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REPORT OF INVESTIGATIONS/1993

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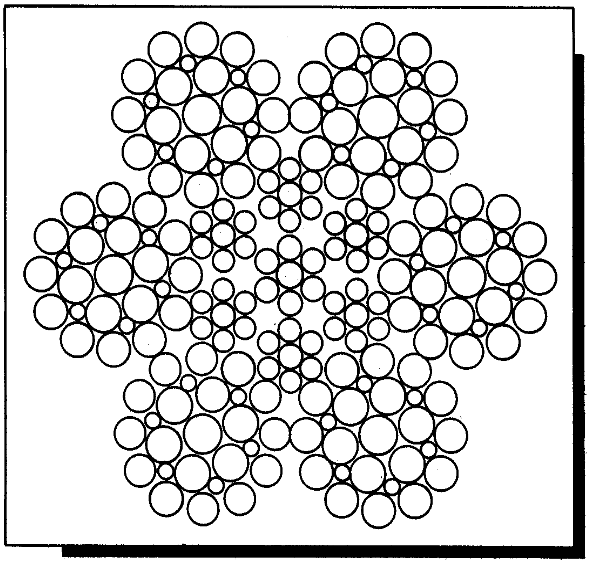

United States Department of the Interior

Bureau of Mines

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

With Factors for Conversion to Units of the International System of Units (SI)

Abbreviation	Unit of measure	To convert to—	Multiply by—
deg	degree		
ft	foot	meters	0.3048
ft/min	foot per minute	meters per second	.00508
gpm	gallon per minute	10^3 liters per second	.0631
h	hour		
hp	horsepower	kilowatts	.7457
in	inch	centimeters	2.54
in/min	inch per minute	meters per second	.06096
kip	10^3 pound (force)	newtons	444.8
kip/in^2	kip per square inch	megapascals	6894.8
lbf	pound (force)	newtons	4.448
lbf•ft	pound force per foot	newton-meters	1.3558
lbf•ft/kip	pound force per foot per kip	newton-meters per kilonewtons	.3048
min	minute		
pct	percent		
pct in/in	strain, inch per inch•0.01	strain, meter per meter•0.01	1
psi	pound (force) per square inch	kilopascals	6.8948
s	second		

WIRE ROPE RESEARCH: ANALYSIS OF BENDING FATIGUE IN A 2-INCH IWRC WIRE ROPE

By A. J. Miscoe[1] and W. M. McKewan[2]

ABSTRACT

A unique machine for inducing bending fatigue in wire ropes was built at the U.S. Bureau of Mines' Pittsburgh Research Center. This machine can produce nine levels of degradation through repetitive cycling of long samples of wire ropes of the types used in the mining industry. This report provides an analysis of the results of the first wire rope to be fatigued on this machine. These results have indicated that as a wire rope accumulates bending cycles, its strength first decreases because of wear and then increases due to cold working of the wires. As the amount of cold working increases, more and more of the embrittled wires break and the strength of the rope decreases rapidly. In this test, application of several of the regulatory retirement criteria to various sections of the rope suggests that there may be some inconsistency among them.

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INTRODUCTION

The Wire Rope Research Laboratory is located at the U.S. Bureau of Mines' Pittsburgh Research Center in Bruceton, PA (figs. 1-2). The laboratory was setup as part of the Hoisting System Development project, which has been a continuing effort by the Bureau for several years. Since personnel hoists carry many people at a time, the failure of a rope could result in a catastrophic accident. While focusing on the hoisting of personnel and materials in shafts and slopes of underground mines, the products of this research will apply to draglines for surface mining and to wire ropes for guying, guidance, staying, and for general use in the industry.

Essentially, the objective of the project is to improve the safety and economics of hoisting systems by quantifying the degradation process. The research approach is to develop accurate data on the factors that reduce wire rope strength, such as fatigue (both bending and axial), wear, and corrosion. This data can also be used to improve nondestructive testing equipment for better measurement of rope condition. It can be seen that the safety and economic concerns are interrelated, and that the potential benefits of such research are high.

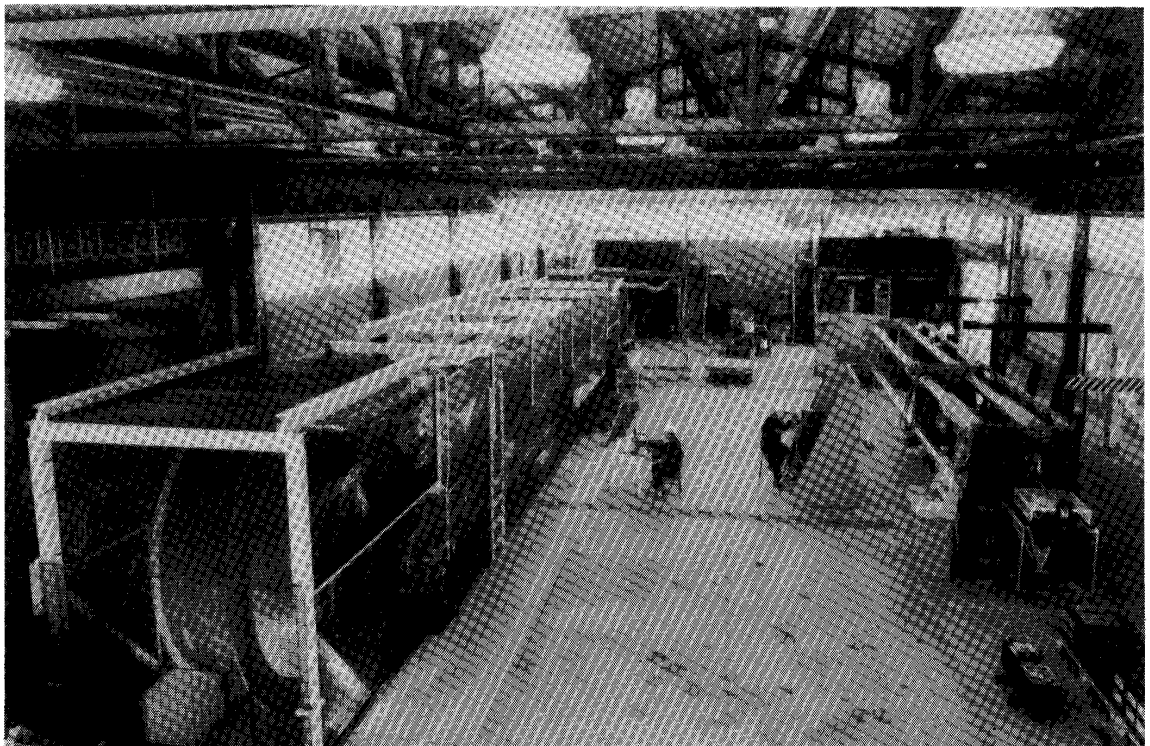

Figure 1.—Wire Rope Research Laboratory.

