of Rope in Slightly Oversize Sheave Groove



a. No Load Condition

b. Loaded Condition Strand 4 and IWRC Distorted

c. Distortion Changes With Rope Movement

FIGURE 53. Seven-Circle Model of Loaded Rope Moving Onto Sheave Groove That is Somewhat Larger than Loaded Rope

from tensioning and relaxing, so this slipping-off aspect does not cause all the damage. Nevertheless, it contributes to loss of rope durability and has been singled out for attention many times in the past, in terms of sheave groove dimensions. One development employed a segmented sheave built so that when the rope tensioned around it, the groove segments closed around the rope in a firm grip; upon feeding off the sheave the segments relaxed into an open position. There is no evidence the scheme is useful on large ropes working at high loads.

Rope pinching from a too-small groove dimension can be visualized as the inverse of effects with an oversize groove. On first glance, pinching might appear to be worse than a loose fit; however, under load the rope gets smaller, thus making pinching less of a worry and looseness more so. Definitive results for either situation have not likely been obtained for large ropes, and extrapolation from smaller sizes begs the question of scale effects, the root of the dilemma in rope design and development.

Groove quality presents a different reaction; no one seems to argue against the desirability of keeping sheave grooves smoothly dressed to target configuration. Some field operations are set up to alternate rope lay directions with this in mind; the left lay marks are rubbed out by reeving on a right lay next time. Once again, however, there appears to be no definitive work addressing the point of how bad is bad. In light of the usual attitude toward keeping grooves clean, there is little motivation to pursue such definitions.

A related aspect--groove hardness--merits appreciation. Customarily, the sheave groove is hardened to approximate the outer strand wire hardness. The process of hardening may, in some situations, be shallow, or of asymmetrical response. After service exposure, such conditions may permit or induce groove wear of such extent that the target groove geometry is grossly violated. Resulting rope damage can be dramatic and almost sudden; rope durability is quickly compromised. An operator has no choice but replacement or re-contouring and re-hardening--very expensive at best.

The bend-over-sheave fatigue tests on 3-in. ropes reported under this project were all conducted with a sheave constructed from commercial mild steel plate 5 in. thick. After more than a million rope bending cycles the unhardened sheave grooves were not grossly distorted. The loaded rope quite obviously does not grind the groove into a broader and broader shape while the rope flattens, as shown in Figures 51 and 53. Probably both the twist-tightening effect and moderate support to the strands from the mild steel are adequate to maintain a near-round shape. Nevertheless, cast-in-place replicas of rope shape in a sheave, under various loadings, would be instructive.

Reasonably maintained sheave grooves built to industry standards do not degrade large-diameter wire rope durability. Big improvements in field rope life are not likely to result from practical changes in sheave groove dimensions or quality.

Sheave/Rope Diameter Ratio (D/d)

Quite different conclusions can be stated about the influence of sheave/rope diameter ratio on rope life under BOS fatigue. Maximum wire stresses due to bending only, double when the ratio halves (Morgenstern et al. 1980, p. 4.22). Because the superimposed axial tension loadings add linearly, in an elastic sense, the maximum wire stress can reach the wire elastic limit under modest tensions when the sheave is relatively small. Individual wire damage and, hence, rope damage, accumulates quickly when local conditions become inelastic. A final result of dramatically lowered BOS fatigue life is indicated by test data trends pictured in Figure 54.

Comparable data for 3-in. and larger ropes are not available, but effects at one D/d can be demonstrated by combining the bending and tensile stress calculations for the strand outer wire (Morgenstern et al. 1980, Sec. 4.4). This combined result is shown in Figure 55. The vertical dashed line is for a D/d of 30, and the curves are for different axial load factors.

Note that as the load factor approaches one-half (0.5), the total tension stress (in the worst location in the worst wire) must be bordering on the elastic limit of the wire (Table 10). It would be expected that rope life is

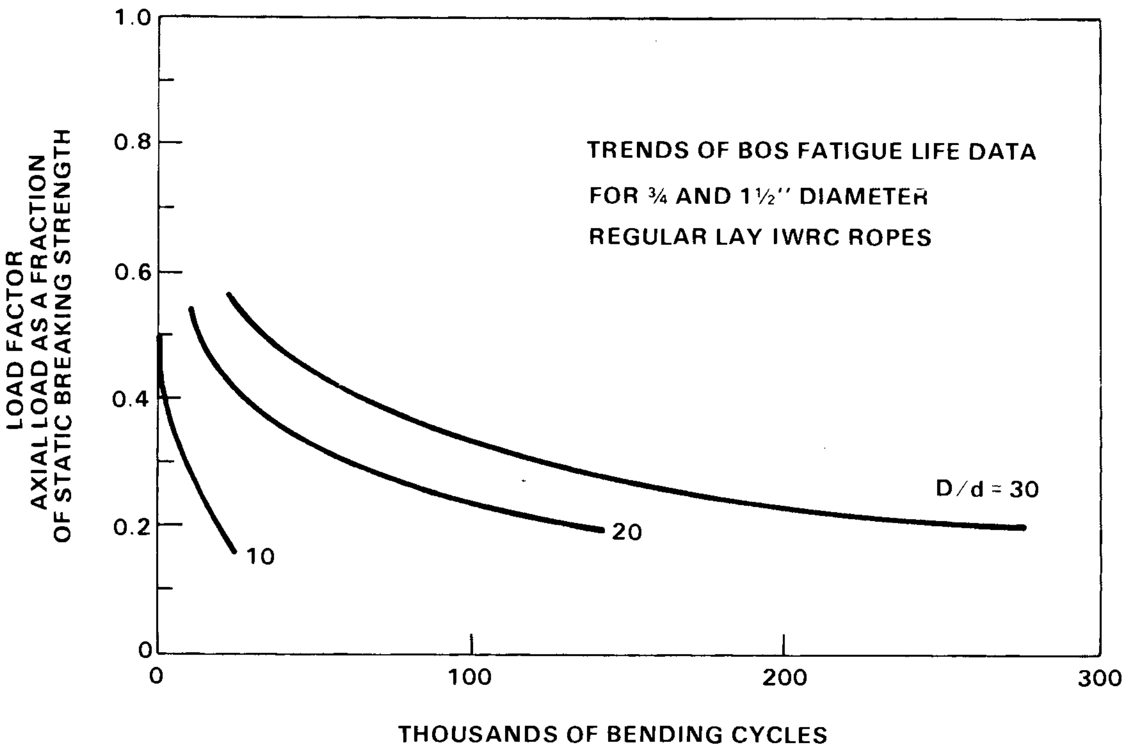


FIGURE 54. Linear-Life Plot of Small-Diameter Ropes in BOS Fatigue

markedly shortened by loadings that exceed wire elastic properties; hence the large rope performance at high load factors, as indicated in Figure 56, should not be surprising.

Figure 56 is useful in comparing the actual load factor performance of 3/4-, 1-1/2- and 3-in. ropes at constant D/d, particularly since the 3-in. data are all for one type product. When presented in a linear scale, and when results are plotted in a consistent reference frame, the three rope sizes exhibit clearly similar behavior at D/d = 30. This is not to say that similarities in performance should be expected at smaller D/d ratios, because the combined effects are so nonlinear, as seen in Figure 55. Nevertheless, when attempts are made to compare performance based on some means of "correcting" for D/d and other factors, useful comparisons like that shown in Figure 56 can be developed.

Finally, with regard to correlating large- and small-diameter rope data in BOS fatigue, Figure 56 does provide evidence that similarly constructed ropes

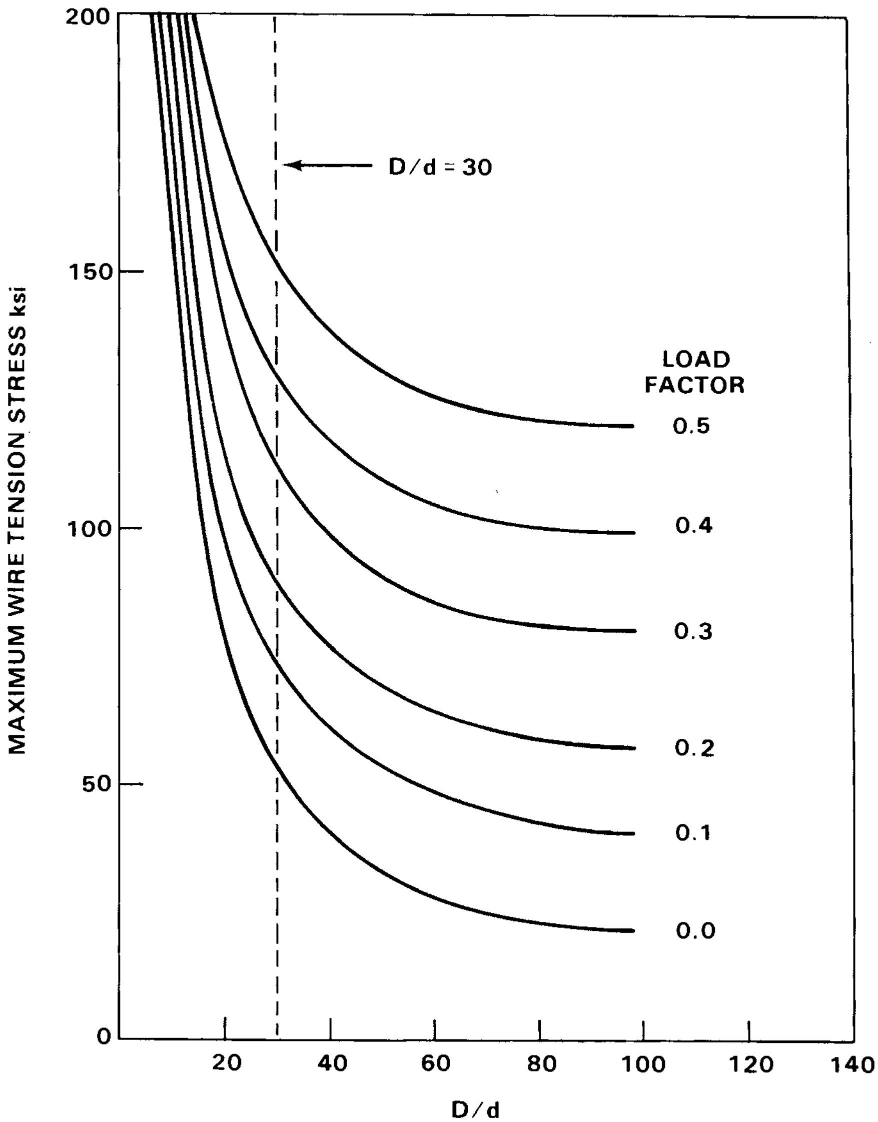


FIGURE 55. Combined Effects of Rope Bending and Axial Tensile Loads on Maximum Wire Stress in 3-in. Diameter B' Rope

operated at reasonable load factors, e.g., less than 0.3, will perform in similar ways at D/d ratios near 30. Furthermore, the behavioral trends and scatter-band in the figure provide a valuable baseline of performance against which rope life in BOS fatigue may be evaluated; this is a new and useful contribution to rope literature.

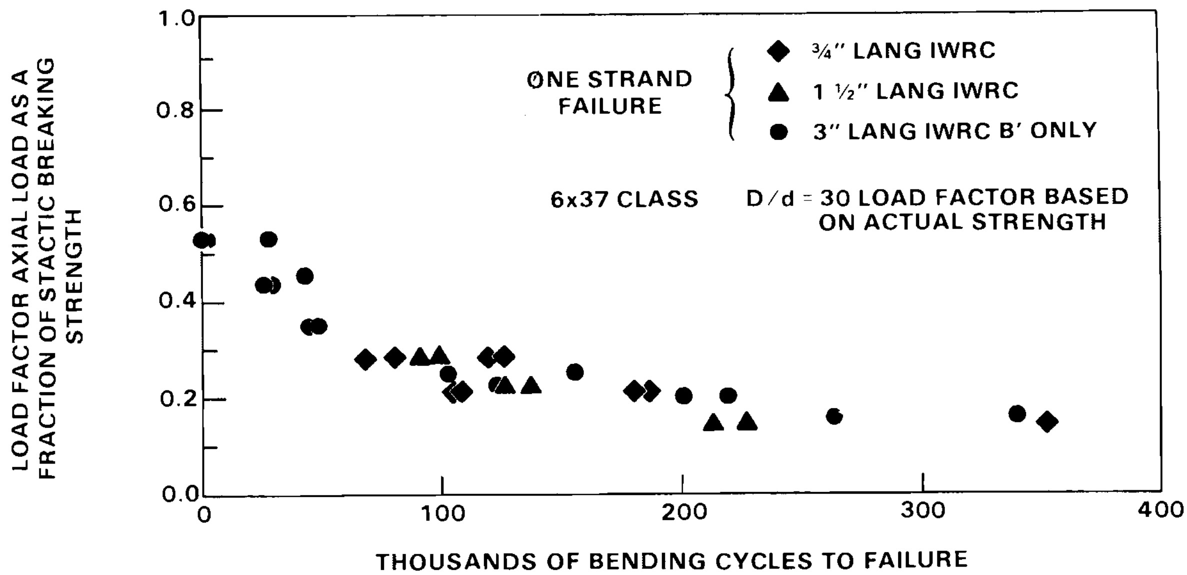


FIGURE 56. BOS Fatigue Life at One-Strand Failure for 6 x 37 Class Ropes at D/d = 30

Reverse Bends, Load Factors and Bucket Position Effects

Reverse bends are just what the name implies: rope coming off one sheave is then bent the other way onto another sheave. Other factors, including distance between reversed bends and the load factor, make important differences, too. However, these aspects are not discussed further here because the trend effects should be clear, and detailed results would not materially alter this presentation.

In this document an effort has been made to systematically employ the term "load factor" as the inverse of design factor; that is, load factor is a fraction of rope strength, either rated or actual, and design factor (sometimes referred to as safety factor) is a numerical reciprocal of load factor. The dramatic effect of load factor on BOS fatigue life was displayed in Figure 56, where an order of magnitude difference in life resulted between load factors of 25% and 50%. Clearly, load factor plays the dominant role in BOS fatigue performance at a given sheave/rope ratio. Hence, improved rope life can nearly always be achieved with no other actions than reducing the operating loads.

An important contributor to the level of operating loads can be identified from considerations of the bucket rigging system, described earlier. Recall that after the bucket is filled it is tipped up (cocked) by tensioning both the hoist and drag ropes. Consequently, under these conditions the bucket system must hang in under the point sheave of the boom, pulled toward the house by the drag rope tension keeping the bucket cocked. Proportionate loads shared by the hoist and drag ropes depend on the particular position of the bucket with respect to the angles the ropes make with horizontal, against the gravity pull of the bucket system weight.

Because the relative loads on the hoist and the drag ropes depend on position of the bucket system, and because the loads on either set of ropes will vary with position thus causing the respective ropes to experience varying load factors, the overall effect is termed "bucket position factor". Its direct influence on rope loads makes it one of the more important but overlooked reasons for diminished hoist rope life. Actions to reduce maximum bucket position factors experienced by the lift-to-dump portion of an operating cycle will usefully extend hoist rope life.

Appreciation for how large these loads can become may be gained by considering the diagram in Figure 57, and referring to Appendix A for more detailed analysis. Lines of action of the drag ropes and the hoist ropes intersect exactly with the (static) line of gravity pull on the bucket system. For conditions shown in Figure 57 the hoist ropes are pulling 1-1/2 times the weight of the total bucket system. Some dragline operators commonly pull the bucket right up to the house during a typical fill operation, so the hoist ropes may see large bucket position factors every cycle. Furthermore, the high loads in the hoist rope induce commensurate high loads in the boom components. These high loads reflect into the structure at the house and generally add to fatigue problems on all related systems.

Because there will be a particular physical relationship among drag rope loads, dump rope rigging geometry, and the suspension point of the bridle at the bucket, optimizing these arrangements to permit easy bucket cocking and quick bucket dumping will improve hoist rope life. This can probably be done without sacrificing productivity, but specific solutions pose a practical challenge to mine operators.

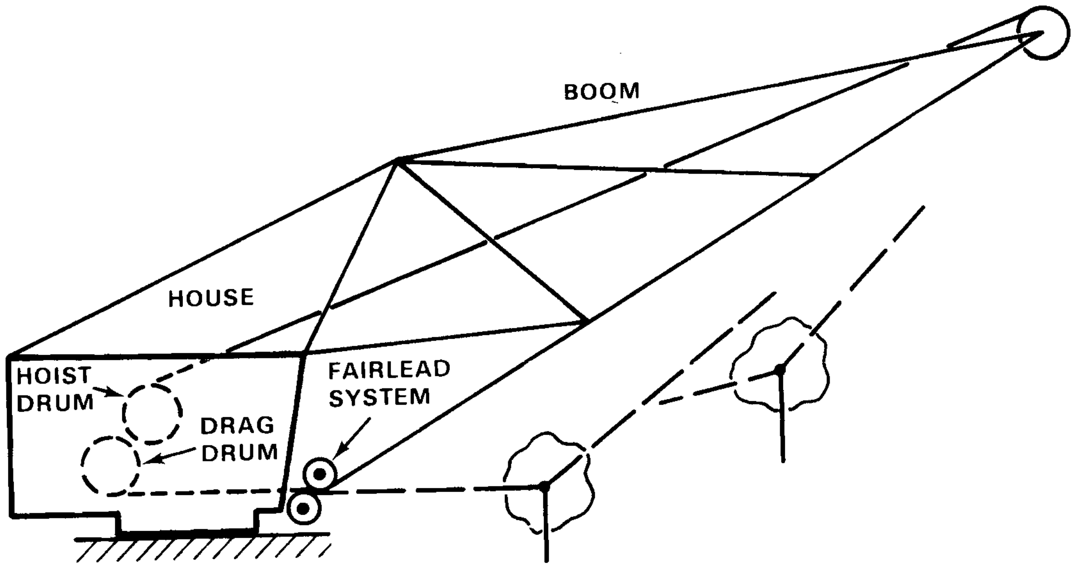


FIGURE 57. Situation in Which the Bucket Position Factor Causes Loads on the Hoist Ropes to be 1-1/2 Times the Bucket System Weight

Summary

Summarizing the key elements of macroscopic aspects influencing rope durability, sheave-to-rope diameter ratio was shown to have a dominant effect. At a given ratio, loads were seen to be the governing factor affecting running rope life. As a byproduct of this situation, the bucket position factor was shown to be an important variable in producing surprisingly larger operating loads than might appear obvious. Operational practices that can keep this factor to its lowest practicable maximum on each cycle will materially increase rope life. Such practices are currently employed at several mine sites with attendant benefits.

MICROSCOPIC ASPECTS OF ROPE DURABILITY

Some technologists maintain that all structural behavior is ultimately governed by the specific atomic and metallurgical performance of the materials involved. Others point to the biased view engendered by such an attitude and prefer to consider structural performance as an interactive response among shape (geometry), loads, material and environment. This latter view is favored here. In the following remarks microscopic aspects affecting rope durability are discussed in relation to their interaction with the total rope situation.

Microstructural Morphology

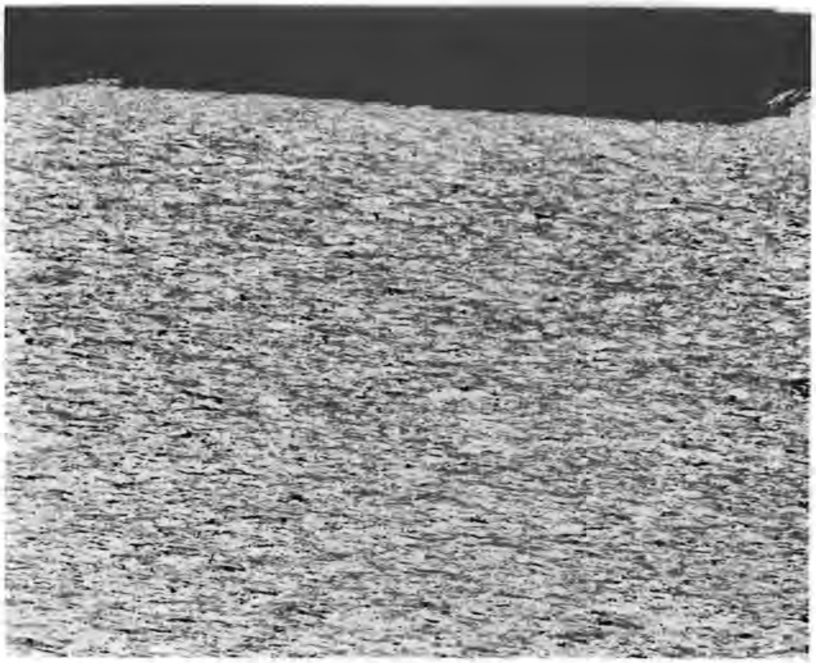
Morphology, the study of shape (and changes), is particularly relevant to rope wire because of the unique microstructure that results from repeated drawing and patenting. Both the grain shapes and distribution of constituents are important to wire properties that make rope wire functionally practical. Included with this view is the aspect of submicroscopic features resulting from wire drawing (cold work) in the final stages of production; cold-working generates dislocation structures that, together with the grain boundaries and intermetallic dispersions, are responsible for the very high damage tolerance rope wires must possess to provide a practical running rope.

