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ELECTRON MICROSCOPY ABRASION ANALYSIS of CANDIDATE FABRICS for PLANETARY SPACE SUIT PROTECTIVE OVERGARMENT APPLICATION

In Support of the
Abrasion Resistance Materials Screening Test

Prepared by: Mary J. Hennessy

Final Report to:

NASA
Lyndon B. Johnson Space Center
Crew & Thermal Systems Division

The University of Houston
Cullen College of Engineering
Dept. of Mechanical Engineering

JSC-25761

CREW AND THERMAL SYSTEMS DIVISION

NASA - LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

ELECTRON MICROSCOPY ABRASION ANALYSIS OF CANDIDATE FABRICS FOR PLANETARY SPACE SUIT PROTECTIVE OVERGARMENT APPLICATION

DOC. NO. CTSD-ADV-040 DATE AUGUST, 1992

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*Note: Due to the large number of figures in this report, a complete description of the lunar dust simulant figures and woven fabric sample figures can be found in the corresponding chapters.

ACRONYMS, ABBREVIATIONS and DEFINITIONS

CRT	Cathode Ray Tube
CTSD	Crew and Thermal Systems Division
denier	weight in grams of 9000 m of fiber
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
FEP	Fluorinated Ethylene-Propylene
JSC	Lyndon B. Johnson Space Center
LSS	Life Support System
micron	10^{-6} meter (μm)
mil.	0.001 inch
NASA	National Aeronautics and Space Administration
PGA	Pressure Garment Assembly
PLSS	Primary Life Support System
psi	pounds per square inch
PTFE	Polytetrafluoroethylene
rpm	revolutions per minute
SEM	Scanning Electron Microscope
SSA	Space Suit Assembly
TMG	Thermal and Micrometeoroid Garment

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2.0 INTRODUCTION

2.1 Presidential Directive

In commemoration of the 20th anniversary of the Apollo 11 lunar landing on July 20, 1989, President Bush called for a long range commitment to space exploration. He named the Space Station Freedom project as the next step in this country's space endeavors. As for the next century, Mr. Bush stated, "Back to the moon. Back to the future. . . this time to stay." The National Commission on Space agreed that "early outposts on the lunar surface are essential in the development of the space frontier". Included in his commitment to space exploration, the President called for a manned mission to Mars. Our President and our country's interest in space exploration is for practical and scientific reasons along with the desire to extend the human presence in our Solar System.

2.2 Importance of Extravehicular Activity

As a result of President Bush's space exploration directive, Extravehicular Activity (EVA) systems have been identified as being critical for the future investigation of the lunar and Martian planetary surfaces. EVA is defined as any operation performed outside the protective environment of a spacecraft by an astronaut requiring supplemental or independent life support equipment. During the Apollo lunar surface activities in the late 1960's and early 1970's, the importance of EVA increased and space walks became a fundamental part of NASA's manned operations. Today, EVA is a common procedure in our current Space Shuttle program.

There are advantages to having humans perform EVA tasks. Astronauts provide both mental and physical flexibility that is not currently available with robots or automated equipment. A crewman is able to make real-time decisions about tasks that are either practiced, unscheduled or contingent. Astronauts are also able to perform complex physical tasks that cannot be accomplished with machines.

2.3 Purpose and Description of EVA operations

Astronauts engage in EVAs both on planetary surfaces and in zero-gravity conditions. Basic EVA task operations include performing visual inspections, manual repair, maintenance and replacement of equipment, locomotion and translation activities, and the handling of tethers, tools, and equipment modules. Primary tasks performed on the Apollo missions involved exploration of the lunar surface, placement of scientific equipment, and collection of geologic samples of lunar surface material. EVA's are also common during current Shuttle flights. One task performed by suited astronauts that is unique to the Shuttle EVA program is the rescue, repair or deployment of satellites. Generally, our knowledge of 'space' is enhanced by having humans leave the spacecraft to work in extraterrestrial environments.

2.4 Description of EVA Space Suits

The equipment used by an astronaut to leave the protection of the spacecraft and work in extraterrestrial environments is the Extravehicular Mobility Unit (EMU). The EMU maintains the physiological well-being of the crewman and is an anthropomorphic system that provides protection from the extravehicular environmental hazards along with mobility and communications. The EMU is divided into two systems - the Primary Life Support System (PLSS) and the Space Suit Assembly (SSA). The SSA is a pressurized garment and is what one normally thinks of as the "space suit".

The Apollo SSA Pressure Garment Assembly included the helmet and visor, gloves, boots, and a one-piece fabric body garment which covered the torso, arms and legs. The body garment had two layers. The purpose of the inner-most layer, known as the pressure bladder, was to retain the pressurizing oxygen environment inside the suit. The purpose of the outer 'restraint' layer was to handle the suit pressure, man, and equipment loads. A multi-layered fabric Thermal and Micrometeoroid Garment (TMG) covered the gloves, boots and body garment to protect from environmental hazards.

Current Shuttle SSA construction is similar in nature to the Apollo suit. The Shuttle suit includes a helmet/visor assembly, boots, and gloves along with fabric arms and legs; however, the upper torso of the Shuttle SSA is comprised of a hard fiberglass layup. Like the

Apollo suit, the arms and legs are two layers of fabric - a bladder and a restraint layer. A TMG is also worn over the gloves, boots, arms, legs and torso of the Shuttle SSA.

2.5 Dust as an Environmental Hazard

Based on the experience gained from Apollo EVA missions, it was determined that space suits to support future, long-duration planetary missions would be significantly different than the original Apollo suits. A primary reason to redesign space suits for future planetary exploration is the environmental challenge of surface dust.

Surface dust has been identified as the most serious environmental problem for routine EVA operations on the moon and Mars. Dust is an omnipresent fact of life on the moon and poses potential hazards to human health, surface system mechanisms and surface operations. A layer of fine, abrasive dust particles covers the entire lunar surface; these particles adhere to every object and can penetrate very small openings. Martian EVA missions would also have to withstand the additional risk of seasonal dust storms that envelop the planet.

Following are comments made by Apollo astronauts regarding the lunar surface dust:

"I got quite concerned with not only the wear and tear on the suits, but with the effect of the dust on the suits. . ." Apollo 12

"Our feet and hands and our arms were all full of dust when we put the suit on. . ." Apollo 16

"I think dust is probably one of our greatest inhibitors to a nominal operation on the moon. I think we can overcome other physiological or mechanical problems except dust. . . I think one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal and its restrictive, friction-like action to everything it gets on. . . "Apollo 17

Figure 1 shows an Apollo 16 astronaut collecting lunar surface samples. The soot-like dust covers the entire lunar terrain. The

Figure 1

astronaut's EVA suit is contaminated by dust, especially the lower leg and knee area, lower arms and elbows, and gloves. It is easy to see that the dust is also soiling the other EVA equipment.

Figure 2 shows an Apollo 11 astronaut footprint. This photo gives a closer look at the lunar surface and illustrates the depth of a footprint in the lunar dust.

During the Apollo EVAs, lunar dust contamination resulted in the deterioration of SSA materials, mechanical closures and bearings. It is of utmost importance that future planetary suits be designed to withstand the effects of the abrasive, contaminating, surface dust so that space suit performance will not be compromised.

3.0 BACKGROUND

There are many adverse effects of planetary surface dust on EVA systems and equipment. This study addresses the abrasive effects of the dust on the outermost fabric layer of the SSA.

In response to the problem of contaminating, abrasive planetary dust, the Abrasion Resistance Materials Screening Test originated at NASA - JSC in the summer of 1990 under the direction of Joseph J. Kosmo of the Crew and Thermal Systems Division. Test activities included the preliminary screening of five candidate protective overgarment fabrics for potential, future, lunar and Martian planetary surface space suit applications. A test cylinder of each fabric was placed in a rotary tumbler with simulated lunar surface material and continuously tumbled for eight hours representing 'worst case' Extravehicular Activity. After tumbling, the fabrics were vacuumed cleaned and visually inspected for abrasion.

Along with the visual inspection of the woven fabric samples, the investigation continued by means of a Scanning Electron Microscope (SEM). This paper presents an SEM analysis of the abrasion seen by the five candidate fabrics. Additionally, an SEM analysis of Alan Bean's Apollo 12 Thermal and Micrometeoroid Garment (TMG) outer cover layer fabric was completed as a comparative baseline.