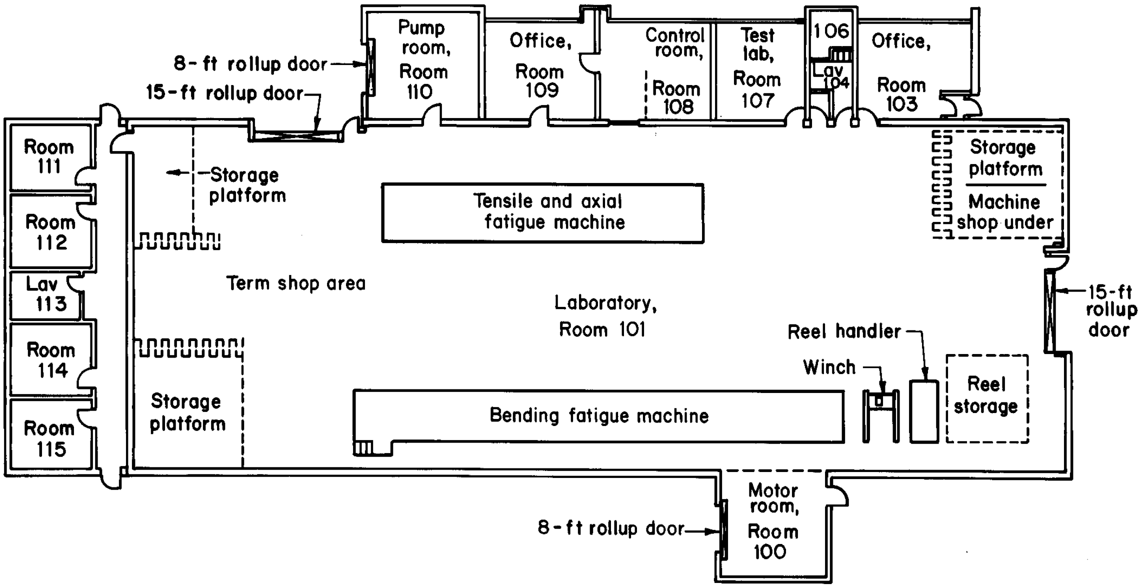

Figure 2.—Layout of laboratory.

EQUIPMENT

BENDING FATIGUE MACHINE

Because the primary mode of wire rope degradation is fatigue from bending under high stresses on sheaves and drums, the principal machine in the laboratory is one designed to cause fatigue damage in varying degrees in a long sample (about 1,000 ft) of wire rope. By using a long sample, the possible variation among short samples is avoided. These variations include differences in samples obtained at different times and from different manufacturers, as well as changes in machine operations due to such things as sheave wear. The bending fatigue machine is shown in figure 3.

The "three-sheave" configuration not only shortens the load frame, but also is a convenient means of accommodating a range of sheave diameters without affecting the maximum fleet angle when sheaves are changed. Fleet angle is the angle made by the rope at any wrap on the drum and the line made when the rope is in a plane perpendicular to the drum axis through the plane of the sheave. Another important benefit of this configuration is that there are up to eight rope-bending cycles for each machine cycle. This benefit is important to the test plan because it increases the number of tests that can be accomplished in any given period and greatly improves the statistical significance of the resulting experimental data.

Perhaps the most interesting result of the three-sheave configuration is how the specimen is degraded. Because of the different number of bends experienced by adjacent segments of the rope, a staggered degradation profile results. Thus, in a single specimen and a single test period, there will be available for further examination multiple samples of rope at each of nine different levels of degradation (fig. 4). This feature is very advantageous when doing studies relating to service life and establishing new or revised retirement criteria, because it reduces the test time requirements as compared to an ordinary test machine.

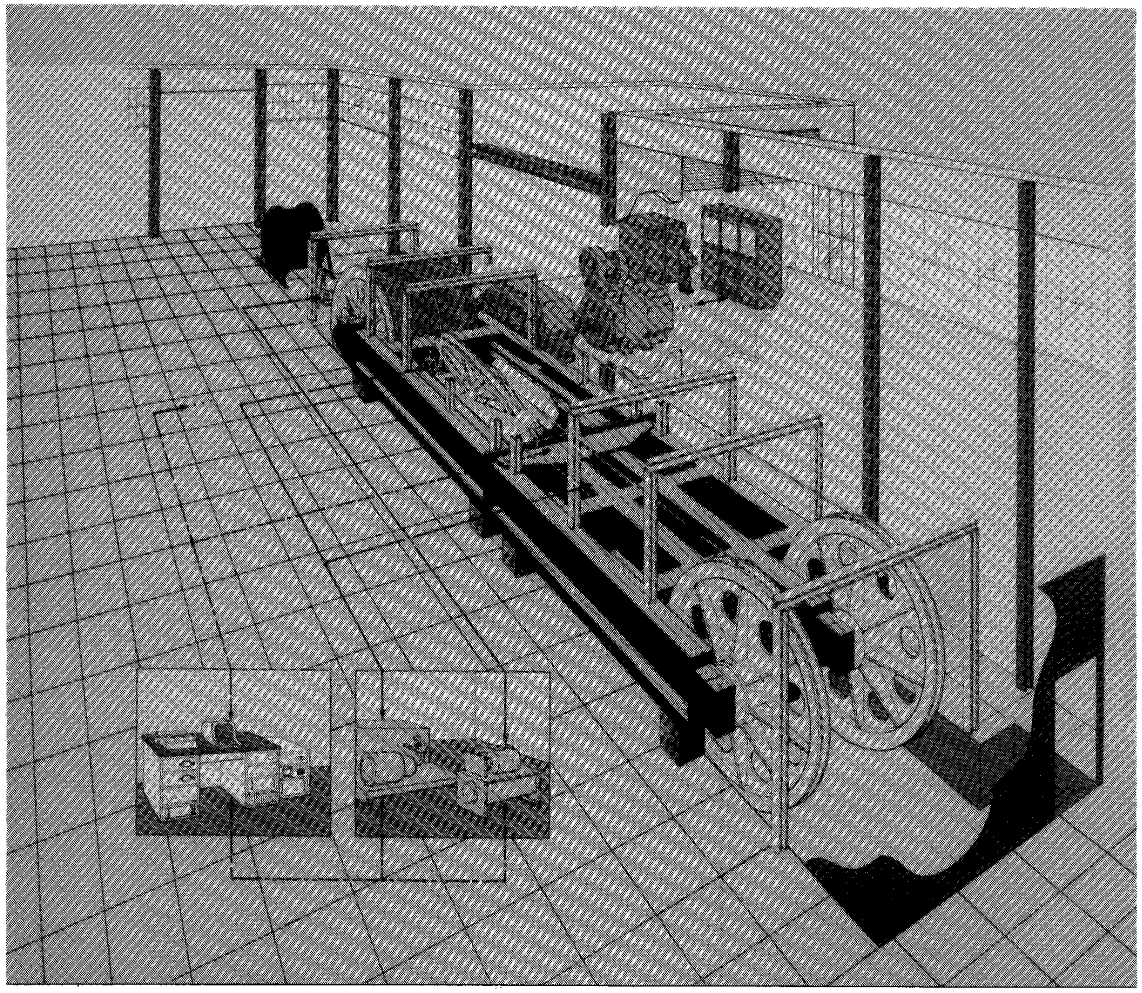

Figure 3.—Bending fatigue machine.