The important elongated wire texture is readily seen in Figure 58. Along the boundaries of each elongated grain are dispersions of intermetallics. Around the outside of the wire is a film of oxide, resulting from reaction of iron atoms with the surrounding atmosphere. Generally the atmospheric chemical species that dominate this film chemistry are simply oxygen atoms, and they form one kind of "rust". If the oxide film is broken locally, fresh metallic surfaces are exposed to react, and they do so quite violently at the atomic scale, with available reactants.

This visualization will be called upon to help explain the author's interpretation of what happens during corrosion and cracking, and in wear processes. First, however, a situation wherein the wire microstructure is significantly altered will be briefly described.

Microstructural Transformations

Iron and many of its carbon alloys are "polymorphic", that is, "many-shaped". In this sense the shape refers to atomic organization, as referenced to a steady-state condition at a particular temperature. Thus the terms austentite and ferrite refer to specific atomic organizations which are "stable" at particular temperature ranges. However, if the austenite form in simple carbon alloys is quenched quickly, a "metastable" form called martensite is produced; it can become ferrite, the stable form if certain thermodynamic requirements are satisfied.

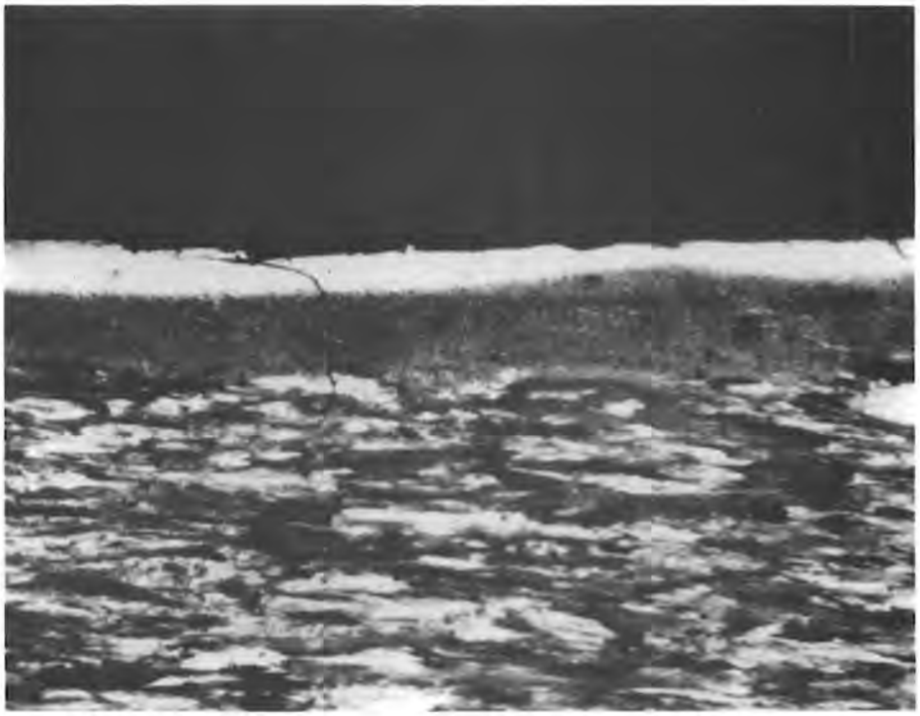


100X

FIGURE 58. Longitudinal Section Demonstrating Elongated Texture

Carbon alloys of iron as used in rope wire can form martensite in local regions if locally intense heating occurs so quickly that after the occurrence nearby material quenches-in the metastable state. Such transformations can encompass a few of the elongated grains, producing a "transformed layer". If the local heating cause is continuous, the layer may extend a considerable distance along the wire. Highly localized heating can occur under very rapid shearing displacements, either by sliding contact or by very fast shear straining in a narrow band. When prepared by normal metallographic procedures, such layers on the outside of the wire etch white; hence the name "white etching layer". An example of this is provided in Figure 59. In rope wires the layer is usually hard and brittle.

There is little doubt that the white etching layer forms on rope wires from skidding across metallic or rock surfaces, on the one hand, and from violent local impacts causing high strain rate shear, on the other. Surprisingly, no evidence is available to suggest that cracking through the layer is responsible for very many wire failures by directly breaking from the surface crack.



High Magnification View of White Etching Layer Showing Crack

FIGURE 59. Example of White Etching Layer on Rope Wire

Alloying could dramatically alter the picture of microstructural transformation, but it is now difficult to argue whether any gains would be worth the price. Current practices produce wires that are amazingly damage tolerant; improvements in the wire properties might have a very valuable payoff in longer rope life if coupled with improved lubrication.

Corrosion and Cracking

Corrosion is the process of a chemical specie reacting with the steel wire to produce a compound that does not remain mechanically contiguous with the wire; the resulting formation does not help carry loads along the wire. If the corrosion is general, corrosion products may accumulate inside the rope and resist relative wire sliding conditions caused by rope stretch and flexing. At the same time, such corrosion diminishes each wire cross section, making it more susceptible to breakage under service conditions.

Local corrosion may form pits and may be a precursor to more general degradation. But local corrosion at a crack tip is more dramatic in its action. Once a crack is initiated, by whatever means, the presence of chemical specie that reacts with fresh metallic surfaces generated by local deformation can markedly alter the cracking process.

The type of chemical specie presented to the running wire rope is clearly related to mine site specifics. Consequently, anticorrosion measures that work well at one site may not be so effective at another. Although these differences are real, there is adequate reason to believe that useful preventive measures can be incorporated in any practical additive. But, however such measures perform, their decisive activity is at the microscopic, even atomic, structure level. Two methods might mitigate the effects of general corrosion and corrosion cracking: one, by keeping the corrodent away from the metallic surface; the other by chemically altering the active specie to a benign or even favorable form. Although the details are unclear, the broad shape of what needs to be done can be pictured from considerations of lubrication and wear.

Wear/Lubrication Processes

Wear consists of metal removal; the particular process by which it takes place is important to its understanding and amelioration. Wear differs from corrosion in that a mechanical movement between parts occurs during wear; corrosion can diminish the affected parts volume without relative mechanical motion. Almost all wear is accompanied by elements of the same chemical reaction processes associated with corrosion, as well as other factors related to extreme pressures at the contacting interfaces when that occurs. Contrasted with film boundary lubrication in ordinary rotating pin and sleeve systems, where virtually no metallic contact arises in the ideal case, the wire rope situation abounds with violent contacts.

Wear

One drastic wear process was pictured earlier in discussion of the white etching layer and its possible role in spalling off under subsequent sliding impacts. This form of wear may account for sectional loss in the outer wires and lead to their early failure. However, just what fraction of wire damage develops this way is yet unknown.

Another process related to sliding damage is delamination wear. It is limited by, or maybe even a result of, the deformed grain structure generated by the sliding itself. Here it may be visualized that a hard object locally contacts the wire surface in a sliding motion and scrapes out a layer of metal by causing internal fracture along planes defined by the intermetallic distribution; thus a flake is torn out. This seems clearly caught by the picture of delaminated layers in Figure 60.

After loss of the "flakes", several hard particles possibly including oxidized debris from the wear process but more likely external "dirt", have gouged and scratched the remaining surface. This is abrasion, an undesirable form of single-point tool machining.

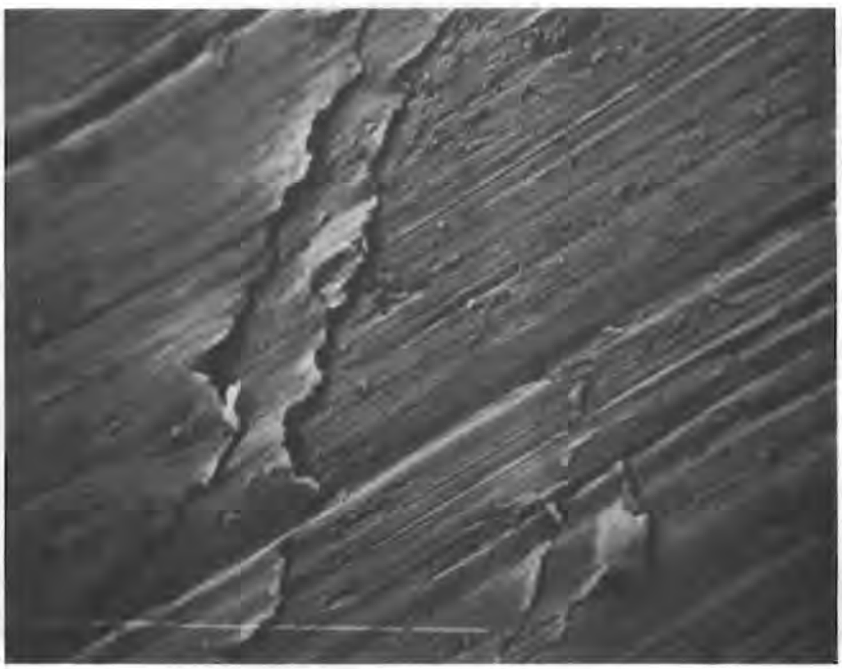


FIGURE 60. Detail of Abrasion Zone Showing Surface Flow and Delamination Type Wear

When wires are forced together during bending over a sheave, local contact forces not only deform the wire surfaces plastically but break the oxide film at the same time, thus welding the two wires together at a tiny spot(s). This is one form of adhesion. Sliding motions associated with flexing then tear away these tiny spotwelds and some of the pieces form metallic debris. Some of the debris may get caught between wires in subsequent operations and act as a cutting tool to gouge and "machine" away more of the wire surfaces. This situation can be visualized in views shown as Figures 61 and 62. The pock marks and generally torn surfaces suggest local welding and tearing into chunky debris.

However, the more important effect of adhesive wear is associated with the usual corrosion that develops on the freshly torn surfaces. Corrosion buildup generally results in wire lockup, preventing the relative wire sliding necessary for a well-behaved rope.

Extensive local deformation from plastic flow can accompany these wear processes. These deformations accentuate changes in wire shape and aggravate the detrimental stress concentrations. It will be recalled that wires experience both axial and bending loads in normal use, either from BOS conditions or travelling wave and "whip" kinks. Hence, any stress concentrations along the wires of the rope can act as fatigue crack initiators, particularly if some scratch or other surface defect is in the highly stressed region.

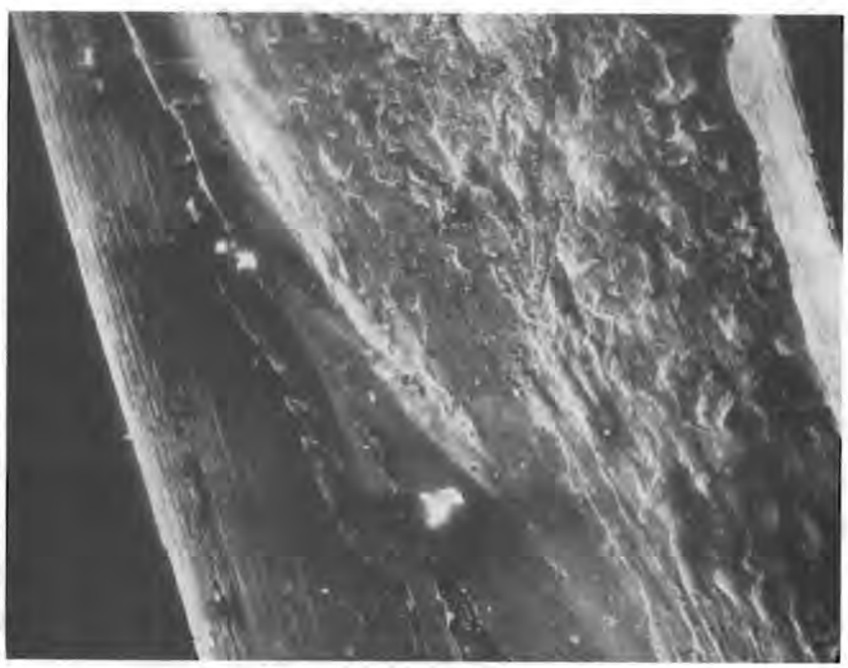


FIGURE 61. Detail of Wire Notching

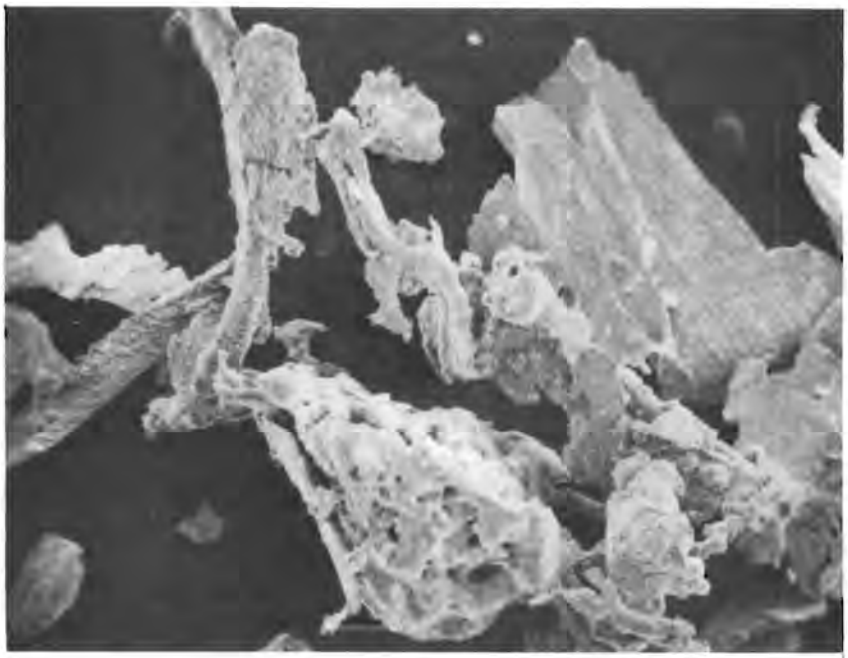


FIGURE 62. Steel Wear Debris Extracted from Wire Rope Sample

In this way wear that causes extensive local shape changes becomes responsible for generating fatigue crack failures at susceptible sites. Because rope design permit selection of various hardness wires at selected locations in the strand and IWRC, it is not suprising to find many fatigue breaks occurring where wire contact pressures are greatest and cause the most wire distortion. Of course the strand-strand wear surfaces become worn more than plastically deformed because the outer strand wires are hard, while the IWRC outer wires will usually be deformed more than the strand outer wires because they are often not as hard.

Lubrication

Lubrication can be described as an antifriction/antiwear treatment. Its purpose is to prevent the mechanical and chemical steps of wear as much as is practicable. For the wire rope this means a lubricant must somehow perform under drastic contact sliding conditions, not at all like the requirements for full-film hydrodynamic boundary lubrication. Because the contact sliding pressures seem to rule out any ordinary thick-film lubrication process, other attacks on the problem are warranted. One view focuses on the aspect of inducing favorable actions with freshly torn surfaces.

If certain chemical specie are presented to a freshly abraded steel surface, the reaction produces a coherent film quite different from ordinary oxidation. It conceivable that some combination of specie may be developed such that the film formed after reaction with the steel is more resistant to subsequent welding and tearing than the usual film. This lubricant would be of different type, but would satisfy the requirement of diminishing wear. Together with appropriate selection of wire hardness, and perhaps with the aid of alloying, it can be imagined that such lubricant could indeed practically improve the life of wire rope on dragline operations.

Summary

Microstructure of the carbon steel wire developed from stages of drawing and patenting is primarily responsible for its amazing durability in wire rope. If some means could be found to suppress the metallic tearing associated with high contact pressures between components of the rope systems, an improvement of rope life would certainly result. A corrosion-inhibiting carrier of some to-be-developed chemical specie(s) that accomplishes this goal is worth considerable effort; who can pursue it?

TYPICAL SERVICE PROBLEMS

The concepts outlined as key elements can be applied by considering some field problems and phrasing them in terms employed during the concept descriptions. The following situation descriptions are intended to conclude with an informative or provocative thought or suggestion. They are, themselves, one form of technology transfer.

Switching End-O, Cutting-Off

Rope damage arises from external contacts as well as from interior wear and deformation. Passing over sheaves or rollers causes controlled bending that can be related to laboratory BOS fatigue tests. Contacts with rocks, rope, jewelry, or other structures causes uncontrolled bending or kinking that is not readily reproducible in the laboratory nor easily evaluated for damage level. But the contacts and kinks certainly degrade a rope faster than if they had been avoided. Recognizing that rope damage is often localized in nature, some operators cut off the bucket end of a drag rope and resocket; or they swap ends of the rope after some level of use, putting the drum end at the bucket, and vice-versa.

Cutting-off and end-o switching of the drag ropes can be particularly useful if the digging/operating conditions tend to concentrate damaging effects at the drag socket region. Abrasive wear from overburden grinding is one example. Rope whip flexing damage is another; its actions are described below.

Switching ropes end-o or cutting off and resocketing may usefully extend rope life in certain situations; in others, the efforts may have been fruitless or even dangerous. Operators should have a clear reason for whichever tack they choose.

Socketing and Wire Slide

When socketing a rope, the wedge contour provides a controlled shape for the rope to fit as well as producing inclined planes that match the socket interior and thereby secure the rope. However, the wedge contour causes much sharper bending of the rope than any other intentional service experience. The tight bend can cause an unobvious difficulty.

If the rope is welded or otherwise tied at the bitter end so that strands and wires cannot slide to accommodate the sharp bend, the "extra" wire lengths may buckle in the socket bend region or feed back into the running section. There, the slackened wires cause uneven load distribution and induce local damage near the socket, adding another factor that can shorten rope life.

Drag Rope Whip and Rope Damage

During certain digging operations, particularly when the drag ropes are about full-out, they are often observed to undulate obviously. This behavior consists of "waves" that can be seen moving along the rope to the socket and then back to the fairlead and so on. Sometimes the motion is very marked; especially at these times, but to some degree whenever there are reflected waves, the ropes experience rather sharp curvature, or bends, at both the socket and the fairlead area.

This sharp bend causes both wear by sliding motions and fatigue damage from the bending itself. Because the waves may reflect every second or two there may be something on the order of 10 or 20 such cycles on the drag ropes for each digging cycle that the waves are operative. Although the magnitude of stressing damage or wire wear damage has not been assessed by laboratory simulation or direct measure, the flexing actions may account for some drag ropes to wear out so soon.

The practical effect of this might be clarified in a particular mine by comparing drag rope life when substantial and obvious rope whipping occurred as against filling with similar overburden when rope whip did not occur. Certainly it can be recommended that digging be done in such a way that rope whip is minimized.

LABORATORY TESTS/FIELD RELEVANCE

Wire rope behavior on a dragline could be simulated very closely in a laboratory, possibly at no more cost than that of a dragline itself. But a more practical question is "What are the important factors in field rope experience and, of these, what laboratory tests would be informative with respect to improving field rope life?" Bend-over-sheave fatigue testing was unanimously nominated as a useful laboratory test. This section will describe the BOS tests and their relevance to field use.

Bend-Over-Sheave Laboratory Fatigue Tests

By constructing a machine with two sheaves in the same plane, and which are displaceable in a controlled manner, rope can be reeved around them and cycled forth and back with auxiliary mechanisms. This cycling reproduces two principal aspects of field ropes: the sheave-to-rope diameter ratio, and the repeated flexing. All other factors aside, these two common features are indeed primary to an understanding of BOS rope performance (but of course through study of the wear and corrosion processes).

Bend-over-sheave performance of wire rope has been compared by plots of rope life against some factor involving the constant tension load, the rope and sheave diameter, and sometimes another factor or two, such as wire strength or wire size, or number of wires in a strand. They all testify to the fact that rope performance is predictable in the sense that results of another BOS fatigue life test of similar rope within the test boundaries can be predicted quite accurately. Reason limits such predictions or correlations to the same type of ropes and rope constructions, cycling conditions, lubrication and environment.

To date, the WRIP has generated a useful, though narrow, data baseline on conventional, large wire ropes (Appendix D) against which to compare either field performance or the laboratory-tested BOS fatigue lives of some new rope construction or rope treatment. At this point, use of the data should not exceed these applications.

