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LAKEHURST, NEW JERSEY

ADA026115

NAEC-ENG 7898 04 Jun 1976

INFLUENCE OF WIRE PROPERTIES
ON THE FATIGUE PERFORMANCE
OF ARRESTING GEAR PURCHASE CABLE

DEPARTMENT OF THE NAVY ★ NAVAL AIR ENGINEERING CENTER ★

PLATE NO. 11740A

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NAVAL AIR ENGINEERING CENTER

LAKEHURST, NEW JERSEY 08733

ENGINEERING DEPARTMENT (SI)

CODE IDENT. NO. 80020

NAEC-ENG 7898 04 Jun 1976

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PREPARED BY L. MOSKOWITZ

P. SOLTIS

APPROVED BY K. A. TATE

PLATE NO. 28856

4JUN1976 BH

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(14)

1. REPORT NUMBER: NAEC-ENG-7898
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER: (9)

4. TITLE (and Subtitle): (6) Influence of Wire Properties on the Fatigue Performance of Arresting Gear Purchase Cable,
5. TYPE OF REPORT & PERIOD COVERED: Final rept.
6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): (10) L. Moskowitz, P. Soltis
8. CONTRACT OR GRANT NUMBER(s):

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Commanding Officer, Naval Air Engineering Center, Lakehurst, NJ 08733 (Code 915)
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (11) (12) 61p.

11. CONTROLLING OFFICE NAME AND ADDRESS: Commander, Naval Air Systems Command, Washington, DC 20361 (Code AIR-537)
12. REPORT DATE: 4 Jun 1976
13. NUMBER OF PAGES: 57

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Wire Rope,
~~Arresting Gear Purchase Cable~~
Fatigue Life,
Metallurgical Properties.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A metallurgical investigation was made of the cause of a decrease in fatigue life of a new contract of purchase cable. Using fractography, supported by scanning election microscopy, metallography and tensile testing, it was possible to explain how very subtle differences in the wire quality used to make the cable had led to the decrease in fatigue life.

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I. INTRODUCTION

1. Fatigue testing of 1 7/16" diameter 6 x 25 FW LL RS FC wire rope (purchase cable) from new contracts showed fatigue life running approximately 1700 cycles lower than previous contracts.

2. A metallurgical investigation was made of the new wire rope to determine the cause of the decrease in fatigue life. Fractography and metallography of wire sections were used to study the material microstructurally, while tensile and hardness tests were used to check its mechanical behavior as it relates to fatigue performance.

3. In the fractographic study, a new system of categorizing or classifying fractures was developed in order to more readily sort out and distinguish fatigue-initiated from non-fatigue-initiated fractures.

4. A test was devised to check the high carbon steel wire for surface decarburization that would give a clear indication of its extent (depth of penetration) in the wire.

5. Fatigue tests and metallurgical examination of samples of 1 7/16" diameter purchase cable from two additional suppliers were also conducted. Results from these samples were used to augment the findings of this study.

II. SUMMARY

1. The wire rope samples used in the test program was 1 7/16" diameter 6 x 25 FW LL RS FC.

2. Sections of the various cables were tested for individual wire strengths within a strand.

3. Fractures on all samples were graded using a system which modified that used by Battelle Memorial Institute in previous studies they had conducted for the Naval Air Engineering Center (NAEC). By backing up visual to 30x magnification inspection with scanning electron microscope examination, it was possible to determine the number of fatigue oriented vs. tensile oriented fractures within a failed strand.

4. Wires were tested for chemical composition. In addition, many samples were examined for the degree of surface decarburization using a special test technique.

5. The test involved packing samples in such a way as to prevent fresh decarburizing while annealing the sample to allow easy identification of the metallurgical phases present in decarburized metal.

6. According to the fracture characterization scheme adopted herein, fractures were categorized essentially as those having no tensile necking, Modes 1 and 2, and those showing tensile necking prior to fracture, Modes 3 and 4. Modes 1 and 2 are considered to be fatigue-initiated, whereas, Modes 3 and 4 are considered to be non-fatigue-initiated.

7. Of great significance is the fact that most of the fatigue-initiated fractures were found in the inner lay wires of the strands evaluated. This shift of fatigue predominance to the inner lay wires is undesirable since there is then no warning (evidence) of impending failure.

8. The inner lay wire was found to be much higher in strength than the outer lay wire. Hence, the lower fatigue strength may be attributed to lower crack propagation resistance of the much higher strength wire, i.e. higher crack propagation rate.

9. Even higher strength was found in the inner lay wire of the newer cable which exhibited the lower fatigue life; it is believed that much of the poorer fatigue life can be attributed to the higher strength.

10. Variable amounts of surface decarburization of the wires used in making up the cable was found. Samples of the earlier cable having good fatigue life had especially small amounts of surface decarburization — otherwise, correlation was poor.

11. Wire supplied by another vendor having inner lay wire strengths closer to that recommended as a result of this study did, in fact, show superior fatigue life. In these samples, outer lay wire fatigue was much more predominant.

12. Samples of cable supplied by WRI exhibited poor fatigue life in spite of wire tensile strengths which are considered desirable. Here it was noted that reduction-in-area values were significantly lower than those which gave the better fatigue life.

III. RESULTS & CONCLUSIONS

1. Analysis of failed fatigue samples of 1 7/16" diameter 6 x 25 FW LL RS FC wire rope (purchase cable) from both contracts 73-C-1573 and 75-C-0838 revealed that the cable failures started primarily from fatigue fracturing in the inner lay wires.

2. Since the best in fatigue performance is expected when the inner lay wire strength is in the vicinity of 285,000 psi, the much higher strength, 316-321,000 psi, in the 1973 and 1975 contracts caused a drop in fatigue life of the inner-lay wires. The average increase of 5,000 psi in the 1975 contract material over that of 1973 contract material is felt to be at least some of the cause of the observed decrease in fatigue life.

3. While all cable wire normally contains some surface decarburization which reduces fatigue life, it was observed that one sample of 1973 Greening-Donald contract material had abnormally low amounts on the inner lay wires. This cable had good fatigue life in spite of the high strength of the inner lay wires. The possibility exists that for this material, the improved performance resulting from low amounts of decarburization had offset the effects of excessive high strength.

4. Cable supplied by Bethlehem had wire strengths in the ranges predicted by this program to be closer to optimum. The resulting cable did, in fact, exhibit superior fatigue life.

IV. RECOMMENDATIONS

1. Both because it is preferrable to have cable fail in the outer lay wire first and because excessive high strength of the inner lay wire caused premature fatigue life, it is recommended that the future 1 7/16" diameter cable be made using inner lay wire of lower strength.

2. In addition, while the wire rope specification is primarily a performance specification, it would help to require the manufacturer to include a report on the quality of the wire making up the cable, thus alerting NAEC on a possible trend that might be detrimental. Thus data should also include a spot check on the extent of the surface decarburization.

3. A study of fatigue life vs surface decarburization might also be warranted at this time, since it is possible that special (no decarburization) wire might lead to a 1-2000 cycle increase in fatigue life.

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VIII. REPORT TEXT

1. Background

To increase the ability of purchase cable to withstand higher loads with improved fatigue life, the Naval Air Engineering Center (NAEC) has gone from 1 3/8" diameter cable to 1 7/16". Testing was started on the heavier cable in 1970, and the first production buy was made in 1973.

Acceptance criteria had been established for the 1 7/16" diameter material. Results for the production buys from the 1973 contract helped to verify the validity of the results.

Testing of cable made for the second commercial contract for 1 7/16" cable in 1975 quickly revealed that the new cable was inferior in fatigue life to the 1973 material; much of the cable in the newer contract would not meet the acceptance criteria established for the 1 7/16" cable. Studies were made to determine the possibilities of test error having created the discrepancy. While some differences were noted, it was finally established that a true difference in fatigue life of 900 cycles at 90,000 lb. load existed.[1] (See tables 1 & 2.)

A metallurgical investigation was made to determine if the cause of the drop in fatigue life could be determined. In addition to mechanical tests and metallographic studies, a complete fractographic analysis was also made to provide baseline information for future studies. The fractures were studied using visual examination (up to 30x) and Scanning Electron Microscopy. In the course of the study, results of fatigue tests on cable samples supplied by two other vendors (WRI Industries and Bethlehem Steel) were used to explain some of the differences found in the 1973 and 1975 Greening Donald contracts.

2. Preliminary Observations

A typical break in wire rope that failed in fatigue is shown in Figure 1. This sample is from N-501-34-2 which failed after 7481 cycles. The fatigue test is stopped after the first sharp report indicating the breaking of one strand, but oft times, a second strand might partially or completely break.

