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Failure Analysis Study and Long-Term Reliability of Optical Assemblies with End-Face Damage

*Robert A. Kichak, Melanie N. Ott, and Henning W. Leidecker
NASA Goddard Space Flight Center, Greenbelt, Maryland*

*Richard F. Chuska
MEI Technologies, Seabrook, Maryland*

*Christopher J. Greenwell
NASA Goddard Space Flight Center, Greenbelt, Maryland*

October 2008

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NASA Goddard Space Flight Center, Greenbelt, Maryland*

NASA Engineering and Safety Center
Langley Research Center
Hampton, Virginia 23681-2199

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**Failure Analysis Study and Long-Term Reliability of Optical
Assemblies with End-Face Damage
Technical Assessment Report**

*Phase I: International Space Station (ISS) Termini Root Cause
Analysis Report*

August 3, 2006



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Volume I: Technical Assessment Report

1.0 Authorization and Notification

The request to conduct a technical assessment was initiated as a result of the NESC Review Board (NRB) decision on June 7, 2005.

Mr. Robert Kichak, the NESC Discipline Expert (NDE) at Goddard Space Flight Center (GSFC), presented the initial evaluation of the plan on July 7, 2005. The Technical Assessment (ITA) Plan was approved by the NESC Review Board (NRB) on August 12, 2005.

Mr. David Beverly from Johnson Space Center (JSC) is the key stakeholder and will receive the final report.

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2.0 Signature Page

Assessment Team Members


Mr. Robert A. Kichak Date
NESC Lead

Ms. Melanie N. Ott Date
Deputy Lead

Dr. Henning W. Leidecker Date
GSFC


Mr. Richard F. Chuska Date
GSFC/MEI Technologies

Mr. Christopher J. Greenwell Date
GSFC

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3.0 Team Members List

Last Name	First Name	Position/ Team Affiliation	Center/ Contractor
Kichak	Robert	NDE, Lead	GSFC
Leidecker	Henning	Principal Investigator	GSFC
Ott	Melanie	Principal Investigator	GSFC
Chuska	Richard	Electro-Optical Engineer	GSFC/MEI Technologies
Greenwell	Christopher	Failure Analysis Engineer	GSFC
Moran	Erin	Technical Writer	LaRC, Swales Aerospace

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4.0 Executive Summary

In June 2005, the NESC received a multi-faceted request to determine the long term reliability of fiber optic termini on the ISS that exhibited flaws not manufactured to best workmanship practices. There was a lack of data related to fiber optic workmanship as it affects the long term reliability of optical fiber assemblies in a harsh environment. A fiber optic defect analysis was requested which would find and/or create various types of chips, spalls, scratches, etc., that were identified by the ISS personnel. Once the defects and causes were identified the next step would be to perform long term reliability testing of similar assemblies with similar defects. The goal of the defect analysis would be for the defects to be observed and documented for deterioration of fiber optic performance.

Also discussed was a repair kit composed of completed cables with terminations on both ends that would require the crew to de-pin both ends of the cable and re-pin with a replacement fiber length, maybe a little longer than the original. However, this report only focuses on Phase I of the request and summarizes the defect analysis conducted at NASA Goddard Space Flight Center, Parts, Packaging, and Assembly Technologies Office. With the defects summarized, the study will continue with a set of assemblies that are purposely damaged in a similar manner as the ones observed from Node 2 and these will be subjected to stress tests to assess how long the assemblies will last before replacements are necessary. The work that continues after submission of this report will be conducted in coordination with the ISS Project Engineer, David Beverly at JSC.

The intent of this analysis is to identify the damage to the ISS fiber optic termini from Node 2, and discuss the physics of crack propagation. A reliability study of fiber optic cabling will be performed after the analysis has been completed. The reliability study will include vibration and thermal cycling testing where the assemblies will be damaged in a manner similar to the defects identified during this study.


The proposed assumption when this study began – that defects originated from a single proximate cause – was incorrect. In fact, the summary and results will explain that the defects were caused by a number of errors related to workmanship and improper manufacturing and inspection (quality) procedures. Therefore, there were multiple contributors that caused the damage to these termini. Without being present during the manufacturing process, it is not possible to identify each individual proximate cause. The conclusions are based on the physics of fiber cracks and past lessons learned. The team has access to the manufacturing document, but it is proprietary, so it will not be included in this report. However, it will be explained when improper manufacturing and quality procedures were identified as a contributor to the termini end-face defects, when possible. Examination of the samples yielded evidence of cases where

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the manufacturer's documented processes and/or procedures were not followed or were inadequate (i.e., concave/convex end-faces). See [Section 7.0](#).

In systems that move data and information via optical fiber, the fiber must be pristine and free of any debris to minimize optical signal loss over the long term. Manufacturing specifications are established to ensure optimal signal transmission and to produce a reliable product. When a flaw is introduced into glass and moisture is present, cracks can and will propagate due to the forces applied to the glass. Some of the processes that were used in manufacturing these termini are not used and are prohibited by high reliability spacecraft applications because of the high risk of inducing a flaw. Manufacturing, handling, and quality assurance practices, which are not used or prohibited in high reliability spacecraft applications, were found among the written procedures and through examination of the termini. Issues and concerns as a result of this study regarding manufacturing processes documented, workmanship, and quality assurance processes are as follows:

1. **Documented Polishing Procedure:** Lapping film of 30 μm was used to grind excess fiber and epoxy after the cleaving process. This is high/coarse grit lapping film. The danger in using this is the deep scratches left behind will cause crack propagation over time. NASA recommends using no larger than 9 μm to grind and, for rework, 5 μm or less lapping film to "polish" away excess fiber and epoxy because it will remove the excess, but will not create scratches that are too deep [ref. 10]. The scratches from the 30 μm film should have been completely removed using the finer grit lapping film. Sections 7.3, 7.4, 7.5, 7.8, and 7.13 illustrate signatures of this type of defect.
2. **Contamination and Grinding Material Evidence:** The damage to the coating observed in every sample appears to have been caused by larger contaminant particles than the grinding material of the lapping film. Grinding material may have been embedded in the coating, but the damage was overshadowed by the deeper "cuts". Some very large and deep scratches are illustrated in Sections 7.2, 7.7, 7.9, and 7.15. These may have been caused by contaminant debris that scratched the end-face of termini as they are mated into connectors.
3. **Documented Procedure on Epoxy Curing:** During the epoxy curing process, the fiber experiences stress due to the differences in CTE. The CTE of silica is $0.55 \times 10^{-6} / ^\circ\text{C}$, the CTE of the epoxy is $54 \times 10^{-6} / ^\circ\text{C}$, and the CTE of the zirconia ferrule is $10 \times 10^{-6} / ^\circ\text{C}$. Curing at higher temperatures such as 200 $^\circ\text{C}$ induces large amounts of stress and will cause acceleration in crack propagation. GSFC cures the epoxy at temperatures ≤ 120 $^\circ\text{C}$ to reduce this stress.

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4. **Documented and Evidence of Inadequate Quality Assurance Practices:** As described in Section 7.8, defects cannot always be identified at lower magnifications. Analyzing an optical fiber at 50X magnification is not sufficiently effective to identify flaws in the end-face. Magnifications of 200X or higher must be used.

In many applications, a physical contact connection is implemented to mate fiber optic connectors such that the insertion losses are reduced. In the case of this connector, the high vibration levels originally used to “qualify” the connectors for military standard applications showed data indicating that the terminus/connector system should not be of a physical contact type. Therefore, the same processes were specified in this application. For a “concave” polish, it is imperative that the glass end-faces do not come in contact with one another in order to comply with the military standard method and reasoning for non-contact. As stated in OHB’s “Fibre Optic Manufacturing Procedure” Section 4.6: “Inspect the profile of the terminus end-face under 40X magnification. The surface should be slightly concave with the face of the ceramic tip.” This is not an effective method for determining the fiber’s profile. Figure 4.0-1 shows what the profile looks like at 40X magnification. The end-face appears to be flat, and not protruding. This method is non-conclusive for true determination of the end-face profilometry. The profile should be determined using an interferometer or confocal microscopy as illustrated in Figure 4.0-2. The confocal data clearly shows the end-face of the fiber to be convex, which should have failed inspection.

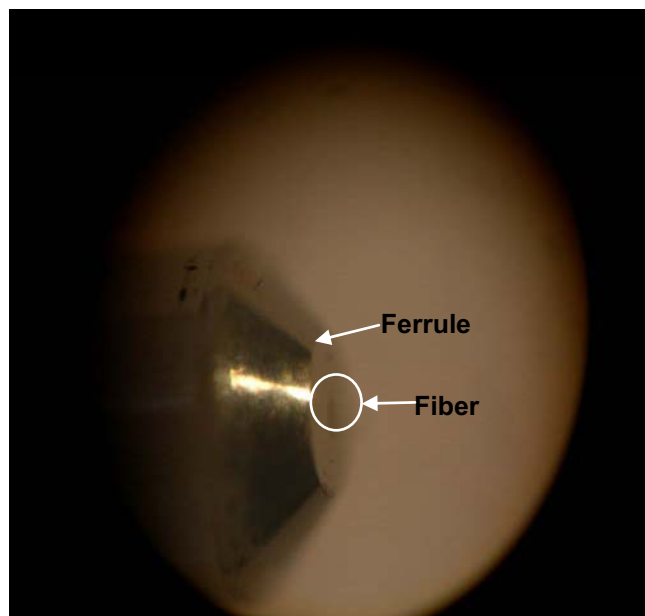

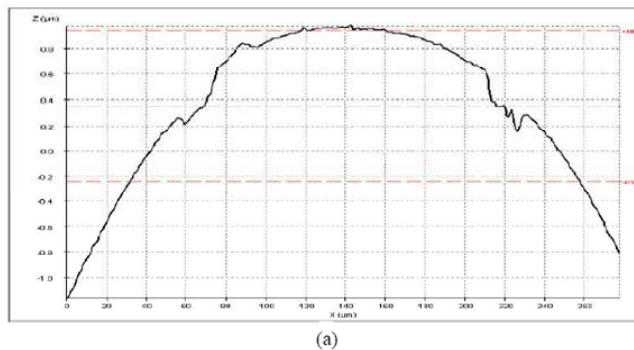


Figure 4.0-1. Visual End-Face Profile @ Magnification of 40X

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Fiber end-face geometry

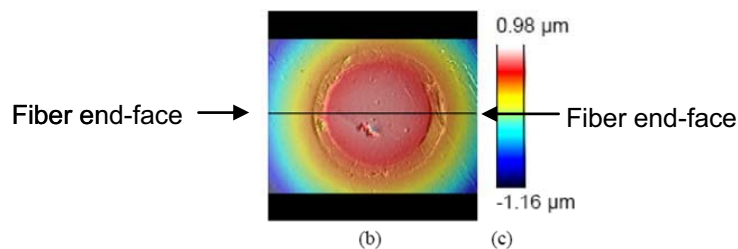


Figure 4.0-2. Confocal Profile


The horizontal line appearing in the top chart of Figure 4.0-2 corresponds to the profile plot shown in the colored image figure below the chart.

The inspection process did not detect 46 percent of the termini that should have been rejected.

- Evidence of Cleanliness Mishandling:** The end-faces of all termini were heavily contaminated with debris. Debris causes secondary damage, and this hinders the analysis because it is not certain where in the life of the termini the debris was introduced. It is imperative that fiber optic components stay clean and free of debris.

Nine out of nine, or 100 percent, of the samples that had accurate EDS data collected had traces of Na and Cl present. Silica glass is very resistive to corrosive chemicals like Na and Cl, but when doped with germanium as these fibers are, the resistance can be decreased. The presence of Na and Cl is expected to result in reduced life for the fiber optics. This will be studied in the Phase II effort.

Though this report mostly discusses what has been determined as evidence of poor manufacturing processes, it also concludes the majority of the damage could have been avoided with a rigorous process in place.

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As described in Section 7.14, four out of thirteen, or 31 percent, of the termini will likely have signal degradation in the short-term. Nine out of thirteen, or 69 percent, are likely to experience no degradation or degradation in the long-term. Long-term reliability tests such as thermal and damp heat will need to be performed to calculate how long fibers with these types of defects will last. The apparent presence of Na and Cl on the end of the fibers was a finding that was very discouraging. It was determined that a study will need to be performed on the effects of salt when it comes in contact with germanium doped silica, but will not be included in this report.

5.0 Assessment Plan

During the Program’s assessment and based on crew inputs, the ISS Program system managers recommended waiting until a cable fails and then have the ground build the entire cable. The cable would then be flown up and laid over the offending cable. The crew would only have to remove and replace connectors, making the task easier. In some cases, a failed single fiber may be buried in a complex harness that will require several connectors to replace one bad fiber without de-pining. It was also recommended that the ground team build up the correct fiber replacement with the right terminations on both ends and then fly it up with specific work instructions. There was a differing opinion from the Communications and Tracking (C&T) recommendation that the crew should de-pin the defective single fiber and re-pin the new fiber into the existing on-orbit connectors. There was a risk with this approach since it required a crew that was “tool smart”.

The scope of the NESC activity was limited to an assessment of the following objectives raised by the requestor. This report covers only item 1 below.


1. Determine the likely proximate root cause of the damage (including deep cracks and chip outs) observed by the ISS at the ends of fiber optic cables that were supplied to them. If no single root cause is determined, likely sources of the damage will be identified and explained. If no single root cause is determined, likely sources of the damage will be identified and explained. This supports re-designing the manufacturing processes so that future cables will be free of this damage. It will also allow the NESC team to damage a number of specimens in the same way as the presently supplied cables. From these specimens, the NESC will perform a statistical study of the aging of cables damaged in the same way.
2. Study the aging of the transmission of cables made like the ones supplied to ISS to establish their reliability — the probability that a cable will meet its specifications for the planned lifetime on ISS. This study would require more specimens than those that are currently available from the ISS. Therefore, Objective 1 is used to guide the NESC in making the required number of appropriate specimens.

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3. Study new types of fiber and cabling methods that will be replacing the ones in present use, so that their reliability can be estimated.

The ISS Program accepted the cables supplied for Node 2, accepting the risk that the cracks in their termini may degrade transmission enough to damage communications before the planned end of the ISS mission. However, this risk was not quantified and was unknown. Although several literature searches were made, no studies have been located that allow an estimation of the degradation in transmission that can be expected for these damaged termini. One reason was that ISS requires a fiber optical cable that tolerates a uniquely wide range of temperatures (from $\pm 100^{\circ}\text{C}$). This requires the use of a polyimide buffer, rather than the acrylate in common use, and also requires radiation tolerance (this requires the use of a unique glass in the fiber). Both requirements move the “cracking proneness” of the fiber in this buffer outside the ranges of experience of commercial vendors. Their traditional methods no longer necessarily apply to the ISS cables. The work at GSFC has shown that the radiation-tolerant fiber is noticeably more fracture-prone than the fiber used in telecommunications. GSFC will damage similar cables in a comparable manner to determine the life expectancy of the existing compromised cables that are currently integrated into the ISS communications node [ref. 1].

Also, because of the systemic lack of industry cause/effect data on the long-term aging of surface defects, this study examines new kinds of fiber, which offered the potential for use in the Crew Exploration Vehicle (CEV).

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6.0 Problem Description, Proposed Solutions, and Risk Assessment

Background

Node 2 was manufactured by European Space Agency (ESA)/Alenia and was accepted by NASA for integration into the ISS. During integration testing at the Kennedy Space Center (KSC), based on loss data, two cables were determined to be too long. Replacements were fabricated and inserted into the Node harnesses. KSC then carried out a pre-mate inspection at 200X magnification and determined that 58 out of 60 termini required cleaning and that four termini were defective. The defects included one spall, two cracked termini, and one unpolished termini. Note that neither the integration contractor (Alenia) nor the manufacturer of the fiber cables (OHB in Germany) reported the damaged end-faces on the optical fiber termini.


From the damage reported by KSC for the Node 2 fiber, there was concern about the condition of Node 3 fiber (which was still at Alenia and not yet integrated in the Node). An inspection team traveled to Alenia in April 2005 and inspected and photographed (at 200X/400X) all the Node 3 fiber cables; 326 termini were inspected and only nine were acceptable. The Node 3 summary after inspection includes:

- 20 cracked end-faces
- 20 with spalls, pits, or chips
- 39 badly scratched fibers
- 10 with surface contamination that cleaning could not remove

It was recommended by the inspection team that a total of 89 termini be re-polished or replaced. The inspection found a defect rate of $89/326 = 27$ percent.

Since there is no understanding of the cause of this damage and this indicts further manufacturing, it is imperative that the following questions/concerns be answered:

1. What effect would curing the epoxy at 200° C have? NASA recommends curing epoxy at temperatures $\leq 120^\circ$ C.
2. Was the damage initiated during the polishing process and missed because it was inspected at only 50X magnification?
3. Did the fiber crack because high grit lapping film was used and not followed up with the lower grit to remove the flaws?
4. Was the damage caused by inadequately cleaning the termini prior to integration?

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5. Was the damage initiated by grinding material embedded in the coating or epoxy, causing latent contamination of the end-faces?
6. There are no industry studies that were found to analyze the affects of cracks, spalls, and deep gouges on the long-term reliability of the fiber cables. The ESA's position for the hardware that they delivered to NASA is: if the system margin is acceptable and each cable length meets the insertion loss criteria, then the fiber is compliant. Per ESA quote:

“The visual condition of the termini is not important because the signal level meets requirements.”

Therefore, one of the major purposes of the overall NESC study is to generate rigorous data that shows the effects of end-face surface damages of the kind observed in these specimens on the long-term system reliability.


It is possible that either one or all of the above damaging events happened, which resulted in the damaged termini. It is also possible that some other aspect of the present production methods is responsible for these damaged termini. In either case, making more cables without changing the processes would only produce cables that also have damaged termini. The only way to ensure undamaged termini is to establish the root cause(s) of the damage happening to these termini.

The inspection results convinced the ISS Program that a repair of the damaged termini was required prior to the integration of the cables into Node 3. Alenia agreed to repair the cables and NASA agreed to supply new termini and fiber cable and one KSC technician.

Thirteen termini were submitted to GSFC to determine the root cause of the damaged fiber end-faces as well as the signal reduction observed by the ISS. In conjunction, a study will be performed on new cabling methods, which will replace the ones currently being used, so their reliability can be estimated.

The investigation team used a variety of techniques to perform root cause analysis including optical microscopy, Scanning Electron Microscopy (SEM), EDS, and confocal microscopy. These tools are essential to understanding the root cause of the damage.

This report documents the results of Phase 1 analysis of the cables to determine the likely root cause(s) as described above. Phase 2 will be completed after Phase 1 and will be documented as a separate report.

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7.0 Data Analysis

Optical microscopy is normally the first step in failure analysis. It is a tool that is used to magnify features of the fiber too small to see with the naked eye. Illumination of the fiber can be manipulated to observe sub-surface flaws as well. The disadvantage of optical microscopy is that at higher magnifications (500X and up), only one plane of the object can be focused in on.

SEM is performed because it can take pictures at very high magnifications and generate clear surface images, which allows microscopic flaws to be analyzed. The advantage of SEM over optical microscopy is it can magnify objects over 50,000X, and produce a clear 3-dimensional image. The disadvantage is that any sub-surface flaws cannot be viewed.


It is important to understand the geometry or profile of the end-face. These termini are supposed to be manufactured with a concave profile to reduce the risk of physical contact with the mating surface. The best tools to identify the end-face geometry are either an interferometer or confocal microscope. These instruments report the shape of the profile by means of a topographical image as well as graphs in the X- and Y-axes.

EDS identifies elements present that cannot be identified visually, and plots them on a graph. If a certain element or elements have been identified from EDS, elemental mapping can be performed to locate the areas where these elements exist. This is particularly useful when identifying areas on the fiber that may contain elements that cause the glass to have a reaction.

It is important to acquire as much information about the samples before performing destructive analysis, because once a sample has been compromised, it is not possible to put the pieces back together and draw definitive conclusions. Destructive analysis, such as cross-sectioning, will allow a better view of the crack depths as well as enable a view of the face of the break. This will be the key to determining propagation rate of the cracks. Some of the destructive analysis includes cross-sectioning and removal of the fiber from the ferrule. To remove the fiber from the ferrule, the sample will need to soak in an acid bath. The likelihood of losing the fragments from the break is high.

The analysis of each individual terminus was broken down into detail and divided into the following sections of this report.

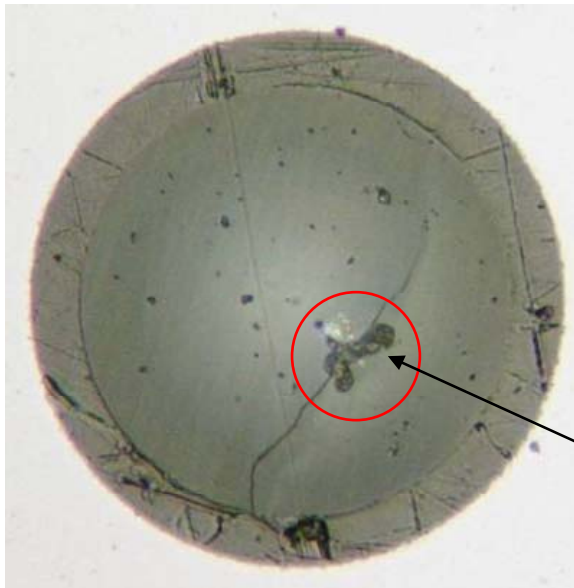
- Section 7.1 Sample HMU-302 P21-UP4 SKT A
- Section 7.2 Sample HMU-303 P3-VSU5 SKT F
- Section 7.3 Sample HMU-303 J31-BKT VSU SKT S
- Section 7.4 Sample HMU-303 P5-VSU5 SKT E
- Section 7.5 Sample HMU-302 P14-NODE1 SKT P

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- Section 7.6 Sample HMU-304 P20-UP4 SKT Z
- Section 7.7 Sample HMU-303 P3-DAIU SKT C
- Section 7.8 Sample HMU-303 J31-UP4 SKT C
- Section 7.9 Sample HMU-303 J1 BKT-VSU SKT G
- Section 7.10 Sample HMU-303 J1 BKT-VSU SKT P
- Section 7.11 Sample HMU-303 J21-UP4 PIN A
- Section 7.12 Sample HMU-303 P3-ABC 5 SKT B
- Section 7.13 Sample HMU-303 P3-VSU5 SKT T

7.1 Sample HMU-302 P21-UP4 SKT A


The images in Figures 7.1-1 and 7.1-2 were taken at 200X magnification. The first observations made were: 1) the apparent impact fracture on the end-face, 2) the crack(s) propagating from the fracture, 3) damaged or scarred coating or buffer, and 4) the excessive contamination on the end-face of the fiber.



Impact Fracture/Cracking

(Refer to Figures 7.1-3 and 7.1-4 for magnifications of this feature.)

Figure 7.1-1. Bright Field Image

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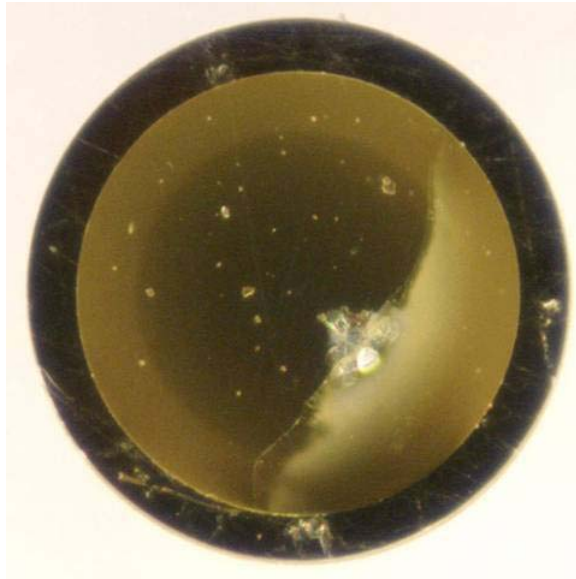



Figure 7.1-2. Dark Field Image

The origin of the impact fracture needs to be observed closer. If a higher magnification were used with the microscope, the features of the fracture would not be clear, and no solid conclusions could be made. To analyze the fracture closer, the terminus was observed using SEM.

The SEM images in Figures 7.1-3 and 7.1-4 were taken to identify stress signatures in the origin. At 4.86×10^3 and 12.1×10^3 magnifications, a corrosive attack on the glass inside the impact fracture was observed. The elements that are causing the corrosion cannot be identified visually, so EDS was performed to identify what was attacking the glass.

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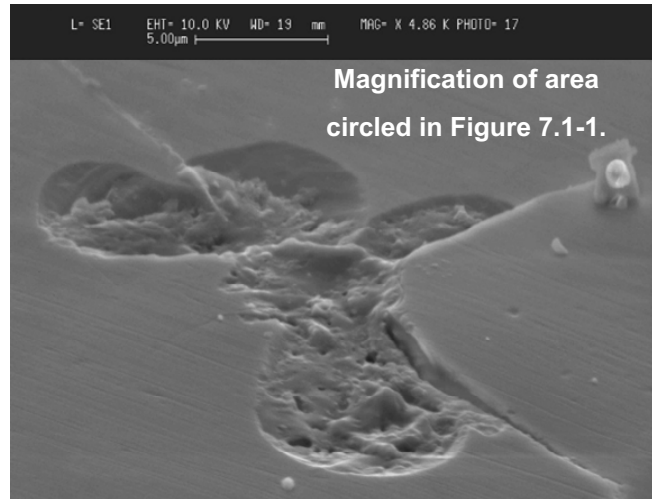


Figure 7.1-3. Magnification of 4,860X SEM Images

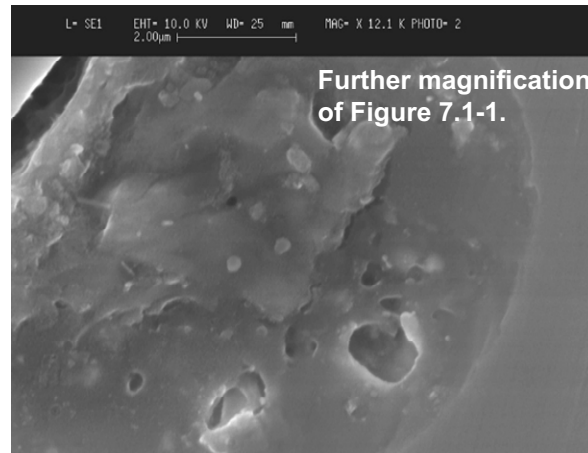


Figure 7.1-4. Magnification of 12,100X SEM Image

The EDS data (Figure 7.1-5) from the fracture area indicates the presence of carbon, oxygen, sodium (Na), germanium, magnesium, silicon (Si), chlorine (Cl), potassium, and calcium. The presence of Na, Cl, and potassium suggests a finger came in contact with the end-face. It is not known exactly what material was used to polish the termini, but there are some popular lapping films that are widely used (e.g. aluminum oxide, silicon carbide, and cerium oxide) [ref. 3].



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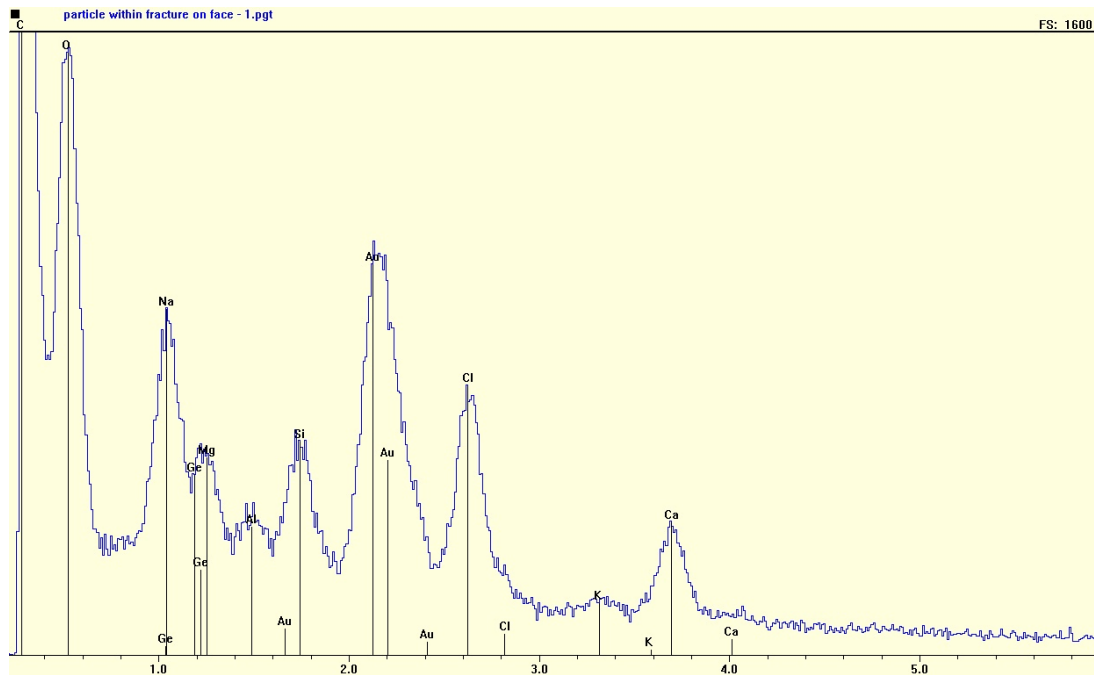
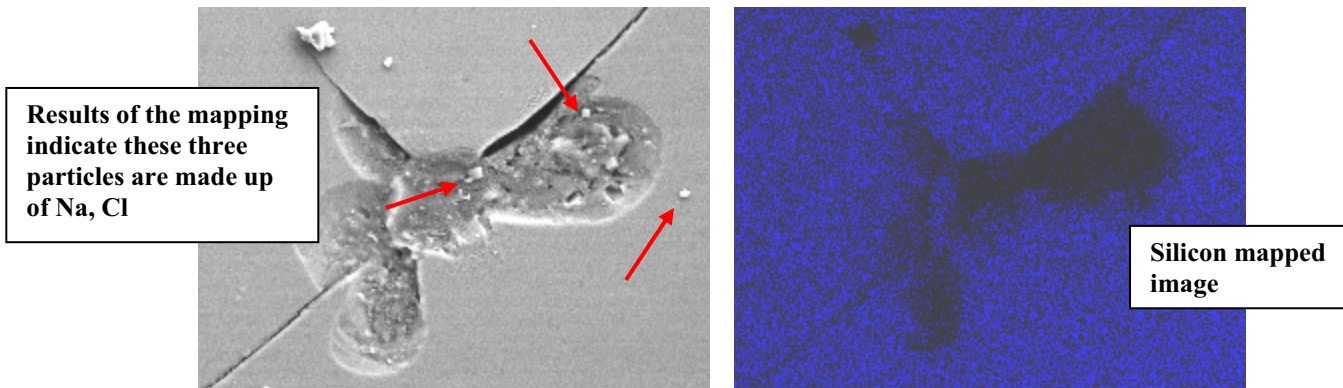



Figure 7.1-5. EDS of Particle inside the Fracture

The discovery of salt crystals in the glass was puzzling. To identify where the salt crystals are located on the end-face, elemental mapping was performed. Elemental mapping was not effective at 500X magnification to locate small traces of certain elements, so to locate Na and Cl, a higher magnification was used. Figure 7.1-6 shows the results when this sample was mapped for Si, Na, and Cl.