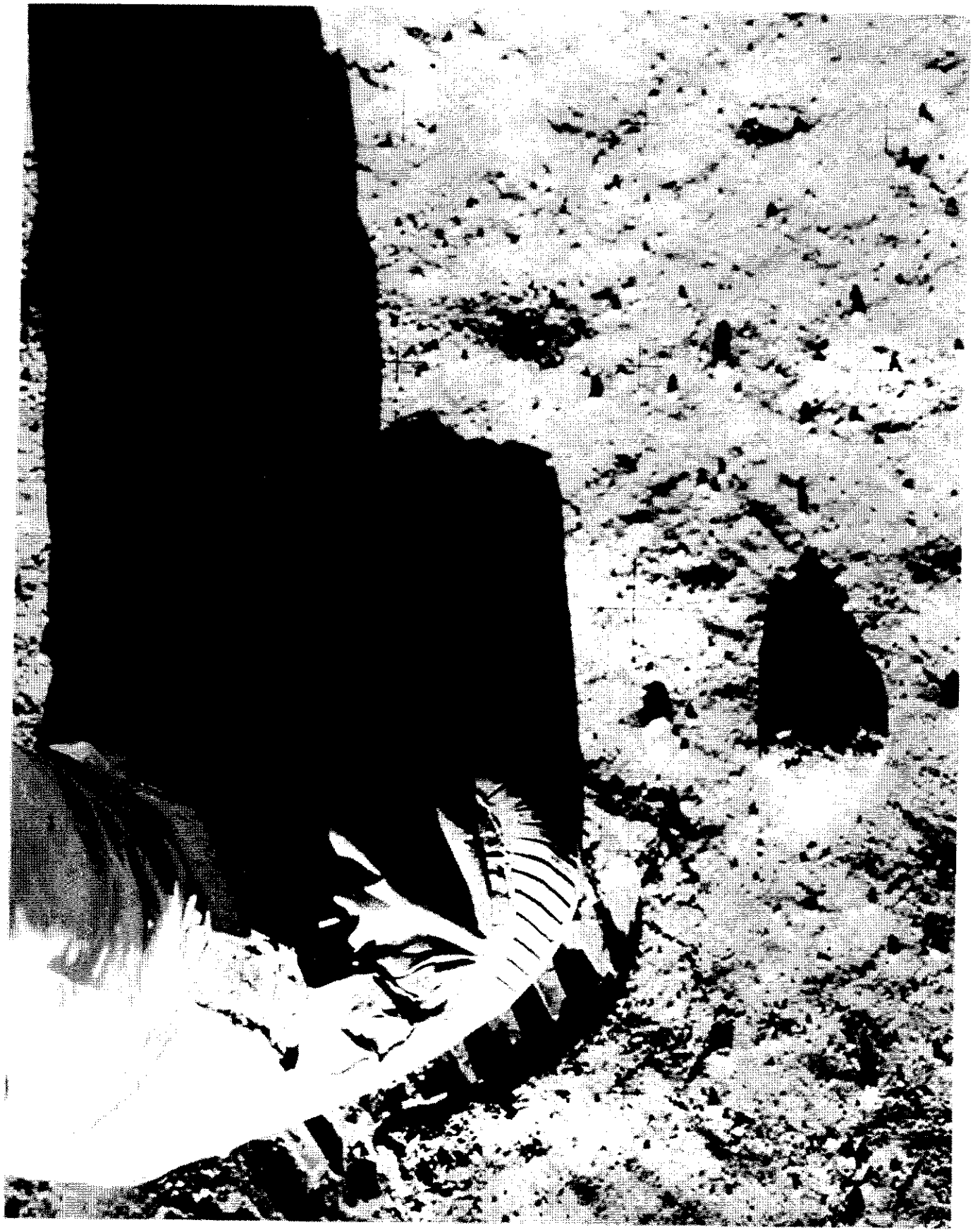


Figure 2

4.0 PURPOSE

The Electron Microscopy Abrasion Analysis of Candidate Fabrics for Planetary Space Suit Protective Overgarment Application is in support of the Abrasion Resistance Materials Screening Test.

The fundamental assumption made for the SEM abrasion analysis was that woven fabrics to be used as the outermost layer of the protective overgarment in the design of the future, planetary space suits perform best when new. It is the goal of this study to determine which of the candidate fabrics was abraded the least in the tumble test. The sample that was abraded the least will be identified at the end of the report as the primary candidate fabric for further investigation. In addition, this analysis will determine if the abrasion seen by the laboratory tumbled samples is representative of actual EVA Apollo abrasion.

5.0 SCOPE

The electron microscopy abrasion analysis of the candidate fabrics included the following activities:

1. Devising a logical, systematic approach to the data collection. This included deciding to inspect each sample under three fabric conditions - new, tumbled and cleaned. The third condition involved subjecting a piece of the vacuum cleaned, tumbled fabric to an additional ultrasound cleaning procedure to remove as much dust as possible.

2. The SEM was used to inspect each sample under the above mentioned fabric conditions. The strategy of the SEM analysis included the following considerations:

   - Abrasion is a process of wear in which a soft surface is scratched by hard particle.
   - The effects of abrasion are found by studying the topography of the damaged surface.
   - The analysis involved discovering what kind of micromechanism was active during the wear process; this identified mechanism will be held responsible for producing the observed damage resulting in the sample surface being scarred.

3. Data collection involved producing a series of micrographs (SEM photographs) for each candidate fabric sample. To determine the extent of abrasion, the micrographs were used to answer the following questions:

   A. How do the three conditions of the sample compare?
   B. On the tumbled samples, is the viewer looking at abrading particles or at fiber debris?
   C. How much of the dust can be cleaned off of the samples with the ultrasound procedure?
   D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?
   E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

F. Did the back face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

G. How do the results of the SEM analysis compare with the tumble test visual inspection?

4. The outermost layer of an Apollo 12 TMG that was worn and abraded during actual lunar EVAs was inspected with the SEM in the same manner as the candidate fabrics from the Abrasion Resistance Materials Screening Test. The Apollo sample micrographs were used to answer the same questions that were asked of the other candidate fabrics.

5. The primary reason for the SEM evaluation of the Apollo 12 TMG sample was to determine if the tumble test accurately simulated actual Apollo EVA abrasion of woven fabrics.

6. After the comparsion of each sample to itself, the samples were compared to each other.

7. The final activity of the analysis is to answer the questions: Is it possible to determine which sample was damaged the least? If so, which sample should be identified as the primary candidate fabric for further investigation?

6.0 ABRASION RESISTANCE MATERIALS SCREENING TEST

6.1 Lunar and Martian Dust Characteristics

The first task in preparing for the Abrasion Resistance Materials Screening Test was to review the characteristics of lunar and Martian surface dust.

Organic topsoil, rock, sand, and water are a few examples of the varied surface materials we have here on Earth. In contrast, the lunar surface is comprised of essentially one material - lunar dust. The geotechnical properties of lunar dust have been evaluated by testing core samples, by in-situ penetrometer measurements and by observations made during Apollo EVA missions. These evaluations have revealed that there are fewer geotechnical properties of the lunar surface material than there are of surface materials from Earth because a large portion of the soil is glass-like. Its composition is due to the absence of terrestrial geological processes which produce well-sorted sediments.

The most important difference between terrestrial and lunar surface material is the relative density of the dust. Bulk densities of lunar dust range from 0.85 to 1.9 g/cm^3 for the upper 30 cm of the lunar regolith.

Another characteristic of lunar surface dust is that it is comprised of extremely fine, irregularly-shaped, sharp-edged debris. The median particle size is 40 to 130 microns (micron = 10^{-6} meter). The average particle size is 70 microns while particles smaller than 20 microns constitute 10 to 20 percent of the regolith material.

Electric charge, vacuum adhesion and low gravity are the causes for the thin layer of lunar dust that adheres to every object it comes in contact with. The dust is easily dislodged and rises in a cloud when disturbed, with each particle following a ballistic trajectory. The low gravity also permits the dust to be kicked in long trajectories above the lunar surface. When the dust particles travel at a significant horizontal velocity, they can cover considerable distances and may have a sand-blaster effect on other exposed surfaces.

The Martian surface material has been characterized based on information from the Viking lander mission.

Refer to Figure 3 for list of lunar and Martian dust characteristics.

6.2 Description of Dust Simulant

The University of Minnesota, Space Science Center, has done extensive research in the area of simulating lunar and Martian surface dust. Their guidelines state that dust simulants can be "any material manufactured from natural or synthetic terrestrial or meteoritic components for the purpose of simulating one or more physical and or chemical properties of a lunar or Mars rock or soil."

Due to the nature of the tumble test, a simulant was required that would represent the characteristic physical properties of size, shape and density of lunar soil. Such a simulant would allow the necessary physical interaction of the dust and suit fabric during tumbling, modeling the EVA abrasion of the outer-layer of the SSA.

A lunar dust simulant of ground and sieved glass with a mesh of 35 to 150 microns was obtained from the University of Minnesota for use in the tumble test. This glass, along with crushed volcanic rock were the materials chosen to model lunar surface dust during the in-house tumble test of the candidate, outer-layer fabrics.

6.3 Candidate Fabrics Used in This Investigation

Future lunar and Martian planetary EVA missions require space suits that will be able to withstand the effects of the abrasive, contaminating surface dust. The outermost fabric layer of the SSA softgoods will be most affected by the dust. In the tumble test, five candidate woven fabrics were evaluated for potential, future, lunar and Martian planetary surface space suit protective overgarment applications.

For the purposes of this analysis and report, the five candidate woven fabrics were assigned sample numbers:

Sample 1:	Orthofabric
Sample 2:	Orthofabric - back face coated with 10 mil. silicone
Sample 3:	Gore-Tex - back face laminated with 2 mil. FEP (Teflon)
Sample 4:	Gore-Tex - front face laminated with 2 mil. FEP (Teflon)
Sample 5:	Apollo Test Article Teflon (T162)

Throughout the rest of the paper, the candidate woven fabrics will be identified by their sample numbers.

These samples represent potential woven fabrics to be used in the design of the future, planetary SSA. Samples 1 through 4 represent candidate fabrics for possible use in a single fabric design as the outer protective layer of the SSA. Sample 5 is the outermost layer of a double-outer-layer design used in the Apollo program. This design included Beta (4484) underneath the Teflon (T162) - both were considered the outer-layer; however, only the T162 will be analyzed in the tumble test study.

Detailed information about each woven fabric used in this test can be found in the individual sample chapters later in the report.

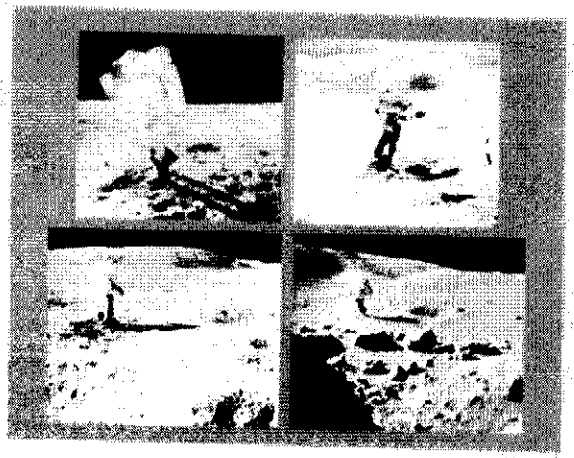
6.4 Description of Tumble Test

The goal of the Abrasion Resistance Materials Screening Test was to simulate the physical interaction of the simulated planetary dust and candidate protective overgarment space suit material. This was accomplished by means of a 'tumble test' which is described in Figure 4.

