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Methods of Measuring the Mechanical Behavior of Wire Rope

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Laboratory investigations revealed a correlation between rope specimen preparation techniques and final accuracy of the measured rope parameters. Methods were developed for alignment and termination of rope specimens to insure a normal sharing of the test load by wire and strand components of the rope.

An illustration of specimen preparation and a demonstration of the instrumentation is provided through measurement of the load-strain and torque-load behavior of a 3/4-inch-diameter, type 304 stainless steel wire rope of 6 X 19 (7 X 7 IWRC) Warrington construction.

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CONTENTS

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METHODS OF MEASURING THE MECHANICAL
BEHAVIOR OF WIRE ROPE

INTRODUCTION

Recent oceanographic research utilizing marine structures has imposed a close dimensional tolerance upon its wire rope components. For example, the specifications being written for marine experiment support platforms, in water depths of four to five miles, requires an operational position accuracy of less than 1% of cable length. Existing wire rope data is inadequate for this design trend. The current study is concerned with the precise measurement of basic wire rope characteristics needed in marine technology.

Most frequently a marine cable must endure an axial tensile force upon which is superimposed a variable amplitude, low frequency load. Response of this intricate construction of wires and strands to an external load is unlike that of any other structural member. For example, the construction of most wire ropes is such that torque is generated when the rope is loaded. Elastic behavior of wire rope is also unique in that it consists of both structural stretch and elongation of individual wires. "On-the-shelf" measurement techniques available for testing materials do not directly apply to the accurate measurement of these rope parameters.

The following report describes the test procedures and instrumentation developed for an accurate laboratory measure of rope behavior under static and dynamic axial modes of loading.

WIRE ROPE

An understanding of rope constructional form and the manner in which this form relates to the rope's behavior when axially loaded, was a necessary prerequisite to this study. The wires in a wire rope are arranged in a centric symmetry. They are woven together into strands, and several strands into ropes according to specific lay patterns. Literally hundreds of rope constructions are available to the user. Certain general constructional features, however, are common to a number of rope types and it is possible to describe these as they appear in a specific construction. A 3/4-inch-diameter wire rope frequently employed as a support cable in NOMAD moored buoy systems (1) was selected for this discussion. The rope is shown in Fig. 1. Caption nomenclature, Fig. 1, indicates a rope having six outer strands of 19 wires per strand. Note that the six outer strands are helically wound about an independent wire rope core (IWRC) which itself has seven strands of seven wires per strand. The cross-sectional view of the rope depicts the Warrington construction, i.e. wire of a different diameter is present in the outer wire layer of rope strands.

This 3/4-inch-diameter rope has two salient constructional features that are important. First, outer strands of the rope and IWRC are formed in a right regular lay. In this pattern wires of the strand wind to the left while strands themselves twist to the right in forming the rope. Finally, the rope is preformed; individual wires and strands were pre-shaped prior to assembly. Both of these features contribute to a mechanical stabilization of the rope. In regular lay construction, wires are tucked securely under the strands and the rope is less likely to kink and untwist during service. This same behavior is further impeded by the preform process.

Mechanical response of wire rope to axial load depends upon its construction and the material properties of the wires. An axial load imposed on the rope generates three types of force. There is a tensile force on each wire (2), a radial force which presses wires and strands against their respective cores (3) and tangential forces (4). The tangential forces produce torque, which tries to unlay the helically wrapped strands. Wire rope elongation is particularly complex. It consists of both structural stretch and elongation of individual wires and strands. Structural stretch is a consequence of lengthening of the rope lay, compression of the strands and IWRC, and an adjustment of wires and strands to the load.

TEST SPECIMEN PREPARATION

In preparing for an accurate measurement of wire rope behavior, certain precautions regarding experimental procedures must be observed. Procedures that permit the full transfer of test load to the rope, without the introduction of abnormal wire stresses, are essential. A few precautions that will assist in meeting this ideal condition include:

1. The normal position of wires and strands during cutting, terminating and testing of the rope must be preserved.

2. The pre-test configuration of the rope should be relatively straight and the rope in near-perfect axial alignment with its terminators.

3. The free-length of the test section must be sufficiently great so as to render any small constructional distortions, introduced during termination, ineffective.

Commercial open-end spelter sockets were selected for terminating wire ropes because they permit the full rope strength to be developed. A schematic cross-sectional view of a terminated wire rope is shown in Fig. 2. The molten zinc should completely fill the socket basket and provide optimum penetration into the wire interstices. Penetration of zinc into the wire transition zone, wherein the "broomed-out" wires resume the normal rope configuration, is desirable. Incomplete zinc penetration in this area can result in abnormal wire stresses and pull-out of the wires. As a consequence, in a rope rupture test, wires will prematurely fail at or in the rope socket. Furthermore, rotational displacement of wires within the sockets would produce errors in torque measurements when, in later tests, a torque transducer would be placed in series with the rope.

The procedures given in Ref. 5 were followed in regard to seizing and "brooming-out" of the wires, however, cleaning procedures were changed. Broomed rope ends were ultrasonically cleaned in fresh solutions of trichloroethylene. After air drying, the broomed ends were immersed in a bath of solder flux to insure wetting and a good bond between the zinc and wires of the rope. The cleaned, "broomed-out" wires were drawn together with a special clamp so that the socket could be forced down over them. Next, the assembled rope and socket was mounted in the alignment fixture, Fig. 3. This device was designed to hold the rope and socket in near-perfect axial alignment. The socket was preheated to 160°F to expel moisture and prevent the molten zinc from solidifying before completely filling the lower end of the basket. An alloy of 10% tin and 90% high purity zinc heated to 950°F was then poured into the large end of the socket.

The foregoing procedures enhanced the flow of zinc. For purposes of inspection, terminators were disassembled by cutting the rope at the socket ends and pressing-out the remaining core from the socket baskets. An actual rope-socket-core is shown in Fig. 4. The extent of metal flow was sufficient to engulf the rope throughout the wire transition zone. Top view of the core, Fig. 4, presents a near-perfect cross-sectional view of the normal rope construction. For purposes of comparison, Fig. 5 depicts two poorly terminated socket-cores.

PRELIMINARY ROPE TEST

In order to establish criteria for the wire rope instrumentation, it was necessary to conduct a rope tensile test. The methods and techniques employed during this effort were only preliminary in nature.

The primary purpose of this investigation was to compare two different methods of measuring strain in a rope. A first method, commonly employed, involved the measurement of machine cross-head displacement while the other technique utilized an instrument for manually measuring extension over a marked length of rope. Figure 6 illustrates the experimental set-up. The 3/4-inch-diameter wire rope mounted in the 60,000 lb capacity test machine is of the type previously described and used for all tests in this report. A 30-inch length of this rope was seized and terminated in accordance with the procedures mentioned earlier. After the specimen was assembled in the test machine, two gage marks were scribed on the rope circumference in a plane normal to its axis. The distance between gage marks was approximately 24 inches. During the test, rope elongation was monitored by means of alignment stand indices and rope gage marks. A measure of the index spacing was accomplished with the vernier calipers shown on the indexing stand, Fig. 6. Rope extension measurements were coordinated with load indicator readings in order to provide data for a load-strain plot. A continuous graph of load-strain behavior was simultaneously obtained from the test machine's load-displacement recorder. Initial rope length for the latter strain measurement was based upon the length of rope between terminators.

The two representations of the rope's load-strain behavior are given in Fig. 7. Curve A more accurately depicts the actual behavior of the rope under tensile loading since strain readings were derived from manual elongation measurements over a gage length on the rope. Curve B illustrates the extent to which error in machine head displacement readings can contribute to an erroneous load-strain response. For example, the strain error at 40,000 lb of load is about 50% of actual rope strain.