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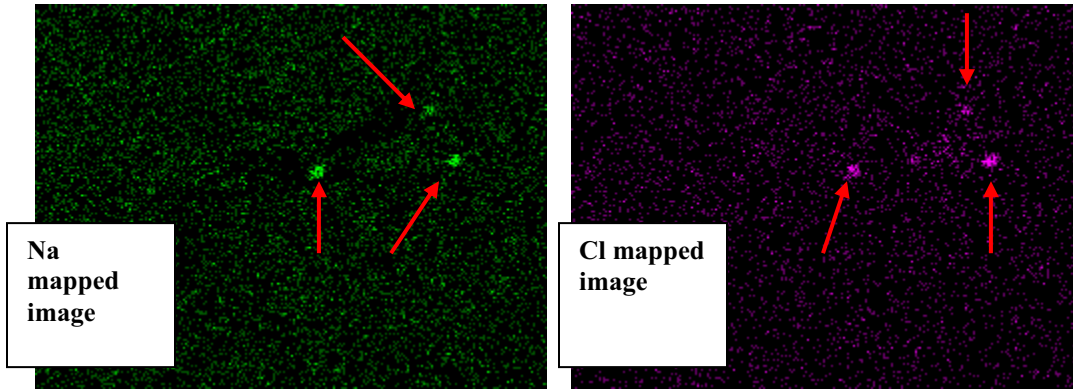


Figure 7.1-6. Elemental Mapping of Si, Na and Cl

Optical microscopy and SEM do not have the ability to generate a profile of the end-face so confocal microscopy is performed. Confocal microscopy (Figure 7.1-7 and Table 7.1-1) will generate a topographical map and a profile in the X-Y axis. It was discovered that the fiber has a convex end-face rather than concave.

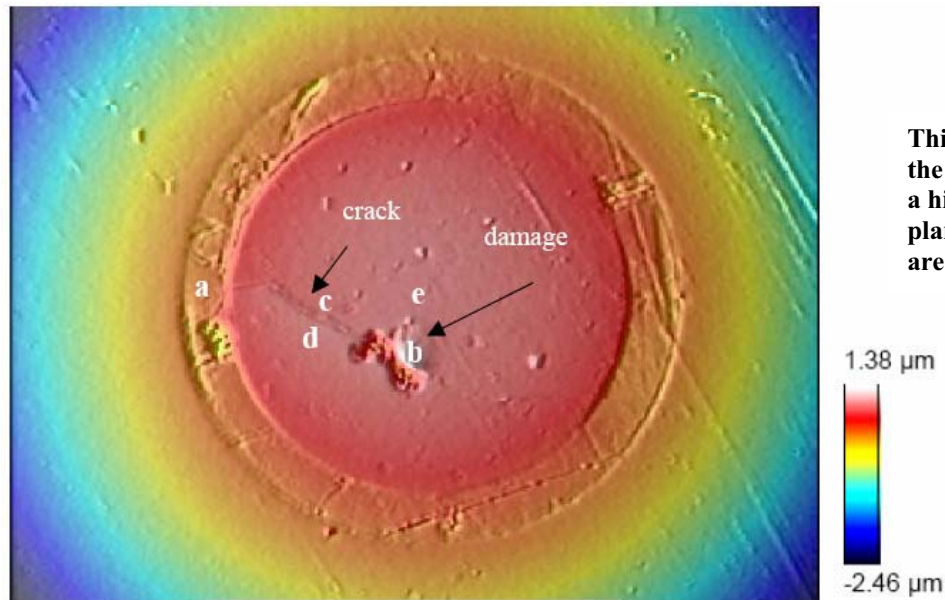
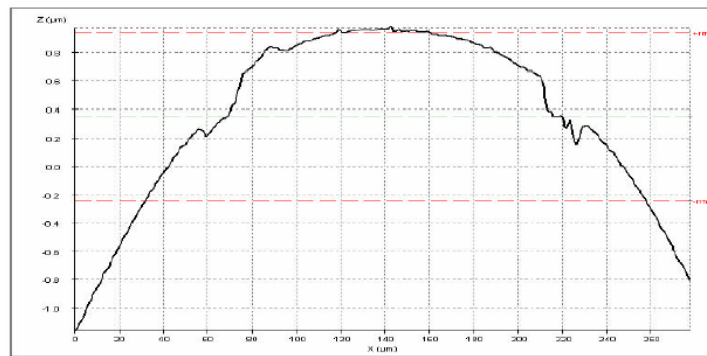


Figure 7.1-7. Confocal Topographical Image

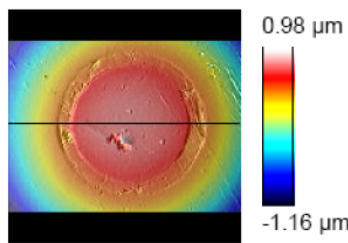
Table 7.1-1. Height of Selected Points Relative to Point “a” on Figure 7.1-7

Point of Interest (see Figure 1)	Height relative to point “a” (μm)
a	0
b	1.150
c	0.640
d	0.710
e	0.790

These termini are supposed to be manufactured with a slight concave end-face as observed in Figure 7.3-5. This is per the manufacturing procedure [ref. 4]. Since this particular sample has a convex end-face, the fiber more than likely contacted what it was mated to and was damaged.



(a)



(b)

(c)

**The X & Y-Profiles
confirm the end-face
of the fiber is convex.**

Figure 7.1-8. Confocal X-Profile Image (Above)

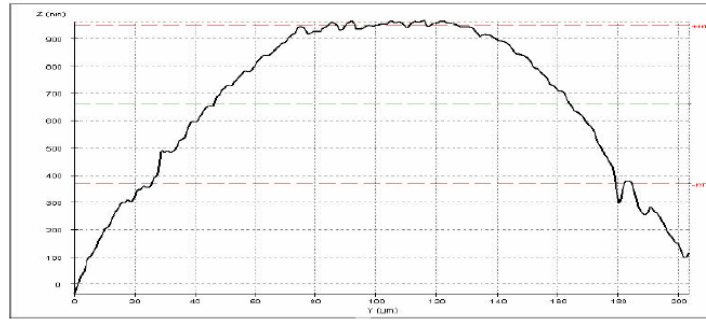
The horizontal line appearing in the top chart of Figure 7.1-8 corresponds to the profile plot shown in colored image figure below the chart.



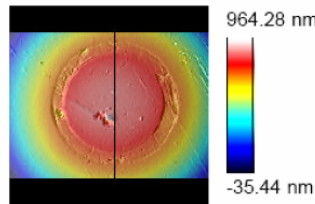
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(a)



(b)

(c)

Figure 7.1-9. Confocal Y-Profile Image

The vertical line appearing in the top chart of Figure 7.1-9 corresponds to the profile plot shown in colored image figure below the chart.

Table 7.1-2. Radius of the Fiber Optic Using the X-profile, Y-profile, and Topographical Data

	Radius (mm)
x-profile	8.5 - 9
y- profile	6.5
topographical data	7

Atomic Field Microscopy (AFM) was performed which further supported this sample is convex, and not concave as expected. The first AFM analysis was taken in a 30µm x 30µm area, in the northwest region of the core. The second was taken in the fracture area.



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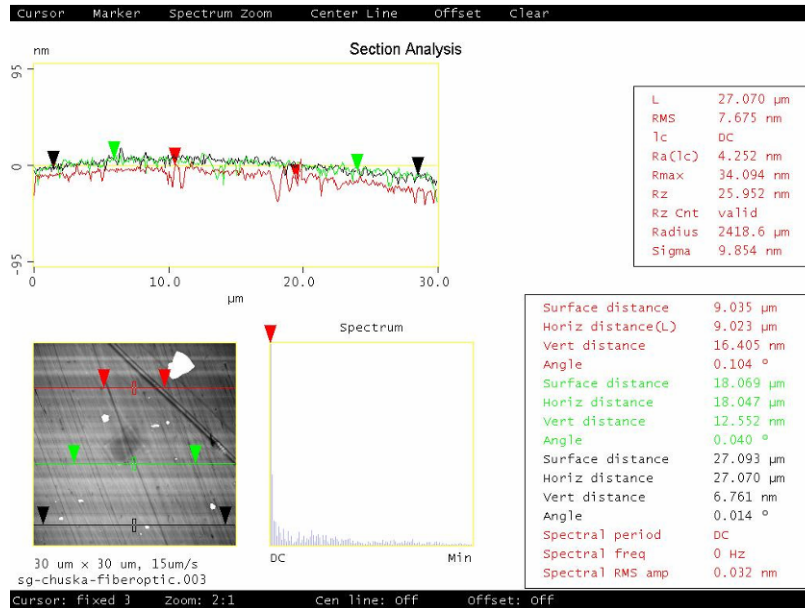


Figure 7.1-10. Fiber End-face AFM Data

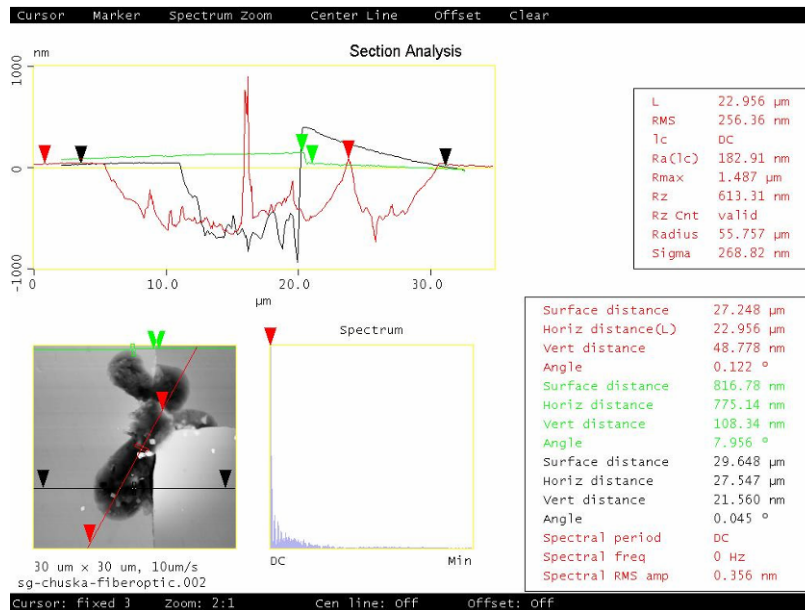



Figure 7.1-11. Impact Fracture AFM Data

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7.1.1 Summary

1. The fracture on the end-face suggests an impact fracture. Since the fiber end-face is convex (which is non-conforming per the manufacturing procedure [ref. 4]), it would have been easily damaged when connected.
2. The elements found in the fracture suggest the end-face of the termination came in contact with a finger. Silica is very resistive to corrosion, but when doped with germanium, the resistance can be decreased [ref. 5].
3. The deep linear scratches in the coating are evidence of cleaning the end-face with an abrasive material.
4. The end-face of the termination has considerable debris which is very destructive to this type of doped glass fiber.

7.1.2 Conclusion


The convex end-face of the fiber is the primary suspect in the root cause of the end-face damage. Section 4.6 (Inspection and Acceptance Criteria) of document number N2-PR-OHB-0005 (Fibre Optic Manufacturing Procedure) states “Attention: In no case should the fiber end be convex or protrude from the face of the ceramic tip” [ref. 3]. The document also states to inspect the terminus profile at a 65 to 70 degree angle with 40X magnification. Using this method it would be very difficult to conclude whether or not within a few mm if the profilometry of the end-face is convex or concave.

7.2 Sample HMU-303 P3-VSU5 SKT F

At 100X (Figure 7.2-1) and 200X (Figure 7.2-2) magnifications, the observations made were:

1. Gross misalignment of the fiber in the coating.
2. Debris and smudge on the ferrule end-face.
3. Deep scratches in the coating.
4. Apparent fracture origin and two cracks propagating from that fracture.

A bubble in the draw process could have caused the misaligned fiber feature. This fiber cable should not have passed the incoming inspection performed by the manufacturer prior to termination. This termination should not have passed quality assurance inspection at the manufacturer’s site upon completion of the assembly fabrication. Specification #SSQ 21654 sec 3.7 indicates that there should be no “thin spots” in the coating of the fiber [ref. 5].

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The deep scratches indicate the end-face was “wiped” with something that had an abrasive particle present. It could have been mated with debris present as well.

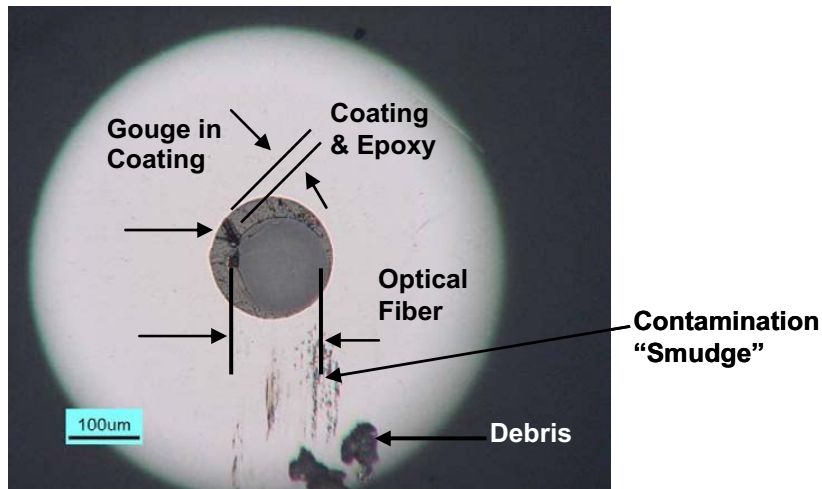


Figure 7.2-1. Magnification of 100X Optical Image

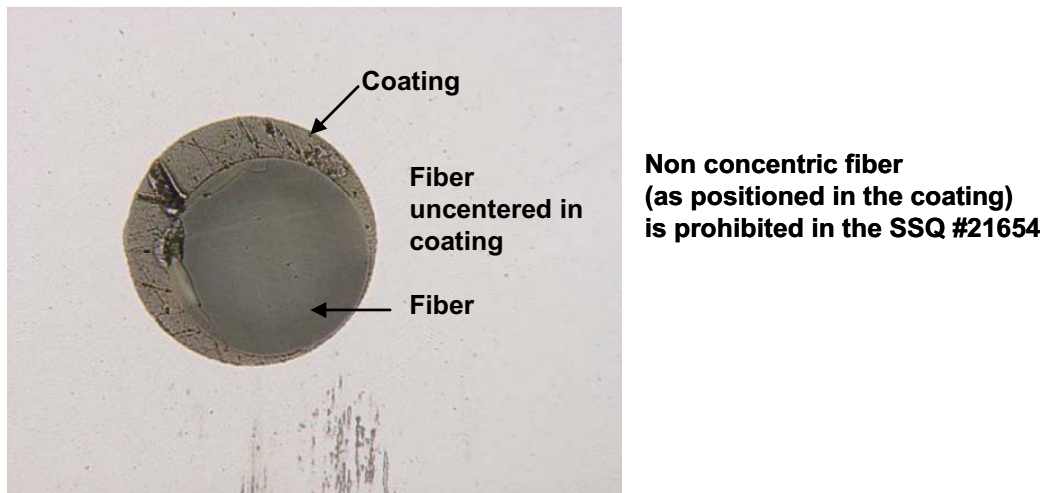



Figure 7.2-2. Magnification of 200X Optical Image

At 500X, a gouge in the coating has an interesting V-shaped pattern and is quite a deep cut. It was noted that the point of the V and the heavy damage at the origin of the break do not line up. The origin of the break suggests an impact fracture from the side. This fracture could easily have been caused by thermal-induced stresses from non uniform CTE distribution around the fiber

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during the epoxy curing procedure. The non-uniform distribution is due to the non-concentric location of the fiber in the coating.

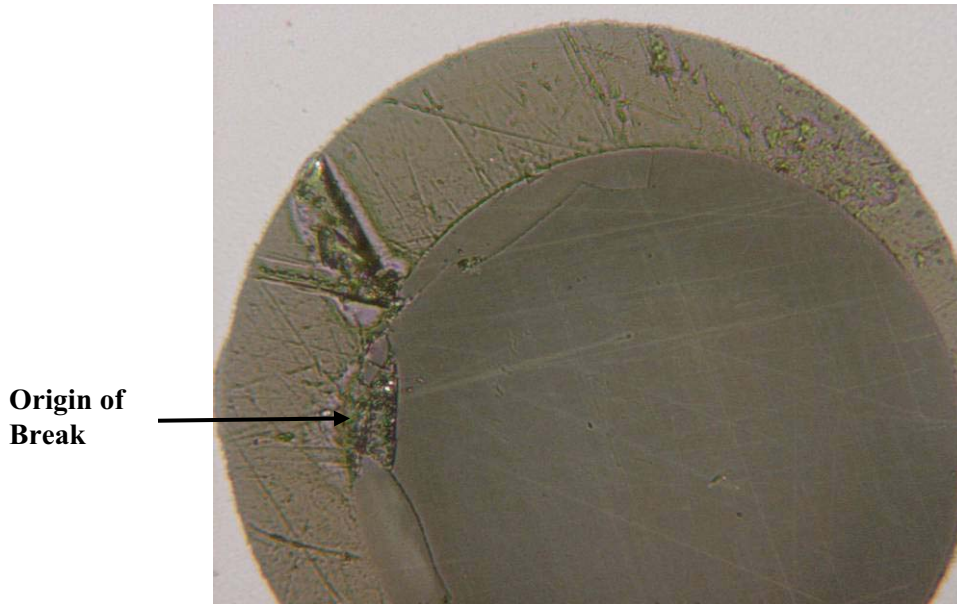


Figure 7.2-3. Deep Gouge in Coating

The SEM images were taken at 1.26×10^3 and 3.32×10^3 magnifications (Figure 7.2-4). At the higher magnification (Figure 7.2-5), there is similar corrosion as in HMU-302 P21-UP4 SKT A.



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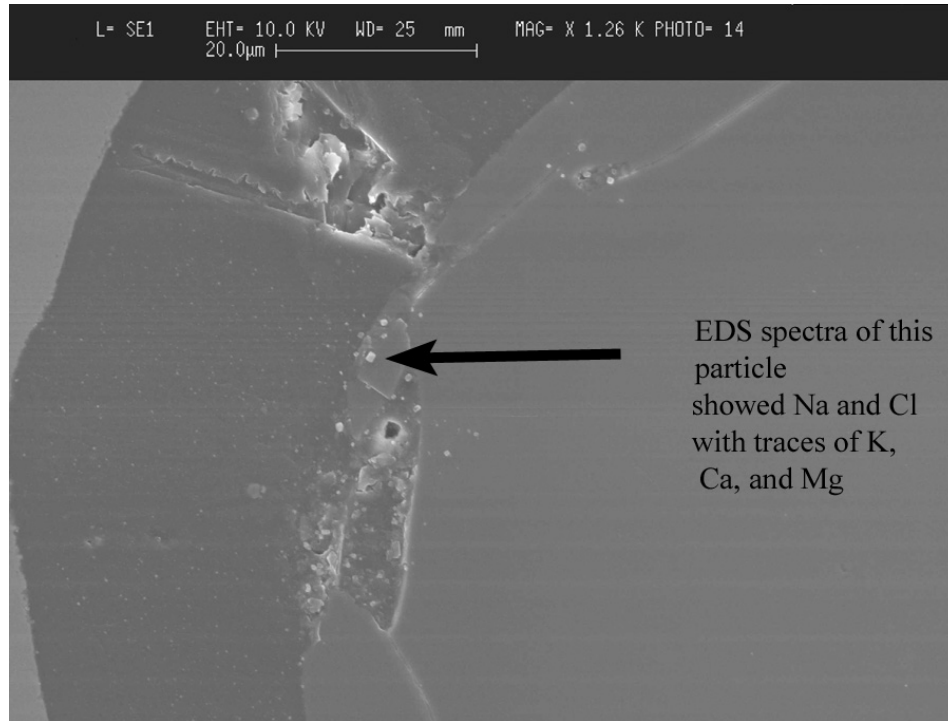



Figure 7.2-4. Magnification of 1,260X SEM Image

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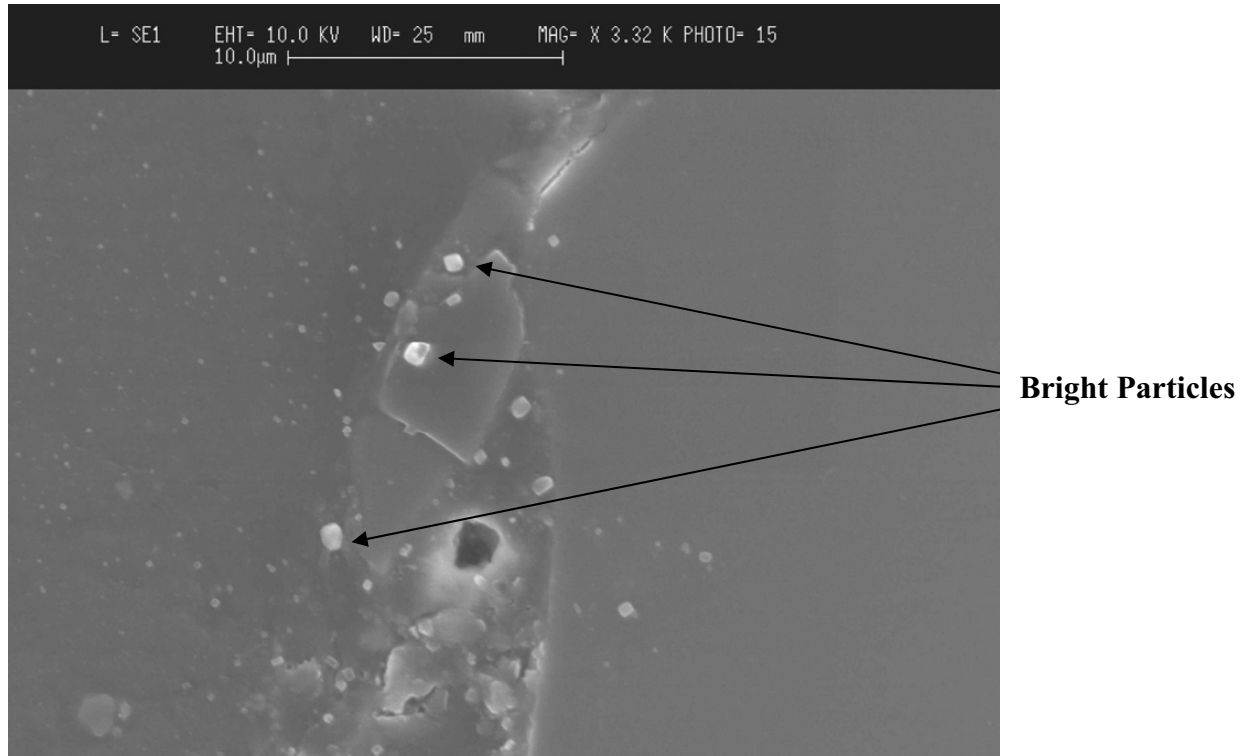


Figure 7.2-5. Magnification of 3,320X SEM Image

An EDS data analysis was performed on one of the “bright” particles and traces of oxygen, Na, magnesium, aluminum, Si, Cl, potassium, and calcium were found.



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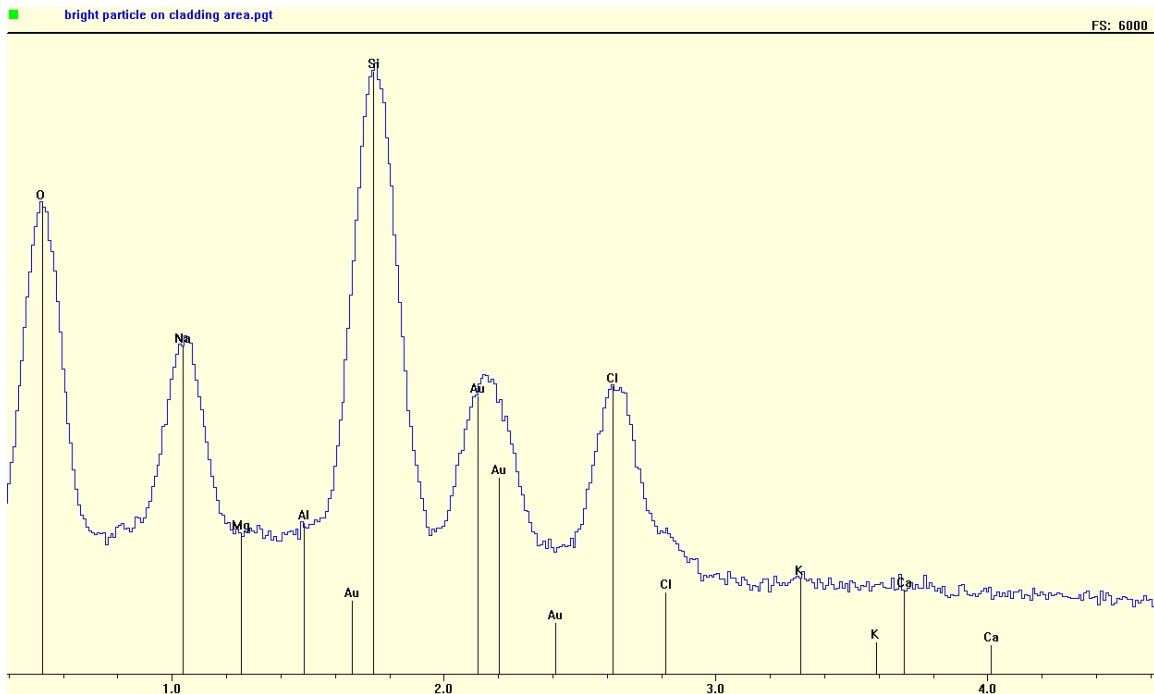



Figure 7.2-6. EDS Data of Cladding Area

Elemental mapping of the debris on this sample was performed very similar to the previous sample. At higher magnifications, traces of Na and Cl can clearly be identified. The bright areas of the images in Figure 7.2-5 are the elements that have been mapped. Refer to Figure 7.2-7.

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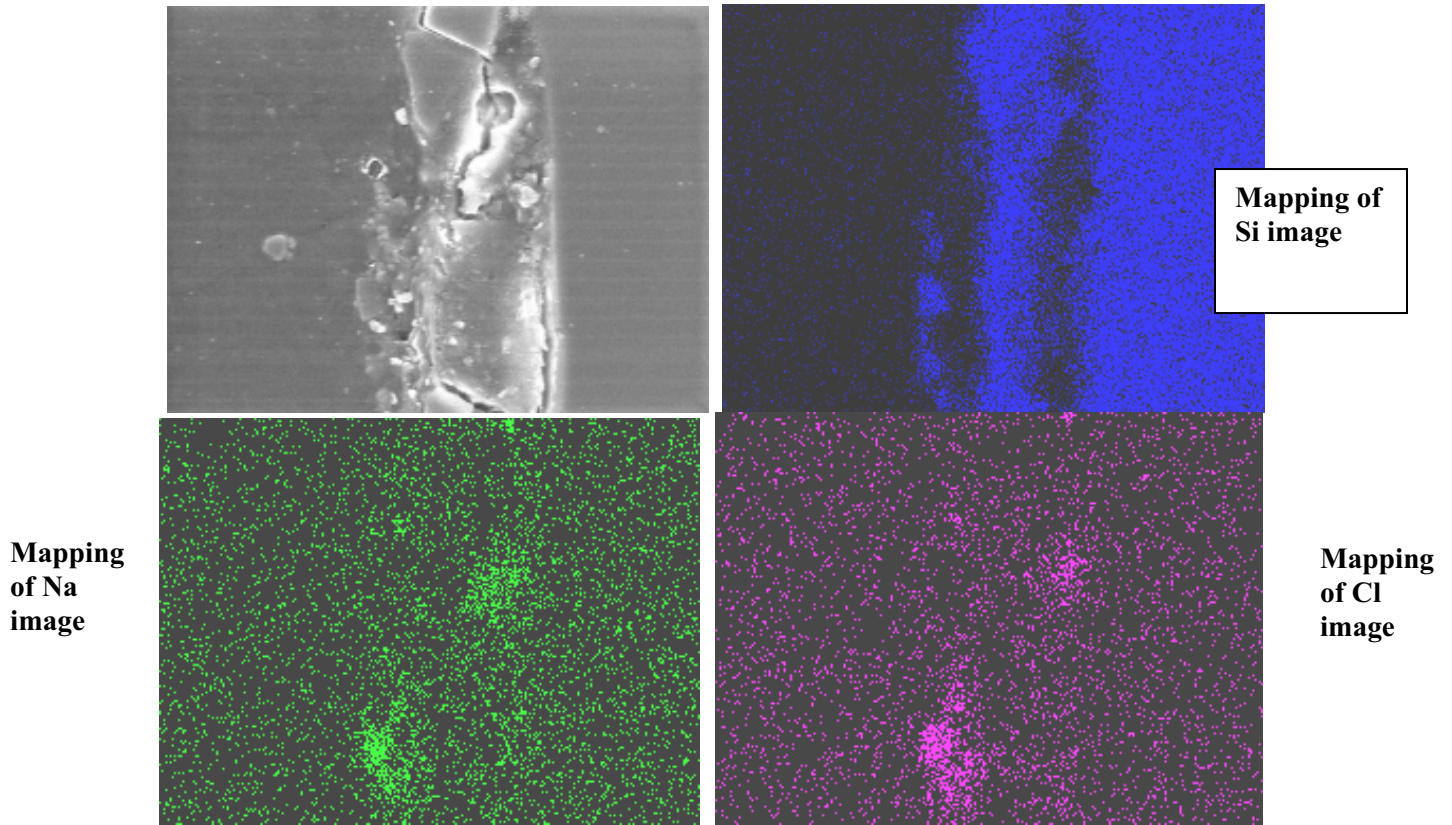


Figure 7.2-7. Elemental Mapping of Corrosion

Confocal microscopy data (Figure 7.2-8) indicates a convex profile of the end-face, which violates the specification. The radius of convex curvature is 9.0 mm.