Overall control of the machine is provided by a computer that permits unmanned operation over extended periods since fatigue life will be tested to many thousands of cycles. At the maximum speed of 1,000 ft/min, a machine cycle takes about 1 min; since the center of the rope is cycled eight times for each machine cycle, 1,000,000 rope bending cycles would require 24-h operation for about 87 days. It is not planned to run the ropes to destruction since the objective is to measure remaining strength at certain intervals of load, speed, and number of rope bending cycles. The computer manages the hydraulic system as well as the drive system. The hydraulic system, through the ram, maintains constant rope tension and compensates for stretch in the rope. It also manages the braking system used for changing the direction of drum rotation during cycling as well as the friction brakes for emergency

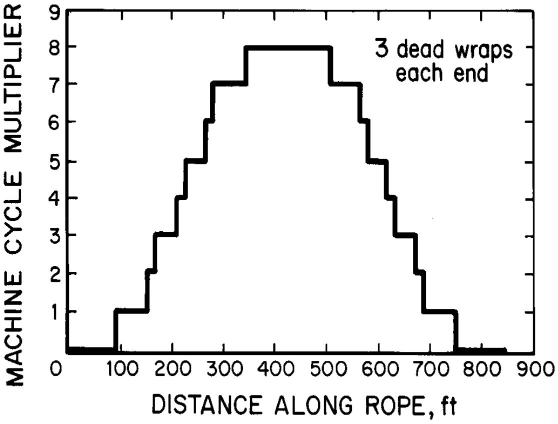

Figure 4.—Test rope fatigue cycle profile.

shutdown. The main means of changing the drum rotation is through a regenerative braking system in the drive, thus the hydraulically actuated friction brakes are a backup system. The friction brakes can stop the drum in about three-fourths of one rotation from maximum speed. The computer is programmed to recognize and react to emergency situations, via a variety of sensors, such as when the tension cylinder runs out of travel, when the rope is nearing the end on the drum, or if the rope should break. Operations are monitored continuously throughout a test.

The drum liner can be replaced with other surface materials such as urethane-coated materials or grooved liners for tracking and wear studies. The sheaves are all built with bolt-on segments that are replaceable for shape and wear studies, as well as for accommodation of different rope diameters.

An environmental chamber is mounted at one location on the rope travel path. It can provide sprays of water, corrosives, and dirt to simulate environmental effects. The chamber is not intended for simulation of particular mine environments because they are so highly variable from mine to mine and seasonally as well.

Provision is also made for mounting nondestructive testing devices along the rope path to evaluate their effectiveness in measuring deterioration of the rope such as broken wires and loss of metallic area due to wear and corrosion. One model is presently being used as a normal part of the testing procedure and a second is on order.

The specifications for the bending fatigue machine are given in table 1.

Table 1.—Bending fatigue machine specifications

Maximum rope tension	lbf	300,000
Maximum rope speed	ft/min	1,000
Maximum fleet angle	deg	2.9
Maximum rope stretch (without regripping)	ft	20
Rope diameter	in	1 to 2-1/2
Rope length	ft	up to 1,100
Drum diameter	ft	10
Drum width	ft	8.4
Tension sheave diameter	ft	10
Idler sheave diameter	ft	8
Drum drive motor	hp	500
Hydraulic system:		
Flow rate	gpm	30
Pressure	psi	3,000

TENSILE TEST MACHINE

The second major piece of equipment in the laboratory is the tensile machine (fig. 5). Although this facility is

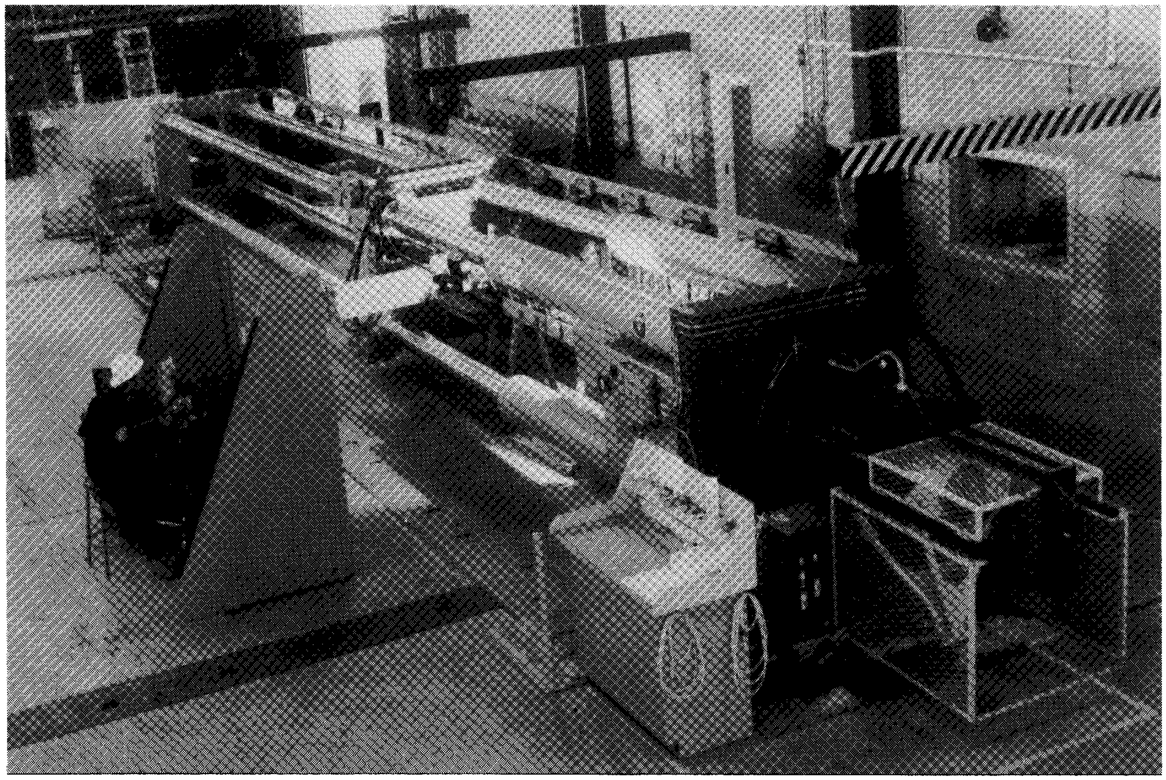

Figure 5.—Tensile and axial fatigue testing machine.

planned primarily for tensile strength tests on wire rope specimens in support of bending fatigue research, it also has the versatility to create fatigue under a cyclic axial force. The bending fatigue machine is not capable of applying cyclic tensile forces. Axial fatigue work is planned to occur later in the program. The main application of the tensile machine is to measure actual breaking strengths of ropes as received for comparison with similar measurements made after the rope has been degraded on the bending fatigue machine. These measurements provide quantitative data to establish the effects of service conditions on the life of wire ropes. The performance of this machine was reported in a previous publication.[3]

New and used ropes from mine hoists, obtained through cooperative agreements with mining companies, are also tested to assess the effects of real-life use.