All the 1-1/2-in. and 3-in. diameter rope data generated during the WRIP reported here are summarized in a simple linear plot of single-flex cycle life against estimated actual load factor divided by D/d. The plot is shown in Figure 63.

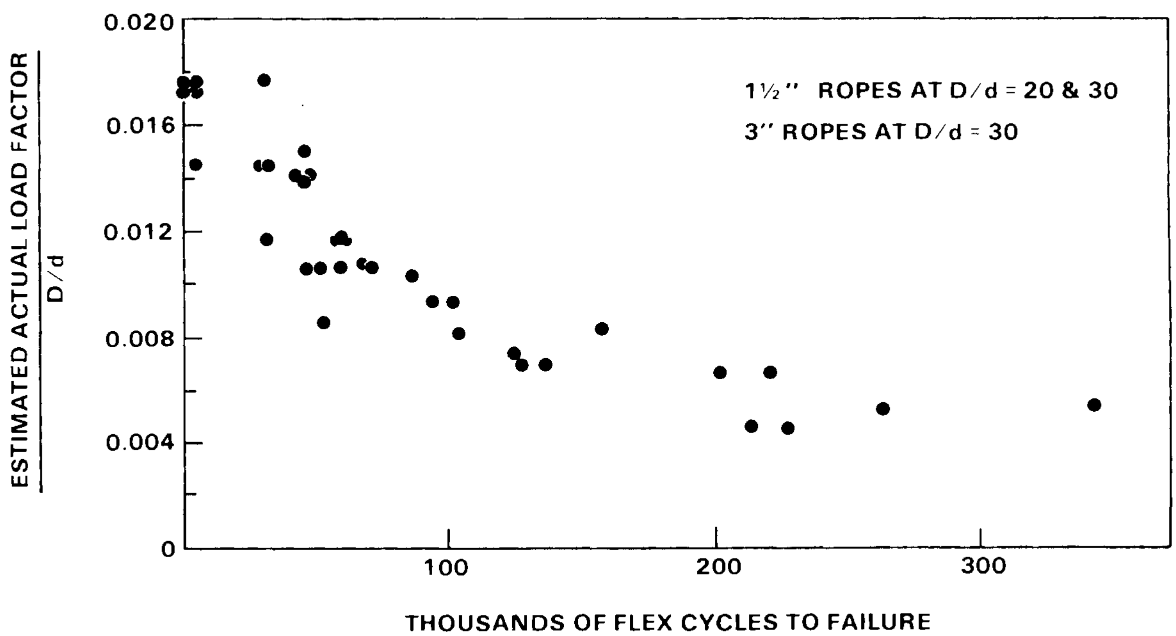


FIGURE 63. Bend-Over Sheave Fatigue Life Plots for 1-1/2- and 3-in. Ropes

A baseline performance curve for these ropes may easily be constructed. The curve is the reference BOS fatigue life behavior which must be significantly exceeded to indicate an improved rope situation that would be worth considering for actual field service. This baseline incorporates the two principal measures of dragline rope experience in BOS fatigue: operating load and sheave-to-rope diameter ratio.

This reference behavior is generally relevant for hoist ropes, but will be less so for drag ropes in those situations where soil abrasion rather than BOS fatigue dominates behavior. For these abrasion-dominant situations, another criterion is needed; unfortunately we have not demonstrated a cost-effective solution at this time.

Field Relevance Factors

In addition to the difference between simple laboratory BOS fatigue tests and drag rope experiences under rocky abuse, other factors could be incorporated into more sophisticated testing.

When ropes are pulled onto the drums under load, they move over their sheaves in a particular tension state that is anything but steady. Upon paying out from the drum, during and after the swing-to-dump, the ropes are under significantly less tension and thus feed over their sheaves differently than before. Simulating these conditions in the laboratory would be considerably more complicated than a constant load test. In part, this difference hinges on how to define a flex cycle of the rope. Hence, the literature descriptions emphasize whether the region of rope length under discussion is single-flex or double-flex or something else. Nevertheless, these aspects could be incorporated into more sophistiated laboratory testing programs if needed.

Missing from the lab-to-field relevance as a second-level importance factor is the actual loading exerienced by ropes during their operations. This aspect has been addressed and some limited field data gathered, but a broader base is surely required for clearer insight to the range of loads that ropes experience, and why.

Summary

Laboratory testing of large-diameter ropes in BOS fatigue has demonstrated that the dominant factors of applied load and D/d ratio are relevant to field BOS fatigue performance because both experiences can be rationalized in these terms. A baseline of data has been generated and is available for comparing performance of new rope construction or other modifications intended to improve rope life under BOS fatigue.

ROPE WEAR AND FAILURE MECHANISMS

Drag ropes wear out by combinations of abrasion wear and fatigue damage, in different proportions according to the particular equipment and its conditions, type of rope, digging conditions, dragline operator handling and the specifics of bucket design and rigging. Hoist ropes wear out primarily in BOS fatigue. The degradation mechanisms for both hoist and drag ropes[a] may be described in the following way:

- Exterior surface abrasion consisting of metal removal wear process via hard particles of overburden material;
- internal wire notching consisting of local plastic deformation caused by loadings of the wires in bending, which can also lead to...
- wire-wire microwelding at high-load contacts points with subsequent tearing of the weld joints, producing bits of debris and reducing the section size as well as exposing freshly torn metal surfaces to...
- corrosive actions that reduce metallic volume or aggravate cracking enlargement under the...
- fatigue processes of repeated loads, particularly when concentrated in local regions by microscopic imperfections or macroscopic stress-risers, like nicks and notches, and directly related to the damage from...

(a) Dump ropes may also be included in the similarities, but they can suffer additional damage from mechanical impacts associated with floppy jewelry.

- high loads in tension and bending that can result from various handling procedures as well as equipment design or condition, thus causing individual wire fractures to eventually cascade into a strand failure and rope burst.

Hoist ropes generally fail in a succession of actions by all but the first mechanism, which, although sometimes dominant in drag ropes, is accompanied by the other mechanisms as well.

CONCLUDING REMARKS

Based on the described mechanisms, corrective actions can be envisioned; these are described in the Conclusions section of this report. Although more research and development efforts in laboratory testing and related analyses are warranted, it is apparent that industry action can bring immediate improvements as demonstrated by changes already implemented at some mine sites. Wire rope and equipment manufacturers may also be able to help, but their efforts will take longer to show up in field performance.

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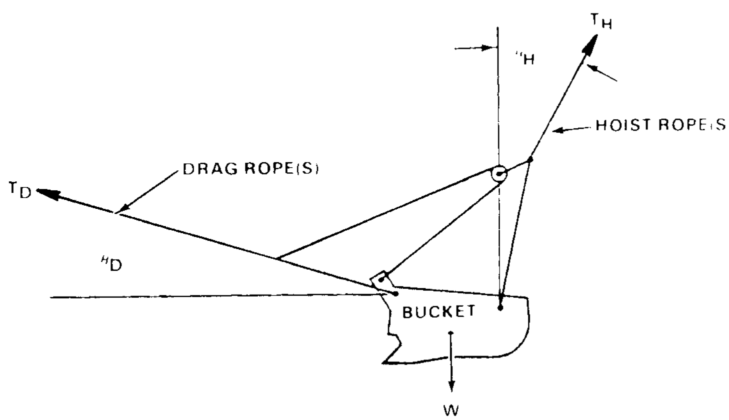
APPENDIX A

BUCKET POSITION FACTORS FOR HOIST AND DRAG ROPES

APPENDIX A

BUCKET POSITION FACTORS

An elementary calculation of loads on the hoist and drag ropes can be conducted for various positions of the bucket in space. The static free-body diagram in Figure A.1 shows the drag rope line of action and the hoist rope line of action intersecting on a vertical line through the total effective center of mass represented by "W". Complicating effects of changes in relative position of the drag or hoist jewelry during changes in bucket position are ignored in this simple treatment; so too are the rope weights neglected.



Σ OF HORIZONTAL FORCES $T_D \cos \theta_D = T_H \sin \theta_H$

Σ OF VERTICAL FORCES

$W = T_H \cos \theta_H + T_D \sin \theta_D$

$T_H = \dfrac{W - T_D \sin \theta_D}{\cos \theta_H}$ AND $\dfrac{T_H}{W} = \dfrac{1}{\cos \theta_H + \sin \theta_H \tan \theta_D}$

$T_H = W \cdot$ BUCKET POSITION FACTOR HOIST

$W = T_D \cos \theta_D \cot \theta_H + T_D \sin \theta_D$

$T_D = W \dfrac{1}{\sin \theta_D + \cos \theta_D \cot \theta_H}$

FIGURE A.1. Free-Body Diagram of the Bucket System

On the following pages the results of calculations for hoist and for drag rope(s) are displayed; first for hoist alone, then for drag alone. The concluding figure shows them both together. In this treatment, each rope system utilizes a separate angular reference coordinate. That is, a common global reference system is not employed. Cautionary notes with Figures A.2, A.3, and A.4 are intended to help clarify this point.

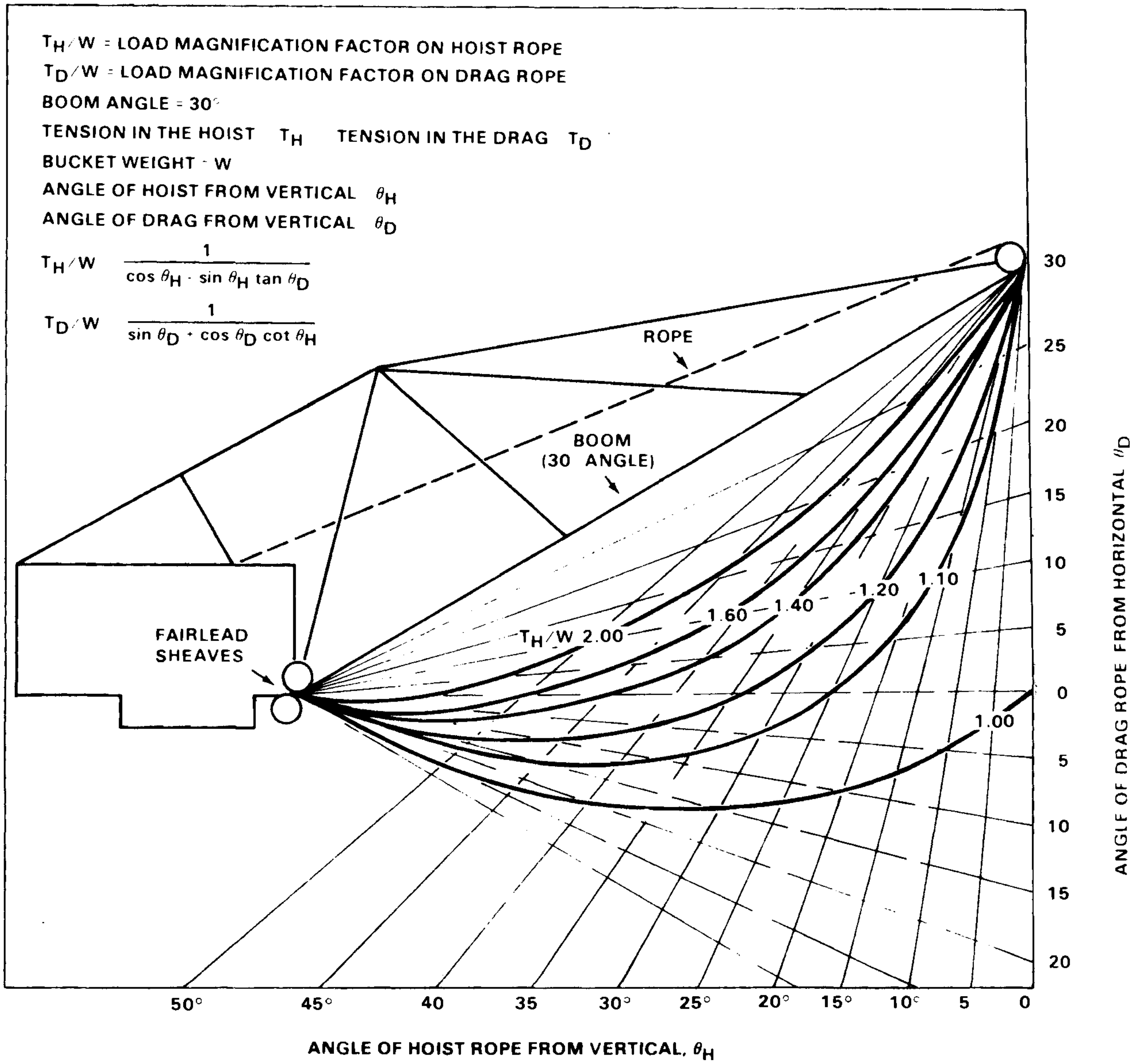


FIGURE A.2. Bucket Position Factor Effects on Hoist Rope(s)

For the Hoist Rope equation, the drag rope angles above horizontal are positive and those below horizontal are negative.

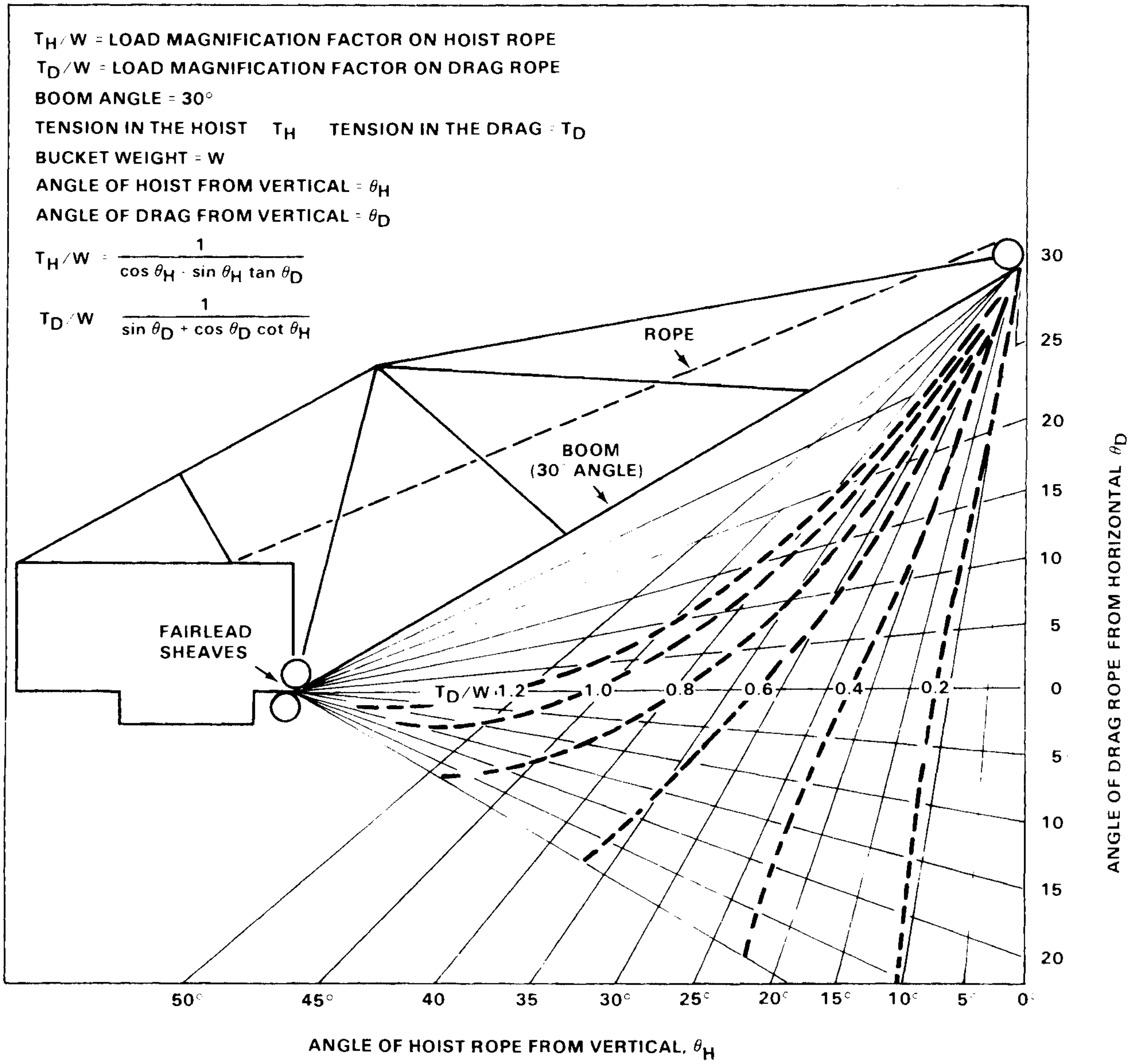


FIGURE A.3. Bucket Position Factor Effects on Drag Rope(s)

For the Drag Rope equation, the drag rope angles above horizontal are negative and those below the horizontal are positive.

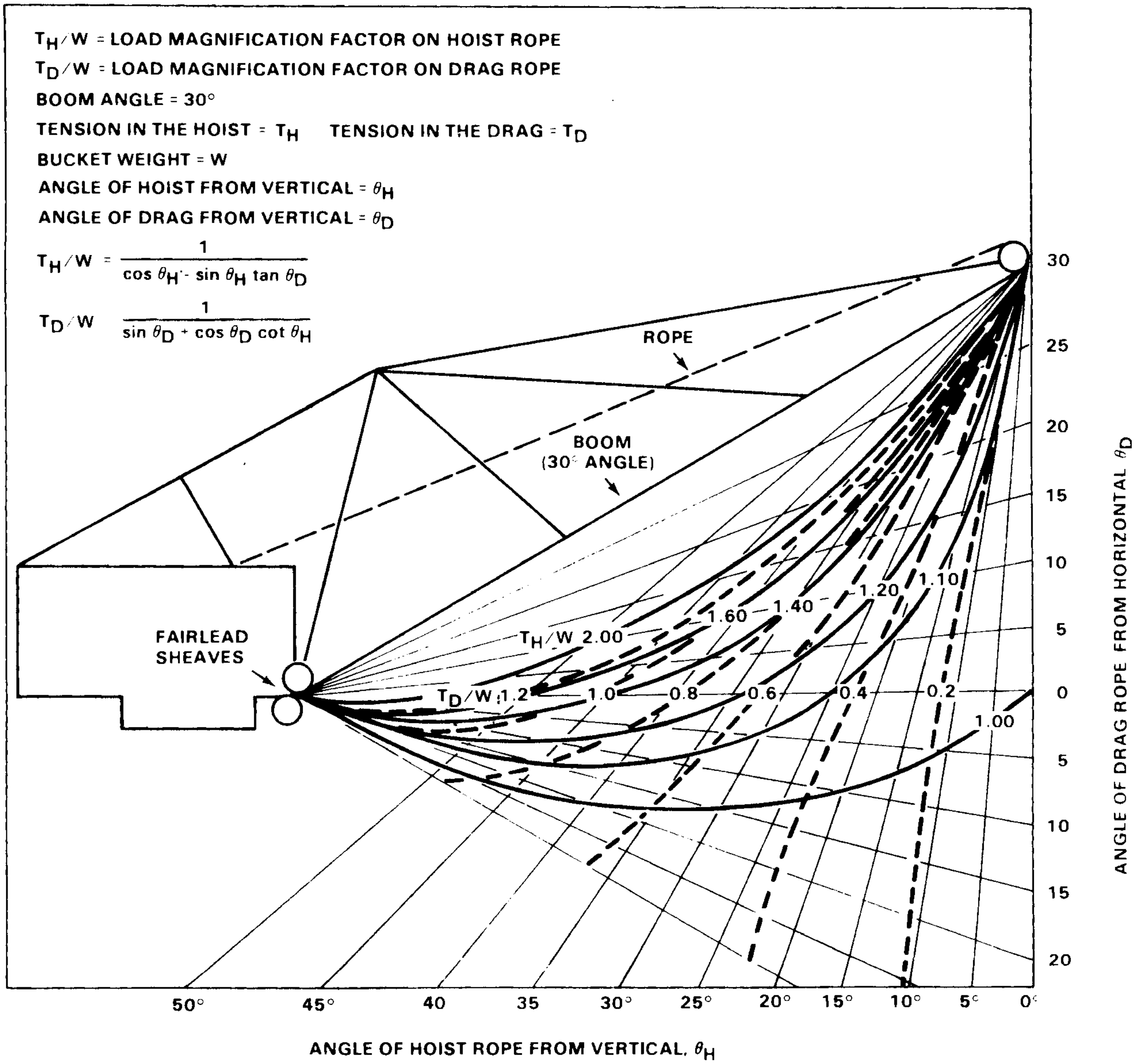


FIGURE A.4. Overlay Diagram of Hoist and Drag Rope Loads as a Function of Bucket Position

Even though the hoist and drag rope equations employed a different reference system with regard to horizontal angles and vertical angles, they were describing a common situation, so they can be superimposed, as shown.

