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Gravity Probe B Relativity Mission

Closure of Probe Contamination Discrepancy Reports

S0582 Rev. –

September 28, 2001

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ITAR Assessment Performed
ITAR Control Req'd? Yes ☐ No ☒
Date

Memorandum

To: B. Muhlfelder, R. Brumley, E. Ingram, D. Ross

From:: M. Keiser

Subject: Closure of Probe Contamination Discrepancy Reports

Date: September 28, 2001

There were three discrepancy reports generated after Payload Test I related to particulate contamination in the Science Mission Probe. The numbers and titles of these discrepancy reports are as follows:

Number	Title
299	Contamination on inside of Window #4
310	Particulate Contamination on Inside of Windows #3 and #2
311	Particulate Contamination on Inside of Exhaust Vatterfly Valves

For these discrepancy reports, some of the contamination was due to rubbing of clean wipes over sharp edges, but the variety of the particles indicated that it was not due to any one event. Appendix A discusses this particulate contamination in more detail.

To close out these discrepancy reports, it is necessary to demonstrate either
(1) that the cause of the problem has been resolved and it is unlikely to occur again, or
(2) that if it does occur again, there will be very little impact on the operation and science data.

These discrepancy reports all are concerned with contamination that was observed on the windows, on the interior of the probe near the top hat, or near the spin-up exhaust valves.

This contamination, by itself, is not a concern. It would only be a concern if the contamination found its way into the interior of the gyroscopes or onto the roof prism of the image divider assembly in the telescope. Both of these possibilities are very unlikely. The image divider assembly is completely sealed except for a small hole that allows it to be evacuated. Particulate contamination would have to find its way through this hole and then land on the roof prism. Similarly, for a particle to enter the gyroscope, it would have to migrate through the entrance to the cylindrical hole in the quartz block and into the gap between the gyroscope rotor and housing. The experience at Gravity Probe B is that the greatest risk of contamination is during assembly. After the parts have been assembled and tested, it is unlikely that contamination will occur.

The results of Payload Test I and Payload Test II indicate that the observed contamination had no observable effect on the performance of the gyroscope or telescope. In both of these tests, the gyroscopes and the telescope were tested and found to perform satisfactorily indicating that they are free of contamination. As an added precaution, procedures have been developed to try to maintain all gas flow away from the gyroscopes. Furthermore, a close examination of the contamination (see Appendix A) indicates that the contamination was considerably less closer to the Science Instrument Assembly (SIA), which indicates that the migration of the contamination was limited.

One other concern is that a future occurrence of particulate contamination on the windows might impact the performance of the telescope. Obscuration of the windows reduces the light intensity at the photodiodes and will lead to a slight degradation of the telescope performance. To cause this level of obscuration, significantly greater contamination levels than anything so far observed would have to occur. The GP-B Spacecraft Contamination Control Plan [8] (p.9) specifies the external surface cleanliness requirement to be 2.5% BOL (beginning of life).

If additional contamination on the windows or probe false walls does occur in the future, it is very unlikely to have a significant impact on the operation of the gyroscopes or the telescope or on the total light transmitted through the windows. In addition, at least some of the contamination was due to the cleaning of the probe surfaces during manufacture of the probe. Since these surfaces will never be cleaned again, the contamination is unlikely to occur again. For these reasons, I recommend that these discrepancy reports be closed.

Appendix A
Investigation of Particulate Contamination
in the Gravity Probe B Low Temperature Probe C

I. Introduction –

History and Observation of Particulate Contamination

In the process of removing the windows in Probe C as part of the probe redesign, reflected light from the surface of the windows was taken as evidence of particulate contamination. The observation of particulate contamination is a concern because of the potential impacts on either the telescope or gyroscope performance in the Gravity Probe B satellite. The preliminary evidence for particulate contamination was the light that was reflected from the surfaces of the windows.

Because of these observations, the Gravity Probe B Vacuum and Cleanliness Committee was asked to review the evidence for particulate contamination and examine any potential impacts on the overall performance of the payload of the GP-B satellite. Particle counts were made on the removable surfaces, tape tests were performed on some of the surfaces that were not removable, the front surface of the telescope was examined with a theodolite, and the compositions of some of the particles removed from the probe were determined with FIR analysis [1], [2]. The existing requirements were reviewed, and the potential impact on the performance of the telescope and the gyroscopes was examined. This report contains a summary of the results of this investigation.

Requirements

The cleanliness requirements for Probe C are specified in GP-B document P0059, Probe C Contamination Control Plan1 [6]. In this plan, the probe is divided in various regions with cleanliness requirements for each region. The most critical region, Region I, is the interior of the gyroscope. The region which is affected by these observations of particulate contamination is region V, which includes the interior of the probe from the quartz block mounting flange to the top of the probe. Within this region the requirements specify

- the initial cleanliness level of the surfaces (level 100),
- the environment in which the probe must be maintained whenever it is open,
- design considerations to reduce the likelihood of particulate contamination, and
- special procedures to be used for the evacuation and venting of the probe .

Within this region the reasons for concern about particulate contamination is that it communicates directly with other regions of the probe and that the telescope image divider assembly is within this region.

Previous Observations of Particle Contamination

Particulate contamination was previously observed on the flight telescope when it was removed from the test probe before integration with the quartz block [4],[5]. Although it was originally thought that source of the particulate contamination was the test probe or the ground support equipment, investigation of the composition of the particulate contamination failed to support this hypothesis. An alternate explanation for the observed particulate contamination was that the integration of the flight telescope was performed in a class 1000 clean room instead of the class 10 clean room and that during the integration there was no use of the ion sprayer to reduce the charging of the quartz block. If the quartz block becomes charged, dielectric particles with be attracted to it and adhere. Before integration of the telescope with the quartz block, the exterior surfaces and the accessible interior surfaces were cleaned. In the first payload integration test there was no evidence of degradation of the telescope performance due to particulate contamination.

II. Potential Impact of Particle Contamination

Magnetic Contamination

The residual magnetic field within the probe at the location of each of the gyroscopes when the gyroscopes are cooled through their superconducting transition temperature determines the magnitude and the distribution of the trapped magnetic flux in the gyroscope. The requirements on the trapped magnetic flux within the gyroscope are that the uniform field equivalent be less than 10 microgauss. Therefore, the residual field within the probe be less than 10 microgauss . The residual magnetic field could be degraded if magnetized particles migrated to a region close to the gyroscope. The allowable residual magnetic field is specified in the Gravity Probe B Magnetic Control Plan, P0057 [7]. The impacts of any potential magnetic contamination are examined in the attached memorandum by J. Mester [3].

Gyroscope

The gap between the surface of the rotor and the electrodes on the interior of the gyroscope housing is 31 microns, and some features of the housing come as close as 25 microns to the surface of the rotor. Because of these tight tolerances, particulate contamination may either prevent the gyroscope from levitating, intensify the very large electric fields necessary to levitate the gyroscope during ground testing, or act as a source of drag or torque on the spinning gyroscope. Tests designed to determine the presence of particles within the gyroscope consist of levitating the gyroscope and determining the freedom of motion of the gyroscope within the housing, and measuring the gyroscope spin-down rate at slow spin speeds. These tests are good indicators of freedom from particulate contamination. Once a gyroscope in operating well, experience has shown that it is not likely to become contaminated, if care is used in the procedures and handling of the gyroscope.

Telescope

The telescope is sensitive to particulate contamination because the light from the telescope is focused to a spot at each of the two image diving roof prisms which divide the light for the two perpendicular axes. This spot is the most sensitive region of the telescope. Additional areas which may be of some concern but are less sensitive include the light paths in the Image Dividing Assembly and the Detector Package Assembly.

III. Observed Contamination

Telescope

Some top surfaces of the telescope and some nearby parts of the probe were examined using a theodolite. The theodolite has a field of view that allows an examination of several square inches of the telescope surface. It also has a magnification and short focal length that permits an identification of the size and location of particles.

One important result of this examination is that many of the features, which were previously identified as particles, are actually "watermarks". The larger features were streaks of these marks. These marks are normally visible only on glass parts with thin transparent coatings under some lighting conditions. They are difficult to remove but should have negligible effect on the performance of the telescope.

For those surfaces examined with the theodolite, the estimated number particles of various size ranges are listed in the table below:

Particle Size (mils)	Particle Size (microns)	Number/in^2	Number/ft^2
< 1	25	10-50	1440-7200
1-3	25-76	<10	1440
>3	76	0	0

Although it was impossible to evaluate the entire surface, the distribution of particles seemed to be even and random throughout. It was impossible to determine the composition of the particles. A nearby section of the inner probe wall appeared to have a similar density and distribution of particles.

Particle Counts on Windows

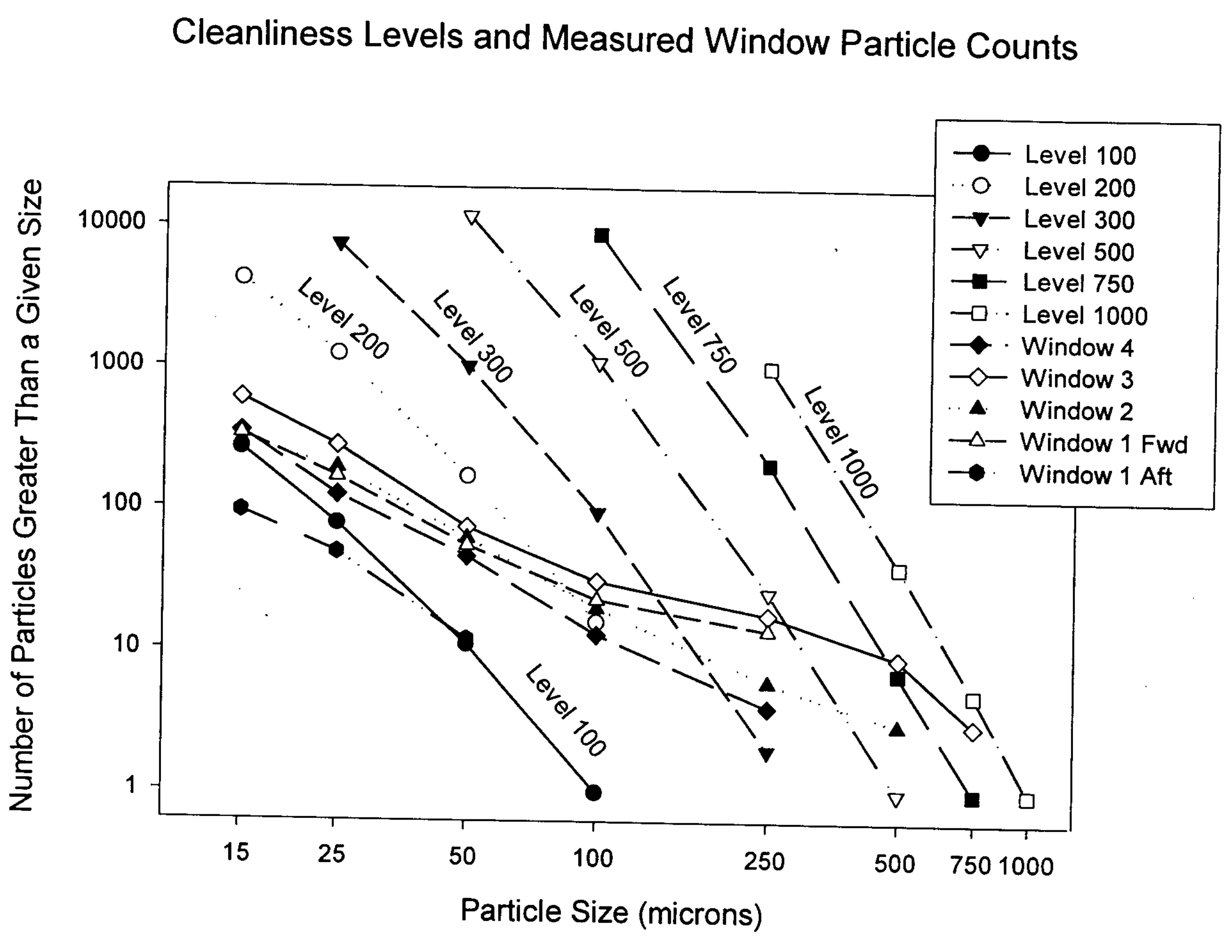
The tables below summarize the size and number of particles per square foot that were collected and counted from each of the four windows.