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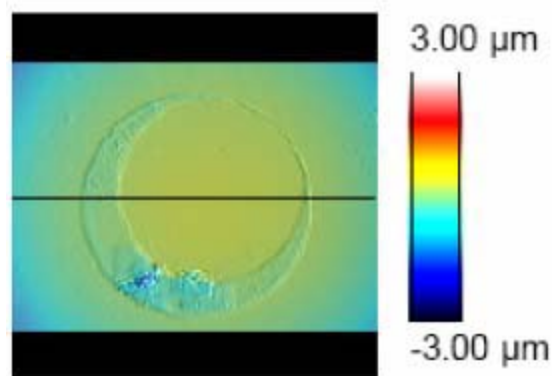
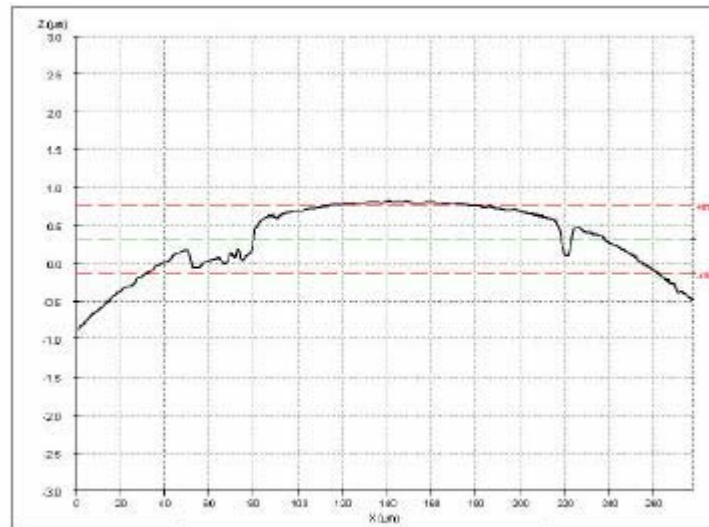



Figure 7.2-8. Confocal Data

The horizontal line appearing in the top chart of Figure 7.2-8 corresponds to the profile plot shown in colored image figure below the chart.

7.2.1 Summary


1. The eccentricity of the fiber is a violation of the specification, and should have been discovered at the manufacturer's site. Specification #SSQ 21654, Section 3.7, indicates that there should be no thin spots in the coating of the fiber. Unbalanced stress would have been applied to this fiber during the epoxy cure process, accelerating the crack.
2. The impact fracture on the edge of the glass suggests an impact from the side.

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3. The EDS data suggests the end-face of the termination was touched or wiped with a human finger. Again, the salt and oils in fingertips are very corrosive to germanium-doped silica glass.
4. The deep linear scratches in the coating are evidence of cleaning the end-face with an abrasive material.
5. The end-face of the termination has considerable debris which is very destructive to glass fiber.

7.2.2 Conclusion

Although the convex end-face of the fiber with particulate contamination could have been the root cause of the impact fracture in a normal concentric fiber, in this case it was probably caused by non-uniform thermal induced stresses. The eccentricity of the fiber would diminish the optical signal if this terminus were mated to a fiber that was concentric to the ferrule. This terminus should have never passed final inspection since it is clear that this termination was defective prior to shipment even if the surface of the fiber was pristine and the end-face clean.

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7.3 Sample HMU-303 J31-BKT VSU SKT S

When looking at this fiber at 500X magnification, a deep scratch can be seen. There is also a crack in the fiber that first appeared to be a scratch. This signature of linear scratches is indicative of polishing with high grit lapping film, and not removing the scratches with lesser grit lapping film. Refer to Figure 7.3-1.

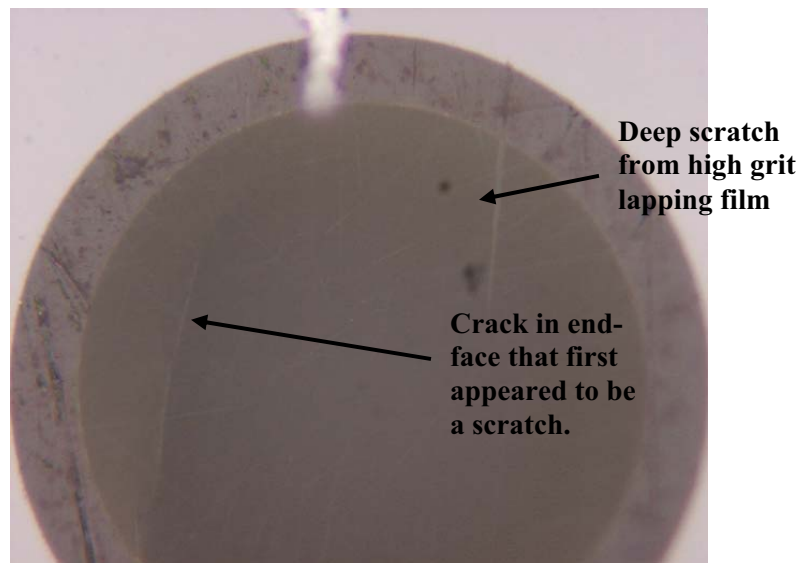


Figure 7.3-1. Scratched/Cracked End-Face

This sample was cross-sectioned to get a profile view of the fiber end, and identify features that have not yet been observed in other termini. There was some large metallic debris observed in Figure 7.3-2 that may have initiated the flaw.



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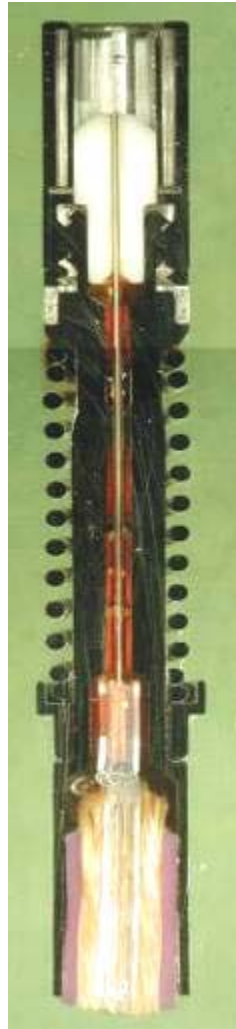


Figure 7.3-2. Cross-Section View of the Optical Fiber Termini



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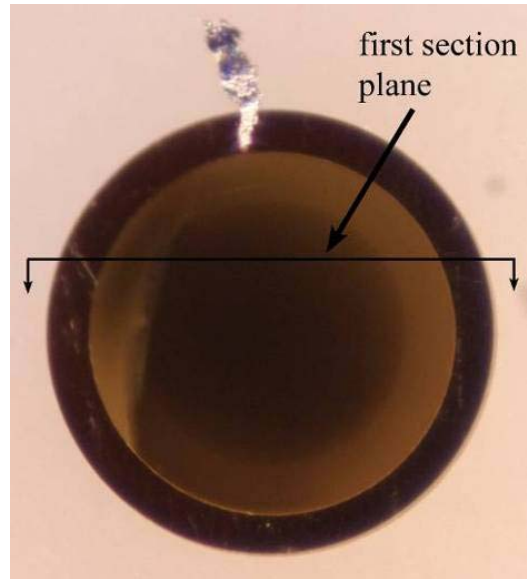


Figure 7.3-3. Section Plane

The magnified images in Figures 7.3-4 and 7.3-5 indicate (without a doubt) that the end-face is concave. This is by design so the glass does not make physical contact to another terminus end-face when mated into the connector. Note that the crack has not propagated all the way to the edge of the fiber, leaving the fiber intact.



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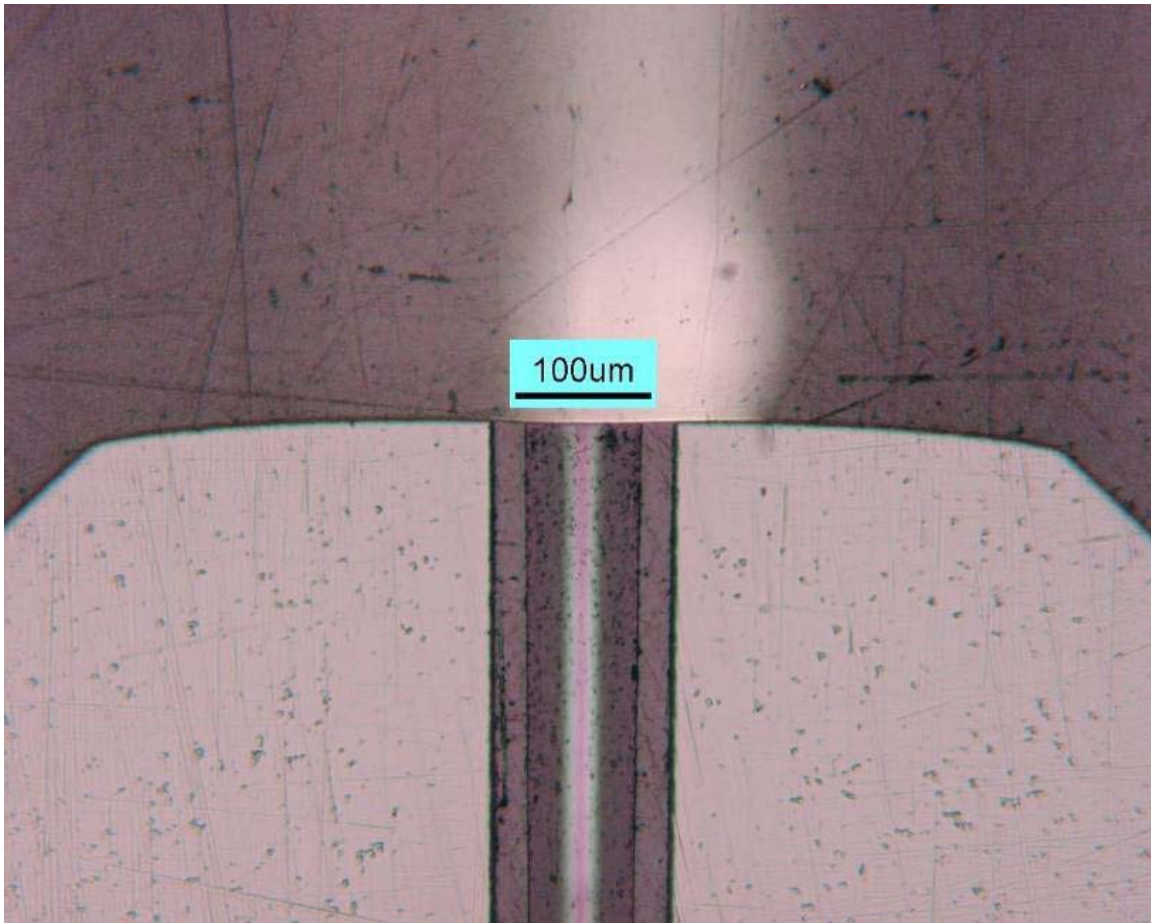



Figure 7.3-4. Magnification of Cross-Section @ 100X

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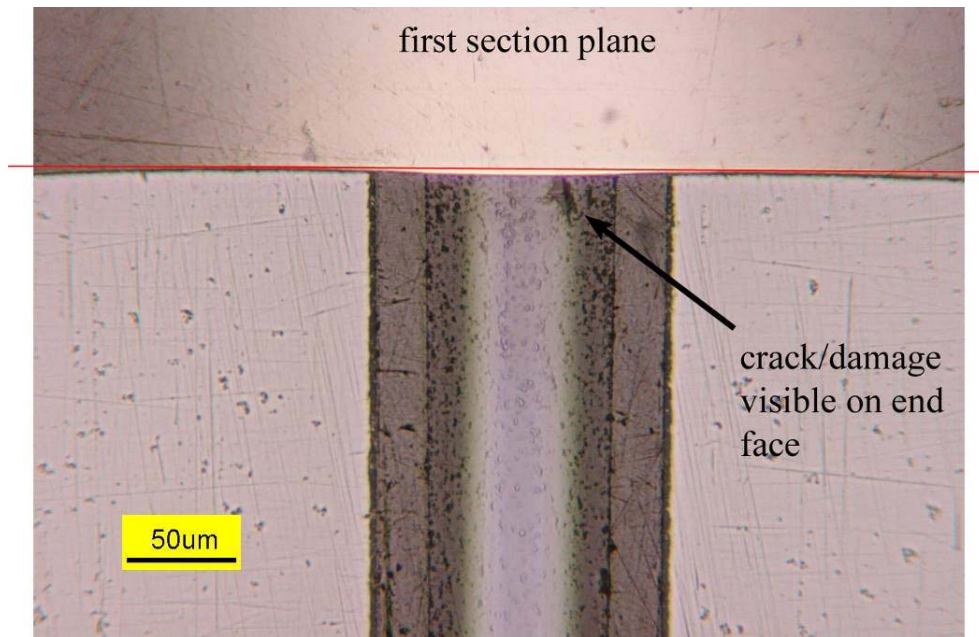



Figure 7.3-5. Magnification of Cross-Section @ 200X

7.3.1 Summary

1. The deep linear scratches were not removed during the final polishing process.
2. The cleanliness of the termination was not maintained. The metallic debris could have scratched the glass causing the flaw.
3. The crack on this particular sample has not propagated completely to the outer edge. The crack propagates mostly through the cladding, which would not affect the optical signal too much.

7.3.2 Conclusion

The deep scratches in the end-face of the fiber were not removed with a finer grit lapping film. As per Section 4.5 (Inspection and Acceptance Criteria) of document number N2-PR-OHB-0005 (Fibre Optic Manufacturing Procedure) [ref. 3], 30 μ m lapping film is used to grind the fiber prior to polishing. Failure to remove the scratches from this coarse grit film would likely initiate latent crack propagation. Section 4.6 (Inspection and Acceptance Criteria) of N2-PR-OHB-0005 indicates Type 5 (Deep Scratches) flaws are not permitted. If the end-face does not pass visual inspection, the polishing procedure is to be repeated. It is the NESC team's assessment that the OHB process for polishing with a large grit lapping film makes it difficult to remove all residual cracks in the fiber end-face. Therefore, additional cracking will appear and propagate over time.

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7.4 Sample HMU-303 P5-VSU5 SKT E

At 500X, some deep scratches on the end-face can be observed (Figure 7.4-1). By changing the illumination field settings, a crack in the fiber can be seen (Figure 7.4-2). ***Light will pass through a crack that is $<1/8\lambda$, and the crack will not be visible.*** Some debris on the end-face can also be observed.

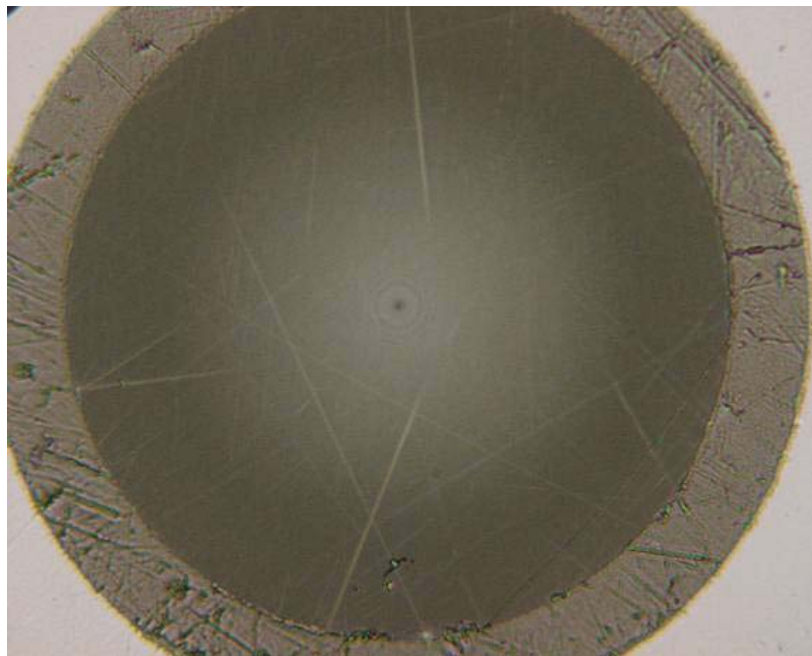



Figure 7.4-1. Bright Field Image Magnification of 500X

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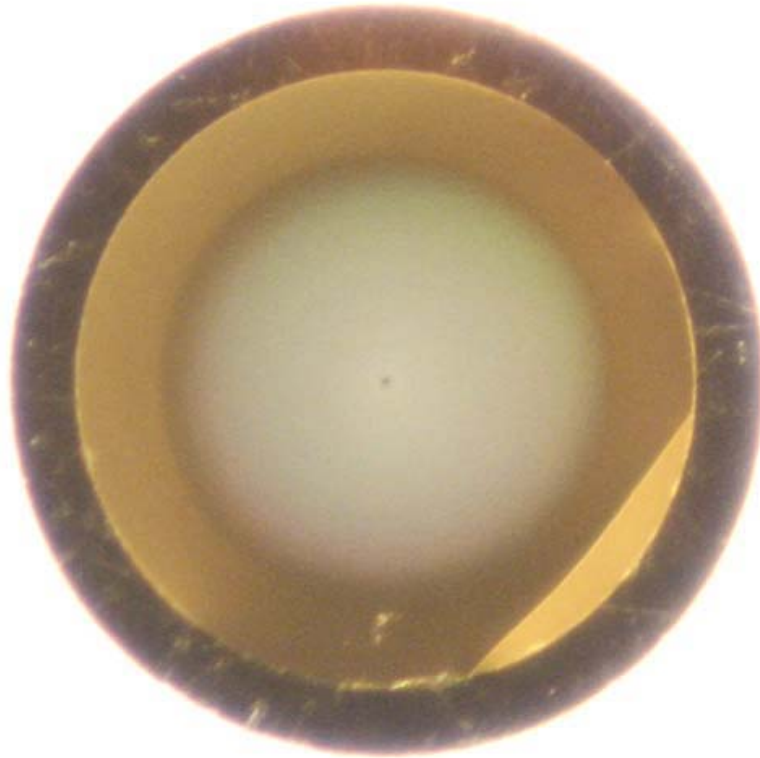


Figure 7.4-2. Dark Field Image at Magnification of 200X

The SEM image taken at 1.1×10^3 magnification (Figure 7.4-3) shows an area suspected of being the break origin, a crack propagating through the cladding, and delamination between the coating and glass where the crack ends. If this is in fact the origin, the crack could have propagated with the help of shrinkage of the epoxy.



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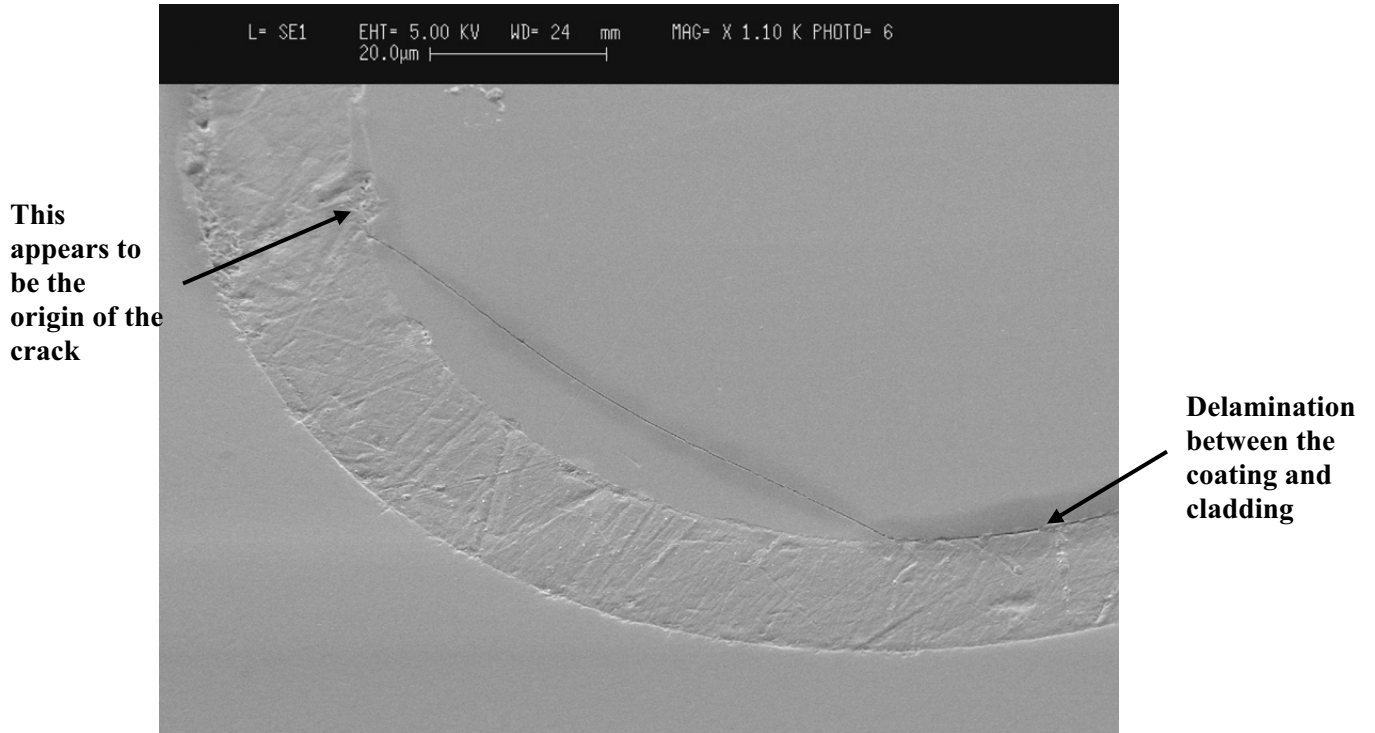


Figure 7.4-3. Magnification of 1,100X SEM Image

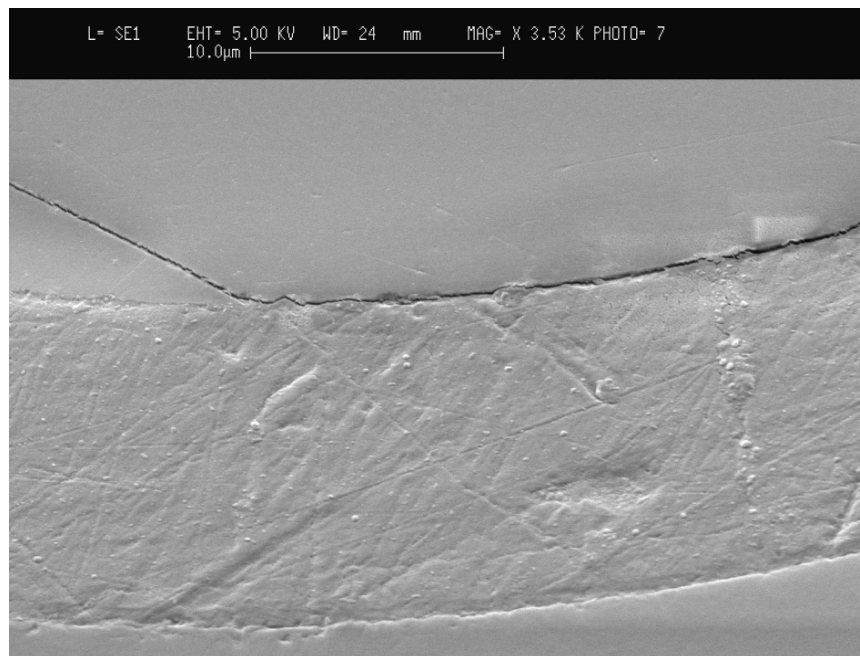



Figure 7.4-4. Magnification of 3,530X SEM Image

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An EDS data analysis was performed (Figure 7.4-5) in the crack region to identify any foreign particles, and a high concentration of carbon, oxygen, and silicon was found. This may suggest the grit of the lapping film was too coarse.

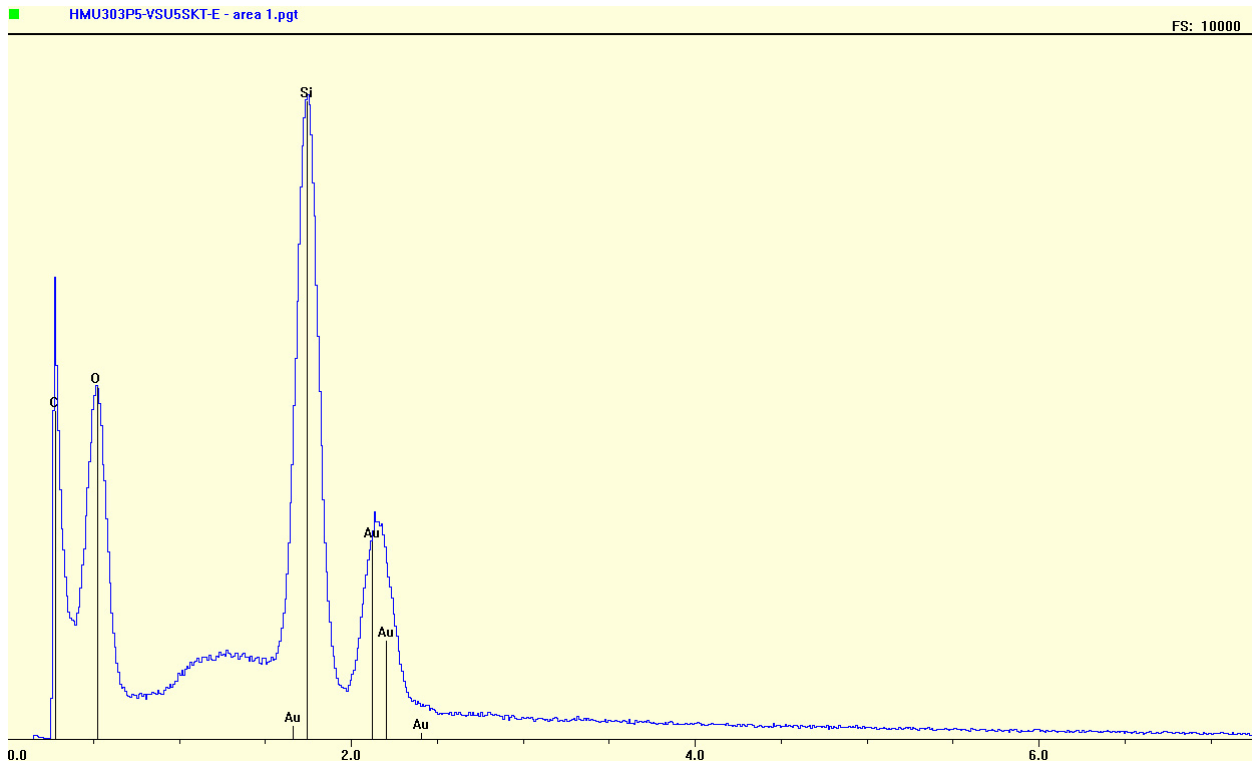



Figure 7.4-5. EDS Data of Crack

The confocal microscopy data (Figure 7.4-6) indicates the end-face has a concave profile. This conforms to the manufacturing procedure [ref. 3]. The radius of curvature measures 2.0 mm.

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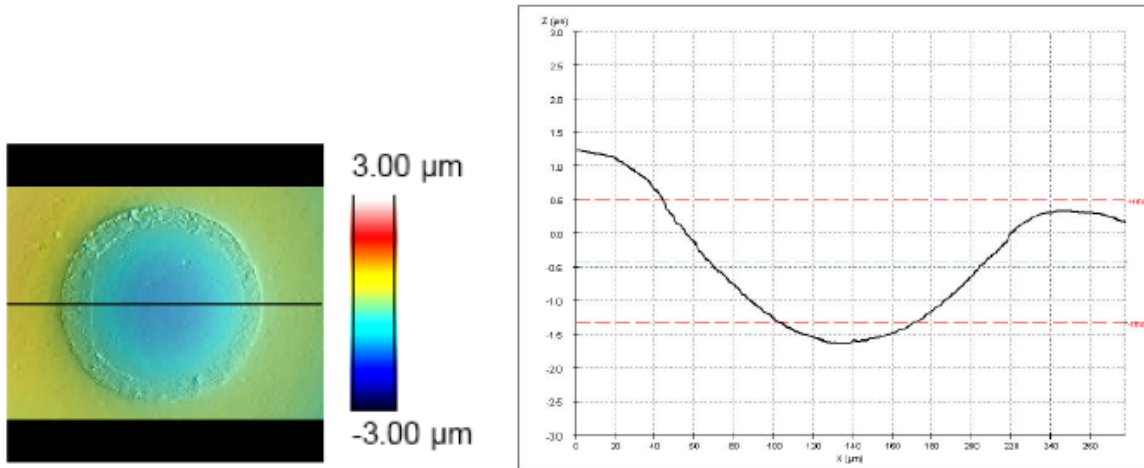



Figure 7.4-6. Confocal Data

7.4.1 Summary

1. The location of the suspected origin suggests the flaw started from the edge of the fiber. This likely was caused by an abrasive particle used to wipe the fiber.
2. The scratches observed in Figure 7.4-1 are fairly deep, and this terminus should have been polished with a finer grit lapping film to remove them.
3. Debris on the end-face suggests the cleanliness was not maintained.