Strain readings for Curve B contain error from a number of sources. Because strain was based upon displacement of the machine crosshead, it must therefore include the effect of elastic deformations in machine columns, crossheads, rope sockets and socket adaptors as well as extension in the rope. Deformation of the foregoing load train components during the test was small, however; with the exception of zinc-pull-out from the sockets. Localized irregularities in curve B are evidence of this creep effect. These irregularities were introduced when loading was interrupted to allow time for manual measurement of rope extension. As a safety precaution manually derived strain readings for curve A are not given for test loads near specimen rupture. A comparison of the two test results indicates that an extensometer that can achieve continuous readings of extensions, over a rope gage length, up to and including specimen rupture would be advantageous.

INSTRUMENTATION

Transducers that can accurately measure load, elongation and torque induced in a wire rope were the primary objective of this study. The tension and torque instrumentation was combined into a single unit by utilizing the strain gage techniques described in Ref. 6. An electro-optical tracking system was adapted for use as a rope extensometer. Measurement of elongation is performed continuously and directly upon a section of the rope. Furthermore, expendable optical-targets permit extension measurements up to and including specimen rupture. Principles of operation and implementation of these measuring systems are described in the following paragraphs.

Load-Torque Measuring System

The tension-torque transducer shown in Fig. 8 is designed for the simultaneous but independent measurement of applied load and torque generated in a wire rope. Machined from high strength maraging steel, the transducer is designed for maximum combined working loads of 50,000 lb tension and 500 ft-lb of torque. In terms of rope specimen size, it will accomodate most 1/4- to 7/8-inch-diameter wire ropes loaded to failure. The unit is instrumented with two separate sets of four strain gages. Each set of gages is utilized in a four-arm Wheatstone bridge circuit for the independent measurement of tensile and torque loads.

Mechanical calibration of the transducer was accomplished with the Calibrator, also shown in Fig. 8. The device was mounted in a 60,000 lb capacity universal test machine for application of known axial loads. Torque calibration was performed by disengaging the Calibrator's lower threaded adaptor from the test machine and utilizing the two bolts as force transducers. Each bolt was previously instrumented with strain gages and separately calibrated for the measurement of bolt load. Bolt forces were applied in a plane perpendicular to the axis of the transducer and at a known distance from its axial centerline to produce the required torsional moments. Transducer calibration data revealed that the axial load and torque bridge circuits had negligible response to torque and axial load respectively. Furthermore, the accuracy of this dual measuring system was determined to be 1%.

Electro-Optical Extensometer

The electro-optical tracking system in Fig. 9 consists of two optical heads with control units, a differential amplifier, and two targets which are rigidly attached to the rope. Mounted on each optical head is a lens system that must be focused on the optical discontinuity created by the back-lighted lucite panel and the upper edge of the target. A special photomultiplier tube within the optical head converts this optical image into an identical electron image. Electrical signals from the optical head control unit causes the photomultiplier tube to examine this electron image. Any displacement of a rope target is evidenced by a sharp change in photomultiplier tube voltage output and is directly proportional to target displacement. A differential amplifier subtracts the two optical head voltage signals and thus represents elongation of the rope between targets.

Figure 10 is a photograph of the actual measurement system arranged for a wire rope test. The two optical heads in the photograph are shown mounted on adjustable platforms that are attached to the seismic stand on the right side of the rope. This stand is capable of being positioned away from the targets to insure a large enough optical field of view. For testing purposes, a field of view equal to 125% of estimated target displacement determines the optical head to target working distance. Accuracy of the tracking system is 0.1% of the field of view.

The procedure for extensometer calibration is illustrated in Fig. 11. A specially designed mechanical micrometer slide is shown clamped to the pre-loaded rope. The device had its own targets which are situated parallel to and flush against the rope targets. By rotation of the micrometer slide screw its targets are displaced in known increments.

Targeting techniques are important. They are the only items in the complete measuring system that can be considered expendable because wire rope break strength tests frequently destroy them. The targets shown in Fig. 12 were designed specifically for the 3/4-inch-diameter wire rope. Prior to a rope test, the targets are clipped to the rope and positioned so that each weld point is at least one rope lay length away from the nearest terminator. Next, the targets are rigidly attached to a single wire of the rope by means of a spot-weld. The spot-weld is sufficiently small so as not to effect the gross behavior of the rope.

MECHANICAL BEHAVIOR OF A WIRE ROPE

With the specimen preparation techniques perfected and the instrumentation made operational it was possible to accurately measure the load-strain and torque-load behavior of the 3/4-inch-diameter wire rope shown in Fig. 1.

A three million pound capacity testing machine was selected for this work. The test machine is shown in Fig. 10. It has a single-screw drive and applies load to the rope at a constant rate of machine head displacement. Maximum crosshead clearance is 11 feet, three inches, which permitted a rope free length of seven feet, four inches after allowance for test fixtures, load-torque transducer and operational clearance. The test machine was to be used to only 1.7% of its load capacity since during the test axial load would not exceed 50,000 lb. The machine load frame is extremely massive. This feature afforded an advantage in that the torsional loss in transducer output, due to rotational displacement of the upper crosshead, would be negligible. Excessive capacity, however, provided a disadvantage because the machine weigh system had insufficient load sensitivity for rope tension measurements. This was remedied with the addition of axial load capability to the transducer described earlier.

When conducting wire rope tests, a small pre-load is often necessary to eliminate initial measurement error. In this instance, a 150 lb load was utilized to straighten the initially loose 3/4-inch-diameter rope and provide it with sufficient rigidity to permit calibration of the electro-optical system. The test machine was operated at a head displacement rate of 0.0745 in./min. Test procedure was simply to give the rope a single load cycle and then load it to rupture. The specimen was loaded from 150 lb to 33,000 lb, 33,000 lb to 4000 lb, and 4000 lb to rupture. Load was continuously applied during the test.

Load-elongation and torque-load data were simultaneously recorded on X-Y recorders. The load-strain behavior is given in Fig. 13. A rope break strength of 47,350 lb, with 4.0% elongation at rupture, was achieved in this test. The effect of constructional stretch is clearly evidenced by the contrast in load-strain behavior of the initial and first cycle load curves. From Fig. 13, the constructional and first cycle elastic moduli were calculated to be 8.88×10^6 psi and 14.48×10^6 psi respectively. Note that the initial load-strain curve is never reached again in the subsequent loading. Under the cycled load, the rope yields a hysteresis loop between the loading and unloading curves A and B. This behavior directs attention to the internal frictional forces present in the rope.

In order to measure the torsional response of the rope it was necessary to impede rotation of the rope ends. Torque-load behavior of the rope is illustrated in Fig. 14. For all practical purposes, the initial torque-load curve (0 to 33,000 lb) is linear. Slope of the initial curve is 0.0574 in.-lb per lb of rope load. Upon load cycling the rope, a small difference in torque-load behavior was evident. Torsional response during the second loading was also linear at 0.0552 in.-lb per lb of load, a decrease of 3.8% over the initial loading.

Figures 13 and 14 represent the mechanical response of this rope to a given single load cycle. Parameters that include load, induced torque and elongation were measured to an accuracy of 1%. Three facts are available for corroboration of this statement. First, all measurement systems were calibrated to an accuracy of at least 1%. Second, post test examination of terminator cores indicated that they both met the standards outlined earlier. Finally at rupture, Fig. 15, wires and strands broke near the center of the test length.

CONCLUDING REMARKS

Efforts during the current study had largely been directed towards a perfection of technique and development of instrumentation necessary for an accurate measurement of rope parameters. Even though instrumentation capability was demonstrated for static loading, it does have the capability to measure rope parameters under dynamic loading. Furthermore, the instrumentation can be extended to accomodate fiber ropes and electromechanical cables.