A pressure test cylinder was manufactured to model a space suit element without a TMG. The cylinder itself was fabricated of current Shuttle SSA materials - an inner bladder of urethane coated nylon and an outer restraint layer of Dacron polyester. The

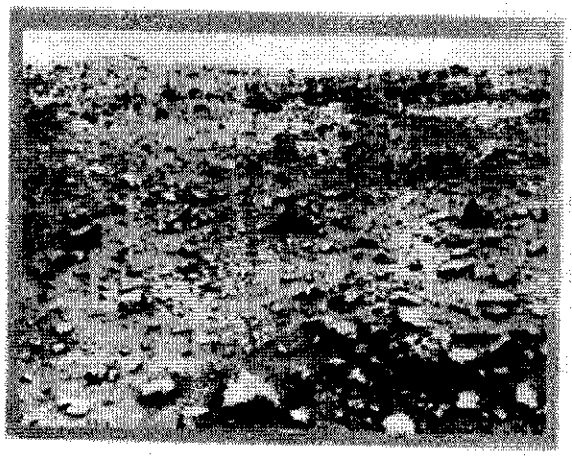
Planetary Dust Characterization
(EVA Systems)

Lunar



- Benign environ.; no atmosphere
  - No transport medium (wind)
  - No saltation (particle movement)
- Particle characteristics:
  - Sharp-edged, irregularly shaped
  - Size range: 40 - 130 microns
  - Composition: rock/mineral fragments; glasses in various forms
  - Potentially more abrasive than Mars particles
- Higher/longer "kick-height" particle range
  - Due to lower gravity than Mars

Mars

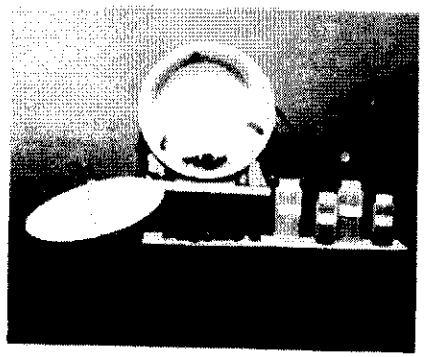


- Active environ.; CO_2 atmosphere
  - Wind: few m/sec. - 30 m/sec. gusts
  - Low density/pressure (7 mb)
  - Minimum saltation (due to wind effects) (No concern above 1 m heights)
- Particle characteristics
  - Rounded shape due to "weathering"
  - Size range: 0.1 - 10 microns
  - Composition: rock/mineral fragments, oxides, etc.
  - Potentially corrosive (?)
- Dust storm phenomenon
  - Low dust concentration and fall-out (<1 micron annually/Viking 2)
  - Lighting contrast only slightly affected
  - Good visibility (~10 km) even during storm
  - Less concern than originally thought (Termination of EVA not required)

Figure 3

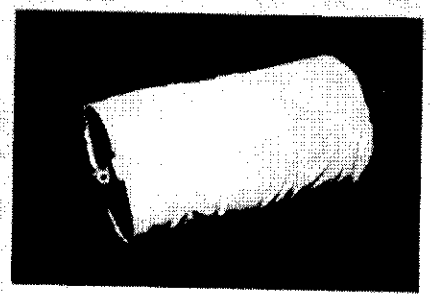
Abrasion Resistance Materials Screening Test

Comparative Evaluation Baseline



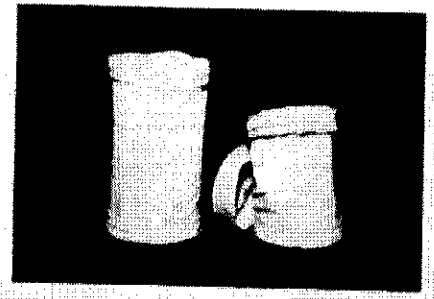
NASA-JSC In-House Developed Rotary Tumbler

- 16 in. diam. by 20 in. length cylinder
- Belt driven by 1/4-HP motor
- Cylinder rotates at 13 rpm



Pressure Test Cylinder

- Urethane coated nylon bladder
- Polyester (Dacron) restraint
- Pressurized - 6.0 psig



Candidate Fabric Materials

- Various outer layer materials and insulation layups
- Utilize standard fabric space suit fabrication techniques

Test Conditions

- Simulated planetary surface
  - 5 lbs. volcanic rock
  - 10 oz. sieved refactory glass particles (35-140 mesh)
- Continuous tumbling
  - 8 hr EVA "worse case"

Figure 4

ends of the cylinder were capped with pressure plugs and the whole assembly was pressurized to 6.0 psig.

A protective overgarment test article, with various insulation layups, was constructed of each candidate fabric. The protective overgarments were manufactured with standard fabric space suit techniques and were made to fit over the pressure test cylinder as a TMG fits on the SSA. The end-caps of the test article attached to the body of the garment with a velcro closure.

The rotary tumbler was built in-house at NASA-JSC. The tumbler's test cylinder measured 40.6 cm (16 in.) in diameter and 50.8 cm (20 in.) long. It was belt driven by a one-quarter horsepower motor; the cylinder speed was 13 rpm.

The actual test involved placing the pressure test cylinder covered by the candidate fabric overgarment in the tumbler with the lunar surface simulant. The simulant consisted of 2.3 kg (5 lbs.) of volcanic rock and 284 g (10 oz) of sieved refractory glass particles with 35-150 micron mesh. The tumbler was sealed and the test involved continuous tumbling for eight hours to simulate 'worst case' EVA planetary abrasion exposure representative of extensive EVA use.

Each of the five candidate fabric samples were tumbled separately. After tumbling, the outside of the test cylinder assembly was vacuum cleaned and the protective overgarment removed from the pressure test plug. A longitudinal seam was opened and the excess dust from the inside of the layup was shaken out; both this and the external vacuum cleaning insured that the majority of the loose dust had been removed from the test article.

6.5 Results of Tumble Test

After tumbling, the sample protective outergarments were visually inspected for surface and structural damage.

The inspection of Samples 1, 2, 3 and 5 revealed that there was still a significant amount of dust on each sample fabric even after vacuuming. Additionally, Sample 1 had a few very small cuts and holes in the fabric along the longitudinal seam and on the endcaps. Sample 2 did not have any holes or cuts. Sample 3 had fewer small

cuts and holes than Sample 1. Sample 5 had only one small hole on the endcap.

Sample 4 was clearly the most abraded candidate protective outergarment. Although there wasn't as much dust adhereing to the fabric after vacuuming as there was on the other samples, the outer surface laminate layer was shredded and peeling away from the fabric on both the body of the test article and on the endcaps. Due to the extent of the abrasion, Sample 4 was eliminated from consideration as a candidate fabric.

The visual inspection of Samples 1, 2, 3 and 5 was inconclusive as to which suffered the least abrasion; it was decided that further investigation was necessary. These four samples were given a closer look with a scanning electron microscope.

Refer to the individual sample chapters that follow in the report for photos of the protective overgarment test articles from the tumble test and an SEM analysis of Samples 1, 2, 3 and 5.

7.0 ELECTRON MICROSCOPY ABRASION ANALYSIS

7.1 Explanation of Microscopy as an Investigation Tool

The basic function of the SEM is to scan an electron beam across the surface of a specimen and return to the operator an image of that specimen on a CRT screen. The image is intuitively interpretable as a three-dimentional likeness of the specimen's surface topography. The operator is then able to produce micrograph data by recording the image photographically.

The SEM has the ability to magnify images from 5x to 300,000x. Due to the practical resolution limit of the fabric specimens, the magnification range used in this abrasion analysis was 7x to 14,700x.

The SEM models used in the study were a Cambridge 250 MK3 located at the University of Houston in the Electrical Engineering Department and an Amray Model 1400 located at NASA-JSC in the Structures and Mechanics Division.

7.2 Sample Introduction

This abrasion analysis includes an electron microscopy evaluation of the following samples:

Sample 1:	Orthofabric
Sample 2:	Orthofabric - back face coated with 10 mil. silicone
Sample 3:	Gore-Tex - back face laminated with 2 mil. FEP (Teflon)
Sample 4:	Not Included*
Sample 5:	Apollo Test Article Teflon (T162)
Sample 6:	Apollo 12 Teflon (T162)

Samples 1, 2, 3 and 5 are the candidate protective overgarment fabrics that experienced eight hours of tumbling in the Abrasion Resistance Materials Screening Test. (*Note: The abrasion resistance of Sample 4 was very poor so it was eliminated from consideration).

The tumble test described in Section 6.4 was chosen to simulate worst case EVA abrasion of the candidate fabrics. However in the textile industry, it is a widely recognized fact that none of the various laboratory abrasion tests accurately simulate actual fabric abrasion. The decision to include the Apollo 12 Teflon (T162) protective outerfabric in the electron microscope analysis was made so that a comparison could be done of Sample 5 and Sample 6. The goal of the comparison was to determine if the abrasion seen by the Apollo test article from the tumble test resembled the damage of the Apollo 12 TMG that was abraded during real-time lunar EVA use.

7.3 Sample Preparation

Initial note: During the entire electron microscopy abrasion analysis, extreme care was taken when handling the test articles and the Apollo 12 sample. This was to avoid rubbing off the tumble test dust simulant or lunar surface dust, or causing further abrasion. All cut samples were manipulated with tweezers to also avoid adding foreign dirt to the specimens.