7.4.2 Conclusion

The deep scratches were not removed with finer lapping film. Scratches this deep can and will cause crack propagation.

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7.5 Sample HMU-302 P14-NODE1 SKT P

At 100X magnification (Figure 7.5-1), observations made were:

1. There was a deep scratch in the ferrule outside of the fiber area.
2. Debris was observed on the fiber core and ferrule end-face.
3. There were deep scratches in the polyimide coating.

The scratches indicate the end-face was cleaned with a contaminated product, or mated with present debris. The foreign material indicates the ferrule was not cleaned properly.

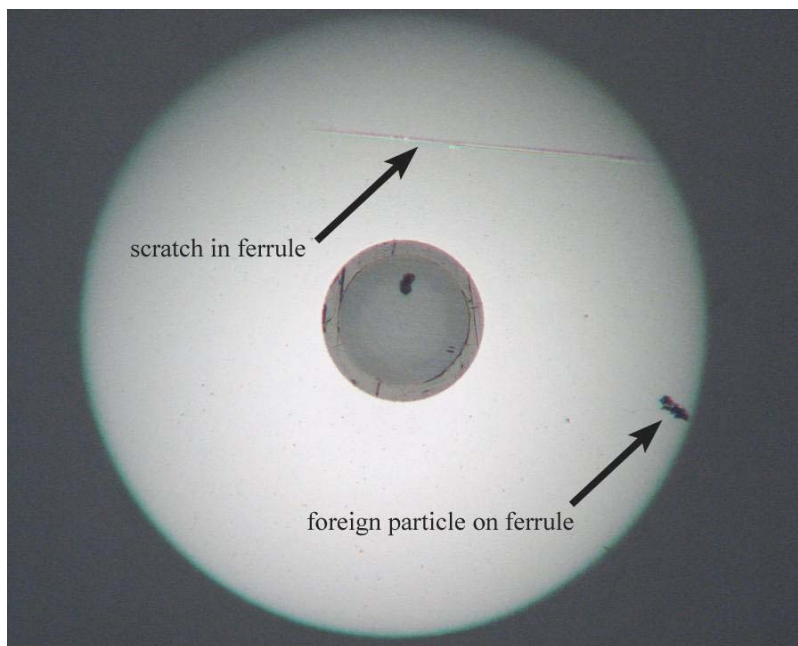


Figure 7.5-1. Magnification of 100X Optical Image

At 200X magnification (Figure 7.5-2), deep scratches and a crack in the core can be seen (Figure 7.5-3).



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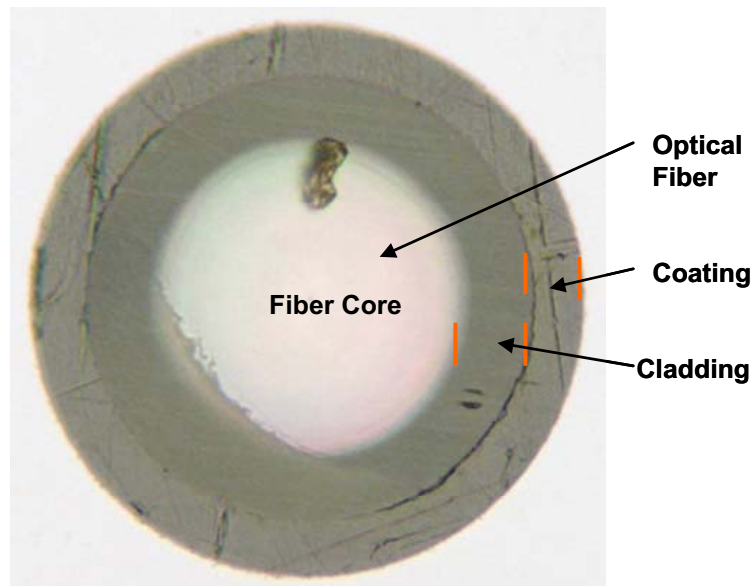


Figure 7.5-2. Magnification of 200X Optical Image



Figure 7.5-3. Scratches

The SEM image taken at 586X magnification (Figure 7.5-4) identified two small scratches in the cladding area that appeared to be debris under the microscope. Connecting the termination when debris was present was likely the cause.



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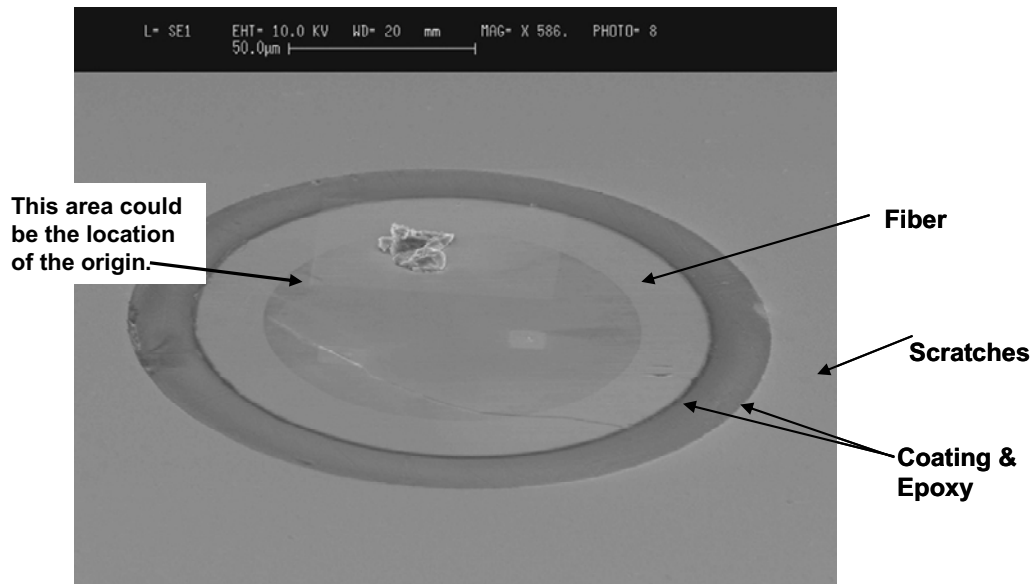



Figure 7.5-4. Magnification of 586X SEM Image

At 24.4×10^3 magnification, a view of the crack through the glass can be observed. This image does not confirm if one side of the crack is depressed or not. AFM would have to be performed to make a determination.

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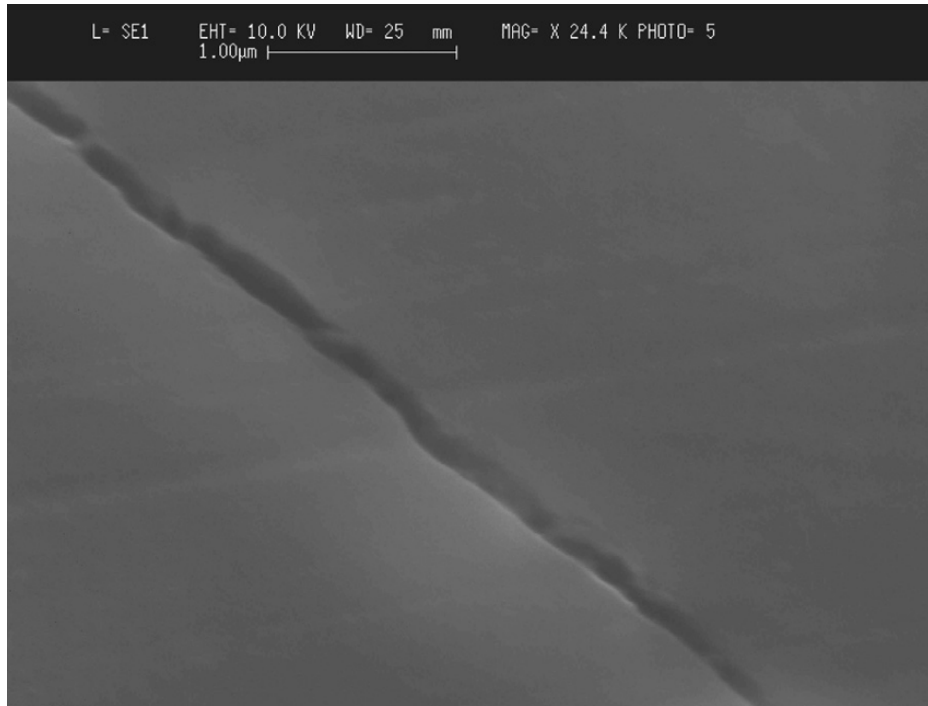


Figure 7.5-5. Magnification of 24,400X SEM Image of Crack

An EDS data analysis (Figures 7.5-6 through 7.5-9) was performed on several areas of the sample.



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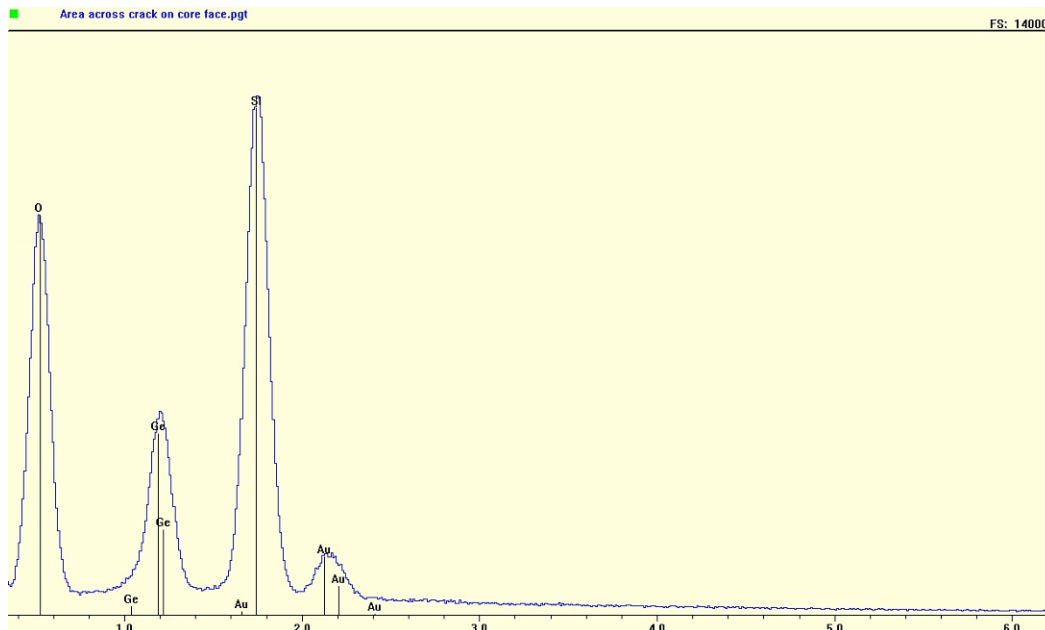


Figure 7.5-6. EDS of Crack Area

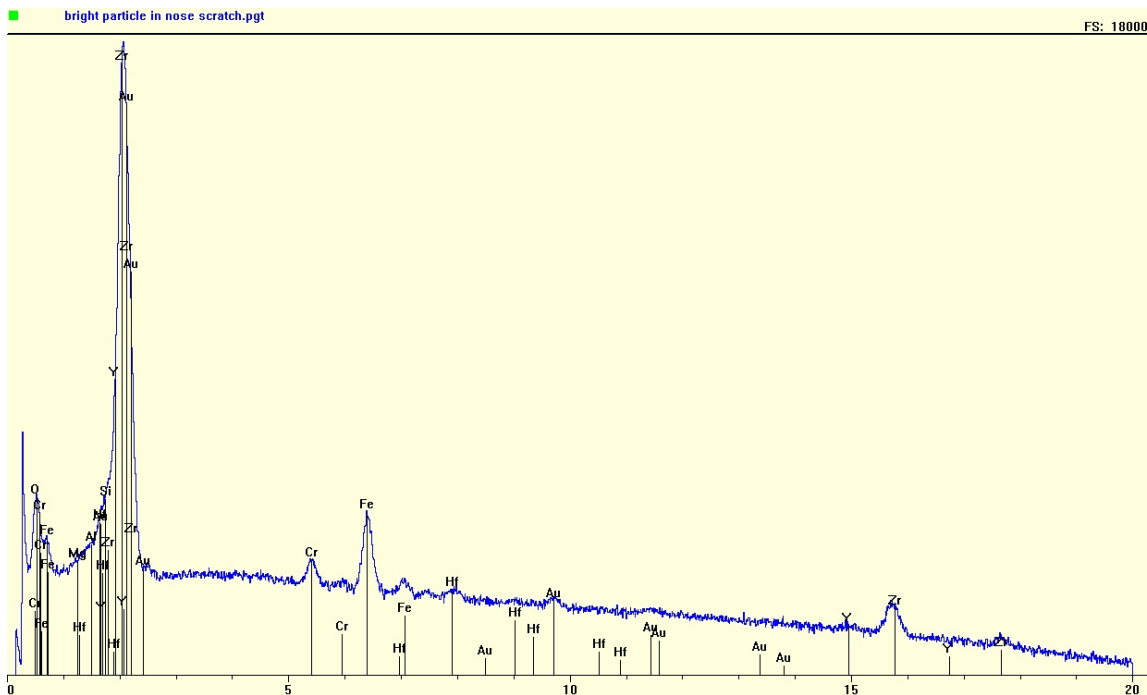


Figure 7.5-7. EDS of Scratch in Ferrule (Figure 7.5-1)



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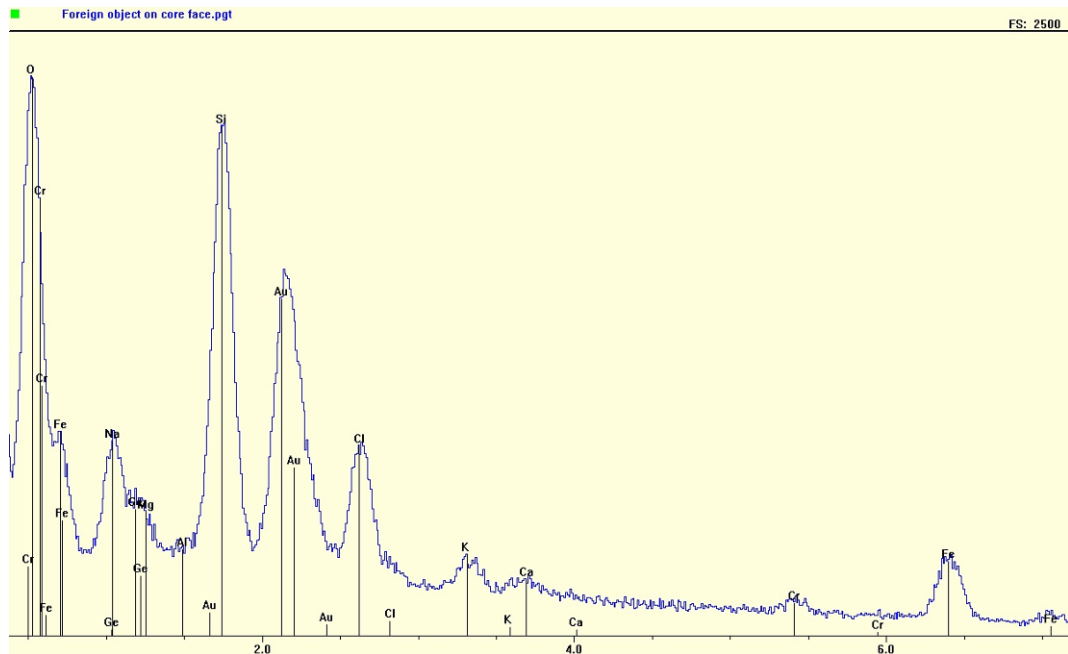


Figure 7.5-8. Foreign Object on Core Face (Figure 7.5-2)

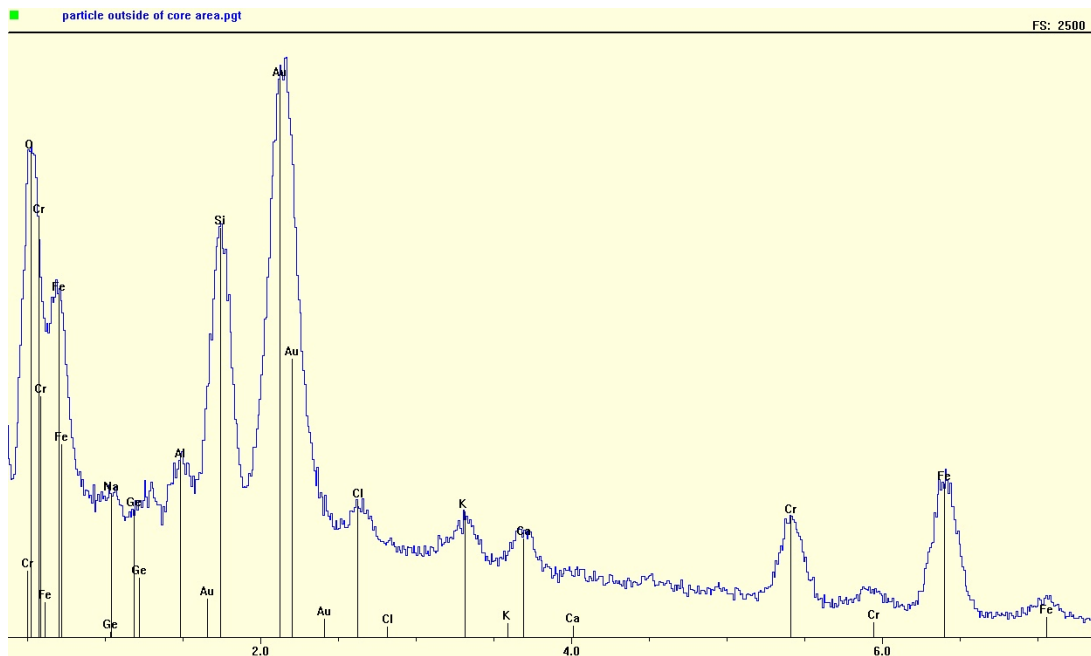



Figure 7.5-9. Foreign Particle Outside of Core Area (Figure 7.5-1)

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The confocal data (Figure 7.5-10) indicates the fiber is convex which, again, violates the requirements stated in the manufacturing procedure [ref. 3]. The radius of curvature is 4.0 mm.

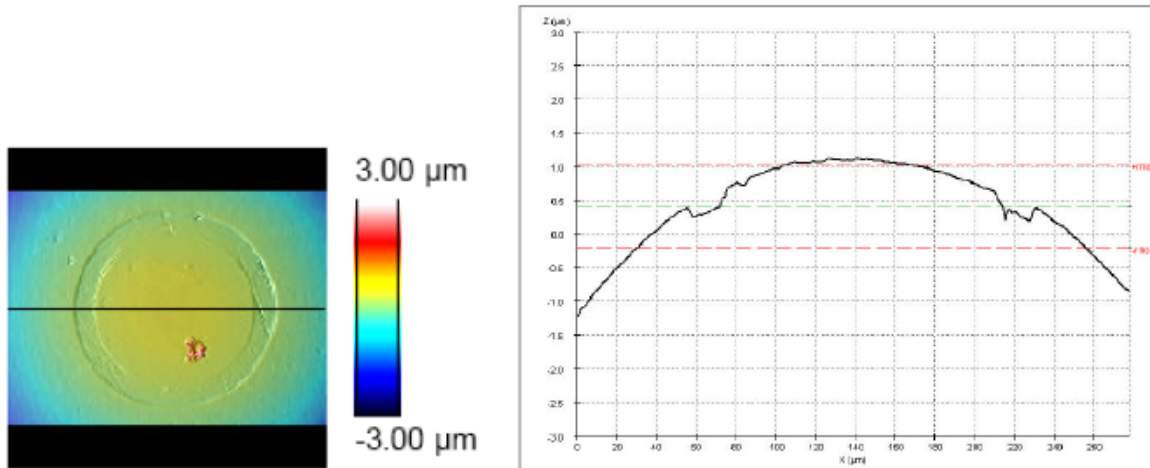



Figure 7.5-10. Confocal Data

7.5.1 Summary

1. Deep scratches were not removed with a finer grit lapping film.
2. The presence of Na and Cl in the EDS data suggests a finger came in contact with the end-face.
3. The presence of metallic debris indicates the termination was not cleaned properly and possible connected with metal particles present.
4. The convex end-face of the fiber does not conform to requirements stated in the manufacturing procedure [ref. 3].

7.5.2 Conclusion

The glass has numerous deep scratches, which appear to have originated from the grinding process. These scratches should have been removed using a lower grit lapping film. The zirconia ferrule has a deep gouge. The end-face has a convex profile which violates the manufacturing process document. The crack could have propagated due to any combination of the convex end-face, the contamination, and the high grit lapping film used.

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7.6 Sample HMU-304 P20-UP4 SKT Z

At 200X (Figure 7.6-1), observations made were:

1. There was a crack in the cladding area.
2. There was damage to the glass in several areas around the perimeter of the cladding.

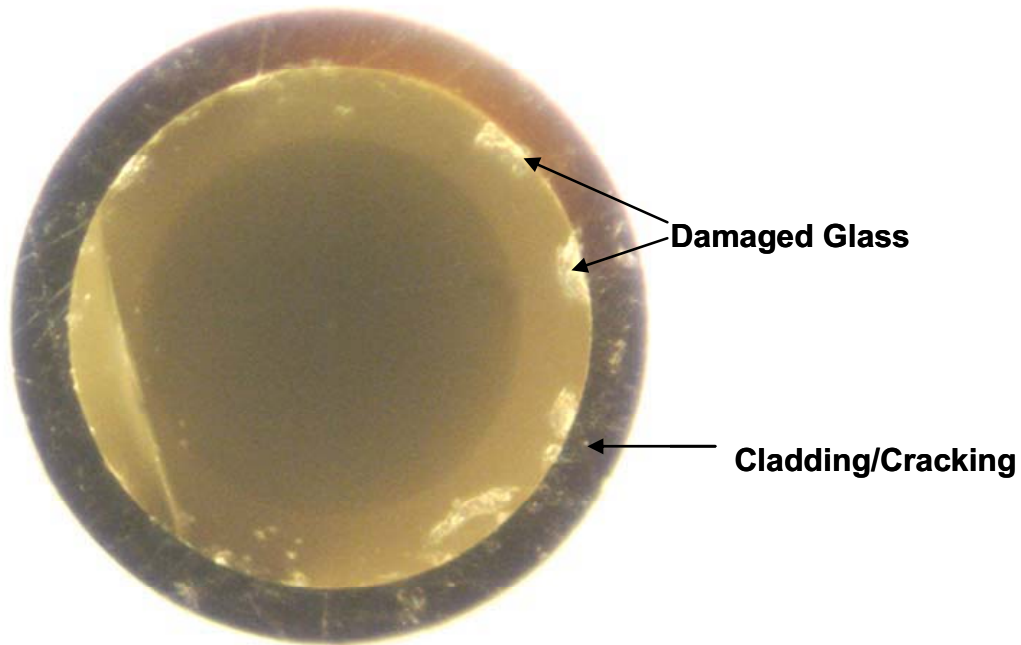



Figure 7.6-1. Magnification of 200X Optical Image

This SEM image at 504X (Figure 7.6-2) shows a feature in the crack that may suggest two separate cracks. There appears to be a discontinuity.

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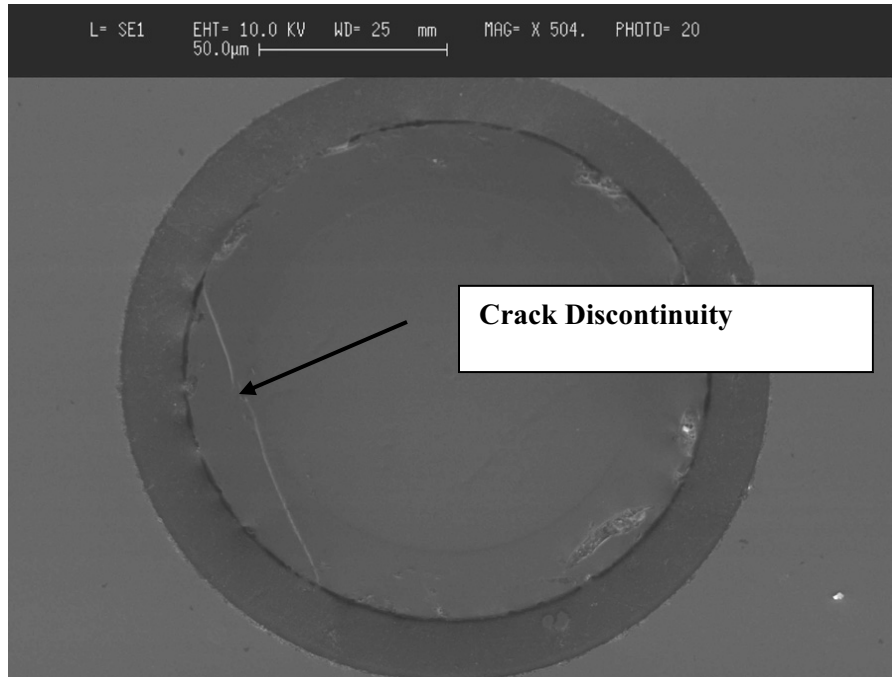


Figure 7.6-2. Magnification of 504X SEM Image

Figures 7.6-3 and 7.6-4 show a corrosive attack in some of the damaged areas, similar to what was observed on some of the other termini.



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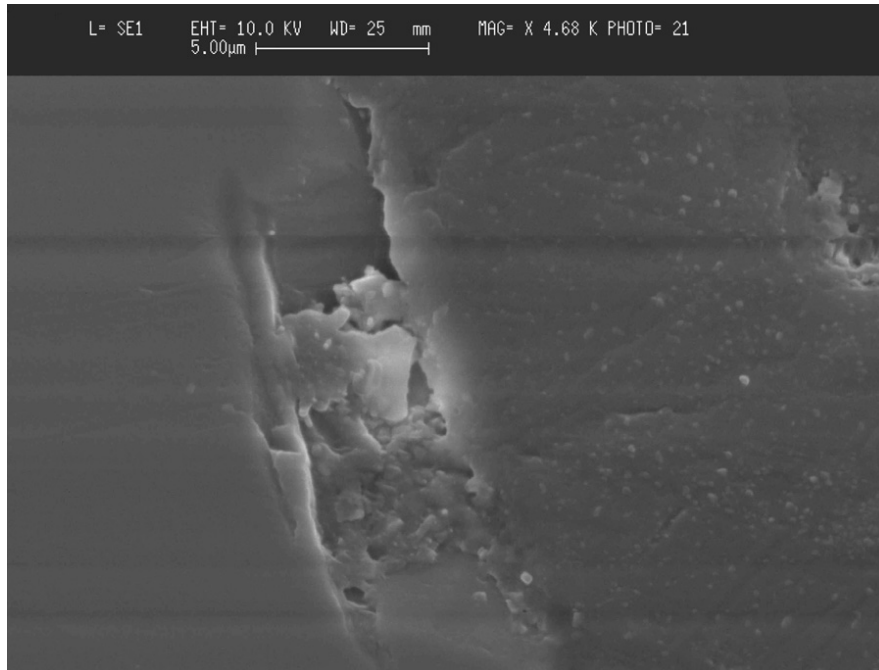


Figure 7.6-3. Magnification of 4,680X SEM Image (Corrosive Attack)

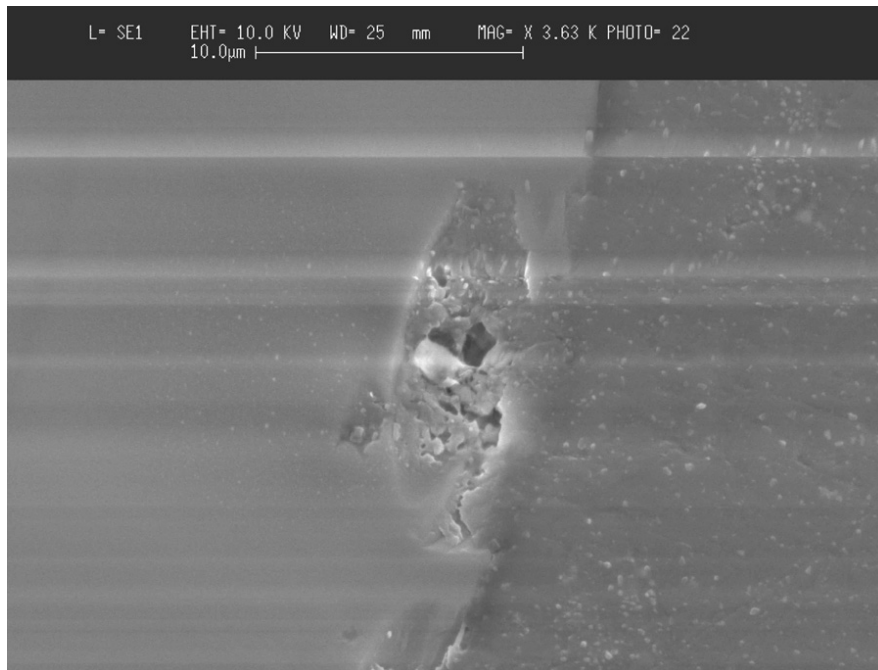


Figure 7.6-4. Magnification of 3,630X SEM Image (Corrosive Attack)



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An EDS data analysis (Figure 7.6-5 and Figure 7.6-6) was performed on some debris on the ferrule end-face.