The peculiarities of wire rope constructional form requires special precautions with regard to specimen preparation. Because of this, procedures have been developed for mounting rope specimens with a minimum amount of relative displacement of wires and strands during cutting and terminating. A special alignment fixture was also designed to insure near-perfect axial alignment between the terminators and rope. Speltering techniques were modified to obtain a more complete flow of zinc-spelter. All of the above served to guarantee that the test machine would transfer load to the rope without the introduction of abnormal wire stresses.

Currently these methods are being utilized for the test and evaluation of a newly developed titanium rope and also to analyze the effect of marine service damage upon the mechanical behavior of mooring lines. A precise knowledge of their performance characteristics is required and can be obtained through use of these techniques. It is intended that this report will serve as a eference to these and future NRL rope studies.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of Mr. John Bachman during the experimental development of termination and targeting techniques.

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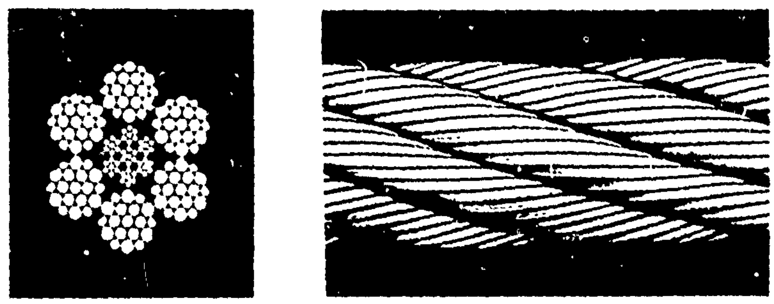

Fig. 1 - A 3/4-inch-diameter, type 304 stainless steel wire rope of 6 × 19 (7 × 7 IWRC) Warrington construction.

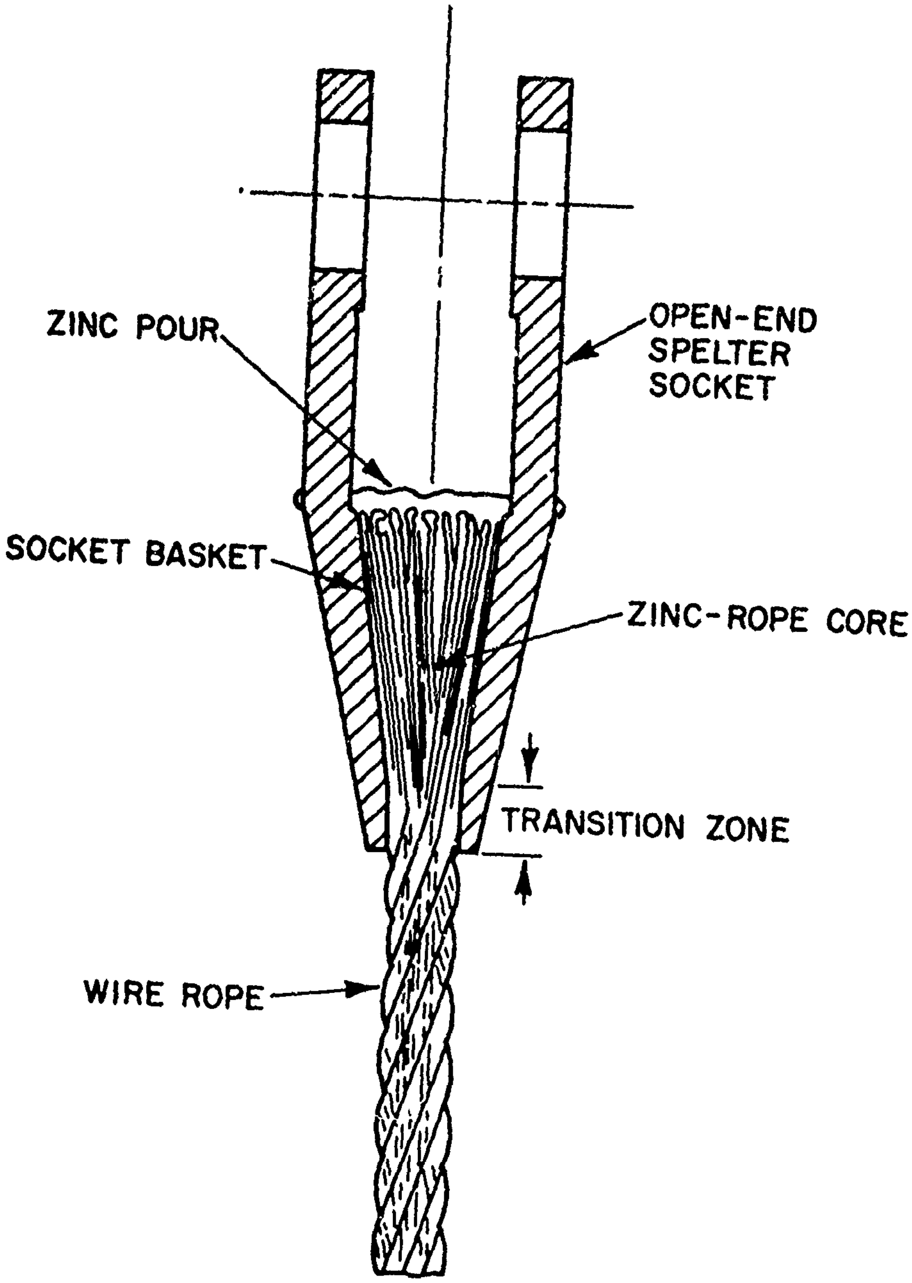

Fig. 2 - Penetration of zinc throughout the wire transition zone is desirable

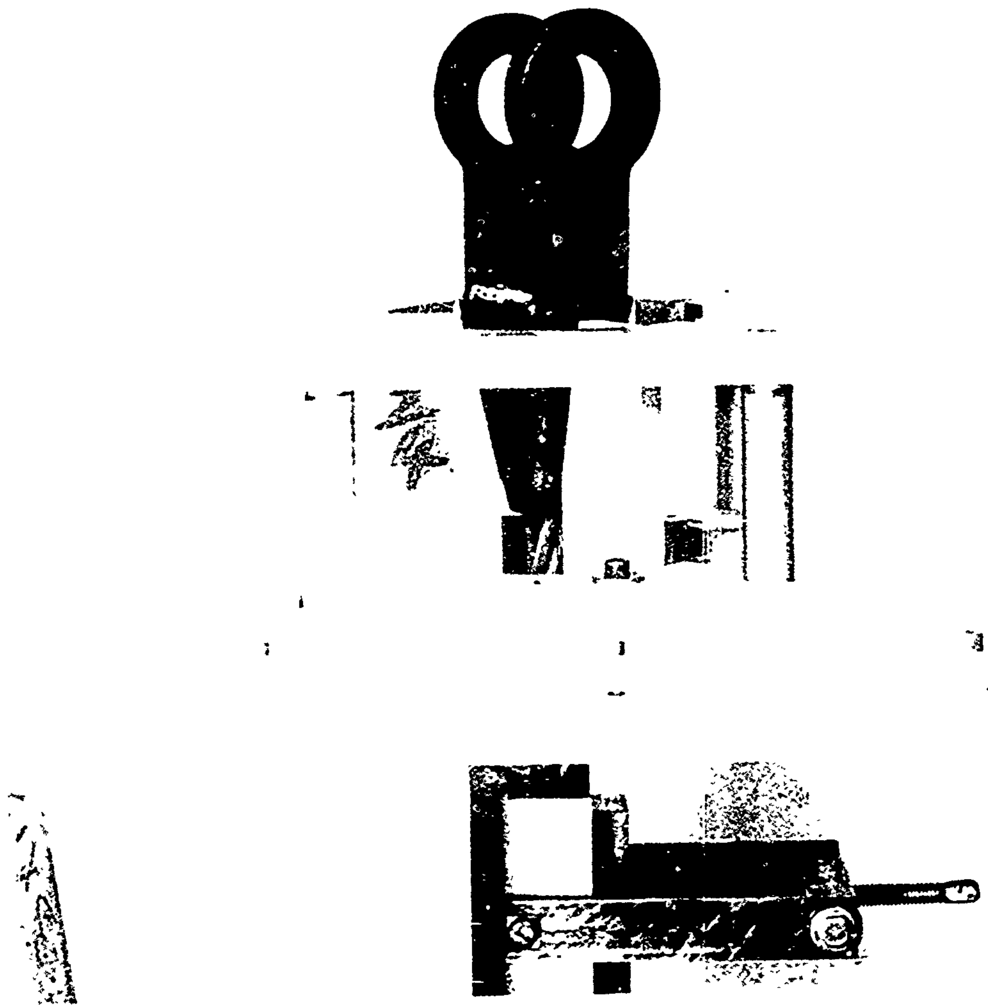

Fig. 3 - Tapered holders adjust to the socket size and move laterally for centering of the socket and rope axes

Fig. 4 - Zinc has penetrated the full length of the socket basket to grip the rope in near-perfect configuration.