Swatches of Samples 1, 2, 3, and 5 measuring 10 x 10 cm (3.9 x 3.9 in.) in the three conditions of new, tumbled and cleaned were obtained. New specimens were cut from bolts of fabric. The tumbled specimens were cut from representative dusty areas of the tumbled test articles. To obtain cleaned samples, a swatch of the tumbled fabric was subjected to an ultrasound cleaning procedure. A 5 x 5 cm (1.9 x 1.9 in) tumbled sample was cut and submersed in a beaker of deionized water (approximately 50 ml). The beaker was placed in an ultrasound generator for five minutes. Then the fabrics were removed, rinsed with deionized water and blown dry with facility air.

A 10 x 10 cm (3.9 x 3.9 in) swatch of Alan Bean's Apollo 12 A7L SSA was obtained for Sample 6. The swatch was taken from the left knee of the TMG; this was one area of the SSA that became heavily abraded during the lunar EVAs. The White Sands Test Facility conducted an examination of this space suit in 1970. The goal of their test was to determine the particle size range distribution of lunar dust on the SSA; the left knee was investigated three inches below the knee area used in the abrasion test. During the White Sands test the SSA underwent extensive cleaning. This is probably the primary reason that the ultrasound procedure did not clean the fabric any further during the SEM analysis. Additionally, there has been an unknown amount of handling of the Apollo 12 TMG over the past twenty-three years. Since the main difference between Samples 5 and 6 is that one was abraded in a laboratory test and one was abraded during actual use, the new specimen obtained for Sample 5 was also used as the new specimen for Sample 6.

The new, tumbled and cleaned fabric specimens of Samples 1, 2, 3 and 5 and the dusty Apollo 12 specimen were cut into 1.5-2 cm (0.59 - 0.79 in.) squares and mounted on SEM sample holders. Since the specimens acted as a ground for the electron beam in the microscope, it was necessary to make the samples conductive by coating them with gold. The average depth of the gold coating on each sample was 1000Å (Å = 10^{-10} m); the gold was thick enough to completely coat the surface of the specimen but thin enough so that it would not hide the dust and minute details of the fabric surfaces under high magnification.

7.4 Description of Microscopy Procedure

The samples were individually placed in the SEM vacuum chamber which was pumped down to 1 x 10^{-7} mm Hg (1.93 x10^{-9} psi). Once all necessary adjustments were made to the SEM, an initial visual observation was made of the specimens to get an overall feel for what the fiberous structures looked like. Areas of interest were identified and photographed. A set of micrographs was assembled for each sample according to the data collection logic described in the next section.

7.5 Introduction to Sample Chapters

7.5.1 Sample Chapter Logic

The SEM analysis begins with a familiarization of the lunar dust simulant. Chapter 8 presents three simulant micrographs along with a complete description of what the dust looks like. It is important to be familiar with the simulant so that the dust particles can be recognized on the fiberous structure samples.

Chapters 9 through 14 contain the micrograph data sets and the analysis of each candidate sample. Note that even though Sample 4 was not included in the electron microscopy analysis, a chapter has been dedicated to this sample to explain the results of the tumble test in greater detail.

Chapters for Samples 1, 2, 3, 5 and 6 are arranged according to the following outline:

I. <u>Sample Introduction</u>
   - Fabric name
   - Fabric application
   - Reason for including the sample in the test
   - Yarn count and name of fiber(s) in the fabric
   - How the fiber(s) are made
   - Denier of fiber(s)
   - How the fabric is woven

II. <u>Specifications of the Woven Fabric</u>
   a. Fabric Weight
   b. Physical Properties:
      - specific gravity
      - breaking strength
      - ultimate elongation
   c. Mechanical Properties:
      - tear resistance

III. <u>Abrasion Resistance Materials Screening Test Results</u>
   - Photos of the sample fabric test cylinder before and after tumbling along with the test results

IV. <u>Micrograph Analysis</u>
   - Micrograph figure arrangement chart
   - Complete set of micrographs for the sample
   - Analysis of each individual micrograph view to answer the

following questions:

A. How do the three conditions of the sample compare?
B. On the tumbled samples, is the viewer looking at abrading particles or at fiber debris?
C. How much of the dust can be cleaned off of the samples with the ultrasound procedure?
D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?
E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?
F. Did the back face of the fabric abrade? If so, what was the abrasion mechanism and what was the extent of the damage caused by the abrasion?
G. How do the results of the SEM analysis compare with the tumble test visual inspection?

V. Sample Chapter Conclusion
- Determination of the extent of sample abrasion

Once the individual sample analysis is complete, the samples will be compared to each other. The final activity of the electron microscopy abrasion analysis will be to answer these three questions: (1) Is it possible to determine which tumble test sample was damaged the least? (2) If so, what is the best-worst ranking with respect to abrasion resistance and which sample should be identified as the primary candidate fabric for further investigation? (3) Does the comparison of Samples 5 and 6 indicate that the laboratory tumble test is representative of actual EVA abrasion?

7.5.2 Methodology for Picture Sequence

A set of micrograph data points was generated during the electron microscope investigation of each sample. To aid in the SEM data collection procedure, the Micrograph Data Matrix (Fig. 5) was created to function both as a checklist and a guideline. The goal of using the photo matrix was to offer a systematic approach to the data collection while producing a relevant set of micrographs for each sample. This approach allowed for the comparison of the sample to itself and the comparison of the sample to other samples.

MICROGRAPH DATA MATRIX

A	B	C
FRONT FACE Rep. View - Low Mag.	FRONT FACE Rep. View - High Mag.	FRONT FACE Seam - Low Mag.
NEW	NEW	NEW
TUMBLED	TUMBLED	TUMBLED
CLEANED	CLEANED	CLEANED

D	E	F
FRONT FACE Seam - High Mag.	FRONT FACE Fold	FRONT FACE Fiber Abrasion
NEW	NEW	TUMBLED
TUMBLED	TUMBLED	TUMBLED
CLEANED	CLEANED	TUMBLED

Figure 5

The logic behind the arrangement of possible micrographs in the data matrix is that the set of photos collectively answers the questions posed in the micrograph analysis outline of the previous section (7.5.1).

This matrix was used during the data collection of all samples evaluated during the electron microscopy abrasion analysis. In the

case of the Apollo 12 sample, actual EVA abraded fabric micrographs were substituted in the tumbled spots of the matrix.

Note that the Figure 5 matrix lists only the micrographs for the front face of one fabric sample. The same data matrix was also used for the back face.

As shown, the micrographs are arranged in groups of three; each group illustrates a comparison of the sample to itself. The first group (A) begins the set with representative views of the three fabric conditions at low magnifications of generally 50-60x. This group familiarizes the reader with the fabric. The second group (B) is the same view and comparison as the first, at a higher magnification of generally 150-400x.

The third and fourth groups (C & D) investigate the seam area. As with the first two groups, the same view and comparison is presented both at low magnifications to get an overview of the area of interest and at higher magnifications to see what has happened to the sample on a closer level.

The fifth group (E) is included to see if there was any useful information that could be gained from viewing an area that became folded during the test.

The final grouping (F) was reserved for the highest magnification micrographs of the tumbled fabric. Each specimen was explored and areas of interest that helped to answer abrasion questions were photographed.

The general idea when exploring the candidate fabric SEM specimens was to use the Micrograph Data Matrix as a checklist / guide. If a particular view included information relevant to the abrasion analysis of the sample fabric, a micrograph was made of that view. If a view was inconclusive, no photo was taken. And if desirable information not listed on the matrix was found elsewhere on any condition of the sample, a micrograph of the view was included in that sample's data set. Therefore, each sample had a unique set of micrographs; the number of micrographs in a set varied from sample to sample.

Included in each sample chapter is a Micrograph Figure Arrangement Chart. This chart is the complete list of micrographs for the sample

and is arranged in the same manner as the Micrograph Data Matrix. Figure 6 is an example of how a group of micrographs is referenced in the chart:

Fig. No.	View
CONDITION	
Mag.	Ref.
Fig. 14	Front
TUMBLED	
150x	100μm
Fig. 29	Back
SEAM, TUMBLED	
8x	1mm
pg. XX	

Figure 6

The top box is a key to how the identifying information is presented for each micrograph in the figure arrangement chart. Choices for 'Condition' are either new, tumbled or cleaned. Choices for 'View' are either front or back (of the fabric sample). The magnification appears in the lower left-hand corner while the reference line length is found in the lower right-hand corner. Examples are given in the second and third boxes. The page number of the micrograph group is also listed for reference purposes.

One last note before presenting the micrograph analysis:

It is necessary to understand how a direct comparison can be made of the micrographs in each group. It is the resolution of the photos, not the magnification, that must match to make a direct comparison of the micrographs. Refer to the distance reference line located at the bottom of each micrograph; this line functions like a mileage reference line on a road map. Due to the physics of the electron microscope, two photos may have the same reference line length (which is necessary for direct comparison), but be of different magnifications. If the reference line length and value is the same, a direct comparison can be made between micrographs.

CHAPTER 8

LUNAR DUST SIMULANT MICROGRAPHS

8.0 LUNAR DUST SIMULANT MICROGRAPHS

Before analyzing the woven fabric samples that were abraded in the tumble test, it was necessary to become familiar with what the lunar dust simulant itself looked like.

A simulant specimen was prepared for the SEM as follows. The vial of dust that was collected from the inner layer of the Orthofabric tumble test cylinder was obtained. A small portion of the simulant was poured onto an SEM specimen holder that had been coated with 3M Photo Mount Spray Adhesive. When the adhesive was completely dry, the simulant specimen was sputtered with gold in the same manner as the woven fabric samples. After preparation, three lunar dust simulant micrographs were taken.