The fractured wires were examined and characterized for fracture mode. Initially, fractures were characterized per a system established by Gibson et al at Battelle.[2] Here individual wire fractures were broadly categorized into two types, i.e. failure modes produced by fatigue, and failure modes produced by tensile overload. Mode I in fatigue consists of wire failure on a plane of 45 degrees to the longitudinal axis of the wire and occurs at high loads, whereas, Mode II in fatigue consists of failure on a plane roughly 90 degrees to the longitudinal axis of the wire and occurs at lower loads. Mode I in tensile overload consists of a cup-cone type fracture and occurs at low strain rates, whereas Mode II in tension consists of a more irregular

(1, 2 - See Section IX, Page 7, for References) fracture surface, limited reduction in area, and occurs at higher strain rates.

Using a binocular microscope at about 30x magnification, wire fractures were further characterized according to the list of modes or types given in Table 3. These are categorized first by fracture showing no tensile necking, (Modes 1 and 2), and those having some necking prior to fracture (Modes 3 and 4).

Mode 1 fractures are almost all 45^{o} shear with little or no fatigue. When fatigue does exist, it appears as a ledge oriented almost normal to the longitudinal axis of the wire. To verify the presence of fatigue, SEM analysis is required. Mode 2 fractures are very certain to be fatigue-initiated. Mode 3 fractures rarely showed fatigue, while Mode 4 could contain some fatigue. Indeed, one of these fractures showed fatigue to a great extent, hence, SEM analysis was required in their evaluation. On the other hand, Mode 5 fractures were deformed beyond recognition and were almost impossible to identify.

As a result of the above observations, clues seen at 30x magnification made identification of various fracture modes easier and fairly certain.

3. Fracture appearance

The fractures of many of the tests were examined and these results based on the 30x microscopic examination are shown in Tables No. 4 through 20. Strands taken from Reel N502 and N-50-1 (1973 contract wire) were examined 100% by the Scanning Electron Microscope at the Franklin Institute.

Of immediate significance was the fact that most of the fatigue-initiated fractures were found in the inner lay wires. In the sample examined by the SEM, none of the outer lay wires including Modes 1 and 4 fractures showed any fatigue. (See Figures 3 through 11). Some of the 1973 outer wires did show fatigue including a Mode 4 and Mode 1 failure, but again it is the inner lay wire that shows the greater predominance of fatigue failures. A graph plotted in Figure 2 shows a strong trend toward fatigue fracture predominance in the outer lay wires only after long fatigue lives, 7000 to 8000 cycles.

In arresting gear service cable failures occur when enough outer-lay wires fail in fatigue to weaken the cable until the remainder of the strand fails in tension. It has been a common practice to examine cable whenever possible during inspection periods. At these times, whenever four individual wire breaks are found in a specified length of cable, the cable is scrapped. Of greater significance was the revelation that with all of the Greening-Donald cable tested, it was the inner lay wire which was failing first.

The shift of fatigue failures to the inner lay material minimizes chances of spotting premature failures and as such is undesirable.

4. Tensile Tests

Individual wires were tested from several strands of 1975 contract cable and one strand from cable produced in 1973. Results of the tests showed the following:

	1975 UTS, KSI	% Red. Area	1973 UST, KSI	% Red. Area
Outer Lay Wire	281 KSI		276 KSI	52% RA
Inner Lay Wire	321 KSI		316 KSI	50% RA
Center Core	325 KSI		323 KSI	48% RA

Of significance was the fact that the inner lay wire was much higher in strength than the outer lay wire.

Previous studies of 1 3/8" cable had shown the following average tensile values:

Outer Lay Wire	280-285 KSI
Inner Lay Wire	285-290 KSI
Center Core	290-295 KSI

The larger difference in strength between inner and outer lay wire for the 1 7/16" material was verified by the Greening Donald Company. Their records also verified that a difference of 5000 psi for inner lay wire between 1973 and 1975 contract material was a real and consistent difference.

Since outerlay wires take significantly higher bending stresses than do the inner lay wires, this material is picked at a strength believed to give optimum fatigue life for the conditions under which the purchase cable performs.[3,4] Inner lay wire strength can then be raised to a higher value to increase overall wire rope tensile strength, and thus allow the wires to resist tensile fracture after the outer lay wires fail. The fact that inner lay wires fail in fatigue before the outer lay wires for these 1 7/16" diameter cables is an indication that the higher tensile strength values has very significantly decreased the fatigue strength of the inner lay wires. Note that depending on test conditions, 260-280 KSI ultimate has been found to be optimum for fatigue life. In view of this, it is very possible that the increase of 5 KSI in the inner lay wire strength of the 1975 contract was responsible for at least part of the 900 cycle decrease in fatigue life.

5. Chemical Analysis

The chemical analysis of the wire run at the Naval Shipyard, Philadelphia, PA show the following:

	C	Mn	P	S	Si	Ni
I.L.	0.73	0.74	0.015	0.031	0.27	0.01
O.L.	0.68	0.60	0.011	0.022	0.28	0.01

	Cr	Mo	V
I.L.	0.01	0.02	0.07
O.L.	0.07	0.02	0.06

The wire was identified with AISI Grade 1070 plain carbon steel. This analysis compares favorably with the specification for purchase cable which designates extra improved plow steel. In reference to the composition of the plow steel, the ASM Handbook (1948 edition) simply specifies the carbon range, i.e., 0.75 to 0.80C. This is near the eutectoid composition for steel and it is noted that the carbon content of N-502-34-1 wire rope is not within this range. The higher carbon shown by inner lay wires, i.e., 0.73C compared to 0.68C for outer lay wires could explain the fact that the inner lay wires show significantly higher strength, 321 KSI compared to 281 KSI for outer lay wires.

6. Metallography

Longitudinal sections of wires from samples of N-500 series wire rope showed the flow lines typical of highly drawn wire. Microhardness readings taken on the transverse sections indicated the hardness is approximately 47Rc on the outer lay wires and 50Rc on the inner lay wires. It was not possible to obtain valid hardness readings near the surface of the wire to check for decarburization. Hardness readings taken directly on the surface of the wire using a Superficial Rockwell Hardness Tester indicated that surface hardness is generally approximately 40Rc; however, there is some question about the validity of such a test. Hence, it is necessary to use a heat treatment technique as described in the next section to check for surface decarburization.

7. Surface Decarburization

In testing for surface decarburization, approximately 1/4" long pieces of wire are packed in high-carbon cast iron chips in a short-length of heavy walled steel tubing whose ends are packed with asbestos wool and normalize-annealed at approximately 1475°F to convert the metallurgical structure of the wire to pearlite. After such a heat treatment, a eutectiod steel should show 100 percent pearlite, a dark appearing mixture of phases in the microstructure. A sample of eutectoid steel, which has lost a significant amount of carbon at its surface, begins to show a band of soft, white phase (alpha-ferrite) at its surface.

Inner and outer lay wires taken from sample N-502-34-1, and heat treated in this way show some surface decarburization (See Figures 12 and 13). The continuous white band of alpha-ferrite at the surface is estimated to be approximately 0.002 inch. Dr. T. Torrak (Homer Research Laboratories, Bethlehem Steel Company), reference (c), indicated that this amount of surface decarburization is not regarded as detrimental and that it has not affected their wire rope performance. When queried about whether acid pickling might be used to remove surface decarburization measured in excess of 0.002 inch, Mr. Torrak replied that this method has been used.

In the way of comparison, Figure 14 shows purchase cable from Contract No. 73-C-1573 practically free of surface decarburization. The micrographs shown are typical for samples N-188-1, -2 and -3, which according to Table 2, gave results of 7605, 7677 and 6827 cycles to failure respectively. On the other hand, results on sample N50-1 and -2 were inconclusive with individual wires showing varying degrees of surface decarburization. Samples N50-1 and -2 showed 7401 and 5947 cycles to failure respectively according to Table 2.

If surface decarburization was completely responsible for poor fatigue life, then outer lay wire would show less effect than the inner lay material; this was not the case.

The inner lay wire of cable N-188, 1973 Contract Material showing good fatigue life is almost free of decarburization; this was not the case from the two samples of 1973 wire obtained from NATF (N-50-1, N-50-2). The inner lay wire from both samples showed significant amounts of decarburization, even though they had significantly different fatigues lives (5907, 7401). Thus, while lower fatigue life of inner lay wires (as a result of excessive hardness) limited fatigue life of the cable, better than average surface decarburization may have extended the life of these inner lay wires to where acceptable cable life was seen. The acceptable cable fatigue life could then have masked the fact that it was the inner lay wire failures that controlled the cable life.