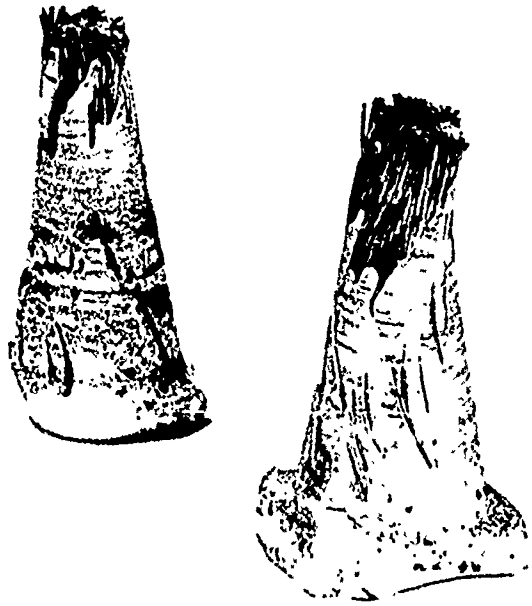

Fig. 5 - Early congealing of the zinc prevented a complete metal flow throughout the length of socket basket.

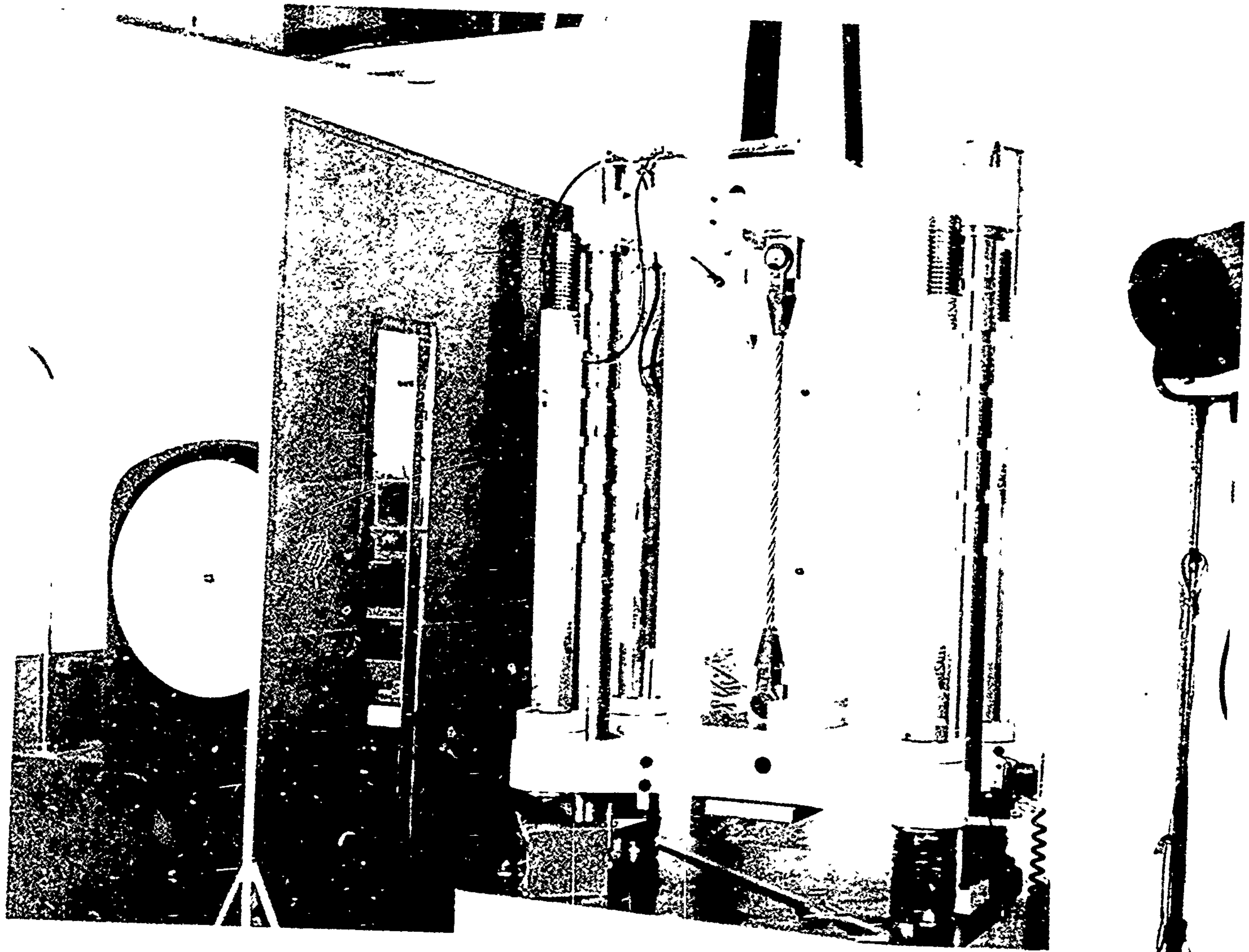

Fig. 6 - The index stand, shown to the right of the rope, and the load-displacement recorder of the test machine were utilized to measure rope strain.

