Failure Analysis Associates

Failure Analysis Associates, Inc.
Engineering and Scientific Services
149 Commonwealth Drive, P.O. Box 3015
Menlo Park, California 94025
(415) 326-9400 Fax (415) 326-8072
Internet Site: www.fail.com

FaAA-SF-R-96-06-16

Investigation of the Failure of an SCBA Cylinder

Prepared by:

Robert S. Frankle
Harry F. Wachob, Ph.D.

Failure Analysis Associates, Inc.
149 Commonwealth Drive
Menlo Park, California 94025

Prepared for:

EFI Corporation
5357 Randall Place
Fremont, California 94538

July 2, 1996

Failure Analysis Associates, Inc. (FaAA) was retained by EFI Corporation (EFIC) to investigate the failure of a self-contained breathing apparatus (SCBA) cylinder fabricated by EFIC. This report summarizes work performed during the investigation, results of this work, and the cause of the failure based on these results.

1.0 The Failure

On March 4, 1996, an SCBA cylinder failed at the Bayview Station of the Humboldt Fire Department in Eureka, CA. Failure occurred at approximately 9:15 p.m., while the cylinder was stored in Engine 1-7, which was parked inside the fire house. Although no one was injured, the failure did cause significant damage to Engine 1-7 and minor damage to Engine 1-4, which was parked next to Engine 1-7. Photos taken after the failure by the Humboldt Fire Department, shown in Figures 1 through 4, document the scene and the damage.

In Figure 1, Engine 1-7 is on the right, and the failed SCBA cylinder is on the floor between the two parked engines. Close-up views of the failed cylinder appear in Figures 2 and 3. The compartment on Engine 1-7, where the cylinder was stored prior to the failure, is visible in Figure 4. The door to this storage compartment was blown off and is on the floor in the foreground of Figure 1. The door to the adjacent storage compartment was blown open and deformed, as shown in Figure 4.

1.1 The Inspection

On March 8, FaAA inspected the Bayview Station. The inspection activities included:

- examining and photographing the scene, the failed cylinder, and other SCBA cylinders
- interviewing members of the Humboldt Fire Department
- examining the SCBA cylinder fill station at the Eureka Fire Department Headquarters

The failed cylinder was transported to FaAA for further examination and testing. The SCBA cylinder storage rack in Engine 1-7, where the failed SCBA cylinder was stored at the time of the failure, was also removed and subsequently sent to FaAA. The interior of the storage compartment following removal of the storage rack is shown in Figure 5. Visible in Figure 5 is the dent in the back wall of the compartment, where the cylinder struck the wall, and the gap along the bottom of the storage compartment, where the top of the fire engine was displaced from the bottom.

1.2 The Failed Cylinder

The failed cylinder is a half-hour capacity fully-wrapped composite cylinder, which is part of an SCBA manufactured by International Safety Instruments (ISI). The label on this cylinder, shown in Figures 6 through 8, contains the following identification:

- Manufacturer - EFIC
- Serial Number - 32176
- Date of Manufacture - January 1991
- Working Pressure - 4500 psi

Cylinder Pedigree. EFIC provided drawings and manufacturing information for the failed SCBA cylinder, serial number 32176, which was manufactured on January 4, 1991. The fiberglass composite material consists of S-901 glass (a type of S glass) fibers in epoxy resin. The glass fibers are oriented in the circumferential and longitudinal directions. The metal liner is 6061-T6 aluminum. The SCBA cylinder is painted with a yellow urethane paint. Visual examination indicates the likely presence of a clear coating, such as a clear paint, in the label area. FaAA reviewed EFIC's manufacturing data for the failed cylinder and for cylinders made on the same day, on the same equipment, and from the same lots of fiber and resin. Our review determined that the fabrication materials and processes did not contribute to the failure.

Cylinder Usage. Based on information received from the Humboldt Fire Department, this cylinder was last used during a training exercise on February 27, 1996. The pressurized cylinder was returned on February 27, and was stored on Engine 1-7, where it failed on March 4. A visual inspection by the Humboldt Fire Department of the building used in the training exercise revealed no evidence of contact by an SCBA cylinder, such as yellow paint scrapings on the building. Such evidence would have suggested that the cylinder may have been damaged in the exercise.

The Humboldt County firemen that were interviewed had no specific recollection of any extraordinary events which may have contributed to the subsequent failure of this cylinder. The cylinder passed the most recent hydrostatic test on April 22, 1994. On March 6, 1996, other cylinders from the Bayview Station, including six cylinders from the same manufacturing lot as the failed cylinder, were successfully hydrostatically tested in Eureka.

During the inspection, information was obtained on the handling, maintenance, and refilling of the Humboldt Fire Department SCBA cylinders. Other Humboldt Fire Department SCBA cylinders were also examined. In particular, cylinders used in the training exercise and stored on Engine 1-7 at the time of the failure, shown in Figures 9 and 10, were examined for evidence of damage or other unusual surface features. Nothing in the practices of the Humboldt Fire Department or the condition of the other SCBA cylinders provided an explanation for the failure of the SCBA cylinder.

2.0 The Failure Investigation

FaAA's failure investigation consisted of the following activities:

- Information Gathering
- Visual Examination
- Optical and Scanning Electron Microscopy

- Chemical Analysis
- Stress Corrosion Cracking Testing
- Chemical Exposure Testing

Physical and chemical testing was performed on the accident SCBA cylinder, samples removed from the accident cylinder, and exemplar SCBA cylinders from the same manufacturing lot. These tests were performed in order to determine the mode of failure, source of induced cracking, and the effects of a controlled exposure of exemplar cylinders to an alleged potentially degrading corrosive fluid. Specific test results and observations are discussed in the following sections. Table I summarizes the test samples removed from the failed SCBA cylinder, the approximate sample locations, and the tests performed on each sample.

2.1 Information Gathering

Additional information on the handling of the SCBA cylinders during the training exercise provided important input to the failure investigation.

The Training Exercise. Information about the use of the Humboldt Fire Department SCBA cylinders during the training exercise on February 27, 1996, was obtained from members of the Humboldt Fire Department; Mr. Lee Figas, a deputy sheriff with the Humboldt County Sheriff's Department; and Mr. Stan Ehler, an assistant chief with the Eureka Fire Department. Based on this information, the following sequence of events was reconstructed:

1. On February 27, the SCBA cylinders were used during the training exercise in Eureka.

2. On the evening of February 27, Lee Figas transported the cylinders in his trailer to the Eureka Fire Department for refilling. He estimates that the cylinders were in the trailer approximately 30 minutes. Stan Ehler remembers that one fiberglass cylinder and 4 to 5 metal cylinders were on the floor of the trailer, with other cylinders on top of these.

3. During loading or transport, a spray bottle containing aluminum cleaning fluid, that was in the trailer, broke and spilled its contents. Mr. Figas estimates that the 12-ounce bottle was approximately one-third full at the time.

4. After delivering the SCBA cylinders to the Eureka Fire Department, Mr. Figas emptied and washed his trailer.

5. Approximately two hours later, Mr. Figas retrieved the refilled bottles from the Eureka Fire Department and returned them to the Humboldt Fire Department.

The potential exposure of a fiberglass SCBA cylinder to a corrosive fluid was a key piece of information in the failure investigation. In response to our request, Mr. Figas visually examined his trailer and reported that he observed no indication of the aluminum cleaner spill. He had cleaned the trailer on the evening of February 27, and it had rained since that time. Also, the wood floor of the trailer was generally a dark color, which would not easily show such a spill.