Size (microns)	Window 4 & Cross Flange	Window 3 (both sides)	Window 2 (both sides)	Window 1	
				Forward	Aft
6 to 15	2573	1417	1161	899	311
16 to 25	221	323	105	164	46
26 to 50	78	203	130	112	37
51 to 100	33	43	42	32	12
101 to 250	9	13	14	9	0
251 to 500	4	9	3	14	0
501 to 750	0	6	3	0	0
750 to 1000	0	3	0	0	0
> 1000	0	0	0	0	0

Although the numbers in the above table are given in terms of particles per square foot the actual sample area varied considerably. For window 4 and the cross flange the sample area was 522 in^2, for windows 2 and 3 the sample area was 100 in^2, and both the forward and aft areas of window 1 the sample area was 50 in^2. It is encouraging to note that the cleanest of these surfaces was window 1 which is the surface closest to the Science Instrument Assemble (SIA).

These particle counts may be compared with the particle counts specified for different cleanliness levels by MIL STD 1246 C. Figure 1 shows the distribution of the particles on each of the windows compared to the specifications for each of the levels. It is interesting to note that the distribution of the particles on the windows is has a small number of large particles. Except for this small number of large particles the surface cleanliness levels meet level 200 standard. Also note that the surface closest to the probe meets the level 100 standard.

Figure 1. Cleanliness Levels and Measured Window Particle Counts.



In addition to the particle counts on the windows, the number of particles on the false walls were measured and found to have similar density.

Identification of Composition of Particles

The composition of the particles is discussed in references [1] and [2]. The magnetic properties of the particles are discussed in reference [3]. Some of the particles are consistent with particles being cleaned. However, reference [1] concludes that "Due to the varied types of debris collected and identified, it is felt their source of orgin into the probe may not have been a result of one single event."

IV. Conclusions

Magnetic Contamination

Based on the measured trapped flux in Payload Test II, the residual magnetic field meets specifications. There is no evidence of additional magnetic particles. In addition, it is unlikely that any magnetic particles would migrate to a position where they would significantly increase the residual magnetic field in the any of the four gyroscopes. J. Mester's memorandum on the "Magnetics Review of the Probe C Particle Debris" [3] is attached and concludes that "The magnetics risk posed by the Probe C debris particles is minimal."

Telescope Contamination

Based on the telescope performance during Payload Test II, the telescope meets all requirements and there is no evidence of telescope contamination. It is very unlikely that any contamination will migrate to a position where it will interfere with the optical path of the telescope.

Gyroscope Contamination

Based on the measured gyroscope performance during Payload Test II, the gyroscopes meet all requirements and there is no evidence of particulate contamination. It is unlikely that any particle contamination near the top hat section of the probe will migrate to the gyroscopes. Procedures have been developed to minimize the risk to the gyroscopes.

References:

[1] P. Sadler-Horn, A. R. Cooper, A. Heynen, Identification of Particulate Contamination located in Probe C Top Hat and CNT Region, Lockheed Martin Engineering Memorandum SMS 297, 22 June 2000. (Attached)

[2] P. Sadler-Horn, A. R. Cooper, Memorandum: Preliminary Material Identification on Microscopic Debris from Gravity Probe-B Hardware. May 25, 2000 (Attached)

[3] J. Mester, Magnetics Review of Probe C Particle Debris, Memorandum, May 26, 2000. (Attached).

[4] K. Gibb, A. Joshi, Laboratory Report - Analysis of Particles on Filter Paper from Gravity Probe B Telescope, Lockheed Martin, Material and Process Control Laboratories, Lab Request/Job AF1694, MLP File 519377, 1 July 1998. (Gravity Probe B Document S0578)

[5] D. Gill, Identification of Particulates Removed From Flight Telescope #3, GP-B Document S0328, May 13, 1998.

[6] Probe C Contamination Control Plan, GP-B Document P0059.

[7] GP-B Magnetic Control Plan, GP-B Document P0057.

[8] Gravity Probe B Relativity Mission Spacecraft Contamination Control Plan, SCSE-19, LMMS/P086822, 25 July 1997.

Memorandum

To: S. Buchman, M. Keiser, J. Lockhart, B. Muhlfelder, D. Ross, E. Ingraham

From: J. Mester,

Subject: **Magnetics Review of Probe C Particle Debris**

Date: May 26, 2000

Magnetics Review of Probe C Particle Debris

Scope

This document reviews risk of magnetic contamination based on particle debris analysis conducted on particles collected from Probe C windows 2, 3, and 4.
A previous document, S0416, examined analysis of procedures followed to minimize risk of magnetic contamination during probe C Repair.

Debris Analysis

In all but two specific cases, the analyzed debris particles fall into one of two categories: (1) nominally non-magnetic materials, such as cellulose, glass fibers, aluminum and noble metals, and various organic materials, and (2) small (micron sized) possible magnetic materials such as stainless steel. Magnetic fields generated form debris particles form either of these categories are negligible at distances greater than a few or a few tens of microns. Therefore particles from these categories present no magnetic risk.

The two specific debris examples not falling into these categories were found on window 4. They are, particle ID N, a metallic piece approximately $190\mu \times 80\mu \times 10\mu$, and particle ID 3, an approximately 1mm long metallic chip described as very thin possibly a plating remnant. Analysis conducted at Lockheed under the direction of Pam Sadler (RT-IR and Scanning electron microscopy) indicates that piece ID N is composed of elemental nickel and ID 3 is composed of nickel, phosphorus, and aluminum oxide.

Magnetics Analysis

As a worst case we assume that particles ID N and ID 3 are made of pure elemental nickel magnetized to nickel's saturation magnetization, $M_s = 512$ emu/cm^3 at 0 K[1]. As a comparison, $M_s = 484$ emu/cm^3 at room temperature[1]. Therefore the low temperature magnetic moment of ID N, $m_N = 7.7\times10^{-5}$ emu, and of ID 3, $m_3 = 5.4\times10^{-4}$ emu, where we have estimated the width and thickness of ID 3 to be 100μ and 10μ respectively. At the level of the cryoperm shield, station 199, the ambient field requirement is • 1 Gauss and therefore particles with magnetic moments in the range of m_N or m_3 pose no risk unless they can migrate close to the gyros.

To determine how close such particles would need to migrate to pose risk we take, again as a worst case, that the field generated in free space by particle ID 3, a distance d cm away equals $5.4 \times 10^{-4} / d^3$. Such a particle would then need to approach a gyro within 5.5 cm to produce a field in free space of 3×10^{-6} Gauss. However due the presence of superconducting shielding the fall off of field from the dipole will be faster. In particular if a particle were to migrate during launch vibration (after the probe is cryogenic) the local shield will attenuate the field by at least a factor of 100. Thus particles the size encountered in the debris analysis with worst case magnetic moments would have to migrate inside the local superconducting shield to pose a magnetics risk. Such a combination of migration and worst case magnetization is highly unlikely.

Conclusion:

The magnetics risk posed by Probe C debris particles is minimal.

Reference:

1. *American Institute of Physics Handbook*, Ed. by D. Gray, McGraw-Hill, 1957.

LOCKHEED MARTIN

Space Systems Company
Advanced Technology Center

Memorandum

TO: J. Vanden Beukel

FROM: P. Sadler-Hom, A. R. Cooper

DATE: May 25, 2000

SUBJECT: Preliminary Material Identification on Microscopic Debris from Gravity Probe-B Hardware

The Materials and Structures Group, O/L9-21, is performing an investigation on microscopic debris collected from Composite Nec-Tube (CNT) optical windows and CNT internal surfaces. Analysis is being conducted using two analytical techniques. Fourier Transform-Infrared Spectroscopy (FTIR) is used to characterize organic compounds and Scanning Electron Microscopy (SEM) is used to determine elemental composition (excluding hydrogen, helium, lithium, and beryllium elements). SEM is most helpful in characterization of metals, ceramics, and dielectric materials.

Debris has been collected primarily from three areas in the CNT portion of the probe—the four optical windows, the vent valves, and tape-lifts from the CNT internal surface walls. This preliminary report details the chemical evaluation of debris removed from windows #2, #3, and #4 (PTR-017). This debris was performed in a cleanroom using a freon sprayer. For each window, debris was collected from both sides of the window onto a single Millipore filter. Window #4 showed the most debris, Window #3 showed comparatively less, and Window #2 had the least amount of debris. Particle counting of this debris was performed after removal of "large" representative debris for chemical analysis. Visual observation of the debris collected from these three windows showed similar-looking materials on all three windows. These materials included both particle- and fiber-shaped debris. Descriptions of these materials are listed below:

Opaque, white particles
Opaque, white particles containing dark-colored flakes
Black particles
Yellow, metallic-looking particles
Flat, shiny metallic-looking flakes (resembled molten metal splatter)
Orange particles
Straight, clear fibers
Curly, clear fibers

Curly, dark-blue, grey fibers

A majority of the particles that have been evaluated are organic—polyamide/polyimide; natural rubber; polyurethane; polyester (for example the curly, clear fiber); fluorocarbon; and cellulose-type materials.

The straight, clear fiber was a glass containing oxygen, silicon, aluminum, calcium, and small amounts of magnesium and sodium. These are probably in the form of a complex oxide, which is typical for a glass. Representative cured CNT material was examined for comparison and it was found that the fibrous support material contained two different diameter fibers, neither of which was the same as that of the unknown fiber. The chemistry of the two CNT fibers varied only a little, however, both appeared to contain alumina and silica. The chemistry of the unknown straight, clear fiber was comparable to that of the smaller diameter fiber in the cured CNT composite, but variation in magnesium and sodium was evident. Additional evidence is needed to indicate that this fiber was from the CNT.

There were several metallic particles identified, including aluminum; nickel; nickel and phosphorus (possibly from an electroless nickel-plating operation); and a piece containing gold, rhodium, and copper (possibly a layered piece from an inside wall of the probe). Other metallic flakes that were detected on organic constituents were: gold, silver, bronze (copper and tin), barium titanate—a dielectric material (barium, titanium, and oxygen), and stainless steel particles (iron, chromium and titanium—not a common alloy at all). Nickel-based materials could be magnetic and it was suggested to John Mester (Stanford physicist working with the GP-B project) that these particles be tested to evaluate their magnetic behavior.

Chemical identification of commonly used cleanroom materials is being performed to provide direct chemical composition comparison to the unknown debris. Evaluation is not completed to allow for direct comparison at this time.

Visual examination of the three tape-lift samples received in the laboratory on Wednesday indicates there are similar looking microscopic particulates to those found on the optical windows, but there was an abundance of yellow-colored metal-like particles on all of the tape-lift samples. SEM will be used to determine if these particles are metallic. There is a strong indication that these particles are gold and were removed from the walls during sampling. Tape-lift sampling is a more aggressive technique than freon spraying.

This preliminary information leads one to believe that since several different types of debris have been identified, their source of origin into the probe may not have been a result of one single event.

Teamwork & Innovation
RELATIVITY MISSION
SPACE VEHICLE

GRAVITY PROBE B SPACE VEHICLE DEVELOPMENT

ENGINEERING MEMORANDUM

TITLE:	EM NO. SMS 297
Identification of Particulate Contamination located in Probe C Top Hat & CNT Region	DATE: 22 June 2000
	REVISED:

AUTHORS:	PHONE:	ORGN:	APPROVALS:
P. Sadler-Hom, A. R. Cooper, A. Heynen	(650) 424 - 2236	L9-21	H. J. Dougherty J. Vanden Beukel

Background:

The Gravity Probe-B telescope was undergoing hardware maintenance when various types of debris were found in the Composite Nec-Tube (CNT) area, on four optical windows and around the vent valves. The debris was collected and brought to the Materials and Structures Group (O/L9-21) for chemical identification under PTR-017. Analysis of several commonly used clean-room materials was requested for comparative purposes.

Procedure:

Debris was removed by Stanford clean-room personnel using clean-room swabs or by tape-lift methods, except in the case of the optical windows. Each optical window was carefully removed and contaminant debris collected in a clean-room using a freon sprayer. For windows #2, #3, and #4, debris was collected from both sides of the window onto a single Millipore filter. Particle counting of this debris was performed after removal of "large" representative debris for chemical analysis. Conversely, debris removal was performed on window #1, where debris was removed and collected for each side. Particle counting was performed for each of these two samples collected but no further investigation occurred.

Two analytical techniques were used for material identification. Fourier Transform-Infrared Spectroscopy (FT-IR) was used to characterize organic compounds and the Energy Dispersive Spectroscopy (EDS) system on the JEOL Scanning Electron Microscopy (SEM) was used to determine elemental composition (excluding hydrogen, helium, lithium, and beryllium elements). EDS is most helpful in characterization of metals, ceramics, and dielectric materials. These are the only techniques available to us for these small sized particles.