Other Samples

Recently, two samples were submitted from two other manufacturers. Results of examination of these cables give some further insight into the general causes of fatigue life.

The supplier, fatigue life and tensile data are listed below:

Supplier	Fatigue Life cycles to failure	UTS, KSI	% RA
WRI	4792	Outer lay 279	40-44
	5140	Inner lay 296	44
		Center core 276	
Bethlehem	7830	Outer lay 285	47-50
		Inner lay 293	50-54
		Center 278	50-54

Fracture analysis of the wires are shown in Tables 23 thru 27

Decarburization data is summarized along with Greening Donald results in Table 28.

The Bethlehem results verify that with lower strength of the inner lay wire, the fracture mode shifts to fatigue of the outer lay wires first. The surface decarburization, even though it was at least as great as that of the Greening Donald wires, did not cause the premature failure of the inner lay wires.

The WRI wire also showed fatigue failures of the outer lay wire; inner lay wire sometimes shows fatigue, sometimes only tension failures. Since the spread on fatigue life is not too great, the difference in inner lay wire failure mode was apparently not the governing factor.

The tensile strength data is somewhat surprising at first glance, since the range is similar to that of the Bethlehem wire which gave excelled fatigue life. The significant difference is the lower ductility of the WRI wire.

In studying parameters which governed fatigue life of purchase cable, Black[3] had shown that wire ductility has significant effect. The comparative low fatigue life of the WRI wire rope, where everything else looked normal except the reduction of area values, tends to confirm this.

IX. REFERENCES

(1) TPR 75-42; Quality Assurance Testing of Contract 75-C-0838 Wire Rope

(2) R. D. Jones, D. N. Williams, P. T. Gibson, and H. A. Cress, Battelle Final Report "Experimental Investigation of Aircraft Arresting Gear Purchase Cable", Battell Columbus Laboratories, Long Beach Ocean Engineering Research Facility, 965 Harbor Scenic Way, Berth 249 - Pier J, Long Beach, CA 90802, 31 Jul 72

(3) R. Black, Naval Air Engineering Center, Philadelphia, PA 19112, Report No. NAEC-ENG 7625, Code Ident. No. 80020, "Mark 7 Arresting Gear Purchase Cable and Deck Pendant Development Program" Jul 68 through Jun 69 AIRTASK No. A34-537-200/70F32461402 A05-537-020/200/5/000-000-03

(4) VPI Directive #2358 - Cables for Conveying Devices, Dec 67, Page 20

TABLE 1

FATIGUE TEST RESULTS[(a)] (CONTRACT 73-C-1573)

Reel No.	Breaking Strength (lbs)	Cycles to Failure at 90,000 lbs.
N501-12-1	217,400	6396
N501-32-1	210,760	6432
N501-34-2	210,760	7481 (b)
N501-34-1 (extra)	210,760	7822 (b)
N502-12-1	215,860	6213
N502-12-2	215,860	5437
N502-12-3	215,860	6663
N502-34-1	217,960	5795
N502-34-2	217,960	6186
N503-12-1	211,140	6332
N503-34-1	217,200	8198 (b)
N504-12-1	216,000	5957
N504-12-2	216,000	6607
N504-12-3	216,000	7602 (b)
N504-34-1	216,300	5830
N504-34-2	216,300	6164
N505-12-1	217,700	7250
N505-34-1	217,560	5740
N505-34-2	217,560	6287
N506-12-2		5799
N507-34-1		5708
N508-34-1		6612
N508-12-1		6442
N509-34-1		6536
N509-12-1		6723

(a) Tests run on #2 Two-Sheave Tester; Q.A. Data from April 1975.

(b) Cycles to Failure at 80,000 lbs.

TABLE 2

FATIGUE TEST RESULTS[a] ON NATF PURCHASE CABLE
(CONTRACT 73-C-1573)

Reel No.	Cycles to Failure at 90,000 lbs.
N50-1	7401
N50-2	5947
N80-1	6427
N80-3	6745
N188-1	7605
N188-2	7677
N188-3	6827

(a) Tests run on #2 Two-Sheave Tester: Q.A. Data from April 1975

TABLE 3

WIRE FRACTURE CHARACTERIZATION

Mode 1	45° Fracture
1-A	Fracture initiated at or near parallel longitudinal wire marks.
1-B	Fracture initiated at interstrand notch.
1-C	45° fracture along with longitudinal splitting.
Mode 2	Transverse Fracture
2-A	Full transverse fracture initiated at or or near parallel longitudinal wire marks.
$2\text{-}A_1$	Transverse fracture with final failure in shear.
$2\text{-}A_2$	Transverse fracture with longitudinal splitting.
$2\text{-}A_3$	Transverse fracture with final failure in tension.
2-B	Transverse fracture with initiation site at interstrand notch.
Mode 3	Necked Tensile Fracture
3-A	Cup-cone fracture.
$3\text{-}A_1$	Star fracture.
$3\text{-}A_2$	Fibrous fracture.
Mode 4	Necked Tensile With Possible Fatigue
4-A	Cup-cone fracture with longitudinal splitting.
$4\text{-}A_1$	Wolf ear fracture.
Mode 5	Irregular Tensile Fracture
5-A	Irregular fracture with no perceptible necking.
5-B	Crushed with no recognizable fracture modes.

TABLE 4

WIRE FRACTURE CHARACTERIZATION

Ident. N-502-34-1 (90,000 lbs.-5701 cycles)

Wire (Location)	Fracture Mode 30x Microscope Determinations	Fatigue Presence as identified in the Scanning Electron Microscope
Center Wire	$2A_1$	Fatigue (See Figure 3)
Inner Lay Wire		
1	1B	Possible Fatigue
2	$2A_1$	Fatigue
3	$2A_1$	Fatigue
4	$3A_2$	Fatigue (See Figure 4)
5	$4A_1$	Fatigue (See Figure 5)
6	-	Surface Partially Destroyed
Outer Lay Wire		No Fatigue in any Wires
1	1A	(See Figure 6)
2	1B	(See Figure 7)
3	$3A_1$	(See Figure 9)
4	$3A_1$	
5	$3A_1$	
6	$3A_1$	
7	$3A_2$	(See Figure 10)
8	$3A_2$	
9	$4A_1$	(See Figure 11)
10	$4A_1$	
11,12		

TABLE 5

WIRE FRACTURE ANALYSIS FOR SPECIMEN N508-12-1, STRAND #1

Wire No.	Initial Failure Mechanism	Final Fracture Mode	
C.W.	Fatigue	1B	
I.L.1	Fatigue	$2A_1$	
I.L.2	Fatigue	$2A_1$	
I.L.3	Fatigue	$2A_1$	$\frac{\text{Fatigue}}{\text{Tensile}} = \frac{6}{1}$
I.L.4	Tensile	$3A_2$	
I.L.5	Fatigue	$2A_1$ (long split)	
I.L.6	Fatigue	$2A_2$	
O.L.1	--	5B	
O.L.2	Tensile	3A	
O.L.3	Fatigue	1A	
O.L.4	Tensile	$3A_1$	
O.L.5	--	5B	
O.L.6	Tensile	3A (interstrand notch)	
O.L.7	Fatigue	$2A_1$	$\frac{\text{Fatigue}}{\text{Tensile}} = \frac{3}{7}$
O.L.8	Tensile	$3A_1$	
O.L.9	Tensile	3A (incl.45° fracturing)	
O.L.10	Fatigue	1A	
O.L.11	Tensile	$3A_1$ (crushed)	
O.L.12	Tensile	$3A_1$	

TABLE 6

WIRE FRACTURE CHARACTERIZATION

Iden. N505-12-1 Strand #1 (90,000 lbs. - 7200 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_1$ (some necking in part)
I.L.	1A
I.L.	$2A_1$
I.L.	1A
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
O.L.	$2A_1$ (some necking in part)
O.L.	1A
O.L.	3A
O.L.	3A
O.L.	$3A_2$
O.L.	$4A_1$
O.L.	$3A_1$
O.L.	$2A_2$
O.L.	$1A_1$
O.L.	$4A_1$
O.L.	$2A_2$
O.L.	$2A_2$

Inner Lay Wires -4 fatigue, 2 possible fatigue.
Outer Lay Wires -4 fatigue, 6 possible fatigue, 2 tensile.
Center Wires - fatigue.