The Aluminum Cleaner. Interviews were conducted with a number of people, including Mr. Figas, in an attempt to identify the specific aluminum cleaner contained in the broken bottle in Mr. Figas's trailer. The following information was obtained:

More than five years ago, Mr. Figas purchased a large container of aluminum cleaner from Redwood Reliance Trailer Sales, a truck company in Eureka, CA. He would routinely fill a spray bottle from this container, which he then used to clean aluminum on his vehicles. Mr. Figas recollected that he did not further dilute the fluid when transferring it to the spray bottle.

- The broken spray bottle contained the last of the aluminum cleaner from the large container. Mr. Figas did not retain the large container. He recollects that the cleaner was Zep aluminum cleaner (Alume-E™).

- Information on aluminum cleaners used by Redwood Reliance Trailer Sales was obtained from Mr. Chuck Gradek of Redwood Reliance. Mr. Gradek reported that Redwood Reliance was currently using Alume-E™, manufactured by Zep Manufacturing. In the past, they had used either Alume-E™ or Alume™ from Zep Manufacturing or an aluminum cleaner manufactured by Fremont Industries. Redwood Reliance's purchasing records were not available to provide more specific information on their past purchases of aluminum cleaner. Available records of Fremont Industries and Zep Manufacturing did not indicate purchases by Redwood Reliance.

- Zep Manufacturing manufactures an aluminum cleaner, Alume™, which contains acids that are known to chemically attack glass.

- Fremont Industries of Shakopee, MN, manufactures from 20 to 40 different products that could be used as aluminum cleaners. They were unable to narrow the potential identity of a cleaner for automotive parts. Their cleaners are basic, rather than acidic.

Alume™. Based upon the Material Safety Data Sheet (MSDS) documentation, Alume™ has a pH of less than 1.0 and contains the following chemical components:

Constituent	Amount, %
Hydrofluoric Acid	<5
Phosphoric Acid	<5
Sulfuric Acid	<5
Ethylene Glycol Monobutyl Ether (2-butoxyethanol)	<5
Nonylphenoxypoly(ethyleneoxy) Ethanol	<5

According to information obtained from Zep Manufacturing, Alume™ has been available since at least 1988, and the primary ingredients listed on the MSDS have not changed during that time period. Alume-E™ (Alume-Economical) is a 50% dilute solution of Alume™. The labels on the Alume™ and Alume-E™ containers include the following warning:

> "Keep product off glass, fiberglass, and ceramic surfaces. Should product accidentally contact any of these surfaces, flush immediately with water."

Containers of Alume™ and Alume-E™ were obtained from Zep Manufacturing in Santa Clara, CA, for use in this failure investigation.

2.2 Examination of the Accident SCBA Cylinder

The failed SCBA cylinder was visually examined to evaluate the macro-fractography of the failed fiberglass composite and the aluminum liner. Detailed examinations were performed subsequently using optical binocular and scanning electron microscopy (SEM) to determine the micro-fractography of the composite fracture.

The overall fracture has an "H" shape, as shown in Figure 6, with the horizontal bar of the "H" oriented in the longitudinal direction of the SCBA cylinder and the vertical bars of the "H" oriented in the circumferential direction. Failure of the SCBA cylinder appears to have initiated in the circumferential fibers, near the right hand edge of the label, as viewed with the cylinder vertical and the valve at the top (see Figures 7 and 8).

The flat fracture surfaces of the failed fiber bundles are indicative of stress corrosion cracking. The fracture surfaces are perpendicular to the circumferential direction, the direction of maximum stress caused by the internal pressure in the cylinder. The mating fracture surfaces to these circumferential fiber bundles, which were displaced upon failure, also exhibit the flat fracture features. The circumferential bundles appear to be in equi-width segments in the longitudinal direction, which may be associated with autofrettage cracking of the composite during the manufacturing process. This cracking did not contribute to the failure initiation or propagation. The longitudinal fibers that failed above and below the label have a broom or splayed array appearance typical of an overload event in a composite structure. The macro-fractographic features of failed circumferential and longitudinal fiber bundles can be seen in Figures 11 and 12.

In the aluminum liner, the longitudinal crack orientation experiences the highest stresses in the circumferential direction and appears to be the plane where the first liner fracture occurred. The longitudinal crack propagated a short distance when the crack turned abruptly from the longitudinal direction into four circumferentially propagating cracks. The longitudinal crack turns as a result of the decreasing driving stress as the crack nears the thicker neck region in the liner, where the composite does not provide the same loading constraint as in the cylindrical portion of the SCBA cylinder. The turning of the crack may also be associated with the loss of circumferential driving stress and increased tendency for the crack flaps to open such that the crack then propagates in the circumferential direction.

The aluminum liner fracture is shear in nature and occurred as the result of overload after the composite lost its load carrying ability. No evidence of a pre-existing fatigue crack, material inclusions or other manufacturing defects was observed in the liner.

2.3 Scanning Electron Microscopy of SCBA Cylinder Samples

Detailed fractographic and chemical analyses were performed on a number of samples removed from the failed SCBA cylinder. Fractographic evidence on the fibers immediately adjacent to the fracture show clear evidence of environmental stress corrosion cracking. No chemical entities characteristic of an aggressive environment were observed using energy dispersive x-ray spectroscopy (EDS) on the fractured glass fibers and adjacent resin.

Chemical analysis by EDS was performed on samples E, 4, 5 and 6. Our EDS analyses were only sensitive to elements with atomic numbers greater than 10, i.e. sodium and above on the Periodic Table. Therefore, any hydrocarbon compounds or oxides would not be detected using our EDS technique. No significant evidence of the presence of sulfur or phosphorus, from possible Alume™ mineral acid components, was observed. A typical EDS spectra is shown in Figure 13. The EDS spectra from sample 6, Figure 14, exhibited additional titanium spectral peaks which are associated with the yellow paint pigment.

SEM fractography confirmed that the SCBA fracture initiated as a result of stress corrosion cracking. The flat fracture regions observed adjacent to the edge of the label were both macroscopically and microscopically consistent with stress corrosion cracking of fiberglass. Overall and progressively higher magnification photographs of the fracture area from sample D are shown in Figures 15 through 18. Note the characteristic stress corrosion cracking feature of a moon-shaped mirror region on the individual glass fibers followed by the rays or hackle marks radiating outward from the initial crack region. This mirror region is produced as the chemical environment and stress interact to produce initial crack growth. When the crack becomes sufficiently large for the given stress and chemical environment, the crack propagates rapidly through the remaining fiber cross section, resulting in the failure of that fiber. The process continues until the load carrying capacity of the composite and liner combination is reduced below the rupture strength of the SCBA cylinder.

2.4 Demonstration of Stress Corrosion Cracking

Based on the statements of Mr. Figas and the investigation into the composition of the aluminum cleaning solution, a laboratory test was performed using an as-received solution of Alume™ and two fiberglass samples (samples F and G) from the failed SCBA cylinder. Sample F was 0.038 inches thick and sample G was 0.072 inches thick. For each specimen, bundles of circumferential fibers were bent into a semi-circular shape with a bend radius of approximately 1 inch and restrained in that position using rubber bands to provide an elevated state of constant strain. The bent sample was then placed into a beaker containing the Alume™ solution. Almost immediately after immersion, cracking of fibers was heard, and the specimens were seen to move and fracture. After less than one minute of exposure, sample F had fractured completely. Sample G remained in solution for several minutes and multiple fiber failures occurred. SEM examination of sample F revealed fractographic evidence of features on the broken fibers very similar to the accident sample D described in Section 2.3. In the photographs of sample F, shown in Figures 19 through 21, note the characteristic mirror region and radiating hackle marks present on the fibers.

