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ANALYSIS OF DAMAGE TO INSTRUMENTATION CABLES REMOVED FROM WATTS BAR NUCLEAR PLANT

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INTRODUCTION

As a result of an Employee Concern program, a group of instrumentation cables was removed from conduits at the Watts Bar nuclear plant (WBN) of the Tennessee Valley Authority (TVA). This program had specifically cited the possibility of thermal damage to instrumentation cables inside a conduit that had received an electric welder arc strike. When the cable was removed from this conduit, there was no readily apparent thermal damage to the jackets of any of the 26 cables in the conduit cited. However, a number of areas on the cable jackets contained damage ranging from slight abrasions/cuts into the jacket, to exposed conductors. The damage appeared, upon inspection by TVA, to have been mechanically introduced. The Electrical Insulation Research Center (EIRC) was contacted for an independent evaluation of the nature of the damage to the cable jackets and to determine how and when it may have occurred.

Approximately four weeks later, another group of cables was removed by TVA from Unit 1 of the Watts Bar facility for the express purpose of assessing whether any damage similar to that found in the aforementioned cable conduit was to be found. Some locations on the surfaces of the latter cables contained damage similar to that found on the surfaces of the previous cables, as examined by TVA.

EIRC was specifically asked to use its expertise and experience to determine the cause of the damage to these cables. All testing/analysis was witnessed by TVA employees, including Frank McGovern, Brian Reagan, Kent Brown, Tom Hughes, and Jim Hutson.

Tables 1 and 2 indicate the inventory of cables evaluated which were removed as a result of the Employee Concern program and those removed at TVA's discretion to assess the extent of damage to other instrumentation cables at the WBN facility.

Table 1
Selected Cables Removed As A Result of Employee Concern Program from WBN Unit 2

2PM-506-D	2PS5281D
2PM-516-D	2PS-283-D
2PM-4781-D	2PM-696-D
2PM-508-D	2PS-284-D
2PM-1694-D	2PM-881-D
2PM-1041-D	2PM-871-D

Table 2
Cables Removed At Discretion of TVA from WBN Unit 1

X9	0-SP-285-529
1-2PM-203-4470-B	1M-2450-B
1-PM-506-D	1-PM-1656-D
1-PM-778-D	SP565 (2-3PL-26-5080-B)
1M-591-B	V976B
1RM440A	1-RM-452-B
1-2RM-90-450-B	1-2RM-90-448-B
1-2PL-83-1085-B	1-2PM-3-3990-A
2V-2846-B	1-3M-74-2451-B
1-2PS-68-283-D	1PM4470B

Table 3
Remaining Samples Submitted By TVA for Reference/Background

parachute cord	pull rope
flexible conduit	"Yellow-77" lubricant
"Polywater G" lubricant	"Polywater J" lubricant
virgin cable(CPE)	virgin cable (Hypalon®)
virgin cable (XLPE)	concrete anchor
Wasp killer spray	fire stop "breaching tool"

In meetings with TVA, a number of items were discussed as background to the investigation. These are as follows:

* It is known that "Yellow-77" was the predominant pulling compound used during the original installation of the instrumentation cables at the Watts Bar facility.
* The complement of cables were installed as sub-bundles (pull-bys) in a given conduit, rather than as one complete bundle (bulk pull).
* To aid in removing the cables with as little subsequent damage as possible, the conduits were lubricated with "Polywater G" pulling compound. This was later washed from the surfaces of the cables prior to their shipment to EIRC.
* TVA prepared isometric drawings of the instrumentation cable conduit system at the Watts Bar facility and compared the locations of damage on the instrumentation cables to the corresponding locations in the conduit system. A significant amount of damage was found to correspond to the location of a flexible conduit. The latter was also provided to EIRC for analysis.
* The instrumentation cables contain three different types of jackets, including chlorinated polyethylene (CPE), Hypalon® rubber, and crosslinked polyethylene (XLPE).
* The Unit 2 instrumentation cables had all been installed between 1982 and 1985 and were removed between June and July, 1989. The unit 1 cables from conduit MC 400B were installed between 1979 and 1985 and were removed in September, 1989.
* TVA stated that cables 1-PM-778-D and 1-PM-1656-D were known or suspected to have suffered accidental contact with an abrasive cut-off wheel used to dismantle a fire seal during removal of this cable.

INSTRUMENTATION USED FOR ANALYSES

Infrared Microspectrophotometry (μIR)

This instrument consists of a dispersive type infrared spectrometer that is integrated into a special optical microscope. This system allows conventional infrared absorption spectra to be obtained from very small, user selected areas of specimens that are too small for conventional, bulk IR spectroscopy. The system is used by focusing a reference (visible) light beam over an area of interest then the infrared spectrometer scan is started. The spectrometer consists of a variable wavelength infrared light source that is scanned from a wavelength of 2.5 to 14.5μm. While the spectrometer is scanned at a user-selected rate, the transmitted infrared signal through the specimen is simultaneously monitored with a mercury cadmium telluride detector. The infrared wavelength is plotted against the corresponding absorbance to produce a spectrum. Virtually all organic compounds contain chemical bonds that actively absorb infrared radiation at selected wavelengths. Each compound contains its own fairly unique "fingerprint" of absorbances. These are catalogued in a number of references on the subject [1,2].

Optical Microscopy (Stereo, Polarized)

Three types of optical microscopy were used throughout this investigation. These included stereo microscopy, photo macroscopy, polarized microscopy. Stereo microscopy provided a magnification range from 1 through 80 magnifications, with the Nikon SMZ-1, serial #193348, used for this project. This type of microscope provides two concentric optical paths in order to maintain a high depth-of-field. This instrument was used to aid in viewing the surface details at all of the damaged sites on the cable jackets. It was also used to inspect the surface of the concrete anchor for any debris that might have indicated its time of placement in the conduit from which it had been removed.

Photography of larger areas, in the magnification range of 1x through 50x, was accomplished with a macro-photography system.

This operates in much the same way as the stereo microscope previously described, except that only one optical path is used. This system, a Leitz model 301-182101, serial #604, was used to photograph many of the damaged sites on the cable surfaces.

Polarized microscopy consists of a microscope with a single optical path and various polarizing accessories incorporated for the purpose of measuring the optical properties of a specimen. A Nikon Biophot, serial #520114, was used throughout this project. This instrument has a magnification range from 40 through 1000x. The "Yellow 77" and "Polywater" pulling compounds were examined with this microscope in order to identify their components. The ends of the conductors of one cable section that was found broken within a conduit were examined with this instrument.

The polarizing microscope previously described can be used with either transmitted or reflected illumination. The former is typically used for the examination of optically transparent materials, while the latter is used to examine opaque specimens. Thicknesses of the insulation from the coaxial cables were measured with this instrument, using a scale calibrated with a reference grating from Reticules, Inc., traceable to NBS standards.

Hardness Testing

Shore hardness measurements were made on the surfaces of all of the cable jackets selected for analysis. A Shore hardness tester was used for all tests cited herein. The Shore hardness A probe, serial #88766 and D probe, serial #87458, were used exclusively for all hardness testing. This instrument consists of a series of calibrated styli that are impressed into the surface of a material with a constant force. The displacement, or penetration of the stylus into the material's surface is measured with a built-in dial micrometer. The displacement is proportional to the hardness of the material. The Shore hardness value is dependent on the type of stylus used (Shore A or D) and the stylus displacement. The relationship is described in tables provided with the tester. Calibration of the hardness tester was conducted with standard blocks supplied with the instrument. Hardness testing was used to determine if any cable jackets were improperly manufactured or had suffered some deleterious damage while in the conduits or during handling prior to their installation. Hardness of polymers can be adversely affected by solvent interaction, thermal damage, or improper manufacture, among other considerations. Hardness values obtained from the damaged cables were then compared with values provided from the manufacturers of these cables, as obtained by Frank McGovern, in the presence of EIRC.

Tensile Testing

An Instron model TTCM6, serial #856, tensile tester was used to determine the tensile strength of the "parachute cord" which had been found in one of the implicated conduits and was known to have been used for cable pull-in operations. The tensile properties of a 2 conductor #12 AIW cable were also obtained with this instrument. This instrument consists of a grip system that is used to hold a specimen from either end. One grip is fixed to a load cell while the other is attached to a moving frame that has a user-selectable rate of displacement. From this instrument, the user obtains a chart showing displacement plotted against load. The tensile strength of a material is obtained by measuring the maximum load obtained when a specimen breaks under load. The Instron system was calibrated with an Instron weight set, traceable to NBS standards for Class C Laboratory Weights.

Pull-by "simulations" were also conducted with the Instron system. This afforded a means for obtaining a known contact load between a cable and a pull rope, for example, while simultaneously allowing for a controlled rate of contact velocity.

Gas Chromatography/Mass Spectroscopy (GC/MS)

This instrument is used to identify volatile organic compounds, based on their molecular weight and retention time in a special column. This system consists of two subsystems, as the name suggests. The gas chromatograph is an instrument that makes use of a special, small bore (i.e., 20µm) column into which a gas sample is injected. At the end of the column is one of a variety of detectors that sense a gas evolving from the column based on its thermal conductivity, infrared absorbance, dielectric constant, or other property, depending on the type of detector used. Larger gas molecules pass through the column more slowly than the smaller ones. In this manner, the column separates a gas mixture into its constituents. The measurement consists of determining a retention time, in a given column, as a function of temperature. Standard, high purity gases are used to calibrate the column before and after an analysis.

The mass spectrometer system uses the gases separated by the GC system and measures their mass as they are accelerated through a strong magnetic field. By combining the GC and MS systems, each gas component can be identified by its retention time and mass. This instrument was used in an effort to identify the agent responsible for the apparent swelling of the jackets of cables 2V-2846-B and X9. This will be explained in detail in this report.

Micrometry

A hand-held micrometer was used to measure the thickness of some of the cable components. The micrometer used was a Mitutoyo 1 inch range, serial #Y12549. The calibration was checked with a set of Do-All gage blocks, serial #826. Thickness measurements were made in at least three locations for each measurement, with the average results recorded.

X-Radiography

X-radiographic inspection of selected specimens was accomplished with a Faxitron model 805 system, serial #1472. All inspections were accomplished with a potential of 90 kV, using copper kα X-radiation. The distance of the specimen to the X-ray source was maintained at 8 inches. Photographic records were made of all radiographic inspections and appear within this report.

Metallographic Inspection

This inspection technique involves mounting a metal sample into a hard, polymeric resin, with subsequent polishing through successively finer abrasive steps to obtain a highly polished cross-section of the metal sample. This procedure was used to determine the thickness of the oxide layer on the surface of copper conductors that had been exposed due to damage to the jacket and insulation of the cable in which they were included. Inspection of the metallographic specimen is accomplished with a reflected light microscope, as previously described.

Thermal Aging

To experimentally determine the rate of oxidation of the copper conductors in cable 2PM-516-D, a section some location away from the damaged site on this cable was removed. On this section, the jacket and insulation were removed to exposed approximately the same area as that exposed in the damaged site. This was then inserted into a hot air oven at 60°C for a period of 60 days.

EXPERIMENTAL PROCEDURES

Cable Shipment and Initial Inspection

The cables listed in Tables 1 and 2 were separately shipped in wooden crates to EIRC. Figure 1 shows the first set of shipping crates containing the cables listed in Table 1. These crates were opened in the presence of TVA personnel. Figure 2 shows the flexible conduit section, as removed from its shipping container. Note that care was taken to keep the conduit in its original conformation, as found at the Watts Bar facility. The cables were removed from their shipping containers and laid out on a floor for inspection by EIRC personnel and to review the labelling system used by TVA to identify the cables and the damaged sites on each cable. Figure 3 shows one bundle of cables as they were removed from their shipping container. Figure 4 shows two damaged sites on the cables removed from conduit MC 400B, covered prior to shipment by TVA with protective wrap, as requested by EIRC. This precaution was taken to reduce the chances for subsequent damage or contamination to the damaged sites.

The items listed in Table 3 were received in five separate shipments over the course of six weeks. The virgin cable samples were shipped at the request of EIRC for the purpose of comparative hardness measurements and for use in pull-by simulations.

Representative damaged sites were removed from the instrumentation cables according to a priority ranking system as suggested by TVA and agreed to by EIRC. These sites correspond to those listed in Tables 6 through 8.

Infrared Microspectrophotometry

Infrared microspectrophotometric analyses were conducted on fibers of the pull rope and the parachute cord. In addition, the pulling compounds and surface residues from the concrete anchor were also analyzed. Individual fibers from the ropes were removed with a fine tweezer and supported over an open hole in an aluminum holder. This was then imaged on the µIR microscope. The IR spectrometer was then scanned at a rate of $4cm^{-1}$/minute, from $4000cm^{-1}$ to 690 cm^{-1}. The spectrometer was calibrated with a Perkin-Elmer standard polypropylene film, serial #1667-1. Samples of the pulling compounds, "Yellow-77", "Polywater G", and "Polywater J", were placed on thin salt crystals for µIR analyses. The salt crystals were first analyzed without pulling compound present, to established a background spectrum. The salt crystals containing the pulling compound were then analyzed, with the background spectrum from the crystals alone subtracted.

Visual and Stereomicroscopic Examination

Visual inspection was first conducted to assess the extent of damage to the cable components. The cables were divided into three categories according to the extent of damage observed, as will be discussed. Figure 5 shows a representative visual examination of three damaged sites removed from the instrumentation cables listed in Table 1. Following visual examination, a stereomicroscope was used to examine the damaged sites in more detail. Figure 6 shows one such cable being examined with this instrument. These examinations concentrated on the details at the damaged sites, such as surface characteristics, presence of embedded materials, presence of material flow, sharp cuts, crushing, etc.

The fracture surface of cable 2PS5281D was examined for its morphology to determine its mode of fracture. These details were subsequently photographed.

Physical Dissection

Physical dissection of a number of sites on selected cable samples was conducted. This was accomplished with a number of sectioning tools, including scalpels, razor blades, pliers, and other tools, selected as needed. All such dissections were conducted in the presence of TVA personnel. In all cases, such dissections were preceded by X-radiographic inspection so as to be certain that destructive sectioning would not inadvertently destroy areas or information that would hinder the investigation.

Polarized Microscopy

The pulling compounds were analyzed with the polarizing microscope to determine if they were homogeneous and might contain any constituents that may have aided in identifying the time of damage to any of the cables. A few drops of each pulling compound were mounted on glass slides and observed under polarized, transmitted illumination at magnifications ranging from 40x through 400x. The components were characterized by their optical properties (polarizing characteristics, color, solvent interaction, texture, etc.) and identified with the aid of reference [3].

Hardness Testing

Hardness testing of the cable jackets was conducted with the jacket in place over the cable core. The Shore A or Shore D scales were used for all of the hardness tests conducted. Hardness testing was conducted on virgin cables of each jacket type (CPE, Hypalon®, and XLPE). It should be noted that the virgin cables are of the same vintage and manufacturing source as the damaged cables. Hardness values were obtained from various locations on the surfaces of the damaged cables. These included sites in the immediate vicinity of the damage and sites some distance removed from those sites.

Tensile Testing

Tensile testing of the pull ropes and one wire specimen was conducted with the Instron machine previously described. All tensile tests were conducted with an extension rate of 0.25 in/minute. Loads were determined from a calibrated recorder scale. The tensile strength data obtained corresponded to the ultimate tensile strength (i.e., the load measured at the break point).

Pull-By Simulations

Pull-by "simulations" were conducted on the Instron tensile testing machine previously described. Various combinations of cable-over-cable and parachute cord-over-cable were used to determine the nature of the surface damage inflicted at the interface between these materials. Cables of the various jacket types were sequentially pulled over cables of the same and other jacket types. The parachute cord was pulled over each of the cable jacket types. To accomplish this, a loop of each cable was formed and fixed to the traveling (lower) end of the Instron test frame. To the upper, or stationary part of the frame, the cable or parachute cord being pulled over the cable loop was attached at one end. The free end of the latter was then held by hand at a 90° angle to the load axis. This arrangement is shown in Figure 7. In Figure 8, a pull-by simulation is shown as it is being conducted. The operator is controlling the tension on the parachute cord, in this case, to assure that a desired contact load is maintained, as indicated on the load-indicating chart recorder shown at the left edge of this Figure. Contact loads of approximately 75, 100, and 150 lbs were used for all combinations of pull-bys. The selected load was maintained by physically restricting the movement of the free end on the lower cable or rope, while observing the load detected by the Instron load cell. These loads were chosen to be representative of moderate and upper limits of the pulling forces achievable by a single person installing cables. The contact velocity was maintained at 20 inches/minute and a standard pull-by of 12 in. of material was maintained for all tests. This velocity, though perhaps slower than a true cable pull-in operation, was the highest speed available on the equipment at the disposal of EIRC. Subsequent to these pull-by simulations, the surface damage on each cable was evaluated visually and with the aid of a stereomicroscope.

The pull rope was not used in the pull-by simulations as it was determined by EIRC to be too large in cross-section to have inflicted the type of localized damage found on the surfaces of the cables in question.

Gas Chromatography/Mass Spectroscopy

Analysis of the compound(s) responsible for swelling of the jacket on cable 2V-2846-B (Hypalon®) was attempted using a thermodesorption process to remove the responsible material(s) from the jacket for subsequent identification using GC/MS methods. Sections of the jacket material in the swollen area were heated in a closed chamber to 150°C. The evolved gases were then injected into the GC/MS system which was run through a temperature program from 35°C to 350°C. An OV1 fused silica capillary column, 0.32mm x 50 meter length, was used to separate the gaseous components for identification. To determine what differences might exist in the chemistry of the swollen areas compared with the unaffected areas, analyses of both were conducted. The spectral peaks obtained with this system are identified through use of the Environmental Protection Agency (EPA) search library, among others. As only a single peak could be identified as unique to the swollen area of the Hypalon® cable jacket, a number of steps were taken to attempt to increase the system resolution. These included increasing the sample size, cryo-focusing of the injection step, and other standard concentration procedures. These are not described in detail as no significant results were obtained.

Wasp Spray Interaction with Cable Jacket Material

Using the wasp spray provided by TVA (Superior Industries "No Sting"®), several areas of the jacket of cables 2V-2846-B and X9 were exposed to this material and observed for any swelling. This was done under ambient conditions at a temperature of approximately 72°F. After four days, no swelling had yet become apparent. A final observations was made following ten days and no swelling had become apparent.

X-Radiographic Inspection

X-radiographic inspection was conducted on the samples shown in Table 4 for the purpose of non-destructively inspecting the internal construction. It was suspected that some of the irregularities in these cables might be attributable to splices in the conductor strands. This method was also used to inspect what appeared to be a repair splice identified as 1-2PS-68-283-D, prior to sectioning.

Table 4
Cables and Samples Subjected To X-radiographic Inspection

1-2PS-68-283-D	1-2PM-203-4407-B
1-2PM-3-3990A	2PM-4781-D
2PM-1694-D	

RESULTS

Analysis of Pulling Lubricants, Pull Cord and Pull Rope

Infrared microspectrophotometry (µIR) was used to characterize the pulling compounds "Yellow 77", "Polywater J", and "Polywater G". The "Yellow 77" compound was found to contain three components, including a liquid, cellulose fibers, and a yellow inorganic pigment. Figure 9 is the infrared spectrum from the "Yellow 77" compound, with most of the liquid removed and some yellow pigment present. From reference [1], and excluding the absorbances due to water, the spectrum corresponds to that for cellulose. The liquid phase could not be fully identified using this technique, but was determined to contain water and a hydrocarbon of some type. The yellow pigment was not analyzed beyond the simple determination of its inorganic nature.

The "Polywater G" and "J" compounds were found to consist of a liquid component and, in the case of "Polywater J", a brown inorganic pigment with a particle size of less than 1 µm. The pigment was not analyzed beyond a simple determination of its inorganic nature. Infrared spectra for "Polywater J" and "Polywater G" are presented in Figures 10 and 11, respectively.

Small fibers of the parachute cord and pulling rope were removed for identification using the µIR method. Figure 12 shows identical infrared spectra from two separate parachute cord fibers. Figure 13 is a spectrum for nylon 6,6, obtained from reference [1]. Figure 14 is the infrared spectrum from a fiber of the pull rope.

Inspection of Flexible Conduit

The interior of the flexible conduit section was first examined with the aid of a borescope provided by TVA. This disclosed no evidence of any cable jacket material retained within the convoluted interior surface. The conduit was subsequently sectioned by unwrapping its convolutions, as shown in Figures 15 and 16. These were then visually inspected and, again, no evidence of cable jacket material was found at any point. At the end of the conduit where there is a transition between a female pipe thread and a straight section of galvanized pipe, a sharp edge was found, as shown in Figure 17. No evidence of retained cable jacket material was found at this point.