TABLE 7

WIRE FRACTURE CHARACTERIZATION

Iden. N505-12-1 Strand #2 (90,000 lbs. - 7250 cycles)

Wire (Location)	Fracture (Model)
C.W.	$3A_1$
I.L.	$2A_1$
I.L.	$3A_2$
I.L.	$2A_2$
I.L.	$2A_2$
I.L.	$2A_3$
I.L.	---
O.L.	1A
O.L.	$2A_2$
O.L.	1B
O.L.	$3A_2$ (interstrand notch)
O.L.	$3A_2$ (interstrand notch)
O.L.	$3A_2$ (interstrand notch)
O.L.	$3A_2$ (interstrand notch)
O.L.	$3A_2$ (interstrand notch)
O.L.	3A (crushed)
O.L.	1B
O.L.	$3A_2$ (interstrand notch)
O.L.	$2A_2$

Inner Lay Wires - 4 fatigue, 1 possible fatigue, 1 crushed.
Outer Lay Wires - 3 shear, 2 fatigue, 6 possible fatigue, 1 tensile.
Center Wires - possible fatigue.

TABLE 8

WIRE FRACTURE CHARACTERIZATION

Iden. N-507-34-1, Strand #1, (90,000 lbs./5708 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_2$
I.L.	4A
I.L.	$2A_2$ (cracking and splitting)
I.L.	$3A_2$
I.L.	1B
I.L.	4A
I.L.	5A
O.L.	3A
O.L.	3A2
O.L.	3A
O.L.	3A1
O.L.	3A2
O.L.	3A2
O.L.	1B
O.L.	3A
O.L.	4A
O.L.	3A
O.L.	2A1
O.L.	2A2

Inner Lay Wires - 1 fatigue, 4 possible fatigue, 1 crushed.
Outer Lay Wires - 2 fatigue, 6 possible fatigue, 4 tensile.
Center Wires - fatigue.

TABLE 9

WIRE FRACTURE CHARACTERIZATION

Iden. N507-34-1, Strand #2, (90,000 lbs./5708 Cycles)

Wire (Location)	Fracture (Mode)
C.W.	$3A_2$
I.L.	$2A_1$ (jagged)
I.L.	$2A_1$
I.L.	1A (parallel marks)
I.L.	$2A_1$
I.L.	2A
I.L.	4A
O.L.	$3A_1$
O.L.	$3A_1$
O.L.	$2A_1$ (some necking in part)
O.L.	$4A_1$
O.L.	3A
O.L.	3A
O.L.	$2A_1$ (pronounced necking)
O.L.	4A
O.L.	3A
O.L.	5A
O.L.	$2A_1$ (pronounced necking)
O.L.	$2A_1$

Inner Lay Wires - 4 fatigue, 2 possible fatigue.
Outer Lay Wires - 4 fatigue, 4 possible fatigue, 3 tensile, 1 crushed.
Center Wires - possible fatigue.

TABLE 10

WIRE FRACTURE CHARACTERIZATION

Iden. N507-34-1, Strand #3, (90,000 lbs./5704 cycles)

Wire (Location)	Fracture (Mode)	
C.W.	2A1	(Some necking)
I.L.	1B	
I.L.	2A1	
I.L.	2A1	
I.L.	--	(Mixed mode - partial crush)
I.L.	2A1	
I.L.	2A1	(Jagged - some long split)
O.L.	2A	
O.L.	3A	
O.L.	3A	
O.L.	4A	
O.L.	4A	
O.L.	3A	
O.L.	1B	(Double 45°)
O.L.	4A	
O.L.	--	
O.L.	--	
O.L.	--	
O.L.	--	

Inner Lay Wires - 4 fatigue, 1 possible fatigue.
Outer Lay Wires - 1 fatigue, 4 possible fatigue, 3 tensiles.
Center Wires - fatigue.

TABLE 11

WIRE FRACTURE CHARACTERIZATION

Iden. N508-12-1, Strand #1 (90,000 lbs/6442 cycles)

Wire (Location)	Fracture (Mode)
C.W.	1B
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$3A_2$
I.L.	$2A_1$ (Long split)
I.L.	$2A_2$
O.L.	5B
O.L.	3A
O.L.	1A
O.L.	$3A_1$
O.L.	5B
O.L.	3A (Interstrand notch)
O.L.	$2A_1$
O.L.	$3A_1$ (Interstrand notch)
O.L.	3A (45° Fracture incl)
O.L.	1A
O.L.	4A (Crushed)
O.L.	$3A_1$

Inner Lay Wires - 6 fatigue.
Outer Lay Wires - 1 fatigue, 2 possible light fatigue, 7 tensile, 2 crushed.
Center Wires - possible fatigue.

TABLE 12

WIRE FRACTURE CHARACTERIZATION

Iden. N508-12-1, Strand #2*, (90,000 lbs./6442 cycles)

Wire (Location)	Fracture (Mode)
C.W.	--
I.L.	$2A_1$ (Fatigue cracks)
I.L.	$2A_2$ (Fatigue cracks)
I.L.	--
I.L.	--
I.L.	--
I.L.	--
O.L.	5B
O.L.	$3A_2$ (Crushed)
O.L.	1C
O.L.	1A
O.L.	5B
O.L.	--
O.L.	--
O.L.	--
O.L.	--
O.L.	--
O.L.	--
O.L.	--

* Partly Broken.

Inner Lay Wires - 2 fatigue.
Outer Lay Wires - 1 fatigue, 3 possible fatigue, 2 crushed.

TABLE 13

WIRE FRACTURE CHARACTERIZATION

Iden. N508-34-1, Strand #1, (90,000 lbs./6,612 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_1/2A_2$
I.L.	5A
I.L.	2A
I.L.	$2A_1$
I.L.	4A
I.L.	$2A_1$
I.L.	--
O.L.	$3A_1$
O.L.	$2A_1/2A_2$
O.L.	3A (Notched)
O.L.	1A
O.L.	3A
O.L.	$4A_1$
O.L.	1B
O.L.	$2A_1$
O.L.	1B
O.L.	4A
O.L.	4A
O.L.	$3A_1$

Inner Lay Wires - 3 fatigue, 1 tensile, 1 crushed.
Outer Lay Wires - 2 fatigue, 3 possible light fatigue, 7 tensile.
Center Wires - fatigue.

TABLE 14

WIRE FRACTURE CHARACTERIZATION

Iden. N509-12-1, Strand #1, (90,000 lbs./6723 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$4A_1$
I.L.	3A
I.L.	$2A_1$
I.L.	$2A_3$
I.L.	$2A_1$
I.L.	$2A_3$
I.L.	3A (Wear mark)
O.L.	3A
O.L.	1A (Crushed)
O.L.	3A (Interstrand Notch)
O.L.	3A (Long Wear Mark)
O.L.	5B (Wear mark)
O.L.	1B (Several heavy interstrand notches)
O.L.	3A (Interstrand notch)
O.L.	3A (Wear mark)
O.L.	4A
O.L.	5B (Several heavy interstrand notches)
O.L.	3A (Heavy interstrand notches)
O.L.	1B

Inner Lay Wires - 4 fatigue, 2 tensile.
Outer Lay Wires - 3 possible light fatigue, 7 tensile, 2 crushed.
Center Wires - 1 possible light fatigue.

TABLE 15

WIRE FRACTURE CHARACTERIZATION

Iden. N509-12-1, Strand #2, (90,000 lbs./6723 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$4A_1$
I.L.	3A
I.L.	1A (Irreg.)
I.L.	$2A_3$
I.L.	$2A_3$
I.L.	1A
I.L.	3A
O.L.	5B
O.L.	5B
O.L.	$2A_1$ (Crushed)
O.L.	1A (Crushed)
O.L.	5B
O.L.	1A (Wear)
O.L.	3A
O.L.	3A
O.L.	1C (Wear)
O.L.	3A
O.L.	3A
O.L.	3A

Inner Lay Wires - 2 fatigue, 2 light fatigue, 2 tensile.
Outer Lay Wires - 1 fatigue, 3 light fatigue, 5 tensile, 1 crushed.
Center Wires - possible fatigue.

TABLE 16

WIRE FRACTURE CHARACTERIZATION

Iden. N509-34-1, Strand #1, (90,000 lbs./6536 cycles)

Wire (Location)	Fracture (Mode)	
C.W.	1A	
I.L.	1A	
I.L.	2A1	
I.L.	3A2	(Crushed)
I.L.	2A1	
I.L.	1A	
I.L.	--	
O.L.	5B	
O.L.	3A	
O.L.	3A	
O.L.	1B	
O.L.	3A	(Crushed)
O.L.	3A1	
O.L.	3A	(Interstrand notch)
O.L.	3A	
O.L.	4A	
O.L.	4A	
O.L.	1C	
O.L.	3A2	

Inner Lay Wires - 5 fatigue or possible fatigue,
1 tensile.
Outer Lay Wires - 2 possible fatigue, 9 tensile, 1 crushed.
Center Wires - possible fatigue.