Results and Discussion:

Results of the debris analyses are recorded in Table I. Discussion of the results will be broken down into sections, by area in which the debris was found—on the optical windows, along vent valves, or from tape-lift extractions along interior walls. Identification of the organic constituents was made solely from FT-IR analysis using a library search program at LMSSC, Sunnyvale Operations (O/EJ-50). In most cases, EDS was also performed to identify elements that were either present as trace elements in the organic and/or as separate contaminant debris attached to the organic.

Optical Windows #2, #3, and #4:

Photomicrographs showing the varied shape and morphology of typical debris found on the windows are shown in Figure 1. Visual examination showed that window #4 contained the most debris, window #3 showed comparatively less, and window #2 had the least amount of debris. Table 2 contains the final particle counts from each location within the Probe. The results were normalized from their total surface area to 1 square foot to allow relative comparisons to each other and to MIL-STD-1246 levels. Table 2 also contains a chart to graphically illustrate the relative contamination levels.

The debris collected from windows #2, #3, and #4 showed similar-looking materials on all three windows. These materials included both particle- and fiber-shaped debris. Descriptions of these materials are listed as follows:

Opaque, white particles
Opaque, white particles containing dark-colored flakes
Black particles
Yellow, metallic-looking particles
Flat, shiny metallic-looking flakes
Orange particles
Straight, clear fibers
Curly, clear fibers
Curly, dark-blue, grey fibers

The majority of the particles evaluated were organic and the remainder was metallic or ceramic material.

Those debris materials that were organic were identified as poly(amide-imide); polyamide; natural rubber; polyurethane; polyester; and cellulose-type materials. It should be stated that care must be exercised when comparing these materials to commonly used clean-room materials. However, there were comparable matches between certain debris and clean-room materials.

Several FT-IR spectra having file numbers of 258, 287, and 325 were identified as poly(amide-imide) and the super-imposed spectra are shown in Figure 2. FT-IR spectrum 258 was a large particle found on the squid area between FB3 and MSS3, spectrum 287 was particle B from window 3, and spectrum 325 was from tape-lift (TL)1, on grid G5. The three spectra were similar.

Three debris particles were identified as polyamide, or nylon-type, materials. These particles are: particle A (286), which was found on window 4; TL1 L5 (330); and the greenish colored particles on the probe exterior along the cross-flange (341). Figure 3 shows these three super-imposed spectra with the LM white clean-room tape (322) that was identified as nylon. While TL1 L5 particles found on the cross-flange are highly suspected to be the Duralon JM Type 11 nylon, it should not be interpreted that the other three nylon scans are this brand or type of nylon. It is not easy to distinguish between the various "types" of nylon by FTIR (for example, nylon 6, 66 or 11).

The clear, curly-shaped fiber F (292) was identified as a PET polyester and FT-IR spectra showed similarity of F to the spectra of Misc A (282) and Misc B (283) wiper fibers (also identified as PET). This comparison is shown in Figure 4. The F fiber could be from a PET polyester wiper but no definitive comparison could be made to determine that it was from the Stanford clean-room Contec-brand polyester wipers.

Fiber H (FT-IR file #293) and particles K (297) and L (298) were all identified as cellulose material. Debris H and L were located on window 2 and debris K on window 3. The FT-IR spectral lines of H, K, and L are very similar to that of Misc. E, a Texwipe, clean-room wiper (304) as shown in Figure 5. None of these are similar to the Millipore filter (294), which has cellulose nitrate peaks at 840, 1300, and 1665 cm^{-1} and an ester peak at 1750 cm^{-1}.

There were several metallic particles identified, including aluminum; gold; silver, nickel; nickel and phosphorus; and a piece containing gold, rhodium, and copper (possibly a layered piece from an inside wall of the probe).

The aluminum particle labeled 2 was very curved and resembled a machine turning as shown in the photomicrograph of Figure 6. EDS analysis indicated aluminum and oxygen were present, which is expected since aluminum metal oxidizes readily in air.

Particle 3 was the largest debris particle found and measured one mm in length as shown in the photomicrograph in Figure 7. It consisted of nickel and phosphorus (possibly from an electro-less nickel-plating operation) and the dark spot was rich in aluminum. There is some concern for the nickel-based materials found (particles 3 and N), since nickel can be ferromagnetic. Suggestion was made that the particles be tested to evaluate their magnetic behavior.

Other metallic flakes were detected that were adhered to various organic constituents. They include gold, silver, bronze (copper and tin), and barium titanate—a dielectric material made up of barium, titanium, and oxygen.

The natural rubber particle J had discrete micron-sized particles that contained iron, chromium, and titanium, which is not a common alloy. It could have been a result of a molten, metallic mixture formed during a solder operation.

The straight, clear fiber M (301) was identified as a glass, containing oxygen, silicon, aluminum, calcium, and small amounts of magnesium and sodium. These elements are probably in the form of a complex oxide, which is typical for a glass. Representative cured CNT material, which contains reinforcing glass fibers, was examined for comparison to these glassy fibers. It was found that the known CNT material contained two different diameter fibers, and their chemistry varied a little, but both contained alumina and silica. Their FT-IR spectra and that of fiber M are shown in Figure 8. The FT-IR results show the small (340) and large (338) diameter fibers differ from one another, but that fiber M is very similar to that of the small diameter fiber. Photomicrographs of these three fibers are shown in Figure 9 and relative fiber thickness measurements were made at 300X magnification. The larger diameter fiber in the CNT was 0.1560", fiber M was 0.1030" and the smaller diameter CNT fiber was 0.061". EDS elemental analysis is compared in Figure 10.

Debris from Vent Valve #1, #2, and #3:

Several vent valve 1A (V1A) particles (269, 277 and 275) were identified as cellulose material and the FT-IR spectra are compared in Figure 11. There are close comparisons of these three particle spectral lines and that of Misc E but not to the Millipore filter.

There were several organic debris particles found in the vent valves (V1A and V2A) and a tape-lift particle (TL1 G5) that could not be matched with known materials in the LMSSC, Sunnyvale Operations FT-IR search library. These spectra are compared in Figure 12 but there were no identical matches. There are comparable broad absorption peaks from 3100 to 3600 cm^{-1}, which are indicative of amine (N-H) or hydroxyl (O-H) organic groups.

An organic particle found on vent valve 2, V2D, contained PTFE, or Teflon, and had discrete metal particles of brass (copper and zinc) and of iron, chromium and nickel (stainless steel) embedded in it.

Particles in V3 (266) and the "blue-fibrous debris mass" removed from Station 200 below window 1 (313) were identified as epoxies. FT-IR comparison showed they were not identical to one another. However, each was then compared to the three known epoxies in the CNT area—binder in the CNT, blue death epoxy, and FM-73. V3 (266) had similar general characteristics of FM-73 as shown in Figure 13. The epoxy found at Station 200 compared very well to that of the CNT binder material as shown in Figure 14.

Several organic-containing particles analyzed in the collected vent valve debris had metallic particles on them, such as the four particles analyzed in V1A, two in V2C, V2D, and V3. One metallic particle (from V2C) was identified and it contained brass (copper and zinc) with spots of lead and cadmium on it and a photomicrograph is shown in Figure 15.

Tape-Lift Extractions:

Several organic materials were identified in the tape-lift particles examined. They include poly(amide-imide), resin, polyamide, PET polyester and polyethylene. Most of these have been discussed in earlier sections, with the exception of the organic resin in TL1, C10. The organic resin identified in TL1, C10 (329) was compared to the FT-IR spectrum of the "binder" of the CNT and it was not comparable.

The white piece from TL2, K14 (317) was identified as polyethylene. The presence of titanium found in the EDS was probably due to a TiO_2 colorant in the polyethylene, giving it the white color.

Metallic pieces of gold, silver, and copper were identified. In particular, the gold was probably due to the aggressive nature of the tape-lift extraction process, pulling off small pieces of gold material from the walls.

Summary:

The debris identified could be from common clean-room materials and from components within the telescope. Due to the varied types of debris collected and identified, it is felt their source of origin into the probe may not have been a result of one single event.

Table I. The following table lists chemical analyses on debris particulate removed from Windows #2, #3, and #4, Vent Valves #1, #2, and #3, some flight hardware and materials, and some common clean-room materials.

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
Debris from Windows #2, #3, and #4[1]:					
A	Opaque glob with metallic flakes	Window 4	Polyamide (286)	N/A	
B	Orange piece	Window 3	Poly(amide-imide) (287)	Matrix: C, O;. Bright spots: Ag	0EDK
C	Opaque glob	Window 2	Natural rubber (288)	C, O, Zn, S, Cl	0EDL
D	Black sticky residue	Window 3	Polyurethane (290)	Very high C, O, Cl, S, P	0EDM
F	Clear curly fiber	Window 3	Polyester—PET (292)	C, O	0EDO
G	Dark particle		No transmission in FTIR (not organic)	particle lost	
1	Clear curly fiber	--	N/A	C, O, F	0ECR
H	Metallic or blue fiber	Window 2	Cellulose/cotton (293)	C, O, Na, Si, S, Cl, K, Ca	0EDP
I	Shiny metallic piece 0.4mm wide x 1.6mm long	Window 3	N/A	Au, Rh, Cu	0EDT
2	Flat shiny metal particle (crumbly)	--	N/A	Al, O (maybe machining chip)	0ECS
J	Black particle with clear end	Window 2	Natural rubber (296)	Matrix: C, O, Al, Ca, Si, S, F, Zn, Cl, K; Micron-sized particles: 83w%Fe-13Cr-4Ti	0EDU-2, 0EDU-1
K	Flat piece	Window 3	Cellulose (297)	C, O	
L	Fibrous piece	Window 2	Cellulose (298)	C, O, S, P, Cl	

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
M (or 6)	Clear straight fiber (very brittle)	Window 4	Glass fiber (301)	(#6 for SEM) lot Si, O, Ca, Al	0EDA, 0EDB
N	Metallic piece	Window 4	N/A	Ni with Ni fibers	0EDC, 0EDD, 0EDE
3	1mm long metal piece	Window 4	N/A	Ni, P (dark spot was Ni, P, Al, O) 0ECT from one side, 0EFD from other side	0ECT(BSE); 2-0EFD(BSE &SEI)
4	Black particle	--	N/A	High Cl, C, O, P, S, Ca, Ni, Cu, Zn, some Ti & Al (bright spots same spectrum)	0ECU
5	Metallic/organic flake	--	N/A	C,O (matrix), Cu, Sn particles (bronze) with different Ca levels	0ECV
7	Shiny, light grey metallic flat particle	Window 3	N/A	Al with Au spots on it	0FAA
8	Yellow, metallic-looking pieces	Window 4	N/A	Ag	0FAB

Debris Removed Vent Valves #1, #2 and #3:					
V1 A small part	Particle on swab	Bend of V1 tube	Organic, no definite ID possible (271)	C, O, Mg, Al, Si, P, S, Cl (lots), K, Ca, Ti, Fe, Cu, Zn	
V1 A black part.	Black particle on swab	Bend of V1 tube	Cellulose (269)	C, O, Mg, Al, Si, S, P, K, Na, Ca, Ti, Fe, Cu	0FAC-1
V1 A brown fiber	Brown fiber on swab	Bend of V1 tube	Cellulose (277)	Fiber: C,O,Na,Cl,S,K,Si,Ca,Zn Fine debris: all of above but higher S, Na, O and Fe	0EFF
V1 A	Clear fiber debris	Bend of V1	Cellulose (275,276)	C, O, Si, S, Cl, Al, Ca, Cr, Fe, Cu	

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
clear fiber	removed from swab	tube			
V1 A swab fiber	Swab fibers removed from the V1A sampling swab	N/A	Polyester (279)	N/A	
V1 B	General wipe with swab	V1 inner wall (film)	(too small for handling)	N/A	
V2 A	Black particles	V2 tube wall	Organic, no definite ID possible (336,337)	No particles for analysis	
V2 B	Various particles	V2 tube wall	No particles found	No particles found	
V2 C elong part.	Dark elongated particle		N/A	C, O, K, Ca with particles of: Ni, Fe and Cl	
V2 C black part.	Black particle (very brittle)	V2 tube wall	N/A	C, O, Mg, Al, K, Fe, Zn and lots of: Si, S, Cl, Ca; Agglomerated granular appearance	0FAL
V2 C yellow part.	Yellow fibrous particle	V2 tube wall	N/A	Base material: Cu, Zn (brass) Bright regions: Pb, Cd	0FAK
V2 D	Various particles	V2 tube wall	Fluorocarbon "PTFE" (268)	Discrete metal particles embedded in C & F organic: Cu and Zn, Fe, Cr & Ni. Other elements in matrix: S, Si, some O	0EBT
V2 E	Swab of V2 wall, including reddish colored area	V2 wall	Particles too small for handling	N/A	
V3 valve body	Particles removed from bolt holes	Bolt Holes on V3 valve body	Epoxy (266)	3 types embedded particles: Au; Ba,Ti,O,& S elongated particle; & O,Si,Ca fibers:. Matrix: C,O,Ti, Zn, Si, Al, some N.	0EBR, 0EBS