Assessment of Copper Oxidation

Metallographic inspection of the oxidized surface of the conductors of cable 2PM-516-D disclosed that the oxide was 7µm thick. For comparison purposes, the sample of the same cable, deliberately exposed to a slightly elevated temperature for 60 days, contained an oxide film thickness of 0.5 µm.

Inspection of Cable Repair Sleeve

Inspection of the suspected repair sleeve, 1-2PS-68-283-D, shown in Figure 18, was first conducted with X-radiography. The corresponding X-radiograph of the cable within the repair sleeve, Figure 19, reveals a cut through the cable jacket. The underlying cable components appeared to be unaffected, but the cable was subsequently dissected for more detailed examination. Figure 20 reveals the cable jacket with the repair sleeve stripped away. The cut in the jacket is shown at the center of this figure, with the open end on the right. The cut was found to have been filled with an elastomeric resin. Figures 21 shows the cable components underneath the jacket cut, with no damage to these components evident.

Analysis of Jacket "Bumps" and "Bulges"

A number of cables were found to contain protrusions in their cross-sections, variously referred to as "bumps" or "bulges". The term "bump" was used to describe the short, relatively sharp protrusions from the jacket surfaces. "Bulge" was used to describe the longer, less sharp protrusions. The cables containing these features are identified as follows: 2PM-4781-D, 2PM-1694-D, 2PM-1041-D (2 locations), 2PS-284-D, and 1-2PM-3-3990A. Figures 22 and 23 show one "bump" and one "bulge", respectively, on the surface of cable 1-2PM-3-3990A. The "bump" on the surface of this cable was subjected to X-radiographic examination, as shown in Figure 24. This shows that there is no interruption in the conductor bundle. Similarly, Figure 25 is an X-radiograph of the "bulge" on the surface of the same cable. Again, there was no interruption in the conductors noted. The "bump" site was subsequently dissected and found to contain a large chunk of material embedded within the jacket, as shown in Figure 26. The "bulge" site was found to contain similar inclusions of material within the jacket. Small bits of these materials were removed from the jacket for characterization. They were found to be black, opaque, brittle, and insoluble in a range of polar and non-polar organic solvents. No further analyses were conducted on these materials. Cable 2PS-284-D was found to contain a similar particle embedded in its jacket immediately under a "bump". X-radiographic inspection revealed that this cable did not contain any interruptions or splices within the conductors.

Figure 27 shows cable 2PM-4781-D and the corresponding "bulge" in its jacket. At the top of this figure, the splice in the assembly wrap is shown, including the black thread used to make the joint. This was found immediately under the "bulge". Figure 28 shows cable 2PM-1694-D with its jacket "bulge" at the bottom and the corresponding splice in its assembly wrap shown at the top of this figure. White thread was used to complete the splice. Cable 2PM-1041-D (location 1) was found to contain a similar "bulge" on the surface of its jacket, with a corresponding splice in the assembly wrap, also sewn with white thread. Figure 29 shows the "bulge" in the surface of cable 2PM-1041-D (location 2), with the corresponding joint in its assembly wrap shown at the top of this Figure. In this case, the joint was completed with a yellow Mylar tape. A cross-section through the jacket of the latter cable is shown in Figure 30. No anomalies were found in the wall of this jacket. X-radiographic inspection of the cables containing splices in their assembly wrap tapes disclosed that none contained any interruptions or splices in their conductors. This includes cables 2PM-4781-D, 2PM-1694-D, and 2PM-1041-D.

Examination of Abandoned Cable

Cable 2PS5281D had been found as a short section that had been abandoned in the WBN Unit 2 conduit in which it had been installed. The ends of this cable were examined in order to determine how it had failed, specifically whether it had broken or had been cut. Figure 31 is an overall view of the end of this cable. In Figure 32, more details of the ends of the conductors are shown. These were found to be elongated and tapered which is consistent with a tensile overload fracture [5].

Jacket Hardness Results

Hardness testing of most of the cables listed in Table 1 was conducted. In those cases when a jacket "bulge" or "bump" was present, the reasons for these became apparent as a result of the dissection of these sites. As a consequence, hardness testing of these sites was not necessary. In addition, the cables containing swollen jackets, 2V-2846-B and X9, were tested for their jacket hardness. The hardness of the jacket of cable 2PS5281D was not measured as this had been abandoned within its conduit. Expected hardness values for the cable jackets listed below were obtained from the manufacturers on September 12, 1989, by Mr. Frank McGovern, of TVA, while on-site at EIRC. Table 5 lists the hardness values for each of the cable jackets tested and their corresponding expected values.

The hardness values measured near each of the damaged areas of the cables listed in Table 5 were compared with hardness measurements approximately 4 in. away from the damaged sites. In all cases, these compared within less than $\pm$ 0.2, Shore A units. This range is within experimental error.

Table 5
Expected and Measured Hardness Values for Cable Jackets
All Values Provided In Shore A Units

cable ID	measured hardness	expected hardness
2PM-506-D	89.8	93
2PM-516-D (location 1)	93.6	93
2PM-508-D (location 1)	91.9	93
2PM-871-D (location 1)	92.7	93
2PM-871-D (location 2)	94.5	93
2PM-516-D (location 2)	92.7	93
2PS-283-D	71.0	65-68
2PM-696-D	71.5	65-70**
2PM-508-D (location 2)	93.0	93
2PM-881-D	73.4	65-70**
2PS-284-D	69.6	65-68
2V-2846-B (swollen area)	55.8	65-70
2V-2846-B (non-swollen)	76.7	65-70
X9 (swollen area)	60.3	65-70
X9 (non-swollen)	79.3	65-70

** note: These jackets are made from Hypalon® insulating material. As a result, the values for hardness are those expected for other Hypalon® jacketed cables and these are used for comparison purposes.

Analysis of Damaged Sites

Microscopic examination of all of the damaged sites on the cables failed to disclose any residue of the pulling compounds, including "Yellow-77", "Polywater G", and "Polywater J". In addition, no fibers from any of the pulling ropes or parachute cord could be identified. Microscopic examination of the concrete anchor surface and analysis of selected samples of the surface residues failed to disclose any residues of the three pulling compounds previously described.

Examination of the details of the damaged locations on the cables shown in Tables 1, 2, and 3 was conducted with the stereomicroscope. As a result of this and visual examination, the cables were divided into the categories shown in Tables 6, 7, and 8. Each category contains cables grouped according the the severity of jacket and insulation damage. Details of the damage sites on each cable were examined and the results are itemized in the following paragraphs.

Table 6
Cables with Exposed Conductor Strands
(Manufacturers are Indicated In Parentheses)

2PS-284-D (AIW)	2PM-881-D (Eaton)
2PM-516-D (Anaconda)	1-3M-74-2451-B (Rockbestos)
2PM-871-D (Anaconda)	2PS5281D (abandoned)
O-SP-285-529 (Cyprus)	

Table 7
Cables with Damaged Insulations, Non-Exposed Conductors
(Manufacturers Indicated In Parentheses)

2PM-506-D (Anaconda)
2PM-871-D (Anaconda)
1M-2450-B (Rockbestos)
1-3M-74-2451-B (Rockbestos)
1PM4470B (Eaton)

The cables listed in Table 8 were examined visually and with the stereomicroscope to study their surface damage. Cable 1-2PS-68-283-D was previously discussed and found to contain a damaged jacket under a repair sleeve. Cables 2PS-284-D, 1-2PM-3-3990A, 2PM-4781-D, 2PM-1694-D (2 locations), and 2PM-1041-D (2 locations) were found to contain jacket "bumps" or "bulges", as previously described. Cables 2V-2846-B and X9 were found to have jackets that had been swollen, as previously described. Cables 1-PM-778-D and

1-PM-1656-D were each found to have a groove approximately 0.150 in. wide penetrating through and limited to the jacket, as shown in Figure 33, for cable 1-PM-778-D. In a short experiment, contacting an unaffected area of this cable with an abrasive cut-off wheel (Makita 12-304), at 3500 rpm, resulted in a site with damage similar to that found on this cable.

Table 8
Cables with Damage Limited to Jacket
(Manufacturers Indicated In Parentheses)

1-2PS-68-283-D (AIW) (repair)	2-3PL-26-5080-B (Cyprus)
1M-591-B (AIW)	1-2PM-3-3990A (Eaton)
1-2PS-68-283-D (AIW) (damage site)	1-2PM-203-4470-B (Eaton)
2PS-284-D (AIW)	2PM-696-D (Eaton)
V976B (AIW)	2PM-1694-D (Eaton)
1-2PL-83-1085-B (Anaconda)	1-2RM-90-450-B (Rockbestos)
1-PM-778-D (Anaconda)	1-2RM-90-448-B (Rockbestos)
1-PM-1656-D (Anaconda)	1-RM-452-B (Rockbestos)
2PM-508-D (Anaconda) (2 locations)	1RM440A (Rockbestos)
2V-2846-B (Rockbestos)	1-PM-506-D (Belden)
2PM-516-D (Anaconda)	X9 (Rockbestos)
2PM-1694-D (Eaton)	2PM-4781-D (Eaton)
2PM-1041-D (Eaton) (2 locations)	

Cables 2PS-283-D, V976B, 2PM-508-D (2 locations), 2PM-516-D, 2-3PL-26-5080-B, and 2PM-696-D were found to contain longitudinal cuts through their jackets. These cuts varied in length from approximately 0.25 in. through 1 in. They had a round cross-section and were approximately 0.130 in wide. When compared with the grooves formed during the pull-by simulations, their appearance and features corresponded virtually completely. Figure 34 shows such a feature on the surface of cable 2PS-283-D.

Cables 1-2PL-83-1085-B, 1-2RM-90-450-B, 1-2RM-90-448-B, 1-RM-452-B, and 1RM440A were found to contain a variety of shapes of short, sharp cuts in their jacket surfaces. These varied in length from approximately 0.080 in. to approximately 0.50 in. The cuts were found to have surface features indicative of the surfaces with which they had come into contact (i.e. rough edges). Though examined carefully, the edges of the cuts contained no embedded materials that might have been analyzed to determine their origin. Figure 35 is an example of a surface cut limited to the jacket of cable 1-2PL-83-1085-B. Cross-sections through the damaged areas of the coaxial cables listed in Table 9 were prepared so that the remaining wall thicknesses could be measured with the microscope.

Table 9
Jacket Wall Thicknesses for Coaxial Cables
All Values In Mils

cable ID	damaged wall thickness	non-damaged wall thickness
1-2RM-90-450-B	18	35
1-2RM-90-448-B	22	35
1-RM-452-B	28	35
1RM440A	30	35

The final group of cables from Table 8, cables 1M-591-B, 1-PM-506-D, and 1-2PM-203-4470-B were found to contain splits in their jackets. Examination of the split surfaces indicated that these were caused by excessive, local tensile stresses. This may have resulted from sidewall tension caused by high frictional contact forces (pull-by) or bunching of the cables during secondary pull-by operations. Figures 36 and 37 show examples of splits in the jackets of cables 1M-591-B and 1-PM-506-D, respectively.

The cables listed in Table 7 were found to contain surface damage that extended through the jacket into the underlying insulation, without exposure of the conductors. Two of these, cables 2PM-506-D, 1-3M-74-2451-B, and 2PM-871-D contained narrow grooves cut into their surfaces. These were approximately 0.140 in. wide and varied in length from 0.50 in. to more than 1 in. When compared to the grooves introduced during the pull-by simulations with the parachute cord over the jacketing materials, these grooves shared all observable features. Cable 1M-2450-B was found to contain a shallow, smooth-edged cut into the insulation. To determine the extent of this damage, a cross-section was prepared through the damaged site, as shown in Figure 38. The remaining insulation thickness at this site was 7.4 mils, out of a nominal 30 mil thickness.

Of the cables listed in Table 6, cables 2PS-284-D, 2PM-516-D, 2PM-871-D, and 1-3M-74-2451-B were found to have deep, narrow grooves in their surfaces, sharing virtually all features with those produced in the pull-by simulations with the parachute cord over the jacketing materials. Cable O-SP-285-529 was found to contain a deep, sharp cut into its jacket surface, through the insulation, with exposed the conductor strands. Figure 38 shows one example of a sharp, long cut in the jacket of cable O-SP-285-529. Cable 2PM-881-D was found to be highly twisted and distorted with the jacket severely pulled back along the cable. This apparently resulted from entanglement with other cables or pull cord in the conduit.

<u>Pull-By Simulation Results</u>

The pull-by simulations produced a number of results that provided background regarding possible surface damage mechanisms, given the complement of cables and parachute cord provided. Pull-by simulations of the combinations of cable jackets shown in Table 9 produced only a slight scuffing of the cable jackets. As indicated under the stereomicroscope, no traces of material loss were noted on either cable of the pairs shown in Table 10, as a result of these simulations. The scuffing on the surfaces was so slight that it defied photographic recording. The simulations of parachute cord in combination with Hypalon® at a load of 75 lb. produced some damage and material loss on the jacket surface. At a load of 100 lb. the parachute cord cut a groove into the surface of the Hypalon® jacket. At a contact load of 150 lb., the Hypalon® jacket was cut completely through, exposing the underlying cable components. The groove was measured to have a width of approximately 0.14 in. The edges of the groove were found to be smooth, with no elongated "stringers" of material evident at the edges.

The surface of the CPE jacket was severely damaged by the parachute cord during the pull-by simulations with a contact load of 75 lb. This produced a narrow groove that nearly penetrated the jacket thickness. With a load of 100 lb., the jacket was fully penetrated by the parachute cord, as shown in Figure 39. The groove was measured and found to have a width of approximately 0.13 in. The edges of the groove were found to be smooth, with a great deal of feathering at the edges with "stringers" present. The latter term is used to describe the strings of elongated jacket material extending past the end of the groove cut by the parachute cord. These result from plastic flow of the polymer, caused by high contact forces and high temperature produced by interfacial friction.

Table 10
Combinations of Cable Jackets and Parachute Cord Used In Pull-By Simulations

* chlorinated polyethylene vs. chlorinated polyethylene (CPE)
* Hypalon® vs.Hypalon®
* chlorinated polyethylene vs. Hypalon®
* chlorinated polyethylene vs. parachute cord
* Hypalon® vs. parachute cord

Tensile Testing Results

Tensile testing of a 2 conductor, #12 AWG cable (AIW contract 2PS5281D) was conducted and it was determined that a force of 135 pounds was required to break a single conductor with its insulation intact. Efforts to test the entire cable construction failed due to excessive slippage of the jacket over the conductors. The parachute cord was found to require an average of 335 lb. to break.

Analysis of Swollen Areas of Jackets

Gas chromatography/mass spectroscopy analysis of the jacket of cable 2V-2846-B, which contained visibly swollen areas, was conducted to identify the swelling agent(s). Figure 41 is the gas chromatogram of the swollen area of cable 2V-2846-B. The arrow indicates the only peak that did not appear when the non-swollen area of this jacket was similarly analyzed. Figure 42 shows the mass spectrum for the compound with a retention time of 15.9 minutes (indicated by the arrow in Figure 41). This mass spectrum was insufficient for a complete identification of the compound present, though some of its characteristics are similar to a glycol-containing compound. Figure 43 is the gas chromatogram for the non-swollen area of the jacket of cable X9. Figure 44 is the corresponding chromatogram for the swollen area. Again, a small difference is noted at approximately the same place as for cable 2V-2846-B. A complete analysis of this compound was not possible, due to its low concentration.

DISCUSSION

Limitations of Surface Chemical Analyses

One complication in making a more definite determination of the cause of damage to the cable jackets is that they were cleaned subsequent to their removal from the conduits. The cleaning process could have removed traces of pulling rope in the damaged areas of the jackets, for example. Similarly, residues of the

"Yellow 77" or other pulling compounds could also have been removed from the cable jackets and from the concrete anchor.

Flexible Conduit

Though a significant amount of damage occurred to instrumentation cables located at the flexible conduit, as determined by TVA, little evidence for this was present in the form of transferred jacket material or jacket debris. The inner surface of the conduit is heavily corrugated, though it does not have a very sharp surface. Any debris produced by friction with the cable jackets may have been washed away when the conduit was flooded with pulling compound for purposes of removing the cables for inspection. The outer and inner surfaces of the bend in the conduit did exhibit some degree of surface polishing, indicating that the cables did preferentially contact these surfaces. A simple hand rubbing of a CPE and a Hypalon® jacket over the surface of the conduit only produced a slight scuffing of either jacket, with no material transferred to the conduit. The only sharp area noted in the conduit was at the transition point shown in Figure 17.

Pull-By Simulations

The pull-by simulation used in this study did not seek to fully duplicate those conditions found in the conduit system at Watts Bar, where the cables had been installed. This task can only be duplicated if the geometry, materials, pulling forces, and pulling speeds, and cable combinations could be precisely duplicated. The pull-by simulations used in the present work only sought to determine the nature of localized damaged to a given cable jacket when various other objects were dragged over its surface under conditions of known contact speed and force. As the conditions at WBN could not be duplicated precisely, specific load values cited in this report may not be directly comparable to actual pulling tensions. The forces used for the pull-by simulations were those assumed to be possible from a worker acting alone.

Copper Oxidation

The conditions under which the conductors of cable 2PM-516-D oxidized at the WBN site cannot be duplicated in the laboratory without precise knowledge of the thermal and chemical history to which it was exposed. The conditions used in the experiment to determine the rate of copper oxidation only sought to bracket the reasonable time frame during which the observed oxidation could have taken place. The key question regarded whether this had occurred either when the cable was installed or during pull-by operations, or if it had occurred when the cable was removed. By thermally aging the cable in its original jacket, the local chemistry was preserved to the best degree possible. A temperature of 40°C was chosen following discussion with TVA personnel about the conditions at the WBN facility, with a small margin allowed for acceleration of the oxidation process.

Jacket Swelling

GC/MS analyses of the swollen areas of the jacket of cable 2V-2846-B failed to disclose the causative agent. Insufficient material was removable from the cable jacket to allow a precise identification. This may be due to several possibilities. The agent that caused the jackets to swell could have been lost through evaporation during handling and storage. The compound could have reacted with the cable jacket material in such a fashion that volatiles were not obtained at the sampling temperature used. It is also possible that a different column could be more effective in separating the compounds, with improved sensitivity, but this option was not explored. In the final run, no such swelling was noted at any location on any of the damaged cables removed from the Watts Bar plant. It is clear that the agent that caused the swelling also significantly degraded the hardness of the corresponding jackets, as shown in Table 5. Precautions should be taken to avoid contact with any agents that cause swelling of these jackets as this, and the associated softening, would significantly degrade their physical properties.

Jacket Inclusions

Dissection of the jackets of cables 2PS-284-D and 1-2PM-3-3990A revealed that they contained inclusions of harder material. This is not an uncommon occurrence in cable jackets and often results from either of two sources. The first is that the carbon black used in these materials may contains large "grits" of carbon or mineral-rich carbon inclusions. These can occasionally escape the filtering or screening processes. While a compound is being extruded, such as a jacket on a cable, there is a chance that a small amount of compound may be caught at the edge of the die and retained so long that it oxidizes. The material then becomes hard and may break free to become incorporated into the cable jacket. These are often referred to as "retains". Inclusions of this type cannot result from external heating of the cable jacket. In the latter case, the jacket material would be hottest at its outer surface, where the most charring would occur. In the case of the inclusions noted in the two cables in question, the jacket material surrounding the particles was in good condition, without any apparent thermal damage.

Jacket Surface Damage

The instrumentation cables were found to contain a number of types of surface damage, as discussed in the preceding section. While it is fairly certain, based on geometrical considerations, pull-by simulation results, and materials considerations, that much of this damage occurred as a result of the parachute cord being pulled past cables during secondary pull-in operations, a number of cables exhibited discrete sites of sharp physical damage. In the absence of any retained material, such as sand grains, metal debris, or other materials that might reflect the source of these mechanically-produced marks, an absolute determination of how they occurred is not possible. The concrete anchor found in one of the conduits associated with the cables listed in Table 1 could have caused damage similar to that observed on a number of cables.

CONCLUSIONS

Pulling Compound

The pulling compounds were chemically analyzed and found to contain distinctive residues that would have enabled identification had any of their residues been found on the cables or concrete anchor removed from the conduits in question.