TABLE 17

WIRE FRACTURE CHARACTERIZATION

Iden. N503-34-1, Strand #1, (80,000 lbs./8198 cycles)

Wire (Location)	Fracture (Mode)	
C.W.	$2A_1$	
I.L.	$3A_2$	
I.L.	$2A_2$	
I.L.	1A	
I.L.	$2A_1$	
I.L.	5A	
I.L.	$2A_1$	
O.L.	1B	
O.L.	$2A_2$	
O.L.	3A	(Notched - long split)
O.L.	$3A_1$	
O.L.	$3A_2$	
O.L.	1C	
O.L.	$2A_1$	
O.L.	1A	
O.L.	3A	
O.L.	3A	
O.L.	5B	
O.L.	--	

Inner Lay Wires - 3 fatigue, 2 possible light fatigue, 1 crushed.
Outer Lay Wires - 2 fatigue, 5 possible fatigue, 3 tensile, 1 crushed.
Center Wires - fatigue.

TABLE 18

WIRE FRACTURE CHARACTERIZATION

Iden. N501-34-2, Strand #4, (80,000 lbs./7481 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_1$ (Fatigue cracks noted)
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$ (Jagged)
I.L.	--
O.L.	1B (Notch)
O.L.	1B (Notch)
O.L.	1B (Notch)
O.L.	1B (Possible $2A_1$)
O.L.	$2A_1$
O.L.	3A
O.L.	5B
O.L.	5A (Irreg. but has fatigue cracks)
O.L.	1C
O.L.	$2A_1$
O.L.	--
O.L.	--

Inner Lay Wires - 5 fatigue.
Outer Lay Wires - 8 possible fatigue, 1 tensile.

TABLE 19

WIRE FRACTURE CHARACTERIZATION

Iden. N501-34-2, Strand #1, (80,000 lbs./7481 cycles)

Wire (Location)	Fracture (Mode)	
C.W.	$2A_1$	
I.L.	$2A_1$	
I.L.	$2A_1$	
I.L.	$2A_2$	
I.L.	$2A_1$	
I.L.	2A	(Flat But Jagged)
I.L.	$2A_1$	
O.L.	4A	
O.L.	4A	(Long, split - jagged)
O.L.	3A	
O.L.	3A	
O.L.	3A	
O.L.	3A	
O.L.	3A	
O.L.	1B	(Notch)
O.L.	$2A_1$	(Some necking)
O.L.	$2A_1$	
O.L.	4A	
O.L.	$2A_1$	

Inner Lay Wires - 6 fatigue.
Outer Lay Wires - 4 fatigue, 8 tensile.
Center Wires - fatigue.

TABLE 20

WIRE FRACTURE CHARACTERIZATION

Iden. N501-34-2, Strand #6* (80,000 lbs./7481 cycles)

Wire (Location)	Fracture (Mode)
C.W.	3A
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$3A_2$ (Some necking)
I.L.	$2A_1$
I.L.	--
I.L.	--
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	3A (Sl. long split)
O.L.	3A
O.L.	-- (Mixed mode)
O.L.	5A (Part, crushed)
O.L.	--
O.L.	--
O.L.	--
O.L.	--
O.L.	--
O.L.	--

* Not completely broken

Inner Lay Wires - 3 fatigue, 1 possible fatigue.
Outer Lay Wires - 2 fatigue, 2 tensile, 2 crushed.
Center Wires - tensile.

TABLE 21

WIRE FRACTURE CHARACTERIZATION

Iden. N188-2 (1973 contract) (90,000 lbs./7677 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$4A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	--
I.L.	--
I.L.	--
O.L.	1A
O.L.	1B
O.L.	1A (Heavy notching)
O.L.	$4A_1$
O.L.	4A
O.L.	3A
O.L.	$4A_1$
O.L.	$2A_3$
O.L.	5B
O.L.	$2A_1$ (Notched)
O.L.	$2A_4$
O.L.	3A (Heavy notching)

Inner Lay Wires - 3 fatigue.
Outer Lay Wires - 3 fatigue, 6 possible light fatigue, 2 tensile, 2 crushed.
Center Wires - possible fatigue.

TABLE 22

WIRE FRACTURE CHARACTERIZATION

Iden. N188-1 (1973 contract)(90,000 lbs./7605 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_3$
I.L.	$2A_1$
I.L.	1A
I.L.	1B
I.L.	$2A_1$
I.L.	3A
I.L.	$4A_1$
O.L.	1A
O.L.	3A
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	2B (Notched)
O.L.	2B (Notched)
O.L.	$4A_1$
O.L.	$2A_4$ (Double 45° fracture)
O.L.	3A
O.L.	3A
O.L.	$3A_1$

Inner Lay Wires - 2 fatigue, 3 possible fatigue, 1 tensile.
Outer Lay Wires - 6 fatigue, 1 possible fatigue, 6 tensile.
Center Wires - fatigue.

TABLE 23

WIRE FRACTURE CHARACTERIZATION

Iden. Bethlehem Reel #3-917-B5-19/1 (90,000 lbs/7.830 cycles)

Wire (Location)	Fracture (Mode)
C.W.	$2A_2$
I.L.	$2A_2$
I.L.	$3A_1$
I.L.	$3A_1$
I.L.	1A
I.L.	$2A_3$
I.L.	$4A_1$
O.L.	4A
O.L.	$2A_1$
O.L.	1B
O.L.	1B
O.L.	1B
O.L.	$3A_1$
O.L.	1A
O.L.	5B
O.L.	$3A_1$
O.L.	$3A_1$
O.L.	$2A_1$
O.L.	1A

Inner Lay Wires - 3 tensile, 2 fatigue, 1 possible fatigue.
Outer Lay Wires - 2 fatigue, 6 partial fatigue, 4 tensile, 2 unknown.
Center Wires - fatigue.

TABLE 24

WIRE FRACTURE CHARACTERIZATION

Iden. WRI-2232-1/2 (90,000 lbs./5140 cycles)(Strand#1)

Wire (Location)	Fracture (Mode)
C.W.	5A
I.L.	5A
I.L.	5B
I.L.	$2A_1$
I.L.	3A
I.L.	$3A_1$
I.L.	1A
O.L.	1A
O.L.	$2A_1$
O.L.	$4A_1$
O.L.	$3A_1$
O.L.	$2A_1$
O.L.	5B
O.L.	1B
O.L.	$3A_1$
O.L.	$4A_1$
O.L.	1B
O.L.	$2A_1$
O.L.	1B

Inner Lay Wires - 2 fatigue, 1 possible fatigue, 1 tensile, 2 crushed.
Outer Lay Wires - 5 fatigue, 6 possible fatigue, 1 crushed.
Center Wires - crushed.

TABLE 25

WIRE FRACTURE CHARACTERIZATION

Iden. WRI-2232-1/2 (90,000 lbs/5140 cycles) Strand #2

Wire (Location)	Fracture (Mode)
C.W.	$3A_1$
I.L.	$2A_1$
I.L.	$3A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
I.L.	$2A_1$
O.L.	1A
O.L.	$2A_1$
O.L.	1B
O.L.	$2A_1$
O.L.	$4A_1$
O.L.	$2A_3$
O.L.	1A
O.L.	5B
O.L.	$3A_2$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$

Inner Lay Wires - 5 fatigue, 1 tensile.
Outer Lay Wires - 5 fatigue, 4 possible fatigue, 1 tensile, 1 crushed.
Center Wires - tensile.

TABLE 26

WIRE FRACTURE CHARACTERIZATION

Iden. WRI 47118, Reel No. 3123/1/1 (90,000 lbs/4792 cycles)

Strand #1

Wire (Location)	Fracture (Mode)
C.W.	$3A_1$
I.L.	1A
I.L.	3A
I.L.	$3A_1$
I.L.	$3A_1$
I.L.	$3A_1$
I.L.	--
O.L.	3A
O.L.	3A
O.L.	4A
O.L.	4A
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_1$
O.L.	$2A_2$
O.L.	$2A_1$

Inner Lay Wires - 1 possible light fatigue, 4 tensile.
Outer Lay Wires - 10 fatigue, 2 tesnile.
Center Wires - possible fatigue.