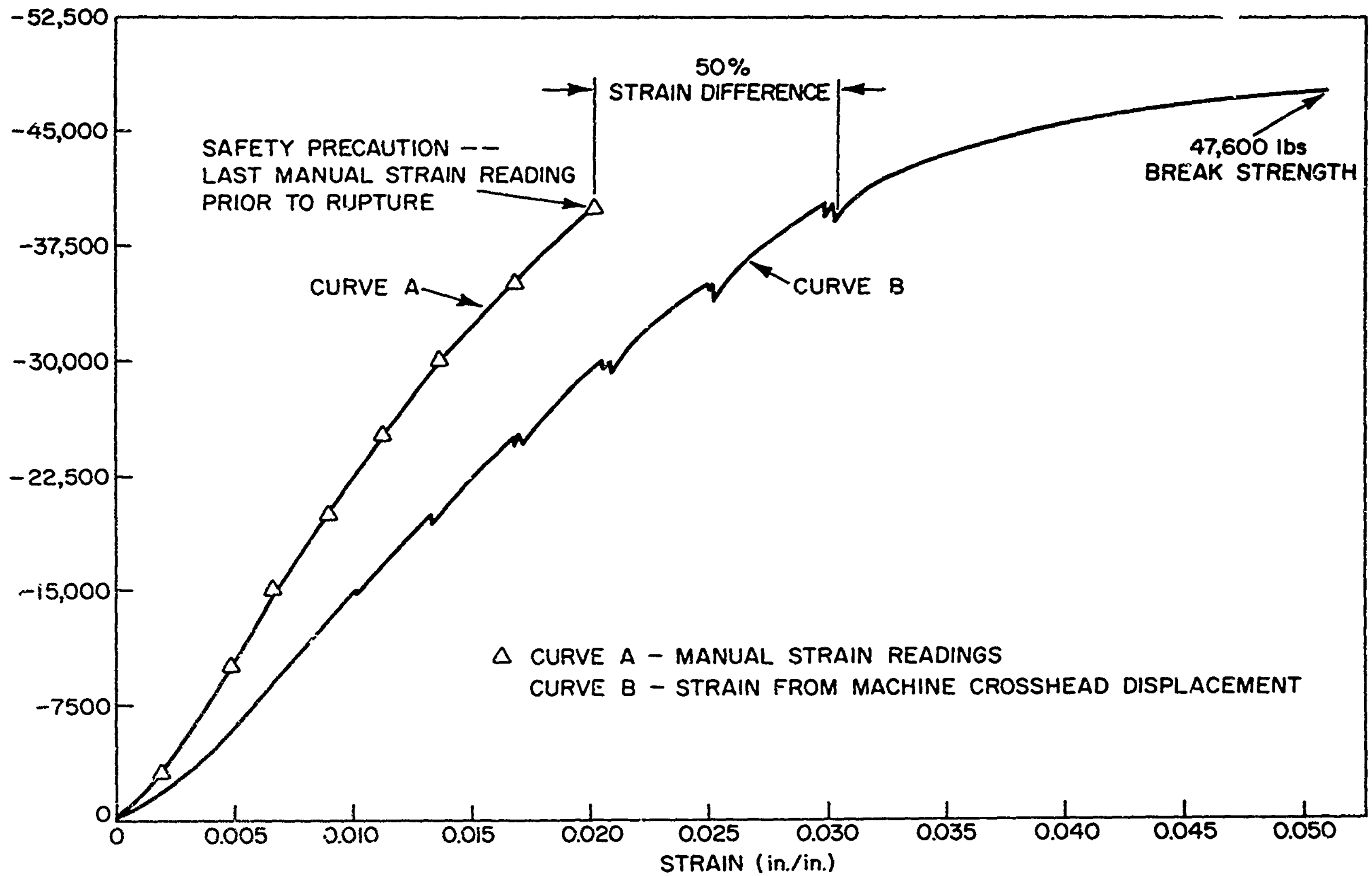

Fig. 7 - Comparison of load-strain measurements

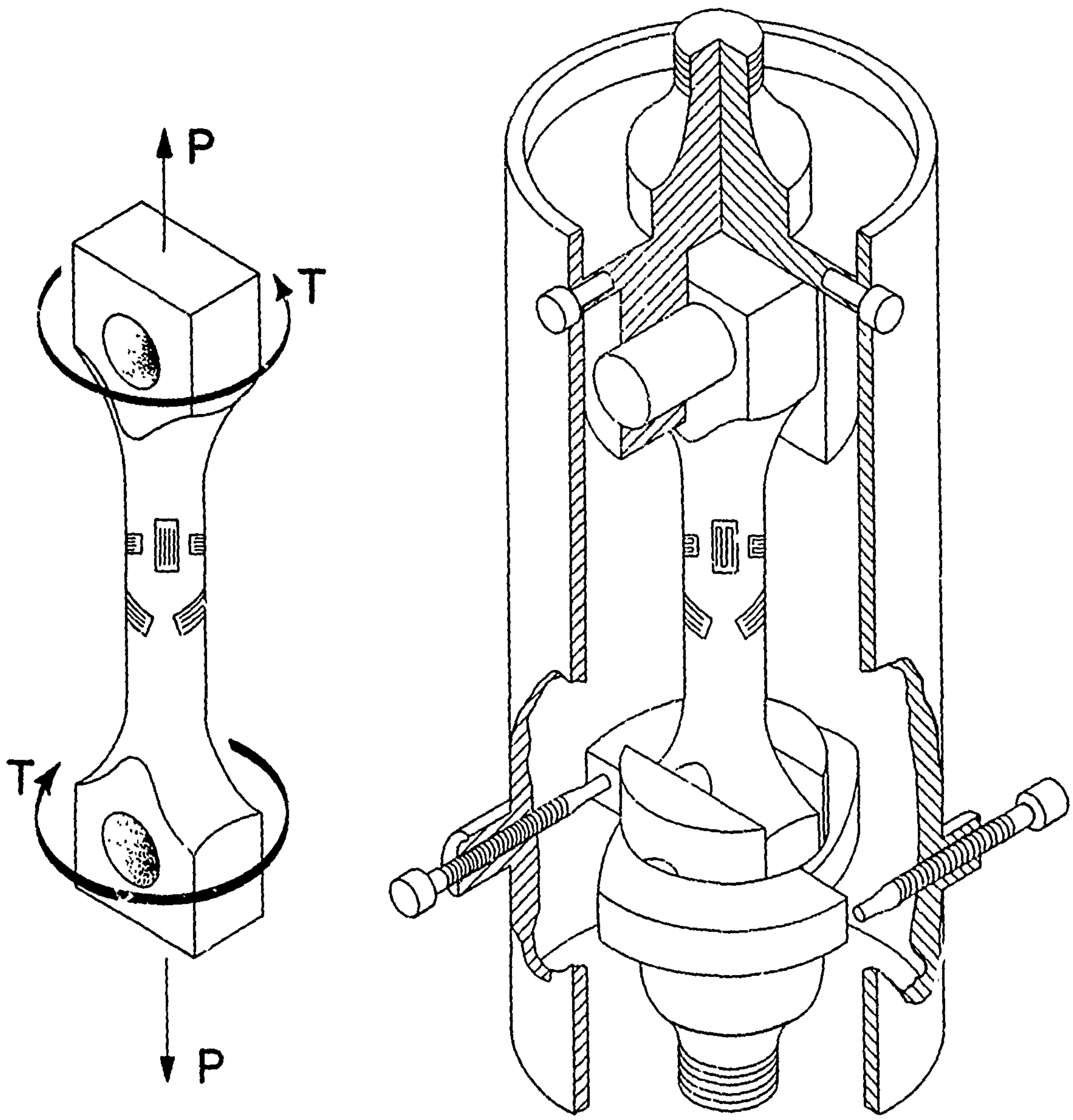

Fig. 8 - Tension-torque transducer is shown assembled
in the calibrator on the right