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
O/Y Tape	Adhesive of orange/ yellow tape around sample holders	N/A	Silicone, polydimethylsiloxane, (274, 280)	N/A	
Debris Removed From Station 200 Below Window 1: (Blue fibrous mass with dark particles inside)					
--	Material holding fibers together	Station 200 below Win. 1	Epoxy (313)	C Spots on it contain Fe,Ni,Cr,Si,O	0EFE
--	2 crushed fibers	Station 200 below Win. 1	Polyester—PET (314)	C, O Bright spots: Ni, P, Rh	
Particle Evaluated January, 2000 (reports issued on 1/28/2000 and 2/03/2000):					
--	Light brown colored particle (about 0.010")	Top hat, removable, light shield	Natural rubber (no file #)	Organic, carbonaceous material with small metallic particles on it—Cu, Zn, Au, Ag	
Squid Area Debris					
--	1 Large orange piece with barrel shape	Squid area btw FB3 & MSS3 @ 1st inch of Ti	Poly(amide-imide) (257, 258)	C, O, spots contain K	

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
Debris from 3 Tape-Lifts (TL) on CNT walls[2]:					
Tape Lift Tape	3M 480 tape		Adhesive: Polyacrylate (326,331)	N/A	
TL1 brown	Small brown piece	TL1, G5	No definite ID (324, 328)	C, O	
TL1 brown	Sticky brown piece	TL1, G5	Poly(amide-imide) (325)	C, O, spotted with Al and Au flecks	
TL1 C10	Yellow particle	TL1, C10	Resin (329)	Polymer: C, O, Cl, Si, S, Cl, Zn Particles: Cu and Ag	
TL1 N11	Yellow particles	TL1, N11	N/A	Cu	
TL1 L5	Particle	TL1, L5	Polyamide (330)	C, O, Mg, Al, Si, S, Ca	
TL1 N11 fiber	Fiber	TL1, N11	Polyester, PET (332)	C, O	
TL2	White flat mass	TL2, K14	Polyethylene (317)	C, O, Ti	
TL2	Yellow particles	TL2, K14	N/A	Au	
TL2	Yellow metal-looking particle	TL2, G14	N/A	Au	
TL2	Black, sticky debris	TL2, Q7	N/A	C, O, S	
TL3	Metallic particle	TL3, H8	N/A	Ti, O	

Cross Flange Debris (suspected to be Thermoclad Duralon JM Type 11 Nylon):					
--	Green-colored particles	Telescope OD @ cross flange	Polyamide (341)	N/A	

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
Flight Hardware/ Materials:					
--	Silver plated screw (hole thru center) and washer	Used in vent valve	N/A	Screw: Ag-coated copper Washer: Cu	
--	CNT[3]—Two different diameter fibers and binder resin (yellow)	N/A	Binder + fibers: epoxy and glassy fibers (248) Small D: silica-like fiber (340) Large D: alumina with some silica (338,339)	Small D: O, Si, Al, Ca, Mg, Na Large D: O, Si, Al Resin matrix: C, O, Cl	S: 0EDW-2, L: 0EDW-1
--	Castrol Braycote[4] Micronic 601 (CRN 003115)	N/A	Perfluoroether grease (299)	C, O, High F	0EDQ-1

Common Stanford Clean-room Materials:					
Misc A	Contec[5] PNHS-99 Polynit Heatsealed CR wipe (examined fibers)	N/A	Polyester—PET (281, 282)	C, O	
Misc B	Contec QTI-99 Quiltec CR wipe	N/A	Polyester—PET (283)	C, O	
Misc C	White clean room tape	N/A	Adhesive: acrylate adhesive (284, 306) Tape: low density polyethylene (285)	C, Ti, O	0EDV-1
Misc E	TX4009 Texwipe, Miracle CR wiper	N/A	Cellulose (304)	C, Lot O	

ID	Debris Description	Location of Debris	FT-IR Spectroscopy (FT-IR File #)	Scanning Electron Microscopy	SEM Photo ID
Misc F	Teflon tape (no adhesive backing)	N/A	PTFE (307)	Tape: C, F	
Misc G	Opaque "yellow" CR tape	N/A	Tape: PVC with phthalate plasticizer (305)	Tape side: Cl, very low C	

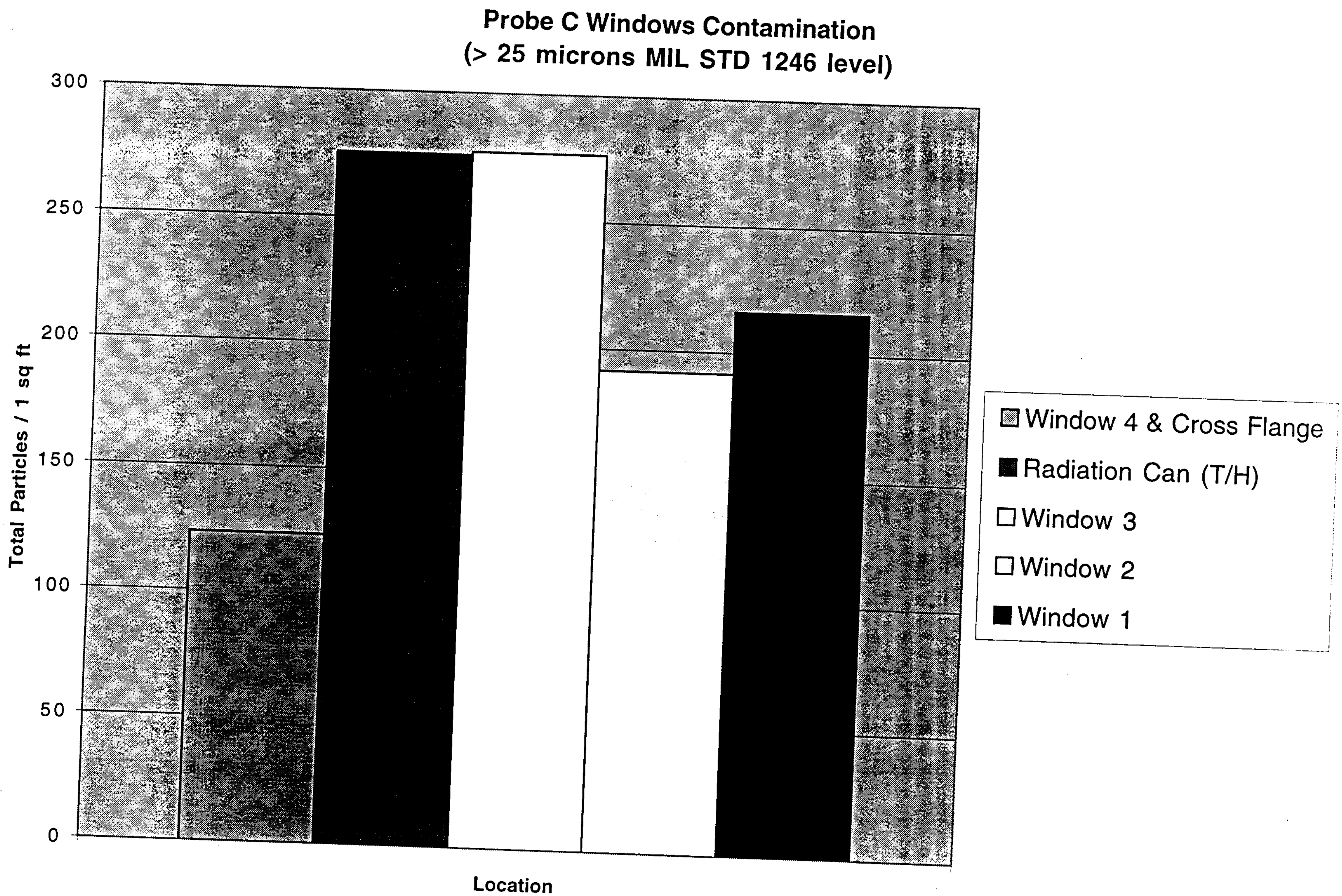
Common Lockheed Martin Clean-room Materials:					
--	LM Type RA Millipore filter, 1.2 micron pore size[6]	N/A	Cellulose acetate nitrate (294)	N/A	
--	LM thermal coating on copper wire	N/A	Polyvinyl formal (321)	C, O, S, Cl, Si, Mg, Na	
--	LM white CR tape	N/A	Tape: Nylon (322)	N/A	

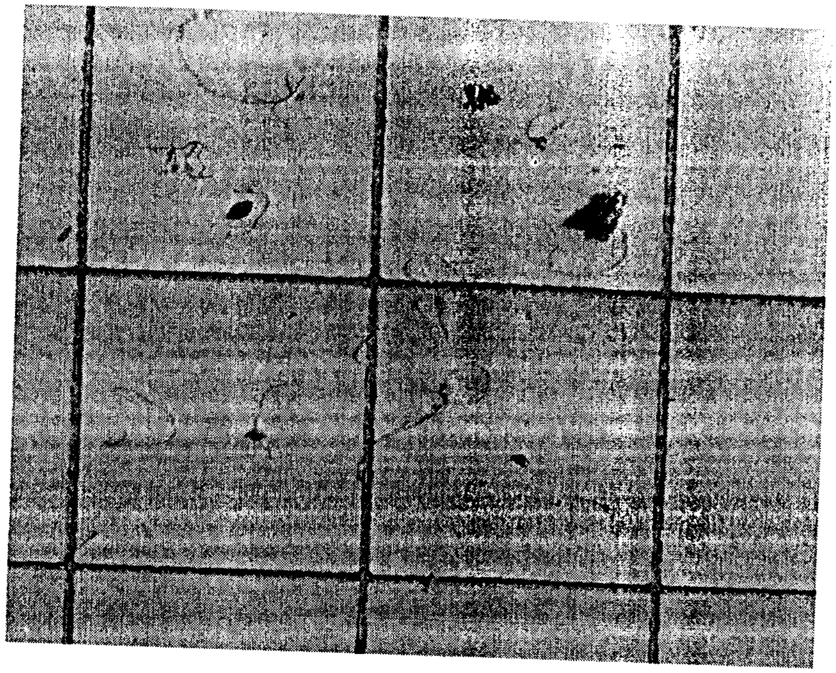
1 Debris collected from both sides of each window was combined on a single Millipore filter paper.
2 Particle location indicated by tape-lift "grid number".
3 Manufacturer specification for fiber reinforcement in CNT is 85% Al_2O_3 and 15% SiO_2.
4 Castrol Braycote Micronic 601, Ultra Low Volatility Perfluorether Grease, Batch #161910, DOM: 2/98 (CRN 003115).
5 Contec-brand materials are polyesters.
6 Manufacturer specification for Type RA Millipore is mixed cellulose acetate/cellulose nitrate.