APPENDIX B

WIRE ROPE WEAR AND FAILURE ANALYSIS DATA

TABLE B.1. Visual Characterization of Rope Segments Investigated

	Rope Strand Wires Breaks		Wear						IWRC				
	Outside Wires	Valley Breaks	Outside	Strand to Strand	Strand to IWRC	Grease	Dirt	Rust	IWRC to Strand Wear	Breaks	Grease	Dirt	Rust
HOIST ROPE SEGMENT A	None	Several	Slight to Moderate	Moderate	Moderate to Several	Marginal	Fairly Clean	Slight	Severe	Severe (Crushed)	Marginal	Very Dusty on one end	Moderate
SEGMENT B	Several on one Side	Yes	Medium	Moderate	Moderate	Marginal	Fairly Clean	Moderate to Severe	Moderate to Severe	Several	Moderate	Fairly Clean	Moderate
FAIRLEAD TRAVERSE	None		Moderate but severe on one side	Moderate	Moderate	Greasy	Trapped in Grease	None	Moderate to Severe	None	Moderate	Clean	Slight in Contacts
BUCKET END	Several	None	Severe	Slight to Moderate	Slight	Dry	Very Dirty	Slight	Moderate & Inter-mittant	None	Moderate	Severe at One End	Slight
S/P PAL	None	None	Very Slight	Moderate	Slight	Fairly well Greased	Clean	None	Moderate to Severe	Few	Marginal	Clean	None
D/P	Several	Yes	Slight	Moderate to Severe	Slight	Marginal	Clean	None	Moderate to Severe	Severe (Crushed)	Marginal	Clean	None
NEW	None	None	None	None	None	Marginal	Clean	None	Slight	None	Marginal	Clean	None
FAIRLEAD TRAVERSE	None	None	Slight to Moderate	Severe	Moderate to Severe	Marginal	Clean	Slight	Severe	None	Moderate	Clean	Moderate
BUCKET END	Moderate to Severe	Several	Moderate	Moderate to Severe	Moderate	Dry	Very Dusty	Moderate	Severe	None	Marginal to Moderate	Fairly Clean	Slight
	Moderate to Severe	None or Few	Moderate on one Side	Moderate to Severe	Moderate	Marginal	Moderate	Moderate to Severe	Moderate	None	Caked	Fairly Clean	Moderate
ORIGINAL BUCKET END	Very Se-vere on one side	None	Very Se-vere on one side	Moderate	Slight	Dry	Moderate	Slight	Moderate	None	Marginal	Fairly Clean	Slight to Moderate
FINAL BUCKET END	None	None	Moderate but Severe on one side	Slight	Slight	Marginal	Moderate	Moderate	Moderate	None		Moderate to Severe	Moderate
LOAD CELL DRAG LINE: (YELLOW) BUCKET END)	None	None	Moderate	Moderate	Moderate	Dry to Marginal	Moderate	Moderate	Moderate to Severe	None	Caked & Dry in Half the Segment	Severe in Dry Regions	Moderate to Severe in Dry Regions
(GREEN) CENTER	None	None	Moderate	Moderate	Moderate	Dry to Marginal	Moderate	Moderate	Moderate to Severe	None	Moderate	Fairly Clean	Slight
(RED) DRUM END	None	None	Slight	Slight to Moderate	Slight to Moderate	Moderate	Fairly Clean	Slight	Moderate	None	Moderate	Fairly Clean	Slight

TABLE B.2. Spectrographic Analysis of the Chemical Composition of Selected Wire Samples

Code	C	Mn	P	S	Si	Cn	Sn	Ni	Cr	Mo	Al	V	Cb	Zr	Ti	B	Co	W	Pb
A	.60	.61	.003	.008	.17	.004	.000	.016	.076	.006	.033	.001	.000	.000	.000	.0000	.000	.00	.00
B	.64	.63	.004	.012	.18	.006	.000	.017	.080	.008	.036	.001	.000	.001	.001	.0000	.000	.00	.00
C	.40	.65	.010	.024	.13	.011	.000	.013	.055	.002	.000	.001	.000	.000	.000	.0000	.000	.00	.00
D	.73	.81	.019	.012	.23	.007	.000	.005	.015	.000	.041	.003	.000	.001	.001	.0000	.000	.00	.00
E	.57	.65	.001	.013	.17	.15	.006	.053	.064	.008	.028	.001	.000	.001	.000	.0000	.004	.00	.00
F	.60	.75	.009	.013	.18	.002	.000	.004	.026	.001	.034	.002	.000	.001	.000	.0000	.000	.00	.00
G	.60	.36	.000	.002	.21	.011	.000	.063	.099	.001	.006	.000	.000	.002	.000	.0000	.001	.00	.00
H	.55	.37	.000	.002	.21	.011	.000	.064	.100	.001	.003	.001	.000	.002	.000	.0000	.002	.00	.00
I	.55	.64	.010	.009	.15	.033	.000	.020	.063	.000	.023	.000	.000	.000	.000	.0000	.000	.00	.00
J	.82	.64	.026	.034	.23	.13	.009	.066	.017	.007	.034	.001	.000	.001	.001	.0001	.013	.00	.00
K	.79	.62	.025	.029	.22	.12	.009	.066	.016	.008	.034	.001	.000	.002	.001	.0001	.013	.00	.00
L	.74	.60	.024	.024	.22	.12	.009	.073	.026	.008	.012	.001	.000	.001	.001	.0001	.012	.00	.00

APPENDIX C

WIRE ROPE RETIREMENT CRITERIA

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APPENDIX C

WIRE ROPE RETIREMENT CRITERIA

The dragline user's ability to accurately predict the remaining life of drag ropes can significantly increase dragline productivity. Increased dragline availability as a result of the reduction of unscheduled downtime and the ability to schedule rope change-outs concurrent with planned maintenance periods are the prime motivations for having accurate rope retirement criteria. Wire rope separation is not a viable retirement criterion due to the potential of personnel injury, structural damage to the dragline and increased downtime. However, the precludement of wire rope failure by the use of overconservative retirement criteria needs to be balanced with increased wire rope change-out costs and necessitates the development of realistic wire rope retirement criteria.

The retirement criteria used in the field have several components that can trigger wire rope replacement. Visual inspection is the most common. The number of individual wire breaks per lay length or per strand, or an increase in the wire breakage rate, are all used in the field. Wear of outer wires, especially near the bucket, and other localized wear or damage are other common components of visual inspection that will cause the retirement of wire rope. Changes in rope diameter in the regions of sheave traverses or total rope elongation are used to retire ropes based on more incipient damage.

The sound and feel of smooth running wire ropes can be distinguished from those of worn ropes by the experienced dragline operator and usually precipitates inspection of the ropes. Factors such as yardage handled, operating hours, or number of swing cycles, are used to evaluate the performance of the wire rope. These factors can also be used as retirement criteria when sufficient experience has been obtained with the dragline.

It is obvious from field interviews and laboratory experience that all wire ropes do not have the same failure progression. The number of visible broken wires prior to wire rope failure can vary significantly from one rope construction or manufacturer to another. Some wire ropes will have broken wires visible long before retirement is needed and others will show few or none just prior to failure. Therefore, it is important to develop new retirement criteria for each rope construction or manufacturer used.

Variations among mines in overburden type and density, operating environment, and the specific operating characteristics of the individual dragline can shift the dominant failure mode of the drag ropes from mine to mine. Therefore, specific variations among mines, draglines, and ropes preclude the use of general retirement criteria.

The unique characteristics of specific rope constructions and manufacturers' variations may make some ropes better suited for specific draglines than others. However, care must be taken in assessing the suitability of specific ropes to assure that the proposed replacement rope's useful lifetime is correctly assessed and not simply compared with another rope based on the development of the latter's rope-specific retirement criteria.

Nondestructive examination (NDE) procedures would provide the ability to monitor internal as well as external wire rope damage and thus allow increased confidence in rope retirement criteria. Electromagnetic techniques have been used successfully on smaller-diameter mine elevator hoist ropes. However, the application of these techniques to large-diameter ropes is still pending. The primary problems with the direct application of these techniques to larger diameter ropes are interpretation of results, the correlation of output versus remaining life and the depth of penetration of the inspection. The feasibility of using other NDE techniques for on-line or periodic inspection or large-diameter wire ropes appears reasonable and worthy of further study.

Field investigations and interviews have established that wire ropes are retired primarily because of rope degradation at two locations. The first location is near the bucket where rope wear is severe and subsequent reduction of the outer wire cross section is significant. This condition is most severe at mine sites where the overburden is rocky and contact of the rope with the spoil causes severe abrasion. The second location is the region of fairlead traverse. This region experiences bending fatigue, severe internal damage as a result of relative wire motion and outer wire wear as a result of sheave contact.

The relative balance between drag rope retirement caused by rope degradation in these two regions was to be studied this year, until program emphasis was shifted to the load sensor. However, the existence of a dominant failure mode is expected to be extremely site-dependent due to variations in overburden type, machine characteristics, operator agility, operating environment and maintenance procedures. Therefore, the suitability of specific ropes and the specification of an "ideal" rope will vary from dragline to dragline. This is reflected by the disagreement among dragline users as to who makes the best rope.

The identification of the dominant failure mechanism is further complicated because the service life of a drag rope is often extended significantly by the common practice of cuttingoff and re-socketing the section of the rope near the bucket which has experienced severe outer wire wear. This practice is repeated until the rope becomes too short to re-socket or retirement occurs because of rope degradation in the fairlead traverse region.

In conclusion,

- Specific retirement criteria must be developed for the particular rope in use on a given dragline.
- Electromagentic techniques for monitoring the failure progression should be adapted to larger-diameter wire rope and other candidate NDE techniques should be evaluated.
- The specific mine and draglines conditions dictate the optimal balance between fracture toughness and fatigue resistance.

APPENDIX D

THREE-INCH ROPE BEND-OVER-SHEAVE DATA SHEETS

D.1

TEST 1

New North and South Rope

Date	Cycles Start	Net	Load (PSI)	NF	SF	DF	Cyl Ext.
3-8-76	0						
3-9-76	292		1100				11 7/32
3-9-76	660						11 7/8
3-12-76	720						12 1/16
3-17-76	1323						12 1/4
3-17-76	1444						12 5/16
3-18-76	1690						12 3/8
3-18-76	1898						12 3/8
3-18-76	1991						12 1/2
3-18-76	2079						12 9/16
3-22-76	2773						12 11/16
3-22-76	3204						12 3/4
3-25-76	3310						12 3/4
3-25-76	3400						12 7/8
3-25-76	3675						12 7/8
3-26-76	4620						13 1/16
3-26-76	4848						13 1/16
3-26-76	5137						13
3-27-76	5445						13 1/16
3-28-76	6512						13 1/4
3-28-76	6933						13 3/16
3-29-76	7180						13 3/8
3-29-76	7565						13 7/16
3-30-76	8126						13 7/16
3-30-76	8348						13 1/2
4-1-76	12251						13 5/8
4-2-76	12606						13 3/4
4-3-76	15652						13 13/16
4-16-76	17557						13 7/8
4-20-76	21944						14 1/8
4-20-76	22200						14 3/16
4-12-76	25650						14 7/16
4-30-76	28486						14 1/2

TEST 1 (CONT'd)

Date	Cycles Start	Net	Rope Dia. NF	SF	DF	Cyl Ext.
4-30-76	28601					14 5/8
4-30-76	28952					14 11/16
5-1-76	29978					14 3/4
5-1-76	30805 North Rope Failed					

① ②

LEGEND

DATE INSTALLED	: 3-8-76
DESIGN FACTOR	: 3.4
LOAD (PSI)	: 1100
DOUBLE FLEX LENGTH	: 6 FT.
DATE FAILED	: 5-1-76
TOTAL CYCLES	: 30805
CYCLES NOT AT LOAD	: 5270
NET CYCLES	: 25535
CYCLE STROKE	: 16 FT.

REFERENCE NOTES

① Cycles not at load, 5270. Pressures started at 300 psi. and increased to 1100 psi.. Other pressures during the test ranged from 500 psi to 850 psi. as unit was run.

② 6933 cycles - 1 broken wire on South Rope.
10057 cycles - 1 broken strand on Nort Rope in double flex area.
10659 cycles - 1 broken strand on North Rope in doube flex area.
1 broken strand on South Rope.
12251 cycles - 2 more broken strand on each Rope.
21883 cycles - North Rope has 8 broken wires. 4 in one lay length and 2 in one strand.
South Rope has 5 broken wires. 4 in one lay length.

TEST 2

New North and South Rope

Date	Cycles Start	Net	Load (PSI)	N.F	SF	D.F	Cyl. Ext.
8 11 76	0		300 To 850				21 1/2
9-21-76	49202						23 1/4
9-21-76	49252		1100				23 3/4
9-21-76	49323						23 13/16
9-21-76	49530						23 7/8
9-22-76	[illegible]		1080				23 15/16
9-23-76	50579						23 15/16
9-23-76	51164						24 1/8
9-23-76	51214						24 1/16
9-24-76	51690						24
9-24-76	52128						24 1/8
9-2[illegible]-76	52401						24
9 27 76	52634						24 1/8
[illegible]	52951		1100				24 1/16
[illegible]	53131						24 1/4
9-30-76	53412						24 5/16
9-30-76	53675						24 3/8
10-[illegible]-76	55323						24 1/4
10-4-76	61032						24 1/2
[illegible]	61248						24 5/8
[illegible]	61781						24 9/16
[illegible]	63408						24 7/16
[illegible]	65812						24 11/16
[illegible]	68410						24 3/4
[illegible]	70446						24 13/16
[illegible]	[illegible]						24 7/8
10-14-76	73679						25
10-14-76	74119						25 1/8
10-15-76	75812						25 3/16
10-15-76	76002 North Rope failed						

① ②

LEGEND

DATE INSTALLED	: 8-11-76
DESIGN FACTOR	: 3.4
LOAD (PSI)	: 1100
DOUBLE FLEX LENGTH	: 6 FT.
DATE FAILED	: 10-15-76
TOTAL CYCLES	: 76002
CYCLES NOT AT LOAD	: 33646
NET CYCLES	: 42356
CYCLE STROKE	: 16 FT.
ROPE LENGTH	: North Rope 57'6"
	: South Rope 57'2"

REFERENCE NOTES

① 33646 cycles not at load. Pressures varied from 300 psi to 850 psi at intervals during test.

② 68410 cycles, broken wire on North Rope
76002 cycles, 1 broken strand on North Rope.

TEST 3

New North and South Rope

Date	Cycles Start	Net	Load (PSI)	NF	SF	DF	Cyl Ext
11-23-76	0						
11-23-76	10		1100				20 3/4
11-23-76	52						21 1/8
11-24-76	158						21 3/4
11-24-76	540						22 1/2
11-30-76	714		1460				24"
11-30-76	981						24 1/4
12-2-76	1163						24 3/8
12-2-76	1263						24 3/4
12-3-76	3678						24 15/16
12-3-76	3826						25 1/16
12-4-76	5970						25 1/8
12-5-76	7007						25 3/8
12-6-76	8913						25 5/8
12-7-76	10541						25 9/16
12-7-76	11569						25 11/16
12-9-76	12649						26"
12-9-76	15408 North Rope failed						

① ②

LEGEND

DATE INSTALLED	: 11-23-76
DESIGN FACTOR	: 2.6
LOAD	: 1460
DOUBLE FLEX LENGTH	6 FT.
DATE FAILED	: 12-9-76
TOTAL CYCLES	15408
CYCLES NOT AT LOAD	: 735
NET CYCLES	: 14673
CYCLE STROKE	: 16 FT.

REFERENCE NOTES

① 735 cycles not at load. Pressure varied from 800 psi to 1100 psi

② 3690 cycles, 1 broken wire on North Rope.

The following broken wires were found as the test progressed.
12-7-76 - 2 wires on North Rope.
12-7-76 - 1 wire on South Rope
12-7-76 - Several wires on North Rope.
12-8-76 - 4 wires on South Rope
7 wires on North Rope
12-9-76 - 1 STRAND on North Rope.

TEST 4

NEW NORTH AND SOUTH ROPE.

DATE	Cycles START	Cycles NET	Load (PSI)	NF	SF	DF	Cyl. EXT.
12-22-76	0		1460				
12-28-76	4228						27 7/8
12-28-76	4985						25 1/8
12-28-76	6669						25 5/16
12-29-76	12831						25 3/8
1-7-77	13450						25 1/16
1-10-77	16207						25 3/16
1-10-77	16377						25 1/4
1-11-77	18524						25 5/16
1-11-77	19001						26
1-12-77	19690						25 13/16
1-12-77	20177						26
1-13-77	21933 ①	South Rope failed					

LEGEND

DATE INSTALLED : 12-22-76
DESIGN FACTOR : 2.6
LOAD (PSI) : 1460
Double Flex Length : 6 FT.
DATE Failed : 1-13-77
TOTAL Cycles : 21933
Cycles NOT AT Load : 53
NET Cycles : 21880
Cycle STROKE : 16 FT.

REFERENCE NOTES

① Cycles NOT AT Load: 53, PRESSURE Load 1100 PSI.

TEST 5

New North and South Ropes

DATE	Cycles START	Cycles NET	Load (PSI)	NF	SF	D.F.	Cyl EXT.
1-21-77	0		1825				
1-21-77	90		↓				22
1-22-77	258						24 1/16
1-22-77	356						23 1/2
1-22-77	590						23 1/16
1-22-77	825						24 1/16
1-23-77	958						23 5/16
1-23-77	1190						24 3/8
1-26-77	1387 ① ②	South Rope failed					

LEGEND

DATE INSTALLED : 1-21-77
DESIGN FACTOR : 2.1
LOAD (PSI) : 1825
Double Flex Length : 6 FT.
DATE Failed : 1-26-77
TOTAL Cycles : 1387
Cycle NOT AT Load : 46
NET Cycles : 1341
Cycle STROKE : 16 FT.

REFERENCE NOTES

① Cycles NOT AT Load: 46, PRESSURE AT 1100 PSI

② 820 cycles, 1 broken wire on South Rope

941 cycles, 2 broken wire on South Rope and 3 broken wires on North Rope

1187 cycles, 6 broken wires on North Rope and 4 broken wires on South Rope

TEST 6

NEW NORTH AND SOUTH ROPE.

DATE	Cycles START	Cycles NET	Load (PSI)	Rope Dia. NF	SF	DF	Cyl. EXT
2-3-77	0		1825				
2-3-77	42						26 1/2
2-3-77	73						27 1/8
2-4-77	211						28 3/8
2-4-77	307 ① ■	North Rope failed					

LEGEND

DATE INSTALLED : 2-3-77
DESIGN FACTOR : 1.7
Load (PSI) : 1825
Double Flex Length : 6 FT
DATE Failed : 2-4-77
TOTAL Cycles : 307
Cycles NOT AT Load : 53
NET Cycles : 254
Cycle STROKE : 16 FT

REFERENCE NOTES

① Cycles NOT AT Load : 53

■ North Rope broke on bottom

TEST 7

(7) South Rope from Test 6

DATE	Cycles START	Cycles NET	Load (PSI)	NF	SF	DF	Cyl EXT.
2-3-77	0						
2-3-77	307	307	1825				28 3/8
2-9-77	340						21 3/4
2-9-77	358						21 1/8
2-9-77	415						21 3/4
2-9-77	432						21 1/2
2-9-77	477 ◆ ■ ●	477	Rope failed				

LEGEND

DATE INSTALLED : 2-3-77
DESIGN FACTOR : 1.7
Load (PSI) : 1825
Double Flex Length : 6 FT.
DATE Failed : 2-9-77
TOTAL Cycles : 784
Cycle from TEST 6 : 307
Cycles on TEST 7 : 477
Cycles NOT AT Load : 175
NET Cycles : 609
Cycle STROKE : 16 FT.

REFERENCE NOTES

◆ ACTUAL TOTAL CYCLES AT Load, 784. Rope numbering system changed at this point

■ Cycles from TEST 6 : 307
Cycles on TEST 7 : 477

● Cycles NOT AT Load : 175
53 Cycles from TEST 6
122 cycles on TEST 7

D.3

Rope 2-1S
(8)

Cycles Not At Load: 427

Date	Cycles Start	Cycles Net	Load (PSI)	Rope Dia. NF	Rope Dia. SF	Rope Dia. DF	Cyl Ext
2-9-77	0		1540				
4-28-77	780						18 9/16
4-29-77	835						18 3/4
5-4-77	4166						19 7/8
5-25-77	15159 (1) (2)		Rope failed				

Legend

Date installed : 2-9-77
Design Factor : 2.3
Load (PSI) : 1540
Double Flex Length : 6 ft.
Date Failed : 5-25-77
Total Cycles : 15159
Cycles Not At Load : 427
Net Cycles : 14732
Cycle Stroke : 16 ft.