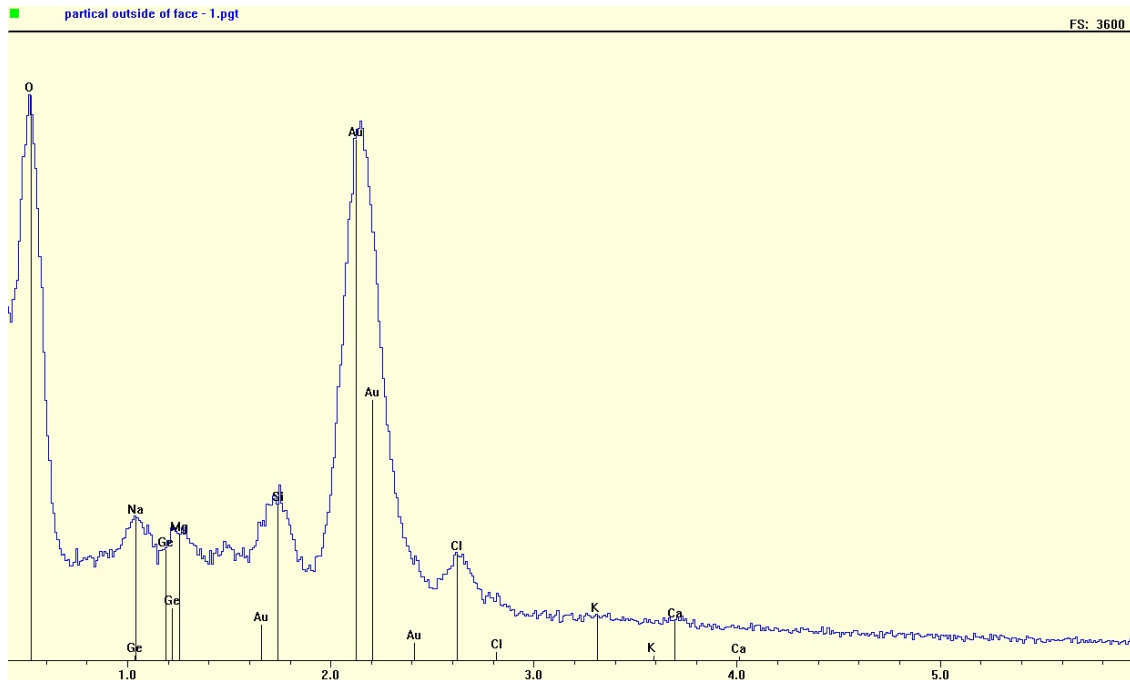


Figure 7.6-5. EDS Data of Particle on Ferrule - 1



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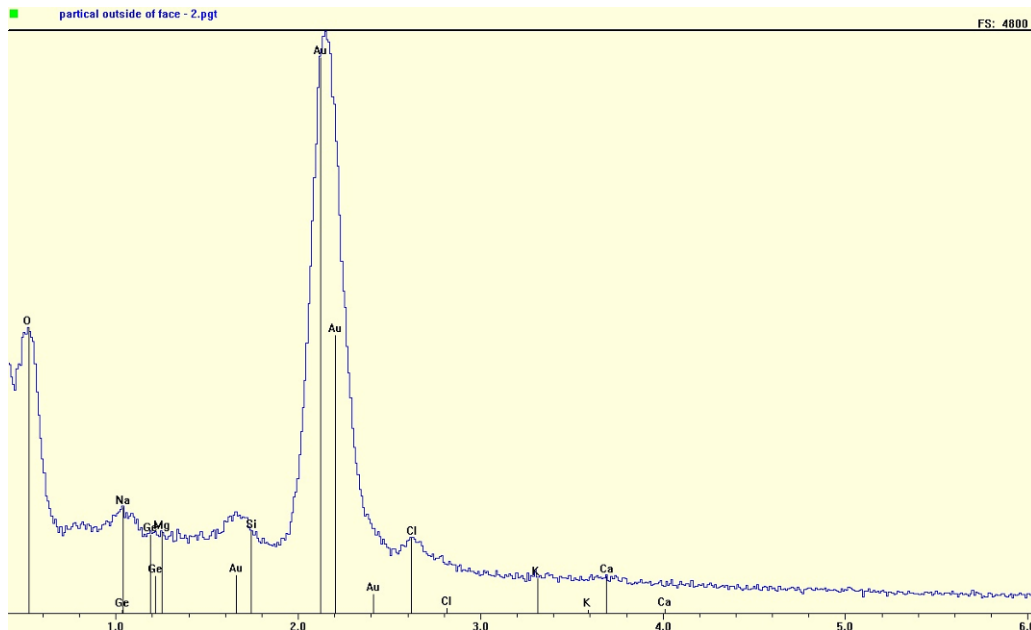


Figure 7.6-6. EDS Data of Particle on Ferrule -2

Confocal microscopy was performed and indicated the fiber end-face is convex (Figure 7.6-7). The radius of curvature is 13.5 mm.

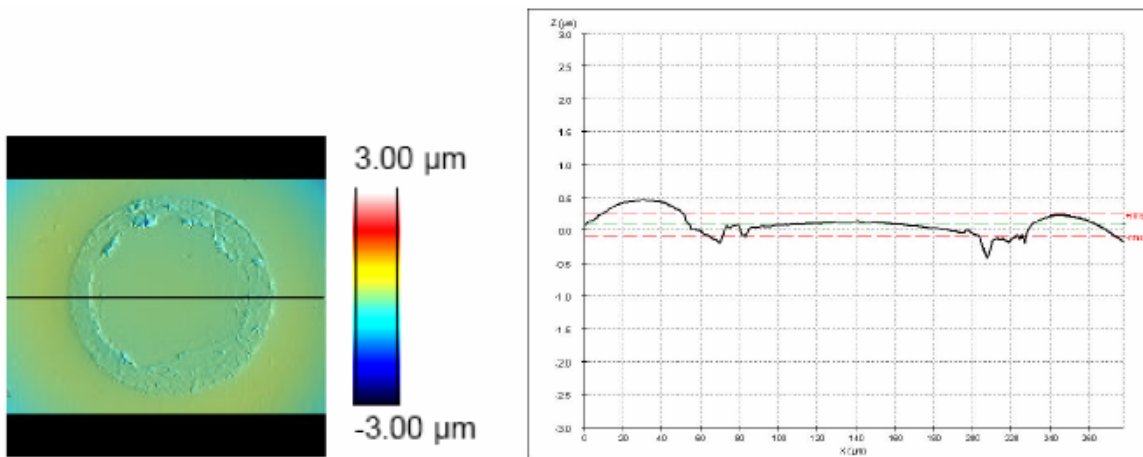



Figure 7.6-7. Confocal Data

7.6.1 Summary

1. The EDS data analysis indicates the presence of sodium and chloride (Na, Cl), which suggests a human hand came in contact with the end-face.

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2. The damage around the perimeter of the glass indicates the end-face was wiped with an abrasive material, which caused numerous impact fractures.
3. The fiber end-face is convex, but does not protrude beyond the ceramic ferrule tip.

7.6.2 Conclusion

This damage around the perimeter of the glass most likely caused the crack propagation. Considering the foreign materials found on the end-face, this terminus was improperly cleaned.

7.7 Sample HMU-303 P3-DAIU SKT C

Figure 7.7-1 shows a deep scratch in the end-face of the fiber. This is not a crack that has propagated deep into the fiber. This is evident from how the light is emitted through the crack. When Figures 7.7-1 to Figure 7.10-2 are compared, how the light is affected by a deep crack is observed. There are two areas in the coating with significant damage as well. The damage in the coating is not linear (like the minor visible scratches), thus suggesting it did not occur due to polishing.

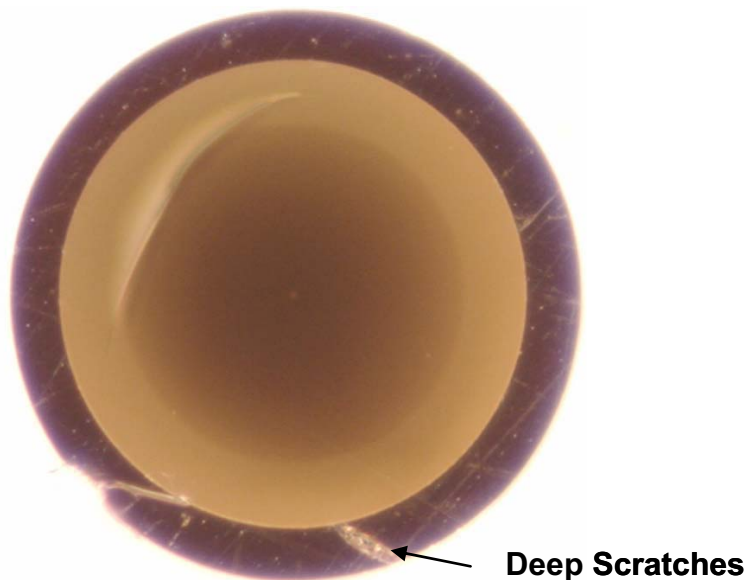



Figure 7.7-1. Dark Field Image @ Magnification of 200X

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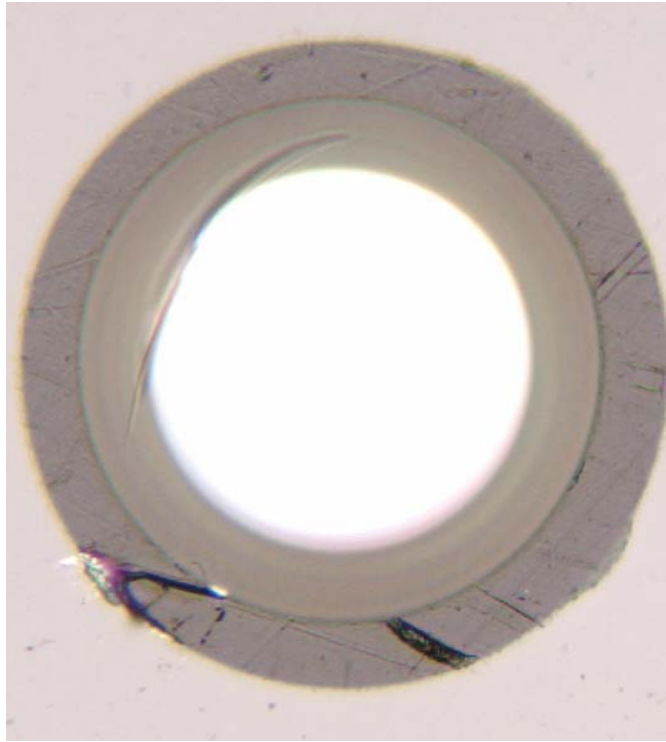



Figure 7.7-2. Bright Field Image @ Magnification of 200X

These termini are inserted into a sleeve when mated. The signature of the scratch might indicate the end-face was not clean when the connection was made.

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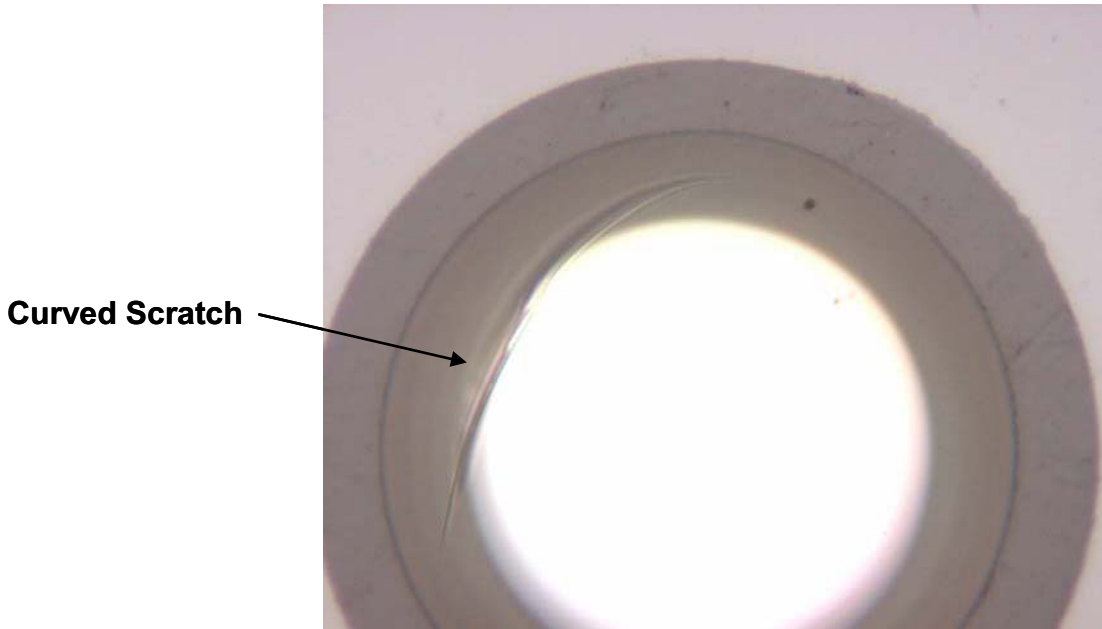


Figure 7.7-3. Curved Scratch in Glass at Magnification of 500X

Under SEM, the surface scratch is not quite as visible at 1.89×10^3 X magnification (Figure 7.7-4), but at 3.63×10^4 X magnification, the indentation from the scratch is very visible (Figure 7.7-5).

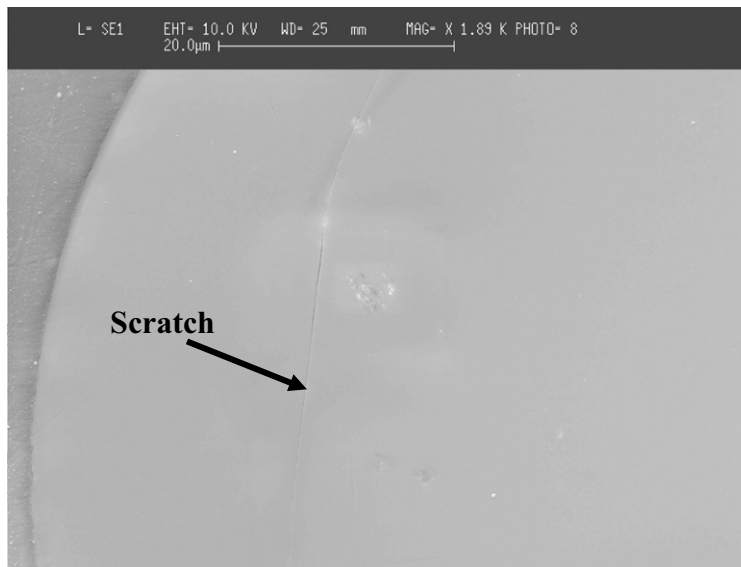



Figure 7.7-4. Scratch at Magnification of 1.89×10^3 X

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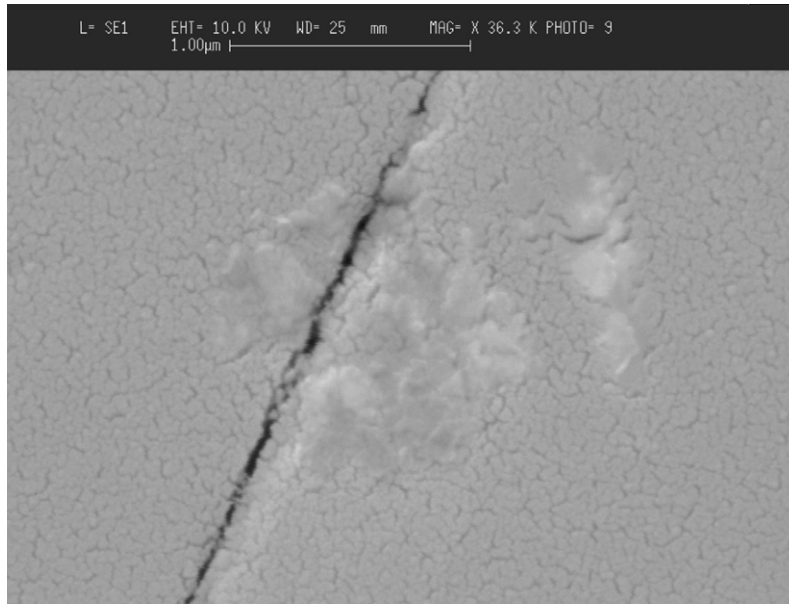


Figure 7.7-5. Scratch at Magnification of $3.63 \times 10^4 \times$

Confocal microscopy (Figure 7.7-6) indicates the end-face is concave per requirements of the manufacturing procedure [ref. 3]. The radius of curvature is 1.4 mm.

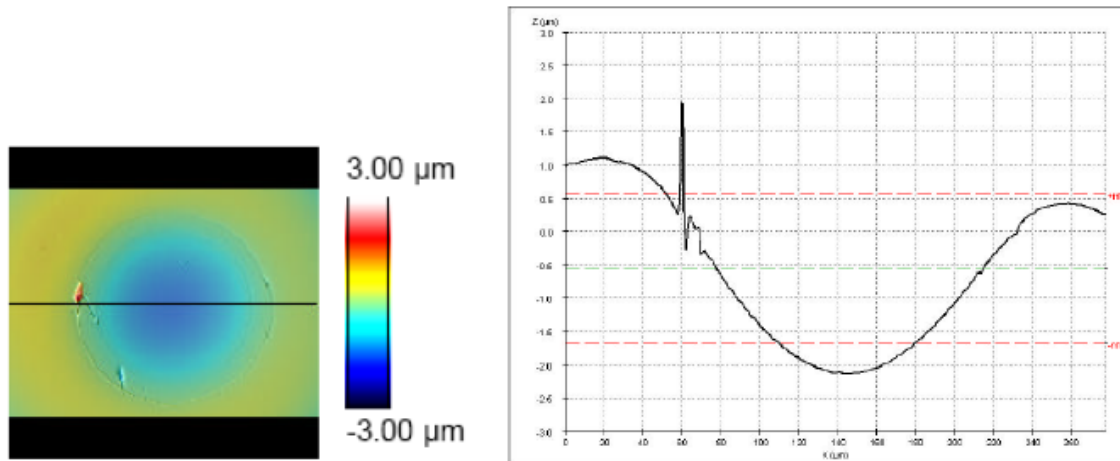



Figure 7.7-6. Confocal Data

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7.7.1 Summary

1. Although the termination appeared fairly clean, the curvature in the scratch could suggest that the end-face was wiped with an abrasive material or perhaps the other mating termini had debris that scratched the end-face of the termini as it was mated into a connector.
2. The crack could have originated by coarse grit lapping film.
3. The geometry of the larger abrasions (non-linear) in the coating suggests the damage did not occur during polishing as a result of debris during polishing.

7.7.2 Conclusion

Mating fiber optic terminations when there is debris present can cause the fiber end-face to be scratched or damaged. If a scratch from the coarse grit used to polish the fiber was not sufficiently removed as observed in other examples, then what started as a deep scratch (possibly not evident at the time of final inspection) could have easily been further propagated as either moisture or humidity got into the crack.

7.8 Sample HMU-303 J31-UP4 SKT C

At 10X magnification (Figure 7.8-1), it is very difficult to identify any possible defects in the fiber. Some debris is present over the fiber area and would appear to only need a cleaning.

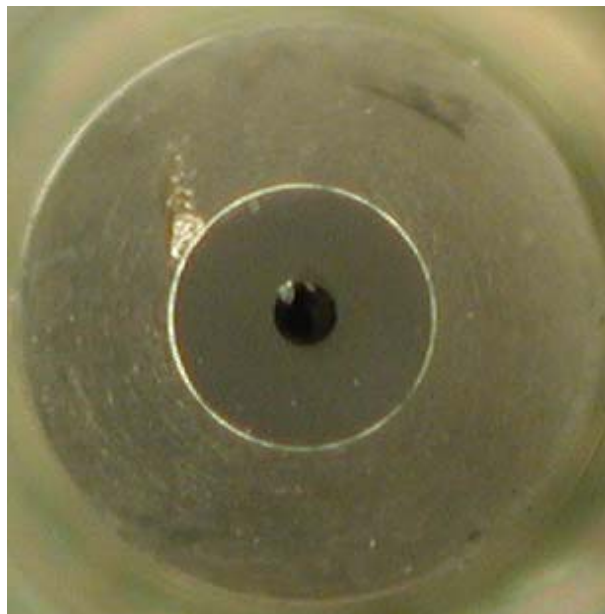



Figure 7.8-1. Optical Image at Magnification of 10X

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At 40X magnification (Figure 7.8-2), debris can be seen in several areas in and around the fiber. There also appears to be a smudge over the core. When a defect cannot be removed by means of cleaning, it must be observed at higher magnifications.

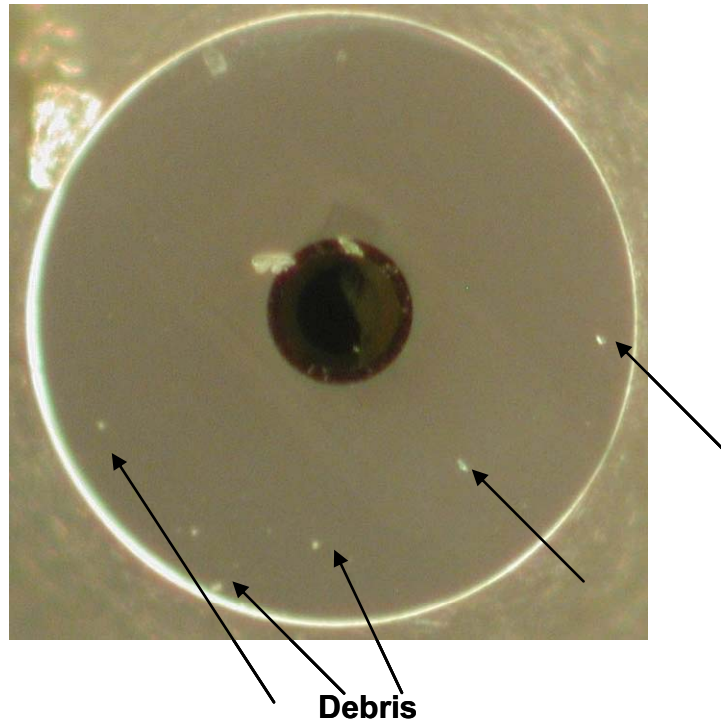


Figure 7.8-2. Optical Image at Magnification of 40X

At 200X magnification (Figure 7.8-3), a crack formation can be seen, and the “smudge” appears to be sub-surface cracking. Optical microscopy is not enough to identify an origin of the crack, so SEM will need to be performed.



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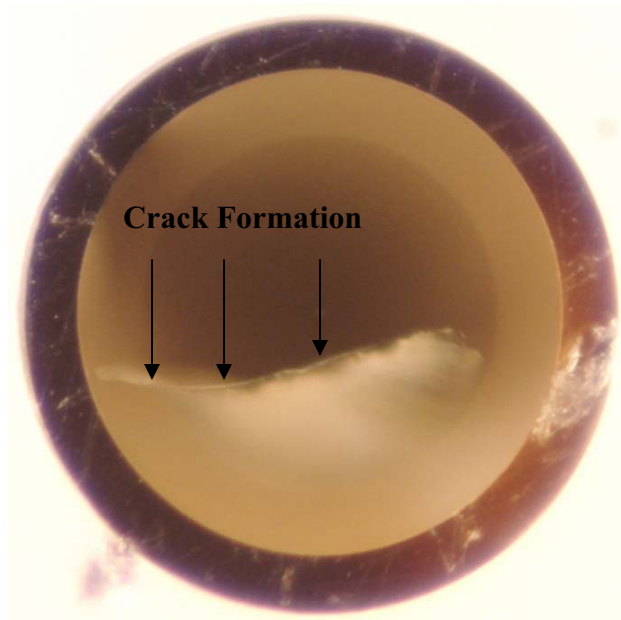


Figure 7.8-3. Dark Field Image at Magnification of 200X

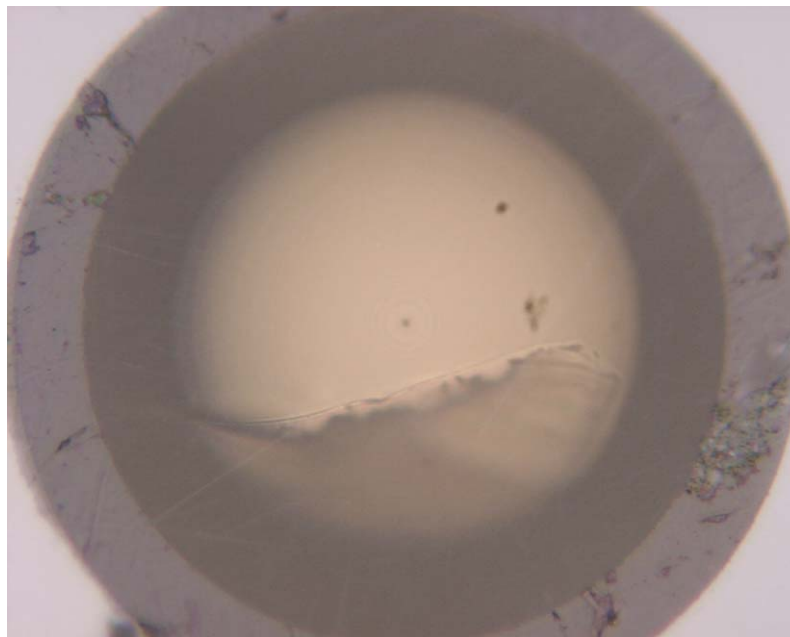



Figure 7.8-4. Bright Field Image at Magnification of 500X

With an adjustment of the lighting, features on the surface become clearer.

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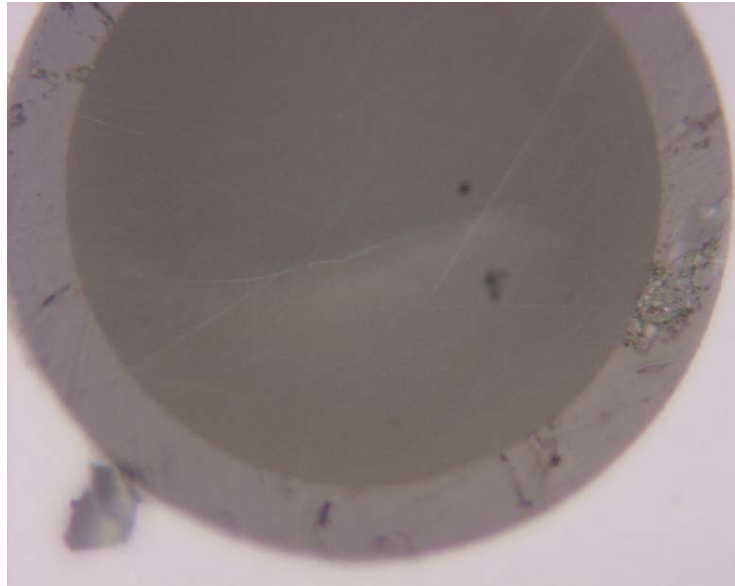
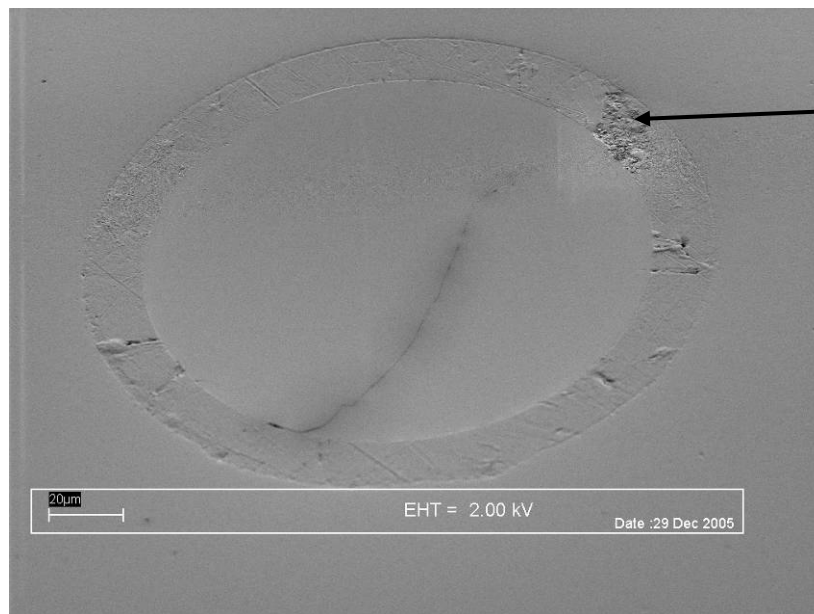


Figure 7.8-5. Optical Image at Magnification of 500X

SEM was performed (Figure 7.8-6), which enabled the crack to be clearly observed.



**Refer to Figure 7.8-7
for a closer look at
this area.**

Figure 7.8-6. Clear View of Crack

At higher magnifications of the corrosive area, crystals can be observed. These crystals appear to be salt crystals.