Table 2 - Probe-C Window Particle Count

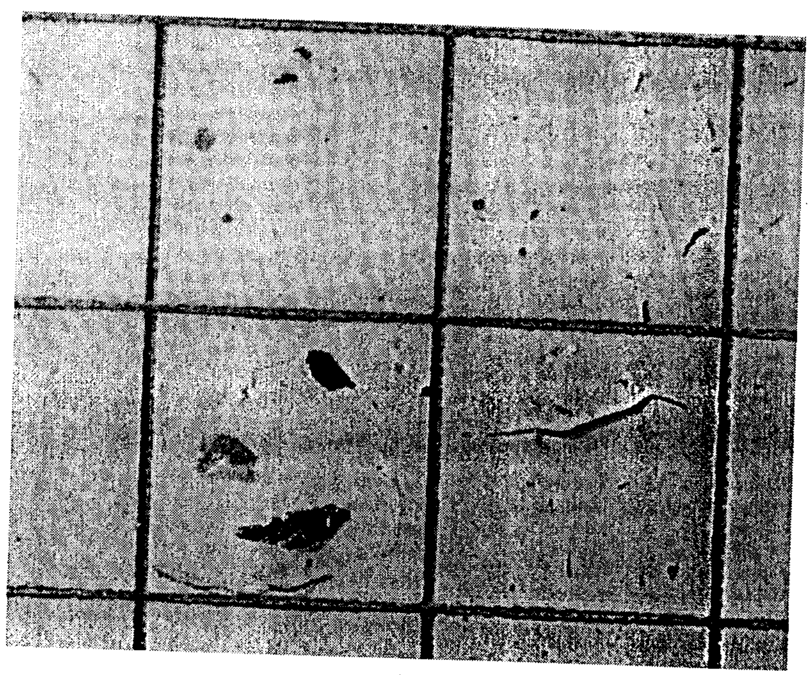
Particle Size (microns)	Window 4 & Cross Flange Sample Area 522 in²	1 sq ft	Radiation Can (T/H) (Both Sides) Sample Area 350 in²	1 sq ft	Window 3 (Both sides) Sample Area 100 in²	1 sq ft	Window 2 (Both sides) Sample Area 100 in²	1 sq ft	Window 1 FWD Sample Area 50 in²	1 sq ft	Window 1 AFT Sample Area 50 in²	1 sq ft
6 to 15	8935	2573	0	0	984	1417	806	1161	312	899	108	311
16 to 25	767	221	522	215	224	323	73	105	57	164	16	46
26 to 50	270	78	371	153	141	203	90	130	39	112	13	37
51 to 100	113	33	197	81	30	43	29	42	11	32	4	12
101 to 250	30	9	101	42	9	13	10	14	3	9	0	0
251 to 500	13	4	0	0	6	9	2	3	5	14		0
501 to 750	1	0	0	0	4	6	2	3		0		0
750 to 1000	0	0	0	0	2	3						
> 1000	1	0										
Total count	10130	2917	1191	490	1400	2016	1012	1457	427	1230	141	406
Level 100 Totals		123		275		276		192	Total=	1636		
										216		

Particle Size (microns)	MIL STD 1246 Level 100	Level 300
26 to 50	67	6434
51 to 100	10	926
101 to 150	1	93
151 to 250	0	1
251 to 500	0	0
501 to 750	0	0
> 750	0	0


Probe C Windows Contamination
(> 25 microns MIL STD 1246 level)
300
250
200
150
100
50
0
Total Particles / 1 sq ft
Location
Window 4 & Cross Flange
Radiation Can (T/H)
Window 3
Window 2
Window 1



Window 3 Debris



Window 4 Debris

Figure 1. Photomicrographs showing representative debris found on windows 3 and 4.

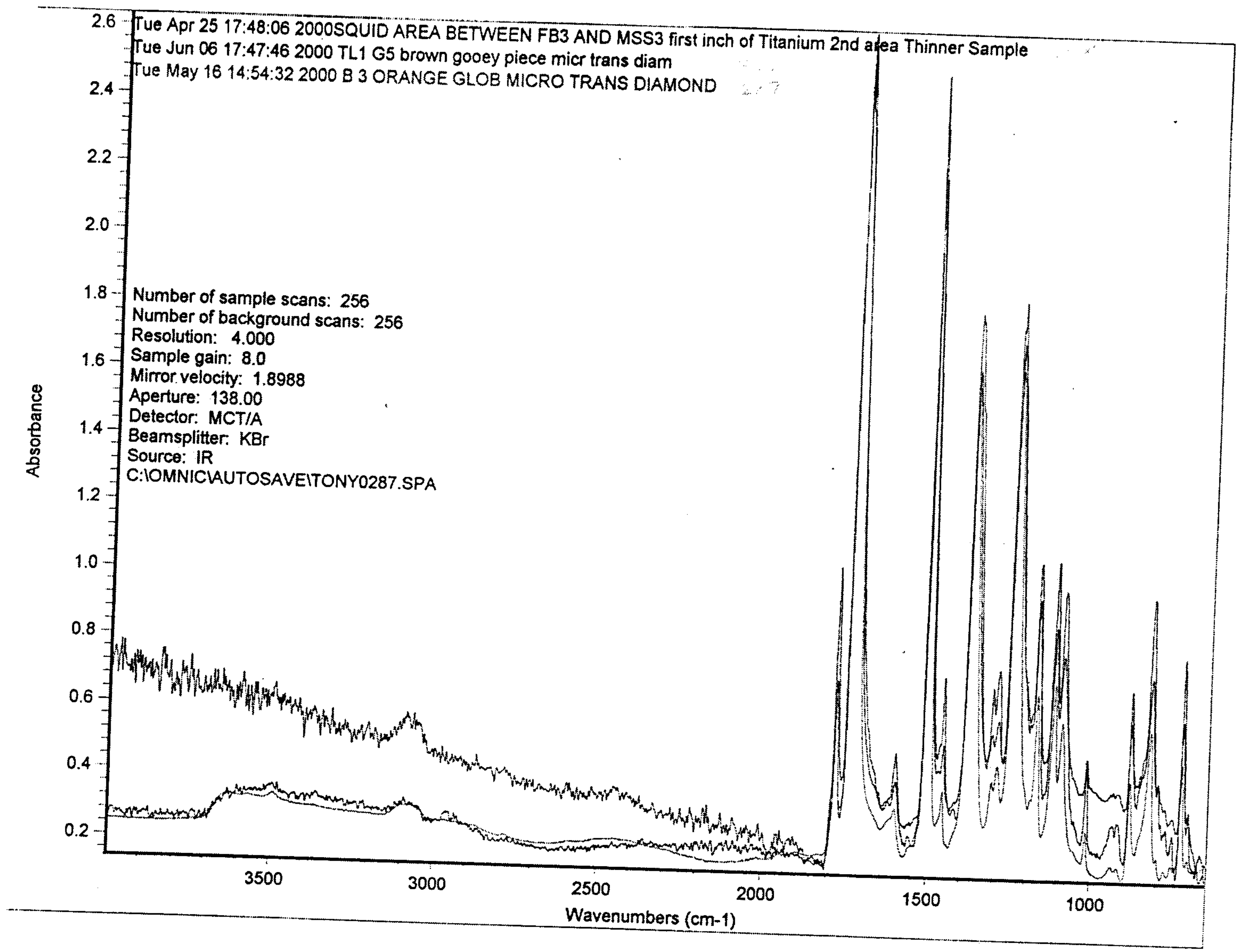


Figure 2. FT-IR Spectra for three particles identified as poly(amide-imide).

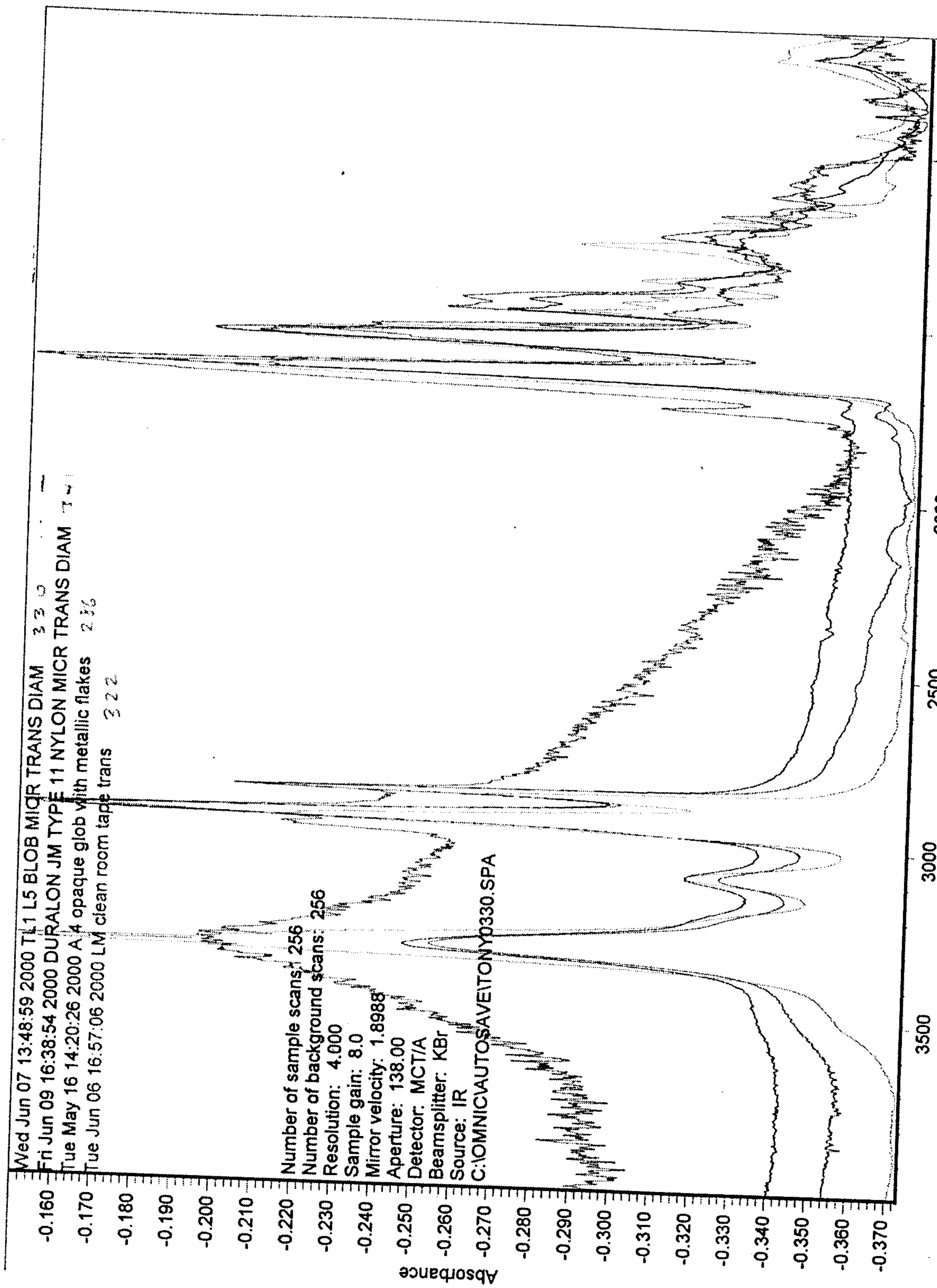


Figure 3. FT-IR Spectra for three particles and a known clean-room tape that were identified as polyamide or nylon.

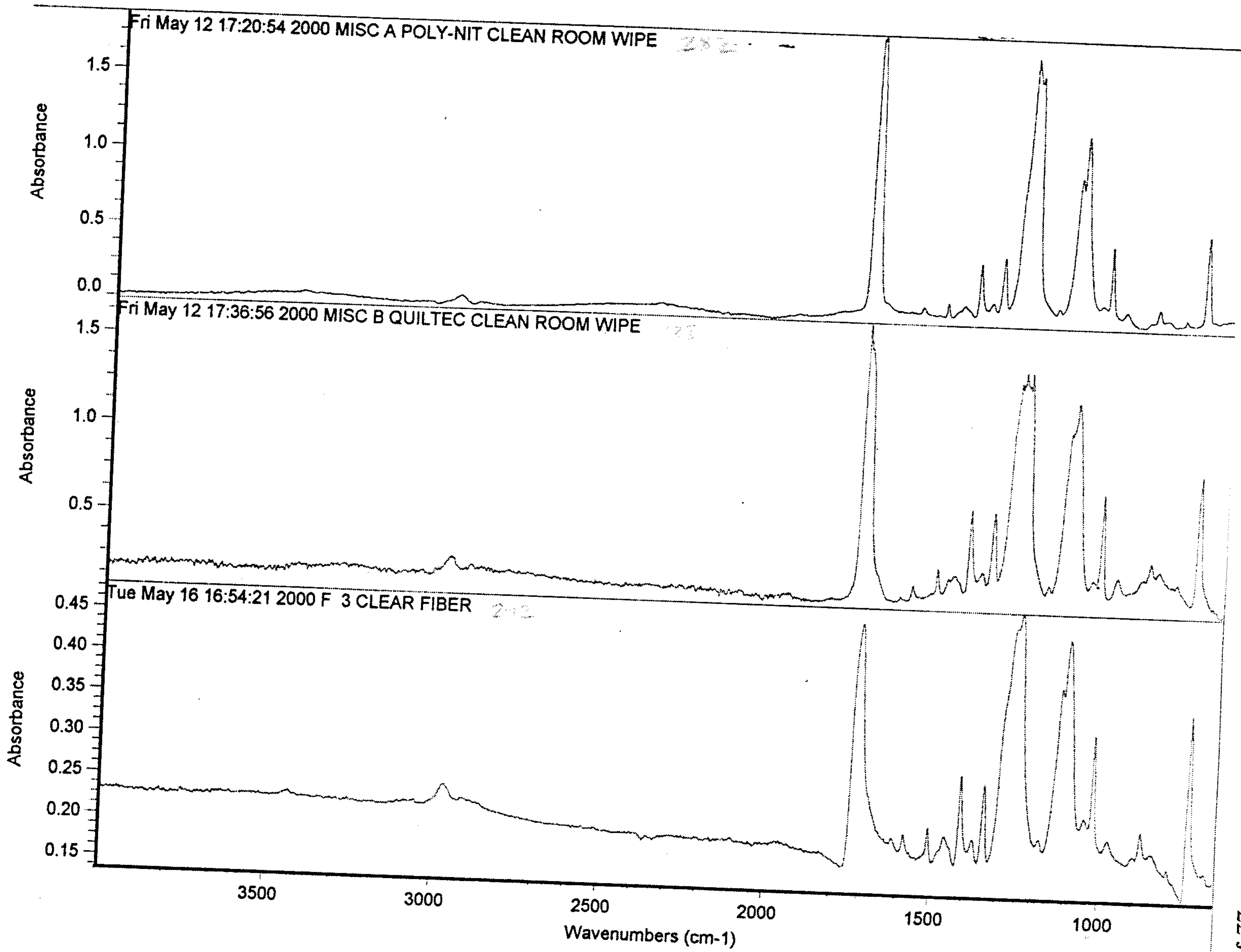


Figure 4. FT-IR Spectra for fiber F and two known clean-room wipers that were identified as PET polyester.