Concrete Anchor

The concrete anchor was found to contain no identifiable surface residues that would attest to the time in which it was placed into the conduit in which it was found. The anchor was found to contain sharp corners that could possible have inflicted surface damage to some of the cables, in the manner observed.

Repair Sleeve

The suspected repair splice, 1-2PS-68-283-D was verified as such. This was applied to cover a cut that was limited to the jacket of this cable. Inspection of the cable following removal of the repair sleeve showed that no damage had been done to the primary insulation or conductors of this cable.

Surface "Bumps" and "Bulges"

The "bumps" on the surfaces of cables 2PM-4781-D, 2PM-1694-D, 2PM-1041-D (2 locations), 2PS-284-D, and 1-2PM-3-3990A, were not the result of splices in the conductors. In cables 2PM-4781-D, 2PM-1694-D, and 2PM-1041-D this resulted from splices in the assembly tapes. In cables 2PS-284-D and 1-2PM-3-3990A this resulted from inclusions of large particles of what appears to be carbon or charred rubber. In no cases did any of the surface irregularities result from externally applied heat.

Surface Damage

The cables listed in Tables 6, 7, and 8 were found to have been damaged in a manner consistent with pull-by damage, resulting from contact with a parachute cord, as supplied by TVA. In addition, others of the cables were damaged following contact with sharp edges, as evidenced by the details of their damaged surfaces. The causative surfaces could not be deductively identified.

Flexible Conduit

The interior of the flexible conduit was inspected and found to contain no evidence of any cable jacket materials. The inner surface was found to be free of any sharp edges except at a transition coupling at one end.

Tensile Properties of One Cable and A Parachute Cord

It was determined that a load of 335 lb. was required to break the parachute cord provided by TVA. The 2-conductor #12 AWG cable manufactured by AIW (contract 79K5-825342-2) was found to have a breaking point of 135 lb., for a single insulated conductor. Roughly doubled, and allowing some additional load for the tensile strength of the overlying jacket, it appears possible that the parachute cord could sustain a load adequate to break a 2-conductor #12 wire, as provided.

Abandoned Cable

The 2-conductor #12 AWG cable (2PS281D) manufactured by AIW and found abandoned in a conduit, had broken due to a tensile overload.

Conductor Oxidation

Thermal Aging of the conductors from cable 2PM-516-D indicated that the oxidation found on the damaged section of this cable most likely occurred while the cable was installed in the conduit and did not occur after the cable was removed for inspection.

Jacket Swelling

The jackets of two cables, X9 and 2V-2846-B, were swollen by by a chemical compound that could be detected but not identified. The compound caused considerable swelling and softening of the jacket materials. Swelling was not caused by the insecticide provided, as originally suspected by TVA.

REFERENCES

[1] The Aldrich Library of Infrared Spectra, Edition 3, The Aldrich Chemical Company, 1981.

[2] The Infrared Spectra Atlas of Polymers and Additives, Volumes 1, 2, and 3, Sadtler Research Laboratories, 1987.

[3] The Particle Atlas, Vol 2, W.C. McCrone, editor, Ann Arbor Science Publishers, 1976.

[4] An Atlas of Polymer Damage, Lothar, Klingele, et al, editors, Prentice-Hall, 1981.

[5] The Metals Handbook, Ninth Edition,Volume 12 (Fractography), American Society for Materials, 1987.

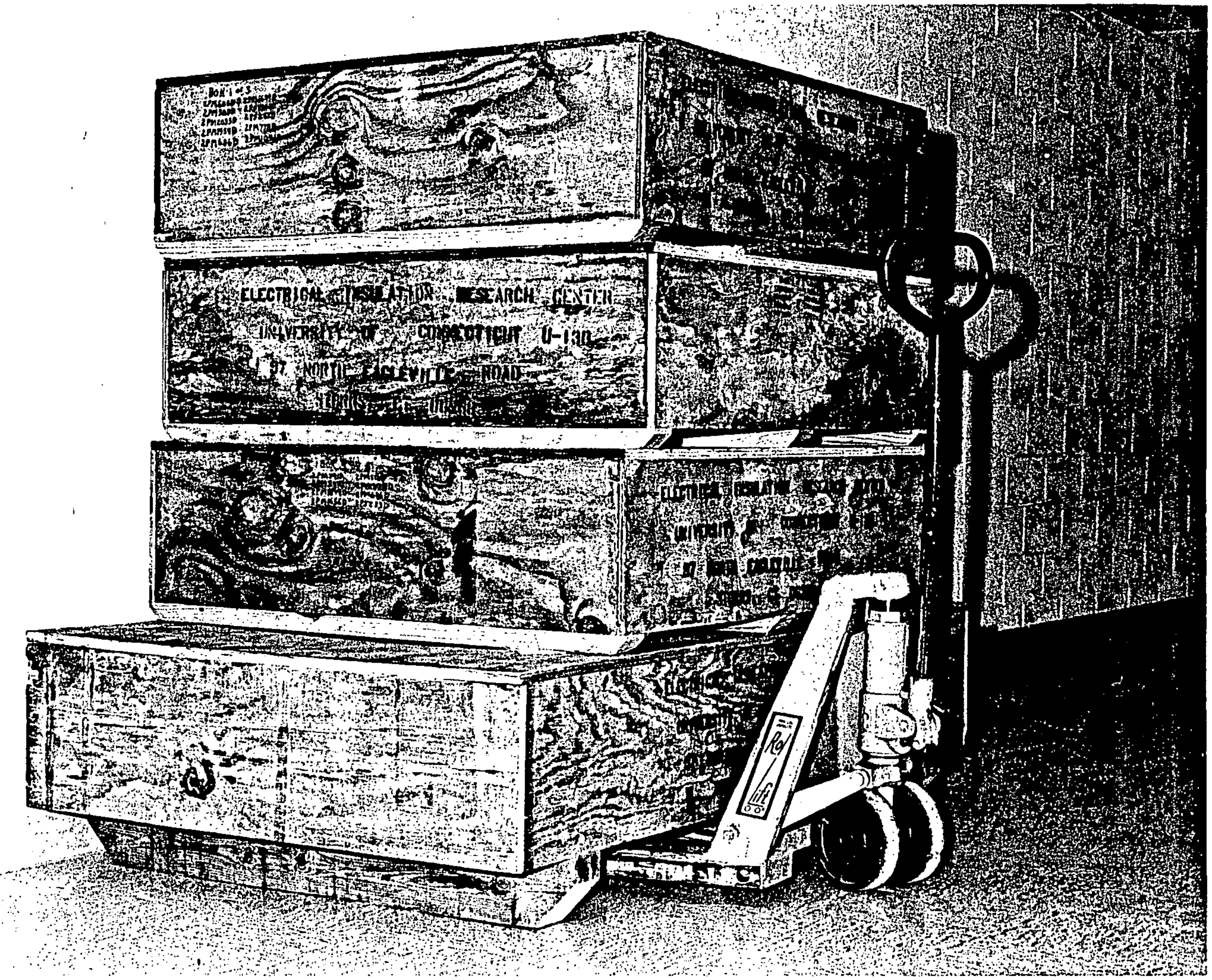


Figure 1
Shipping Containers with Cables Listed In Table 1

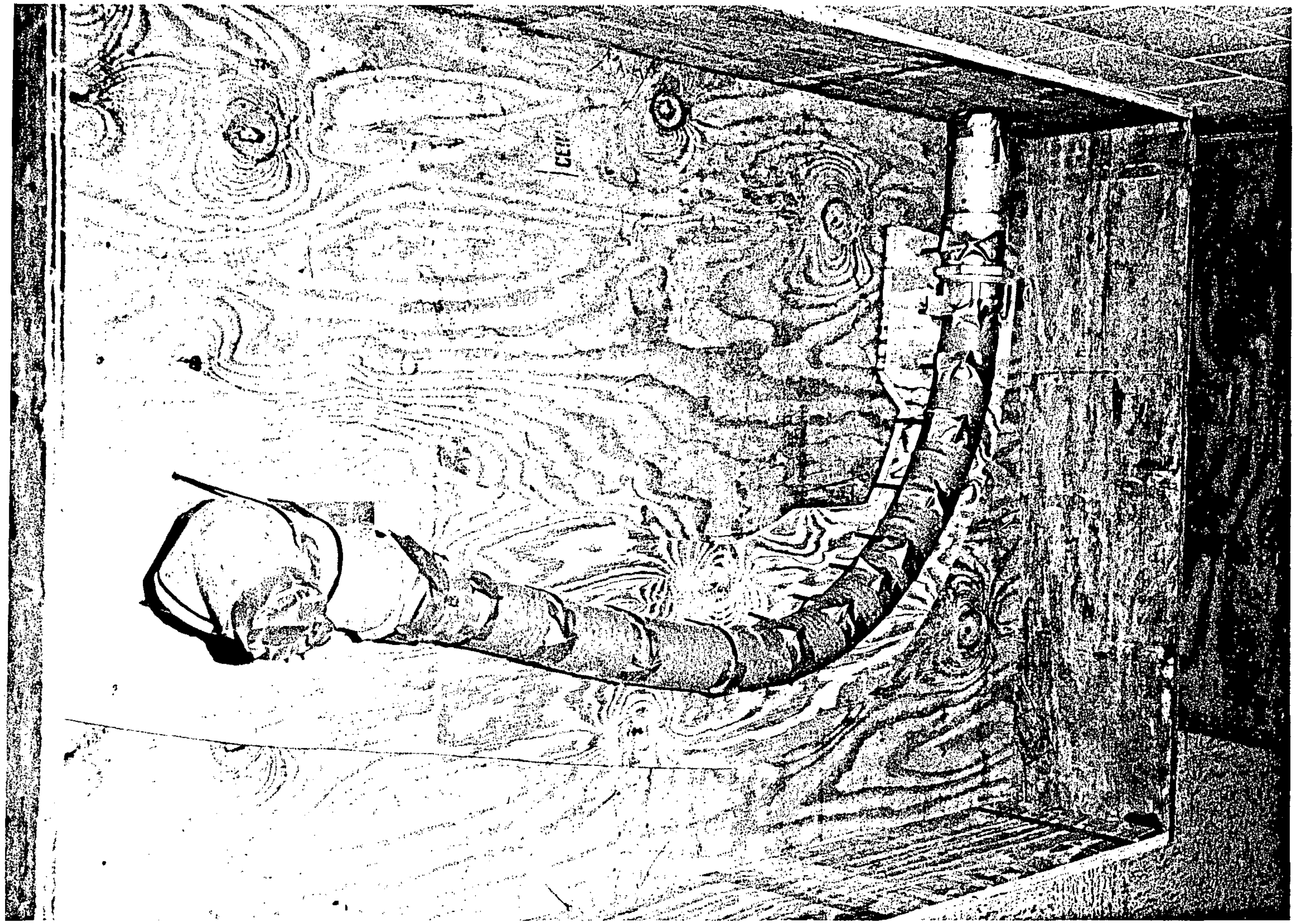


Figure 2
Flexible Conduit Strapped To Plywood Support In
Order To Maintain Original Conformation

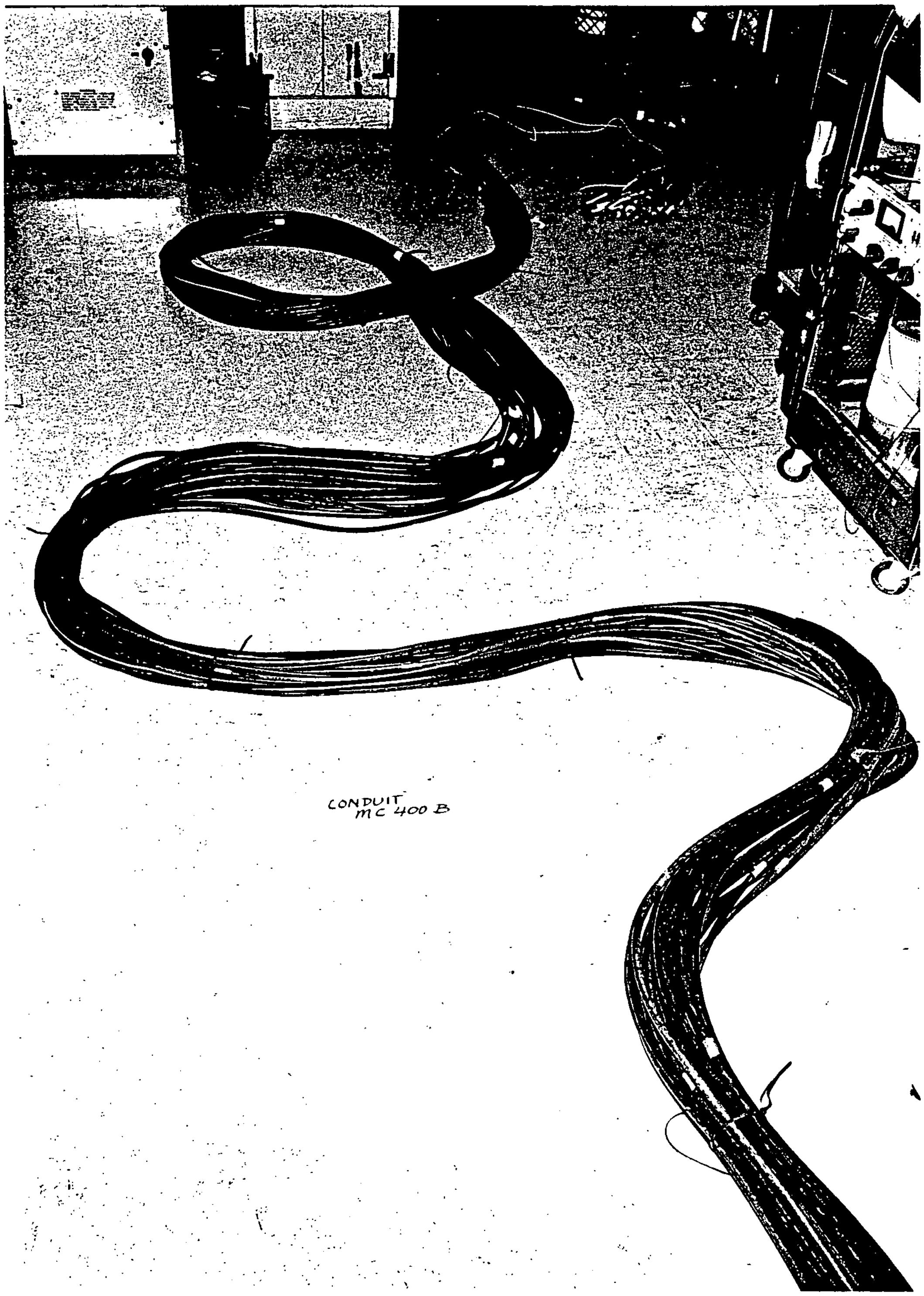


Figure 3
Cables from Conduit MC 400B, As Removed from Shipping Container

CONDUIT
MC 400 B

Figure 4
Damaged Sites On Cables from Conduit MC 400B, Showing Protective Wrapping Applied by TVA Prior To Shipment

Figure 5
Visual Examination of Damaged Sites Removed from Instrumentation Cables Listed In Table 1

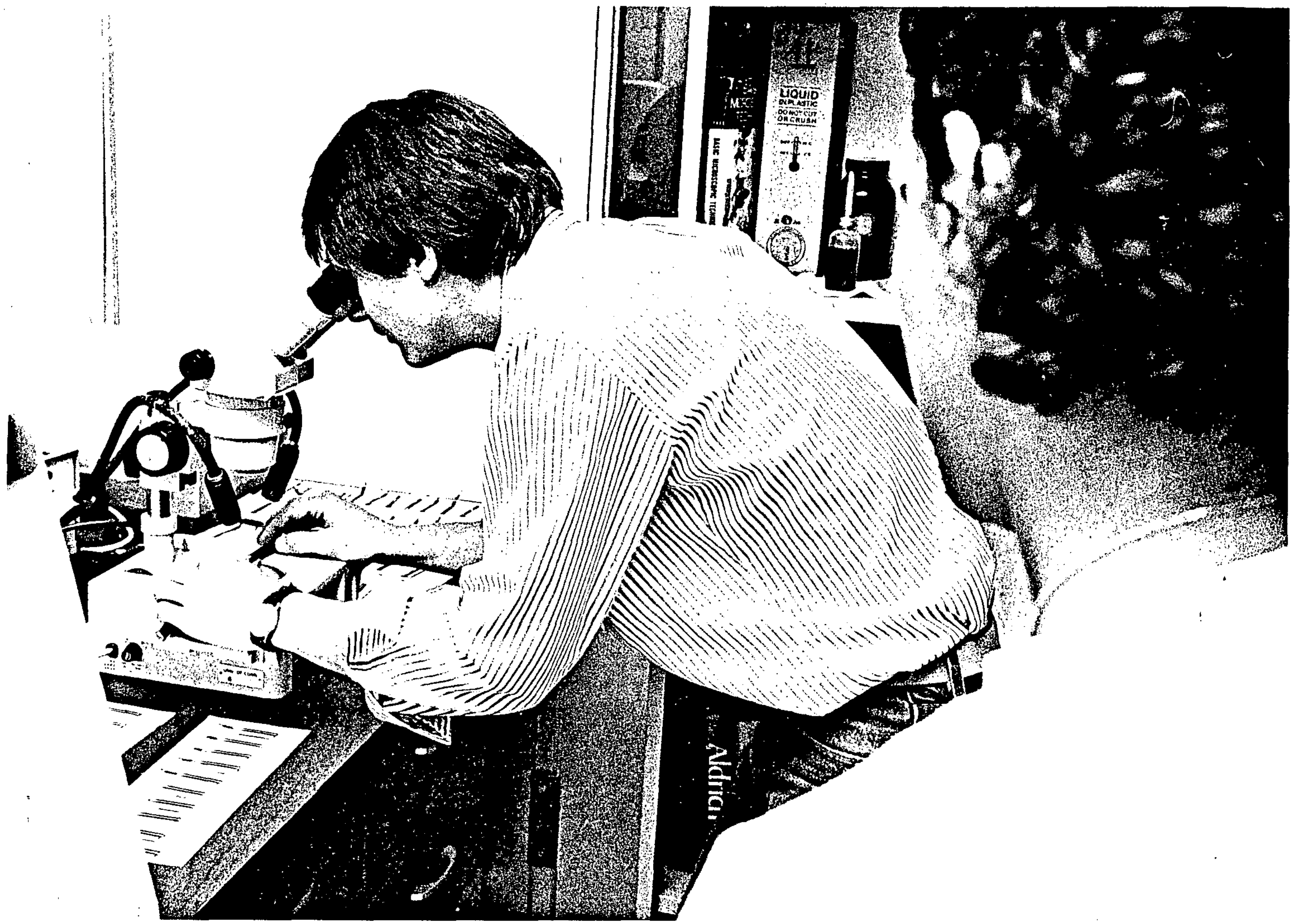


Figure 6
Detailed Examination of Damaged Site Using
Stereomicroscope

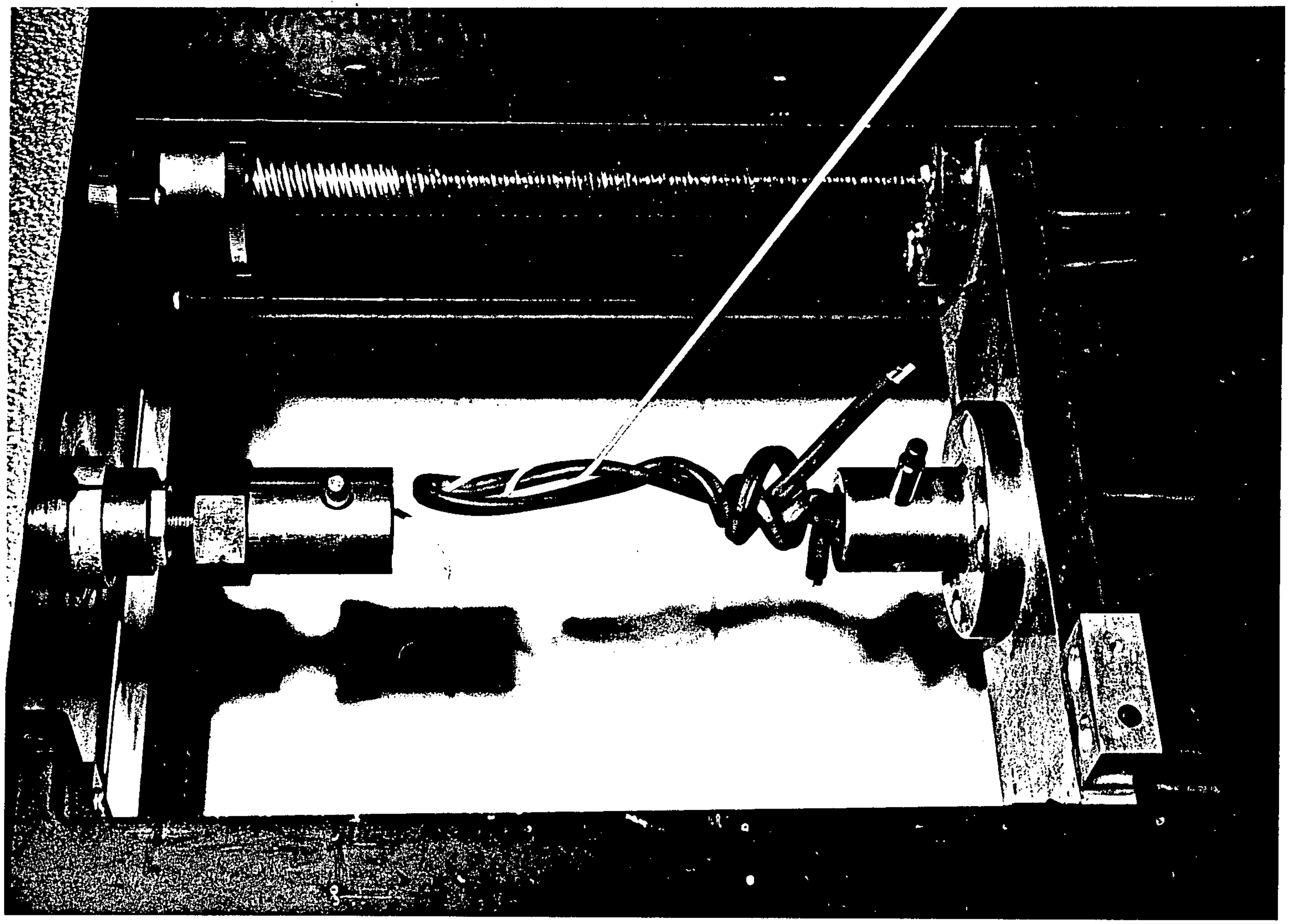


Figure 7
Pull-By Simulation Experiment with Parachute Cord
Over 2-Conductor Cable