TABLE 27

WIRE FRACTURE CHARACTERIZATION

Iden. WRI 47118, Reel No. 2138/1/1 Strand #2

Wire (Location)	Fracture (Mode)	
C.W.	3A	2 Tensile
I.L.	1A	1 Fatigue
I.L.	$2A_1$	1 Possible Fatigue
I.L.	$3A_1$	1 Probable Tensile
I.L.	$3A_1$	
I.L.	$4A_1$	
I.L.	--	
O.L.	$4A_1$	5 Fatigue
O.L.	$4A_1$	2 Possible Fatigue
O.L.	$2A_1$	2 Tensile
O.L.	$2A_1$	2 Probable Tensile
O.L.	1A	
O.L.	$4A_1$	
O.L.	$2A_1$	
O.L.	$2A_1$	
O.L.	$2A_1$	
O.L.	3A (Abraded)	
O.L.	1A (Abraded)	
O.L.	3A	

Inner Lay Wires - 3 tensile, 1 fatigue, 1 possible fatigue.
Outer Lay Wires - 5 fatigue, 2 possible fatigue, 3 tensile.
Center Wires - tensile.

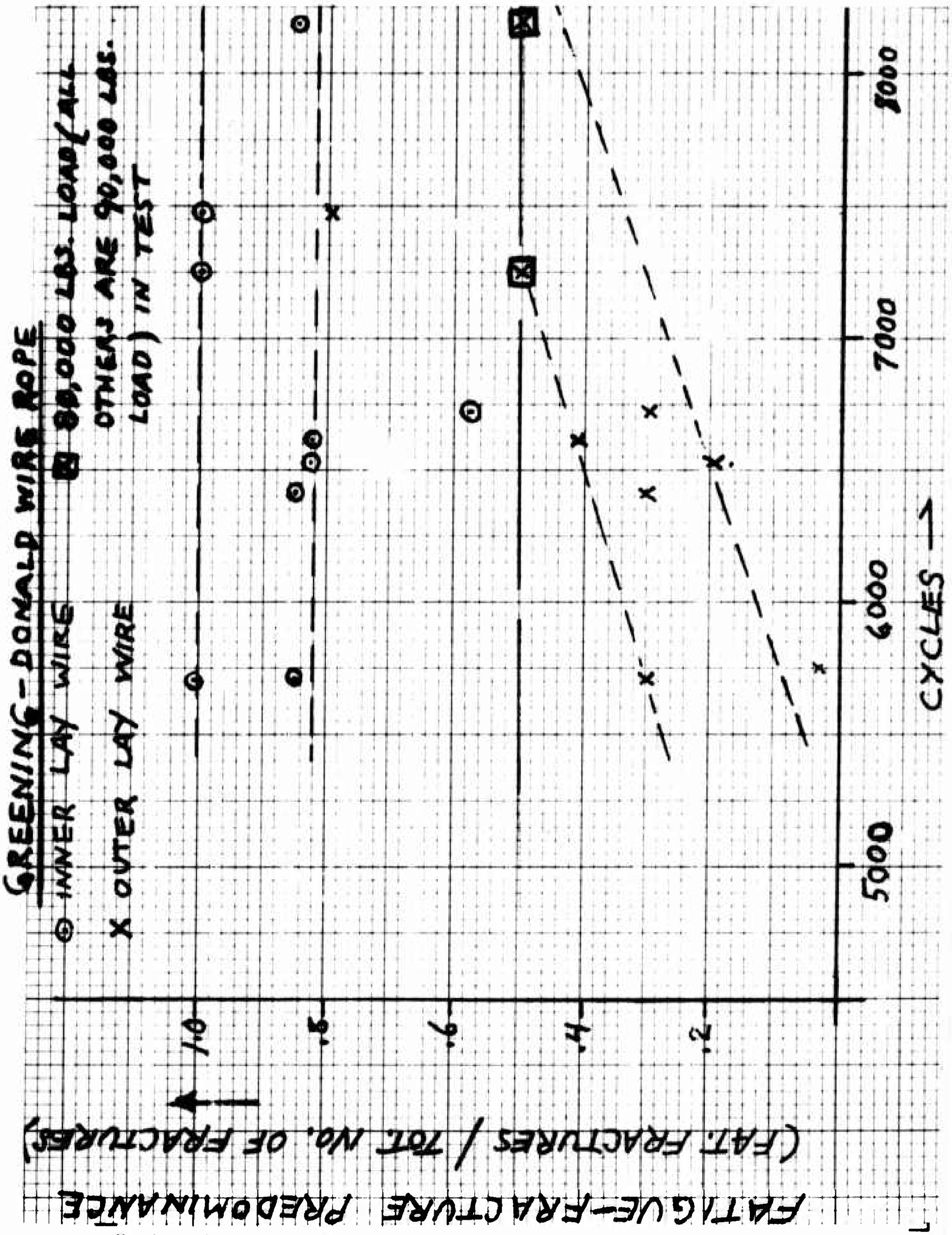
TABLE 28

SURFACE DECARBURIZATION MEASUREMENTS IN WIRE ELEMENTS

Wire Rope Identification	Fatigue Life (Cycles)	Max. Depth of Surface Decarburization (Sample No.) #1	#2	#3
Wire Rope Industries				
WR 2232 1/2 strand	5140			
Inner Lay Wires		.005"	.007"	.007"
Outer Lay Wires		.005"	.005"	.005"
Bethlehem Steel				
BE-47273H	7830			
Reel #3-917-B5-19/1				
Inner Lay Wires		.005"	.005"	.005"
Outer Lay Wires		.005"	.005"	.005"
Greening-Donald				
N518-12-3	5309			
Inner Lay Wires		.002"	--	--
Outer Lay Wires		.005"	.005"	.005"
(Old) Greening-Donald				
N188-1	7605			
Inner Lay Wires		(Negl.)	(Negl.)	(Negl.)
Outer Lay Wires		(Negl.)	(Negl.)	(Negl.)