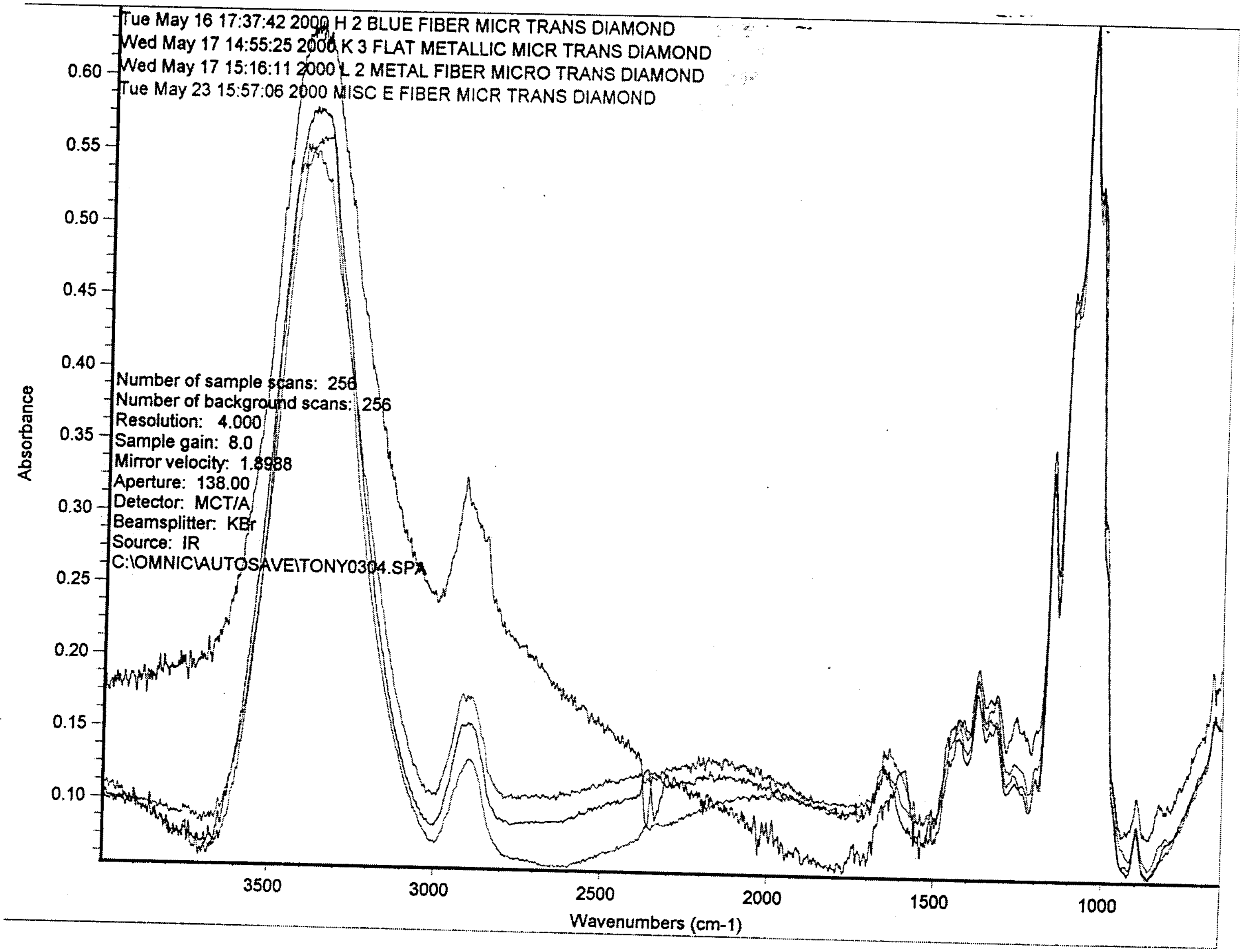


Figure 5. FT-IR Spectra for three particles located on windows 2 (H and L) or 3 (K) and a clean-room Texwipe wiper (Misc E) that were identified as cellulose.

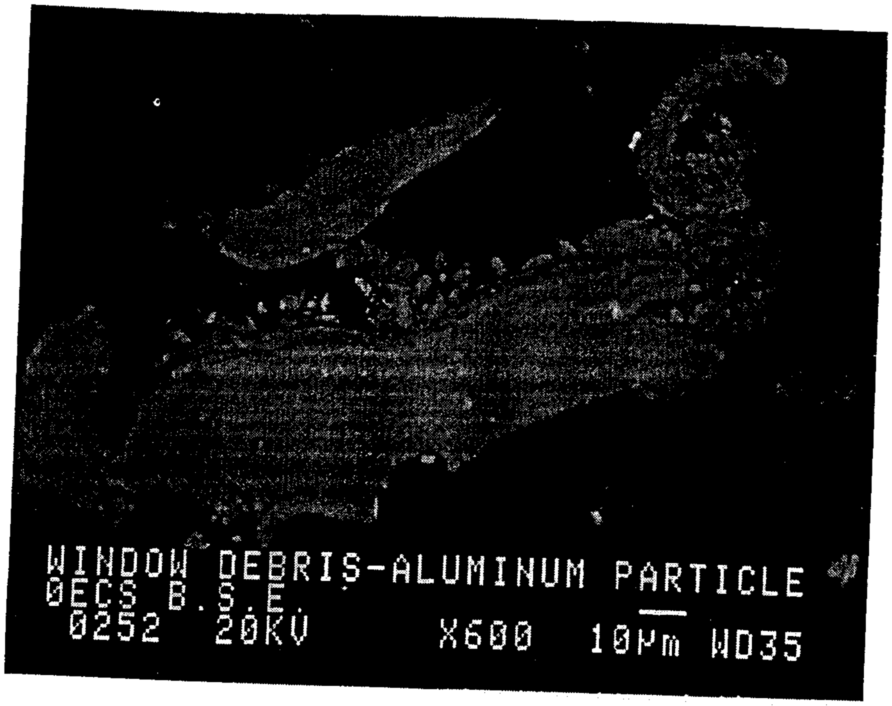


Figure 6. SEM Photomicrograph showing an aluminum debris particle (2) resembling a machine turning.

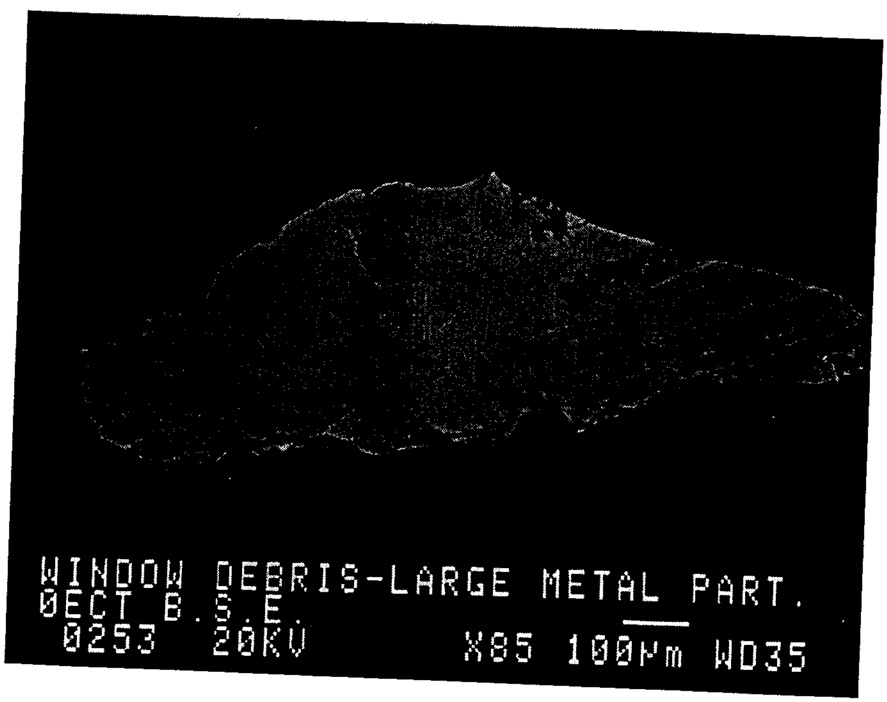


Figure 7. SEM Photomicrograph of a one-mm long particle (3) located in window 4 that contains nickel and phosphorus with dark regions of aluminum.