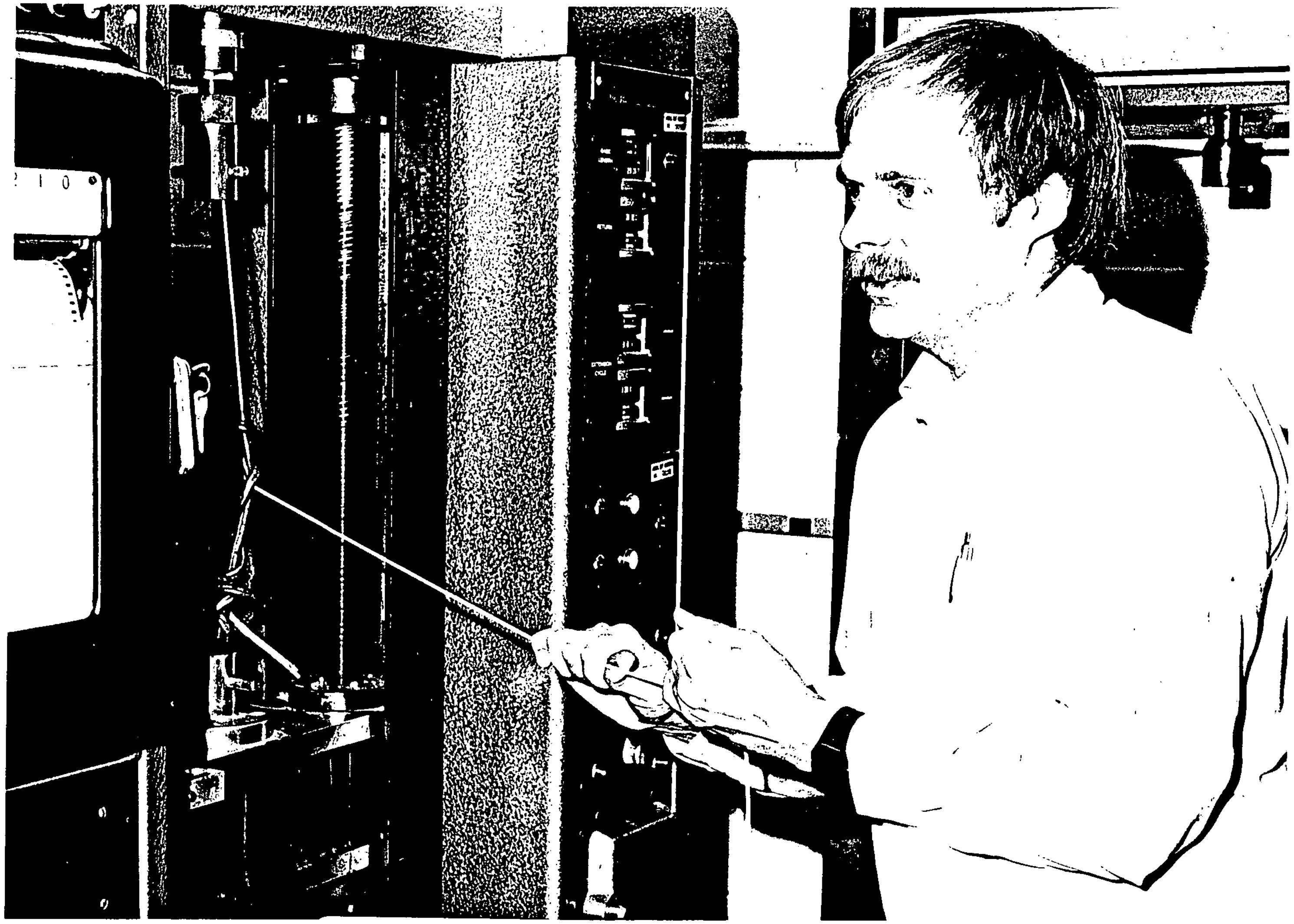


Figure 8
Pull-By Simulation In Progress- Parachute Cord
Contacting 2-Conductor Cable

OPERATOR [redacted] KTW.
GAIN
FILTER TIME
SMOOTHING
REMARKS

DATE 9/11/8[redacted]

SCAN MODE

[redacted]INGLE ☒
REPETITIVE ☐
ACCUMULATIVE ☐
MATH ☐

NANOMETRICS

SPECTRUM NO. Yellow 7[redacted] NaCl
SAMPLE Yellow Fiber Portion
ORIGIN

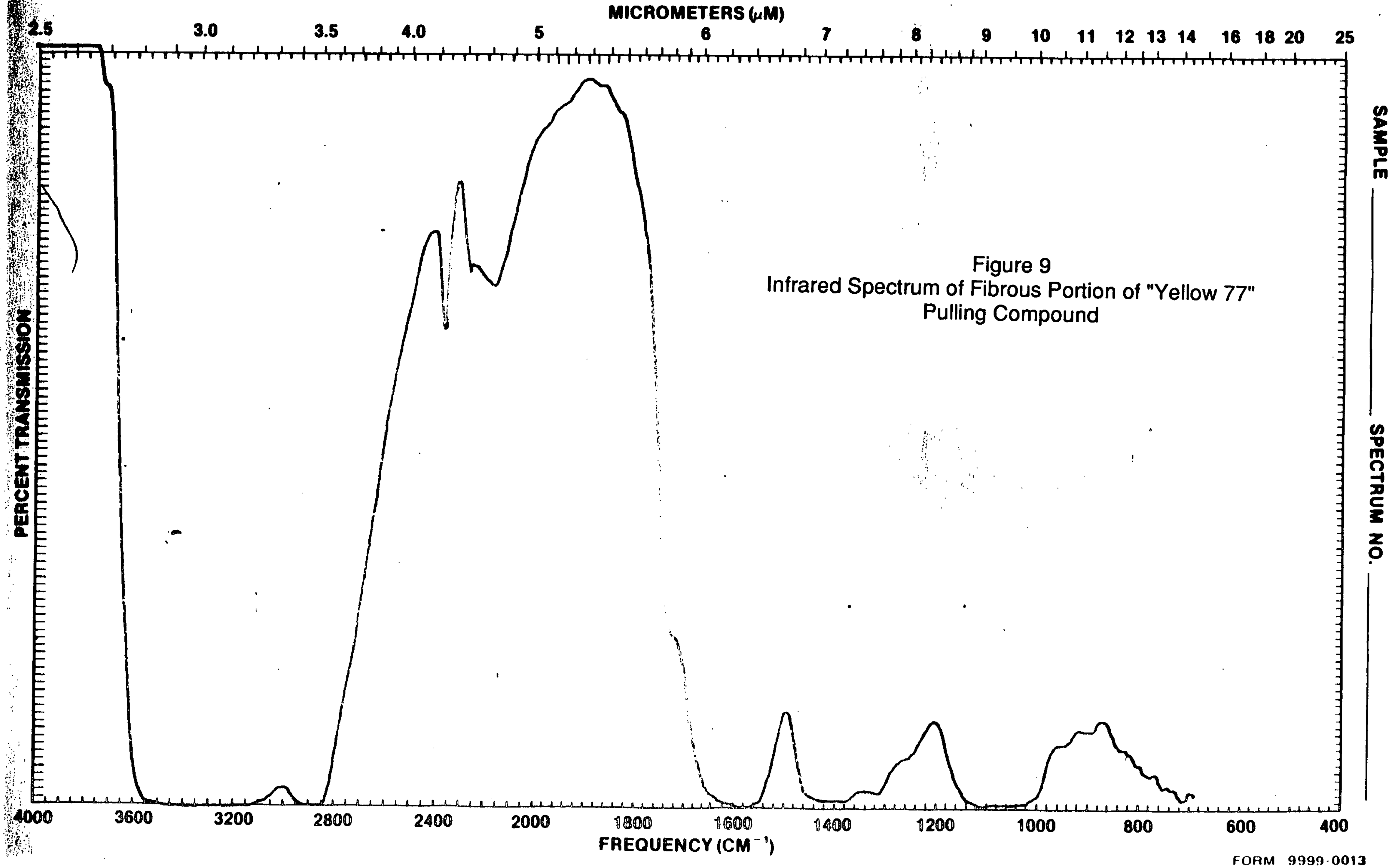


Figure 9
Infrared Spectrum of Fibrous Portion of "Yellow 77"
Pulling Compound

FORM 9999-0013

OPERAT[redacted] ______

GAIN ______

FILTER TIME ______

SMOOTHING ______

REMARKS ______

DATE 9/[redacted]/89

SCAN MODE ______

SINGLE ☐

REPETITIVE ☐

ACCUMULATIVE ☐

MATH ☐

NANOMETRICS

SPECTRUM NO. [redacted]

SAMPLE Polywater J.

ORIGIN ______

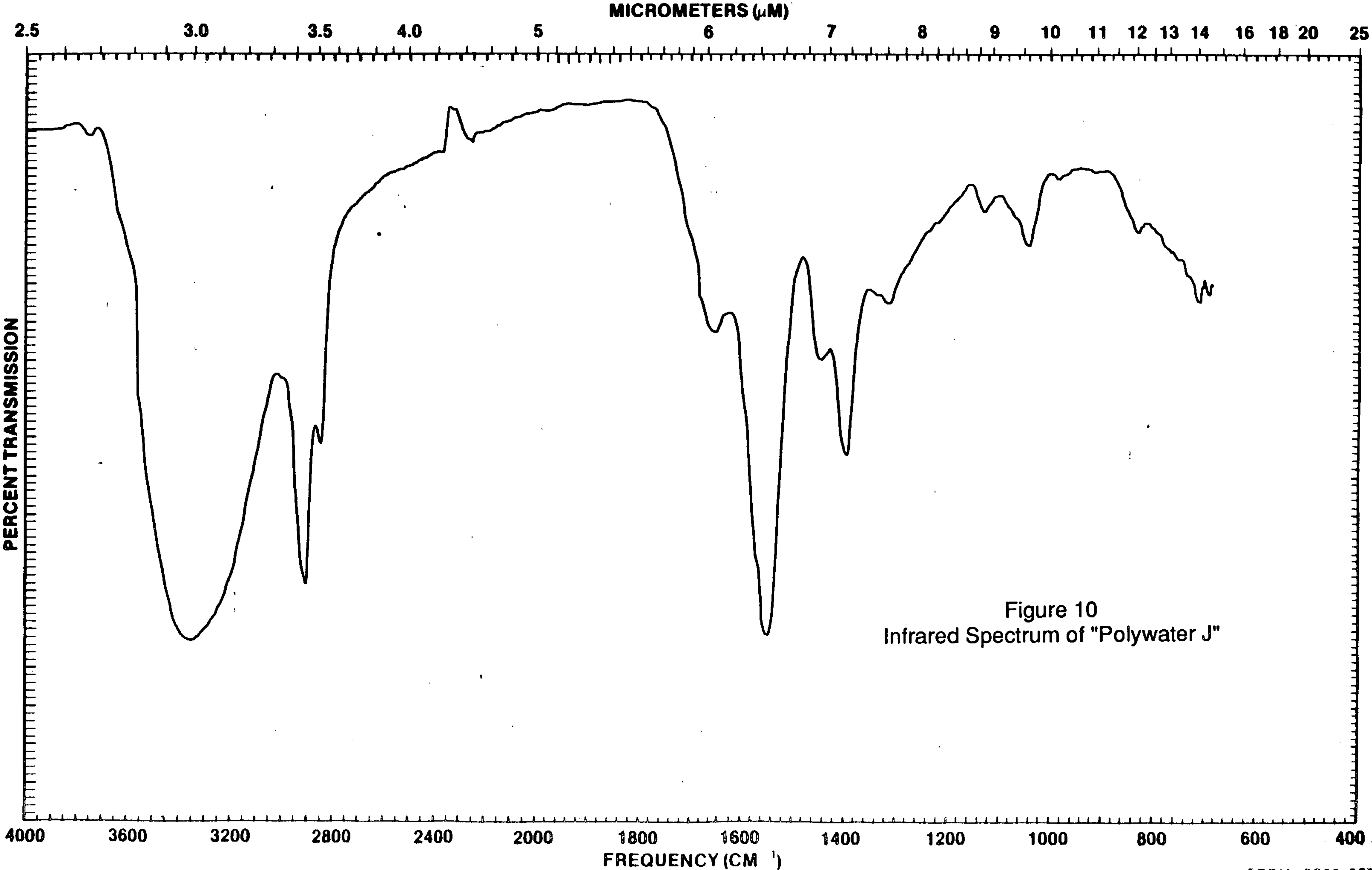


Figure 10
Infrared Spectrum of "Polywater J"

SAMPLE ______ SPECTRUM NO. ______

FORM 9999-001

OPERATOR ____________

GAIN ____________

FILTER TIME ____________

SMOOTHING ____________

REMARKS ____________

DATE 9/13/69

SCAN MODE ____

SINGLE ☐

REPETITIVE ☐

ACCUMULATIVE ☐

MATH ☐

NANOMETRICS

SPECTRUM NO. ____________

SAMPLE Polywater G

ORIGIN ____________

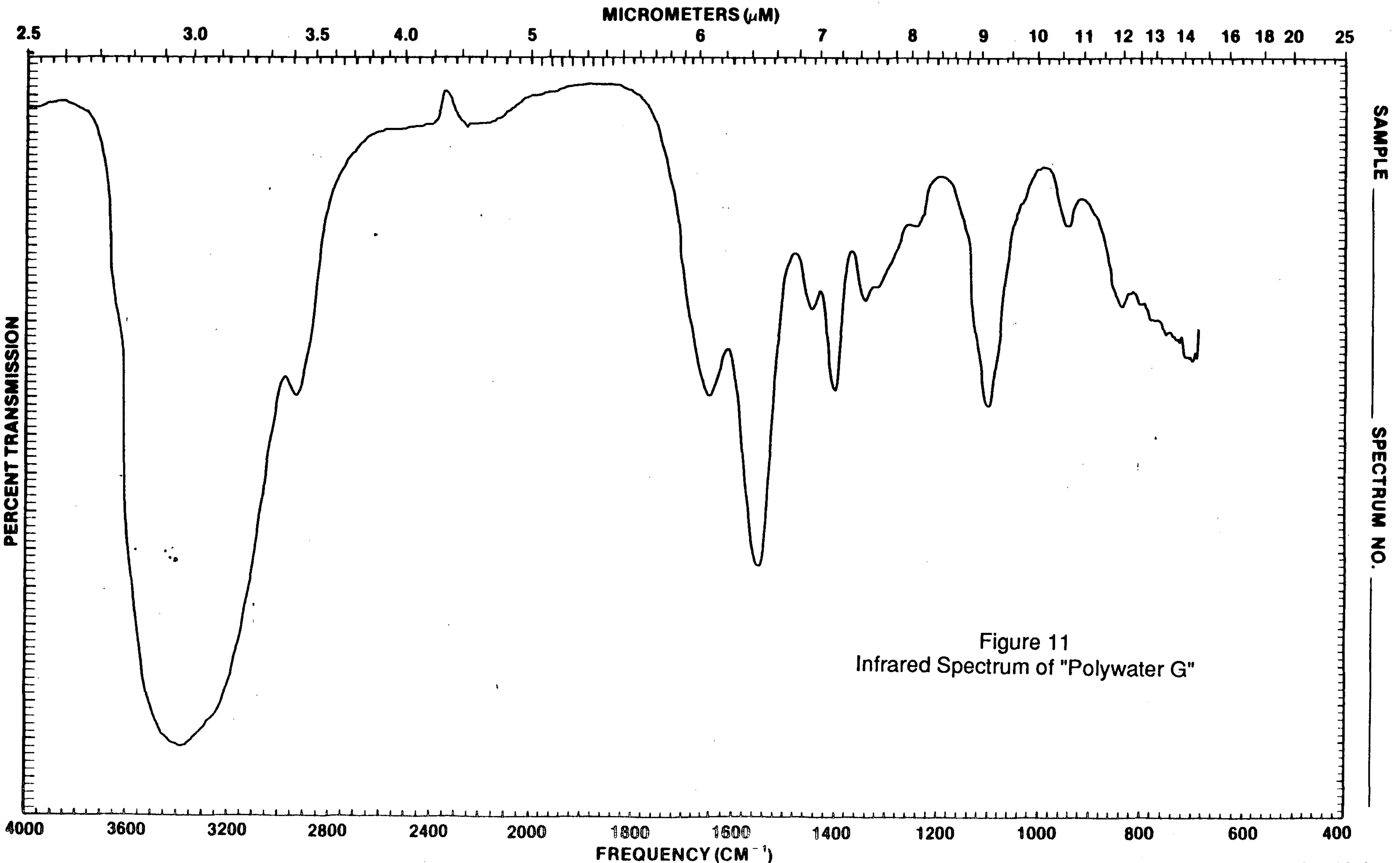


Figure 11
Infrared Spectrum of "Polywater G"

FORM 9999-0012

OPERATOR ?dWionski

GAIN

FILTER TIME

SMOOTHING

REMARKS

DATE 9/13/88

SCAN MODE

SINGLE ☐

REPETITIVE ☐

ACCUMULATIVE ☐

MATH ☐

NANOMETRICS

SPECTRUM NO.