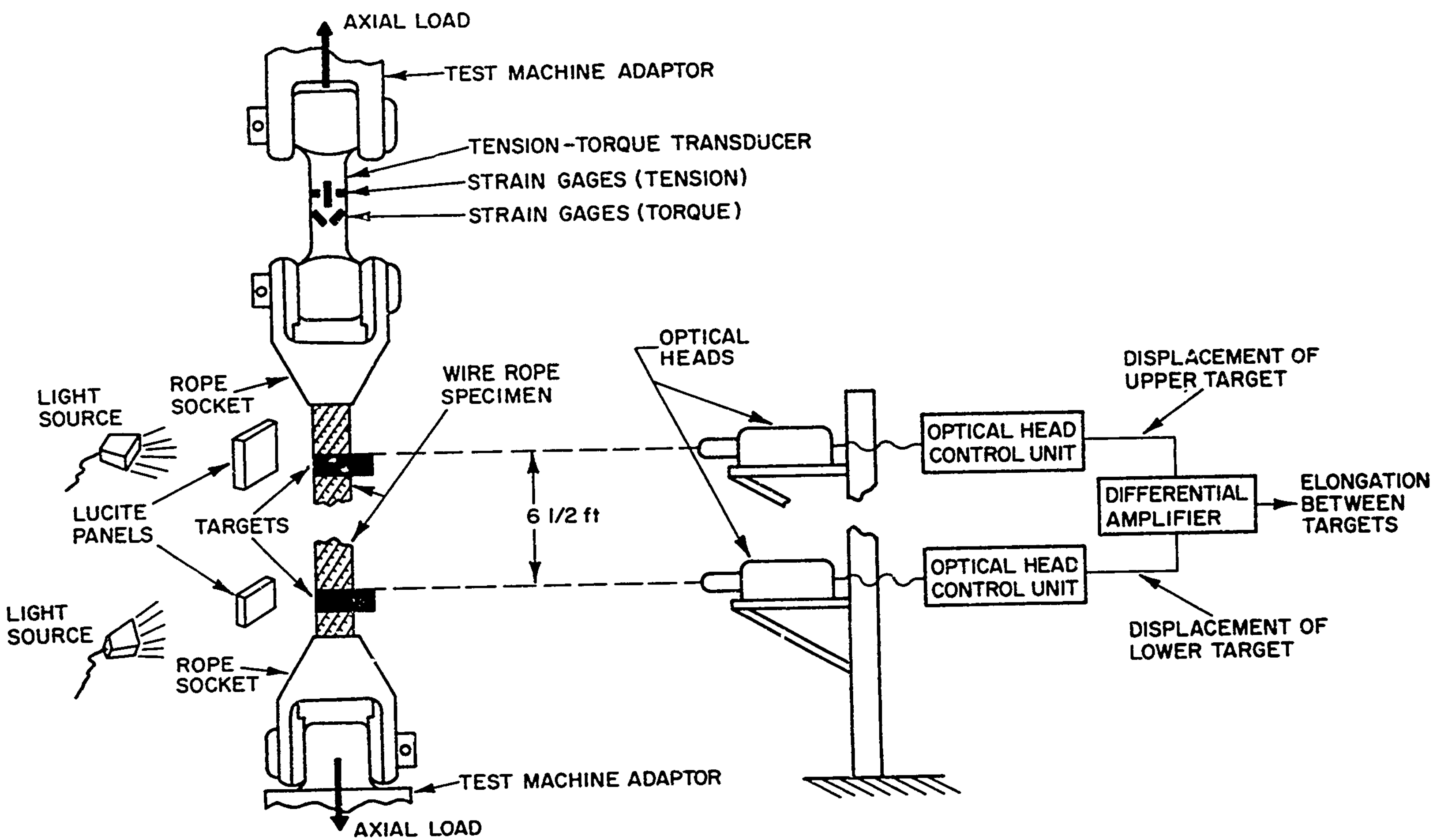

Fig. 9 - Electro-optical tracking system, optical heads are focused on the upper edge of their respective targets.