2.5 Chemical Exposure of Exemplar SCBA Cylinders

Two exemplar SCBA cylinders from the same lot as the failed SCBA cylinder were used to observe the effect of chemical exposure on the fiberglass composite. These cylinders were selected from a group of cylinders manufactured on the same day and using the same lots of fiber and epoxy resin as the failed cylinder. The label region of the unpressurized cylinder, serial number 32191, was marked off into quadrants. One quadrant was left as-is. In an adjacent quadrant, two surface scores were made with an Exacto knife, which were intended to produce one light and one heavy score line. Both quadrants were repeatedly painted for one hour with a full strength Alume™ solution. This SCBA cylinder was examined frequently throughout the following week. No conclusive evidence of cracking or significant degradation was observed. Some discoloration was observed near and underneath the autofrettage cracking.

The label region of a second unpressurized SCBA cylinder, serial number 32201, was submerged locally in the Alume™ solution for three days. No specific damage to the fiberglass composite in the label region was observed upon inspection either immediately after removal from the bath or after a one week time period. However, significant corrosion damage did occur to the bare aluminum liner in the filler neck region, which was partially submerged.

In these chemical exposure tests, the glass fibers were not under the same tensile stress as those in the accident cylinder, because the cylinders were not pressurized. The fibers only had tensile stresses induced during winding and autofrettage. No stress from the 4500 psi internal pressurization of the cylinder was present during the laboratory chemical exposure tests. Therefore, the degree to which cracking would occur was reduced over that actually experienced by the failed cylinder during service. These results illustrate the importance of stress level in failures caused by stress corrosion cracking, as compared to chemical exposure alone.

2.6 Chemical Analysis of Accident SCBA Cylinder Samples

Seven samples removed from various regions of the failed SCBA were analyzed using thermal desorption-gas chromatography-mass spectrometry (TD-GC-MS). The location and description of each of the samples are listed in Table I. Prior to chemical analysis, one sample, sample G, was exposed to Alume™ during stress corrosion cracking testing. Results of the chemical analysis indicate that a unique component of the Alume™ could be found in the control sample

(sample G) that was exposed to Alume™ and in samples from a number of locations on the accident SCBA cylinder.

TD-GC-MS Testing. If a thick film or large residue from chemical exposure was present on the samples from the failed cylinder, the EDS analyses would have exhibited characteristic peaks of observable elements (see Section 2.3). However, if only a thin film of residue was present, insufficient x-rays would be obtained from the film in comparison to the x-rays from the underlying bulk material, and the elements would not be detected by EDS analysis. Based upon these observations, another chemical analysis technique, thermal desorption-gas chromatography-mass spectrometry (TD-GC-MS), was employed to ascertain the possible presence of the Alume™ components. The TD-GC-MS technique was selected because it is more sensitive to the presence of volatile chemicals on the external and fracture surfaces of the samples than EDS analysis. Although TD-GC-MS analysis is typically considered a bulk technique, in this case it is a surface technique, because the glass in the fiberglass does not melt at the test temperature of the TD-GC-MS.

Ideally a unique chemical tag or entity from an aggressive solution that might be responsible for the observed stress corrosion cracking could allow the determination of whether or not the cylinder was exposed to that aggressive environment. If exposure to a chemical solution leaves a trace of a compound either on the fracture surface or in the resin, TD-GC-MS should detect the compound or fractions of that compound. This technique utilizes a small sample that is subsequently heated above the glass transition temperature of the resin matrix to increase the diffusion rate of the volatile species. In these tests, the volatiles were desorbed at 170°C for eight minutes. The volatiles that were on the fracture surface and those that diffused to the exterior surface are entrained in a flowing helium stream and condensed at -90°C at the head of a gas chromatograph column. After a preset desorption time is reached, the condensate is flash vaporized onto the GC column, separated into individual chemical entities, and identified using a mass spectrometer. The chemical entities detected in the TD-GC-MS test are identified from a spectra and reported as a list of entities present and their relative amounts.

Control Sample G - Laboratory Exposed Test Sample. The MSDS data for Alume™ indicates that the solution contains the following components:

- Hydrofluoric acid
- Phosphoric acid
- Sulfuric acid
- Ethylene Glycol Monobutyl Ether (2-butoxyethanol)
- Nonylphenoxypoly(ethyleneoxy) Ethanol

Sample G was a stress corrosion cracking test sample that had been exposed to the Alume™ solution for several minutes. After removal from the beaker, the sample was rinsed in alcohol, stored in a plastic bag and subsequently submitted for chemical analysis.

TD-GC-MS results for the total desorbed volatiles for sample G are displayed on the chromatogram shown in Figure 22. Three major, three minor and several trace components in sample G were obtained and identified on the basis of their mass spectra and are summarized in tabular form in Table II. The number of + symbols in the table indicates the relative amount of each component, based on the relative size of peaks in the spectra for sample G. The retention time listed in Table II is the time of elution of each reported component.

The last two components listed in Table II, cis-Hexahydrophthalide and Hexahydro-1,3-Isobenzofurandione, are assignable to the anhydride hardener of the epoxy, which is consistent with the MSDS information for the resin constituents. The origins of the 1,4-Dioxane, phenol, and ethanol detected in sample G are unknown. One possible source of 1,4-Dioxane may be an acid catalyzed rearrangement of nonoxyl promoted by the heat provided during thermal desorption. Analysis of the Alume™ in the as-received condition after heating in the absence of the composite resin was not performed and may establish the origin of the 1,4-Dioxane.

In sample G, the 2-butoxyethanol had an excellent spectral match, for both the major fragment ions and parent ion, with the spectrum of a reference compound of 2-butoxyethanol. Since 2-butoxyethanol is a constituent of Alume™ per the MSDS and no other source for this compound is known, this result suggests that the 2-butoxyethanol is a good chemical tag for exposure of the SCBA cylinder samples to Alume™.

Failed SCBA Cylinder Samples. Portions of samples 1, 2, 3 H, J, and K from the failed SCBA cylinder were tested using TD-GC-MS in the identical manner to that of sample G. The TD-GC-MS results indicate that samples 2, 3, J and K contained 2-butoxyethanol in trace to small amounts, and samples 1 and H did not contain any reportable quantities of 2-butoxyethanol. The condensed tabular data for all the SCBA cylinder samples are listed in Tables III-VII. The major components detected in these samples are given below:

- *cis*-Hexahydrophthalide
- Hexahydro-1,3-isobenzofurandione
- 2-Heptanone
- Butyl Acetate

The first two components, cis-Hexahydrophthalide and Hexahydro-1,3-isobenzofurandione, are assignable to the anhydride hardener of the epoxy resin. The butyl acetate, and two other components, xylene and alkylbenzenes, are likely associated with the urethane paint on the cylinders. Information from the MSDS for the paint provided verification of the presence of these components. The origins of the 2-Heptanone and many other low concentration components identified by the TD-GC-MS are unknown. However, these compounds are not likely to be converted into 2-butoxyethanol in the presence of high concentrations of Alume™ and heat from the thermal desorption.