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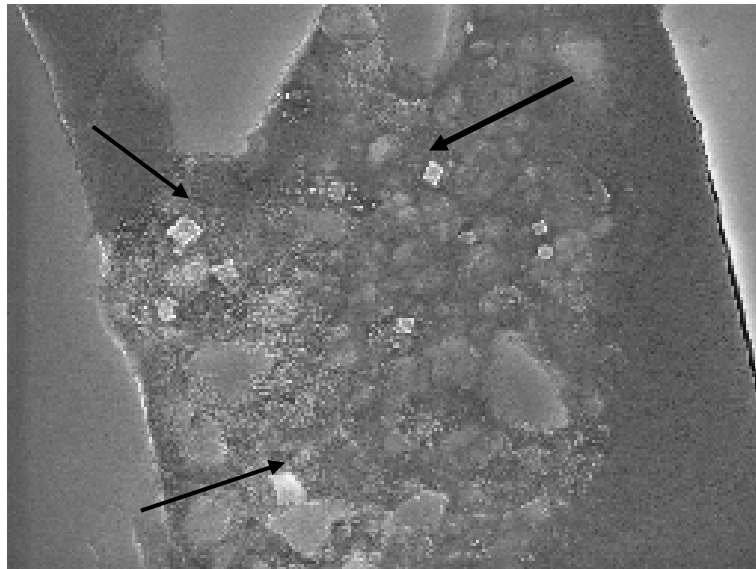


Figure 7.8-7. Visible Crystals in the Polyimide Coating

An EDS data analysis (Figure 7.8-8) of the corrosive area indicates the presence of Na and Cl.

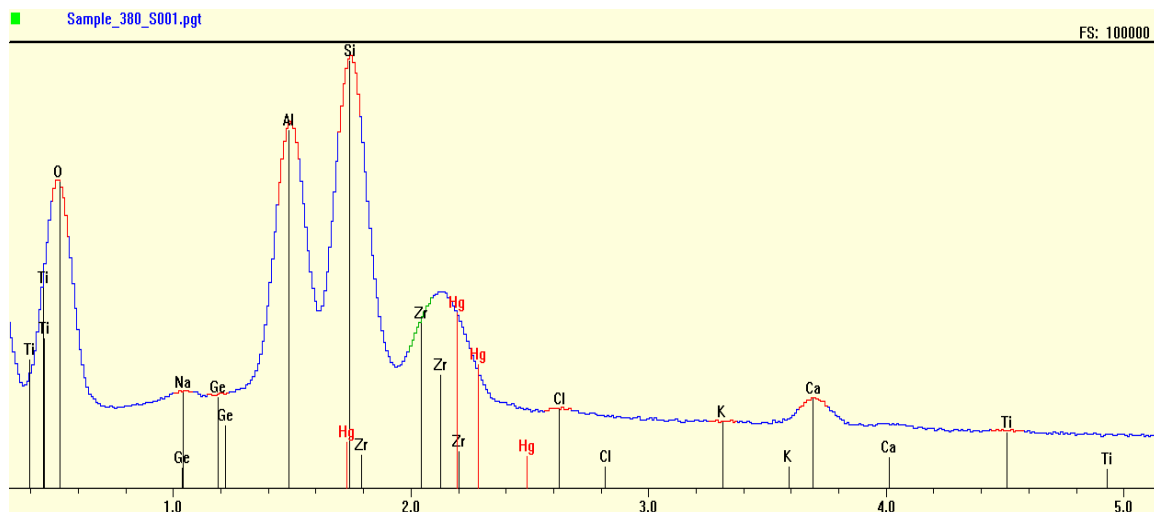


Figure 7.8-8. EDS Data

Confocal microscopy (Figure 7.8-9) indicates the end-face of the fiber is concave. The radius of curvature is 1.3 mm.



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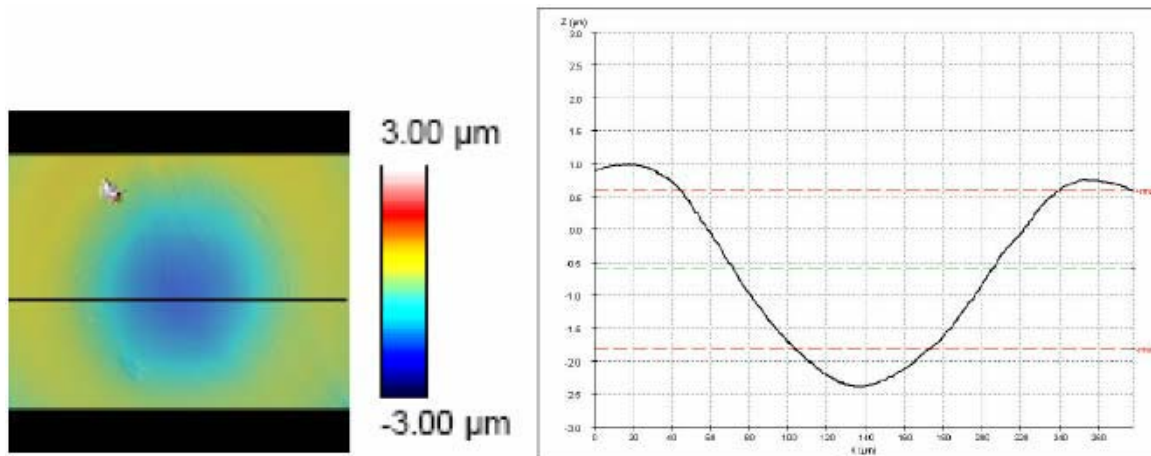



Figure 7.8-9. Confocal Data

7.8.1 Summary

1. The origin of the crack does not appear to be on either end, so it may have originated in the middle.
2. The cleanliness of the termination was not maintained.
3. Deep scratches indicate an improper polishing procedure was conducted.

7.8.2 Conclusion

Crack propagation occurred due to the deep scratches. The scratches are linear, which is an indication the fiber was wiped with an abrasive material, or remnants of the coarse lapping film were not removed during the final stages of polishing.

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7.9 Sample HMU-303 J1 BKT-VSU SKT G

This sample has damage very similar to HMU-303 P3-DAIU SKT C, whereas it appears to have been connected with debris present on the end-face. The scratches in the coating are evidence of a foreign substance being dragged or scraped in a non-linear direction. There is some unidentified debris in the core region that will need to be analyzed with EDS.

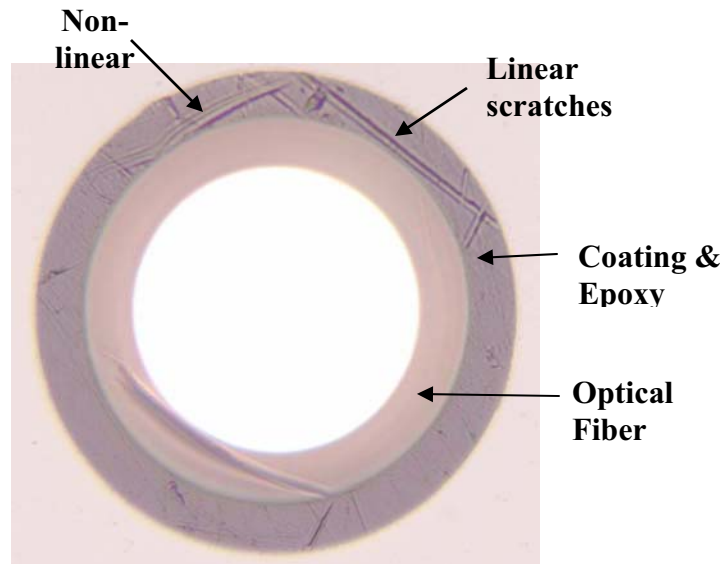


Figure 7.9-1. Bright Field Image at Magnification of 200X

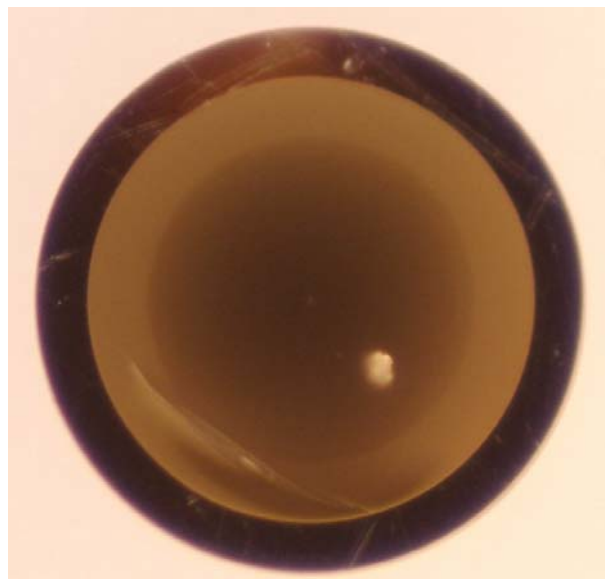



Figure 7.9-2. Dark Field Image at Magnification of 200X

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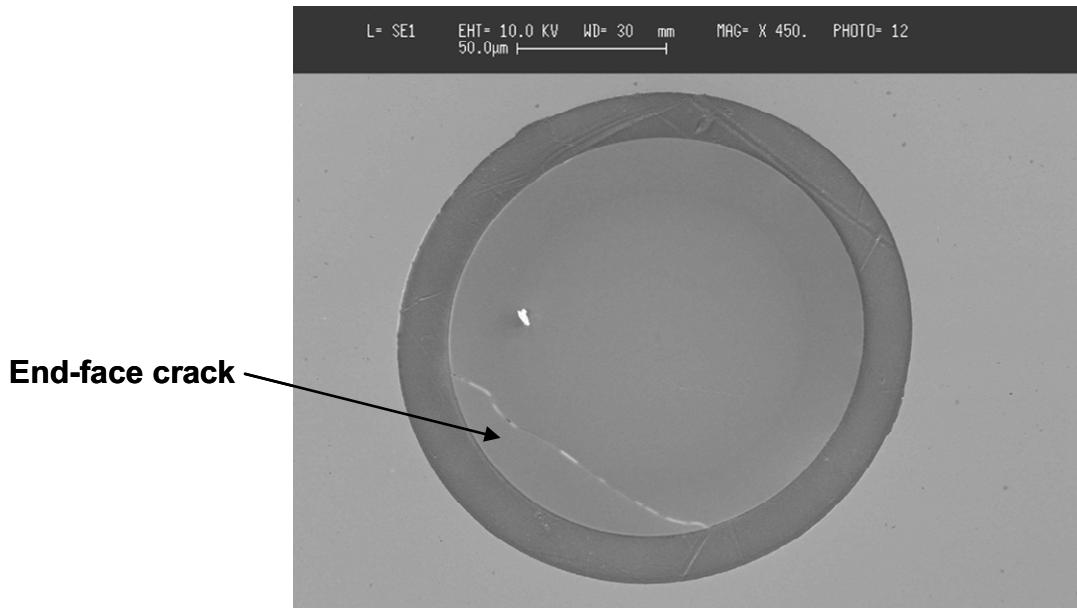


Figure 7.9-3. Crack in the End-Face

SEM shows a clearer picture of the damage (Figure 7.9-3), and what was thought to be a surface scratch becomes a crack in the end-face. There is no obvious origin of the crack. The crack ends at the coating in two locations, and the process of de-lamination occurs (Figure 7.9-4).

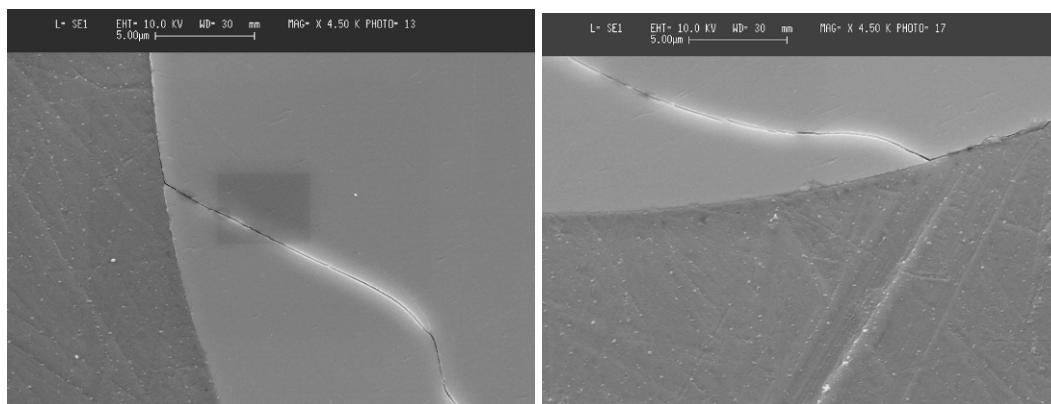


Figure 7.9-4. Crack Ends

No areas of visible corrosion were discovered, but EDS does indicate the presence of Na and Cl (Figure 7.9-5). Figure 7.9-6 shows a comparison of this EDS data to an area free of debris.



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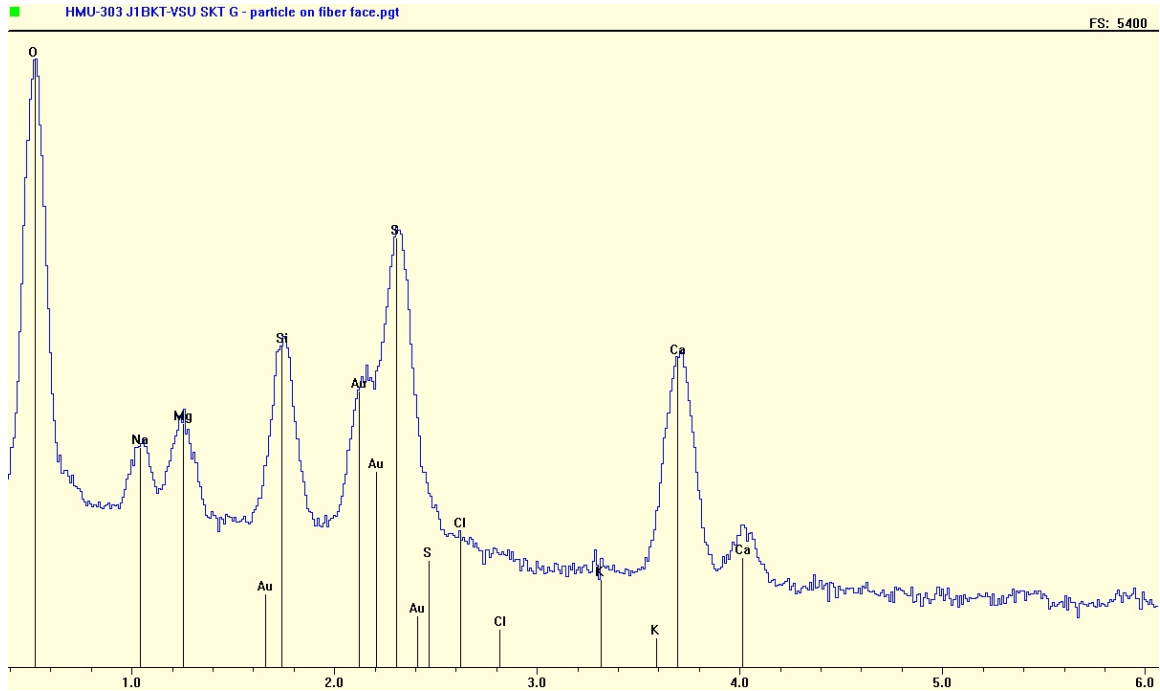


Figure 7.9-5. EDS Data of End-Face

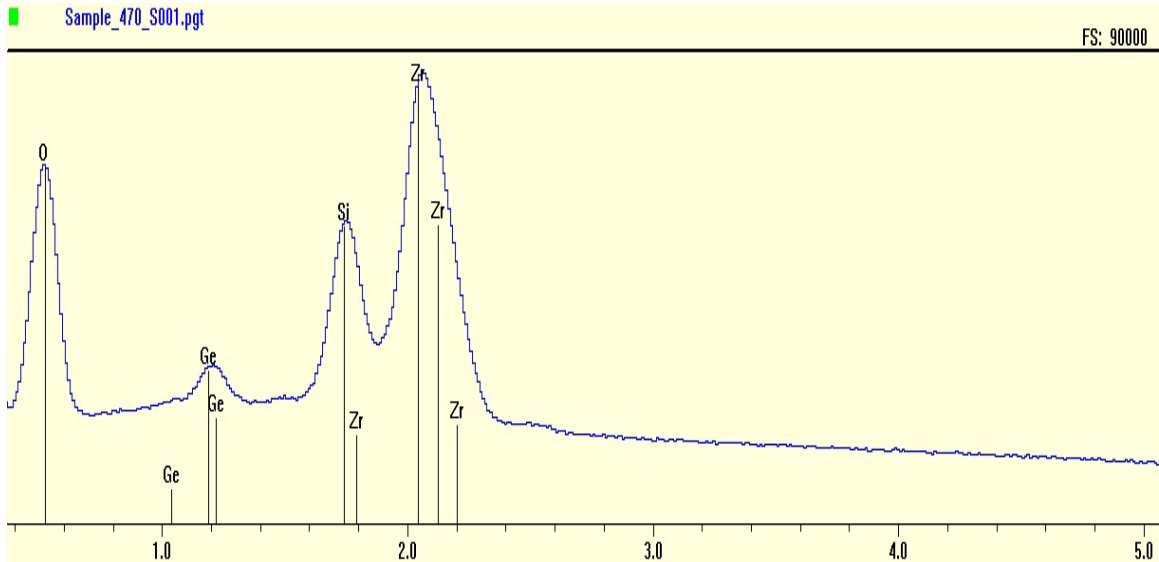



Figure 7.9-6. EDS Data of Uncontaminated Area

Confocal data (Figure 7.9-7) indicates the end-face has a concave profile, with a radius of 1.1 mm.

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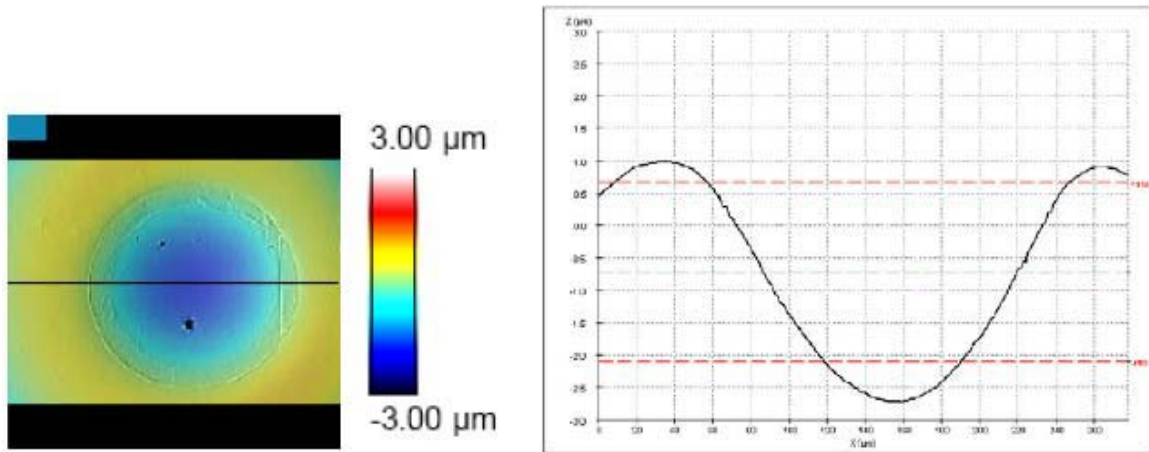



Figure 7.9-7. Confocal Data

7.9.1 Summary

1. The origin of the crack does not appear to be on either end, so it may have originated in the middle.
2. The formation of the scratches in the glass and coating may suggest it was mated with debris present.
3. The cleanliness of the termination was not maintained.

7.9.2 Conclusion

The non-linear scratches are indicative of mating with debris present.

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7.10 Sample HMU-303 J1 BKT-VSU SKT P

This termination is cracked partially through the core and deep into the fiber (Figure 7.10-1). There is some debris present on the ferrule end, and some damage/debris on the bottom of the coating.

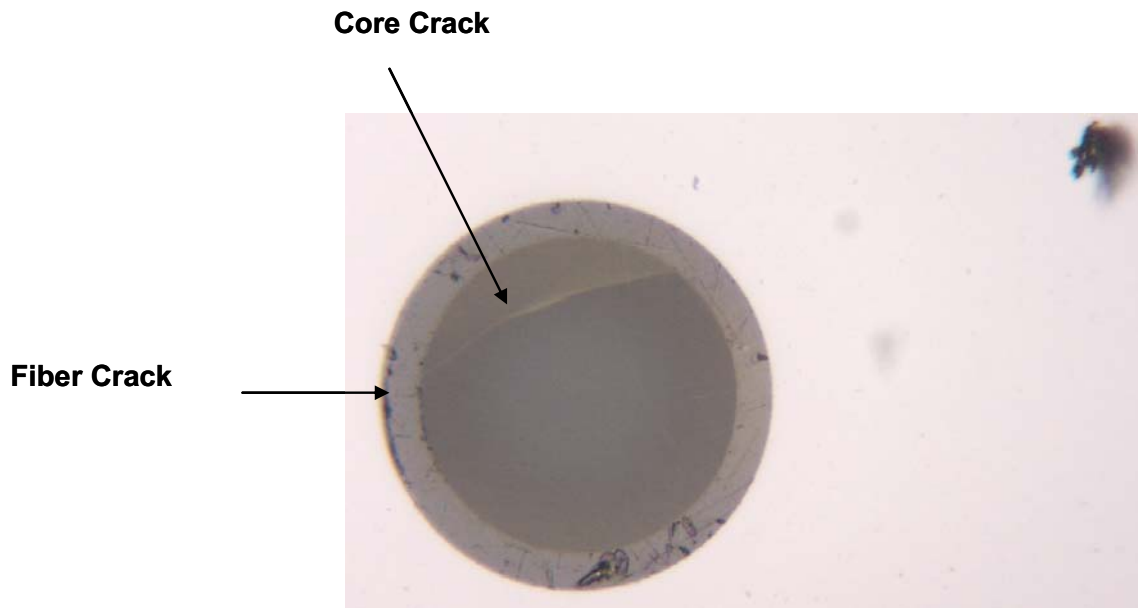



Figure 7.10-1. Bright Field Image

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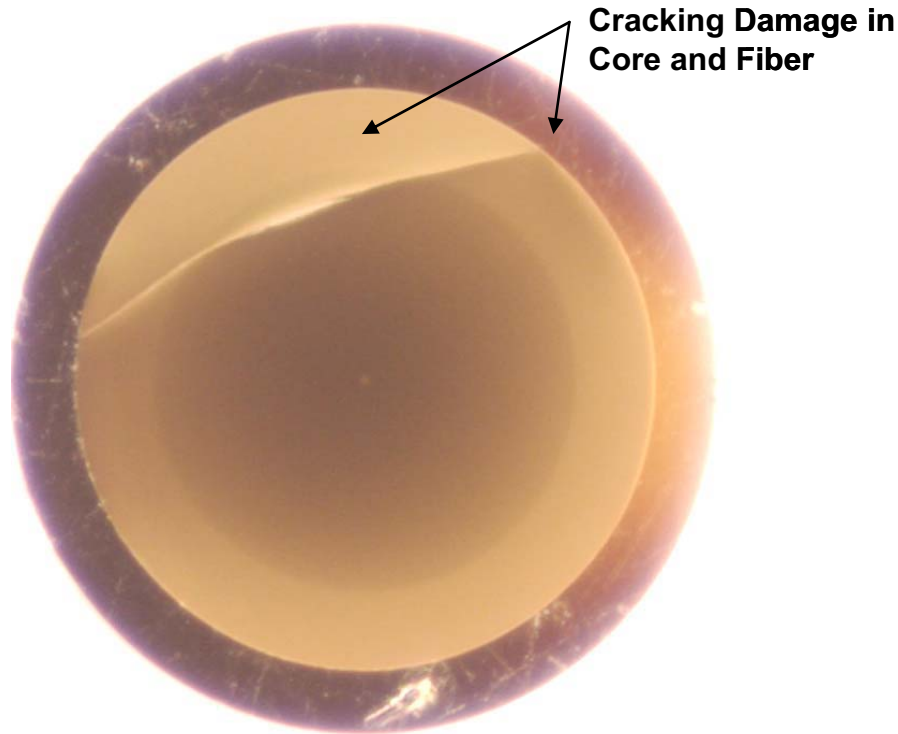



Figure 7.10-2. Dark Field Image

7.10.1 Summary

1. The origin of the crack does not appear to be on either end, so it may have originated in the middle, suggesting the fiber is possibly convex.
2. The cleanliness of the termination was not maintained.

7.10.2 Conclusion

This sample was unsuccessfully cross-sectioned when attempting to determine the profile geometry. The root cause of the damage could not be identified.

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7.11 Sample HMU-303 J21-UP4 PIN A

Some of the initial observations made at 200X magnification, and shown in Figures 7.11-1 and 7.11-2, were:

1. There was a deep crack through the core.
2. There were deep scratches in the coating, which appear linear.

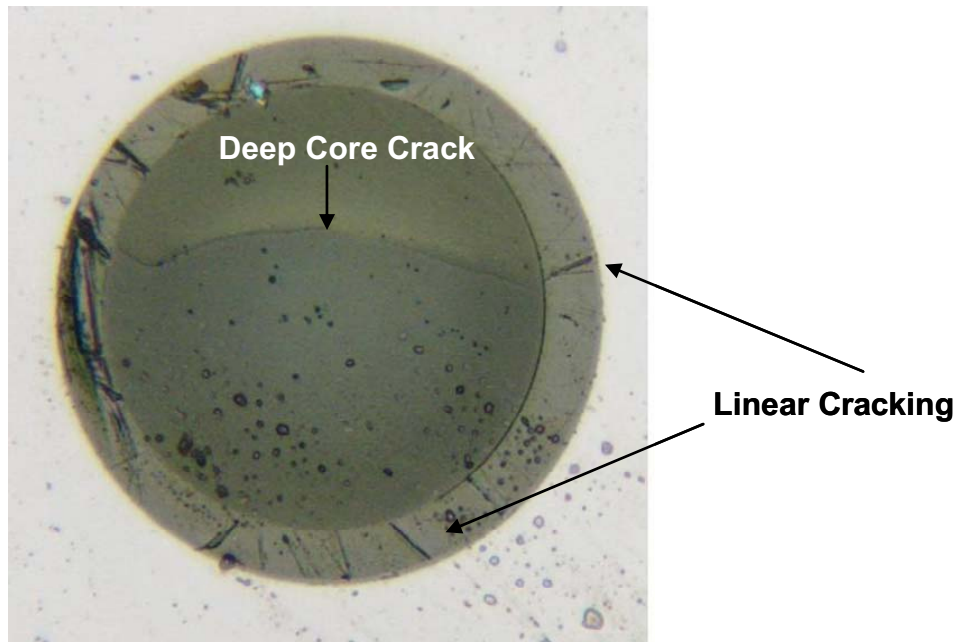



Figure 7.11-1. Bright Field at Magnification of 200X

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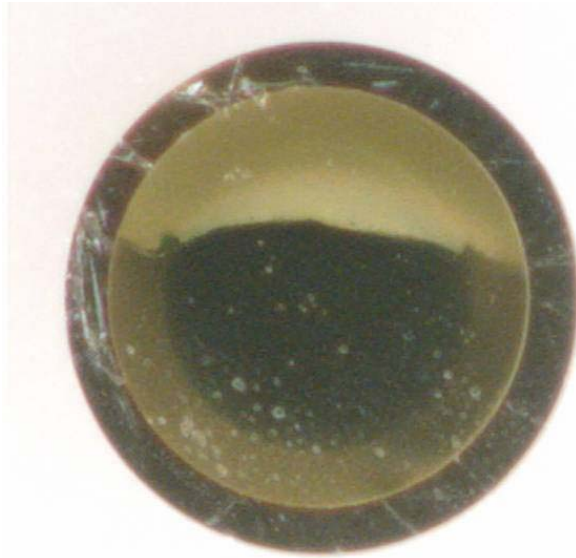


Figure 7.11-2. Dark Field at Magnification of 200X

The ends of the crack can be clearly analyzed under 3.2×10^3 and 2.8×10^3 X magnifications (Figure 7.11-3), but no definitive origin was identified.

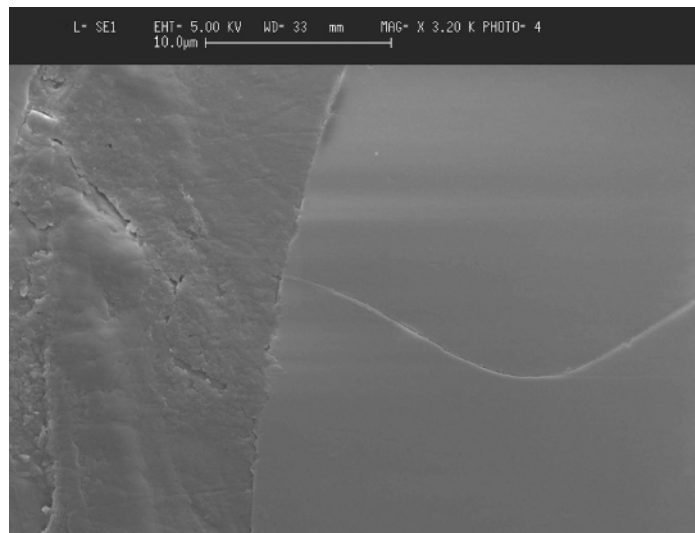



Figure 7.11-3. Magnification of 3.2 KX

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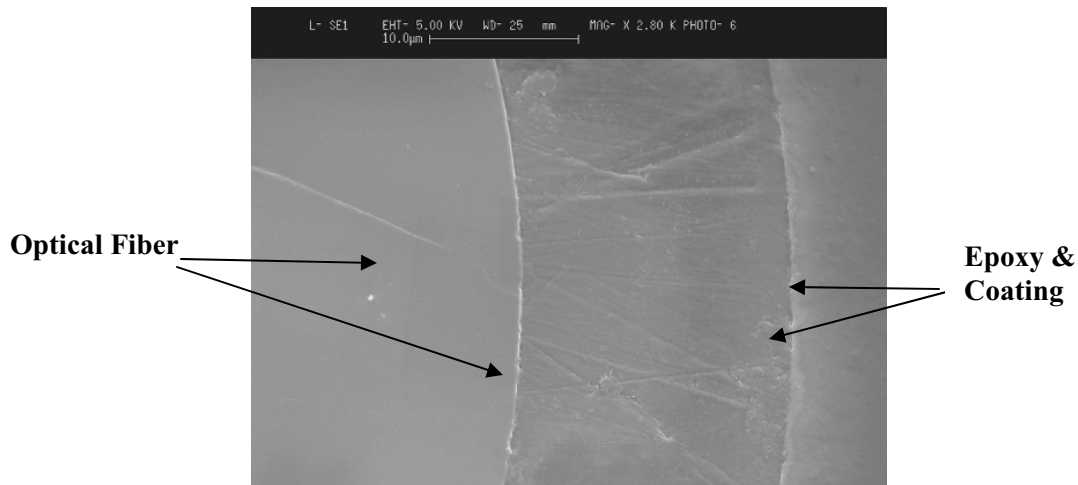


Figure 7.11-4. Magnification of 2.8 KX

Confocal data (Figure 7.11-5) indicates the end-face has a concave profile, with a radius of 1.2 mm.