Figure 7 is a micrograph of the simulant magnified to 440x. In this figure, the layer of dust is partially covered by the coating of spray adhesive. Simulant particles that extend above the coating, range in size from less than 10μm to 80μm (refer to the 100μm reference line located in the bottom boarder of the photo). Although somewhat difficult to distinguish, the refractory glass particles (see A) have the crystalline characteristic of sharp, planar surfaces while the volcanic rock particles (B) appear powdery and amorphous. Each of the glass particles present in this micrograph have pieces of volcanic rock adhering to them. The tear in the adhesive coating at the bottom left of the photo (C) reveals that there is dust all through the layer of coating.

Figure 8 is a second view of the dust simulant at a magnification of 90x. Here, the largest dust particle is 250μm wide. The smaller particles that were easily visible in the previous figure, start to disappear into the relief of the adhesive coating layer. The larger particles share the same characteristics that were observed for both the glass and volcanic rock particles of Figure 7.

Figure 9 is the same view as the previous figure, only at a lower magnification of 45x (the box indicates the micrograph of Figure 8). This figure confirms that 250μm is the maximum size of the irregularly-shaped simulant particles that were collected from the Orthofabric test cylinder.

Figure 7

Sample: Simulant
Ref: 100 microns
Mag: 440x

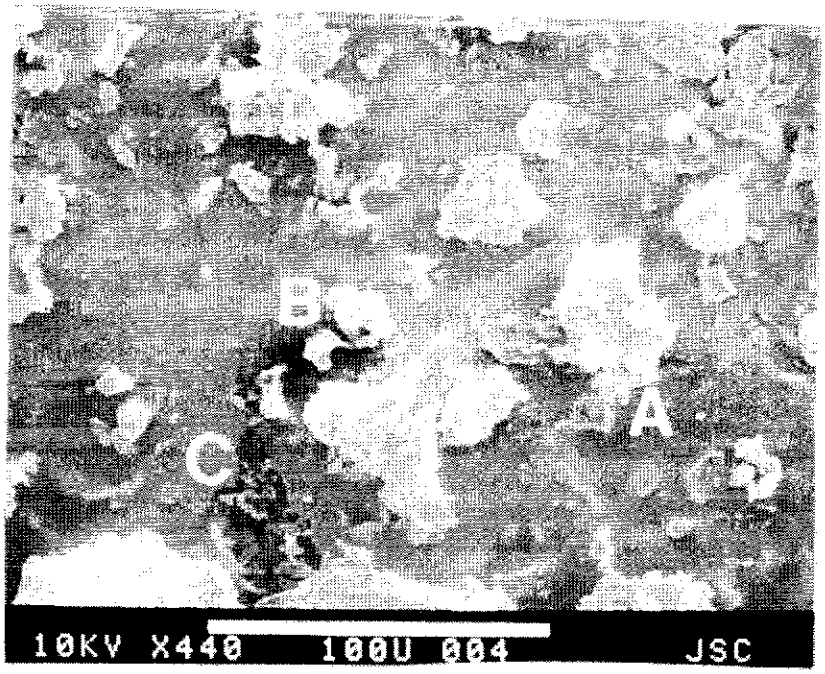


Figure 8

Sample: Simulant
Ref: 100 microns
Mag: 90x

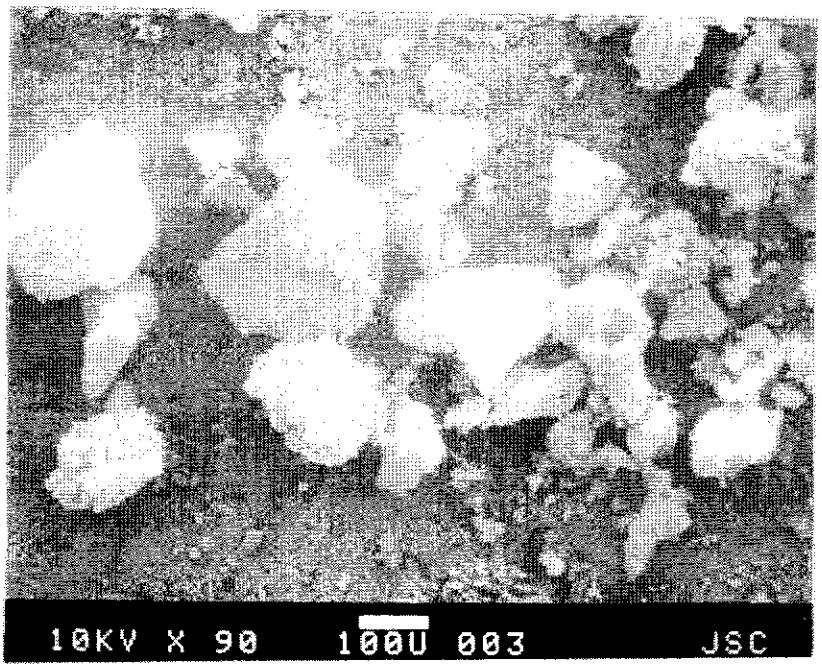
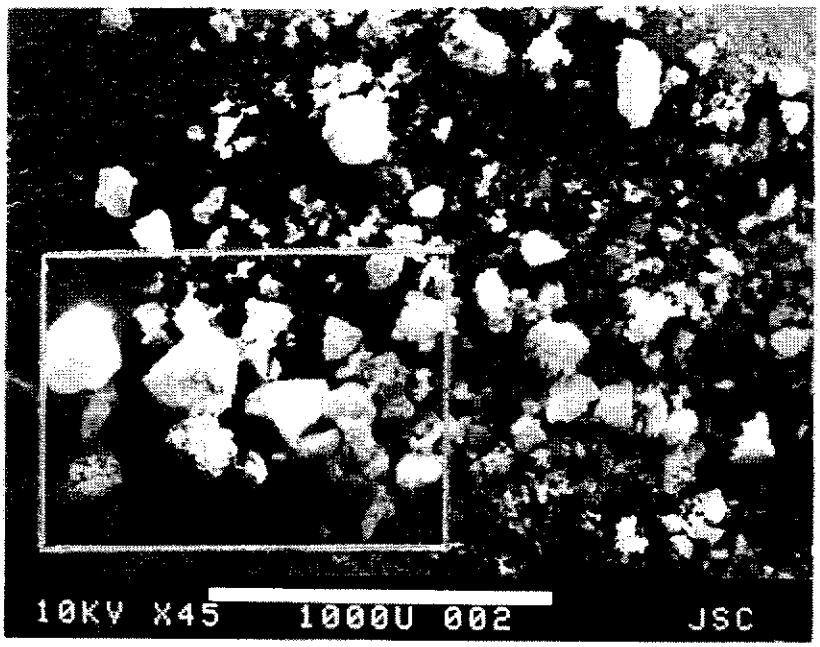


Figure 9

Sample: Simulant
Ref: 1000 microns
Mag: 45x



The simulant particles seen in Figures 7, 8 and 9 are all irregularly-shaped with the refractory glass having sharp edges and the volcanic rock looking powdery. These micrographs give the reader an example of what the dust simulant will look like on the tumbled fabrics during the SEM analysis.

CHAPTER 9

SAMPLE 1

ORTHOFABRIC

9.0 SAMPLE 1: ORTHOFABRIC

Orthofabric was developed for and is currently used as the outermost protective layer of the Shuttle SSA TMG. The function of this fabric in the TMG layup is abrasion and tear resistance, micrometeoroid protection, and thermal control. Orthofabric was included in this abrasion study because it has been used with great success throughout the Space Shuttle EVA program from 1983 to the present.

Orthofabric is a double-sided woven blend of three fibers. The primary fiber is Gore-Tex which comprises 50% of the fabric. The Gore-Tex used is a 400 denier, slit fiber of expanded PTFE (polytetrafluoroethylene). The other two fibers included in the weave are Nomex and Kevlar which comprise 45% and 5% of the fabric, respectively. The Nomex is a 200 denier, two-ply filament, drawn fiber with the Kevlar fiber being a 400 denier single-ply filament, also drawn.

The fabric is constructed in the following manner. The front face is woven of Gore-Tex fibers in a fancy draw, six harness, split basket weave configuration. The yarn count of the front face in the warp direction is 52 ends and in the filling direction is 41 picks. The back face is primarily woven of Nomex yarns also with a fancy draw, six harness, split basket weave configuration. Additionally, there is a two-end repeat of Kevlar yarn after every sixteen Nomex yarns in both warp and filling directions. The yarn count of the back face in the warp direction is 39 ends and in the filling direction is 32 picks. Following are the specifications for woven Orthofabric:

1. Weight		4.46 kg/m^2	(14.6 oz/yd^2)
2. Physical Properties:			
a. Specific Gravity		1.8 g/cc	(1.04 oz/in^3)
b. Breaking Strength	Warp:	5280 kg/m	(295.1 lbs/in)
	Fill:	4327 kg/m	(241.9 lbs/in)
c. Ultimate Elongation	Warp:	33.3%	
	Fill:	20.1%	
3. Mechanical Property:			
Tear Resistance	Warp:	45.50 kg	(100.1 lb.)
	Fill:	37.86 kg	(83.3 lb.)

Figure 10 (NASA-JSC photo # S90-49805) and Figure 11 (NASA-JSC photo # S90-51410) illustrate the before and after tumble test appearance of the Orthofabric sample.

Figure 10 is a photo of the unpressurized Orthofabric test article. The photo illustrates the distinctive, split basket weave of the new, clean fabric. Small depressions in the Gore-Tex weave that occur in evenly spaced rows indicate places where the Nomex yarns from the back face of the fabric have been woven through to the front. The stitching is even and neat, all seams have been finished, and the endplugs are securely attached with Velcro closures.