To summarize, chemical analysis of sample G, which was exposed to Alume™, revealed that 2-butoxyethanol was a good chemical tag for the presence of Alume™ on the fiberglass composite. Results of tests on fiberglass samples from the accident cylinder indicate that 2-butoxyethanol was present at numerous sites. These TD-GC-MS test results provide evidence that the accident cylinder was likely exposed to Alume™.

3.0 Conclusions

Results of the failure investigation indicate that the SCBA cylinder failure is consistent with stress corrosion cracking of the fiberglass composite. Glass fibers failed due to the combined action of an acidic chemical environment and the stress caused by the internal pressure. The SCBA cylinder was likely exposed to an aluminum cleaning fluid (Alume™), which contains acids that are known to aggressively attack glass. The corrosive action on the glass fibers, which are the load-carrying constituents of the fiberglass composite, was assisted by the stress imposed by the internal pressure in the cylinder. This combination of chemical attack and stress acting over several days led to the failure of the cylinder.

This conclusion is supported by the following evidence

- The macroscopic and microscopic fracture surface is characteristic of stress corrosion cracking in fiberglass composites.
- The results of the chemical analysis indicate that fiberglass samples of the failed cylinder contained 2-butoxyethanol, a chemical constituent of Alume™, a highly acidic fluid that chemically attacks glass.
- The rapid failure of specimens in stress corrosion cracking experiments provides qualitative verification that Alume™ did cause stress corrosion cracking of the accident cylinder. The appearance of fracture surfaces on the accident cylinder was very similar to the stress corrosion cracking observed on the sample exposed to Alume™ .
- Personal interviews indicate that during the training exercise on February 27, a fully wrapped composite SCBA cylinder was exposed to an aluminum cleaning fluid, which was likely Alume™.

Table I. Test Samples

Sample	Location[1]	Description[2]	Test
A	Fracture Surface Right of Label	Fiberglass + Beige Paint Tinge	SEM
B	Fracture Surface Above Label	Fiberglass	SEM
C	Fracture Surface Right of Label	Fiberglass	SEM
D	Fracture Surface Right of Label	Fiberglass	SEM
E	Fracture Surface Right of Label	Fiberglass + Beige Paint Tinge	SEM, EDS
F	Center of Label, Above "ISI"	Fiberglass + Clear Paint	Stress Corrosion
G	Fracture Surface Above/Right of Label	Fiberglass + Yellow Paint[2]	Stress Corrosion TD-GC-MS[3]
H	Right Edge of Label to Fracture Surface	Fiberglass + Clear Paint	TD-GC-MS
J	Fracture Surface Right of Label	Fiberglass + Beige Paint Tinge	TD-GC-MS
K	Below/Left of Label	Fiberglass + Yellow Paint	TD-GC-MS
1	Center of Label to Fracture Surface	Fiberglass + Clear Paint	TD-GC-MS
2	Below/Center of Label	Yellow Paint Scrapings	TD-GC-MS
3	Fracture Surface Right of Label	Fiberglass + Yellow Paint	TD-GC-MS
4	Center of Label Below "EFIC"	Fiberglass + Clear Paint	SEM, EDS
5	Below/Center of Label	Fiberglass + Yellow Paint	SEM, EDS
6	Fracture Surface Right of Label	Fiberglass + Yellow Paint	EDS

1. All specimen locations assume the cylinder is oriented vertically with the valve at the top.
2. The presence of paint is based on visual examination of the samples.
3. The portion of Specimen G used for TD-GC-MS testing did not have visible paint.

Approximate Sample Locations on Failed Cylinder

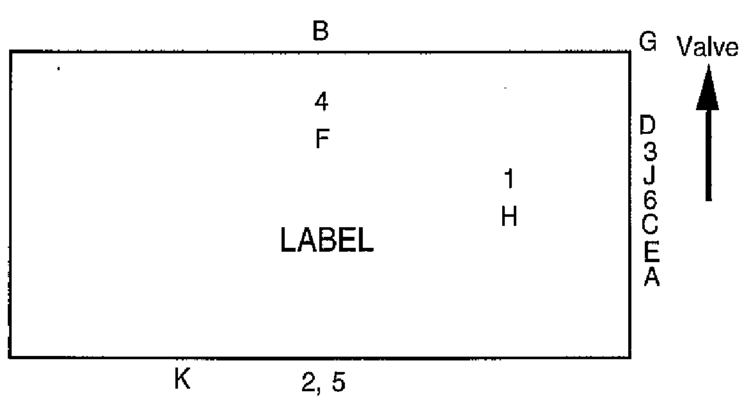

Table II. Summary of Primary Volatiles Found in Sample G

Retention Time, min	Identity of Volatile	Relative amount
1.51	ethanol	+
4.49	1,4-Dioxane	+++++++++++++
8.60	2-Butoxyethanol	+++++++++++
9.43	phenol	+
12.39	*cis*-Hexahydrophthalide	+
12.80	hexahydro-1,3-Isobenzofurandione	++++++++++++

Table III. TD-GC-MS Results for Sample 1

Retention Time, min	Identity of Volatile	Relative Amount
6.72	cyclopentanone	+
7.27	butyl acetate	+
8.42	2-heptanone	++
8.46	cyclohexanone	++
9.03	sec-butyl methacrylate	+
9.31	benzaldehyde	++
9.91	benzyl chloride	+
10.03	dimethyl butanedioate	+
10.09	benzyl alcohol	+
10.99	dimethyl pentanedioate	+++
11.88	dimethyl hexanedioate	+
12.51	*cis*-hexahydrophthalide	++++++++
12.98	hexahydro-1,3-isobenzofurandione	+++++++++++++++++++++
13.19	unidentified compound M/e 57,43,71,96	++
13.65	1-chloro-dodecane	+++
15.39	1,1'-dodecylidenebis[4-methyl-benzene]	+

Table IV. TD-GC-MS Results for Sample 3

Retention Time, min	Identity of Volatile	Relative Amount
2.22	trimethyl silanol	+
2.74	isobutyl acetate?	+++
3.51	1-butanol	++
7.37	butyl acetate	+++++++++++++++++
8.01	ethylbenzene	+
8.12	xylene	++
8.57	2-heptanone	+++++++++++++++++++++
8.66	2-butoxy-ethanol	+
8.88, 9.29, 9.35, 9.64, 9.94	1-ethyl-2-methyl-benzene or isomer	+++
9.35	2,6-dimethyl-4-heptanone	++
9.51	ethyl 3-ethoxy-propanoate	++
10.09	2-propenyl-benzene	+
10.14	1-methyl-3-propyl-benzene	+
10.21, 10.27, 10.47, 10.54, 10.75, 10.83, 10.87, 11.17	1-methyl-4-isopropyl-benzene or isomer	+
10.60	undecane	+
11.05	1-methyl-2-(2-propenyl)-benzene	+
11.39	1-dodecene	+
11.50	naphthalene	+
12.09	diisobutyl hexadioate & an alkane	+++++
12.40	*cis*-hexahydrophthalide	++
13.60	isobornyl acetate & 3,7-dimethyl-. 2,6-octadien-1-ol	+++
14.14	Mannitol?	++