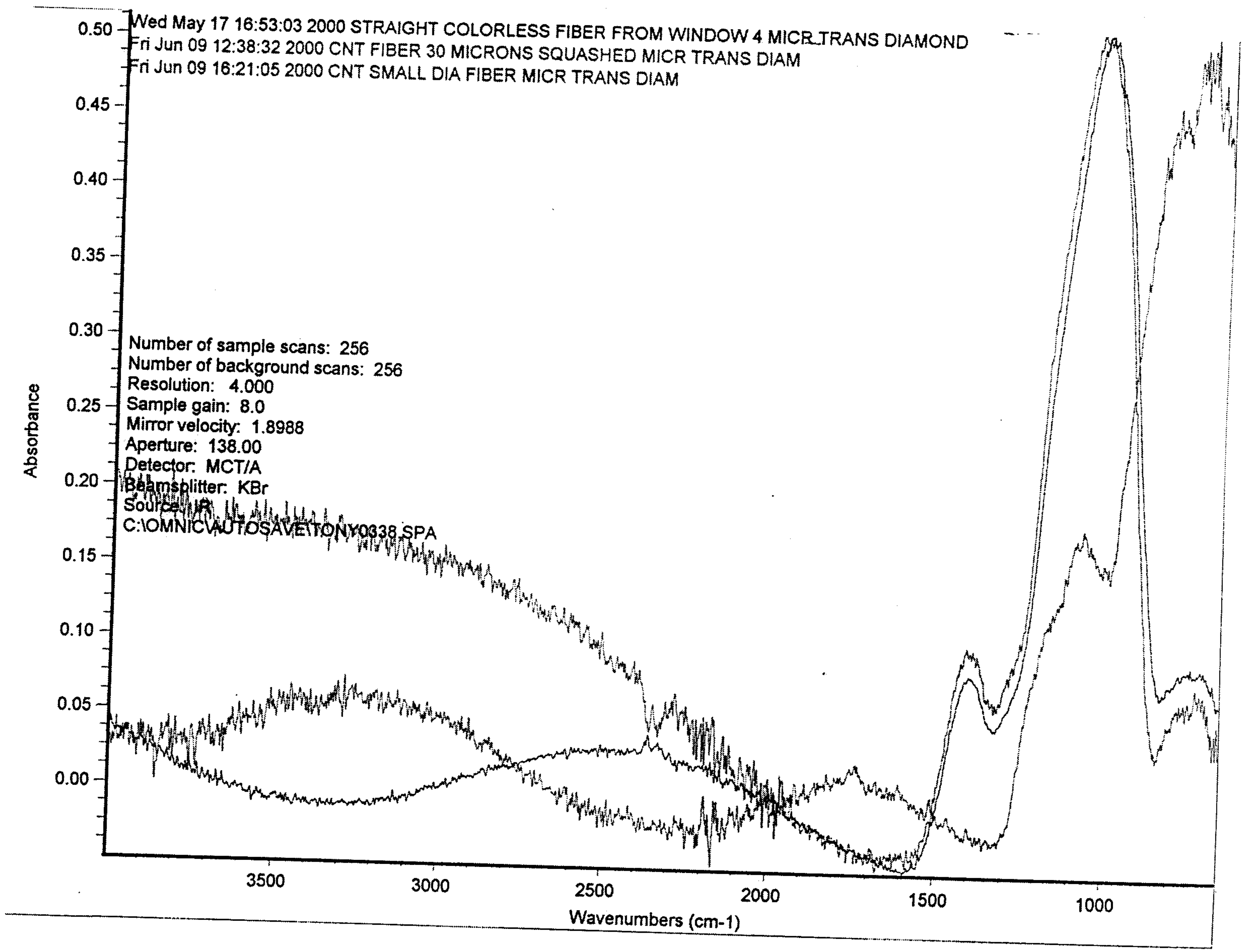
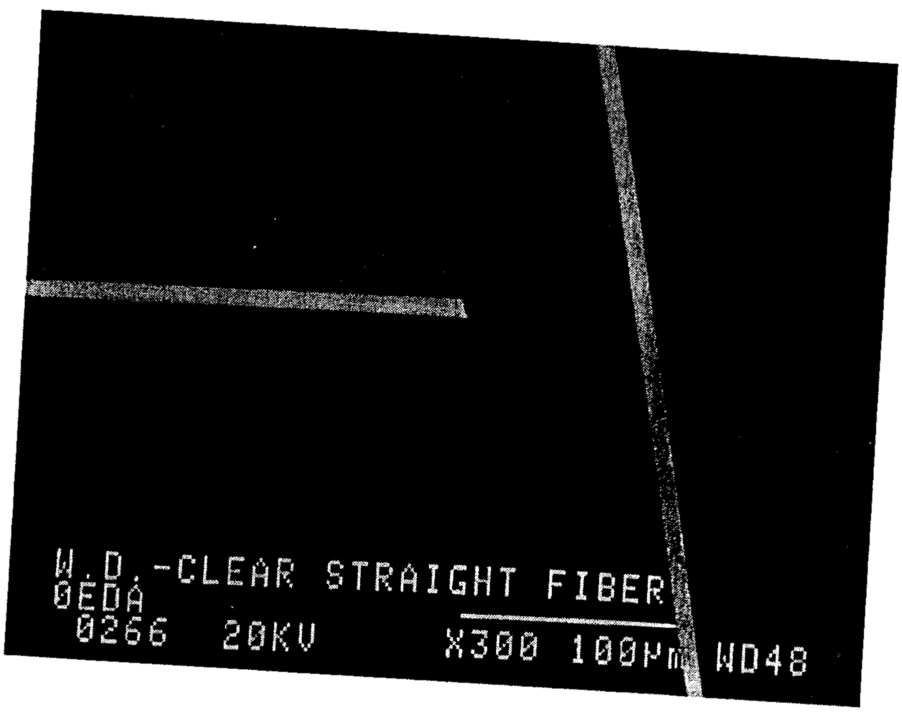


Figure 8. FT-IR Spectra of fiber M from window 4 and the large and small diameter reinforcement fibers found in the CNT material.

Small (left) and large (right) diameter fibers in the CNT material



Clear straight fiber M

Figure 9. SEM Photomicrographs at 300X magnification showing relative fiber diameter differences between the CNT fibers and fiber M.

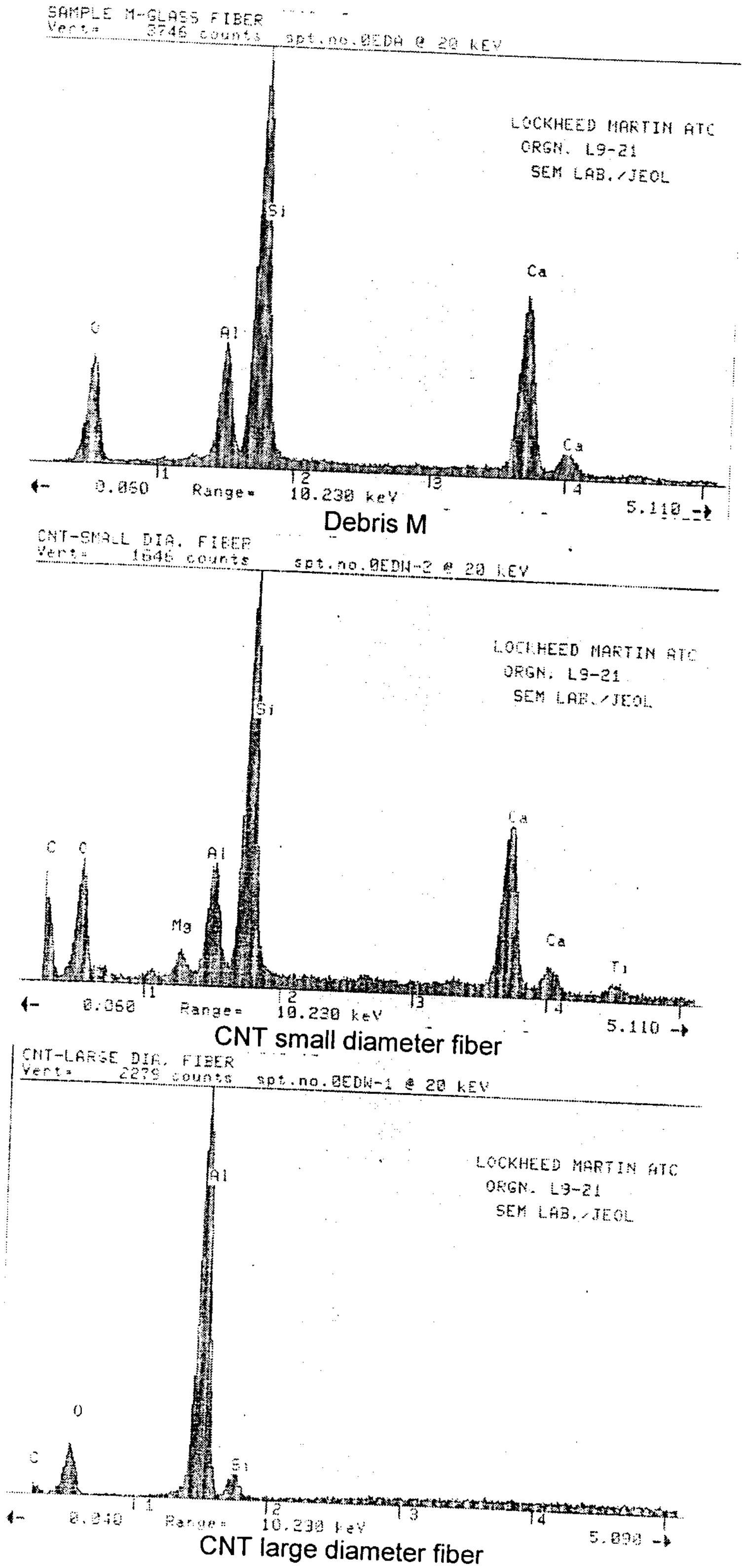


Figure 10. SEM Elemental analysis comparison of Fiber M and CNT reinforced fibers of different diameters.

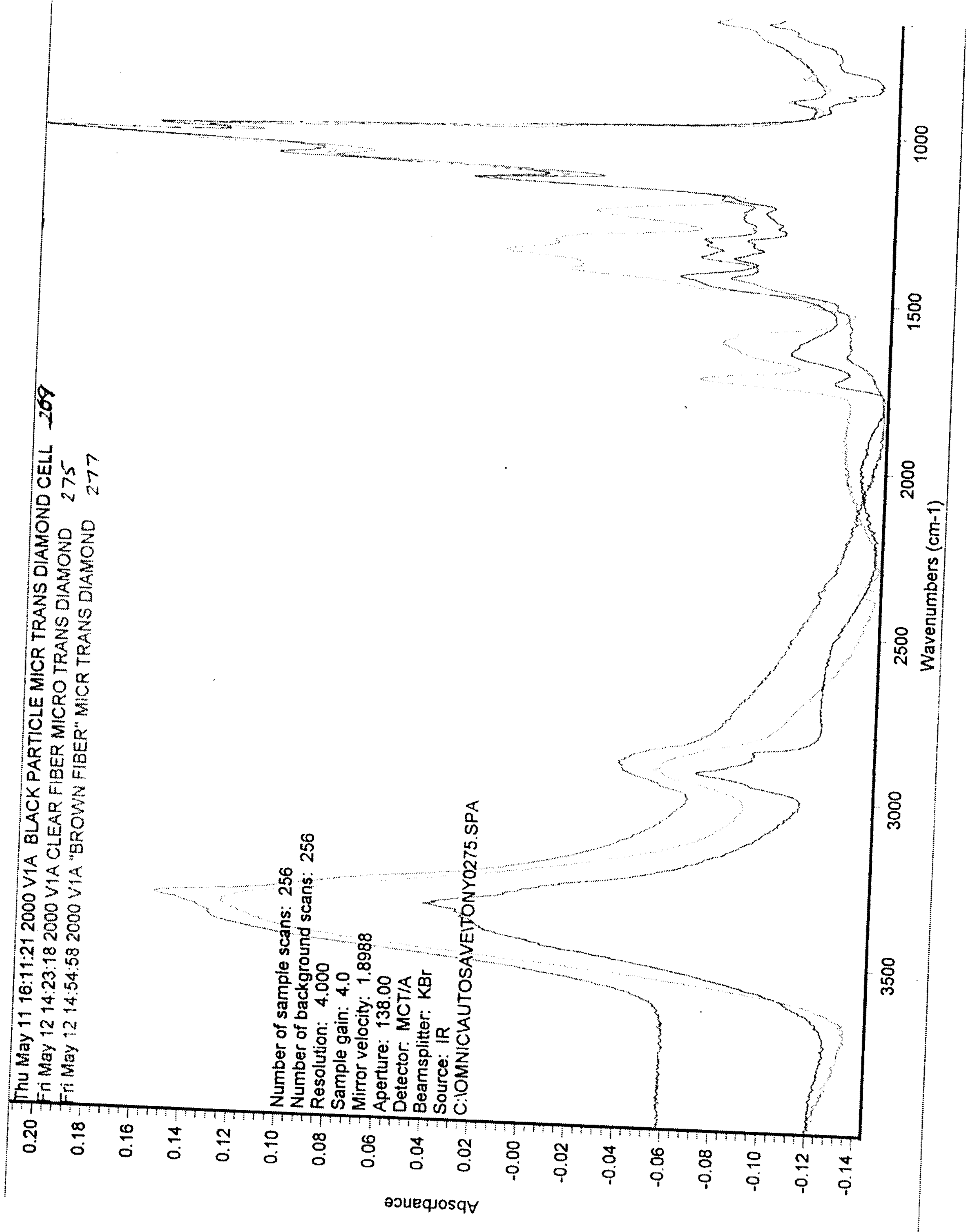


Figure 11. FT-IR Spectra of vent valve 1A (V1A) particles that were identified as cellulose material.