The machine is essentially a hydraulically actuated tensile testing machine in a horizontal position rather than the usual vertical position to reduce vertical height requirements and for ease of access. It is composed of three elements: the load frame, the electrical console, and the hydraulic power supply, all operating in conjunction. The load frame contains the hydraulic actuator assembly and the load cell. The moveable crosshead containing the torque sensor cell has hydraulic positioners and locks. The locks sustain full-rated load in either direction. Safety enclosures for the specimen are provided for operator protection during testing. As a further protection, the building is locked and personnel are cleared from the area.

The load is applied through a closed-loop servohydraulic system in which high-pressure hydraulic fluid, under the precise control of a servovalve, is provided to the actuator. To accomplish this, the system controller compares a control signal with feedback signals from the transducer. Error signals control the servovalve. The controllable parameters are displacement of the actuator, load applied to the specimen, and torque generated by the wire rope specimen as axial load is applied.

The electronic control console contains all the necessary analog components for servo control, hydraulic power control, programming, signal conditioning, test parameter readout, and interlock functions. It also contains a digital computer and necessary interface to control, record, and plot the testing data. System specifications are listed in table 2.

Table 2.—Tensile and axial fatigue machine specifications

Rope tension	lbf	800,000
Actuator speed	in/min	1/32 to 32
Torque	lbf•ft	20,800
Rope diameter	in	1 to 2-1/2
Rope length	ft	2 to 33
Hydraulic system:		
Flow rate	gpm	70
Pressure	psi	3,000

NONDESTRUCTIVE TESTERS

A commercially available electromagnetic nondestructive tester (EM NDT), the Magnograph,[4] Model MAG-1, purchased for laboratory use is shown in figure 6.

Such devices are useful because they can examine the interior of a wire rope. They operate on the principle of magnetically saturating the test rope and then measuring any changes in the saturation level. As a rope wears, metal is lost and thus will show a lower level of saturation. The measuring sensors thus indicate the loss of metallic area (LMA). Because broken wires create magnetic poles, they are recorded as a spike on the chart and can be counted. These are known as local faults (LF) and are an indication of brittleness in the rope.

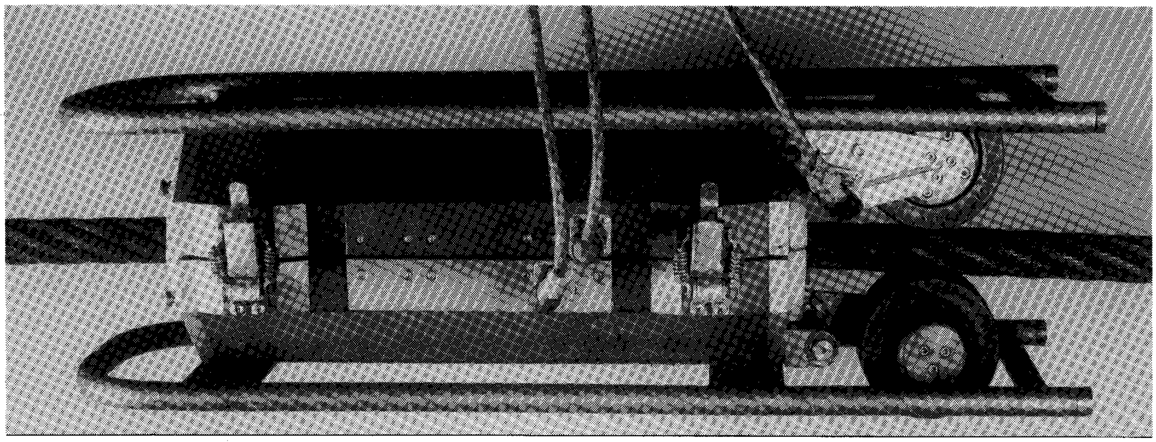

Figure 6.—Magnograph nondestructive sensor.

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[3] McKewan, W. M., and A. J. Miscoe. Baseline Tensile Testing at the Wire Rope Research Laboratory. BuMines IC 9255, 1990, 23 pp.

[4] Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

TEST PROCEDURE

BENDING FATIGUE MACHINE

For the bending fatigue test, the rope specimen was reeved through the machine and wound onto the drum. The rope was 847 ft long. It was the first rope to be run on this machine and was used for shakedown of the equipment. Consequently, it had a highly varied history of loads and speeds. After the shakedown was completed, the rope was run until 28 broken wires were counted in the middle section. The rope was removed from the machine and cut into 25-ft samples for further testing. These samples were cut into three sections: a 17-ft piece for a tensile destructive test; a 5-ft piece for wire-by-wire examination; and a 3-ft section for metallographical analysis. The location of the sample cuts to be used for tensile tests was determined by the cycle pattern in figure 4.

TENSILE TEST MACHINE

The 17-ft samples were terminated with resin-filled, standard closed sockets. This resulted in a finished specimen gage length of about 15 ft. This length was chosen based on the results of a baseline testing program described in the previously mentioned publication.

NONDESTRUCTIVE TESTERS

The instrument was mounted on the rope next to the drum and operated according to the manufacturer's directions. To make a test, the rope is run through the instrument once to properly magnetize it. The sensor head is removed during rewinding to prevent a change in the magnetic polarity of the rope and then it is remounted. The rope is then run through the instrument while the data is being recorded. The Magnograph was not available when this rope was new, so the determination of rope condition was based on the end sections of the rope that never left the drum. While this section experienced loading and unloading stresses, no bending cycles occurred. These "best pieces" amounted to about 90 ft on each end of the rope.