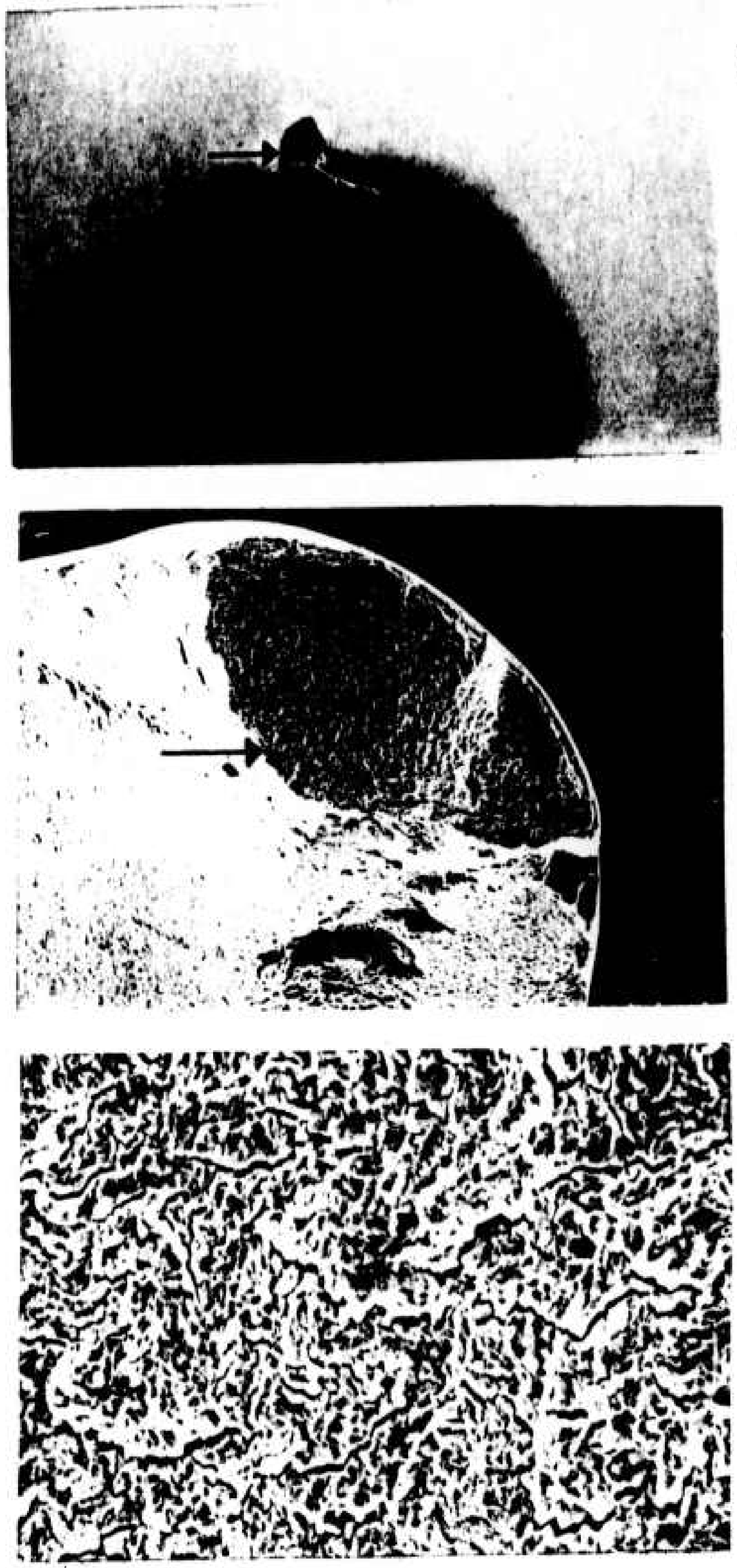
Wire Rope That Failed in Fatigue

FIGURE 1

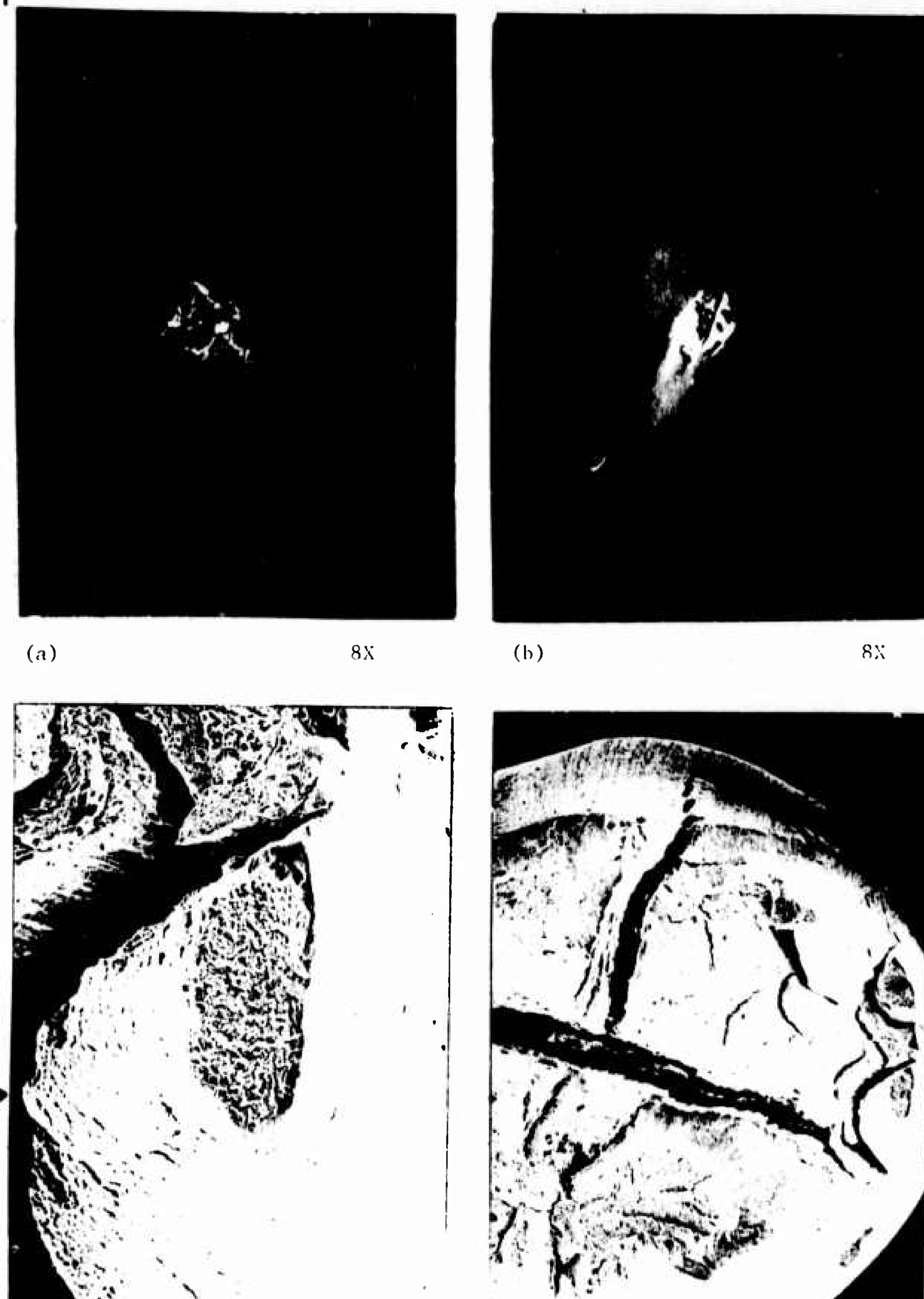


Fatigue Fracturing Predominance V.S. No. Cycles of Test

FIGURE 2



MODE 2A1: Showing Fatigue
FIGURE 3



(a) 8X (b) 8X

(c) 300X (d) 50X

MODE $3A_2$: Showing Fatigue

FIGURE 4

(a) 8X

(b) 8X

(c) 50X

(d) 1000X

MODE $4A_1$: Showing Fatigue.

FIGURE 5

(a) 8X

(b) 50X

(c) 1000X

MODE IA: Showing No Fatigue (1975 Contract outer lay wire)

FIGURE 6

4ND-NAEC-2455(REV. 2-68)

PLATE NO. 11962

(a)

9X

(b)

50X

MODE 1B: Shows No Fatigue (1975 Contract Outer Lay Wire)

FIGURE 7

8X

MODE 3A: Showing No Fatigue

FIGURE 8

(a)

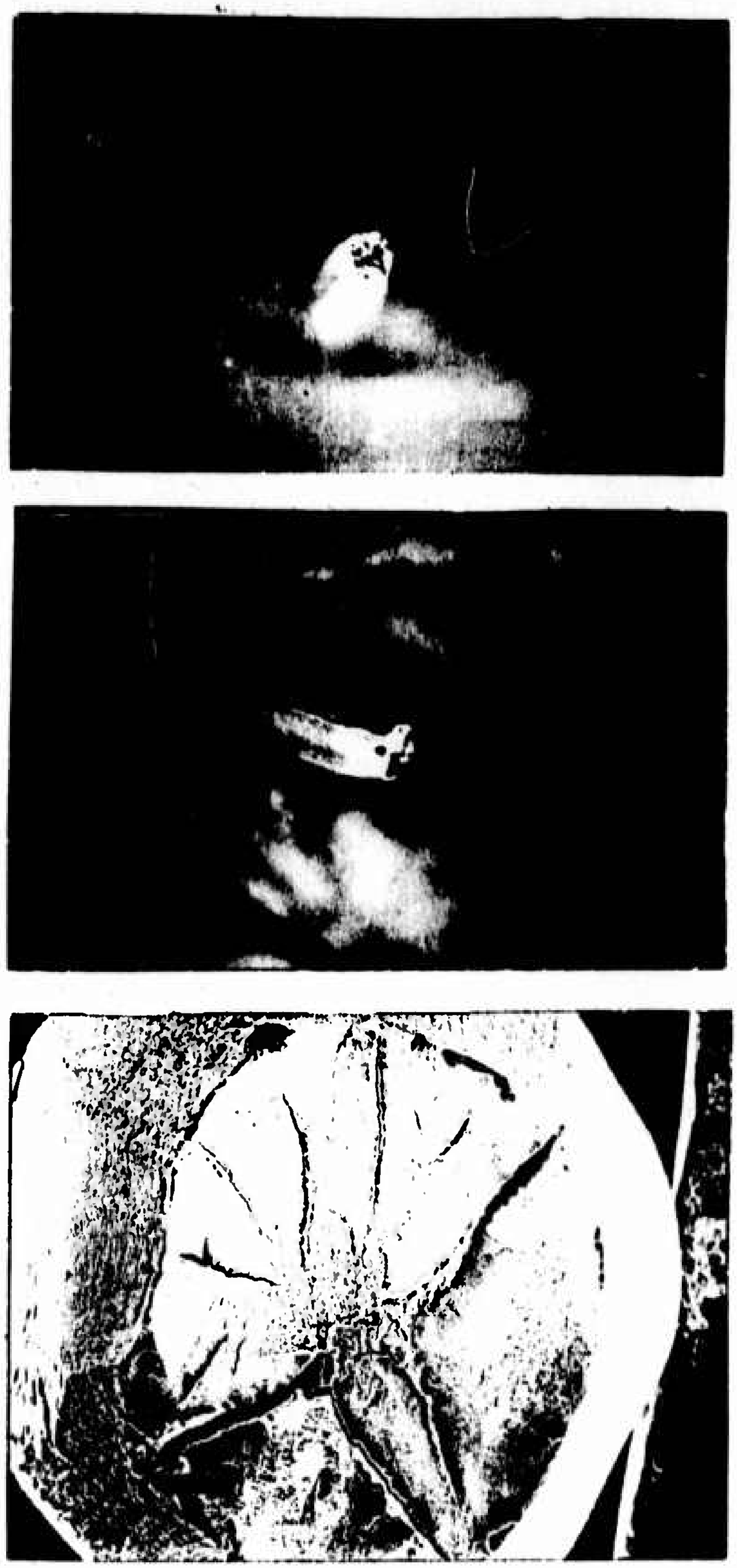
8X

(b)