Table V. TD-GC-MS Results for Sample H

Retention Time, min	Identity of Volatile	Relative Amount
6.02	cyclopentanone	+
8.00	cyclohexanone	++
8.56	2-cyclohexen-1-one	+
8.83	1-chloro-3-methyl-benzene	+
8.94	benzaldehyde	++
9.16	phenol	+
9.57	1-chloro-1,3,5-cycloheptatriene	+
9.73	dimethyl butanedioate	++
9.77	benzyl alcohol	+
10.67	3,5,5-trimethyl-2-cyclohexen-1-one	+
10.72	dimethyl pentanedioate	+++
11.20	1-decene?	+
11.34	decanal	+
11.63	dimethyl hexanedioate	++
12.25	*cis*-hexahydrophthalide	++++++++
12.73	hexahydro-1,3-isobenzofurandione	+++++++++++++++++++++
12.93	tetradecanal	+
13.23	1-(1-cyclohexen-1-yl)-1-propanone	++
13.38	1-chloro-dodecane	+++
13.48-15.03	background	

Table VI. TD-GC-MS Results for Sample J

Retention Time, min	Identity of Volatile	Relative Amount
6.44	N,N-dimethyl-formamide	+
6.52	3-hexene	+
7.08	butyl acetate	+++++++++
8.27	2-heptanone	+++++++++++++++++++
8.46	2-butoxy-ethanol	++
8.80	2-cyclohexen-1-one	+
9.06	1-chloro-2-methyl-benzene	+
9.12	1-chloro-4-methyl-benzene	+
9.16	benzaldehyde	+++
9.36	phenol	+
9.43	ethyl 3-ethoxy-propanoate	+
9.54	trimethyl benzene	+
9.61	3,4-dimethyl-2-hexanol	+
9.76	benzyl chloride	+
9.89	dimethyl butanedioate	++
9.95	benzyl alcohol	++
10.26	1,3-dihydro-2H-indol-2-one	+
10.53	N,N-dimethyl-benzenamine	+
10.59	unidentified compound M/e 57,42,56	+
10.68	2,6-dimethyl-2,5-heptadien-4-one	+
10.82	3,5,5-trimethylcyclohex-2-en-1-one	+
10.86	dimethyl pentanedioate	+++++++
10.99	(dichloromethyl)-benzene	+
11.34	1-decene?	++
11.48	decanal	++
11.75	dimethyl hexanedioate	++
12.05	diisobutyl hexanedioate?	+
12.39	*cis*-hexahydrophthalide	+++++++++++++++++++++
12.80	hexahydro-1,3-isobenzofurandione	+++++++++++++++++++
13.04	undecanal	+
13.34	1-(1-cyclohexen-1-yl)-1-propanone	++
13.49	1-chloro-dodecane	++++
13.56	isobornyl acetate	+
13.62	undecanenitrile	+
14.13	Mannitol?	+
14.17	2,6-di-*t*-butyl-4-ethyl phenol	+
14.82	1-chloro-hexadecane	+
15.14	background	
15.39	unidentified compound M/3 123, 138, 262	+

Table VII. TD-GC-MS Results for Sample K

Retention Time, min	Identity of Volatile	Relative Amount
2.00	trimethyl silanol	+
3.26	1-butanol	+
5.98	toluene	+
7.13	butyl acetate	++++++++++++++++
7.84	ethylbenzene	+
7.97	xylene	++
8.02	2-butanone	+
8.38	2-heptanone	+++++++++++++++++++++
8.50	2-butoxy-ethanol	++
9.04	Camphene	+
9.18, 9.25, 9.39, 9.54, 9.86	1-ethyl-2-methyl-benzene or isomer	+++
9.25	2,6-dimethyl-4-heptanone	++
9.43	ethyl 3-ethoxy-propanoate	++
10.14	1-methyl-3-propyl-benzene	+
10.20, 10.39. 10.47, 10.54, 10.67, 10.77, 10.81, 11.12	1-methyl-4-isopropyl-benzene or isomer	+
10.27	1-isocyanato-2-methyl-benzene	+
10.36	2-methyl-benzenamine	+
10.53	undecane	+
10.86	dimethyl pentanedioate	+
11.01	1-methyl-2-(2-propenyl)-benzene	+
11.34	methyl 2-hydroxy-hexadecanoate	+
11.45	naphthalene	+
12.06	diis0butyl hexadioate & an alkane	+++++
12.36	cis-hexahydrophthalide	++++
12.74	hexahydro-1,3-isobenzofurandione	+
13.58	isobornyl acetate & 3,7-dimethyl-2,6-octadien-1-ol	++++
14.14	Mannitol?	+++

Figure 1. Post-Failure Scene at the Bayview Station of the Humboldt Fire Department