Figure 11 is a photo of the unpressurized test cylinder after eight hours of tumbling with the lunar dust simulant. Before the photo was taken, the excess dust was shaken off the test article and the outside of the fabric cylinder was vacuum cleaned. Still, there is a significant amount of powdery dust adhering to the surface of the cylinder. The dust seems to be uniformly distributed on the body of the cylinder with a high concentration of dust in areas of high relief and a low concentration in areas where the fabric has been indented. Minor tears (see A) appear along the restraint seam, cylinder corners and on the endcaps. There are no visible tears on the body of the cylinder where the dust is fairly evenly distributed. Note that the severity of the tumbling procedure did not cause the seams to pull loose.

Following the tumble test cylinder photos are the Micrograph Figure Arrangement Chart (Figure 12) and the analysis of the individual Orthofabric micrographs.

Figure 10

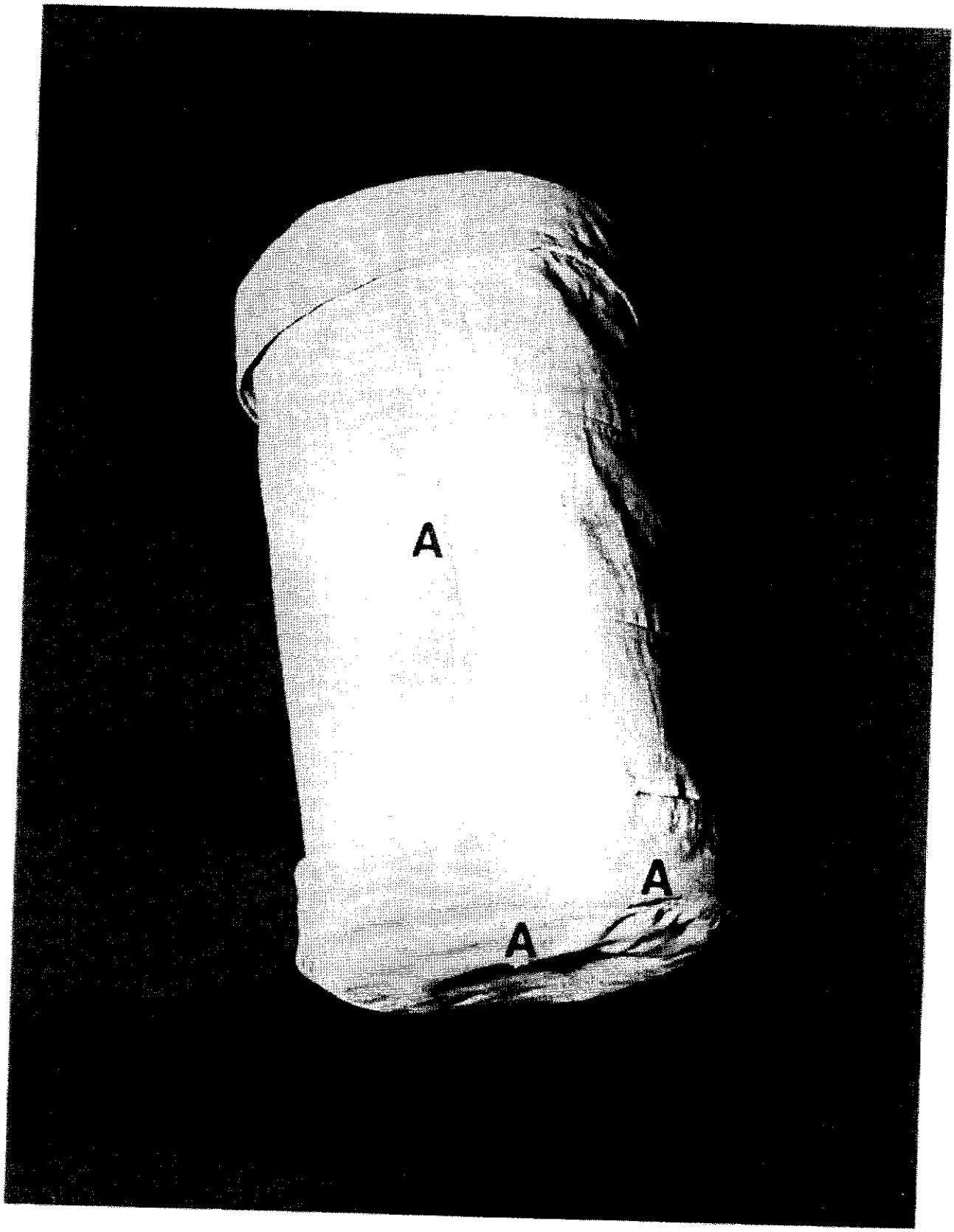


Figure 11

SAMPLE 1: ORTHOFABRIC
Micrograph Figure Arrangement Chart

Fig. 13 Front NEW 33x 400µm	Fig. 16 Front NEW 50x 100µm	Fig. 19 Front SEAM, NEW 11x 1mm
Fig. 14 Front TUMBLED 50x 400µm	Fig. 17 Front TUMBLED 150x 100µm	Fig. 20 Front SEAM, TUMBLED 48x 200µm
Fig. 15 Front CLEANED 47x 400µm	Fig. 18 Front CLEANED 120x 100µm	Fig. 21 Front SEAM, TUMBLED 800x 10µm
pg. 46	pg. 48	pg. 50
Fig. 22 Front FOLD, TUMBLED 17x 1mm	Fig. 25 Back NEW 48x 400µm	Fig. 28 Back NEW 200x 100µm
Fig. 23 Front FOLD, TUMBLED 910x 20µm	Fig. 26 Back TUMBLED 45x 400µm	Fig. 29 Back TUMBLED 230x 100µm
Fig. 24 Front FOLD, CLEANED 890x 20µm	Fig. 27 Back CLEANED 44x 400µm	Fig. 30 Back CLEANED 90x 100µm
pg. 52	pg. 54	pg. 56
Fig. 31 Back SEAM, NEW 8x 1mm	Fig. 34 Back FOLD, TUMBLED 50x 200µm	Fig. 37 Front GORE-TEX FIBER 2500x 10µm
Fig. 32 Back SEAM, TUMBLED 8x 1mm	Fig. 35 Back FOLD, TUMBLED 230x 40µm	Fig. 38 Front NOMEX FIBER 5800x 10µm
Fig. 33 Back SEAM, TUMBLED 460x 20µm	Fig. 36 Back FOLD, CLEANED 200x 40µm	Fig. 39 Back KEVLAR FIBER 2400x 10µm
pg. 58	pg. 60	pg. 62