Reference Notes

(1) Cycles below pressure load: 427, pressures between 500 psi and 1000 psi.

(2) 11448 cycles, 1 broken wire

Rope 2-2S
(9)

Date	Cycles Start	Cycles Net	Load (PSI)	Rope Dia. NF	Rope Dia. SF	Rope Dia. DF	Cyl Ext
5-31-77	15159	0	1540				
6-16-77	22239	7080					18 1/4
6-17-77	22997	7838					18 3/4
6-17-77	23308	8149					18 9/16
6-29-77	27713	12554					18 7/16
6-29-77	28396	13237					18 3/8
6-29-77	28492	13333 (1)	Rope failed				

Legend

Date installed : 5-31-77
Design Factor : 2.3
Load (PSI) : 1540
Double Flex Length : 6 ft.
Date Failed : 6-29-77
Total Cycles : 13333
Cycles Unloaded : 229
Net Cycles : 13104
Cycle Stroke : 16 ft.

Reference Notes

(1) Cycles below pressure: 229

Rope 2-1N
(10)

Cycles Not At Load: 679

Date	Cycles Start	Cycles Net	Load (PSI)	Rope Dia. NF	Rope Dia. SF	Rope Dia. DF	Cyl. Ext.
2-9-77	-477	0					
2-9-77	21		1825				18 1/2
2-9-77	29						19 7/8
2-9-77	50						20 1/8
2-9-77	68						20 1/4
2-9-77	90						20 3/8
2-9-77	117						20 7/16
2-9-77	143						20 9/16
2-9-77	223						20 7/8
2-9-77	258						21 1/8
2-9-77	303						21 3/16
2-9-77	340						21 1/4
2-9-77	358						21 3/8
2-9-77	415						21 5/16
2-9-77	432						21 1/2
2-9-77	477		1540				
4-29-77	835						18 13/16
5-4-77	4166						19 7/8
6-16-77	22239						18 1/4
6-17-77	22997						18 1/2
6-17-77	23308						17 7/16
6-29-77	27713						18 7/16
6-29-77	28396						18 3/8
7-11-77	33185		Rope failed				

(1) (2)

Legend

Date installed : 2-9-77
Design Factor : 2.1 at 1825 psi
2.3 at 1540 psi
Load (PSI) : 1825, Load 1
1540 Load 2
Double Flex Length : 6 ft.
Date failed : 7-11-77
Total Cycles : 33662
Cycles Not At Load : 679
Net Cycles : 32983
Cycles at 1825 psi : 477
Cycles at 1540 psi : 32506
Cycle Stroke : 16 ft.

Reference Notes

(1) Cycles below load pressure: 679, cycle pressures ranged from 500 psi to 1000 psi.

(2) At 27850 cycles, 1 broken wire

Rope 2-3S
(11)

Date	Cycles Start	Cycles Net	Load (PSI)	Rope Dia. NF	Rope Dia. SF	Rope Dia. DF	Cyl Ext
7-1-77	28492	0 (1)	1540				
8-2-77	37636	9144	1875	2.948	2.945	2.940	
8-16-77	38895	10403					17 5/8
8-17-77	38934	10442					17 1/2
8-17-77	39021	10529					17 9/16
8-17-77	39155	10663					17 5/8
8-17-77	39340	10848 (2)					17 3/4
8-17-77	39470	10978					17 13/16
8-18-77	39825	11333					17 3/4
8-18-77	39854	11362					17 11/16
8-18-77	39940	11448					17 7/8
8-23-77	40221	11729					17 15/16
8-24-77	40293	11801		2.956	2.899	2.956	
8-25-77	40443	11951					18"
8-25-77	40460	11968					18 1/16
8-26-77	40627	12135					18 1/4
8-26-77	40931	12439					18 3/8
8-26-77	41106	12614					18 5/16
8-29-77	41243	12751		2.954	2.881	2.871	
9-14-77	42979	14487		2.950	2.904	2.867	
9-14-77	43056	14464					18 5/8
9-16-77	43496	15004					18 5/8
9-16-77	44079	15587					18 7/8
9-16-77	44988	16496					19 1/4
9-18-77	45520	17028 (1)	Rope failed				

Legend

Date installed : 7-1-77
Design Factor : 2.3 @ 1540 psi
1.9 @ 1875 psi
Load (PSI) : 1540 Load 1
: 1875 Load 2
Double Flex Length : 6 ft.
Date Failed : 9-18-77
Total Cycles : 17028
Cycles Unloaded : 230
Net Cycles : 16798
Cycle Stroke : 16 ft.

Reference Notes

(1) Cycles at 1540 psi 4670
Cycles at 1875 psi 12128

(1) Cycles below pressures: 230.

(2) 1 broken wire

Rope 2-2N
(12)

(CONT'd)
Rope 2-2N
(12)

DATE	Cycles START	NET	Load PSI	Rope Dia. NF	SF	DF	Cyl. EXT	DATE	START	NET	Load (PSI)	NF	SF	DF	Cyl. EXT
7-25-77	33185	0	1875					8-24-77	41232	8150	1875				18 5/16
8-?-77	38496	5511		2.956	2.912	2.808		9-13-77	42462	9330					15 1/2
8-?-77	38495	5710					17 3/8	9-13-77	42794	9662					18 3/4
8-11-77	38934	5749					17 3/8	9-14-77	42979	9847		2.955	2.886	2.869	18 3/4
8-11-77	38960	5775					17 1/2	9-14-77	43056	9924					18 7/8
8-11-77	38985	5800					17 1/2	9-16-77	43496	10364					18 15/16
8-?-77	39021	5836					17 9/16	9-16-77	44079	10947					18 7/8
8-17-77	39155	5970					17 5/8	9-16-77	44388	11256					19 1/4
8-17-77	39340	6155					17 3/4	9-18-77	45520	12388					
8-17-77	39362	6177					17 3/4	10-26-77	46778	13646		2.948	2.896	2.872	23 7/8
8-17-77	39398	6211					17 3/4	11-2-77	47146	14064					24 1/8
8-17-77	39451	6244					17 3/4	11-2-77	47166	14034					24 3/8
8-17-77	39470	6265					17 13/16	11-2-77	47184	14052					24 1/4
8-17-77	39506	6301					17 13/16	11-2-77	47205	14073					24 5/16
8-17-77	39523	6318					17 13/16	11-2-77	47123	14091		2.954	2.886	2.883	
8-18-77	39525	6620					17 3/4	11-2-77	47146	14114					24 1/8
8-18-77	39534	6649					17 13/16	11-2-77	47184	14152					24 3/16
8-18-77	39893	6688					17 11/16	11-2-77	47184	14152					24 1/4
8-18-77	39914	6709					17 13/16	11-2-77	47205	14173					24 5/16
8-18-77	39940	6745					17 7/8	11-2-77	47395	14263					24 3/8
8-18-77	40035	6840					17 7/8	11-2-77	47338	14306					24 3/8
8-18-77	40059	6864					17 7/8	11-2-77	47482	14380					24 7/16
8-18-77	40080	6885					17 7/8	11-2-77	47452	14420					24 3/4
8-23-77	40159	6964					17 7/8	11-2-77	47864	14406					24 13/16
8-23-77	40192	6997					17 7/8	11-2-77	47489	14433 / 14440					24 7/8
8-23-77	40221	7089					17 15/16	11-2-77	47625 ①		▢ Rope Failed				
8-25-77	40307	7175		2.956	2.912	2.906	17 15/16								
8-25-77	40443	7311					18"								
8-25-77	40460	7328					18 1/16								
8-26-77	40627	7495					18 1/8								
8-26-77	40931	7799					18 1/4								
8-26-77	41106	7979					18 3/16								
8-26-77	41210	8078					18 1/4								
8-29-77	41243	8111		2.949	2.896	2.892	18 1/4								

Legend

DATE INSTAlled : 7-25-77
DESIGN FACTOR : 1.9
LOAD (PSI) : 1875
Double Flex Length : 6FT
DATE FAILED : 11-2-77
TOTAL Cycles : 14440
Cycles unloaded : 361
NET Cycles : 14079
Cycle STROKE : 16 FT.

REFERENCE NOTES

① 361 CYCLES NOT AT 1875. PRESSURES RECORDED AS BELOW LOAD PSI.

Rope 2-4B
(13)

DATE	Cycles START	NET	Load PSI	Rope Dia. NF	SF	DF	EXT	Extensometer
10-20-77	45520	0	1875					
10-24-77	45593	73						
10-26-77	46760	1240		2.950	2.915	2.901		
10-26-77	46798	1269					23 7/8	
10-26-77	46903	1374					24"	
10-26-77	47029	1500					24 1/8	
10-26-77	47110 ①	1590 ②		Rope failed				

Legend

DATE INSTAlled : 10-20-77
Rope Length : NOT Recorded
Design Factor : 1.9
Load (PSI) : 1875
Double Flex Length : 6FT.
DATE Failed : 10-26-77
Total Cycles : 1590
Cycle unloaded : 128
NET Cycles : 1462
Cycle STROKE : 16 FT.

REFERENCE NOTES

① Cycles NOT AT Load:
73 Cycles AT low load
55 cycles AT 1000 psi

② 1240 cycles 10-12 wires broken in double flex Region

Rope 2-5-S
(14)

DATE	Cycles START	NET	Load PSI	Rope Dia. NF	SF	DF	EXT	Extensometer
11-2-77	47110	0	1875					
11-2-77	47123	13	↓	2.988	2.978	2.977		
11-7-77	47637	527	↓	2.960	2.942	2.943		
11-7-77	47678	568	↓				19 11/16	
11-7-77	47744	634	↓				19 7/8	
11-7-77	47789	679	↓				20"	
11-7-77	47900	790	↓				20 1/4	
11-7-77	47956	846	↓				20 5/16	
11-7-77	48156	1046	↓				20 1/2"	
11-7-77	48180	1070	↓				20 9/16	
11-7-77	48200	1090	↓				20 9/16	
11-7-77	48218	1108	↓				20 9/16	
11-7-77	48237	1127	↓				20 9/16	
11-8-77	48414 ①	1304	↓ Rope failed					

Legend

DATE INSTAlled : 11-2-77
Rope Length : 50 FT
DESIGN FACTOR : 1.9
Load (PSI) : 1875
Double Flex Length : 6 FT.
DATE FAILED : 11-8-77
TOTAL cycles : 1304
Cycle unloaded : 27
NET Cycles : 1277
CYCLE STROKE : 16 FT

REFERENCE NOTES

① cycles NOT AT Load:
27 AT 1000 Psi

Rope 19-S

Cycles Not At Load: 39

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia D.F.	Cyl. Ext.	Extensometer
6-6-79	41 (1) (1)	885	2.990	2.990	2.978	20 1/2	4 7/8
6-11-79	600		2.978	2.967	2.959		
6-11-79	1000		2.983	2.962	2.960		
6-12-79	1200		2.980	2.958	2.952	21 5/8	5 7/8
6-12-79	1757		2.980	2.958	2.954	21 3/4	6
6-12-79	2197		2.976	2.954	2.947	21 13/16	6 1/8
6-13-79	2819		2.972	2.951	2.944	22	6 3/8
6-13-79	3213		2.982	2.981	2.943	22	6 5/8
6-14-79	3720		2.980	2.949	2.945	22 1/8	6 3/4
6-14-79	4144		2.979	2.948	2.945	22 1/8	6 7/8
6-15-79	5067		2.951	2.948	2.941	22 3/16	7 1/8
6-15-79	5539		2.985	2.952	2.946	22 1/4	7 1/4
6-18-79	6260		2.981	2.950	2.938	22 1/8	7 1/2
6-18-79	6681 (1) (2)		2.981	2.945	2.937	22 1/8	7 7/8
6-19-79	7171		2.977	2.941	2.943	22 1/4	7 1/2
6-19-79	7562		2.983	2.947	2.941	22 1/4	7 1/2
6-20-79	9328		2.981	2.943	2.935	22 5/16	7 3/4
6-20-79	9814		2.984	2.943	2.934	22 5/16	7 3/4
6-20-79	10216		2.986	2.942	2.936	22 5/16	7 3/4
6-21-79	12000		2.984	2.941	2.935	22 5/16	7 3/4
6-21-79	12498		2.989	2.940	2.934	22 5/16	7 3/4
6-21-79	12886		2.978	2.935	2.929	22 3/8	7 3/4
6-22-79	14350		2.979	2.985	2.930	21 1/2	7 7/8
6-22-79	14690		2.978	2.937	2.923	21 1/2	7 7/8
6-25-79	21754		2.985	2.981	2.923	22 3/4	8
6-25-79	22480		2.981	2.928	2.923	22 3/4	8
6-25-79	22675		2.977	2.923	2.921	22 3/4	8
6-26-79	24470		2.980	2.930	2.919	22 13/16	8 1/16
6-27-79	25965 (1) (2)		2.979	2.926	2.918	22 7/8	8 1/16
6-27-79	26266		2.979	2.925	2.915	22 7/8	8
6-28-79	28088		2.977	2.927	2.910	22 15/16	8 1/16
6-28-79	28686		2.975	2.925	2.918	22 15/16	8 1/16
6-28-79	29005		2.977	2.924	2.912	23 1/8	8 1/8
6-29-79	30820		2.979	2.925	2.907	23 1/4	8 1/4

Rope 19-N

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia DF	Cyl. Ext	Extensometer
6-29-79	31308	885	2.979	2.925	2.910	23"	8 1/4
6-29-79	31658		2.976	2.928	2.914	23	8 1/4
7-2-79	39112		2.986	2.933	2.911	23 1/8	8 1/4
7-2-79	39842		2.991	2.916	2.912	23 1/8	8 1/4
7-3-79	41829 (3)		2.983	2.925	2.908	23 3/16	8 3/8
7-5-79	47526		2.986	2.920	2.906	23 3/8	8 3/8
7-5-79	48240		2.980	2.913	2.910	23 3/8	8 7/8
7-6-79	50213		2.983	2.921	2.909	23 1/2	9"
7-6-79	50744		2.982	2.920	2.909	23 1/2	9 1/8
7-6-79	51063		2.980	2.911	2.910	23 1/2	9 1/8
7-6-79	51595	Rope Failed (4)					

Legend

Date installed : 6-6-79
Rope length : 50 ft 4 in.
Rope Type : 6x57 RLG
Design Factor : 4
Load (PSI) : 885
Double Flex Length : 6 ft
Lay Length : 16 in
4 1/2 Lay length / D.F. Region

Date Failed : 7-6-79
Total Cycles : 51595
Cycles Unloaded : 39
Net cycles : 51556
Cycle Stroke : 16 ft.

Reference Notes

(1) Cycles Not At load:
Start 27 350 psi and 400 psi
41 Cycles 2 300 psi
2 600 psi
6720 Cycles 2 300 psi
2 600 psi
25965 Cycles 2 300 psi
2 600 psi

(2) Elongation Readings:
6720 cycles : 50 ft 3 in.
25965 Cycles : 51 ft 9 1/2 in.

(3) Broken wire in Single flex Region

(4) Rope failed coming off sheave at bottom. IWRC and 3 strands broke.

Rope 20-S

Cycles Not At Load: 47

Date	Cycles	Load (psi)	Rope Dia NF	Rope Dia SF	Rope Dia DF	Ext.	Extensometer
6-6-79	41 (1)	885	2.994	2.996	2.994	20 1/2	4 7/8"
6-11-79	600 (1)		2.978	2.967	2.959		
6-11-79	1000		2.979	2.967	2.963		
6-12-79	1200		2.980	2.960	2.957	21 5/8	6 1/8
6-12-79	1757		2.981	2.963	2.958	21 3/4	6
6-12-79	2197		2.979	2.955	2.951	21 13/16	6 1/8
6-13-79	2819		2.978	2.956	2.943	22"	6 3/8
6-13-79	3213		2.975	2.957	2.953	22	6 5/8
6-14-79	3720		2.982	2.959	2.948	22 1/8	6 3/4
6-14-79	4144		2.975	2.958	2.951	22 1/8	6 7/8
6-15-79	5067		2.978	2.944	2.945	22 3/16	7 1/8
6-15-79	5539		2.980	2.951	2.943	22 1/4	7 1/4
6-18-79	6260		2.979	2.944	2.944	22 1/8	7 1/2
6-18-79	6681		2.979	2.947	2.942	22 1/8	7 7/8
6-19-79	7171		2.982	2.941	2.940	22 1/4	7 1/2
6-19-79	7561		2.978	2.941	2.939	22 1/4	7 1/2
6-20-79	9328		2.984	2.943	2.939	22 5/16	7 3/4
6-20-79	9814		2.989	2.939	2.941	22 5/16	7 3/4
6-20-79	10216		2.989	2.942	2.941	22 5/16	7 3/4
6-21-79	12000		2.979	2.939	2.936	22 5/16	7 3/4
6-21-79	12498		2.980	2.941	2.935	22 5/16	7 3/4
6-21-79	12886		2.981	2.942	2.938	22 3/8	7 3/4
6-22-79	14350		2.977	2.937	2.935	22 1/2	7 7/8
6-22-79	14690		2.983	2.936	2.934	22 1/2	7 7/8
6-25-79	21754		2.980	2.930	2.925	22 3/4	8"
6-25-79	22480		2.978	2.928	2.920	22 3/4	8"
6-25-79	22675		2.978	2.932	2.927	22 3/4	8"
6-26-79	24470		2.982	2.927	2.926	22 13/16	8 1/16
6-27-79	25965		2.981	2.927	2.926	22 7/8	8 1/16
6-27-79	26266		2.984	2.922	2.921	22 7/8	8"
6-28-79	28088		2.976	2.924	2.925	22 15/16	8 1/16
6-28-79	28686		2.982	2.922	2.919	22 15/16	8 1/16
6-28-79	29005		2.984	2.921	2.920	23"	8 1/8
6-29-79	30820		2.978	2.924	2.921	23	8 1/4

Rope 20-S

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia DF	Ext.	Extensometer
6-29-79	31308	885	2.979	2.929	2.920	23"	8 1/4"
6-29-79	31658		2.976	2.925	2.911	23	8 1/4
7-2-79	39112		2.986	2.932	2.930	23 1/8	8 1/4
7-2-79	39842		2.992	2.923	2.917	23 1/8	8 1/4"
7-3-79	41829		2.980	2.919	2.916	23 3/16	8 3/8
7-5-79	47529		2.974	2.914	2.912	23 3/8	8 7/8
7-5-79	48240		2.978	2.915	2.914	23 3/8	8 7/8
7-6-79	50213		2.983	2.921	2.909	23 1/2	9"
7-6-79	50744		2.975	2.921	2.911	23 1/2	9 1/8
7-6-79	51068		2.980	2.918	2.916	23 1/2	9 1/8
7-6-79	51595 (1)						

Rope 20-S

Date	Cycles	Load PSI	Rope Dia NF	Rope Dia SF	Rope Dia DF	Ext	Extensometer
7-17-79	51595						
7-18-79	51915	885	2.982	2.920	2.911	21 3/8"	7 3/4"
7-19-79	53860		2.982	2.915	2.902	21 5/8	8"
7-19-79	54330		2.974	2.915	2.898	21 13/16	8"
7-19-79	54727		2.981	2.912	2.904	21 7/8	8"
7-20-79	56538 (2)		2.979	2.912	2.908	21 15/16	8"
7-20-79	57019		2.979	2.914	2.903	21 15/16	8"
7-20-79	57478		2.979	2.910	2.909		
7-23-79	58268		2.987	2.904	2.909	22 3/16	8 1/4"
7-23-79	58686		2.970	2.921	2.932	22 3/16	8 1/2"
7-24-79	60572		2.976	2.906	2.898	22 3/16	8 1/2
7-24-79	61098		2.977	2.905	2.900		
7-24-79	61494		2.980	2.907	2.899	22 1/4	8 1/2
7-25-79	63297		2.971	2.907	2.896	22 5/16	8 3/4
7-25-79	63763 (2)		2.973	2.914	2.895	22 5/16	8 3/4
7-25-79	64247		2.978	2.909	2.906	22 3/8	9"
7-26-79	66172		2.986	2.905	2.984	22 3/8	9 1/8
7-26-79	66690		2.975	2.901	2.896	22 3/8	9 1/8
7-26-79	67133		2.977	2.898	2.894	22 7/16	9 1/8
7-27-79	69055		2.970	2.900	2.894	22 7/16	9 1/8
7-27-79	69599 (2)		2.977	2.897	2.893	22 7/16	9 1/4"
7-27-79	69976		2.974	2.899	2.888	22 7/16	9 1/4"
7-30-79	77546		2.980	2.891	2.885	22 3/8	9 1/4
7-30-79	78060	Rope Failed (5)					

Legend

Date installed : 6-6-79
Rope length : 49 ft. 10 in.
Rope Type : 6x57 RLG
Design Factor : 4
Load (PSI) : 885
Double Flex Length : 6 ft
Lay Length : 16 in.
4 1/2 Lay length Per D.F. Region

Date Failed : 7-30-79
Total Cycles : 78060
Cycles unloaded : 47
Net Cycles : 78013
Cycle Stroke : 16 ft

Reference Notes

(1) Cycle Unloaded:
Start 39 - 350 psi
43 cycles 2 300 psi
2 600 psi
51610 cycles 2 300 psi
2 600 psi

(2) Broken Wires:
56538 Cycles, 1 broken wire in S.F Region.
63763 cycles, 1 broken wire in D.F. Region.
69599 Cycles, 1 broken wire in D.F Region.
69758 cycles, 5 broken wires in S.F. Region.