Figure 2. View of Failed Cylinder after Accident

Figure 3. Close-up View of Failed Cylinder after Accident

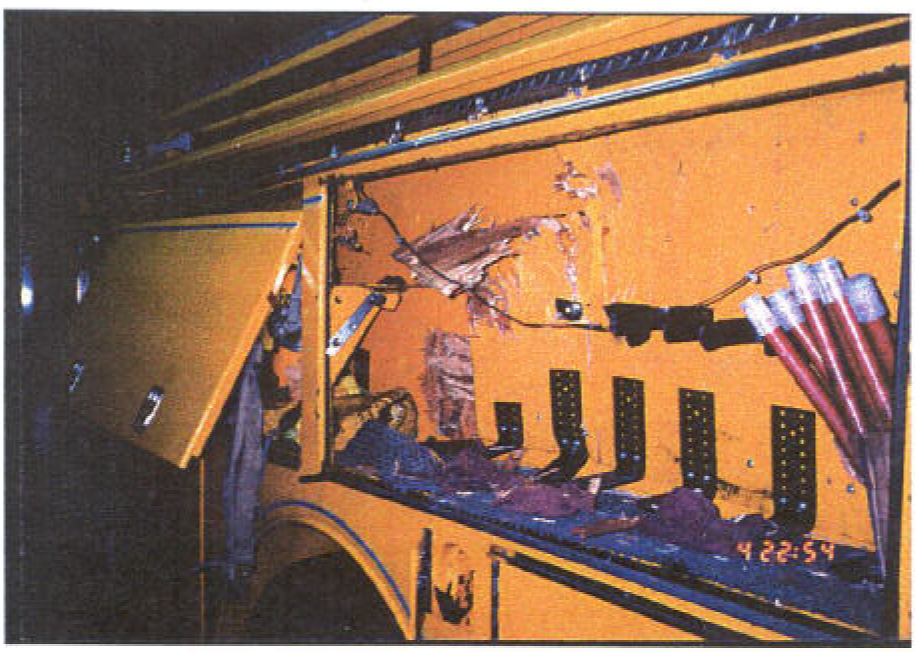

Figure 4. Compartment in Engine 1-7 where the Accident SCBA was Stored

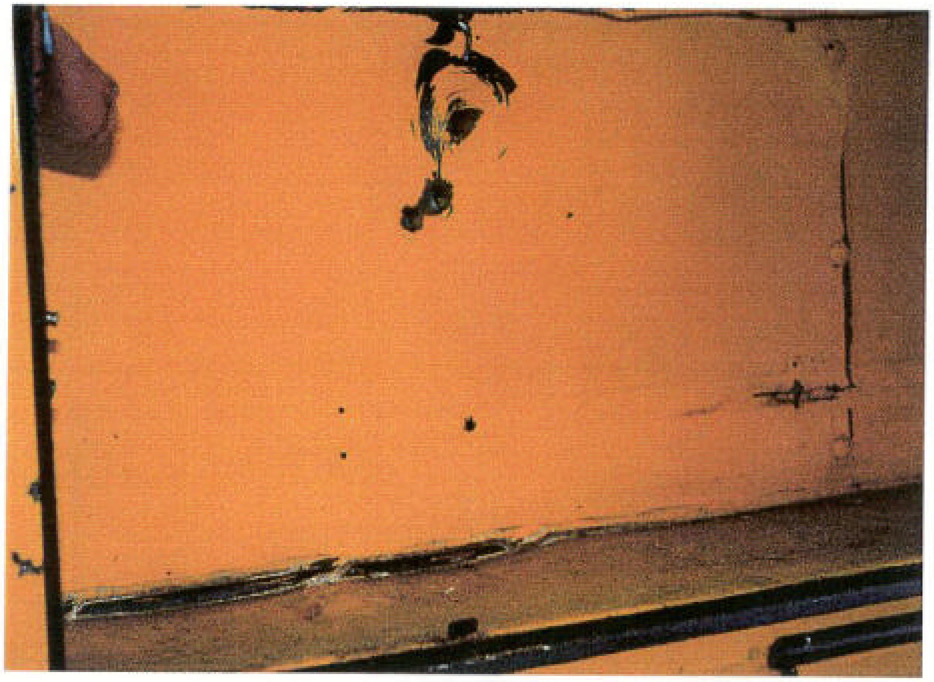

Figure 5. Interior of SCBA Storage Compartment in Engine 1-7

Figure 6. Failure Region of Accident SCBA Cylinder

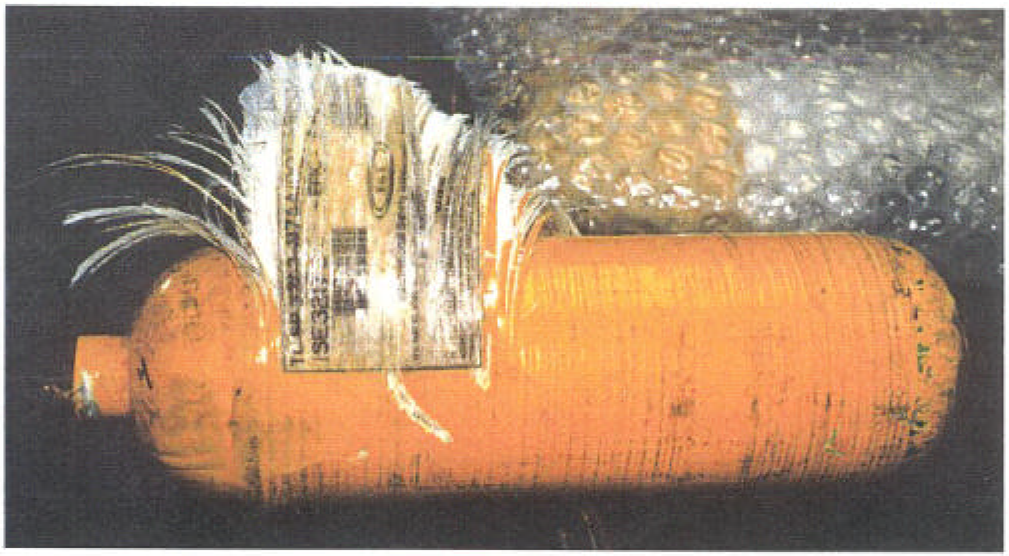

Figure 7. Label of Accident SCBA Cylinder

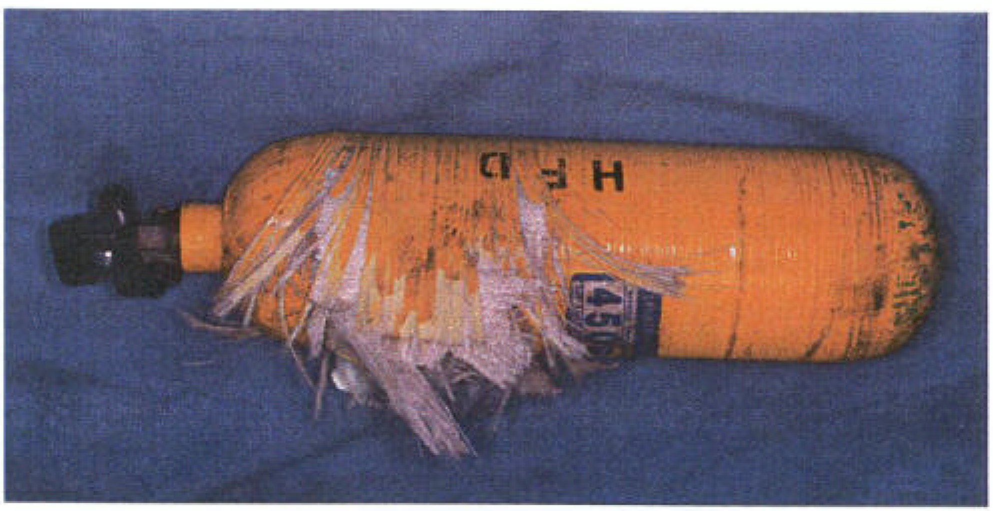

Figure 8. Initial Failure Region of Accident SCBA Cylinder

Figure 9. Exemplar Cylinders at Bayview Station (Label Side)

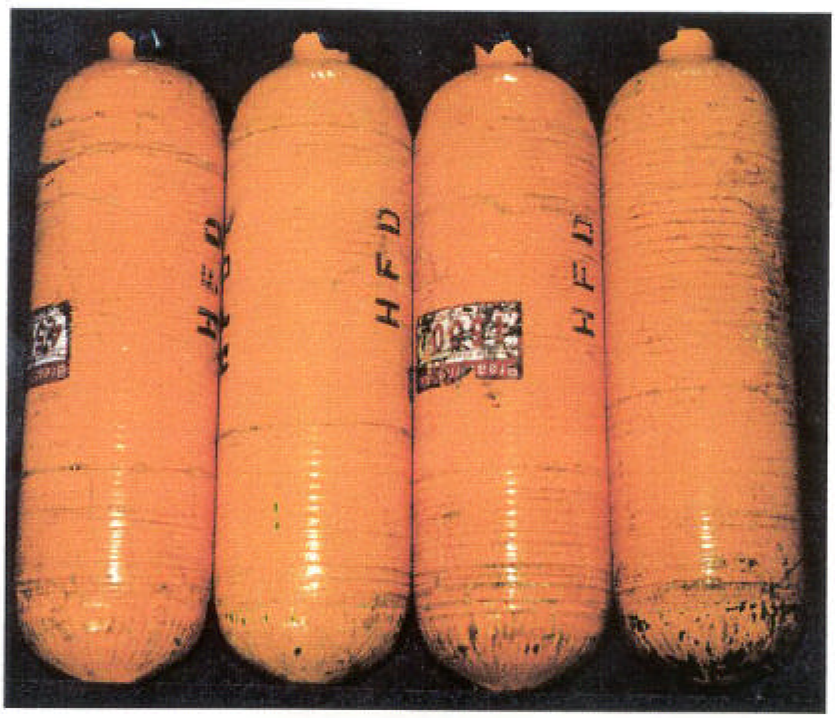

Figure 10. Exemplar Cylinders at Bayview Station (Side Opposite Label)