SAMPLE Parachute cord

ORIGIN TVA

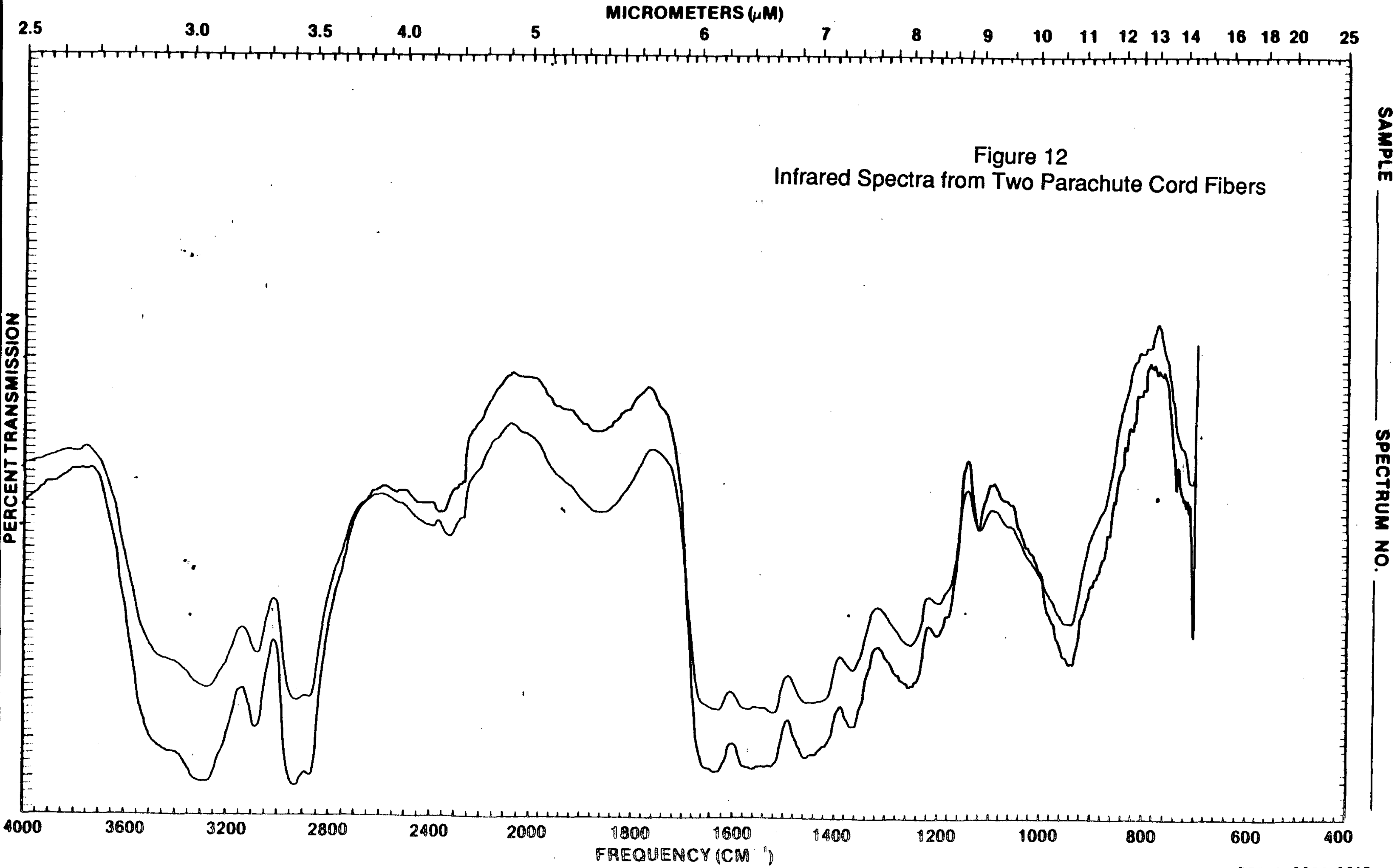


Figure 12
Infrared Spectra from Two Parachute Cord Fibers

FORM 9999-0013

18,111-0
Nylon 6 [poly(caprolactam)]
Pellets

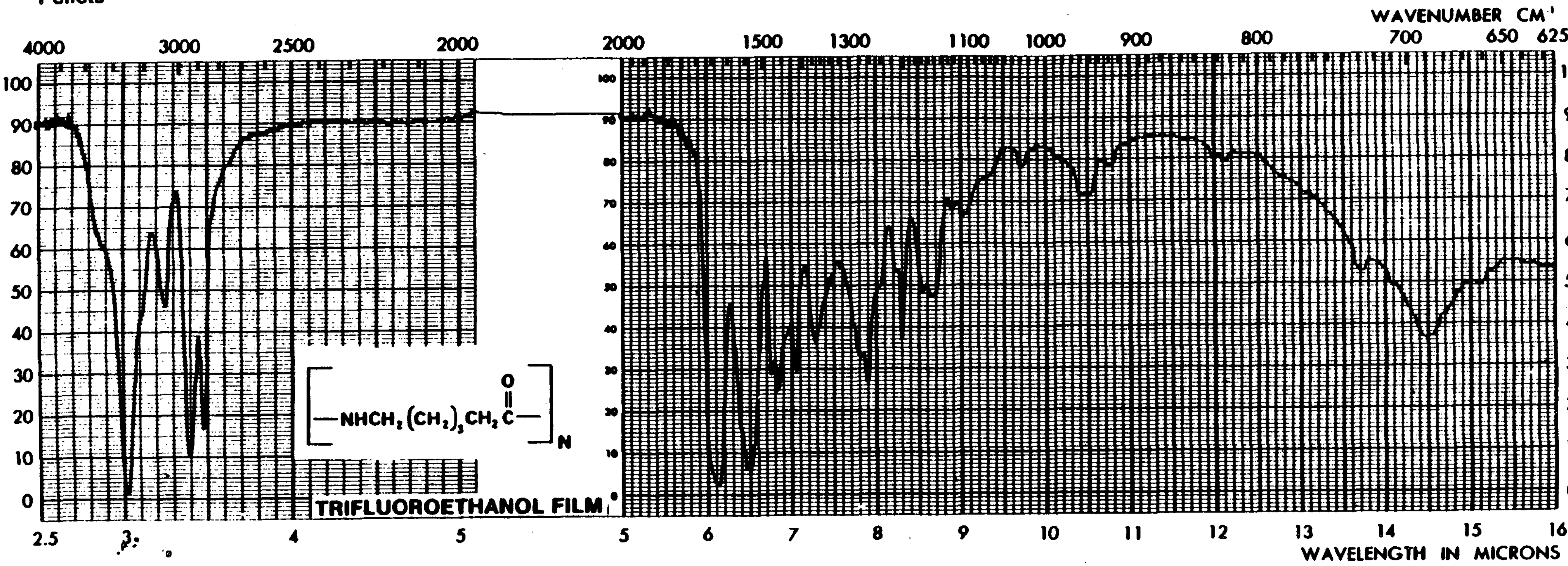


Figure 13
Infrared Spectrum from Reference [1] for
Nylon 6

OPERATO[redacted] J H G.
GAIN
FILTER TIME
SMOOTHING
REMARKS

DATE 9/12/[redacted]

SCAN MODE
[redacted]INGLE ☒
REPETITIVE ☐
ACCUMULATIVE ☐
MATH ☐

NANOMETRICS

SPECTRUM NO. [redacted]
SAMPLE Rope Fiber
ORIGIN

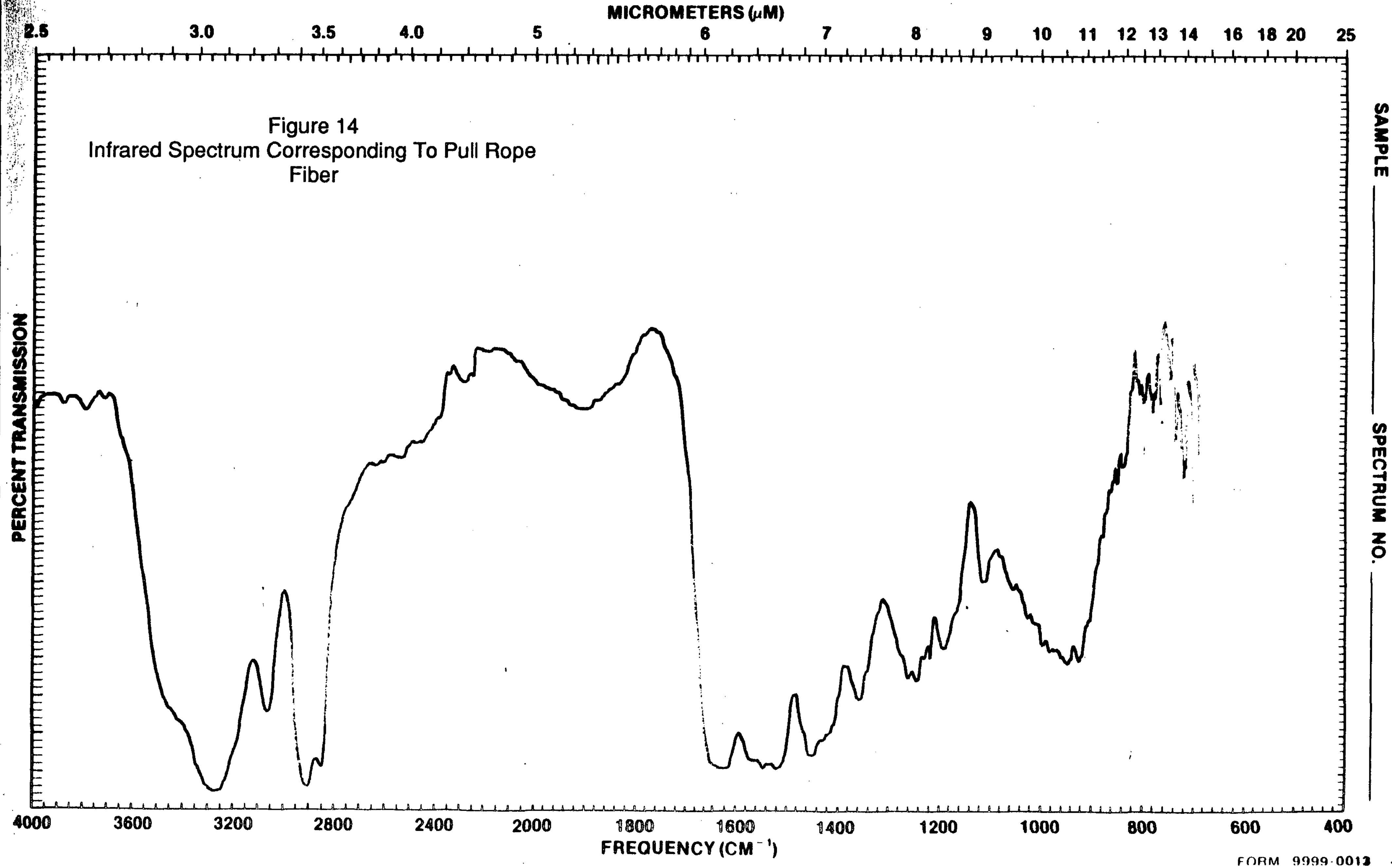


Figure 14
Infrared Spectrum Corresponding To Pull Rope Fiber

FORM 9999-0013

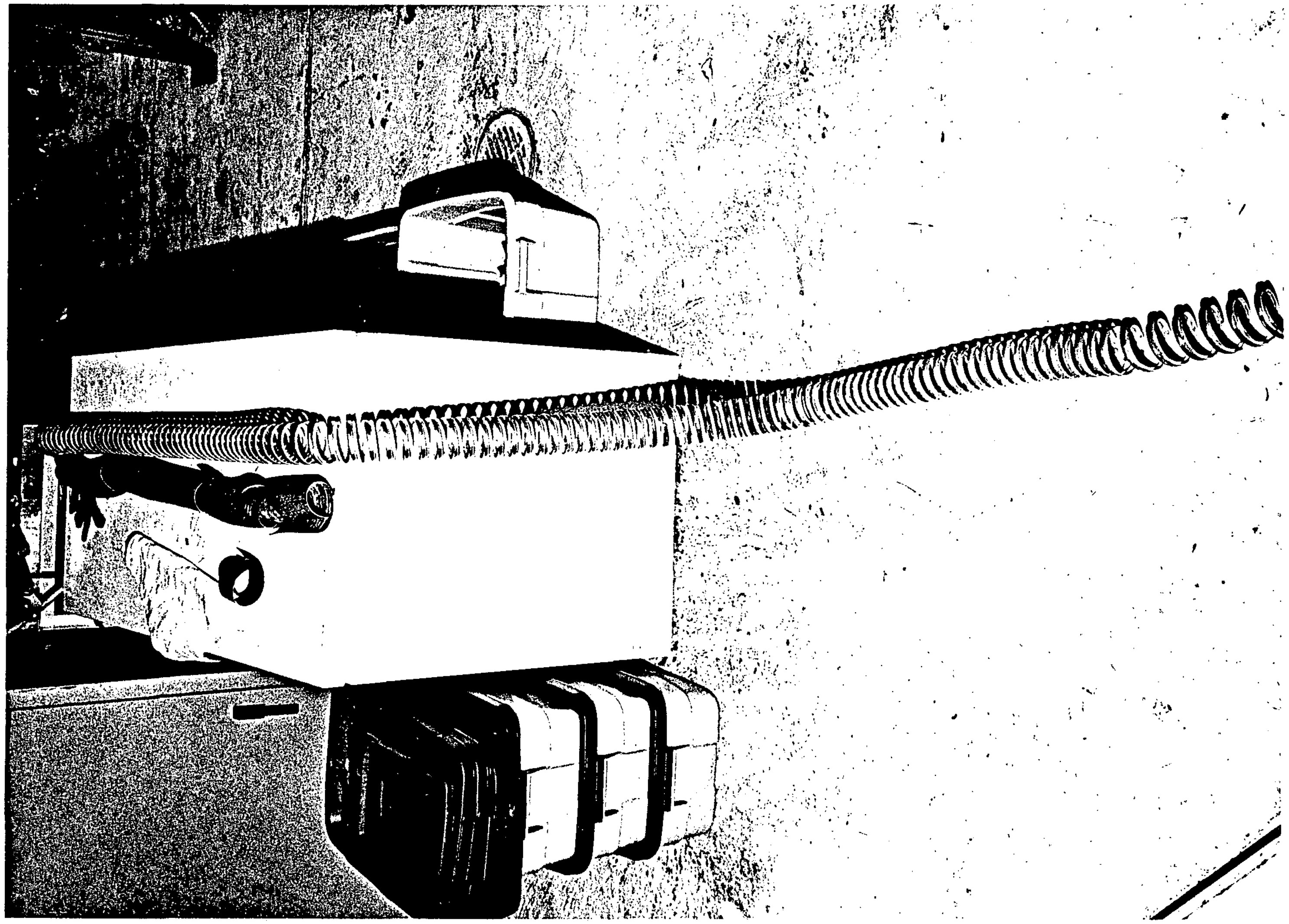


Figure 15
Flexible Conduit As Uncoiled for Visual
Inspection of Interior Surfaces

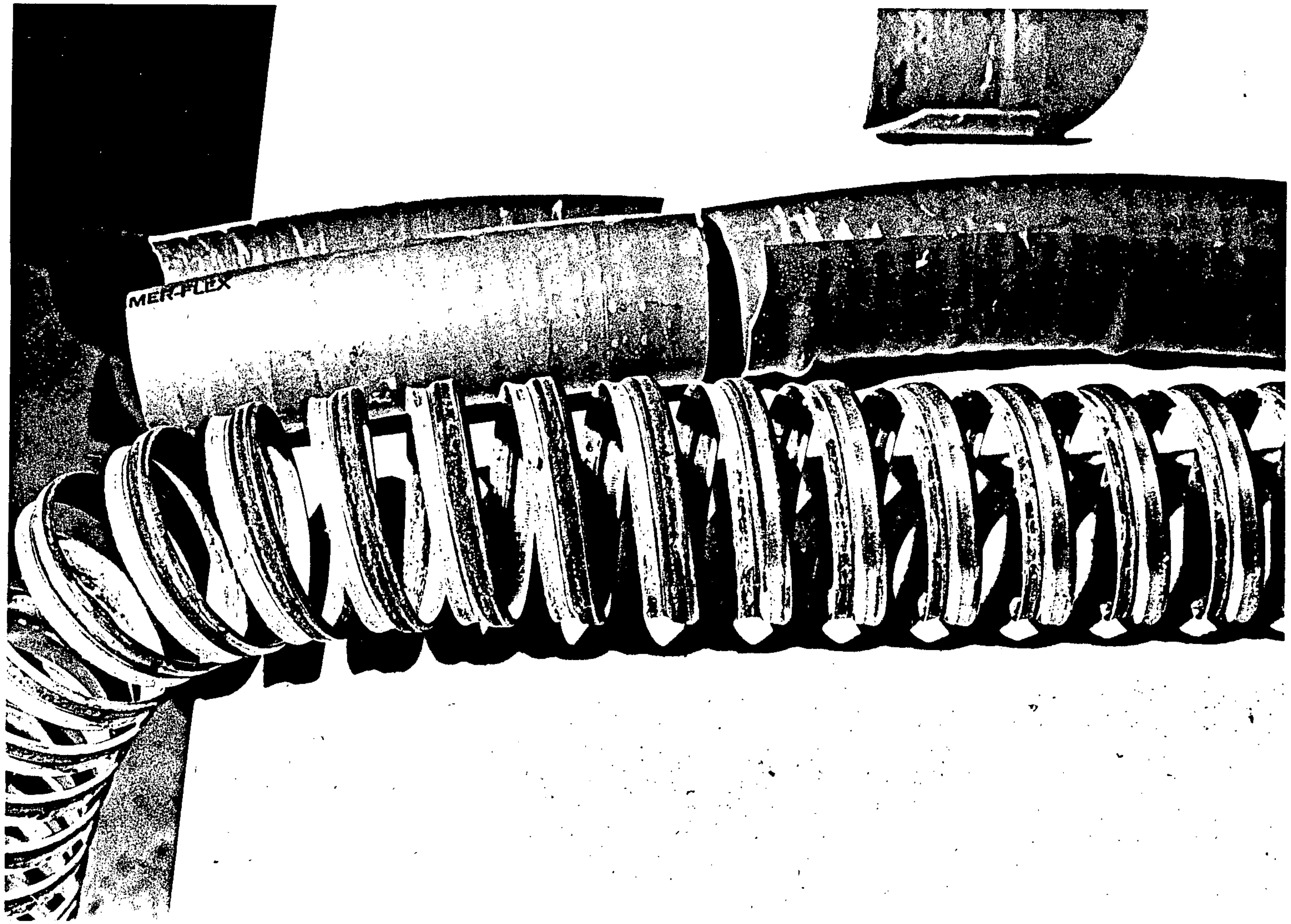


Figure 16
Flexible Conduit Construction with Sleeve
Shown Above

Figure 17
Residue (Not Cable Jacket Material) At Transition
Point At Felxible Conduit End