(5) 78060 cycles, Rope failed in D.F Region on bottom of Sheave. Prior To failure, individual snapping of wire could be heard. 4 broken wires found on pit floor.

D.5

2-3N
(15)

Date	Cycles Start	Cycles Net	Load (Psi)	Rope Dia. NF	SF	DF	Ext.	Extensometer
11-7-77	47625	0	1875	2.985	2.985	2.986		
11-8-77	48414	789 ①		2.953	2.932	2.917		
11-11-77	49879	2254	1235	2.957	2.914	2.906		
11-14-77	50569	2944		2.954	2.908	2.895		
11-17-77	52316	4691		2.960	2.896	2.893		
11-18-77	53746	6121		2.958	2.892	2.888		
11-22-77	56858	9233		2.950	2.880	2.876		
11-23-77	58627	11002		2.952	2.882	2.865	15 5/16	
11-25-77	60712	13087		2.938	2.883	2.864	15 11/16	
11-28-77	67155	19530		2.861	2.867	2.944	15 3/4	
11-29-77	69473	21848		2.938	2.853	2.949	16 1/8	
11-30-77	70530	22905						
12-2-77	70536	22911		2.935	2.855	2.844		
12-4-77	73824	26199	Rope Failed					
	①	②						

Legend

DATE installed : 11-7-77
Rope Length : 56 FT 4 in
Design Factor : 1.9 AT 1875 psi
2.9 AT 1235 psi
Load (psi) : 1875 and 1235
Double flex Length : 6 FT.
Date failed : 12-4-77
Total cycles : 26199
Cycles not at Load : 97
Net Cycles : 26102
Cycle Stroke : 16 FT.

Reference Notes

① Cycles Not AT Load:
789 Cycles AT 1875 psi
95 cycles AT 1000 psi
② 67155 cycles, 2 broken wires in double flex region.

2-6S
(16)

Date	Cycles Start	Cycles Net	Load Psi	Rope Dia NF	SF	DF	Ext.	Extensometer
11-9-77	48444	0	1235	2.957	2.958	2.954		
11-11-77	49879	1466		2.963	2.926	2.944		
11-14-77	50569	2155		2.965	2.929	2.913		
11-17-77	52346	3902		2.964	2.905	2.887		
11-18-77	53746	5332		2.938	2.919	2.884		
11-22-77	56858	8442		2.959	2.914	2.875		
11-23-77	58627	10211		2.953	2.907	2.870	15 5/8	
11-25-77	60712	12296		2.949	2.908	2.855	15 11/16	
11-28-77	67156	18739		2.848	2.904	2.855	15 3/4	
11-29-77	69478	21058		2.942	2.890	2.844	16 1/8	
11-30-77	70530	22116	Rope failed					
	①	②						

Legend

DATE installed : 11-9-77
Rope Length : No Record
Design Factor : 2.9
Load (psi) : 1235
Double Flex Length : 6 FT.
Date Failed : 11-30-77
Total Cycles : 22116
Cycles unloaded : 73
Net cycles : 22043
Cycle Stroke : 16 FT

Reference Notes

① cycles unloaded.
73 cycles AT 1000 psi
② Broken wires:
18739 cycles, 2 broken wires in double flex Region

Rope 2-7S
(17)

Date	Cycles Start	Cycles Net	Load Psi	Rope Dia NF	SF	DF	Ext.	Extensometer
12-2-77	70530	6	1000	2.970	2.968	2.960		
12-3-77	70542	12	1235					
12-6-77								
12-9-77	73828	3266						
12-12-77	74169	3639		2.953	2.928	2.906		
12-13-77	75998	5468		2.911	2.918	2.950		
12-14-77	77782	7252		2.905	2.880	2.879		
12-15-77	79950	9420		2.930	2.886	2.876		
12-16-77	82088	11558		2.930	2.879	2.870		
12-27-77	84694	14164		2.932	2.850	2.860		
12-28-77	87255	16725		2.930	2.878	2.864		
12-29-77	88959	18429		2.925	2.854	2.848		
12-30-77	91119	20589		2.920	2.841	2.828		
1-4-78	93080	22550		2.932	2.836	2.825		
1-6-78	95469	24939	Rope Failed					
		① ②						

Legend

Date Installed : 2-12-77
Rope Length : 55 FT 9 in.
Design Factor : 2.9
Load (Psi) : 1235
Double Flex Length : 6 FT.
Date Failed : 1-5-78
Total Cycles : 24939
Cycles unloaded : 100
Net Cycles : 24839
Cycle Stroke : 16 FT.

Reference Notes

① Cycles Not AT Load:
100 Cycles AT 1000 psi
② 93355 cycles - broken wire in double flex Region.

Rope 2-4N
(18)

Date	Cycles Start	Cycles Net	Load Psi	Rope Dia NF	SF	DF
12-2-77						
12-8-77						
12-6-77	73824	0				
12-9-77	73828	4	1235			
12-12-77	74176	348		2.960	2.941	2.989
12-13-77	75998	2174		2.916	2.928	2.949
12-14-77	77782	3958		2.939	4.908	2.875
12-15-77	79950	6126		2.916	2.888	2.876
12-16-77	82088	8264		2.924	2.879	2.864
12-27-77	84694	10870		2.927	2.871	2.852
12-28-77	87255	13431		2.932	2.964	2.852
12-29-77	88959	15135		2.938	2.864	2.842
12-30-77	91119	17295		2.930	2.894	2.846
1-4-78	93080	19256		2.943	2.852	2.830
1-6-78	95469	21645	Rope Retired			
		① ②				

Legend

Date Installed : 12-6-77
Rope Length : 56 FT 9 in
Design Factor : 2.9
Load (Psi) : 1235
Double Flex Length : 6 FT
Date Retired : 1-5-78
Total Cycles : 21645
Cycles unloaded : 88
Net Cycles : 21557
Cycle Stroke : 16 FT

Reference Notes

① Cycles Not AT Load:
69 Cycles AT 1000 psi
19 cycles Less Than 1235 psi
② 19687 cycles, broken wire

Rope 21 N

Cycles Not At Load: 32

DATE	Cycles	Load PSI	Rope Dia. N.F.	S.F.	D.F.	EXT	Extensometer
7-17-79	0 ①	-					
7-18-79	320	885	2.964	2.982	2.972	21 3/8"	7 1/4"
7-18-79	2265	↓	2.981	2.962	2.955	21 5/8	8
7-19-79	2735		2.980	2.965	2.953	21 13/16	8
7-19-79	3132		2.978	2.962	2.949	21 7/8	8
7-20-79	4943		2.983	2.951	2.943	21 15/16	8
7-20-79	5424		2.982	2.952	2.940	21 15/16	8
7-20-79	5878		2.979	2.953	2.943		
7-23-79	6673		2.966	2.936	2.949	22 3/16	8 1/4
7-23-79	7691		2.968	2.950	2.947	22 3/16	8 1/2
7-24-79	8477		2.979	2.941	2.940	22 3/16	8 1/2
7-24-79	9263		2.982	2.942	2.937		
7-24-79	9399		2.983	2.950	2.938	22 1/4	8 1/2
7-25-79	11762 ① ②		2.977	2.940	2.932	22 5/16	8 3/4
7-25-79	12168		2.983	2.954	2.932	22 5/16	8 3/4
7-25-79	12652		2.989	2.951	2.934	22 3/8	9
7-26-79	14577		2.978	2.939	2.932	22 3/8	9 1/8
7-26-79	15095		2.977	2.932	2.932	22 3/8	9 1/8
7-26-79	15538		2.980	2.936	2.933	22 7/16	9 1/8
7-27-79	17160		2.977	2.940	2.930	22 7/16	9 1/8
7-27-79	18004		2.974	2.933	2.935	22 7/16	9 1/4
7-27-79	18381		2.983	2.938	2.930	22 7/16	9 1/4
7-30-79	25451		2.980	2.928	2.915	22 5/8	9 1/4
7-30-79	26465	↓					

Rope 21-N

DATE	Cycles	Load (PSI)	Rope Dia NF	SF	DF	EXT.	Extensometer
8-3-79	27108 ①	700	2.979	2.928	2.919	14 1/2"	2 1/2"
8-3-79	27377	↓	2.984	2.926	2.921	14 9/16	2 5/8
8-6-79	30705		2.979	2.925	2.916	15	2 7/8
8-6-79	31338		2.974	2.927	2.918	15	2 7/8
8-6-79	31713		2.978	2.921	2.921	15	2 7/8
8-7-79	33730		2.978	2.924	2.920	15	2 7/8
8-7-79	34292 ① ②		2.981	2.925	2.889	15 1/16	2 1/2
8-7-79	34643		2.984	2.917	2.925	15 1/16	2 1/2
8-8-79	36565		2.975	2.919	2.915	15 1/8	2 7/8
8-8-79	37092		2.976	2.912	2.919	15 1/8	2 7/8
8-8-79	37431		2.982	2.924	2.922	15 3/16	2 7/8
8-9-79	39355		2.975	2.922	2.912	15 3/16	3
8-9-79	39936		2.980	2.925	2.911	15 1/4	3
8-9-79	40270		2.979	2.920	2.916	15 1/4	3
8-10-79	42026		2.972	2.922	2.908	15 1/4	3
8-10-79	42508		2.974	2.913	2.905	15 5/16	3
8-10-79	42956		2.972	2.912	2.911	15 5/16	3
8-13-79	50268		2.967	2.921	2.906	15 3/8	3
8-13-79	50757		2.976	2.914	2.908	15 7/16	3
8-13-79	51197		2.982	2.918	2.909	15 7/16	3
8-14-79	53102		2.974	2.924	2.905	15 7/16	3
8-14-79	53568 ① ②		2.973	2.920	2.913	15 7/16	3
8-14-79	53997		2.977	2.918	2.905	15 3/8	2 7/8
8-15-79	56014 ①		2.976	2.919	2.906	15 7/16	3
8-20-79	63879 ① ④		2.979	2.916	2.905	15 5/8	3 1/8
8-20-79	64497		2.976	2.911	2.904	15 5/8	3 1/4
8-20-79	64728		2.977	2.909	2.899	15 5/8	3 1/4
8-21-79	66709		2.980	2.919	2.904	15 11/16	3 1/4
8-21-79	67051 ① ③		2.980	2.913	2.902	15 5/8	3 1/4
8-21-79	67372		2.977	2.916	2.906	15 5/8	3 1/4
8-22-79	69429		2.979	2.917	2.899	15 11/16	3 3/8
8-22-79	69832		2.980	2.910	2.902	15 11/16	3 3/8
8-22-79	70114		2.982	2.918	2.903		
8-23-79	71945 ④	↓	2.985	2.914	2.904		

Rope 21 N

DATE	Cycles	Load PSI	Rope Dia. NF	SF	DF	EXT	Extensometer
8-23-79	72898	700	2.979	2.908	2.903	15 3/4	3 1/2
8-24-79	75110	↓	2.980	2.908	2.905	15 3/4	3 1/2
8-24-79	75427		2.981	2.908	2.904	15 3/4	3 1/2
8-26-79	81334		2.975	2.905	2.898	15 7/8	3 5/8
8-26-79	82003		2.975	2.901	2.898	15 15/16	3 7/8
8-26-79	82297		2.975	2.905	2.895	15 15/16	3 7/8
8-28-79	84235		2.977	2.899	2.899	15 15/16	3 7/8
8-28-79	84850 ① ②		2.978	2.907	2.898	15 15/16	3 7/8
8-29-79	87184		2.977	2.905	2.896	15 15/16	3 7/8
8-29-79	87815		2.980	2.903	2.895	16	3 7/8
8-29-79	88201		2.978	2.903	2.895	16	3 7/8
8-30-79	90149		2.974	2.901	2.890	16	3 7/8
8-30-79	90754	↓	2.981	2.908	2.892	16 1/16	3 7/8
9-4-79	92879	Rope failed ④					

Legend

Date Installed : 7-18-79
Rope Length : 49 FT 8 in.
Rope Type : 6x57 RLG
Design Factor : 4
Load PSI : 885
700
Double Flex Length : 6 FT.
Lay Length : 16 in
4 1/2 Lay Lengths/D.F. Region
Date Failed : 8-31-79
Total Cycles : 92879
Cycles Unloaded : 32
Net Cycles : 92847
Cycle Stroke : 16 FT

Reference Notes

① Cycles Unloaded:
Start 7 300 PSI
2 600 PSI
11702 cyc. 2 300 PSI
2 600 PSI
27108 cyc. 2 300 PSI
2 600 PSI
34082 cyc. 2 300 PSI
2 600 PSI
53568 cyc. 2 300 PSI
2 600 PSI
8-17-79 3 < 700 PSI
66890 cyc. 2 300 PSI
2 600 PSI
85098 cyc 4 < 700 PSI

③ Rope Elongation:
11702 cyc. 50 FT 3 in
34082 cyc. 50 FT 2 3/4 in
53568 cyc. 50 FT 3 1/2 in
66890 cyc. 50 FT 3 1/2 in.
85098 cyc 50 FT 3 in

④ 63879 cyc broken wire in double flex region.
71945 cyc. broken wire in double flex region.

④ Rope failed in double flex region at top of sheave.

Rope 22-S

DATE	Cycles	Load (PSI)	Rope Dia. NF	SF	DF	EXT	Extensometer
8-3-79	641 ①	700	2.982	2.972	2.975	14 1/2	2 1/2"
8-3-79	910	↓	2.980	2.968	2.966	14 9/16	2 5/8
8-6-79	4238		2.980	2.945	2.948	15"	2 7/8"
8-6-79	4871		2.988	2.946	2.951	15"	2 7/8"
8-6-79	5246		2.978	2.946	2.946	15"	2 7/8"
8-7-79	7263 ① ②		2.975	2.940	2.945	15"	2 7/8"
8-7-79	7826		2.968	2.941	2.949	15 1/16"	2 1/2"
8-7-79	8176		2.980	2.950	2.946	15 1/16	2 1/2"
8-8-79	10098		2.979	2.937	2.936	15 1/8	2 7/8"
8-8-79	10625		2.978	2.929	2.946	15 1/8	2 7/8"
8-8-79	10969		2.980	2.937	2.947	15 3/16	2 7/8'
8-9-79	12888		2.984	2.932	2.933	15 3/16	3"
8-9-79	13469		2.985	2.928	2.942	15 1/4	3"
8-9-79	13803		2.979	2.935	2.942	15 1/4	3"
8-10-79	15559		2.983	2.930	2.936	15 1/4	3"
8-10-79	16044		2.978	2.927	2.932	15 5/16	3"
8-10-79	16489		2.987	2.929	2.937	15 5/16	3"
8-13-79	23801		2.977	2.921	2.927	15 3/8	3"
8-13-79	24290		2.967	2.920	2.926	15 7/16	3"
8-13-79	24730		2.972	2.920	2.928	15 7/16	3"
8-14-79	26635		2.979	2.923	2.925	15 7/16	3"
8-14-79	27101 ① ②		2.979	2.931	2.928	15 7/16	3"
8-14-79	27530		2.971	2.920	2.930	15 3/8	2 7/8"
8-15-79	29547 ④		2.991	2.920	2.931	15 7/16	3"
8-20-79	37413		2.916	2.920	2.914	15 5/8	3 1/8
8-20-79	38630		2.981	2.915	2.912	15 5/8	3 1/4"
8-20-79	38261 ① ②		2.981	2.916	2.919	15 5/8	3 1/4
8-21-79	40242		2.984	2.919	2.918	15 11/16	3 3/8"
8-21-79	40584		2.984	2.917	2.912	15 5/8	3 1/4"
8-21-79	40905		2.980	2.920	2.915	15 5/8	3 1/4"
8-22-79	42962		2.983	2.910	2.914	15 11/16	3 3/8
8-22-79	43365		2.982	2.912	2.911	15 11/16	3 3/8
8-22-79	43647		2.982	2.907	2.913		
8-23-79	45478	↓					

Rope 22 S

DATE	Cycles	Load PSI	Rope Dia NF	SF	DF	EXT.	Extensometer
8-23-79	46431	700	2.978	2.912	2.914	15 3/4	3 1/2
8-24-79	48643	↓	2.974	2.904	2.909	15 3/4	3 1/2
8-24-79	48960		2.975	2.907	2.913	15 3/4	3 1/2
8-26-79	54867		2.973	2.901	2.903	15 7/8	3 5/8
8-26-79	55536		2.975	2.901	2.900	15 15/16	3 7/8
8-26-79	55830		2.980	2.901	2.899	15 15/16	3 7/8
8-28-79	57768		2.976	2.902	2.896	15 15/16	3 7/8
8-28-79	58383 ① ②		2.976	2.895	2.901	15 15/16	3 7/8
8-29-79	60717		2.974	2.894	2.893	15 15/16	3 7/8
8-29-79	61348		2.980	2.896	2.893	16"	3 7/8
8-29-79	61734		2.978	2.897	2.893	16"	3 7/8
8-30-79	63682		2.975	2.899	2.891	16"	3 7/8
8-30-79	64287	↓	2.979	2.893	2.894	16 1/16	3 7/8

Legend

Date Installed : 8-3-79
Rope Length : 50 FT 3 in.
Rope Type : 6x57 RLG
Design Factor : 5
Load (PSI) : 700
Double Flex Length : 6 FT
Lay Length : 16 in.
4 1/2 Lay Lengths/
Double Flex Region
Date Failed : 9-25-79
Total Cycles : 109740
Cycles Unloaded : 28
Net Cycles : 109712
Cycle Stroke : 16 FT.

Reference Notes

① Cycles unloaded:
Start 2 300 PSI
2 600 PSI
7615 cycles 2 300 PSI
2 600 PSI
27101 cycles 2 300 PSI
2 600 PSI
29713 cycles 2 < 700 PSI
40423 cycles 2 300 PSI
2 600 PSI
58631 cycles 2 300 PSI
2 600 PSI
66423 cycles 2 300 PSI
99060 cycles 2 300 PSI
2 600 PSI

Rope 22-S

DATE	Cycles	Load (PSI)	Rope Dia. NF	SF	D.F.	EXT.	Extensometer
9-10-79	64423 ①	700				14 1/4"	
9-10-79	66871 ④	↓	2.976	2.893	2.891	14 3/8	1 7/8"
9-10-79	67368		2.973	2.909	2.889	14 1/2	2 1/4"
9-11-79	69490		2.974	2.887	2.886	14 3/8	2 3/4
9-11-79	69978		2.985	2.891	2.887	14 3/4	2 7/8
9-12-79	72157					14 13/16	2 7/8
9-12-79	72678		2.979	2.884	2.888	14 13/16	3"
9-13-79	74990		2.967	2.881	2.886	14 13/16	3 1/8"
9-13-79	75517		2.964	2.887	2.888	14 13/16	3 1/8"
9-13-79	75939		2.983	2.882	2.878	14 15/16	3 1/8"
9-14-79	77890		2.965	2.878	2.876	14 15/16	3 1/4
9-14-79	78983		2.967	2.885	2.877	15	3 1/4"
9-17-79	86925		2.960	2.878	2.880	15 1/8	3 1/4
9-17-79	87511		2.978	2.879	2.879	15 1/8	3 3/8"
9-17-79	89887		2.966	2.873	2.873	15 1/8	3 3/8"
9-19-79	93627		2.985	2.886	2.882	15 3/16	3 1/2"
9-20-79	95865		2.952	2.878	2.866	15 1/4	3 5/8
9-20-79	96892		2.953	2.875	2.878	15 1/4	3 5/8
9-21-79	99060 ① ③		2.861	2.871	2.870	15 1/4	3 5/8
9-21-79	99793		2.970	2.876	2.871	15 5/16	3 5/8
9-24-79	105057		2.967	2.878	2.872	15 5/16	3 3/4
9-24-79	108664	↓				15 3/8	3 3/4
9-25-79	109740	Rope failed					

③ Rope Elongation Readings:
7615 cycles 50 FT 8 in
27101 cycles 50 FT 3 1/2 in.
40423 cycles 50 FT 9 1/4 in.
58631 cycles 50 FT 9 1/2 in.
99060 cycles 50 FT 10 3/8 in.