Figure 12

Figure 13

Sample: 1
View: Front
Condition: New
Ref: 400 microns
Mag: 33x

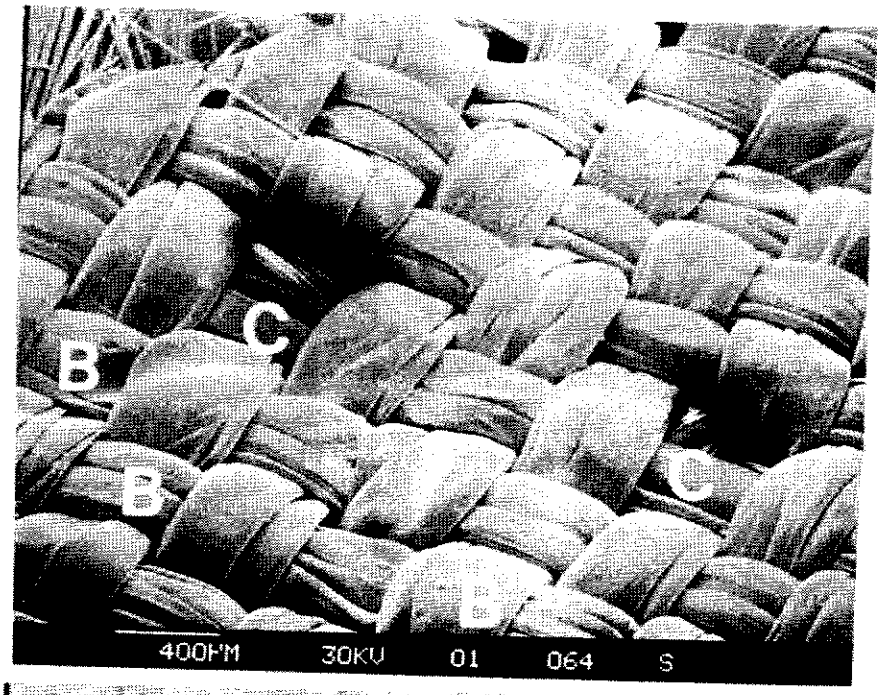


Figure 14

Sample: 1
View: Front
Condition: Tumbled
Ref: 400 microns
Mag: 50x

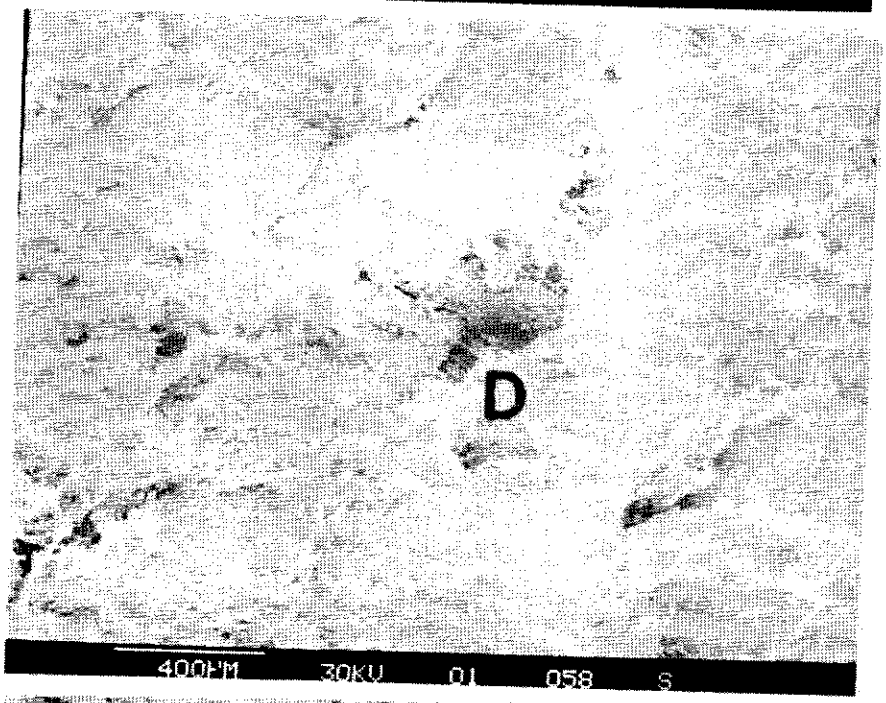


Figure 15

Sample: 1
View: Front
Condition: Cleaned
Ref: 400 microns
Mag: 47x

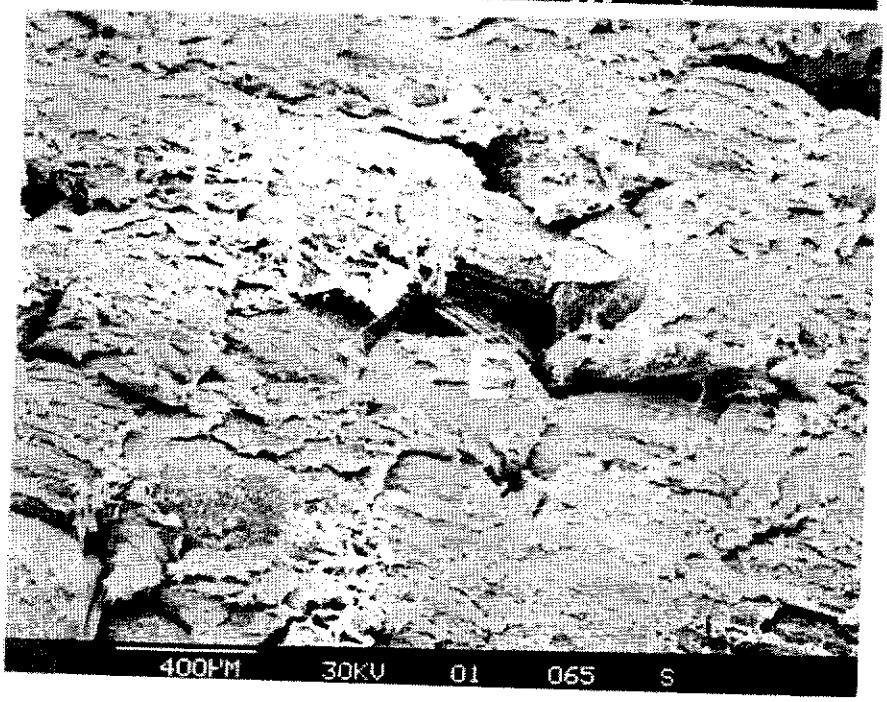


Figure 13:

This is a representative view of the front face of new Orthofabric. Notice the characteristic wide, smooth, ribbon-like appearance of the Gore-Tex fibers. Although new, there is some random pitting (B) on the Gore-Tex fibers, possibly from manufacturing or weaving processes. The Nomex fiber bundles (C) are visible in the small depressions of the split, basket weave which occur after every third Gore-Tex fiber. These depressions are a possible route for dust to travel from the front face to the back of the fabric. (Disregard the cut fibers in the upper left hand corner; this photograph was taken near the edge of the SEM specimen.)

Figure 14:

After tumbling, it is extremely difficult to distinguish the weave of the fabric. There are both abrading particles (volcanic rock and refractory glass) and fiber debris present; however, it is impossible to tell which is which from this view. The Nomex bundle in the weave is barely visible (D); it appears that some of the simulant has collected in this depression. (Note: Keep in mind that the dusty samples such as this one were vacuum cleaned after tumbling.)

Figure 15:

The ultrasound cleaning procedure did remove a large portion of the dust and loose fiber debris that remained on the sample. The Gore-Tex fibers are shredded and heavily damaged. It is still difficult to distinguish the original weave pattern as the tattered fragments lay over each other. However, the Nomex fibers (E) appear intact and there is no visible loose debris or dirt in the depression.

Figure 16

Sample: 1
View: Front
Condition: New
Ref: 100 microns
Mag: 50x

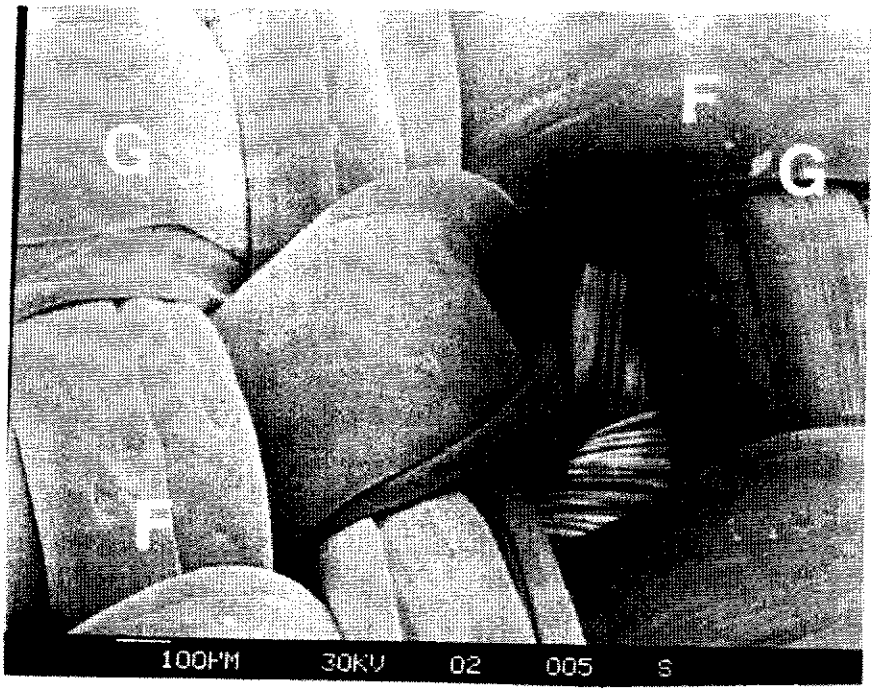


Figure 17

Sample: 1
View: Front
Condition: Tumbled
Ref: 100 microns
Mag: 150x

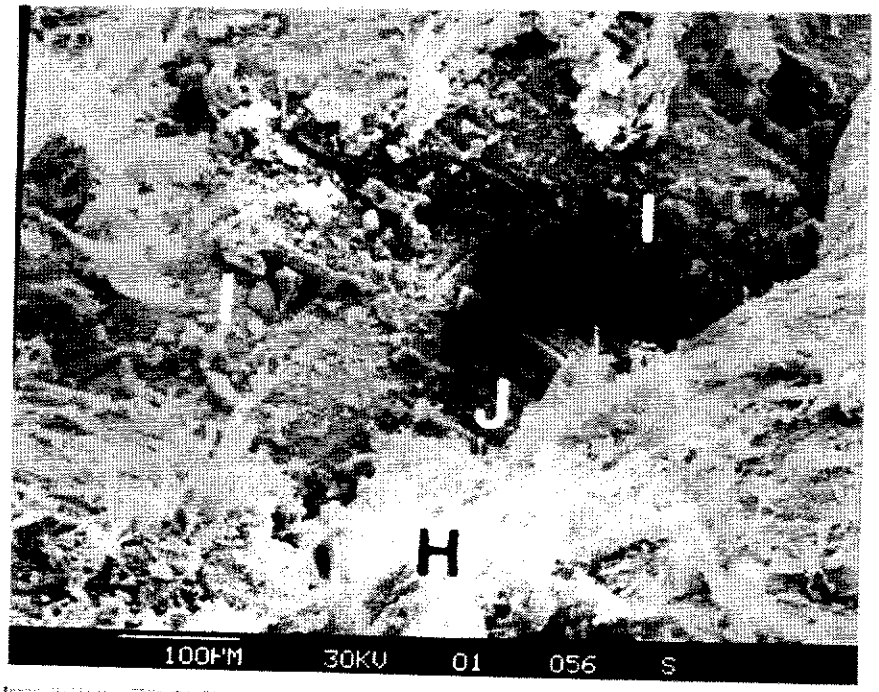


Figure 18

Sample: 1
View: Front
Condition: Cleaned
Ref: 100 microns
Mag: 120x

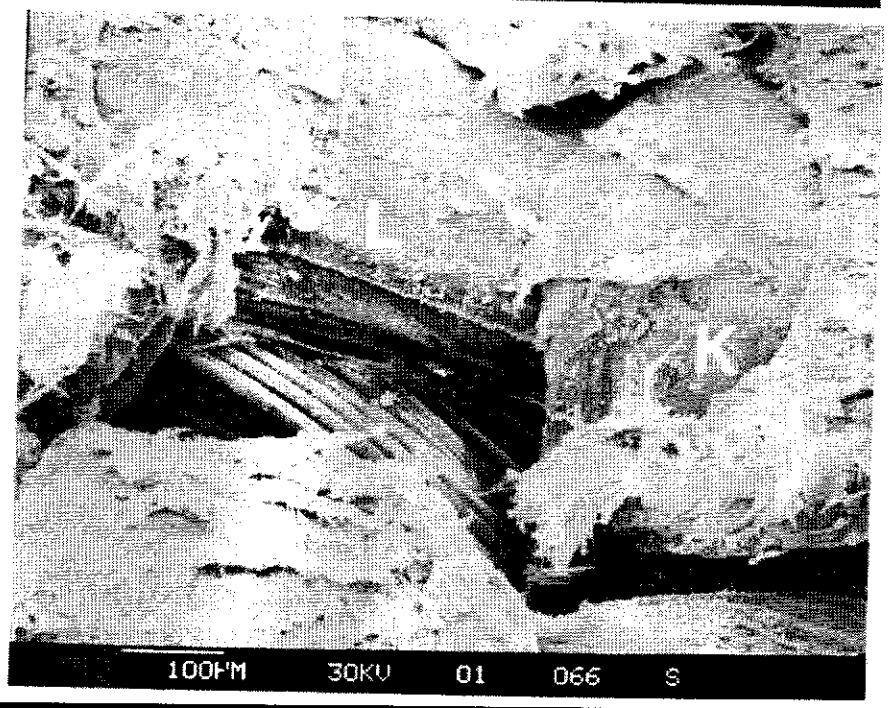


Figure 16:

This micrograph gives a closer look at new Orthofabric. The random pits (F) and surface damage of the Gore-Tex fibers are more easily seen at this higher magnification. Small particles (G) on the Gore-Tex fibers are most likely pieces of dirt that got on the fibers or fabric during the weaving process or during handling. This micrograph is a good illustration of the depression in the weave where the Nomex fiber bundles show through to the front face of the fabric. There is room in the depression for dust to migrate through the fabric; however, the Gore-Tex weave appears fairly tight with little room in the interstices for dust to travel through.