Sections of typical chart records for a best piece and for the most deteriorated part of the rope are shown in figure 7. There are two traces for each chart; the lower

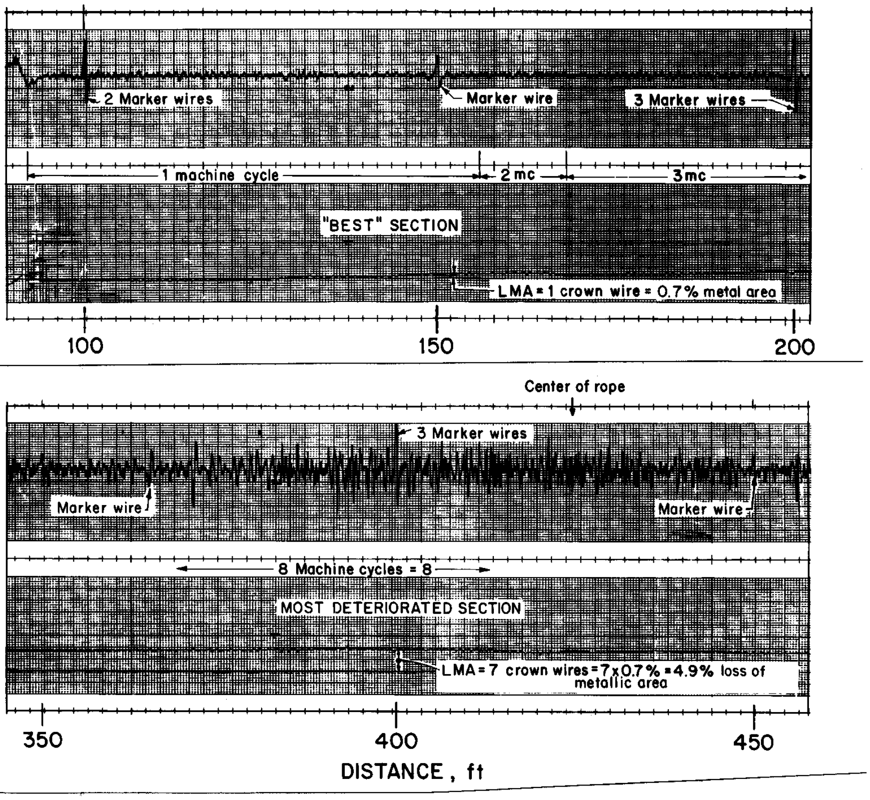

Figure 7.—Typical data from electromagnetic nondestructive test instrument. Annotated chart records show data for a best piece (top) and a badly deteriorated part of rope (bottom).

one shows the LMA, and the upper one shows the LF. Comparing like traces for the two samples, the LMA line is lower, indicating a metal loss of about 5 pct. The LF trace for the best piece shows only normal variations due to the passing of rope-lay peaks and to the high signal magnification. The LF trace for the most deteriorated piece shows large disturbances from the faults. Proper interpretation of such a chart requires highly skilled operators.

TEST ROPE DESCRIPTION

The test rope was of 2-in-diam, 6×25 filler wire construction, with a right regular lay of 12.15 in, and an independent wire rope core (IWRC). In this construction (fig. 8), there are 6 strands containing 19 wires (of approximately the same diameter) with 6 filler wires for spacing; the filler wires are not considered load bearing. The core is composed of seven strands, each containing seven smaller wires having approximately the same diameter. The wire rope core contributes about 15 pct of the total strength of the rope.

Although not identified when purchased, it is believed that the wires were of extra improved plow (EIP) steel based on the data obtained from the "best pieces." As such, the rope had a nominal breaking strength of 396 kips. IWRC rope was chosen because of availability at the time of startup. Such rope is stiff compared to fiber core rope, and so is seldom used for hoist rope in U.S. underground mines.

RESULTS

Two tensile tests were made on samples that were taken from the drum (dead wrap) portion of the rope. These samples had no bending cycles and were used as base tests for comparison. The data from one of the tests are shown in table 3 and figures 9 through 11. Figure 9 is a plot of load versus elongation. Figure 10 is a plot of stress versus strain. From this plot the modulus of elasticity, the breaking stress and strain, and the yield stress and strain are calculated. Torque K is the slope of the line in a plot of the torque generated by a rope sample during a tensile test versus the load (fig. 11). The slope is a straight line until just before rupture.

The data obtained from tensile tests on the rope samples are shown in table 4 and figures 12 through 15.

In table 4, the number listed under "cycle multiplier" is the ratio of machine (or drum) cycles to the number of rope bending cycles. Owing to the nature of shakedown testing, the number of machine cycles was not available from the trial period data. This multiplier was described previously under EQUIPMENT. The final column is the percentage loss of breaking strength based on the 830- to 847-ft drum sample ("best piece").

Figure 12 shows that the rope goes through three phases of degradation: strength reduction due to metal area loss, strength increase due to cold working, and finally, serious strength loss due to the fatigue failure of the wires. The degree of symmetry is indicated in figure 13. As can be seen, there is some scatter in the data, indicating that the machine does not degrade the rope in exact symmetry. The relationship between the machine cycle multipliers in figure 13 and the distance along the rope in figure 12 is shown in figure 4 and table 4.

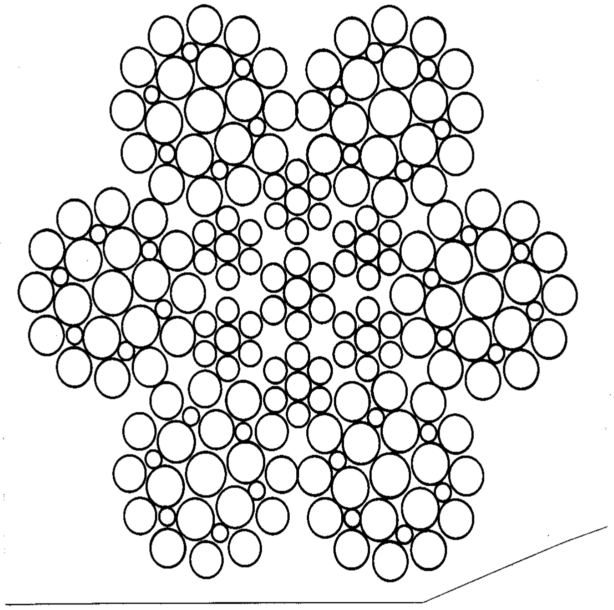

Figure 8.—Test rope construction.

Table 3.—Tensile test data for typical sample

Time, s	Stress, kip/in^2	Strain, pct in/in	Torque, lbf•ft	Load, kips	Elongation, in
1.5	4.420	0.008	128.5	8.207	0.014
15.0	13.471	.127	372.8	25.011	.234
30.0	27.732	.256	764.6	51.489	.470
45.0	44.624	.384	1246.8	82.852	.704
60.0	61.674	.512	1734.0	114.509	.940
75.0	75.777	.642	2129.7	140.694	1.178
90.0	88.722	.769	2497.3	164.728	1.412
105.0	101.457	.902	2854.8	188.373	1.654
120.0	113.718	1.030	3194.5	211.138	1.890
135.0	125.716	1.160	3536.7	233.414	2.129
150.0	137.188	1.292	3850.9	254.714	2.370
165.0	147.765	1.420	4144.8	274.352	2.605
180.0	157.500	1.553	4411.9	292.427	2.849
194.0	166.131	1.684	4649.8	308.452	3.091
210.0	174.077	1.816	4848.3	323.205	3.332
225.0	181.023	1.949	5032.8	336.102	3.576
240.0	187.127	2.082	5180.3	347.435	3.820
255.0	192.337	2.213	5307.6	357.108	4.061
270.0	197.195	2.348	5409.0	366.128	4.309
285.0	201.230	2.481	5502.3	373.620	4.552
300.0	204.861	2.618	5582.3	380.361	4.804
315.0	207.808	2.751	5630.7	385.833	5.048
330.0	210.544	2.886	5679.1	390.913	5.296
345.0	212.860	3.021	5707.0	395.213	5.544
360.0	214.912	3.158	5735.0	399.023	5.795
375.0	216.596	3.292	5745.2	402.149	6.041
390.0	217.964	3.428	5752.8	404.689	6.290
405.0	219.280	3.563	5756.7	407.133	6.538
420.0	220.122	3.697	5745.2	408.696	6.784
435.0	220.911	3.832	5738.8	410.161	7.032
450.0	221.542	3.968	5718.5	411.333	7.281
465.0	221.911	4.105	5698.2	412.018	7.532
480.0	222.272	4.241	5679.1	412.688	7.782
495.0	222.437	4.374	5654.8	412.994	8.026
499.0	222.700	4.419	5652.3	413.483	8.109
501.0	222.648	4.432	5644.7	413.386	8.133