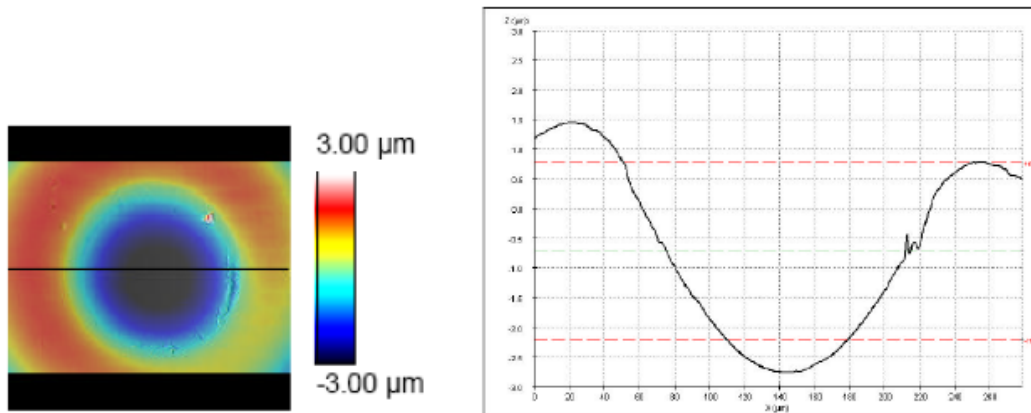



Figure 7.11-5. Profile of End-Face

7.11.1 Summary

1. The deep scratches in the fiber coating are indication the glass could have been damaged during the polishing or cleaning process.
2. The cleanliness of the termination was not maintained.

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7.11.2 Conclusion

This sample was compromised during analysis. Therefore, no definitive conclusions can be made.

7.12 Sample HMU-303 P3-ABC 5 SKT B

This terminus has considerable debris (Figure 7.12-1). There is a crack that has propagated through the core, but if the crack did not occur, the optical signal would still be severely diminished due to the amount of debris.

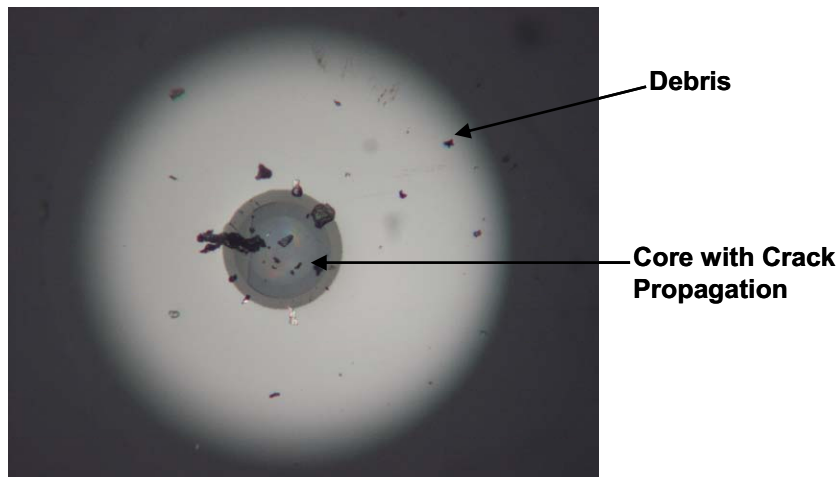



Figure 7.12-1. Connector with Considerable Debris

The crack can easily be observed at a 200X magnification (Figure 7.12-2) and with dark field illumination.

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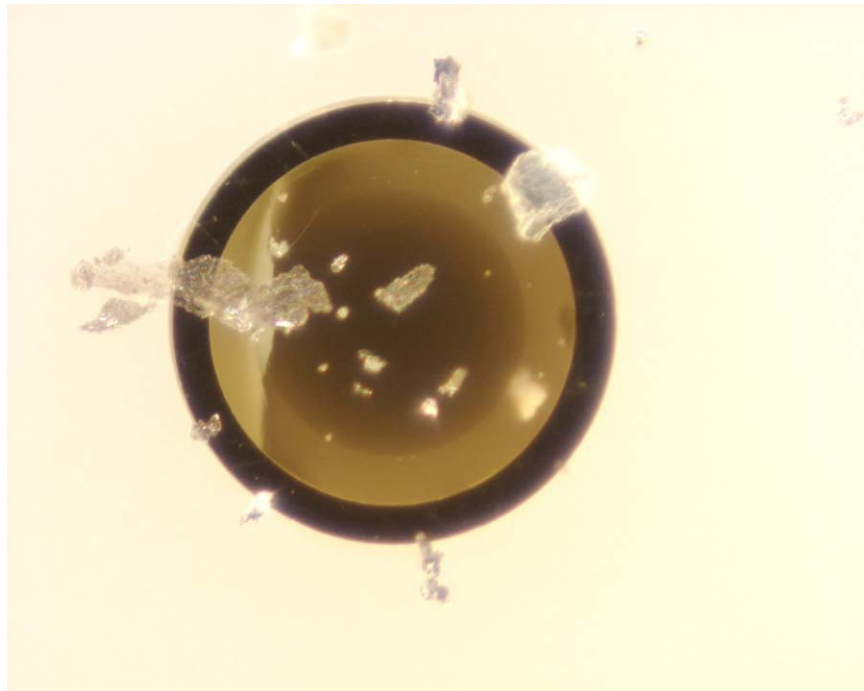


Figure 7.12-2. Magnification of 200X Bright Field Illumination

An EDS data analysis (Figure 7.12-3) of the end-face identifies many foreign elements that make up the debris.



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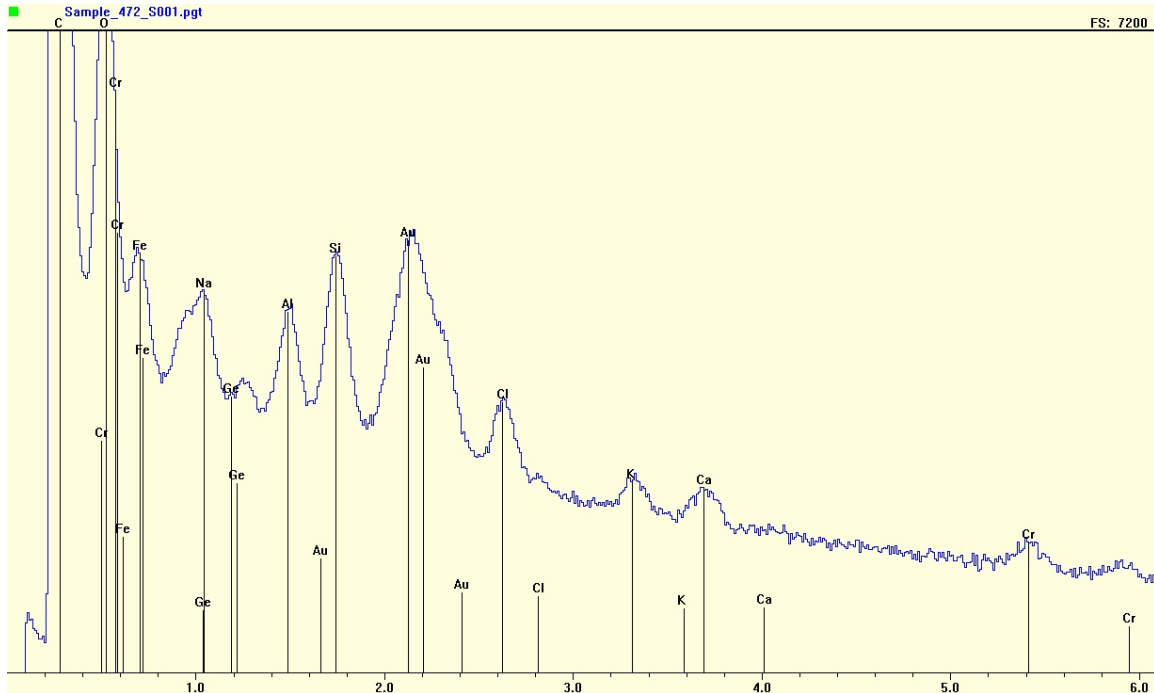


Figure 7.12-3. EDS Data of Debris on End-Face

Confocal data (Figure 7.12-4) suggests the end-face has a slight convex profile. However slight it may be, the fiber still extends beyond the ferrule. The radius of curvature measured 8.7 mm. It is important to note the height of the contamination showed in Figure 7.12-4. The large spike in the center of the graph shows the particles height at that location as being well above the surface of the optical fiber terminus. When this terminus is mated to another terminus in close proximity that particle will undoubtedly make contact with both surfaces as it is compressed between the two interfaces. This impact can cause damage to both optical fibers being mated together.



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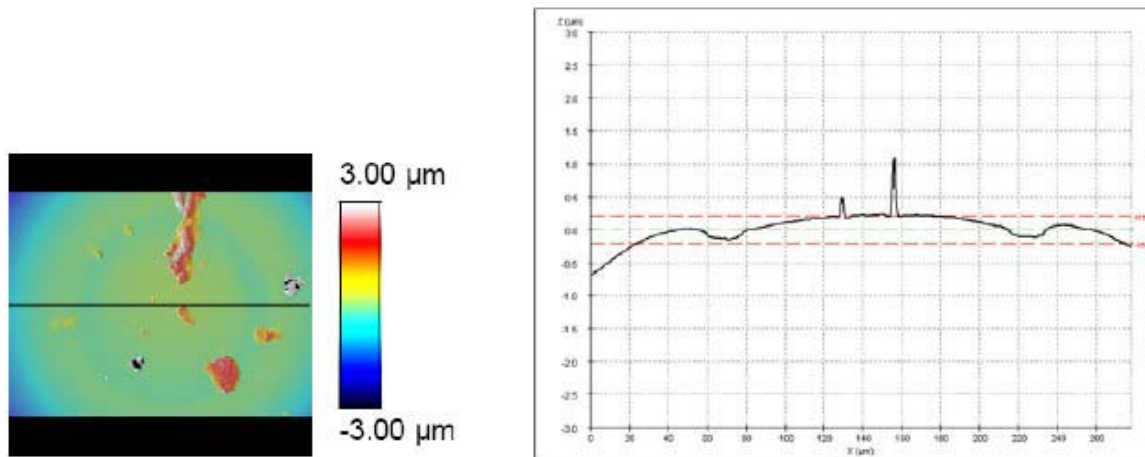



Figure 7.12-4. End-Face Profile

7.12.1 Summary

1. The end-face has considerable debris which suggests the glass was damaged due to improper cleaning techniques. Mating unclean connectors can cause damage to fiber optic end-faces.
2. The confocal data suggests the convex fiber end-face extends beyond the ferrule.

7.12.2 Conclusion

The cleanliness of the fiber was not maintained which would have caused damage to the fiber when mated.

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7.13 Sample HMU-303 P3-VSU5 SKT T

Deep scratches on the face of the fiber (Figure 7.13-1) are indication that it was ground with the coarse grit, and not followed up with a finer grit lapping film. Scratches to this extent can cause latent cracking.

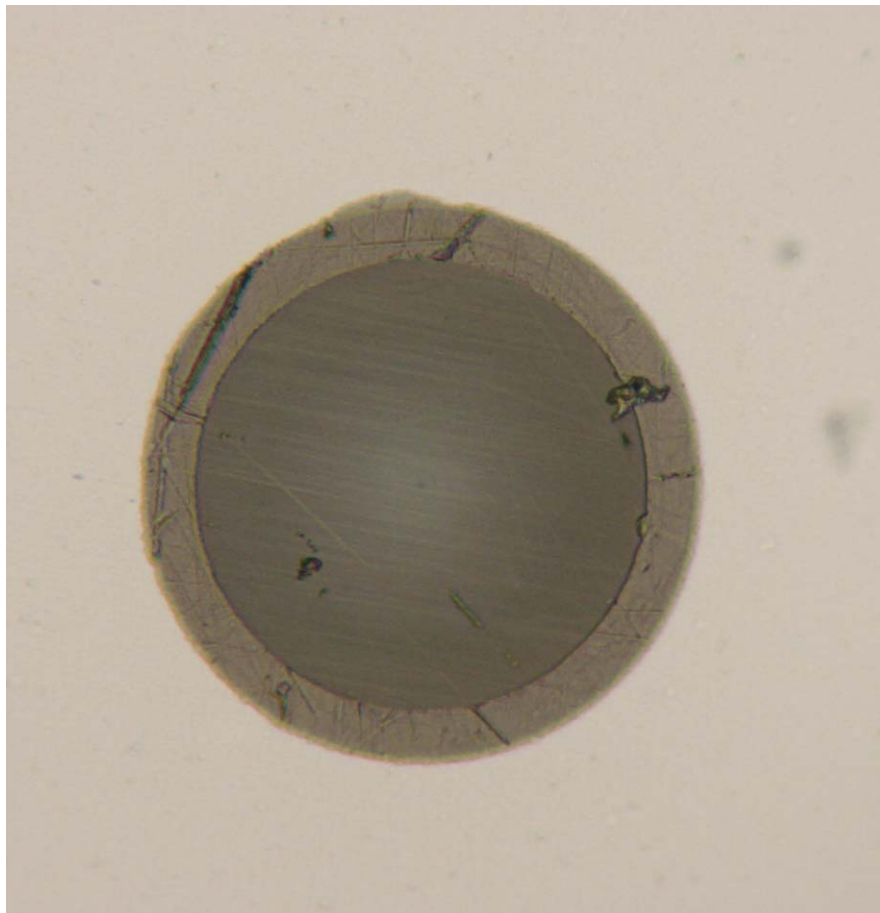


Figure 7.13-1. Deep Scratches from Polishing Process

Despite the scratches from the lapping film, there are no visible cracks in this fiber. However, given enough time, cracks could propagate.



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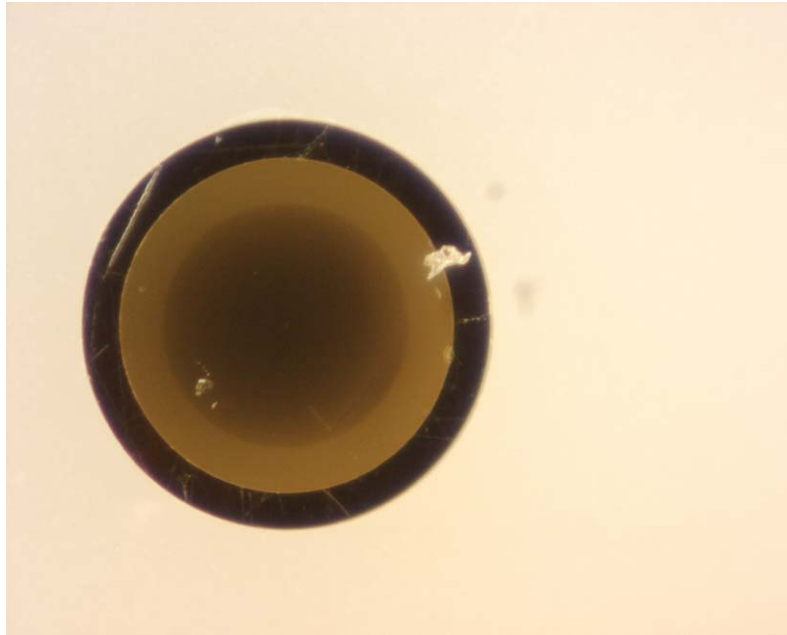


Figure 7.13-2. No Visible Cracks

Confocal microscopy data (Figure 7.13-3) identifies the profile of the end-face to be convex, with a radius of curvature measuring 7.4 mm.

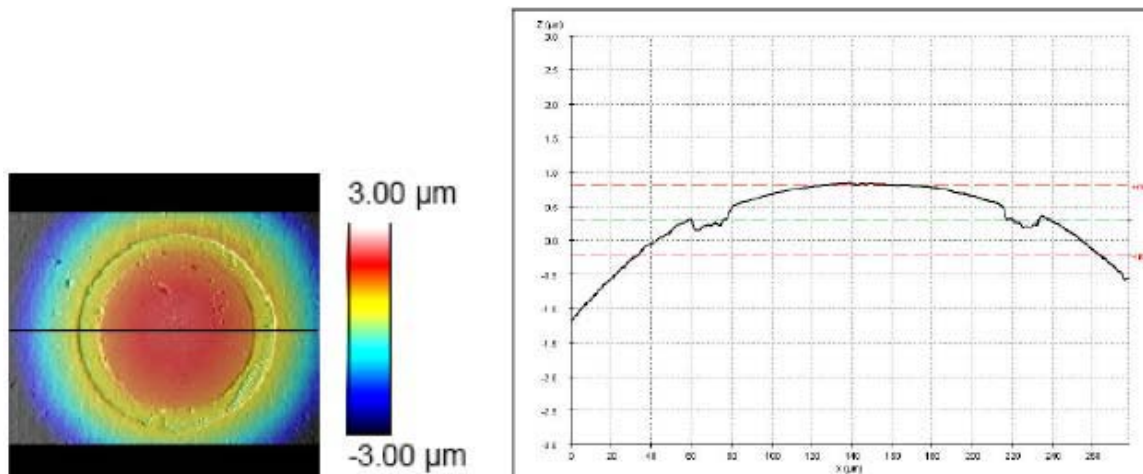



Figure 7.13-3. Confocal Data

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7.13.1 Summary

1. The lapping film used to polish the fiber end-face was too coarse. A finer grit lapping film should have been used to eliminate the deep scratches.
2. The cleanliness of the termination was not maintained.
3. The end-face has a convex profile, which violates requirements specified in the manufacturing procedure [ref. 3].

7.13.2 Conclusion

This sample was compromised before SEM and EDS could be performed. The deep scratches identified using optical microscopy (Figure 7.13-1) indicates the polishing process was not performed per specification.

7.14 Tables

Tables 7.14-1 and 7.14-2 include acquired data about the present condition of the termini, and if the damage will likely cause signal degradation in the short-term or long-term. The time for the signal degradation is based on the location of the damage and how severe it is. For the signal to degrade, the damage must be located in the core region. If the damage is in the cladding region, there will be no significant signal loss, but cracks may propagate from the cladding region into the core.



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Table 7.14-1. Termini Condition Data Table

<i>S/N</i>	<i>Damage by impact /Surface Scratch/Deep crack</i>	<i>Concave (as per spec)/Convex (violates spec)</i>	<i>Debris Present on End-face?</i>	<i>Signal degradation in Short-Term/ Long-Term</i>	<i>Root Cause</i>
HMU-302 P21-UP4 SKT A	Impact	Convex	Yes	Short-Term	Convex End-Face
HMU-303 P3-VSU5 SKT F	Impact	Convex	Yes	Short-Term	Convex End-Face
HMU-303 J31-BKT VSU SKT S	Deep Crack	Concave	Yes	Long-Term	Improper Polishing
HMU-303 P5-VSU5 SKT E	Deep Crack	Concave	Yes	Long-Term	Improper Polishing
HMU-302 P14-NODE1 SKT P	Deep Crack	Convex	Yes	Long-Term	Improper Polishing
HMU-304 P20-UP4 SKT Z	Deep Crack	Convex	Yes	Long-Term	Contamination
HMU-303 P3-DAIU SKT C	Surface Scratch	Concave	Yes	Long-Term	Contamination
HMU-303 J31-UP4 SKT C	Deep Crack	Concave	Yes	Short-Term	Improper Polishing
HMU-303 J1 BKT-VSU SKT G	Surface Scratch	Concave	Yes	Long-Term	Contamination
HMU-303 J1 BKT-VSU SKT P	Deep Crack	---	Yes	Long-Term	---
HMU-303 J21 UP4 PIN A	Deep Crack	Concave	Yes	Short-Term	---
HMU-303 P3-ABC 5 SKT B	Deep Crack	Convex	Yes	Long-Term	Contamination
HMU-303 P3-VSU5 SKT T	Surface Scratch	Convex	Yes	Long-Term	Improper Polishing


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Table 7.14-2. Defect Percentages


<i>Type of Defect</i>	<i># of Occurrences</i>	<i>Root Cause</i>	<i>Percent w/ Defect</i>
Impact Fracture	2	Convex End-face	15 percent
Surface Scratch	3	Contamination/ Improper Polishing	23 percent
Deep Crack	8	Contamination/ Improper Polishing	62 percent
Convex End-face	6	Quality Assurance	46 percent
Debris End-face	13	Fiber Handling	100 percent
Corrosive Attack	4	Fiber Handling	31 percent
Eccentric Fiber	1	Quality Assurance	8 percent

7.15 Summary

To provide more insight into the final conclusions of this investigation it is helpful to understand several aspects of this type of fiber and the necessary procedures that are typically applied to produce optical fiber assemblies that can function reliably long-term in a spaceflight environment.

Germanium Doped Graded Index Fiber

Germanium-doped graded index multimode fiber is known for its brittleness by design of the dopants used. The graded index multimode represents one of the worst cases when identifying multimode constructions that are prone to cracking. Even when viewed through a microscope the cracks that exist are not visible. But, as a result of the dopant concentration, internal stresses exist only by design. The graded index fiber possesses a larger amount of dopant concentration in the center of the core which falls off slowly as one travels out in the radial direction. This sets up an internal stress condition where the CTE of the germanium doped silica at the center is higher than that of the surrounding material and the silica cladding. Micro-cracks can easily originate from this center because of the internal stresses inherent to the fiber structure. Another source of micro-cracking is based on the atomic structure of the dopant and the silica that mismatches in size as well as contaminates that enter the material during processing. So curing at a high temperature can set up a situation where the fiber will crack during thermal extremes. The result is destructive stress induced by a combination of constrained CTE (epoxy is surrounded by rigid geometry such as a fiber ferrule and the fiber itself) and a large temperature excursion which activates the CTE. A slight defect can be grown into a larger crack across an end-face from the stress inflicted and can further propagate from water in the environment getting into the crack well before the flight hardware is ever launched [ref. 6, 7].

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Epoxy Cure Processes for Optical Fiber Terminations


When making choices for spaceflight assemblies, manufacturers are requested to consult the outgassing database hosted at NASA GSFC [ref. 8]. The data shows the results of testing each material to the American Society for Testing and Materials (ASTM)-E595 procedure. For epoxies, it lists the curing schedule used for the various materials under test to ASTM-E595. The logical conclusion when deriving a procedure from the available data is to choose the cure schedule that bests matches the passing criteria for the ASTM-E595 where the TML and the Collected Volatile Condensable Materials (CVCM) are under the necessary limits as mentioned in Section 2.2 on materials analysis. For example, an Epotek epoxy may pass the screening criteria but at a 200 °C cure schedule. So a termination engineer may see this cure schedule as the way to ensure that the epoxy used to bond optical fiber to the termini or connector ferrule will not outgas. If the assembly being built will be used at a lower temperature, then this will create a situation where the CTE can be activated by a large change in temperature which, in turn, will exert a stressful condition on the fiber. Even if cracks do not appear at the time of the first round of thermal testing they could appear later. Germanium doped graded index fiber will exhibit this quicker than other types of optical fiber.

Polishing Procedures

Grinding during the polishing process with too high of a grit typically causes latent defects later that show up as cracks that were temporarily masked during final inspection. Polishing and grinding are two very different processes, but both involve preparing an optical fiber end-face. Grinding essentially cracks the surface of the glass with material particles that are harder than the glass. Polishing is more of a “molecular phenomenon caused by adhesive forces between the molecules of the polishing agent and those of the surface” [ref. 9]. Because of this it is imperative that before the final polishing commences, all scratches and cracks from higher grit grinding processes be thoroughly removed by using finer grit lapping film. If this does not occur, then a surface that appeared “polished” just after termination may show propagation of any underlying micro-cracks later, left over from a grinding process that preceded it with too high of a grit. NASA recommends using no larger than 9 μm to grind and, for rework, 5 μm or less lapping film to “polish” away excess fiber and epoxy because it will remove the excess, but will not create scratches that are too deep. This 9 μm lapping film will remove excess material without creating large scratches that are too large to be removed by the following lapping processes [ref. 10]. Use of these practices is a means to avoid some of the damage seen in the samples.

Cleaning and Inspection

During final inspection of a connector or termini end-face, high reliability spacecraft applications typically use a 200X image and should be inserted into the quality assurance documentation for


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certification of the termination. Back-lighting and dark field images are also used to search for cracking that may be too slim in gap to be detected without changing the lighting geometry. Light will propagate through a crack that is less than 1/8 of a wavelength of light. Use of these practices is a means to detect some of the defects in the samples. Another practice found important to assuring the long-term reliability of all integrated assemblies is to clean termini ends and inspect prior to ever mating two termini or connectors together. If contamination exists on one of the termini, the impact stress could increase the likelihood of any micro-cracking already inherent to the core of the fiber to propagate into a large and visible crack that will greatly affect transmission loss. There are many examples of this type of damage in this study.

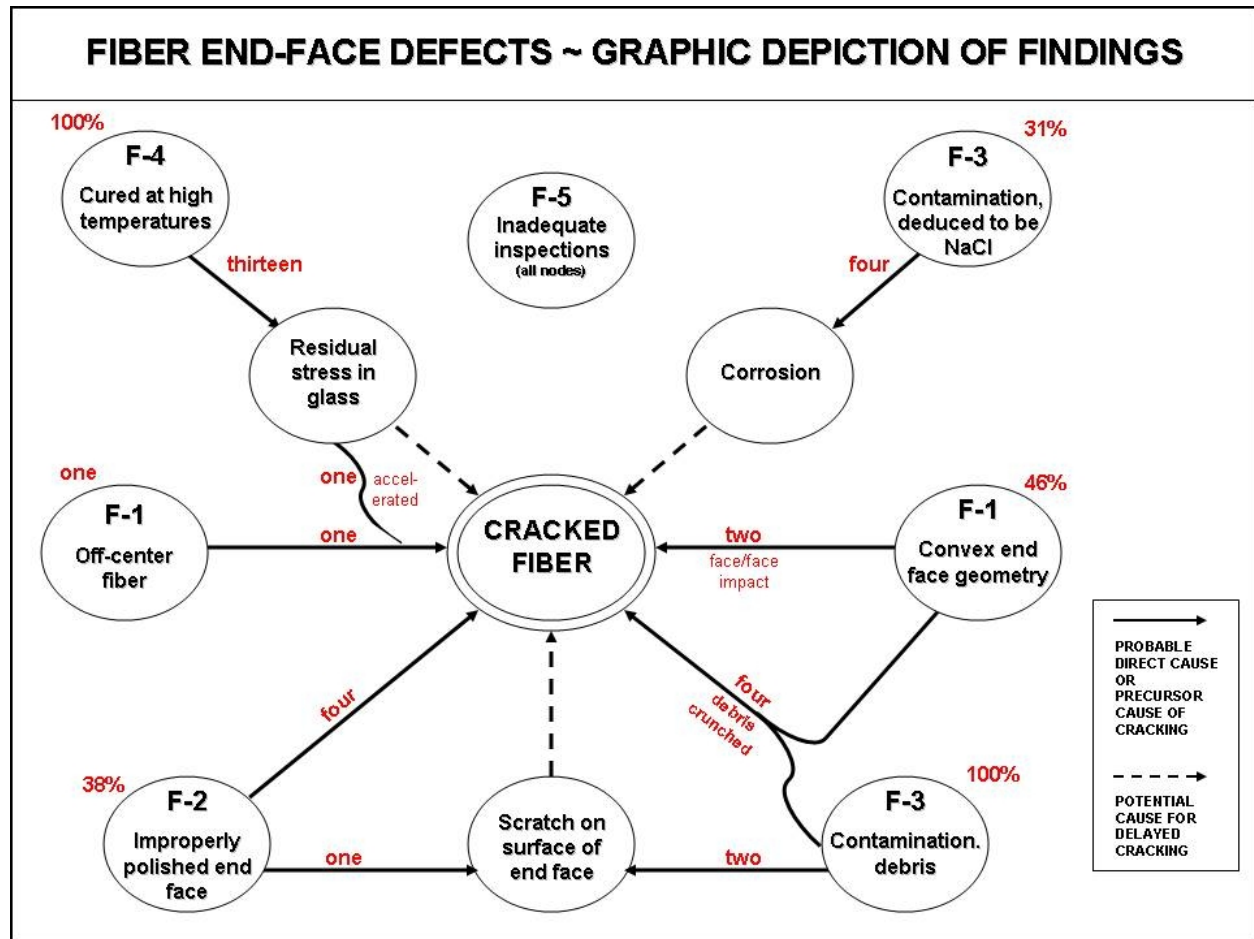
End-Face Geometry

There are many applications that utilize convex or “physical contact” profilometry on the optical fiber assemblies for spaceflight applications. This particular application uses a military terminus that was tested over ten years ago to military vibration conditions. When this particular configuration was tested, using a physical contact type polish on the end-faces of the termini, cracks developed on the fiber as a result of the vibration induced stresses. In this case, a physical contact polish or convex fiber end-face polish is not a good design when qualified to military standards. Other types of connectors such as the Diamond AVIM used on many spaceflight implementations at NASA pass typical launch condition random vibration tests with the end-face geometries being convex [ref. 11,12]. This is mentioned so the reader of this report does not confuse the geometry of convex with that of an improper design. The issue discovered was a noncompliance to the manufacturing procedure as written by the manufacturer and not a dispute over the end-face geometry design. The fact that the non compliance was missed during final inspection means that the inspection process was 1) not adequate to the task, and 2) the manufacturer did not perform proper quality assurance on the final product. There are several examples of this throughout the study. It is also noteworthy to understand that large debris particles as the ones found on the end-faces of the fibers in this study, will cause damage on impact with a brittle fiber such as the germanium doped graded index used for this application.