② Installed strain gauges in rope.

④ Broken wire in double flex region.

Rope 23-N

DATE	Cycles	Load (PSI)	Rope Dia. NF	SF	DF	EXT	Extensometer
9-10-79	0 ①	700					
9-10-79	448		2.988	2.977	2.971	14 3/8	1 5/8
9-10-79	945		2.985	2.974	2.970	14 1/2	2 1/4
9-11-79	3067		2.988	2.960	2.954	14 5/8	2 3/4
9-11-79	3555		2.985	2.963	2.953	14 3/4	2 7/8
9-12-79	5734					14 13/16	2 7/8
9-12-79	6255		2.994	2.957	2.945	14 13/16	3
9-13-79	8517		2.993	2.947	2.944	14 15/16	3 1/8
9-13-79	9094		2.983	2.951	2.937	14 15/16	3 1/8
9-13-79	9516		2.988	2.958	2.950	14 15/16	3 1/8
9-14-79	11487		2.988	2.951	2.939	14 15/16	3 1/4
9-14-79	12566		2.985	2.947	2.939	15	3 1/4
9-17-79	20502		2.979	2.948	2.928	15 1/8	3 3/8
9-17-79	21088		2.983	2.935	2.933	15 1/8	3 3/8
9-17-79	23964		2.986	2.940	2.927	15 1/8	3 3/8
9-19-79	26609		2.987	2.937	2.908	15 3/16	3 1/2
9-20-79	29482		2.990	2.933	2.925	15 1/4	3 5/8
9-20-79	30469		2.987	2.941	2.930	15 1/4	3 5/8
9-21-79	32637 ① ②		2.982	2.938	2.928	15 1/4	3 5/8
9-21-79	33370		2.969	2.938	2.928	15 5/16	3 5/8
9-24-79	41634		2.984	2.934	2.918	15 5/16	3 3/4
9-24-79	42181					16 5/8	3 3/4
9-25-79	43327 ①	↓					

Rope 23-N

DATE	Cycles	Load (PSI)	Rope dia. NF	SF	DF	EXT	Extensometer
9-27-79	43327	700					
11-6-79	44171						
11-21-79							
11-21-79	44487						
11-27-79	44669		2.988	2.927	2.919	13 7/16	2 1/2
11-27-79	45088		2.989	2.919	2.917	13 11/16	2 1/2
11-27-79	45456		2.987	2.929	2.917	13 13/16	2 1/2
11-28-79	47435		2.991	2.925	2.914	14	2 1/2
11-28-79	48026		2.982	2.917	2.908	14 1/16	2 1/2
11-28-79	48362		2.983	2.919	2.904	14 1/16	2 1/2
11-29-79	50336		2.989	2.920	2.908	14 1/8	2 1/2
11-29-79	50855		2.990	2.920	2.909	14 3/16	2 1/2
11-29-79	51838		2.988	2.913	2.910	14 3/16	2 1/2
11-30-79	53331		2.983	2.915	2.909	14 1/4	2 5/8
11-30-79	53647		2.979	2.921	2.911	14 1/4	2 5/8
11-30-79	54043		2.985	2.914	2.909	14 1/4	2 5/8
12-3-79	61790		2.950	2.914	2.902	14 3/8	2 5/8
12-3-79	62139		2.987	2.907	2.906	14 3/8	2 5/8
12-4-79	64635 ① ②		2.978	2.907	2.905	14 7/16	2 5/8
12-4-79	65008		2.974	2.902	2.907	14 1/2	2 3/4
12-4-79	65368		2.981	2.915	2.901	14 1/2	2 3/4
12-5-79	67558		2.979	2.903	2.901	[illegible]	2 7/8
12-5-79	68298		2.985	2.918	2.905	[illegible]	2 7/8
12-6-79	70611		2.982	2.910	2.900	[illegible]	3
12-6-79	70818		2.972	2.907	2.900	[illegible]	3
12-7-79	73199		2.978	2.907	2.899	[illegible]	3
12-7-79	73880		2.969	2.909	2.906	[illegible]	3
12-7-79	74202		2.983	2.903	2.901	14 5/8	3
12-10-79	82187		2.987	2.909	2.899	14 3/4	3 1/8
12-10-79	82521		2.971	2.909	2.900	14 3/4	3 1/8
12-11-79	85160		2.969	2.900	2.899	14 3/4	3 1/8
12-11-79	85813 ③		2.966	2.911	2.899	14 13/16	3 1/8
12-12-79	88106		2.961	2.910	2.898	14 7/8	3 1/4
12-14-79	91421	↓	2.978	2.900	2.897	14 15/16	3 3/8

Rope 23-N

DATE	Cycles	Load (PSI)	Rope Dia NF	SF	DF	EXT	Extensometer
12-14-79	91430	700	2.981	2.909	2.897	14 15/16	3 1/2
12-14-79	91711		2.982	2.912	2.910	14 15/16	3 3/4
12-17-79	98923 ① ③		2.964	2.911	2.899	15 1/4	4
12-18-79	100242 ① ③	Rope failed ④					

Legend

Date installed : 9-10-79
Rope Length : 49 FT 9 inch
Rope Type : 6X57 RLG
Design Factor : 5
Load (PSI) : 700
Double Flex Length : 6 FT
Lay Length : 16 in
4½ Lay Length / D.F. Region

Date Failed : 12-18-79
Total Cycles : 100242
Cycles unloaded : 17
Net cycles : 100225
Cycle Stroke : 16 FT.

Reference Notes

① Cycles unloaded
2 cycles : 300 Psi
2 cycles : 300 Psi
2 cycles : 600 Psi
3 cycles : 300 Psi
2 cycles : 300 Psi
2 cycles : 600 Psi

② Elongation Readings
32637 Cycles : 50 FT 1⅛ in.
64635 cycles : 50 FT 2½ in
99750 cycles : 50 FT 3½ in

③ 85813 cycles 2 broken wires in single flex region

④ Rope failed on top of sheave in single flex region.

Rope 24-S

Cycles Not At Load: 53

DATE	Cycles	Load PSI	Rope Dia NF	SF	DF	EXT	Extensometer
9-27-79	0 ①	700					
11-6-79	520						
11-21-79	844						
11-21-79	1160						
11-27-79	1392		2.981	2.963	2.960	13 7/16	2 1/2"
11-27-79	1764		2.981	2.960	2.956	13 13/16	2 1/2
11-27-79	2129		2.981	2.962	2.957	13 7/8	2 1/2"
11-28-79	4108		2.976	2.953	2.946	14"	2 1/2"
11-28-79	4699		2.976	2.949	2.946	14 1/16"	2 1/2"
11-28-79	5085		2.981	2.946	2.948	14 1/16	2 1/2"
11-29-79	7009		2.982	2.947	2.946	14 1/8	2 1/2"
11-29-79	7558		2.978	2.946	2.942	14 3/16	2 1/2"
11-29-79	8011		2.978	2.948	2.946	14 3/16	2 1/2
11-30-79	10004		2.979	2.949	2.940	14 1/4	2 5/8"
11-30-79	10320		2.983	2.945	2.937	14 1/4	2 5/8
11-30-79	10716		2.978	2.941	2.937	14 1/4	2 5/8
12-3-79	15468		2.990	2.934	2.928	14 3/8	2 5/8"
12-3-79	18812		2.982	2.938	2.928	14 3/8	2 5/8"
12-4-79	21308 ① ②		2.979	2.936	2.925	14 7/16	2 5/8"
12-4-79	21651		2.982	2.931	2.924	14 1/2	2 3/4
12-4-79	22041		2.976	2.926	2.924	14 1/2	2 7/8"
12-5-79	24231		2.979	2.924	2.923	14 1/2	2 7/8"
12-5-79	24971		2.978	2.930	2.916	14 1/2	2 7/8
12-6-79	27284		2.978	2.927	2.923	14 9/16	3"
12-6-79	27491		2.981	2.926	2.918	14 9/16	3"
12-7-79	29872		2.979	2.925	2.922	14 9/16	3"
12-7-79	30553		2.979	2.921	2.922	14 5/8	3"
12-7-79	30875		2.979	2.921	2.922	14 5/8	3"
12-10-79	38860		2.979	2.920	2.916	14 3/4	3 1/8"
12-10-79	39994		2.981	2.920	2.913	14 3/4"	3 1/8"
12-11-79	41833		2.980	2.913	2.913	14 3/4	3 1/8
12-11-79	42486		2.978	2.914	2.915	14 13/16	3 1/4
12-13-79	44779		2.985	2.913	2.913	14 7/8	3 1/4
12-14-79	47699	↓	2.978	2.913	2.909	14 15/16	3 3/8

Rope 24-S

DATE	Cycles	Load (PSI)	NF	SF	DF	EXT	Extensometer
12-14-79	48111	700	2.975	2.921	2.914	14 15/16	3 3/4
12-14-79	48388		2.982	2.912	2.910	14 15/16	3 7/8
12-17-79	55596 ① ②		2.984	2.919	2.903	15 1/4	4"
12-18-79	56915	↓					

Legend

Date installed : 9-27-79
Rope Length : 50 FT 2⅛ in
Rope Type : 6X57
Design Factor : 5
Load (PSI) : Load 1 700 PSI
Load 2 585 PSI
Double Flex Length : 6 FT.
Lay Length : 16 inch
4½ Lay Length / D.F. Region.
Date Failed : 1-22-80
Total cycles : 118489
Cycles unloaded : 53
Net cycles : 118436
Cycle Stroke : 16 FT.

Reference Notes

① Cycles unloaded:
3 cyc. less than 700 Psi
2 cycles 300 Psi
2 cycles 400 Psi
2 cycles 300 Psi
2 cycles 400 Psi
25 cycles less than 585 Psi

② Elongation Readings:
21308 cycles ; 50 FT 6¼ inch
56423 cycles : 50 FT 7⅛ inch

③ Broken Wires:
85065 cycles, 5 broken wires
115725 cycles, 5 broken wires in D.F. Region
118222 cycles, 5 Tot. broke wire on each of 2 strands in double flex region

④ Rope length, when installed at start of test: 50 FT 2⅛ inch

Rope 24-S

DATE	Cycles	Load (PSI)	Rope Dia. NF	SF	DF	EXT	Extensometer
12-26-79	56913	700 ①					
12-26-79	56933	585					
12-27-79	59592		2.983	2.907	2.907	11 1/4	4 7/8"
12-28-79	61778		2.978	2.908	2.901	11 3/8	5 1/8"
12-28-79	62096		2.978	2.904	2.900	11 3/8	5 1/8
12-31-79	69499		2.971	2.902	2.900	11 1/2"	5 3/8"
12-31-79	70056		2.971	2.902	2.897	11 1/2"	5 3/8"
12-31-79	70382		2.972	2.903	2.899	11 9/16	5 3/8"
1-2-80	75175		2.968	2.902	2.894	11 5/8	5 1/2"
1-2-80	75807		2.972	2.899	2.892	11 5/8	5 1/2
1-3-80	77427		2.967	2.898	2.890	11 5/8	5 1/2
1-3-80	78418					11 11/16	5 1/2
1-4-80	79692		2.969	2.894	2.889	11 11/16	5 1/2
1-7-80	84596		2.976	2.893	2.885	11 7/8	5 1/2
1-10-80	85065 ③		2.973	2.892	2.888	11 7/8	5 5/8
1-11-80	87143		2.968	2.892	2.880	11 7/8	5 5/8
1-11-80	87638		2.772	2.891	2.885	11 15/16	5 5/8
1-14-80	95322		2.963	2.883	2.867	12 1/8	5 5/8
1-15-80	97977		2.985	2.882	2.873	12 3/16	5 5/8
1-15-80	98563		2.979	2.887	2.863	12 3/16	5 3/4
1-16-80	100833		2.975	2.883	2.878	12 3/16	5 7/8"
1-17-80	103749		2.973	2.880	2.859	12 1/4	6"
1-17-80	104366		2.963	2.875	2.866	12 1/4	6"
1-18-80	106546		2.963	2.874	2.865	12 3/8	6 1/8
1-18-80	107528		2.962	2.878	2.868	12 3/8	6 1/8
1-19-80	110854					12 7/16	6 1/4
1-21-80	115725 ③		2.966	2.874	2.865	12 5/8	6 3/8
1-21-80	116270		2.964	2.876	2.867	12 11/16	6 3/8
1-22-80	118220 ③	↓	2.965	2.859	2.847	13 1/8	6 5/8
1-22-80	118489	Rope failed ④					

Rope 25-N

Cycles Not at Load: 29

Date	Cycles	Load (PSI)	Rope Dia NF	SF	DF	Ext	Extensometer
12-26-79	0						
12-26-79	18 ①	585					
12-27-79	2672		3.037	2.967	2.968	11 1/4	4 3/8
12-28-79	4858		2.988	2.963	2.960	11 3/8	5 1/8
12-28-79	5776		2.995	2.966	2.960	11 3/8	5 1/8
12-31-79	12578		2.986	2.958	2.950	11 1/2	5 3/8
12-31-79	13136		2.992	2.954	2.948	11 1/2	5 1/2
12-31-79	13462		2.991	2.953	2.947	11 9/16	5 3/8
1-2-80	15255		2.987	2.947	2.937	11 5/8	5 1/2
1-2-80	18887		2.986	2.948	2.943	11 5/8	5 1/2
1-3-80	20507		2.988	2.945	2.939	11 5/8	5 1/2
1-3-80	21498					11 11/16	5 1/2
1-4-80	23772		2.956	2.947	2.933	11 11/16	5 1/2
1-7-80	21676		2.983	2.944	2.934	11 5/8	5 5/8
1-10-80	28145		2.982	2.943	2.935	11 7/8	5 5/8
1-11-80	30223		2.984	2.944	2.936	11 7/8	5 5/8
1-11-80	30718		2.979	2.940	2.937	11 15/16	5 5/8
1-14-80	38042		2.985	2.942	2.938	12 1/8	5 5/8
1-15-80	41057		2.987	2.934	2.927	12 1/16	5 5/8
1-15-80	44643		2.970	2.930	2.925	12 1/16	5 3/4
1-16-80	43913		2.990	2.932	2.924	12 3/16	5 7/8
1-17-80	46829		2.979	2.931	2.924	12 1/4	6
1-17-80	47446		2.990	2.922	2.925	12 1/4	6
1-18-80	49626		2.982	2.934	2.922	12 3/8	6 1/8
1-18-80	50603		2.988	2.935	2.920	12 3/8	6 1/8
1-19-80	53134					12 7/16	6 1/4
1-21-80	58405		2.987	2.921	2.917	12 3/8	6 3/8
1-21-80	59350		2.966	2.918	2.909	12 7/16	6 3/8
1-22-80	61300		2.972	2.924	2.925	13 1/8	6 1/8
1-22-80	61569						

25 N

Date	Cycles	Load (PSI)	Rope Dia NF	SF	DF	Ext	Extensometer
1-28-80	61569	585					0
1-29-80	63579		2.990	2.915	2.908	10 1/8	1 5/8
1-29-80	64509		2.979	2.913	2.910	10 5/16	1 5/8
1-30-80	66666					10 1/2	1 3/4
1-30-80	66932 ② ③		2.976	2.915	2.915	10 1/2	1 3/4
1-31-80	68338		2.990	2.916	2.918	10 3/4	1 3/4
2-1-80	70689		2.991	2.914	2.911	10 7/8	1 3/4
2-1-80	71269		2.985	2.914	2.914	10 7/8	1 3/4
2-4-80	79623		2.986	2.915	2.914	11	1 3/4
2-4-80	80295		2.978	2.909	2.906	11	1 3/4
2-4-80	80620		2.973	2.910	2.903	11	1 3/4
2-5-80	82571		2.988	2.914	2.908	11 1/16	1 3/4
2-5-80	83465		2.995	2.916	2.914	11 1/16	1 3/4
2-6-80	85492		2.991	2.911	2.909	11 1/16	1 3/4
2-6-80	86097		2.998	2.910	2.906	11 1/8	1 7/8
2-6-80	86456		2.993	2.911	2.909	11 1/8	1 7/8
2-7-80	88474		2.993	2.914	2.902	11 1/8	1 7/8
2-7-80	89290		2.982	2.902	2.908	11 1/8	1 7/8
2-8-80	91322		2.994	2.900	2.905	11 1/8	1 7/8
2-8-80	91933		2.988	2.908	2.909	11 1/8	1 7/8
2-8-80	92851		2.990	2.908	2.905	11 1/2	1 7/8
2-11-80	100264 ③		2.989	2.905	2.904	11 1/2	2
2-12-80	103118		2.987	2.907	2.901	11 9/16	2
2-13-80	103699		2.986	2.906	2.898	11 9/16	2
2-13-80	106073		2.991	2.904	2.900	11 1/2	2
2-13-80	107080		2.989	2.908	2.898	11 1/2	2 1/8
2-14-80	109063		2.980	2.903	2.898	11 1/2	2 1/8
2-14-80	109722		2.983	2.902	2.892	11 1/2	2 1/8
2-14-80	110012		2.998	2.902	2.892	11 9/16	2 1/8
2-15-80	111970		2.987	2.900	2.892	11 9/16	2 1/8
2-21-80	115257		2.993	2.902	2.889	11 9/16	2 1/4
2-22-80	115054		2.992	2.896	2.889	11 11/16	2 1/4
2-22-80	115676		2.987	2.900	2.887	11 3/4	2 1/4
2-27-80	123676		2.991	2.892	2.885	11 3/4	2 1/8

Rope 25-N

Date	Cycles	Load (PSI)	Rope Dia NF	SF	DF	Ext	Extensometer
2-28-80	126382	585	2.989	2.889	2.880	11 7/8	2 1/4
2-28-80	126044		2.982	2.892	2.884	11 13/16	2 1/4
2-29-80	127456		2.985	2.892	2.886	12 1/16	2 1/4
2-29-80	127875		2.988	2.987	2.888	12 1/16	2 3/8
2-29-80	128166		2.990	2.887	2.876	12 1/16	2 3/8
3-2-80	131956	Rope Failed ④					

Legend

Date installed : 12-26-79
Rope Length : 49 FT 3 1/2 inch
Rope Type : 6X57 RLG
Design Factor : 6
Load (PSI) : 585
Double Flex Length : 6 FT.
Lay Length : 16 inch
4 1/2 Lay Lengths / DF
Date Failed : 3-2-80
Total Cycles : 131956
Cycles Unloaded : 29
Net Cycles : 131927
Cycle Stroke : 16 FT.