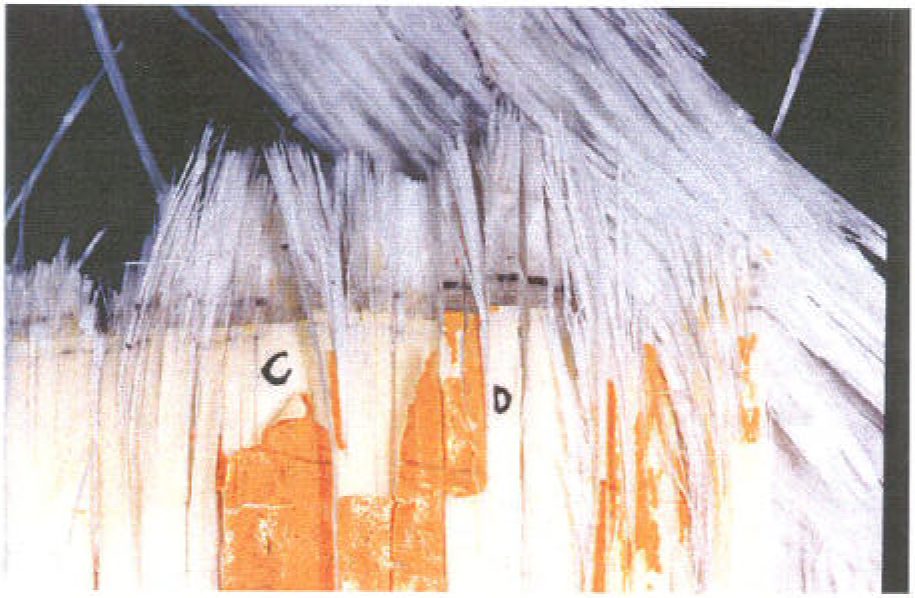

Figure 11. Appearance of Failed Circumferential Fibers at Initial Failure Site
(Letters refer to Test Specimen Locations)