In cases where convex or physical contact polished optical fiber assemblies are used in spaceflight applications, it is necessary to specify the amount of protrusion that the convex end-face is allowed. In all cases where this type of configuration is used, a limit is placed on the value of protrusion and radius of curvature such that the fibers do not extend past the appropriate point where the two ends meet. To go beyond this limit would set up a condition for the two ends to impact against each other and, therefore, create an impending cracking condition.

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8.0 Findings, Root Causes, and Recommendations




8.1 Findings

F-1. Non Compliance to Manufacturing Procedure Quality Assurance

Samples HMU-302 P21-UP4 SKT A (Section 7.1) and HMU-303 P3-VSU5 SKT F (Section 7.2) had convex end-face geometry, contrary to the specification in N2-PR-OHB-0005. A crack that was observed on the fiber of Sample HMU-302 P21-UP4 SKT A (Section 7.1) may have been an impact fracture resulting from the observed convexity.

The fiber in the coating of Sample HMU-303 P3-VSU5 SKT F (Section 7.2) was grossly misaligned beyond specification #SSQ 21654 section 3.7. The observed misalignment

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may have caused a crack that was observed on one side of the fiber, as the misalignment may have resulted in non-uniform thermal stresses during curing.

F-2. Improper Polishing Procedure

Samples HMU-303 J31-BKT VSU SKT S (Section 7.3), HMU-303 P5-VSU5 SKT E (Section 7.4), HMU-302 P14-NODE1 SKT P (Section 7.5), HMU-303 J31- UP4 SKT C (Section 7.8), and HMU-303 P3-VSU5 SKT T (Section 7.13) exhibited deep scratches that may have been produced during high-grit grinding, but that should have ordinarily been removed during subsequent polishing with fine lapping films. Such scratches left on a fiber face without removal can go undetected during inspection, and can grow in the presence of moisture, resulting in latent fiber cracks.


F-3. Contamination and Subsequent Insufficient Cleaning

Debris was observed on all thirteen end-face samples. Elemental mapping suggested that some of this debris could have been derived from material used to polish the termini. Scratches were observed on several samples that may have originated when the end-faces were improperly wiped during cleaning. Scratches were also observed on some samples to be consistent with residual debris being ground into the glass during connection. Scratches can lead to latent fiber cracking. End-face cleaning prior to every mating can prevent these types of scratches from initiating.

Elemental mapping of debris on Samples HMU-302 P21-UP4 SKT A (Section 7.1), HMU-303 P3-VSU5 SKT F (Section 7.2), HMU-302 P14-NODE1 SKT P (Section 7.5), and HMU-303 P3-ABC 5 SKT B (Section 7.12), revealed a composition which included elemental Sodium and Chlorine. These were noted to be physically coincident with small particles resembling salt on Sample HMU-302 P21-UP4 SKT A (Section 7.1). A potential way for salt to have been deposited on an end-face was via touching by a finger. Salt can be very corrosive to germanium-doped silica glass. Salt can also cause abrasions on fibers with convex-shaped end-faces, like any other debris. Scratches of this nature can lead to latent fiber cracking.

F-4. High Curing Temperature

Examination of the manufacturing procedure revealed that the procedure called for curing at the uniquely high temperature of 200 °C, the next highest being 100 °C. This may cause large stresses in a glass fiber, due to the different coefficients of thermal expansion within the different materials used in a connector and termini. This can result in latent fiber cracks.

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F-5. Insufficient Inspection Methods

Inspections for end-face geometry that may have occurred at the manufacturer failed to reject the convex end-face geometry of Samples HMU-302 P21-UP4 SKT A (Section 7.1) and HMU-303 P3-VSU5 SKT F (Section 7.2).

Inspections that may have occurred at the manufacturer or at the integrator failed to reject this cable from gross misalignment of the fiber in Sample HMU-303 P3-VSU5 SKT F (Section 7.2).

Inspections that may have occurred at the manufacturer or at the integrator, failed to detect deep scratches from inadequate polishing after grinding during manufacture.


Inspections that may have occurred at the manufacturer or at the integrator failed to detect scratches from insufficient cleaning following debris contamination. This contamination could have occurred at the manufacturer, in transit between the manufacturer and the integrator, or during integration.

8.2 Root Causes

Table 8.2-1 shows a percentage representation of the number of end-faces from the lot studied as categorized by the findings mentioned above.

Table 8.2-1. Root Cause of Defected End-Face

<i>Root Cause</i>	<i># of Occurrences</i>	<i>Percent w/ Defect</i>
Non Compliance	2	15 percent
Improper Polishing	5	39 percent
Contamination	4	31 percent
Not Determined	2	15 percent

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8.3 Recommendations


- R-1.** The key stakeholder should investigate supplier adherence to the manufacturing process documents (SSQ 21654 and N2-PR-OHB-0005) to specifically ensure that after polishing, end-faces shall be inspected for conformance to specified geometry, using an accurate means of measurement such as an interferometer. (*F-1, F-5*)
- R-2.** The key stakeholder should consider developing a manufacturing process document for suppliers that specifies:
- that each time an end-face is polished, it shall be inspected at 200X magnification (minimum) to ensure the deep scratches have been removed (*F-2, F-5*)
 - that fiber optic terminations shall be visually inspected at 50X or better each time before being connected, and that terminations shall be determined to be free of debris and contamination. Also, that whenever possible when not connected, that end-faces should be kept protected with a ferrule cap (*F-3, F-5*)
 - that epoxy with lower curing temperature (≤ 120 °C) requirements be used [ref. 7, 10] (*F-4*)
 - the use of a fine grit lapping film for polishing, not coarser than 9 μm (*F-2*)

9.0 Lessons Learned

NASA needs to develop a manufacturing process document for termination of fiber optic connectors. No adequate document of this type presently exists for projects to use in audits of fiber optic manufacturing procedures to avoid known problems.

10.0 Definition of Terms


Cladding	The outer layer of silica glass of an optical fiber, used to contain the light inside the core.
Confocal	Having the same focus at various depths.
Convex	Curving or bulging outward.
Corrective Actions	Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.

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End-face	The termination end of a fiber or ferrule.
Ferrule	A cylindrical tube, which aligns the fiber in a connector.
Finding	A conclusion based on facts established during the assessment/inspection by the investigating authority.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Observation	A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment/inspection team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible C/P/P/O in the preparation of a corrective action plan.
Root Cause	Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.
Spall	A chip or fragment from a brittle material.
Terminus	A single fiber optic termination.


11.0 Alternate Viewpoint

There were no alternate viewpoints during this assessment.

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12.0 References

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13.0 List of Acronyms

µm	Micron
AFM	Atomic Field Microscopy
ASTM	American Society for Testing and Materials
C	Celsius
C&T	Communications and Tracking
CEV	Crew Exploration Vehicle
Cl	Chlorine
CTE	Coefficient of Thermal Expansion
CVCM	Collected Volatile Condensable Materials
EDS	Energy Dispersive Spectroscopy
ESA	European Space Agency
GSFC	Goddard Space Flight Center
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LaRC	Langley Research Center
mm	millimeter
Na	Sodium
Cl	Chloride
NASA	National Aeronautics and Space Administration
NDE	NESC Discipline Expert
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
SEM	Scanning Electron Microscopy
Si	Silicon

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- A ITA/I Request Form (NESC-PR-003-FM-01)
- B NESC Technical Assessment Plan, “Failure Analysis Study and Long-Term Reliability of Optical Assemblies with End-face Damage Technical Assessment Plan”, Document number PL-05-18, (6/17/05).

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Appendix A. NESC Request Form



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NASA Engineering and Safety Center Request Form		
Submit this ITA/I Request, with associated artifacts attached, to: nrbexecsec@nasa.gov , or to NRB Executive Secretary, M/S 105, NASA Langley Research Center, Hampton, VA 23681		
Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt		
Received (mm/dd/yyyy h:mm am/pm) 6/17/2005 12:00 AM	Status: New	Reference #: 05-036-E
Initiator Name: William Panter	E-mail: william.c.panter@nasa.gov	Center: JSC
Phone: (281)-792-5579, Ext. _____	Mail Stop:	
Short Title: International Space Station Fiber Optic Workmanship		
Description: This is multi-faceted request to NESC for determining related to fiber optic workmanship: is there knowledge, is there value in testing and would NESC be willing to do the testing?. There is a lack of data related to fiber optic workmanship. It is regarding defining a fiber-optic defect analysis which would find and/or create various types of chips, spalls, scratches, etc and place the fiber in a temperature cycle chamber, and other, and document deterioration. GSFC is interested and have the fiber expertise to do credible job. There is also discussion about supporting a repair kit made up of completed cables with terminations on both ends. That would require the crew to depin both ends of the cable and repin with a replacement fiber length, maybe a little longer than the original. Program system managers are recommending, based on the crew inputs, waiting until a cable fails then having the ground build the entire cable which will be flown up and laid over the offending cable. The crew would only have to remove and replace connectors, making the task easier. But in some cases a failed single fiber may be buried in a complex harness that will require several connectors to replace one bad fiber without depinning. At this time there is a recommendation that the ground team build up the correct fiber replacement with the right terminations on both ends and then fly it up with specific work instructions. There is a differing opinion from the C&T recommendation that the crew should depin the defective single fiber and repin the new fiber into the existing on-orbit connectors. There is risk with this approach and it requires crew that is tool smart.		
Source (e.g. email, phone call, posted on web): email		
Type of Request: Assessment		
Proposed Need Date:		
Date forwarded to Systems Engineering Office (SEO): (mm/dd/yyyy h:mm am/pm):		
Section 2: Systems Engineering Office Screening		
Section 2.1 Potential ITA/I Identification		
Received by SEO: (mm/dd/yyyy h:mm am/pm): 6/16/2005 12:00 AM		
Potential ITA/I candidate? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No		
Assigned Initial Evaluator (IE): Dave Hamilton to lead		
Date assigned (mm/dd/yyyy):		
Due date for ITA/I Screening (mm/dd/yyyy):		
Section 2.2 Non-ITA/I Action		
Requires additional NESC action (non-ITA/I)? <input type="checkbox"/> Yes <input type="checkbox"/> No		
If yes:		
Description of action:		
Actionee:		
Is follow-up required? <input type="checkbox"/> Yes <input type="checkbox"/> No If yes: Due Date: TBD		



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Follow-up status/date:	
If no:	
NESC Director Concurrence (signature):	
Request closure date:	
Section 3: Initial Evaluation	
Received by IE: (mm/dd/yyyy h:mm am/pm):	
Screening complete date:	
Valid ITA/I candidate? <input type="checkbox"/> Yes <input type="checkbox"/> No	
Initial Evaluation Report #: NESC-PN-	
Target NRB Review Date:	
Section 4: NRB Review and Disposition of NCE Response Report	
ITA/I Approved: <input type="checkbox"/> Yes <input type="checkbox"/> No	Date Approved: Priority: - Select -
ITA/I Lead: , Phone () - , x	
Section 5: ITA/I Lead Planning, Conduct, and Reporting	
Plan Development Start Date:	
ITA/I Plan # NESC-PL-	
Plan Approval Date:	
ITA/I Start Date	Planned: Actual:
ITA/I Completed Date:	
ITA/I Final Report #: NESC-PN-	
ITA/I Briefing Package #: NESC-PN-	
Follow-up Required? <input type="checkbox"/> Yes <input type="checkbox"/> No	
Section 6: Follow-up	
Date Findings Briefed to Customer:	
Follow-up Accepted: <input type="checkbox"/> Yes <input type="checkbox"/> No	
Follow-up Completed Date:	
Follow-up Report #: NESC-RP-	
Section 7: Disposition and Notification	
Notification type: - Select -	Details:
Date of Notification:	
Final Disposition: - Select -	
Rationale for Disposition:	
Close Out Review Date:	


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Form Approval and Document Revision History


Approved: _____ <small>NESC Director</small>	_____ <small>Date</small>
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Principal Engineers Office	29 Jan 04

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**Appendix B. NESC Technical Assessment Plan, “Failure Analysis Study and
Long-Term Reliability of Optical Assemblies with End-face Damage
Technical Assessment Plan”, Document Number PL-05-18, (6/17/05)**

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	NASA Engineering and Safety Center Technical Assessment Plan	Document #: PL-05-18	Version: 1.0
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1.0 Identification

ITA/I #: 05-036-E	
Initiator Name: William Panter	Initiator Contact Info: (281) 792-5579
Short Title: International Space Station (ISS) Fiber Optic Workmanship	
Date Received: 6/07/2005	Date ITA/I Initiated: 6/17/05
Description: Determine the root cause of the damage (including deep cracks and chip outs) and the aging of the cable transmission at the ends of supplied fiber optic cables observed by the ISS. Study new types of fiber and cabling methods that will be replacing the ones in present use, so that their reliability can be estimated.	
Initial Evaluator Assigned: Robert A. Kichak	Initial Evaluator Contact Info: Robert.A.Kichak@nasa.gov (301) 286-1199
Lead Assigned: Robert A. Kichak	Lead Contact Info: Robert.A.Kichak@nasa.gov (301) 286-1199


Node 2 was manufactured by the European Space Agency (ESA)/Alenia and accepted by NASA for integration into the ISS. During integration testing at the Kennedy Space Center (KSC), two cables were determined to be too long based on loss data. Replacements were fabricated and inserted into the Node harnesses. KSC then carried out a pre-mate inspection (at 200X), and determined that 58 of 60 termini required cleaning and that four termini were defective. The defects included one spall, two cracked termini and one unpolished termini. Note that neither the integration contractor (Alenia) nor the manufacturer of the fiber cables (OHB, in Germany) reported the damaged end faces on the optical fiber termini.


From the damage reported by KSC for the Node 2 fiber, there was concern about the condition of Node 3 fiber (which was still at Alenia and not yet integrated in the Node). An inspection team traveled to Alenia in April 2005 and inspected and photographed (at 200X/400X) all the Node 3 fiber cables; 326 termini were inspected and only 9 were acceptable. The Node 3 summary after inspection includes:

- 20 were cracked;
- 20 had spalls, pits or chips;
- 39 were badly scratched; and
- 10 had surface contamination that cleaning could not remove.

It was recommended that a total of 89 termini be repolished or replaced. The inspection found a defect rate of $89/326 = 27$ percent.

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Currently, there is no understanding of the cause of this damage, and this indicates further manufacturing. It is imperative that the following questions/concerns be answered:


1. Was the damage caused by thermal stresses due to the high curing temperature (200°C) used for the epoxy, which is extremely high in comparison to NASA GSFC common practices (typically ~100°C)? The stresses built into the fiber in the termini by the high curing temperature will induce large stresses. These may result in faster crack growth.
2. Did the damage happen during the final stages of polishing the termini, but was missed since the manufacturer performed only a 50X inspection after polishing?
3. Was the damage caused by an incomplete polishing process that left latent defects in the glass? If so, then cracks and pits would develop as the assemblies were pending.
4. Was the damage caused by the integration contractor's mishandling, or failure to adequately clean, these cables prior to integration? (Note that Node 2 was integrated before damage was searched for, but Node 3 cables were still sealed in their shipping packages as received from OHB. This suggests that, although Alenia was pre-mate-inspecting at only 10X (which is not sufficiently perceptive of damage), they did not damage any of the cables during installation).
5. Was the damage initiated by grinding material that became embedded into the relatively soft epoxy and/or the polyimide coating, and then released later to contaminate the end faces? This embedding would set up a potential damage mechanism that would become active during integration.
6. There are no industry studies that were found to analyze the effects of cracks, spalls, and deep gouges on the long-term reliability of the fiber cables. The ESA's position for the hardware that they delivered to NASA is: if the system margin is acceptable and each cable length meets the insertion loss criteria, then the fiber is compliant. Per ESA quote:


"The visual condition of the termini is not important because the signal level meets requirements."

Therefore, one of the major purposes of this study is to generate rigorous data that shows the effects of end-face surface damages of the kind observed in these specimens on the long-term system reliability.

It is possible that either one or all of the above damaging events happened, which resulted in the damaged termini. It's also possible that some other aspect of the present production methods is responsible for these damaged termini. In either case, making more cables without changing the

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processes would only produce cables that also have damaged termini. The only way to ensure undamaged termini is to establish the root cause(s) of the damage happening to these termini.

The results of that inspection convinced the ISS program that a repair of the damaged termini was required prior to the integration of the cables into Node 3. Alenia agreed to repair the cables and NASA agreed to supply new termini and fiber cable and one KSC technician.

2.0 Charter

The NASA Engineering and Safety Center (NESC) received a multi-faceted request to determine fiber optic workmanship. There is a lack of data related to fiber optic workmanship. A fiber-optic defect analysis needs to be defined which would find and/or create various types of chips, spalls, scratches, etc. and place the fiber in a temperature cycle chamber, for example, and then observe and document deterioration. Also discussed was a repair kit composed of completed cables with terminations on both ends that would require the crew to de-pin both ends of the cable and re-pin with a replacement fiber length, maybe a little longer than the original. Program system managers are recommending, based on the crew inputs, waiting until a cable fails then having the ground build the entire cable which will be flown up and laid over the offending cable. The crew would only have to remove and replace connectors, making the task easier. But in some cases a failed single fiber may be buried in a complex harness that will require several connectors to replace one bad fiber without de-pinning.


At this time, there is a recommendation that the ground team build up the correct fiber replacement with the right terminations on both ends and then fly it up with specific work instructions. There is a differing opinion from the C&T recommendation that the crew should de-pin the defective single fiber and re-pin the new fiber into the existing on-orbit connectors. There is risk with this approach and it requires a crew that is "tool smart".


3.0 Scope

The scope of this activity is limited to an assessment of the following objectives that were raised by the requestor:

1. To determine the root cause of the damage (including deep cracks and chip outs) observed by the ISS at the ends of fiber optic cables that were supplied to them. This will support re-designing the manufacturing processes so that future cables will be free of this damage. It will also allow the Goddard Space Flight Center (GSFC) team to make a number of specimens damaged in the same way as the presently supplied cables. From these specimens, GSFC can perform a statistical study of the aging of cables made in this way.

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2. To study the aging of the transmission of cables made like the ones supplied to ISS to establish their reliability = the probability that a cable will meet its specifications for the planned lifetime on ISS. This study will require more specimens than those that are currently available from the ISS. Therefore, Objective 1 above will guide GSFC in making the required number of appropriate specimens.
3. To study new types of fiber and cabling methods that will be replacing the ones in present use, so that their reliability can be estimated.


The ISS Program has accepted the cables supplied for Node 2, accepting the risk that the cracks in their termini may degrade transmission enough to damage communications before the planned end of the ISS mission. However, this risk has not been quantified and is unknown. Although several literature searches have been made, no studies have been located that allow an estimation of the degradation in transmission that can be expected for these damaged termini. One reason is that ISS requires a fiber optical cable that tolerates a uniquely wide range of temperatures (from $\pm 100^{\circ}\text{C}$). This requires the use of a polyimide buffer, rather than the acrylate in common use, and also requires radiation tolerance (this requires the use of a unique glass in the fiber). Both requirements move the “cracking proneness” of this fiber in this buffer outside the ranges of experience of commercial vendors. Their traditional methods no longer necessarily apply to the ISS cables. Work at GSFC has shown that the radiation-tolerant fiber is noticeably more fracture-prone than the fiber used in telecommunications. An estimation is needed on the degradation to be expected for ISS-style cables whose termini are damaged in the variety of ways observed in the cables that were supplied to the ISS.


Also, because of the systemic lack of industry cause/effect data on the long-term aging of surface defects, this study will examine new kinds of fiber which offers the potential for use in the Crew Exploration Vehicle. Several potential fibers should be evaluated for propagation of defects to aid future NASA programs in fiber selection, and to further our understanding of the importance of existing inspection criteria.

4.0 Disengagement Criteria

Based on completion of the review and determination as to whether the damage to the fiber optic cable ends have been adequately addressed or not, this assessment will be followed with a report provided in the NESC-specified standard to the Requester, the Program Office, the NESC, and to relevant Stakeholders. The report will contain any observations, findings, and recommendations from the investigation into the damage to the fiber optic cable ends.

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5.0 Team Listing

Last Name	First Name	Position/ Team Affiliation	Center/ Contractor	Office Number	Email Address
Kichak	Robert	Lead	NESC	(301) 286-1199	Robert.A.Kichak@nasa.gov
Leidecker	Henning	Principal Investigator	GSFC	(301) 286-9180	Henning.W.Leidecker@nasa.gov
Ott	Melanie	Principal Investigator	GSFC	(301) 286-0127	mott@pop300.gsfc.nasa.gov
Fullen	Pamela	Program Analyst	NESC, MTSO	(757) 864-4403	Pamela.B.Fullen@nasa.gov
Burgess	Linda	Scheduler	NESC, Swales Aerospace	(757) 864-9139	l.i.burgess@larc.nasa.gov
Moran	Erin	Technical Writer	NESC, Swales Aerospace	(757) 864-7513	e.moran@larc.nasa.gov

6.0 Facilities/Tools/Other Logistics

Work will be performed at the NASA GSFC Center. Outside contractor personnel will also be employed in this effort.


7.0 Activities/Work Breakdown Structure (WBS)


The following is a summary of the GSFC-proposed test plan:

7-1. Identification of root cause of end face damage.

- a. Secure samples of the termini for destructive testing.
- b. Perform Scanning Electron Microscopy (SEM) and Electron Dispersive X-ray (EDX) for identifying the root cause of damage and nature of polish, the radius of curvature of surface, and the elemental identification of debris.
- c. Perform Nomarski microscopy for identification of subsurface cracks, and a characterization of their depths.
- d. Perform materials analysis for determination of intrinsic stresses of the glass/coating/epoxy/ferrule combination.

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- e. Coefficient of Thermal Expansion (CTE) identification.
- f. Perform shear stress analysis and experimentally map the index profile of the optical fiber construction to check the computed stress distribution.

7-2. From the above analysis and conclusions, construct the root cause(s).

7-3. Build a set of specimens to use for reliability and harsh environmental testing.


- a. Identify environmental parameters such as vibration, thermal and highest relative humidity parameters based on the ISS specification.
- b. Secure and/or procure cable, termini and connectors for testing.
- c. Identify new candidate(s) as most likely replacement for future baselined type of optical fiber assembly of future missions, and procure examples of this (or these) cable(s).
- d. Using the same processes as identified through analysis, simulate procedure and damage conditions on several samples for accelerated aging testing.
- e. Perform the following:
 - Random vibration testing.
 - High relative humidity thermal cycling testing.
 - Vacuum ($\sim 10^{-7}$ torr) thermal cycling testing on constructed assembly samples while monitoring the transmission in-situ. Changes in the optical performance will indicate crack propagation.


7-4. Gather data analysis and conclusions performed and write a comprehensive report similar to reports found on the website <http://misspiggy.gsfc.nasa.gov/photonics/>.

8.0 Deliverables

NRB Plan Approval	August 4, 2005
Proceed with Assessment	August 2005 – July 2007
NRB Report	August 2007
NRB Report Approval	September 2007

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9.0 Schedule

See Appendix B for scheduled milestones.


10.0 Key Stakeholders


Mr. David W. Beverly, NASA JSC, is the key stakeholder. No official report will be released without first briefing the Program Office, and providing them a full opportunity to clarify or correct any observations and recommendations as a result of this ITA.

11.0 Constraints

- No studies have been found that could quantify the potential risk to damaged links in space flight. The risk is that one or more cracks will propagate over time, and that some will penetrate deeply enough to cause a damaging loss of transmission through the optical fiber link. Some of the transmission links in the case of Node 2 are for voice control and for instrument communications to the user console, and so the loss of transmission could be a safety issue. The rework of Node 2 was judged too costly to justify the mitigation of link loss risk. Node 3 is being reworked currently.
- The optical fiber itself, although unique in its construction since it is designed to meet needs of space flight, has already been used by several other DoD and NASA programs and will likely continue to be used, likely with changes to the coating materials. The fiber is “graded index” for high data rate communications. This is achieved using germanium doping of the silica glass. Also, conventional dopants¹ have been removed since they could cause a radiation susceptibility of the fiber; however, this is known by us to decrease the fracture toughness, and to increase the crack growth rate under stress. Therefore, key parameters need to be determined, and then relate these parameters to cracking during termination and polishing, and to later crack growth. Working with this type of high transmission multi-mode radiation-resistant fiber is not trivial; there may not be a single cause of the present problems, such as workmanship issues (alone) or inspection noncompliance issues (alone). Understanding the stresses imposed on the fiber by the construction, and understanding what parts of the termination procedure affect the long-term reliability of the assemblies, are key to choosing the best methods for future applications.

¹ A small quantity of a substance, such as phosphorus, added to another substance, such as a semiconductor, to alter the latter's properties.

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3. In the future, different cabling jacketing configurations will be used, as well as different coating materials, but the optical fiber itself is likely to remain unchanged, and therefore is of special to future programs.

12.0 Resources Estimate

See Appendix A.

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Appendix A. Resource Estimate

ITAI #:	05-036-E	
Short Title of ITAI/:	ISS Space Station Fiber Optic Workmanship	
	FTE	\$K
Labor (Fully Loaded)		
Civil Servants	0.39	\$ 84.8
Procurements	0.00	\$ 360.0
Contracts		\$ 160.0
Grants		\$ -
Facilities		\$ 75.0
Other Govt Agency		\$ -
Other Direct Costs		\$ 125.0
Consultants		\$ -
CS Travel		\$ -
Service Pools		\$ -
Fabrication		\$ -
Test		\$ -
Wind Tunnel		\$ -
Other		\$ -
Total		\$ 444.8
Contingency Reserve		\$ 44.5
Total Estimated Funds Required		\$ 489.3

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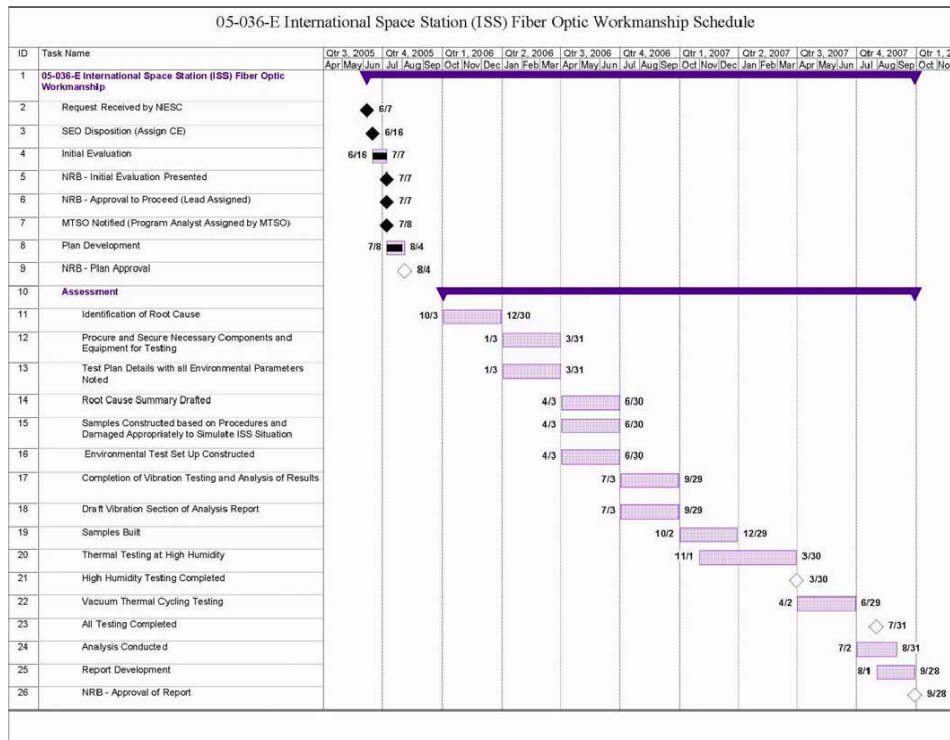
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Appendix B. Schedule



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Plan Approval and Document Revision History

Approved:	_____ Original signed on file NESC Director	_____ 8-28-05 Date
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Plan Version	Description of Revision	Office of Author	Effective Date
1.0	Initial Release	NESC Discipline Expert Office	8-28-05

NESC Request No. 05-036-E

	NASA Engineering and Safety Center Report	Document #:	Version:
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Approved: _____	Original signed on file NESC Director	11-20-06 Date
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Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	NESC Principal Engineer's Office, GSFC	11-20-06

REPORT DOCUMENTATION PAGE

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				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
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14. ABSTRACT In June 2005, the NESC received a multi-faceted request to determine the long term reliability of fiber optic termini on the ISS that exhibited flaws not manufactured to best workmanship practices. There was a lack of data related to fiber optic workmanship as it affects the long term reliability of optical fiber assemblies in a harsh environment. A fiber optic defect analysis was requested which would find and/or create various types of chips, spalls, scratches, etc., that were identified by the ISS personnel. Once the defects and causes were identified the next step would be to perform long term reliability testing of similar assemblies with similar defects. The goal of the defect analysis would be for the defects to be observed and documented for deterioration of fiber optic performance. Though this report mostly discusses what has been determined as evidence of poor manufacturing processes, it also concludes the majority of the damage could have been avoided with a rigorous process in place.					
15. SUBJECT TERMS CTE, ISS, NESC, end-faces, termini, EDS, SEM, optical microscopy, confocal microscopy, (C&T)					
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UU	UU	UU	UU	117	19b. TELEPHONE NUMBER (Include area code) (301) 621-0390