Reference Notes

① Cycles not at load.
25 cycles start
2 cycles, 300 PSI
2 cycles, 400 PSI
② Elongation Readings:
66932 cycles, 49 FT 9 3/4 inch
③ 100264 cycles, 1 broken wire in double flex region.
④ Rope length, when installed at start of test, 49 FT 3 1/2 in at 300 PSI

26-S

Date	Cycles	Load PSI	Rope Dia NF	SF	DF	Ext	Extensometer
1-28-80	0	585				7 1/8	Reset 0(1")
1-29-80	2010		2.994	2.960	2.956	10 1/8"	1 5/8
1-29-80	2940		2.989	2.953	2.950	10 5/16	1 5/8
1-30-80	5097					10 1/2	1 3/4
1-30-80	5363 ① ②		2.990	2.938	2.942	10 1/2	1 3/4
1-31-80	6769		2.989	2.946	2.940	10 5/8	1 3/4
2-1-80	9120		2.990	2.936	2.938	10 7/8	1 3/4
2-1-80	9700		2.986	2.929	2.928	10 7/8	1 3/4
2-4-80	18054		2.990	2.922	2.919	11"	1 3/4
2-4-80	18726		2.982	2.920	2.933	11"	1 3/4"
2-4-80	19051 ③		2.990	2.922	2.931	11"	1 3/4"
2-5-80	21002		2.990	2.921	2.927	11 1/16	1 3/4
2-5-80	21896		2.996	2.918	2.932	11 1/16	1 3/4
2-6-80	23923		2.993	2.921	2.921	11 1/16	1 3/4
2-6-80	24528		2.988	2.922	2.921	11 1/8	1 7/8
2-6-80	24887		2.990	2.919	2.916	11 1/8	1 7/8
2-7-80	26855		2.992	2.920	2.916	11 1/8	1 7/8
2-7-80	27831		2.985	2.920	2.916	11 1/8	1 7/8
2-8-80	29753		3.000	2.915	2.911	11 1/8	1 7/8
2-8-80	30369		2.999	2.918	2.912	11 1/8	1 7/8
2-8-80	30762		2.992	2.909	2.911	11 1/8	1 7/8
2-11-80	38698		2.991	2.908	2.905	11 1/4	2"
2-12-80	41549		2.995	2.908	2.907	11 5/16	2"
2-12-80	43130		2.995	2.907	2.907	11 5/16	2"
2-13-80	44504		2.995	2.903	2.896	11 1/2	2"
2-13-80	45311		2.986	2.909	2.907	11 1/2	2 1/8
2-14-80	47494		2.990	2.899	2.897	11 1/2	2 1/4"
2-14-80	48153		2.997	2.892	2.890	11 1/2	2 1/8"
2-14-80	48442		2.892	2.899	2.898	11 9/16	2 1/8"
2-15-80	50401		2.991	2.875	2.890	11 9/16	2 1/8
2-21-80	51718		2.986	2.902	2.897	11 5/8	2 1/4"
2-22-80	54488		2.927	2.891	2.887	11 11/16	2 1/4"
2-22-80	54107		2.988	2.880	2.885	11 3/4	2 1/4
2-22-80	62107		2.984	2.885	2.885	11 3/4	2 3/8
2-28-80	63813		2.991	2.884	2.876	11 7/8	2 1/4"
2-28-80	64476		2.986	2.881	2.884	11 15/16	2 1/4"
2-29-80	65887		2.987	2.886	2.882	12 1/16	2 3/8
2-29-80	66306		2.994	2.885	2.886	12 1/16	2 3/8"
3-2-80	66597		2.988	2.888	2.880	12 1/16	2 3/8

(CONT'D)

Rope 26-S

Date	Cycles	Load PSI	Rope Dia NF	SF	DF	Ext	Extensometer
3-5-80	70896	585					
3-7-80	70909		2.952	2.922	2.870	11 3/16"	4 3/4"
3-10-80	76450		2.987	2.883	2.877	16 5/16"	5 1/2"
3-10-80	76919		2.990	2.879	2.861	16 5/16	5 1/4"
3-11-80	78402		2.985	2.875	2.865	16 1/4"	5 1/2"
3-11-80	78883		2.981	2.878	2.859	16 5/16	5 1/2
3-11-80	79090		2.984	2.875	2.859	16 5/16	5 1/2
3-12-80	80418		2.982	2.880	2.858	16 7/8	5 5/8
3-13-80	82534		2.988	2.865	2.857	16 5/16	5 3/4
3-13-80	83285		2.985	2.866	2.860	16 5/16	5 3/4
3-14-80	84681		2.983	2.878	2.857	16 15/16	5 7/8"
3-14-80	85125		2.988	2.869	2.857	17"	5 7/8"
3-17-80	94995		2.987	2.861	2.851	17 1/4"	6"
3-19-80	98110		2.978	2.862	2.842	17 1/4"	6"
3-19-80	93504		2.982	2.856	2.842	17 1/4"	6"
3-19-80	93834		2.981	2.859	2.846	17 1/4"	6"
3-20-80	96284		2.982	2.863	2.848	17 1/4	6"
3-21-80	97484		2.981	2.869	2.840	17 5/16	6"
3-21-80	97845		2.988	2.857	2.842	17 5/16	6"
3-21-80	98157					17 3/8"	6 1/8"
3-24-80	102641		2.980	2.859	2.840	17 3/8"	6 1/4"
3-24-80	103080		2.985	2.862	2.841	17 3/8	6 1/4"
3-25-80	104450		2.978	2.859	2.841	17 7/16	6 1/4"
3-26-80	106648		2.981	2.850	2.836	17 1/2	6 3/8
3-26-80	107377		2.980	2.850	2.837	17 1/2	6 3/8"
3-27-80	108841		2.977	2.852	2.838	17 1/2	6 3/8"
3-27-80	109604		2.988	2.844	2.836	17 1/2	6 3/8
3-28-80	111060		2.988	2.844	2.830	17 5/8	6 3/8
3-31-80	117064		2.979	2.848	2.839	17 7/8	6 7/8
3-31-80	118165 ③		2.977	2.847	2.830	17 7/8	6 7/8
4-4-80	118985 ①		2.982	2.877	2.831	18"	7"
4-7-80	126216		2.986	2.843	2.826	18 3/16	7"
4-7-80	126772		2.982	2.845	2.824	18 1/4	7"
4-7-80	127099		2.977	2.840	2.820	18 1/4	7"

(CONT'D)

26-S

Date	Cycles	Load (PSI)	Rope Dia NF	SF	DF	Ext.	Extensometer
4-8-80	128878	585	2.979	2.841	2.817	18 1/4"	7"
4-8-80	129479 ③		2.978	2.846	2.814	18 1/4	7"
4-8-80	129775					18 5/16	7"
4-9-80	131672		2.979	2.830	2.811	18 5/16	7"
4-9-80	132490		2.978	2.836	2.811	18 5/16	7"
4-10-80	134240		2.978	2.846	2.813	18 3/8	7"
4-11-80	136416		2.977	2.830	2.811	18 3/8	7"
4-11-80	137534		2.969	2.836	2.815	18 3/8	7"
4-14-80	138606		2.950	2.841	2.828	18 3/8	7"
4-15-80	140535		2.975	2.826	2.818	18 5/16	7"
4-15-80	141189		2.976	2.823	2.811	18 5/16	7"
4-16-80	143231		2.978	2.829	2.806	18 5/16	7"
4-17-80	145921		2.977	2.826	2.818	18 5/8	7"
4-18-80	148601		2.977	2.819	2.814	18 5/8	7"
4-18-80	149107		2.974	2.820	2.812	18 11/16	7"
4-21-80	150166		2.978	2.815	2.807	18 5/8	7"
4-21-80	150453		2.981	2.819	2.806	18 5/8	7"
4-22-80	152194		2.977	2.827	2.803	18 11/16	7"
4-22-80	152863		2.979	2.828	2.800	18 3/4	7
4-23-80	154878 ② ③		2.935	2.823	2.799	18 3/4	7"
4-23-80	155300		2.980	2.824	2.802	18 13/16	7"
4-24-80	157529		2.978	2.821	2.802	18 7/8	7 1/8"
4-24-80	158159		2.984	2.814	2.801	18 7/8	7 1/4"
4-25-80	160199		2.980	2.811	2.803	18 15/16	7 1/4"
4-27-80	165915					19"	7 3/8
4-28-80	168731					19 1/4	7 1/2"
4-29-80	170382	Rope Failed ④					

Legend

Date installed : 1-28-80
Rope Length : 50 FT.
Rope Type : 6X57 RLG
Design Factor : 6.0
Load (PSI) : 585
Double Flex Length : 6 FT.
Lay Length : 16 inch
4 1/2 Lay Lengths / D.F
Date Failed : 4-29-80
Total Cycles : 170383
Cycles Unloaded : 10
Net Cycles : 170373
Cycle Stroke : 16 FT.

Reference Notes

① Cycles not a load:
6 cycles at 300 PSI
4 cycles at 400 PSI
② Rope Elongation Readings:
5363 cycles at 300 PSI = 50 FT 4 1/2 inch
155282 cycles at 300 PSI = 50 FT 8 inch
③ Broken Wires:
19031 - 2 broken wires in middle of single flex region.
118165 cycles - 1 broken wire in double flex region.
129479 cycles - 1 broken wire.
④ Rope length, when installed, was 50 FT at 300 PSI

Rope 27-N

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia DF	EXT	Extensometer
3-5-80	0 ①	585					
3-7-80	573		2.999	2.974	2.968	11 3/4	4 7/8
3-10-80	6054		2.989	2.951	2.952	16 9/16	5 1/8
3-10-80	6523		2.984	2.942	2.940	16 11/16	5 1/4
3-11-80	8006		2.983	2.964	2.945	16 3/4	5 3/8
3-11-80	8487		2.989	2.947	2.938	16 3/4	5 1/2
3-11-80	8694		2.994	2.939	2.941	16 13/16	5 1/2
3-12-80	10022		2.989	2.943	2.951	16 7/8	5 5/8
3-13-80	12138		2.983	2.919	2.932	16 15/16	5 3/4
3-13-80	12889		2.992	2.929	2.939	16 15/16	5 3/4
3-14-80	14235		2.983	2.931	2.930	16 15/16	5 7/8
3-14-80	14729		2.957	2.926	2.925	17	5 7/8
3-17-80	20599		2.995	2.920	2.922	17 1/8	6
3-19-80	22714		2.993	2.922	2.912	17 1/4	6
3-19-80	23148		2.989	2.918	2.915	17 1/4	6
3-19-80	23433		2.993	2.920	2.912	17 1/4	6
3-20-80	24888		2.990	2.924	2.913	17 1/4	6
3-21-80	27088		2.991	2.920	2.911	17 5/16	6
3-21-80	27452		2.991	2.924	2.913	17 5/16	6
3-21-80	27763					17 3/8	6 1/8
3-24-80	32295		2.987	2.912	2.916	17 3/8	6 1/4
3-24-80	32634		2.989	2.905	2.904	17 11/16	6 3/4
3-25-80	34054		2.988	2.907	2.908	17 3/4	6 7/8
3-26-80	36252		2.990	2.914	2.908	17 3/4	6 7/8
3-26-80	36981		2.992	2.919	2.905	17 3/4	6 7/8
3-27-80	38445		2.990	2.912	2.907	17 3/4	6 7/8
3-27-80	39208		2.987	2.914	2.908	17 3/4	6 7/8
3-28-80	40664		2.990	2.913	2.906	17 3/4	6 7/8
3-31-80	47258		2.987	2.911	2.903	17 7/8	6 7/8
3-31-80	47769		2.987	2.907	2.901	17 7/8	6 7/8
4-4-80	48389		2.990	2.907	2.901	18	7
4-7-80	55820		2.989	2.903	2.899	18 3/16	7
4-7-80	56376		2.986	2.900	2.892	18 1/4	7
4-7-80	56708		2.993	2.899	2.898	18 1/4	7

(Cont'd)

Rope 27-N (Cont'd)

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia DF	EXT	Extensometer
4-8-80	58482	585	2.985	2.900	2.895	18 1/4	7"
4-8-80	59083		2.986	2.902	2.891	18 1/4	7
4-8-80	59382					18 5/16	7
4-9-80	61176		2.987	2.900	2.887	18 5/16	7
4-9-80	62094		2.989	2.896	2.888	18 7/16	7
4-10-80	63852		2.990	2.888	2.891	18 3/8	7
4-11-80	66520		2.981	2.982	2.891	18 3/8	7
4-11-80	67138		2.983	2.899	2.888	18 3/8	7
4-14-80	68320		2.982	2.891	2.886	18 1/2	7
4-15-80	70139		2.986	2.892	2.884	18 9/16	7
4-15-80	70793		2.991	2.893	2.887	18 9/16	7
4-16-80	72835		2.972	2.890	2.886	18 9/16	7
4-17-80	75525		2.987	2.889	2.894	18 5/8	7
4-18-80	78305		2.986	2.883	2.910	18 5/8	7
4-18-80	78711		2.987	2.884	2.882	18 11/16	7
4-21-80	79760		2.989	2.888	2.876	18 5/8	7
4-21-80	80057		2.987	2.886	2.885	18 5/8	7
4-22-80	81798		2.981	2.889	2.878	18 11/16	7
4-22-80	82467		2.989	2.888	2.888	18 3/4	7
4-23-80	84482 ②		2.982	2.885	2.883	18 3/4	7
4-23-80	85112		2.984	2.886	2.885	18 13/16	7
4-24-80	87138		2.989	2.886	2.880	18 7/8	7 1/8
4-24-80	87163		2.986	2.887	2.878	18 7/8	7 1/8
4-25-80	89803		2.987	2.886	2.880	18 15/16	7 1/4
4-27-80	95519					19	7 3/8
4-28-80	98325					19 1/4	7 3/8
4-29-80	99987	Rope Retired ③					

Legend

Date installed : 3-7-80
Rope Length : 50 FT 5 inch
Rope Type : 6X57 RLG
Design Factor : 6.0
Load (PSI) : 585
Double Flex Length : 6 FT.
Lay Length : 16 inch
4 1/2 Lay Lengths/D.F.
Date Retired : 6-9-80
Total cycles : 99987
Cycles Unloaded : 6
Net Cycles : 99981
Cycle Stroke : 16 FT.

Reference Notes

① Cycles Not at Load:
4 cycles 300 PSI
2 cycles 400 PSI

② Elongation Readings:
Rope 27N at 300 PSI, 84886 cycles : 50 FT 9 1/4 inch

③ Rope Length, when installed at start of Test, was 50 FT 5 inch at 300 PSI

Rope 28S

Date	Cycles	Load (PSI)	Rope Dia. NF	Rope Dia. SF	Rope Dia. DF	Cyl. EXT
	0 ①					
6-13-80	145	1585	2.978			
7-9-80	11712		2.947	2.893	2.874	
7-29-80	13022		2.950	2.896	2.875	13 3/8
7-31-80	15521		2.947	2.890	2.868	14 [illegible]
11-12-80	17769		2.945	2.880	2.859	15 [illegible]
12-2-80	18402		2.941	2.877	2.859	15 [illegible]
12-8-80	19163		2.946	2.888	2.859	15 [illegible]
12-9-80	20486		2.937	2.878	2.849	15 9/16
1-13-80	22063	Rope failed ②				

Legend

Date installed : 6-13-80
Rope Length : 50 FT 4 1/2 inches
Rope Type : 6X57
Design Factor : 2.2
Load (PSI) : 1585
Double Flex Length : 6 FT
Lay Length : 16 inch
4 1/2 Lay Lengths/D.F
Date Failed : 1-13-81
Total Cycles : 22063
Cycles unloaded : 24
Net cycles : 22039
Cycle Stroke : 16 FT.

Reference Notes

① Cycles Not Load:
12 Cycles 300 PSI
2 Cycles 500 PSI
8 Cycles 1000 PSI

② Rope Length, when installed at start of Test, was 50 FT 4 1/2 inch

Rope 29-N

Date	Cycles	Load (PSI)	Rope Dia NF	Rope Dia SF	Rope Dia DF	Cyl. EXT
Start	0 ①					
6/13/80	145	1585	2.982			
7/9/80	11712		2.946	2.899	2.895	
7/29/80	13022		2.950	2.905	2.897	13 7/8
7/31/80	15521		2.946	2.911	2.895	14 1/2
11/12/80	17769		2.950	2.897	2.887	15 1/8
12/2/80	18402		2.945	2.895	2.882	15 5/16
12/8/80	19163		2.953	2.894	2.882	15 1/2
12/9/80	20486		2.950	2.883	2.874	15 11/16
1/13/81	22063	Retired ②				

Legend

Date installed : 6-13-80
Rope Type : 6X57 RLG
Rope Length : 50 FT 2 inches
Design Factor : 2.2
Load (PSI) : 1585
Double Flex Length : 6 FT.
Lay Length : 18 inchs.
4 1/2 Lay Length/D.F.
Date Retired : 1-13-81
Total Cycles : 22063
Cycles unloaded : 24
Net Cycles at Load : 22039
Cycle Stroke : 16 FT.

Reference Notes

① Cycles Not at Load:
12 Cycles 300 PSI
2 cycles 500 PSI
8 cycles 1000 PSI

② Rope Length, when installed at start of Test, was 50 FT 2 inch

Rope 31-N

Date	Cycles	Load (PSI)	NF	SF	D.F.	Cylinder Extension
2/19/81	65	780	2.990	2.983	2.977	16 3/4"
2/19/81	522		2.988	2.969	2.971	17 5/8
2/20/81	2375		2.983	2.959	2.956	18 3/8
2/23/81	5539		2.983	2.947	2.945	18 3/4
2/24/81	8146		2.988	2.950	2.949	19 1/8
2/25/81	10188		2.983	2.946	2.941	19 3/16
2/25/81	11139		2.983	2.951	2.943	19 3/16
2/26/81	13042		2.979	2.944	2.941	19 1/8
2/26/81	14020		2.977	2.949	2.946	19 1/4
2/27/81	16103		2.982	2.941	2.937	19 5/16
3/3/81	19601		2.981	2.939	2.940	19 3/8
3/5/81	20329		2.978	2.942	2.938	19 3/16
3/13/81	25355		2.980	2.936	2.937	19 5/8
3/13/81	25944		2.977	2.940	2.922	19 5/8
3/16/81	26890		2.986	2.933	2.931	19 5/8
3/17/81	29680		2.985	2.929	2.922	19 11/16
3/18/81	32016		2.984	2.930	2.924	19 11/16
3/19/81	35101		2.982	2.930	2.924	19 3/4
3/20/81	37455		2.990	2.927	2.923	19 13/16
3/20/81	38406		2.982	2.927	2.921	19 13/16
3/23/81	39318	①	2.981	2.925	2.916	19 13/16
3/24/81	39661		2.986	2.927	2.921	19 13/16
3/25/81	40984		2.981	2.931	2.922	19 7/8
3/27/81	43842		2.983	2.926	2.919	19 7/8
3/30/81	44370		2.981	2.930	2.916	19 15/16
3/31/81	46762		2.985	2.925	2.917	19 15/16
3/31/81	47669		2.980	2.928	2.912	19 15/16
4/1/81	49570		2.983	2.923	2.913	20
4/1/81	50518		2.984	2.925	2.915	20
4/3/81	54037		2.981	2.918	2.909	20 1/8
4/7/81	56325		2.978	2.924	2.909	20 3/16
4/7/81	57290		2.975	2.921	2.911	20 3/16
4/8/81	59190		2.983	2.924	2.914	20 1/4
4/17/81	62417	② Rope failed in D.F. Region				

Legend

Date installed : 2-19-81
Rope Type : 6x57 RLG
Rope Length : 50.0 FT
Design Factor : 4.5
Lay Length : 16 inch
Date failed : 4-17-81
Total Cycles : 62417
Cycle unloaded : 2 at 300 psi
Net cycles at Load : 62415 at 780 psi
Cycle Stroke : 16'

Reference Notes

① 2 broken wires in single flex region

② 62417 cycles. Rope failed in double flex region

Rope 30-S

Date	Cycles	Load	NF	SF	DF	Cyl Ext.
2-19-81	65	780 psi	2.995	2.975	2.962	16 3/4"
2-19-81	522		2.990	2.957	2.950	17 5/8"
2-20-81	2375		2.984	2.951	2.943	18 3/8"
2-23-81	5539		2.981	2.949	2.937	18 3/4"
2-24-81	8146		2.989	2.944	2.937	19 1/8
2-25-81	10188		2.986	2.941	2.933	19 3/16"
2-25-81	11138		2.985	2.949	2.934	19 3/16
2-26-81	13042		2.981	2.940	2.930	19 1/8"
2-26-81	14020		2.985	2.945	2.932	19 1/4"
2-27-81	16103		2.982	2.937	2.930	19 5/16"
3-3-81	19601		2.981	2.937	2.923	19 3/8"
3-5-81	20329		2.978	2.932	2.922	19 9/16"
3-13-81	25355		2.922	2.928	2.917	19 5/8"
3-13-81	25944		2.988	2.921	2.913	19 5/8"
3-16-81	26890		2.980	2.928	2.911	19 5/8"
3-17-81	29680		2.986	2.929	2.914	19 11/16"
3-18-81	32016		2.980	2.925	2.911	19 11/16"
3-19-81	35101		2.984	2.924	2.911	19 3/4"
3-20-81	37455		2.980	2.928	2.907	19 13/16"
3-20-81	38406		2.976	2.915	2.911	19 13/16"
3-23-81	39318		2.988	2.925	2.910	19 13/16"
3-24-81	39661		2.982	2.927	2.912	19 13/16"
3-25-81	40984		2.987	2.927	2.911	19 7/8"
3-27-81	43842		2.989	2.937	2.905	19 7/8"
3-30-81	44370		2.983	2.926	2.930	19 15/16"
3-31-81	46702		2.983	2.924	2.909	19 15/16"
3-31-81	47669		2.985	2.926	2.910	19 15/16"
4-1-81	49570		2.993	2.918	2.907	20"
4-1-81	50518		2.986	2.928	2.909	20"
4-3-81	54037		2.979	2.917	2.987	20 1/8"
4-7-81	56325		2.987	2.922	2.903	20 3/16
4-7-81	57290		2.987	2.918	2.908	20 3/16
4-8-81	59190		2.984	2.919	2.905	20 1/4"
4-17-81	62415	① Rope retired (				

Legend

Date installed : 2-19-81
Rope Type : 6x57 RLG
Rope Length : 49 Feet 7 inch
Double Flex Length : 6 FT.
Lay Length : 16 inchs. 4 1/2 Lay Length / D.F.
Date Retired : 4-17-81
Total Cycles : 62417
Cycles unloaded : 2 at 300 psi
Net cycles at Load : 62415
Cycle Stroke : 16'
Design Factor : 4.5

Reference Notes

① Rope retired 4-17-81 at 62417 cycles

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