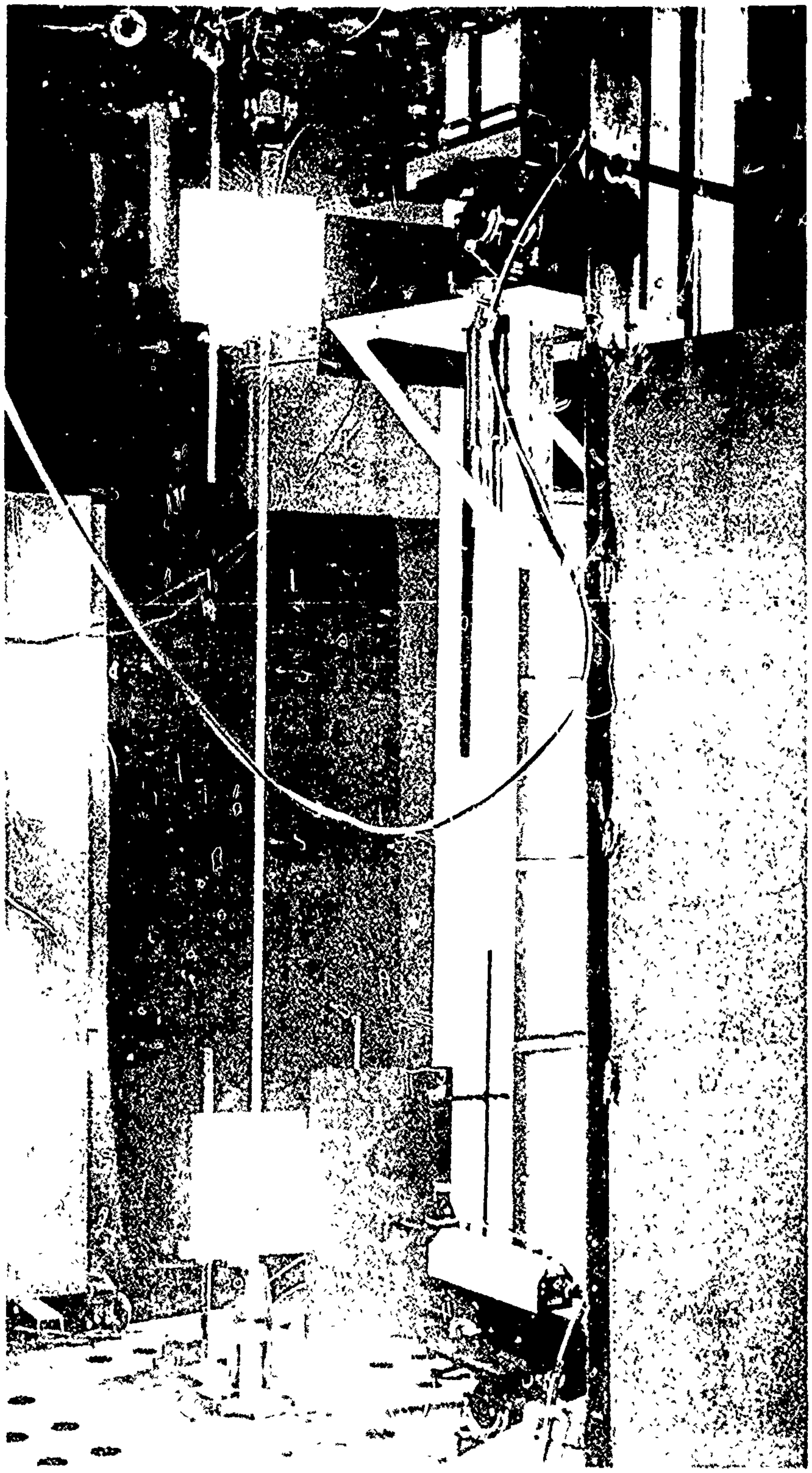

Fig. 10 - Rope test in three million pound capacity test facility

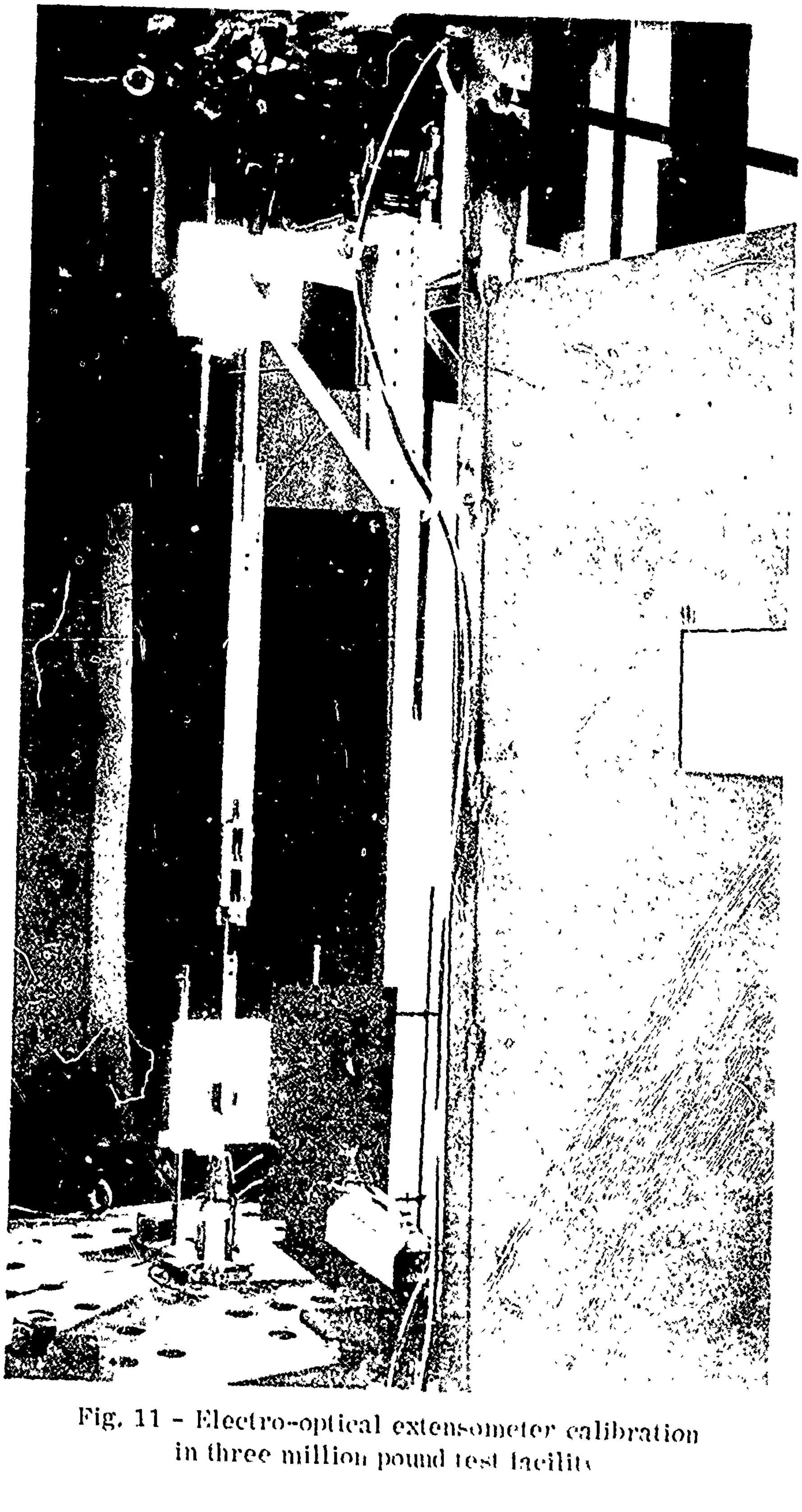

Fig. 11 - Electro-optical extensometer calibration in three million pound test facility