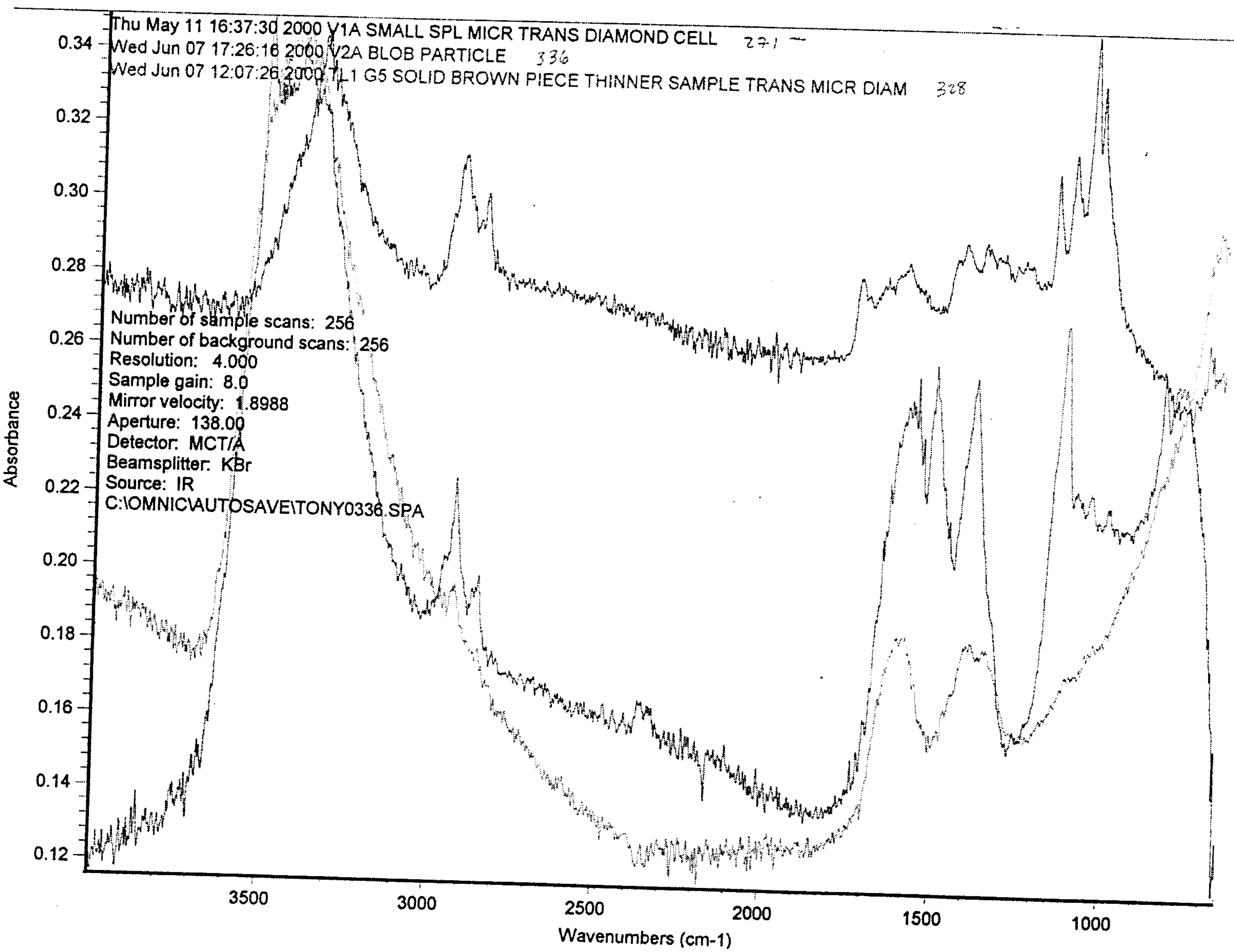


Figure 12. FT-IR Spectra comparisons of three debris materials that could not be identified.

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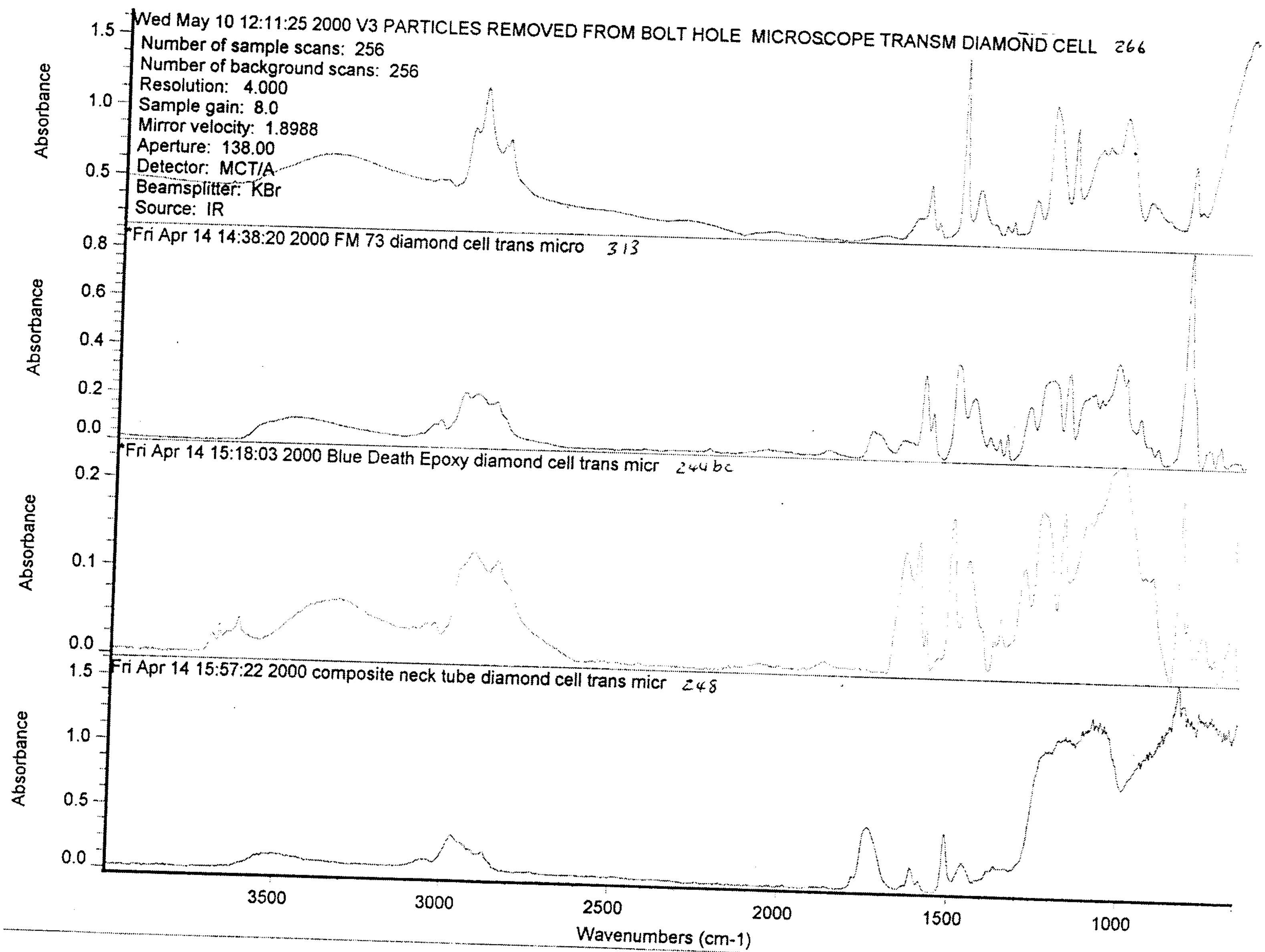

Figure 13. FT-IR Spectra for V3 (debris around bolt holes at valve body 3) and known epoxies (FM-73, blue death, and CNT) are compared.

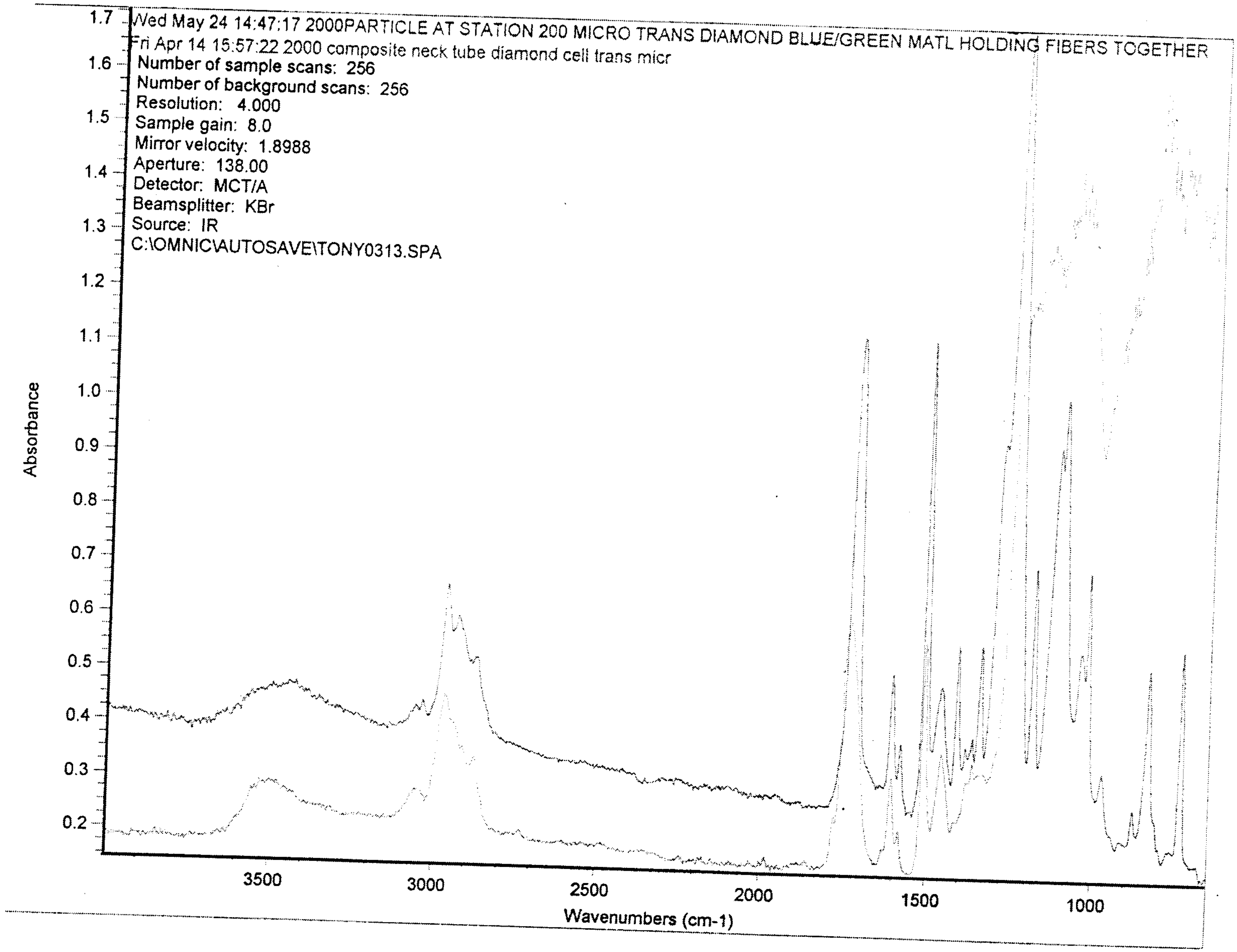

Figure 14. FT-IR Spectra for particle at Station 200 and binder of the CNT epoxy is compared.

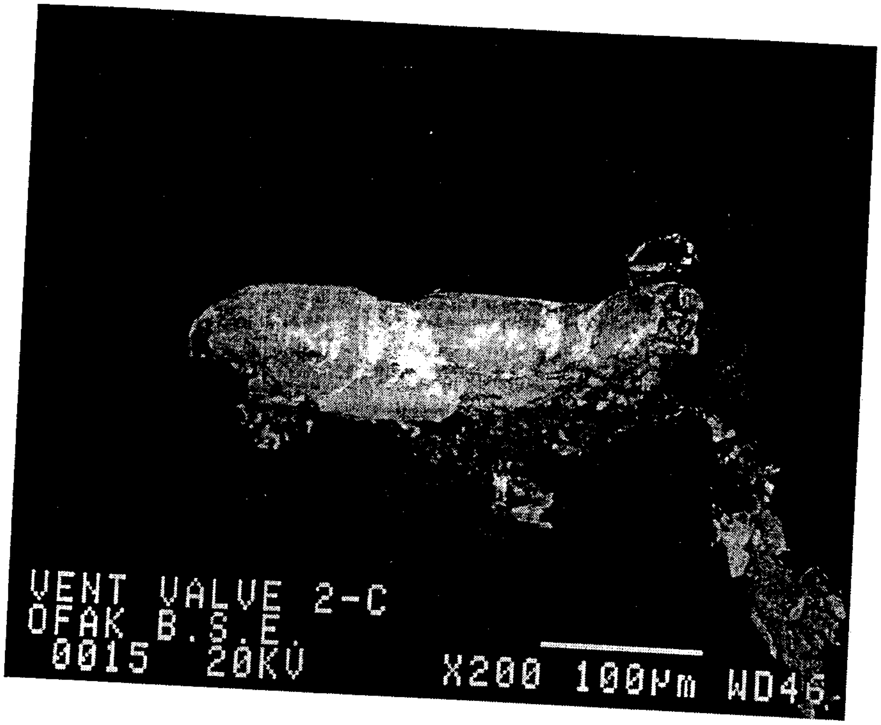

Figure 15. Vent valve 2C (V2C) yellow particle that contained copper and zinc (brass) and had contaminants of lead and cadmium on it.