Table 4.—Measured tensile test data

Position, ft	Cycle multiplier	Breaking		
		Load, kips	Elongation, in	Load loss, pct
110 to 127 . . .	1	376.4	4.16	9.04
165 to 182 . . .	3	389.5	3.88	5.88
190 to 207 . . .	3	385.3	3.71	6.87
245 to 262 . . .	5	415.4	4.02	-.40
300 to 317 . . .	7	418.1	4.13	-1.04
355 to 372 . . .	8	386.0	3.32	6.71
380 to 397 . . .	8	377.8	3.12	8.69
408 to 425 . . .	8	364.8	3.06	11.83
431 to 447 . . .	8	351.9	2.62	14.96
456 to 472 . . .	8	368.4	2.98	10.96
480 to 497 . . .	8	336.9	2.73	18.58
525 to 542 . . .	7	409.8	3.94	.97
580 to 597 . . .	5	411.0	3.98	.66
645 to 662 . . .	3	390.9	3.42	5.53
725 to 742 . . .	1	388.9	4.32	6.02
775 to 792 . . .	0	413.5	8.13	.07
830 to 847[1] . .	0	413.8	7.70	.00

[1] Best piece.

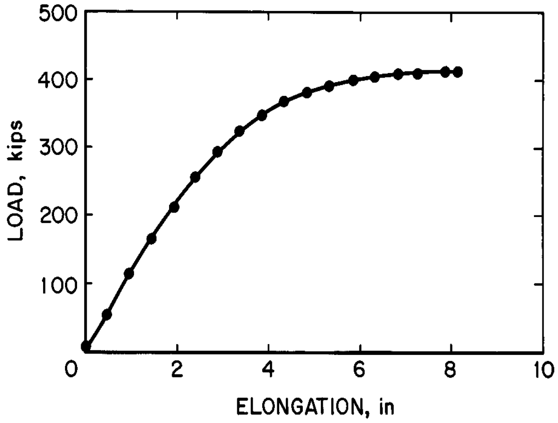

Figure 9.—Typical test–load versus elongation. Breaking strength = 413.5 kips.

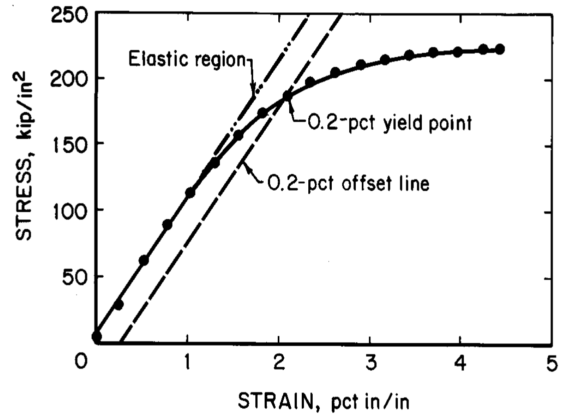

Figure 10.—Typical test—stress versus strain. Yield = 170.8 kip/in^2; breaking stress = 222.7 kip/in^2; modulus = 10.67 × 10^6 psi.

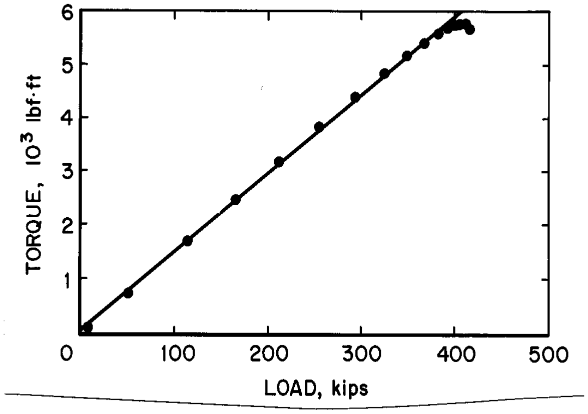

Figure 11.—Typical test—torque versus load. Torque K = 14.81 lbf•ft/kip.

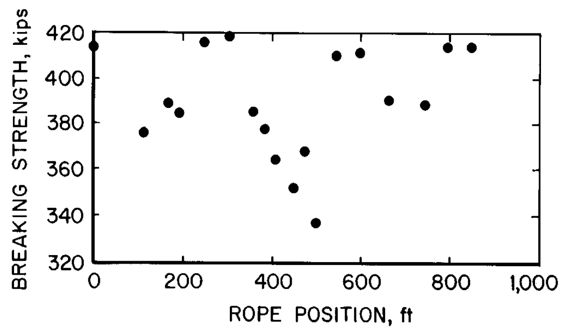

Figure 12.—Effect of distance along rope on breaking strength.

Figure 14 shows that initially the breaking strain followed a pattern similar to that of the breaking strength in figure 12. Figure 15 shows the same degree of symmetry as in figure 13. The significance of decreased strain is that cold working occurred with increased cycling.

Figure 16 shows that Torque K is also sensitive to increased cycling, although not to a great extent.

Table 5 shows the data calculated from the measurements made during the tensile tests. Breaking stress and strain are computed by the operating program when the rope specifications are inserted. The beginning of the plastic deformation is determined by inspection. The modulus of elasticity is then determined by linear regression analysis. The yield stress and strain are then calculated from the 0.2 pct offset line (fig. 9). These calculations were described in the previously mentioned publication. Graphs of these relationships versus distance and cycles are not shown since they are derived from the same data as in table 4 and thus would be similar.

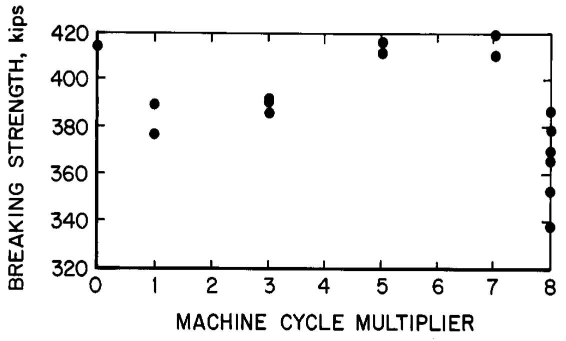

Figure 13.—Effect of number of bending cycles on breaking strength.