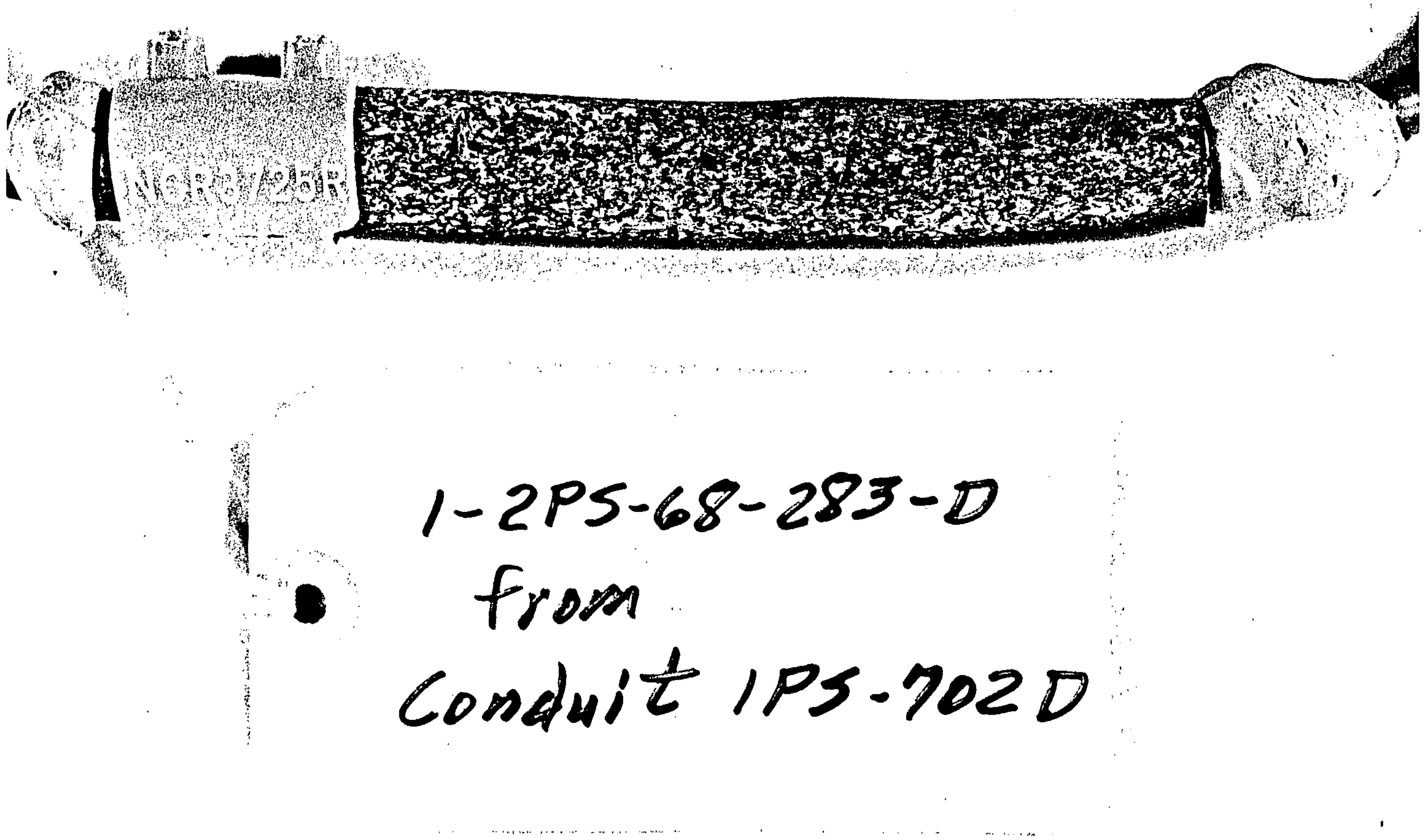


Figure 18
Cable Repair Sleeve 1-2PS-68-283-D Shown In
Its As-Received Condition

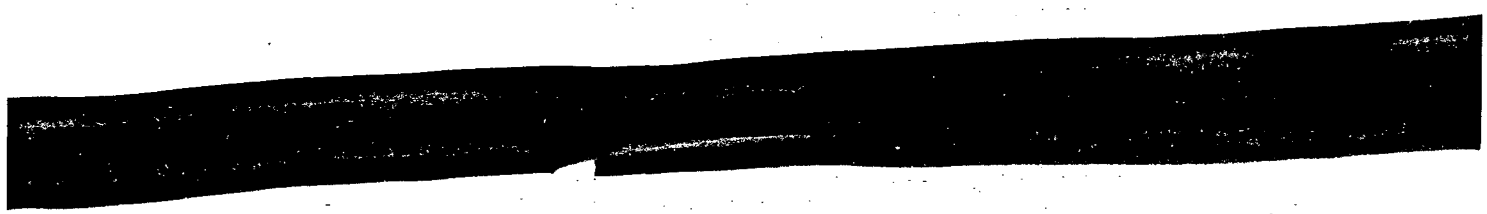
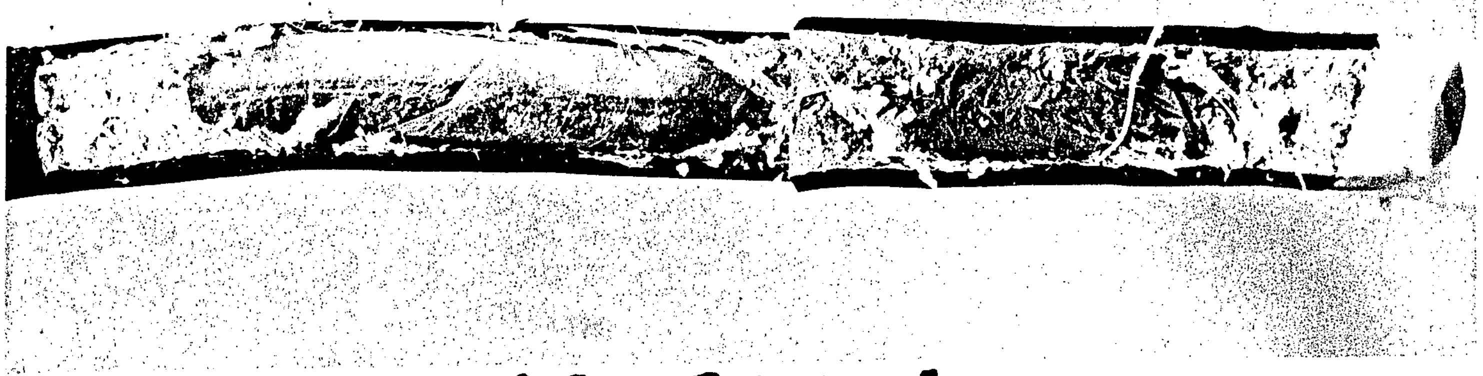


Figure 19
X-Radiograph of Cable Repair Sleeve
1-2PS-68-283-D Showing Cut In Cable Jacket

1-2PS-68-283-D
FROM CONDUIT
1PS-702-D

Figure 20
Cut In Cable Jacket Under Repair Sleeve
1-2PS-68-283-D. Elastomeric Resin Shown In Cut

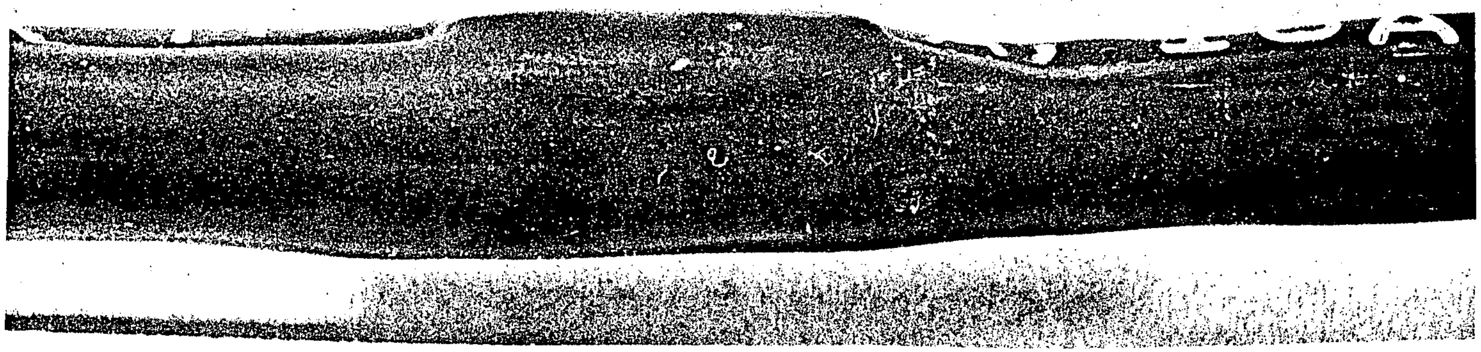


1-2PS-68-283-D
FROM CONDUIT
1PS-702-D

Figure 21
Cable Components Under Jacket Cut Repaired
with Sleeve 1-2PS-68-283-D

1-2PM-3-3990A

Figure 22
"Bump" On Outer Surface of Cable
1-2PM-3-3990A



1-2PM-3-3990A

Figure 23
A "Bulge" On Surface of Cable 1-2PM-3-3990A

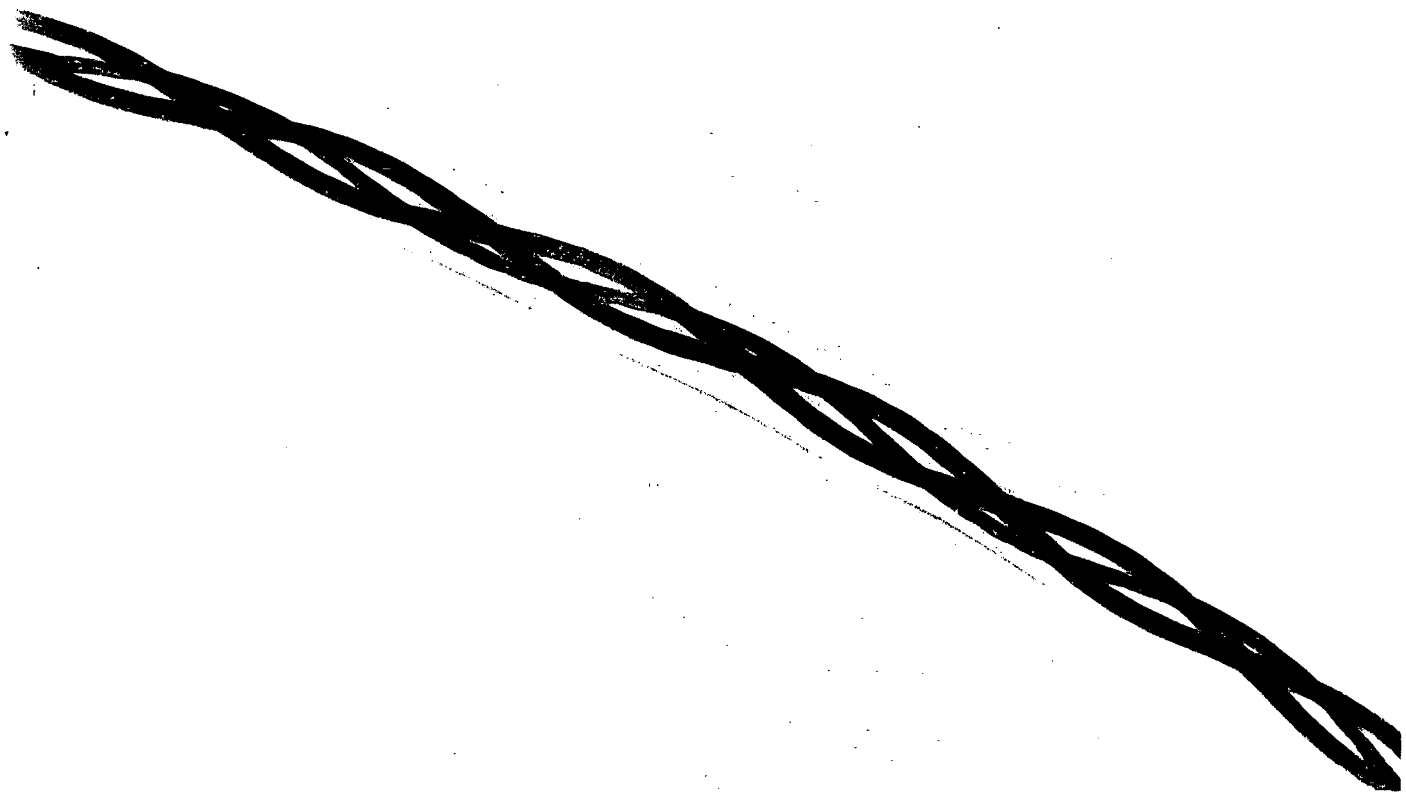


Figure 24
X-radiograph of "Bump" On Surface of Cable
1-2PM-3-3990A. Location Corresponds to that
Shown In Figure 22

Figure 25
X-radiograph of "Bulge" On Surface of Cable
1-2PM-3-3990A. Location Corresponds to that
Shown In Figure 23

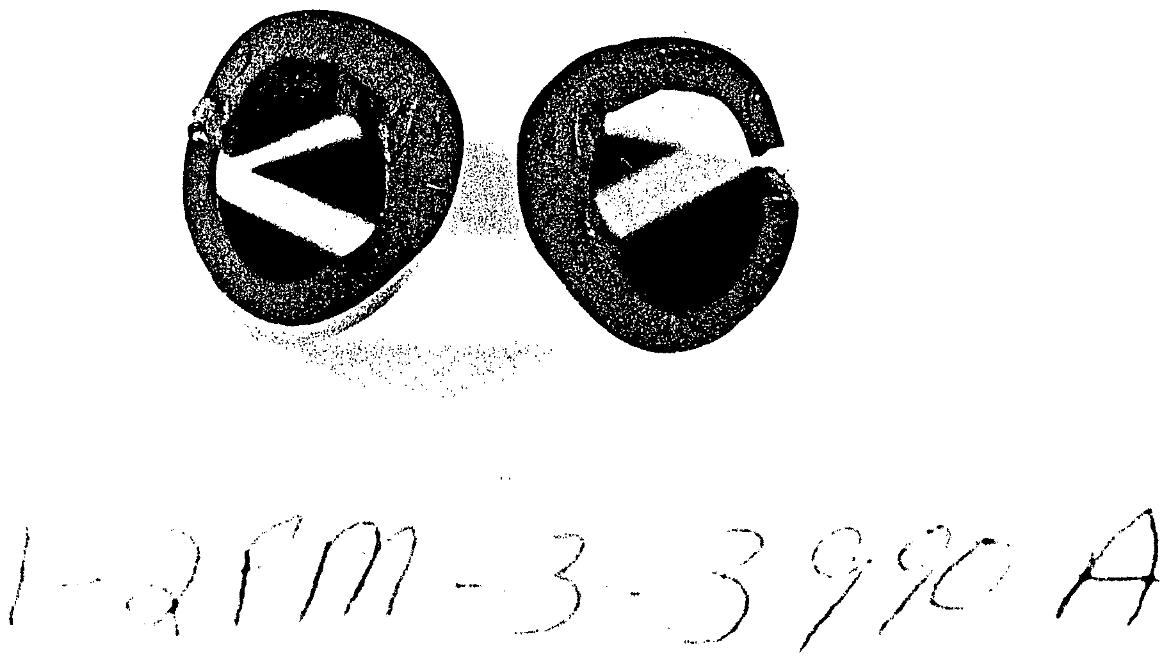


Figure 26
Cross-Section Through "Bump" On Surface of Jacket, Cable 1-2PM-3-3990A. Note Small Particle Embedded In Jacket

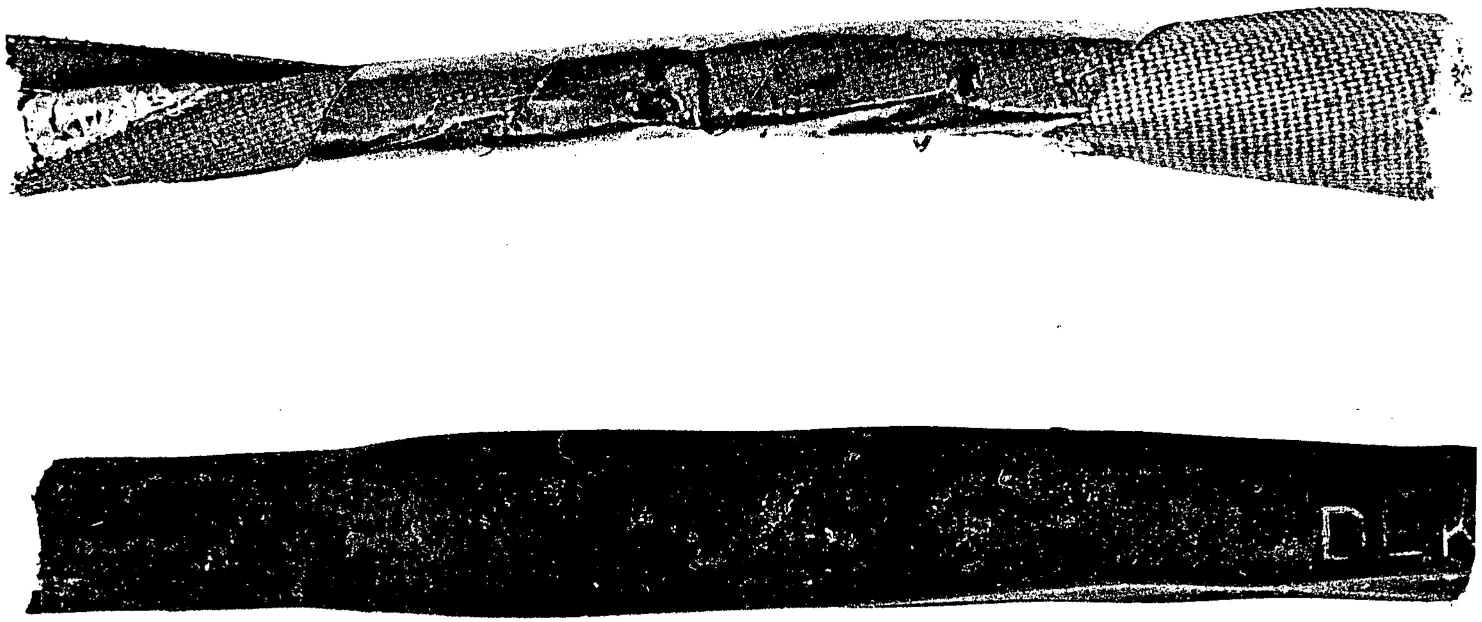


Figure 27
"Bulge" On Jacket of Cable 2-PM-4781-D
(below) and Corresponding Splice In Assembly
Wrap, Sewn with Black Thread

2 PM -1694 D-3

/

Figure 28
"Bulge" On Surface of Cable 2PM-1694-D
(bottom) with Corresponding Splice In Assemly
Wrap Shown Above

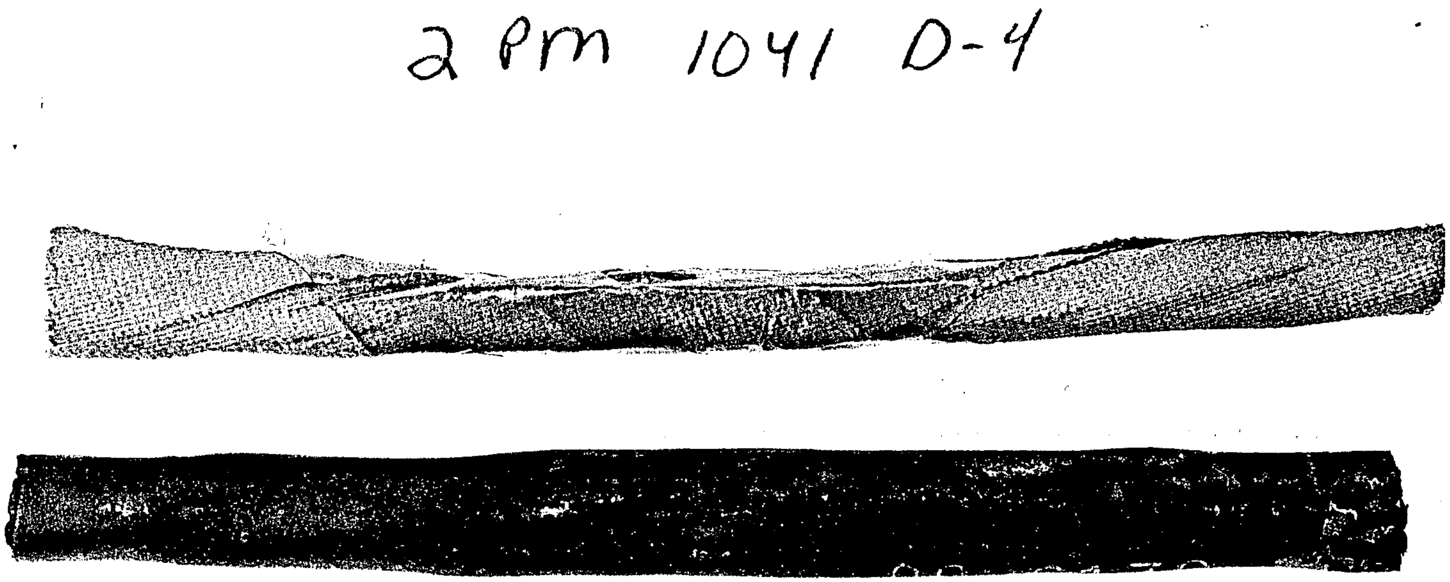


Figure 29
Representative "Bulge" On Surface of Cable
2PM-1041-D (bottom) with Corresponding
Assembly Wrap Splice Shown Above