50X

MODE $3A_1$: Showing No Fatigue

FIGURE 9



(a) 8X

(b) 8X

(c) 50X

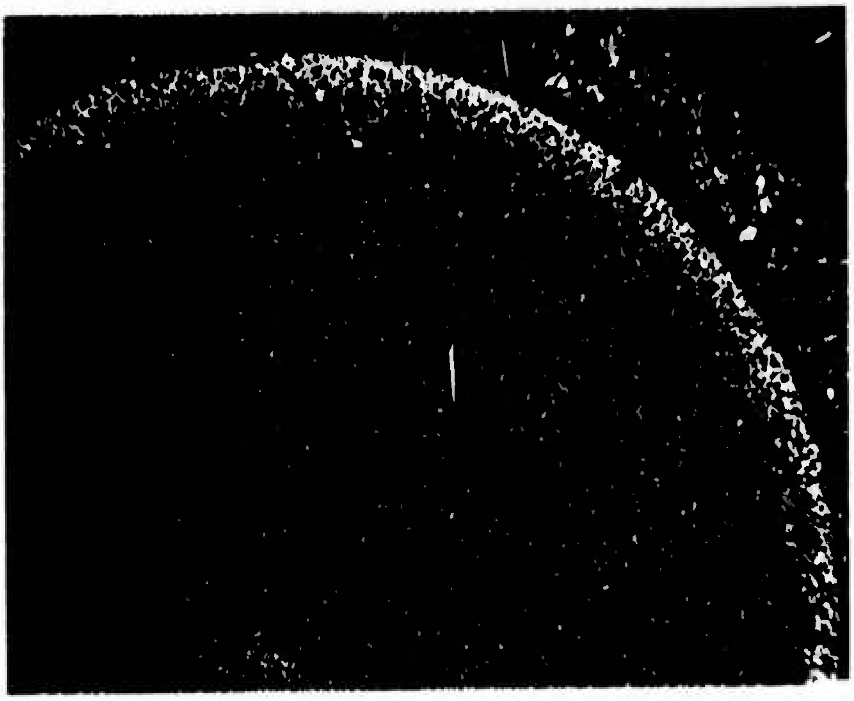
MODE $3A_2$: Showing No Fatigue
FIGURE 10

(a) 8X

(b) 8X

(c) 50X

MODE $4A_1$: Showing No Fatigue (1975 Contract Outer Lay Wire)
FIGURE 11



Inner-lay Wire
Decarb.
N502-34-1

X 60

X 160

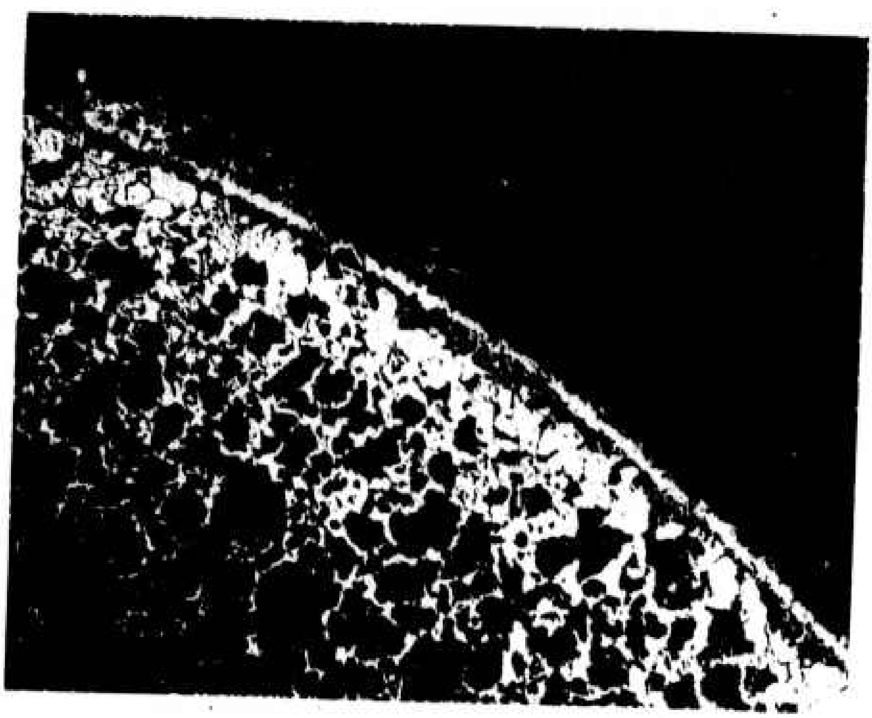
Inner-lay Wire
Decarb.
N-502-34-1

Surface Decarburization in Sample N502-34-1 Wire Rope Inner-lay Wire

FIGURE 12

Outer-lay Wire
Decarb.
N-502-34-1

X 60



X 160

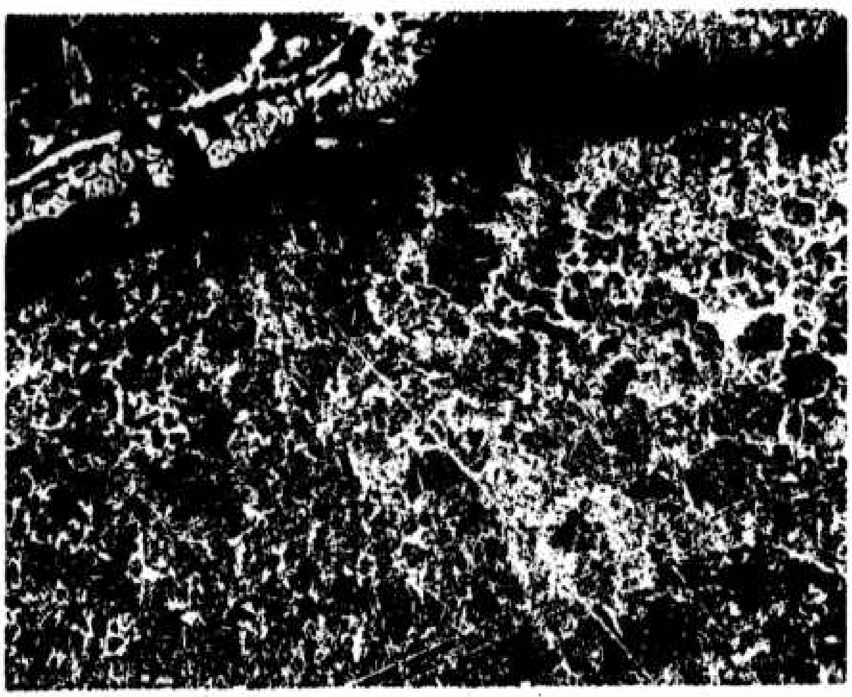
Outer-lay Wire
Decarb.
N-502-34-1

Surface Decarburization in Sample N502-34-1 Outer-lay Wire

FIGURE 13

N188-2
Inner-lay Wire

X 160



X 160

N188-1
Outer-lay Wire

Samples of NATF Purchase Cable from Contract No. 73-C-1573 Practically Free of Surface Decarburization

FIGURE 14

INFLUENCE OF WIRE PROPERTIES ON THE FATIGUE PERFORMANCE OF ARRESTING GEAR PURCHASE CABLE | NAEC-ENG 7898

A metallurgical investigation was made of the cause of a decrease in fatigue life of a new contract of purchase cable. Using fractography, supported by scanning election microscopy, metallography and tensile testing, it was possible to explain how very subtle differences in the wire quality used to make the cable had led to the decrease in fatigue life.

INFLUENCE OF WIRE PROPERTIES ON THE FATIGUE PERFORMANCE OF ARRESTING GEAR PURCHASE CABLE | NAEC-ENG 7898

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