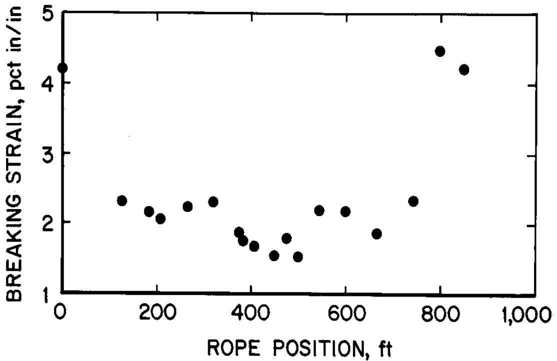

Figure 14.—Effect of distance along rope on breaking strain.

Table 6 contains data from other physical measurements that were made two days before the rope was removed from the bending fatigue machine. The first two columns list the linear locations and the cycle multiplier at that location. The next column shows the rope diameter, as measured by a caliper, averaged from three positions around the rope. The next two columns are computations of the percent reduction in diameter and metallic area compared to the best pieces. The loss of area is obtained from an in-house computer program that will be reported in the near future. The area computed by measurement is compared to the LMA determined by the NDT sensor (column 6) in figure 17. This comparison shows that the largest difference on the first half of the rope is 1.7 pct, but only 0.3 pct on the second half. This indicates that both methods give comparable accuracy. The final column shows the percent loss of diameter of the outer wires of the rope, which also was determined by the previously mentioned computer program.

Table 5.—Calculated tensile test data

Position, ft	Cycle multiplier	Breaking		Yield		Modulus of elasticity, 10^6 psi	Torque K, lbf•ft/kip
		Stress, kip/in^2	Strain, pct in/in	Stress, kip/in^2	Strain, pct in/in		
110 to 127	1	202.7	2.30	174.7	1.48	13.8	14.7
165 to 182	3	209.7	2.15	185.4	1.38	15.8	13.9
190 to 207	3	207.5	2.06	185.8	1.41	15.5	13.9
245 to 262	5	223.7	2.23	199.4	1.43	16.2	13.0
300 to 317	7	225.1	2.30	202.0	1.47	15.8	13.1
355 to 372	8	207.9	1.84	194.2	1.45	15.7	13.2
380 to 397	8	203.5	1.73	194.0	1.48	15.2	13.1
408 to 425	8	196.5	1.65	187.0	1.42	15.5	13.2
431 to 447	8	189.5	1.52	185.9	1.43	15.1	13.2
456 to 472	8	198.4	1.78	185.9	1.42	15.2	13.3
480 to 497	8	177.6	1.43	176.1	1.39	14.8	13.3
525 to 542	7	220.6	2.18	199.3	1.45	16.1	13.2
580 to 597	5	221.4	2.16	199.5	1.43	15.9	13.2
645 to 662	3	210.5	1.85	195.5	1.45	15.7	13.5
725 to 742	1	209.4	2.32	183.0	1.42	15.0	14.2
775 to 792	0	222.7	4.43	170.8	1.77	10.7	14.8
830 to 847	0	222.8	4.19	172.1	1.80	10.4	14.6

Table 6.—Diameter and NDT measurements

Position, ft	Cycle multiplier	Rope diam		Area loss, pct		Wire diam loss, pct
		in	Loss, pct	Calc	NDT	
0	0	2.082	0.14	0.01	0.0	1.2
50	0	2.047	1.82	.36	.0	14.7
100	1	2.048	1.77	.35	1.0	14.3
110	1				1.8	
150	1	2.033	2.49	.57	1.6	20.1
180	3				3.5	
200	3	2.005	3.84	1.48	3.2	30.8
250	5	1.972	5.42	3.06	3.8	43.6
300	7	1.973	5.37	3.01	4.0	43.2
350	8	1.957	6.14	3.86	3.8	49.4
400	8	1.955	6.23	3.97	4.0	50.1
440	8				4.6	
450	8	1.955	6.23	3.97	3.6	50.1
500	8	1.955	6.23	3.97	3.6	50.1
550	7	1.970	5.52	3.16	3.4	44.3
600	5	1.975	5.28	2.90	2.8	42.4
650	3	1.980	5.04	2.65	2.5	40.5
700	1	2.012	3.50	1.20	1.5	28.1
750	0	2.078	.34	.03	.0	2.7
800	0	2.085	.00	.00	.0	.0

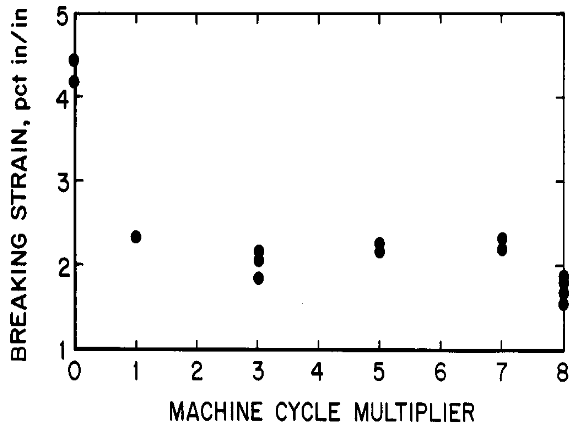

Figure 15.—Effect of number of bending cycles on breaking strain.

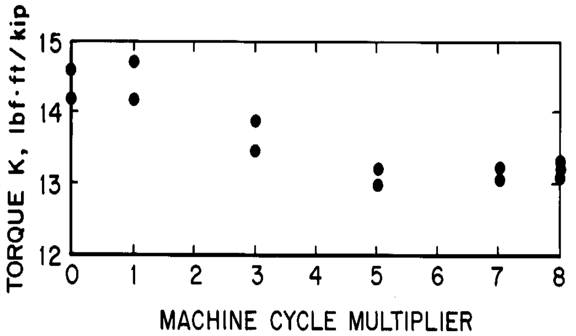

Figure 16.—Effect of number of bending cycles on Torque K.

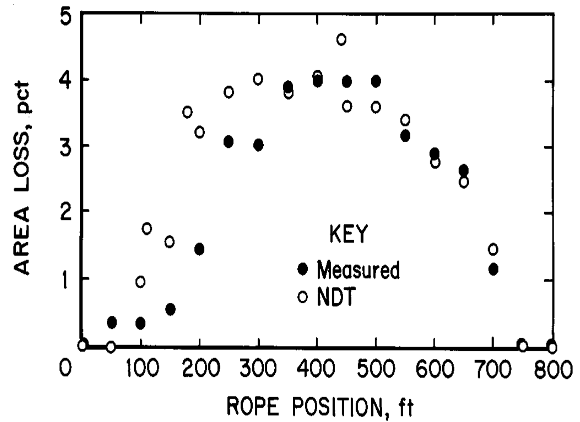

Figure 17.—Area losses from NDT charts and diameter measurements. NDT is nondestructive tester.