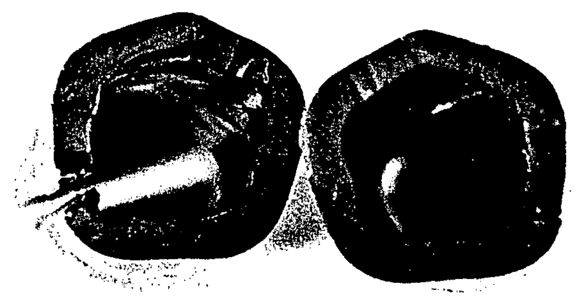


Figure 30
Jacket Cross-Section Through "Bulge" On
Surface of Cable 2PM-1041-D

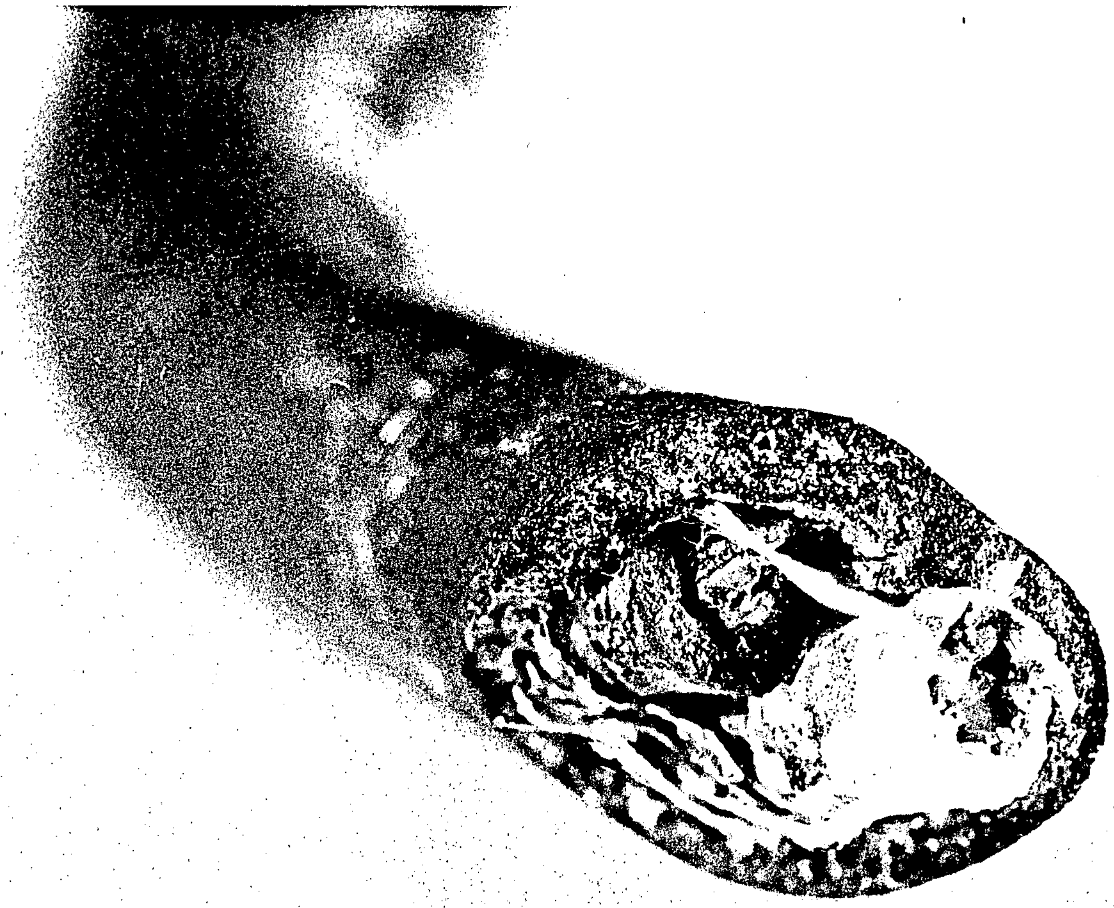


Figure 31
End of Cable 2PS281D Abandoned In Conduit,
WBN Unit 2

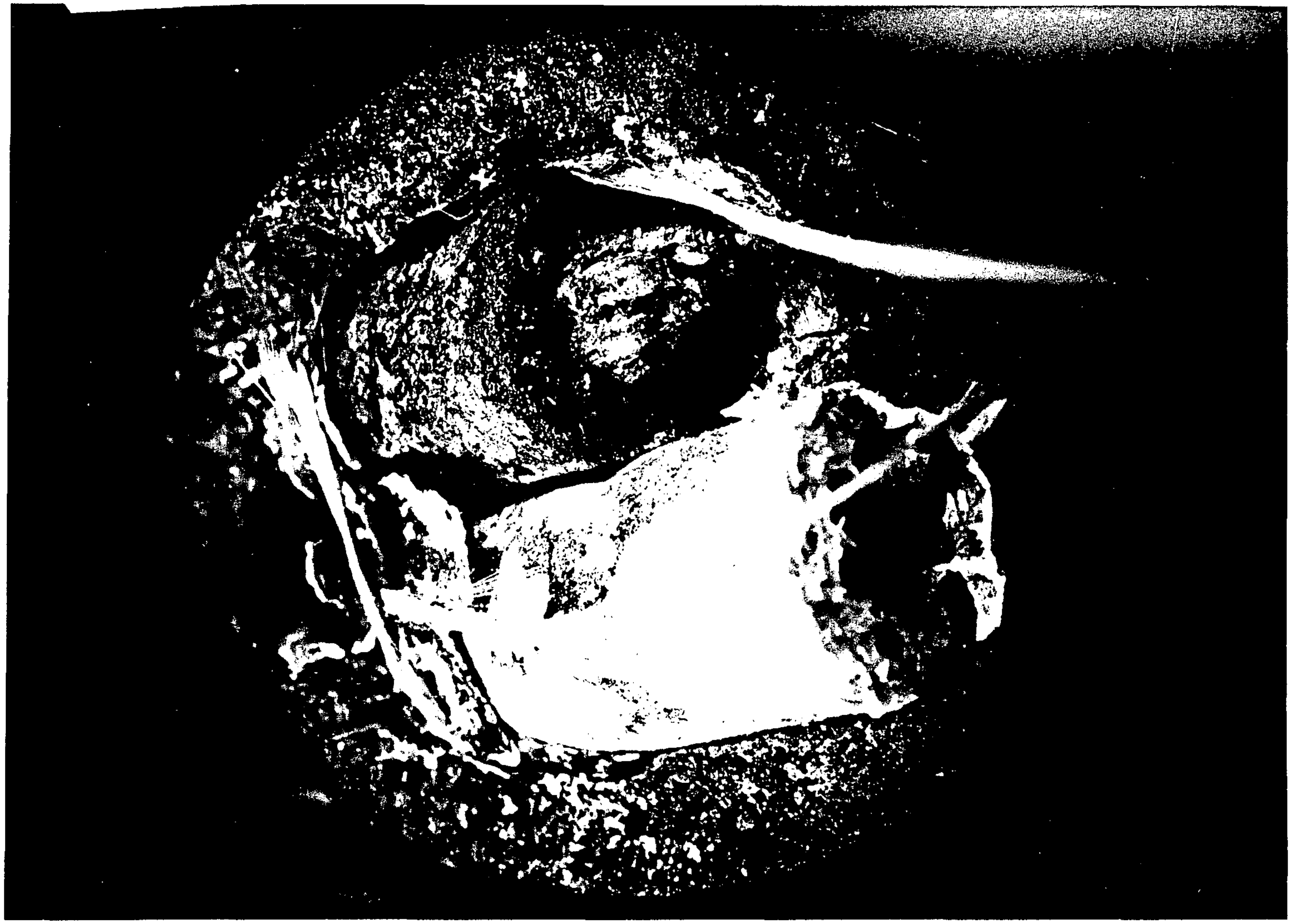
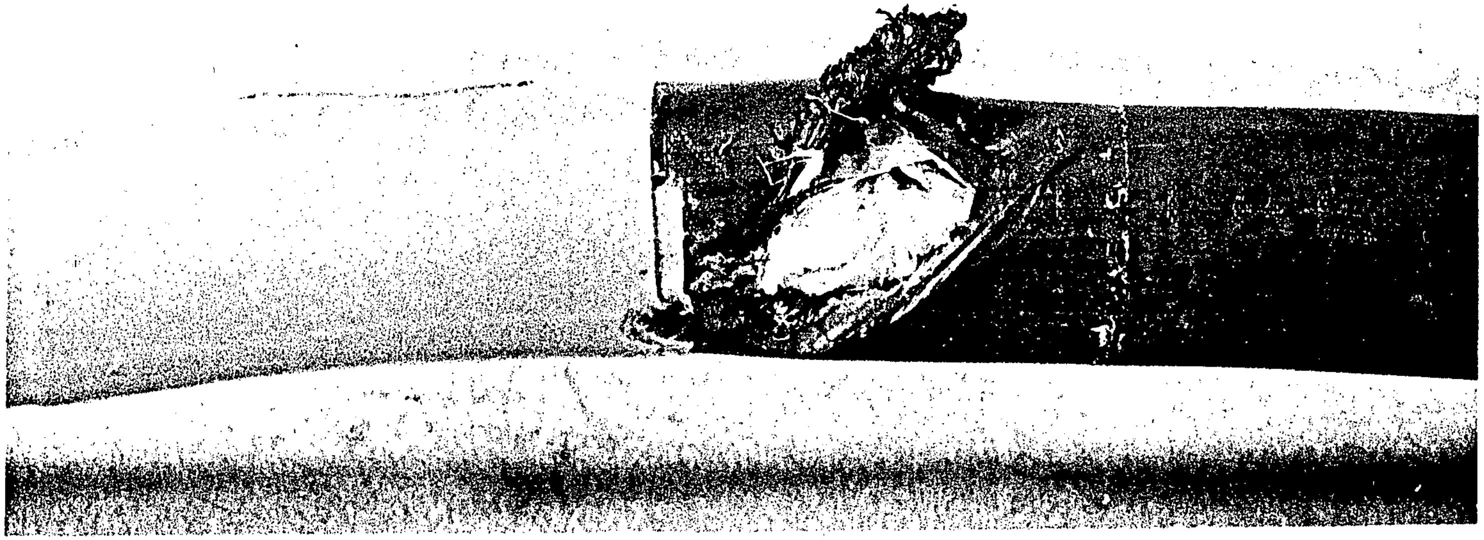


Figure 32
Detailed View of Fractured End of Cable 2PS281D



1-PM-778-D

Figure 33
Groove In Jacket of Cable 1-PM-778-D Caused
by Cut-Off Wheel Contact

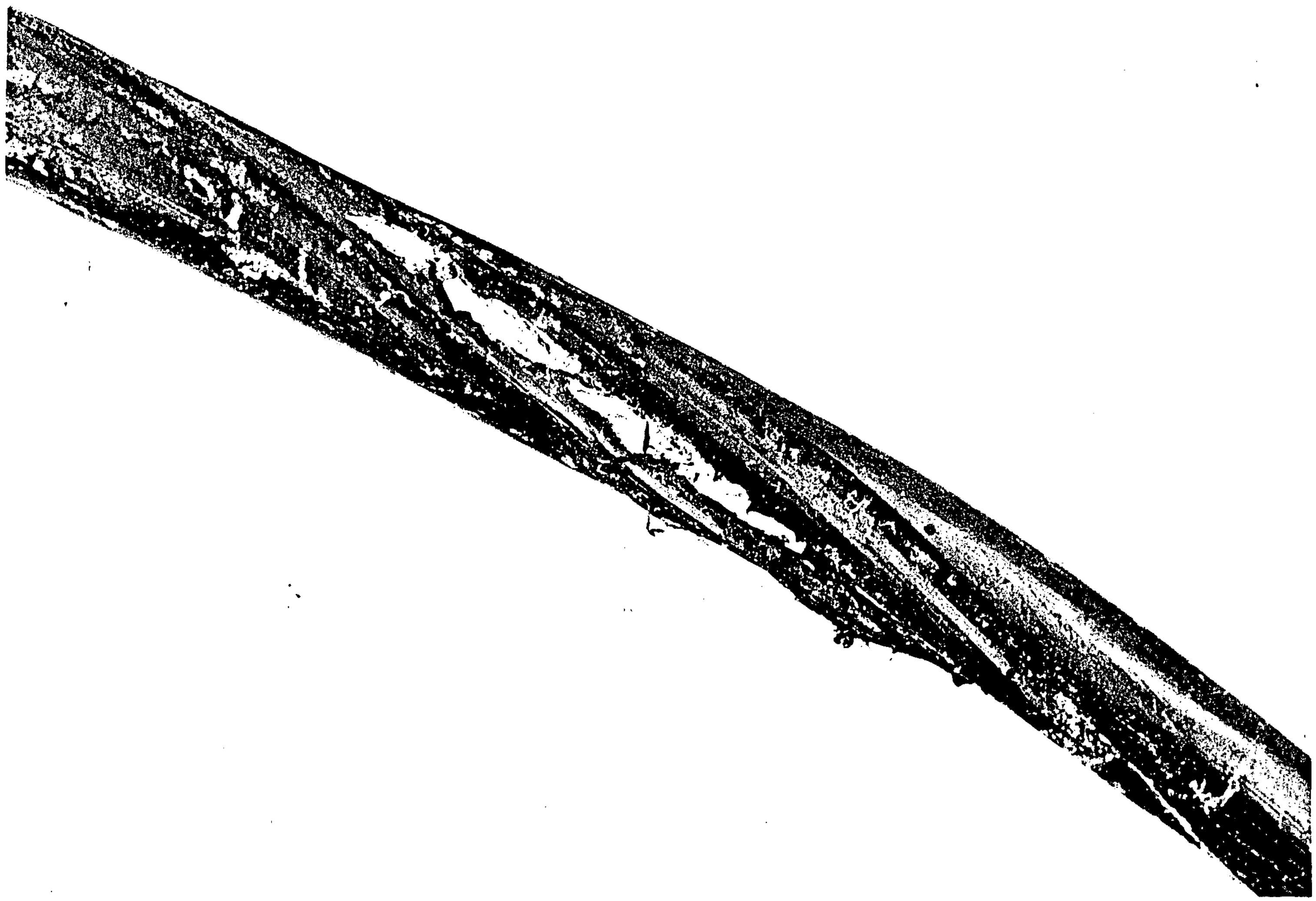


Figure 34
Damage To Surface of Cable 2PM-871-D-I

1-2PL-83-1085 B

Figure 35
Sharp Cut Limited To Jacket of Cable
1-2PL-83-1085-B

1M 591-B

Figure 36
Split In Jacket of Cable 1M-591-B

1-PM-506-D

Figure 37
Split In Jacket of Cable 1-PM-506-D

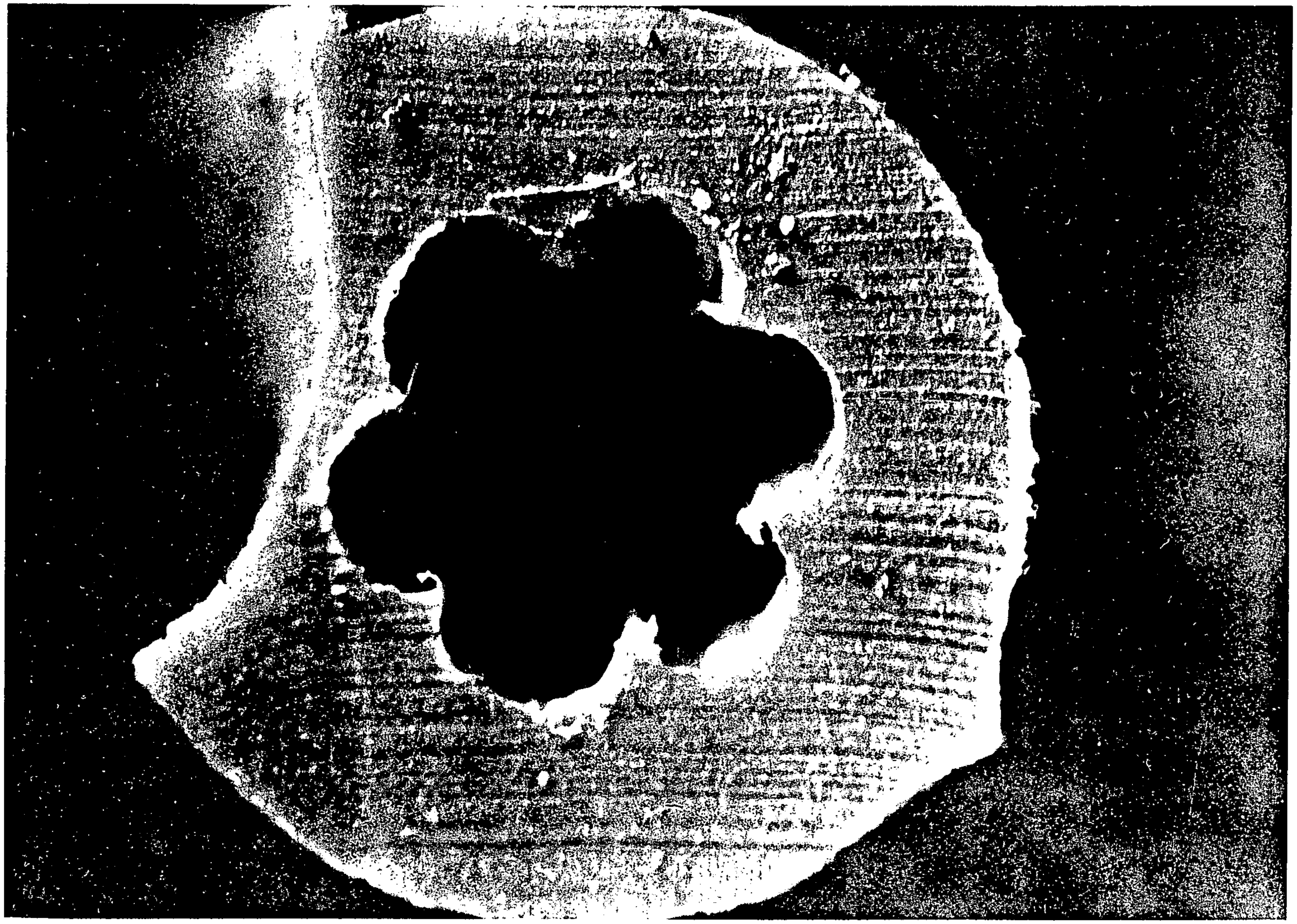
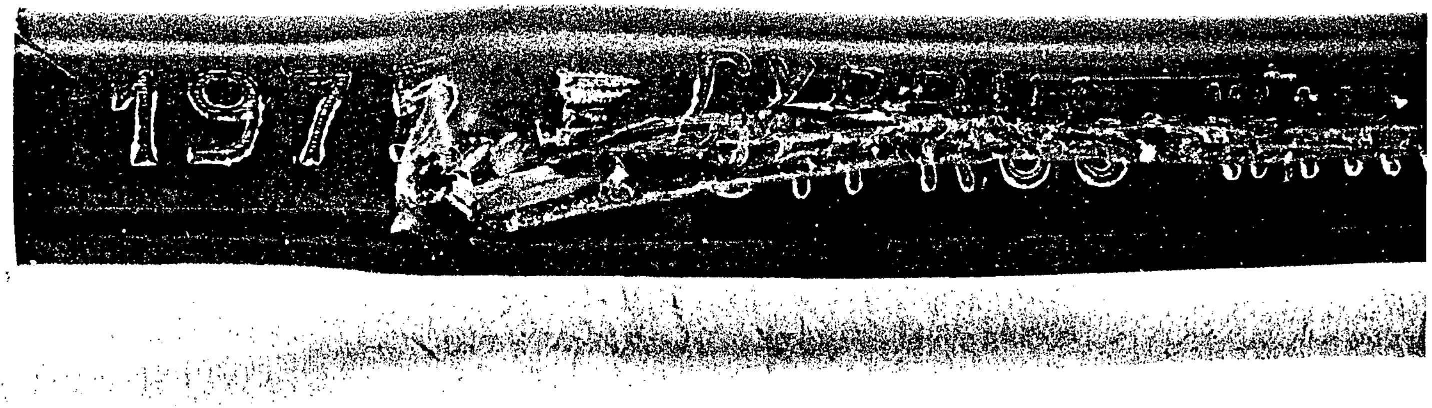
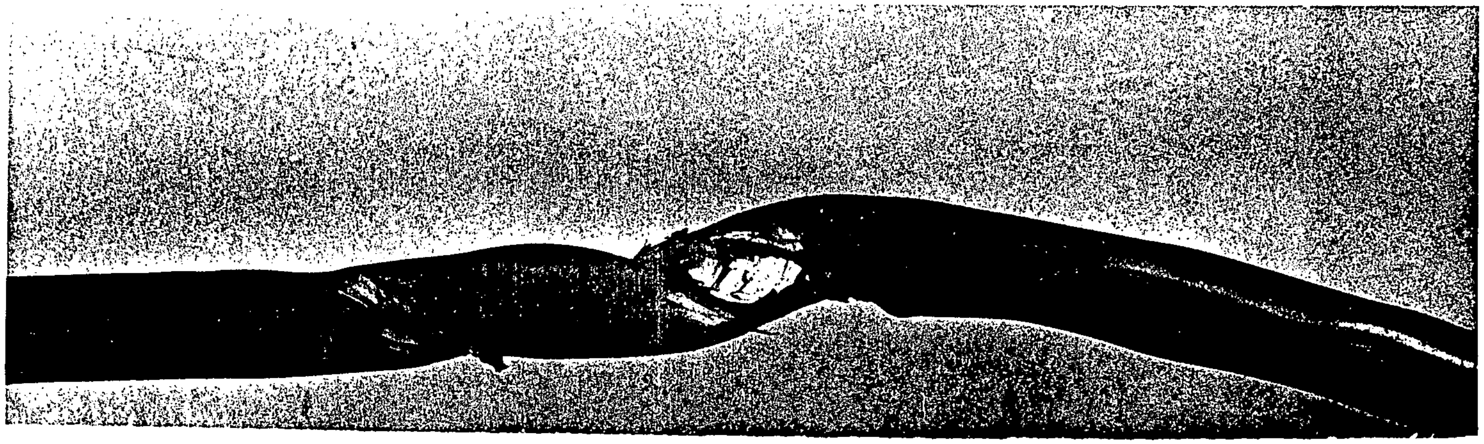