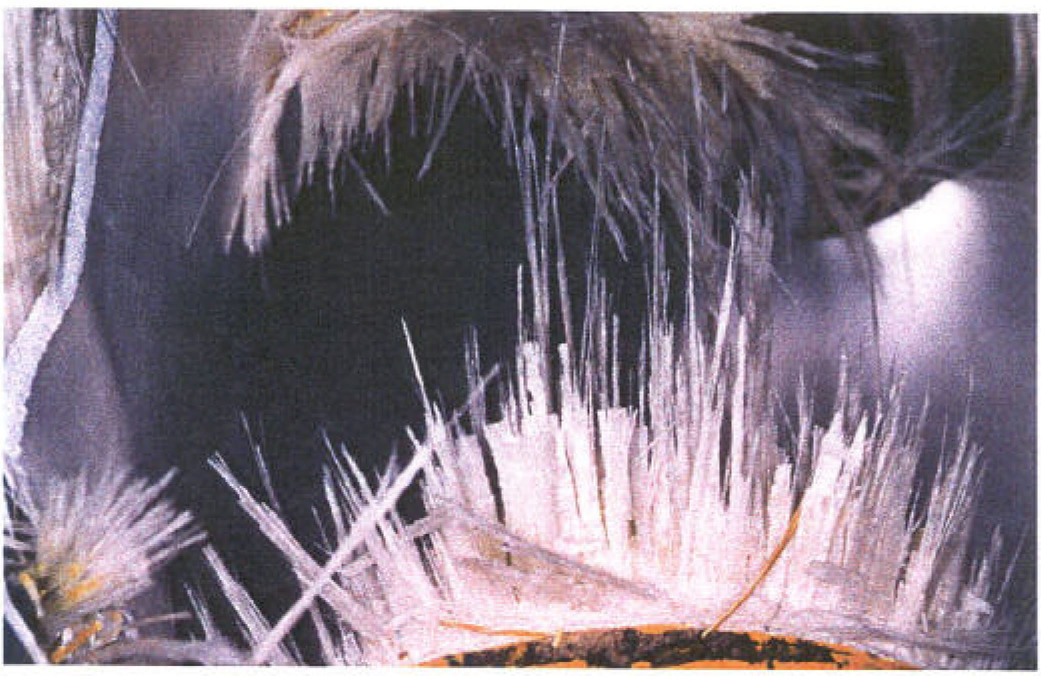

Figure 12. Appearance of Failed Longitudinal Fibers

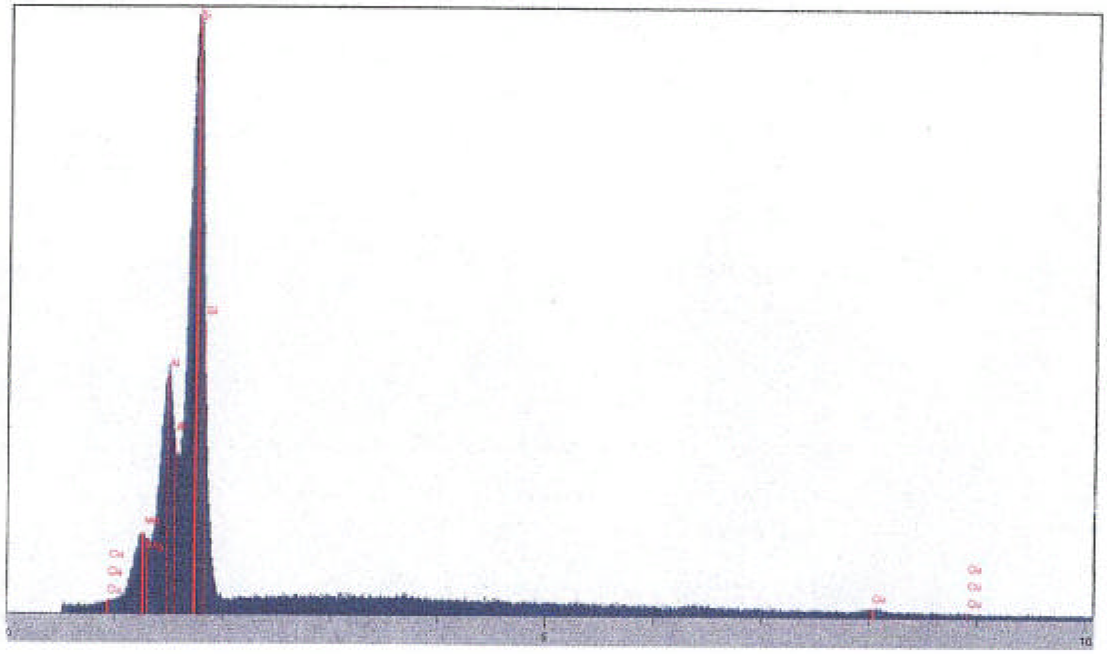

Figure 13. EDS Spectrum of Fiberglass Sample

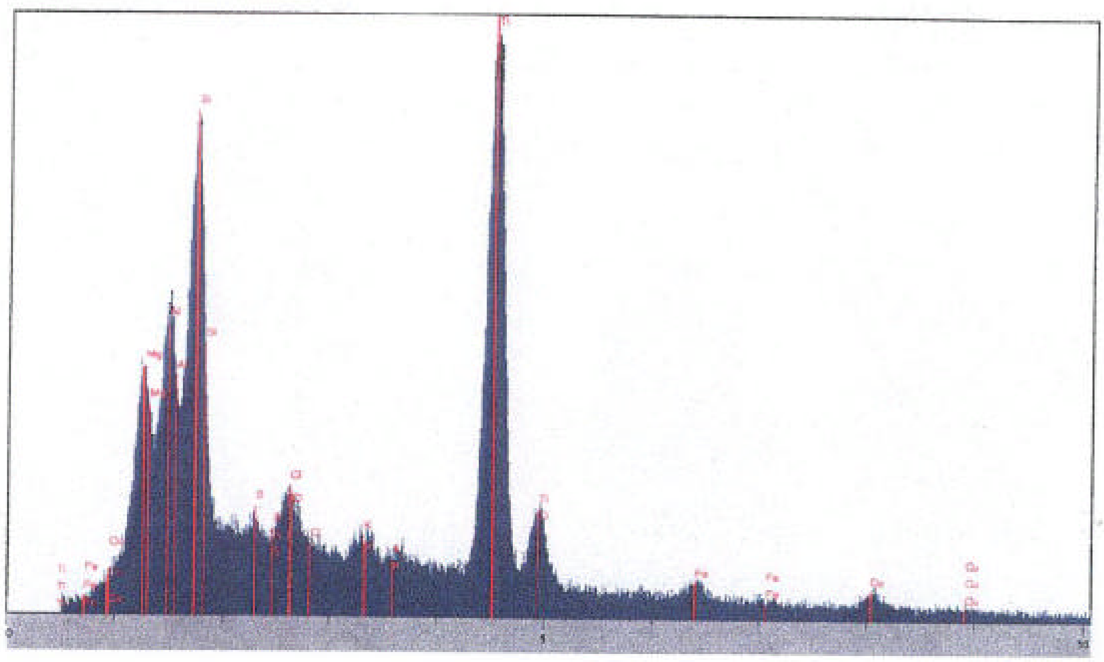

Figure 14. EDS Spectrum of Painted Fiberglass Sample

Figure 15. Scanning Electron Micrograph of Circumferential Fibers at Fracture Surface in Sample D - 50x Magnification

Figure 16. Scanning Electron Micrograph of Circumferential Fibers at Fracture Surface in Sample D - 240x Magnification

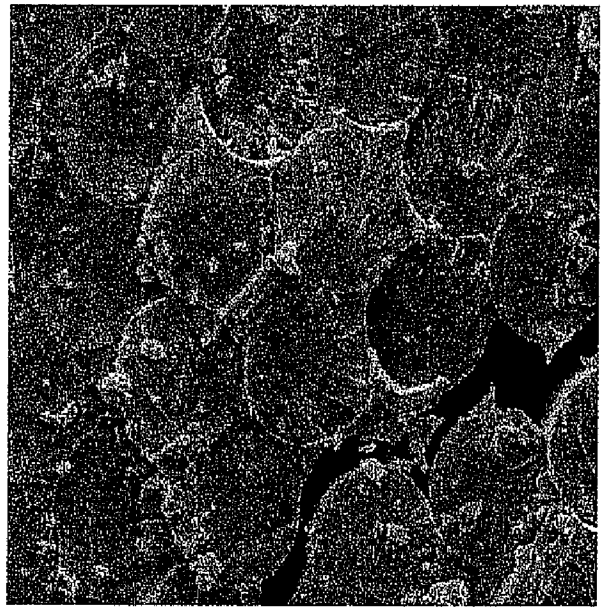

Figure 17. Scanning Electron Micrograph of Circumferential Fibers at Fracture Surface in Sample D - 2000x Magnfication

Figure 18. Scanning Electron Micrograph of Circumferential Fibers at Fracture Surface in Sample D - 4000x Magnfication

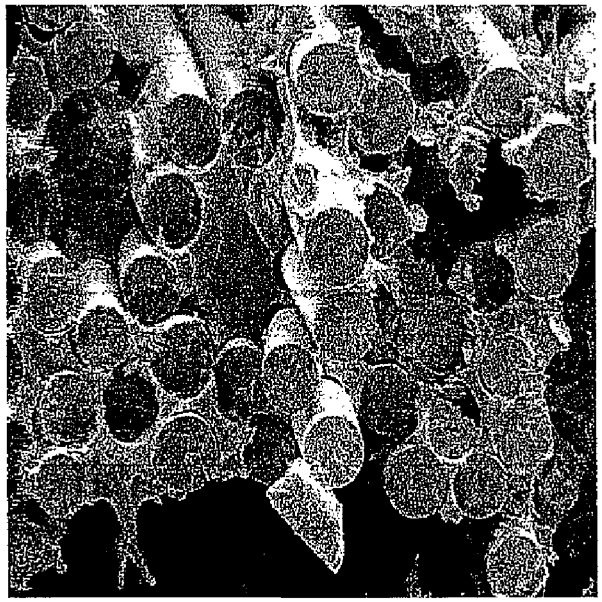

Figure 19. Scanning Electron Micrograph of Circumferential Fibers at Fracture Surface in Sample F after Exposure to Alume™ - 1000x Magnification

Figure 20. Scanning Electron Micrograph of Circumferential Fibers Fracture Surface in Sample F after Exposure to Alume™ - 2000x Magnification

Figure 21. Scanning Electron Micrograph of Circumferential Fibers Fracture Surface in Sample F after Exposure to Alume™ - 3500x Magnification

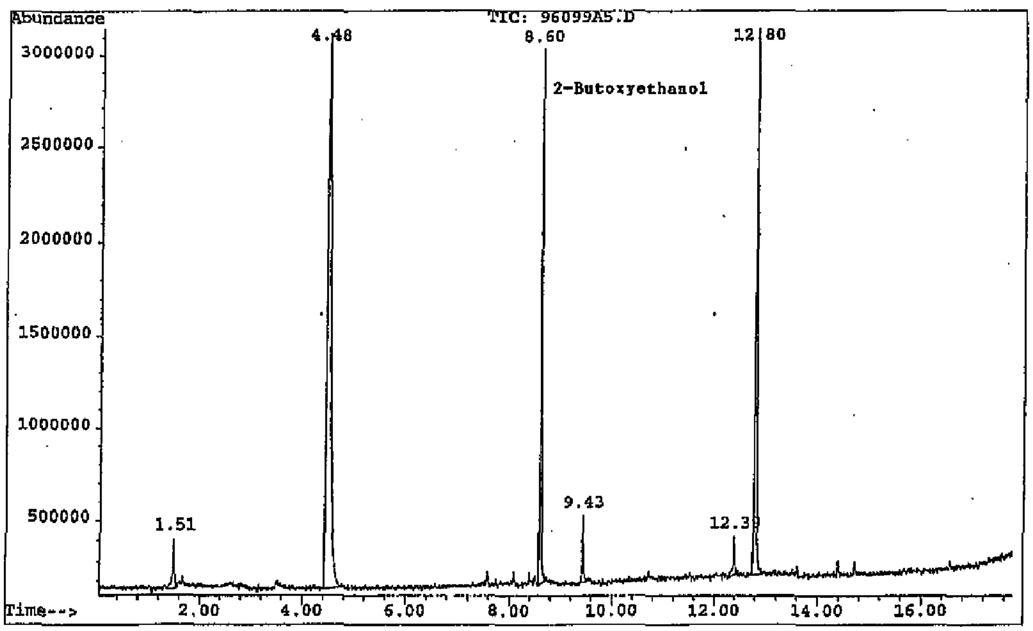

Figure 22. TD-GC-MS Chromatogram for Sample G