The current regulations regarding retirement of hoist ropes[5] include four criteria that pertain to the ropes tested at the Wire Rope Research Laboratory:

- Strength loss exceeding 10 pct as determined by NDT tests.
- Rope diameter loss exceeding 6 pct of the baseline measurement.
- Outer wire diameter loss of more than one-third.
- Number of broken wires in one lay length in excess of 5 pct of the number of load-bearing wires in the rope (six for this rope) or 15 pct of the number of load-bearing wires in a strand (two to three for this rope).

Failure to pass *any* of these criteria is cause for a rope to be retired from service.

Table 7 shows the tabulation of a visual count of the number of broken wires per lay on the surface of the rope. These were the averages for three lay lengths.

Table 7.—Broken wires

Position, ft	Cycle multiplier	Broken wires per lay
105 to 110	1	0
160 to 165	3	0
185 to 190.....	3	0
240 to 245	5	0
320 to 325	7	0
350 to 355	8	4
375 to 380	8	5
400 to 405	8	4
425 to 430	8	7
450 to 455	8	28
478 to 480	8	17
545 to 550	7	1
575 to 580	5	0
640 to 645	3	0
745 to 750	1	0
795 to 800	0	0
825 to 830	0	0

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[5] U.S. Code of Federal Regulation. Title 30—Mineral Resources; Chapter I—Mine Safety and Health Administration, Department of Labor; Subchapter N—Metal and Nonmetal Mine Safety and Health: Subpart R, Article 56, and Subpart R, Article 57, Subchapter O—Coal Mine Safety and Health; Subpart O, Article 75, and Subpart O, Article 77; July 1, 1992.

The criterion of a maximum of 10 pct strength loss can only be determined from destructive testing of the worst section, which obviously cannot be measured until the rope is retired. NDT devices measure loss of metallic area and local faults (broken wires), however, results are not necessarily proportional to strength because they do not include changes in the hardness of the wires.

Destructive tests are sometimes made on the "cut-offs" which result from the periodic necessity to reterminate the attachment to the cage or skip. However, this section is not representative of the condition of the rope. Until several cut-offs are made, this part of the rope has not been over the sheave and so has experienced no bending fatigue. It is subjected to some degree of corrosion, but may not have received the same lubrication as the rest of the rope. Depending on the type of termination used, the cut-off probably has experienced much different stresses. For example, when U-bolt clips are the means of termination, there are high local stresses at each clamp. Experience with testing field samples of cut-offs and retired rope sections has confirmed that tensile tests on cut-offs will not provide an accurate measurement of strength loss.

The criterion of rope diameter loss greater than 6 pct can only be determined by physical measurements. These are time consuming and reflect only the strength loss due to surface wear and internal nicking. Diameter measurements, however, cannot provide any indication of strength loss due to embrittlement.

Loss of one-third of the diameter of outer wires, a third criterion, is extremely hard to measure. It is not possible to get a caliper under a crown wire to make a diameter measurement. The possibility of measuring the width of the flat portion, assuming it to be the chord of the wear arc, to calculate the area of the wear arc has several problems: First, high precision is required in measuring width of the flat, and second, the flat is not flat, but a curve. Third, sometimes peening occurs which causes a "wire edge" burr that distorts the width measurement. Fourth, in "flattened strand" construction, which is increasingly popular, the outer wires are swaged flat during fabrication and true wire diameter cannot be measured. Furthermore, this method yields only an estimate of loss of strength due to wear, but not due to fatigue.

The number of broken wires is useful in that it is an indication of the fatigue state of the rope. However, there are some anomalies in the effectiveness of this criterion, too. First, at present, the correlation between the number of broken wires and the degree of fatiguing is unknown. Second, embrittlement can exist before the wires begin to break. It is expected that future testing under this project will quantify such relationships.

The test data relating to these criteria were extracted from tables 4, 6, and 7, and compared in table 8.

Table 8.—Retirement criteria for test rope

Position, ft	Cycle multiplier	Breaking load loss, pct	Rope diam loss, pct	Outer wire diam loss, pct	Broken wires per lay
0	0	NA	0.14	1.2	0
50	0	NA	1.82	14.7	0
100	1	NA	1.77	14.3	0
105 to 127 ..	1	9.04	NA	NA	0
150	1	NA	2.49	20.1	0
160 to 182 ..	3	5.88	NA	NA	0
185 to 207 ..	3	6.87	3.84	30.8	0
240 to 262 ..	5	-.40	5.42	* 43.6	0
300 to 325 ..	7	-1.04	5.37	* 43.2	0
350 to 372 ..	8	6.71	* 6.14	* 49.4	4
375 to 397 ..	8	8.69	NA	NA	5
400 to 425 ..	8	* 11.83	* 6.23	* 50.1	4
425 to 447 ..	8	* 14.95	NA	NA	* 7
450 to 472 ..	8	* 10.96	* 6.23	* 50.1	* 28
475 to 500 ..	8	* 18.58	* 6.23	* 50.1	* 17
525 to 550 ..	7	.97	5.52	* 44.3	1
575 to 600 ..	5	.66	5.28	* 42.4	0
640 to 662 ..	3	5.53	5.04	* 40.5	0
700	1	NA	3.50	28.1	0
725 to 750 ..	1	6.02	.34	2.7	0
775 to 800 ..	0	.07	0	0	0
825 to 847 ..	0	0	NA	NA	0

NA Not available.

In the case of this rope, the 450- to 500-ft zone had so many broken wires that the LF trace from the Magnograph was unintelligible. It did indicate severe damage, but individual wire breaks could not be distinguished. Normally, of course, a rope would be retired long before that many wires were broken. It would appear from these data that measurement of metal hardness, which is indicative of cold working, could be a valuable supplement in assessing the condition of wire rope.

The four criteria were applied to the data in table 8. As indicated by the asterisks, there is some variation in the retirement range of the criteria under discussion. Considering breaking strength loss of 10 pct, a hoist rope having a section like the test rope's 400- to 500-ft section would be retired. For the criterion of rope diameter loss of 6 pct, a section like the 350- to 500-ft part would cause retirement. Considering outer wire diameter loss of one-third, a hoist rope with a section like the 240- to 662-ft piece would be retired. And for broken wire per lay length, a section like the 425- to 500-ft section would cause retirement. It is expected that further research under this project will confirm and quantify these conclusions, providing data for support of any regulatory changes.

CONCLUSIONS

The most significant finding is that the data provide evidence that the rope goes through three phases of degradation: strength reduction due to the loss of metal area, strength increase due to cold working, and finally, rapid strength loss due to the fatigue failure of the wires. Degradation is not quite symmetrical about the middle of the rope due to inherent differences in the design of the machine. Test results indicate that nondestructive measurement of metal hardness, which is an effect of cold working, would be a valuable supplement to current inspection methods in assessing the condition of wire rope.

Another conclusion that can be drawn from this test is that there is some variation among the current retirement criteria. Further research is needed to define the variations and to establish a better understanding of wire rope behavior.