Figure 38
Cross-Section Through Damaged Site of Cable
1M-2450-B



O-SP-255 529

Figure 39
Sharp, Deep Cut In Surface of Cable
O-SP-255-529 (Conductors Exposed)



CPE JACKET PULL-BY SIMULATION

20 IN/MIN ~ 90-100 LB LOAD

12 IN PULL W/PARACHUTE CORD

Figure 40
Pull-By Simulation Damage To Surface of CPE Jacket from Contact with Parachute Cord

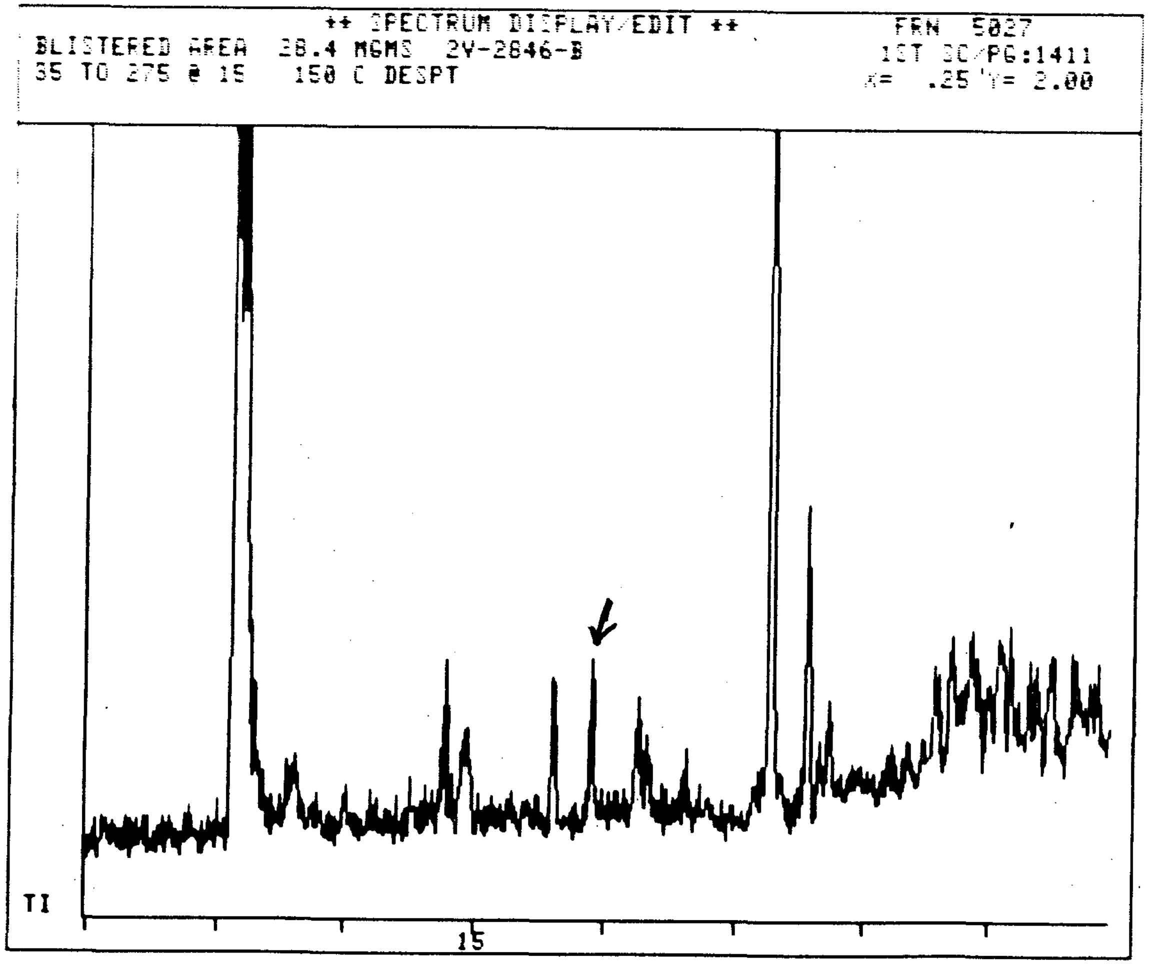


Figure 41
Gas Chromatogram of Swollen Area of Cable Jacket 2V-2846-B. Peak Indicated Was Not Found In Non-Swollen Area

T, 9

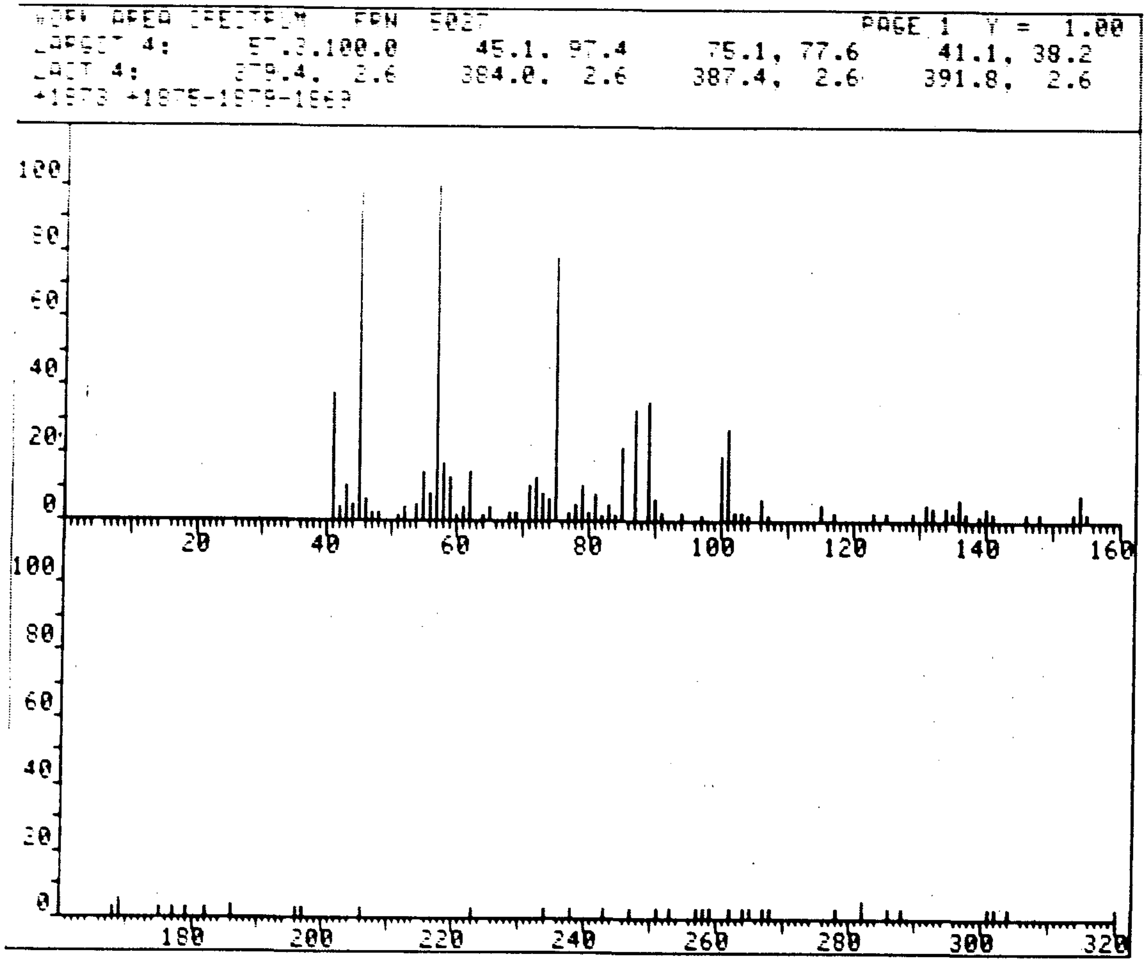


Figure 42
Mass Spectrum Corresponding To GC Peak At 15.9 Minutes, Shown In Figure 41, for Cable Jacket 2V-2846-B

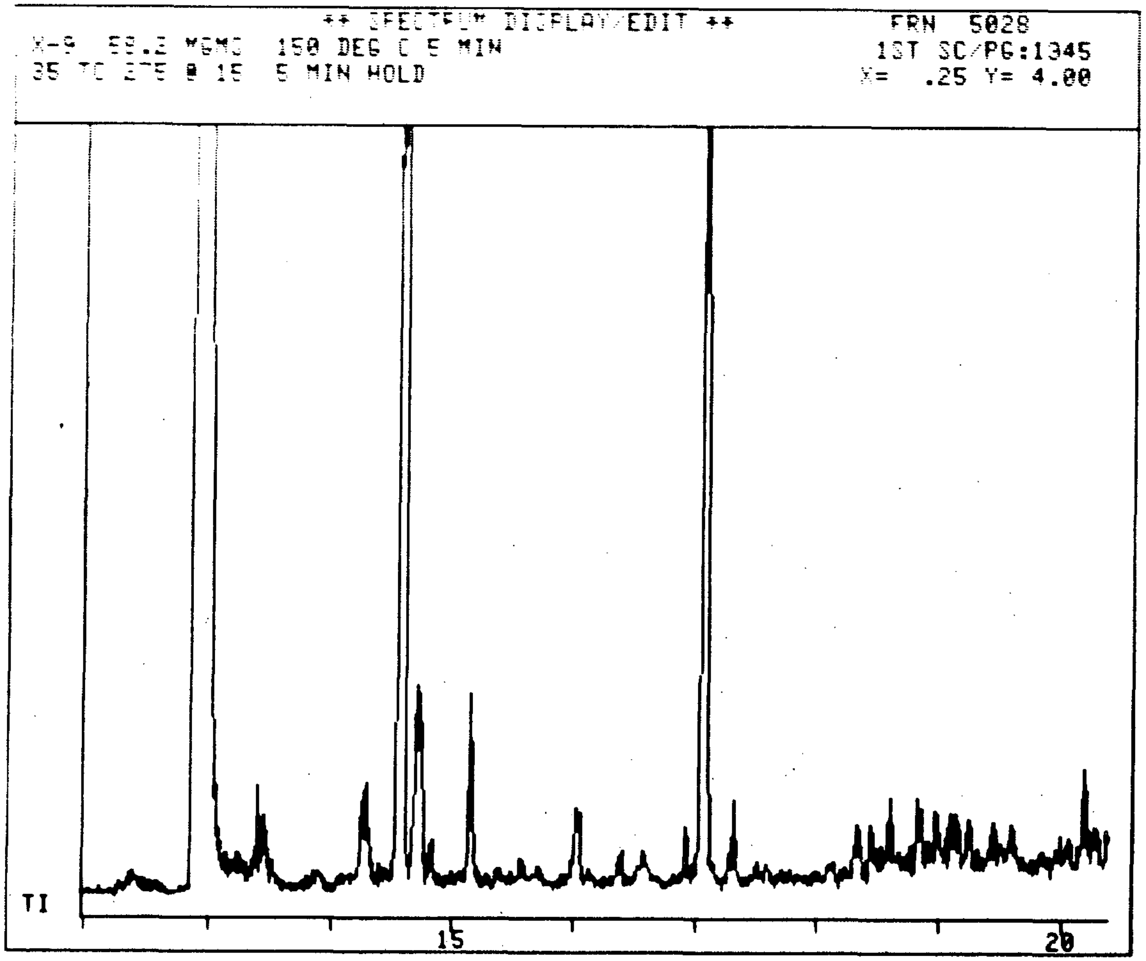


Figure 43
Gas Chromatogram of Non-Swollen Area of
Cable Jacket X-9

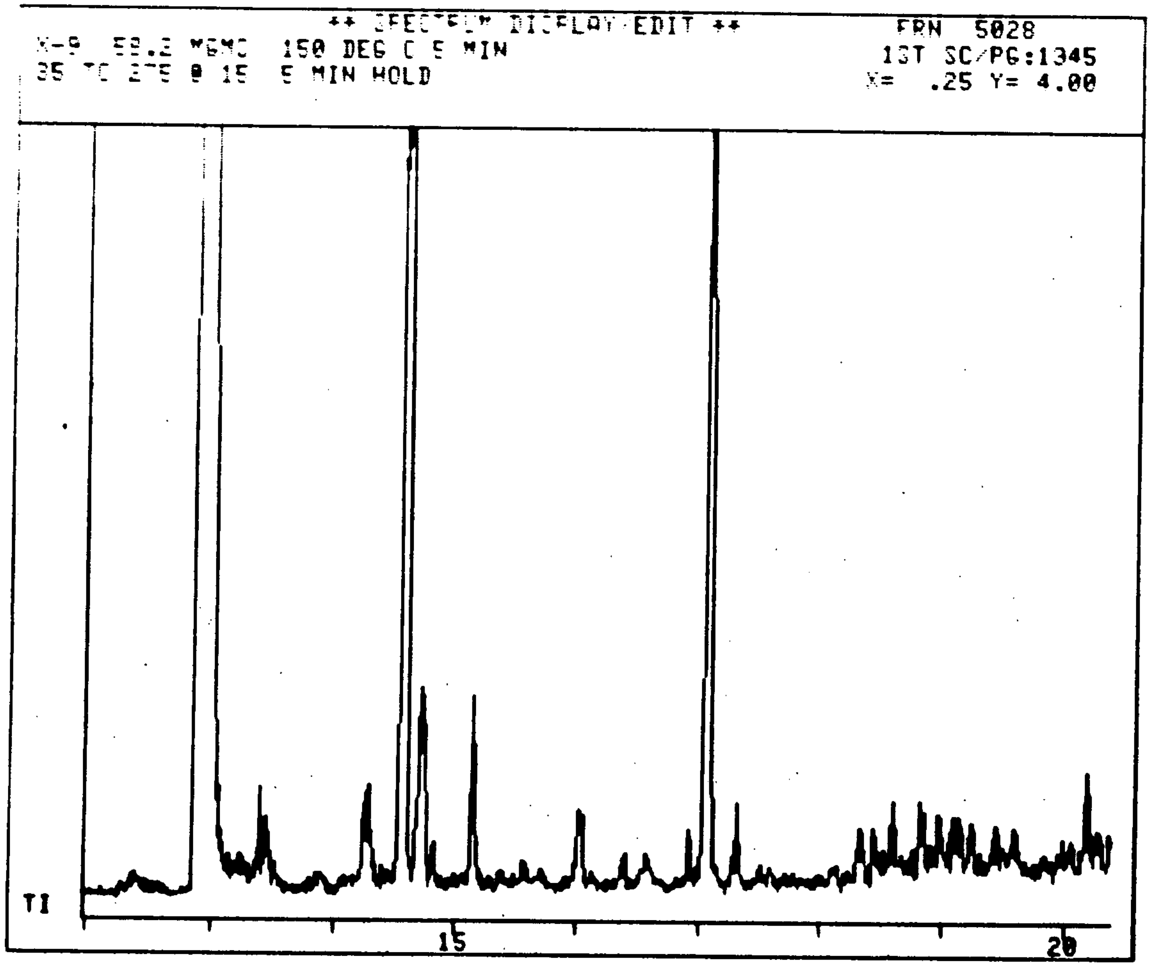


Figure 43
Gas Chromatogram of Non-Swollen Area of
Cable Jacket X-9

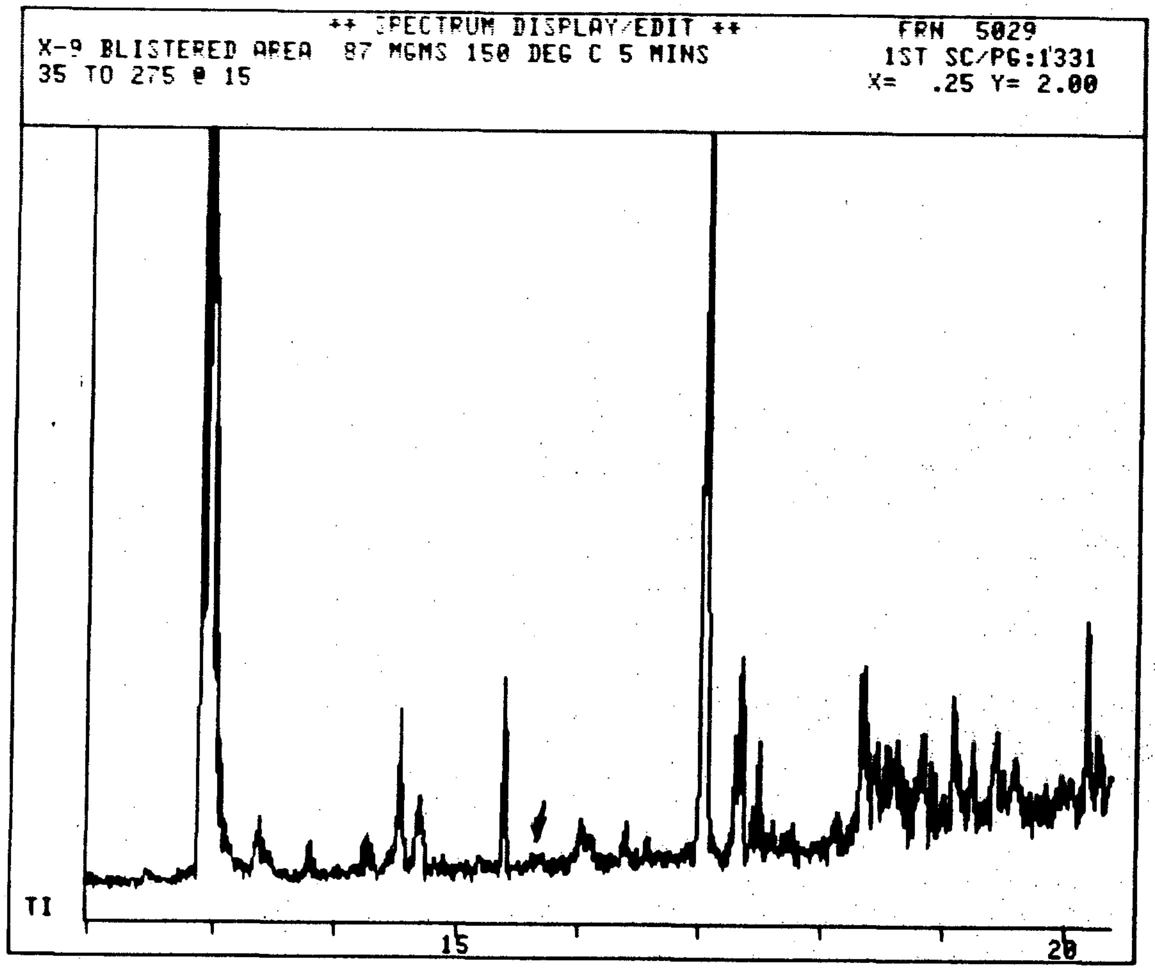


Figure 44
Gas Chromatogram of Swollen Area of Cable
Jacket X-9, Showing Unique Peak At 15.6 Minute
Retention Time

INSTITUTE OF MATERIALS SCIENCE

The Institute of Materials Science (IMS) was established at The University of Connecticut in 1966 in order to promote academic research programs in materials science. To provide requisite research laboratories and equipment, the State of Connecticut has provided $6,000,000, which has been augmented by over $7,500,000 in federal grants. To operate the Institute, the State Legislature appropriates over $1,200,000 annually for faculty and staff salaries, supplies and commodities, and supporting facilities such as an electronics shop, instrument shop, a reading room, etc. This core funding has enabled IMS to attract over $5,500,000 annually in direct grants from federal agencies and industrial sponsors.

IMS fosters interdisciplinary research programs in various areas of materials science with special emphasis on adhesion, composites, corrosion, electrical insulation, interfaces, liquid crystals, metals, and polymers. These programs are directed toward training graduate students while advancing the frontiers of knowledge and meeting current and long-range needs of our state and our nation.

ATTACHMENT 2

An Evaluation of

Cable Damage Susceptibility

from Pullby Events at the

Watts Bar Nuclear Plant

(PLG-0744, Revision 1)

1028g