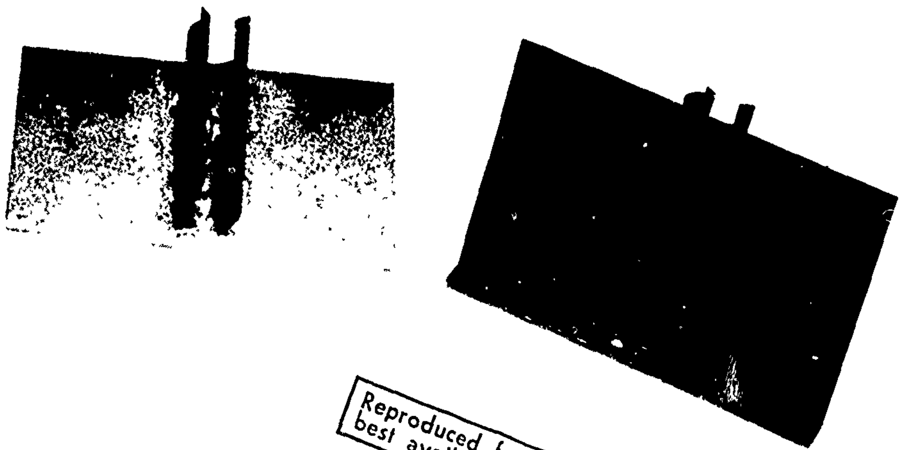

Fig. 12 - Electro-optical target design

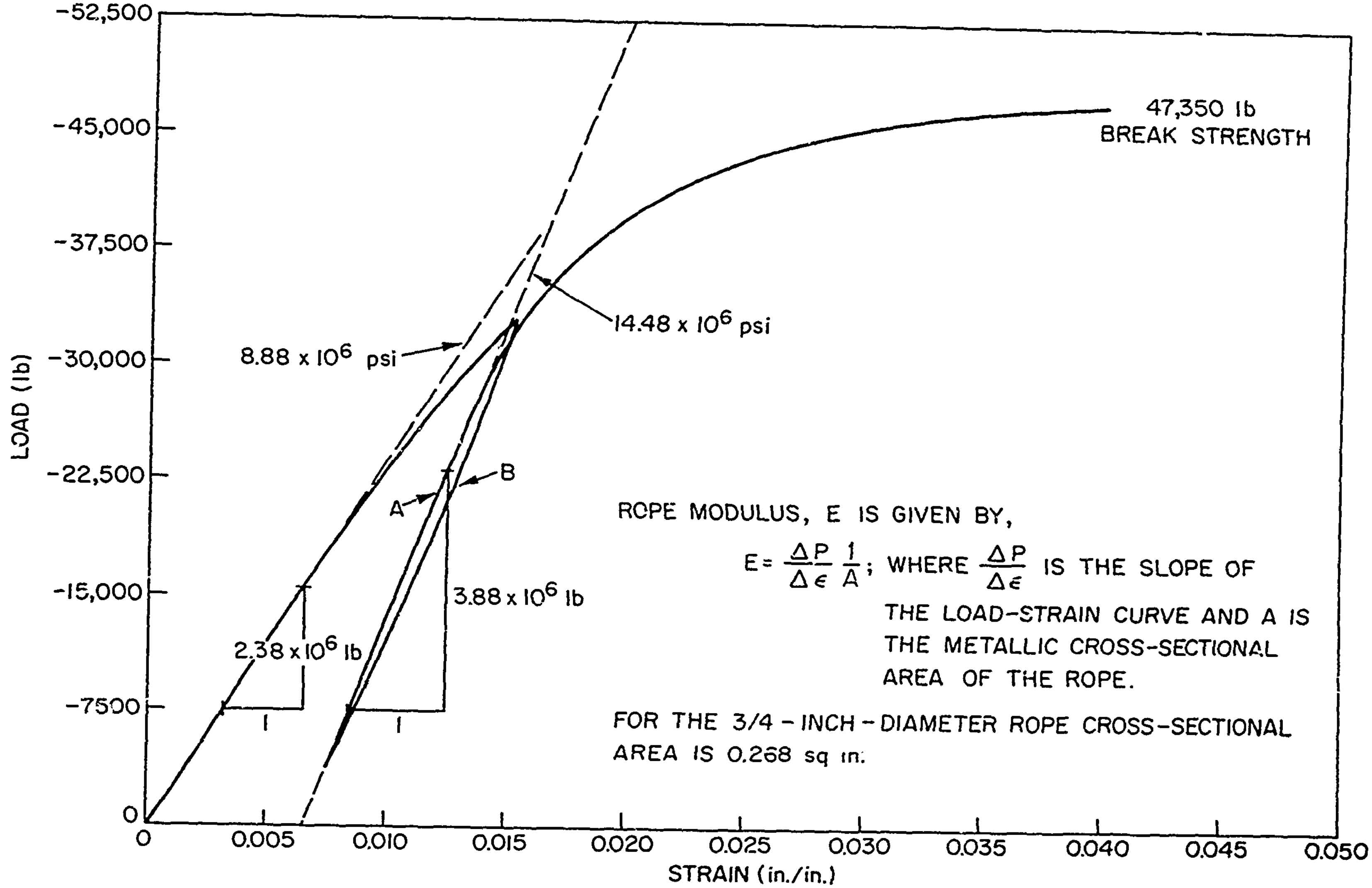

Fig. 13 - Load-strain behavior of a 3/4-inch-diameter wire rope

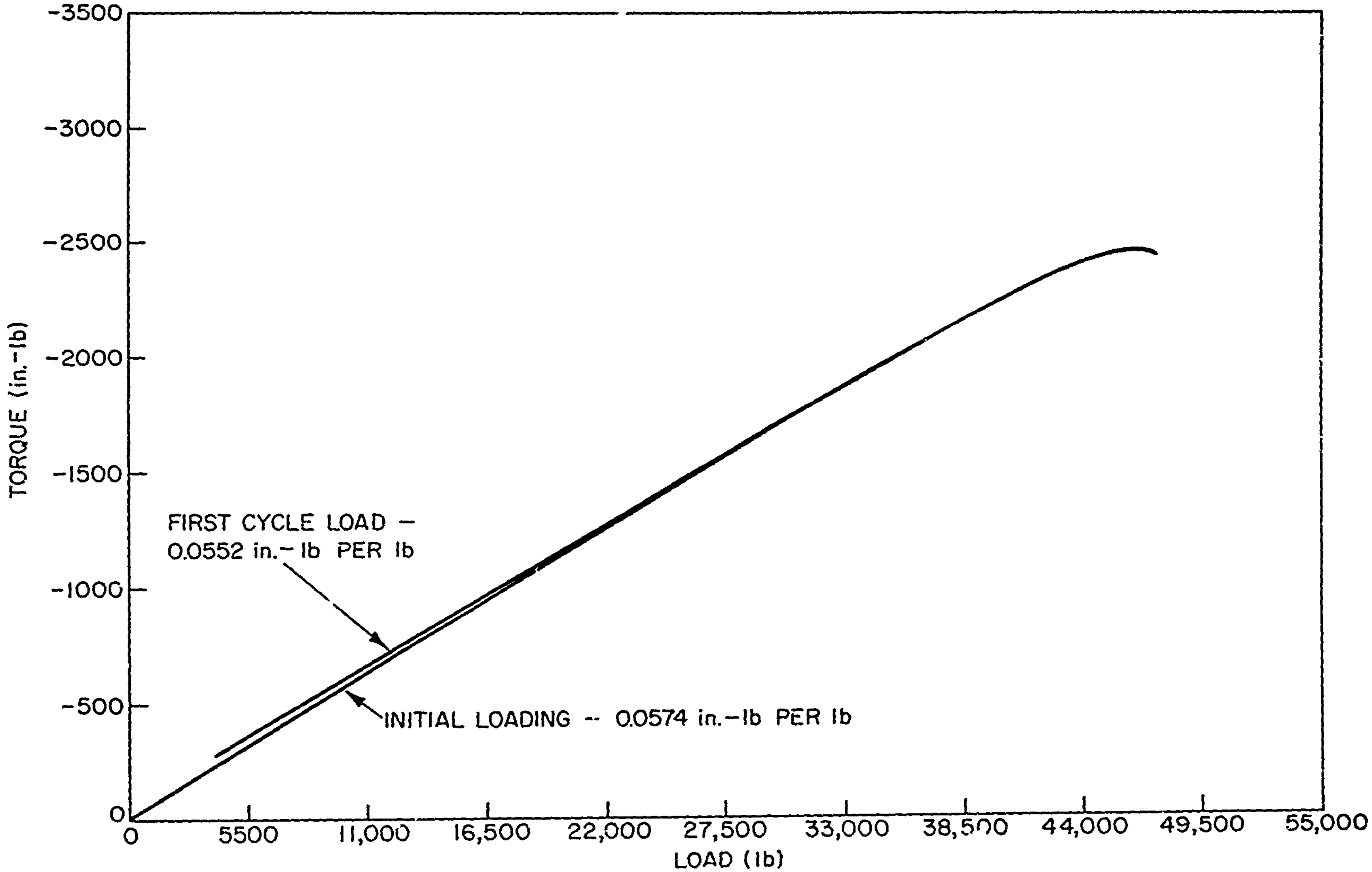

Fig. 14 - Torque-load behavior of a 3/4-inch-diameter wire rope

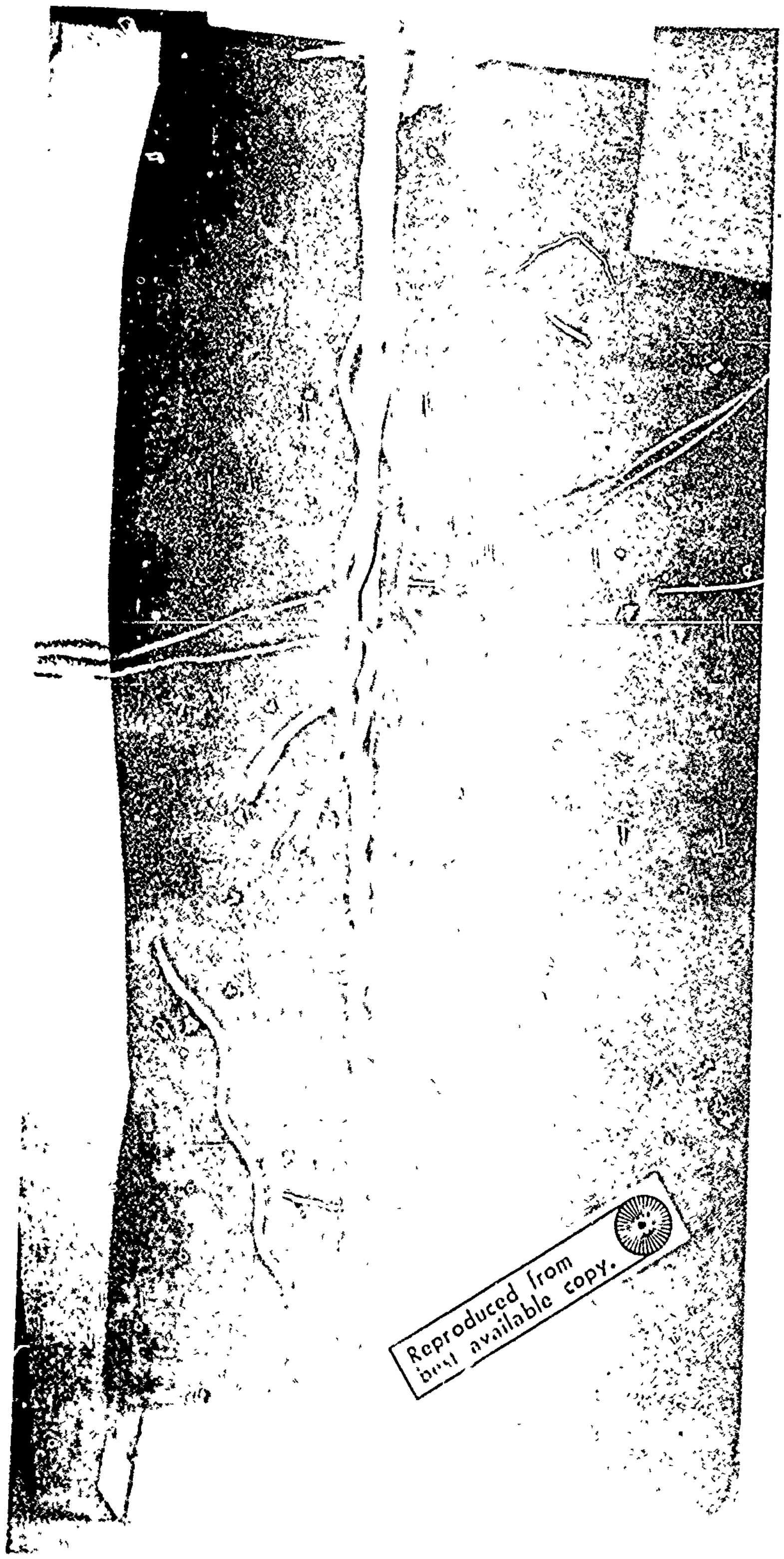

Fig. 1. [illegible]