Figure 17:

There is a significant amount both fiber debris (H) and abrading particles (I) present on the front face of the Orthofabric sample after tumbling. As with Figure 14, it is difficult to distinguish the Gore-Tex fiber weave, although the Nomex bundles (J) are visible in the center of the micrograph. The Gore-Tex has been heavily damaged by the tumbling procedure, whereas the Nomex fibers do not appear to be abraded.

Figure 18:

A majority of the dust and debris seen in Figure 17 has been removed by the ultrasound cleaning procedure revealing sections of the fiber surface (K) that have been peeled back and shredded. The remaining exposed areas of the fiber are pitted (L). The Nomex fibers have not experienced major damage; the most likely reason is that the fiber bundles did not see as much direct contact with the abradant because they were protected by the front face, Gore-Tex weave.

Figure 19

Sample: 1
View: Front
Condition:
Seam, New
Ref: 1 mm
Mag: 11x

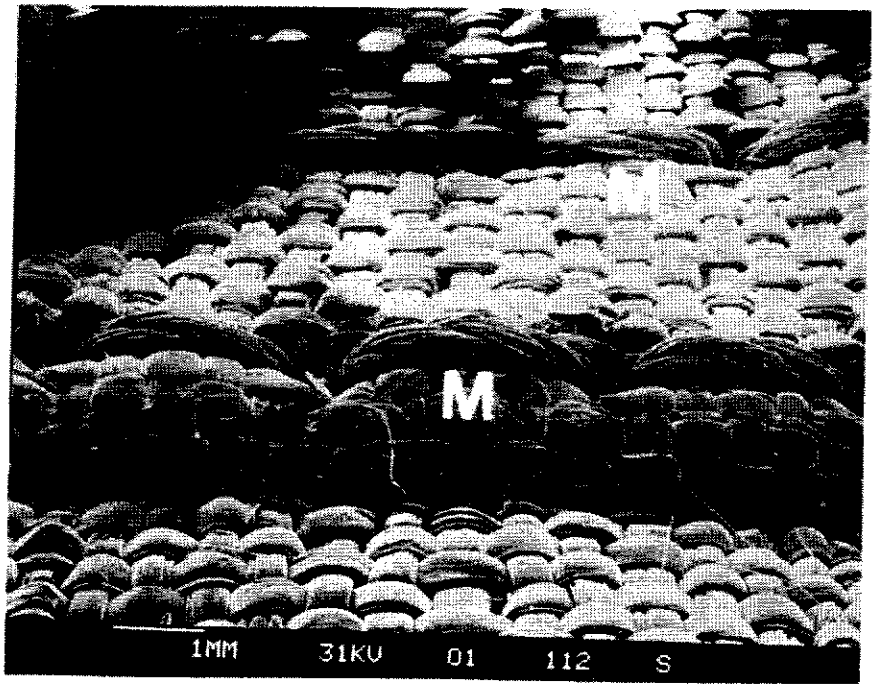


Figure 20

Sample: 1
View: Front
Condition:
Seam, Tumbled
Ref: 200 microns
Mag: 48x

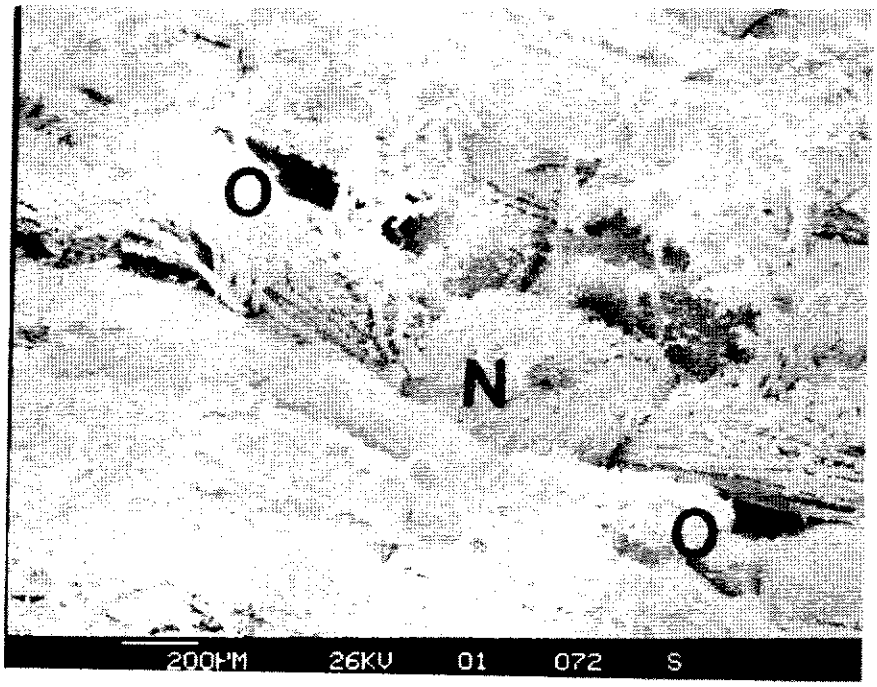


Figure 21

Sample: 1
View: Front
Condition:
Seam, Tumbled
Ref: 10 microns
Mag: 800x

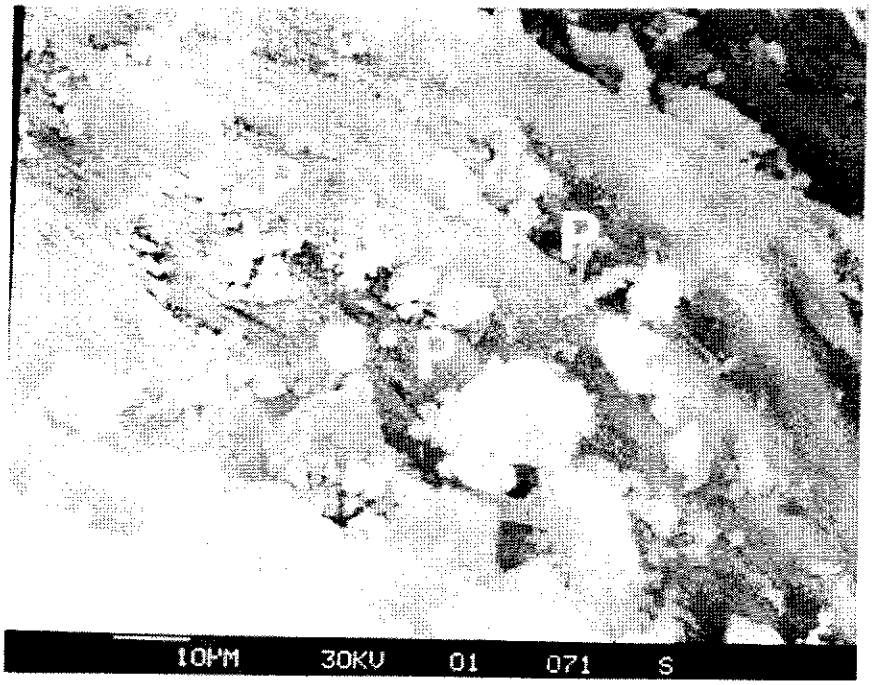


Figure 19:

This micrograph illustrates how a new seam appears when viewed from the front face of the sample. The fabric is joined as follows - one piece is folded under and secured with two parallel seams (M) to a second piece of fabric. In addition to dust migration paths through the interstices of the weave and through depressions in the weave, the seam construction offers two other migration paths. Dust could migrate by following the Nomex thread from the front to the back of the fabric through the needle holes and/or by penetrating the gap between the two pieces of fabric.

Figure 20:

Here is a close-up of a single stitch (N) on one of the Orthofabric seams after tumbling. As with Figures 14 and 17, there is a significant amount fiber debris and abrading particles present. It is again difficult to distinguish the Gore-Tex fiber weave and it appears that the Gore-Tex has been heavily damaged by the tumbling procedure. Notice the two holes on either side of the stitch (O) where the thread feeds through the fabric.

Figure 21:

This micrograph is a view looking into the hole (O) on the left side of the stitch of Figure 20. Inside the hole is evidence that the dust is migrating through the fabric; both refractory glass and volcanic rock particles are present. This view illustrates the particles that are trapped in the weave plowing grooves in the Gore-Tex fiber while abrading the surface (P). It is difficult to tell if during the plowing process, a chip (material cut out of the groove during plowing) is produced.

Figure 22

Sample: 1
View: Front
Condition:
Fold, Tumbled
Ref: 1 mm
Mag: 17x

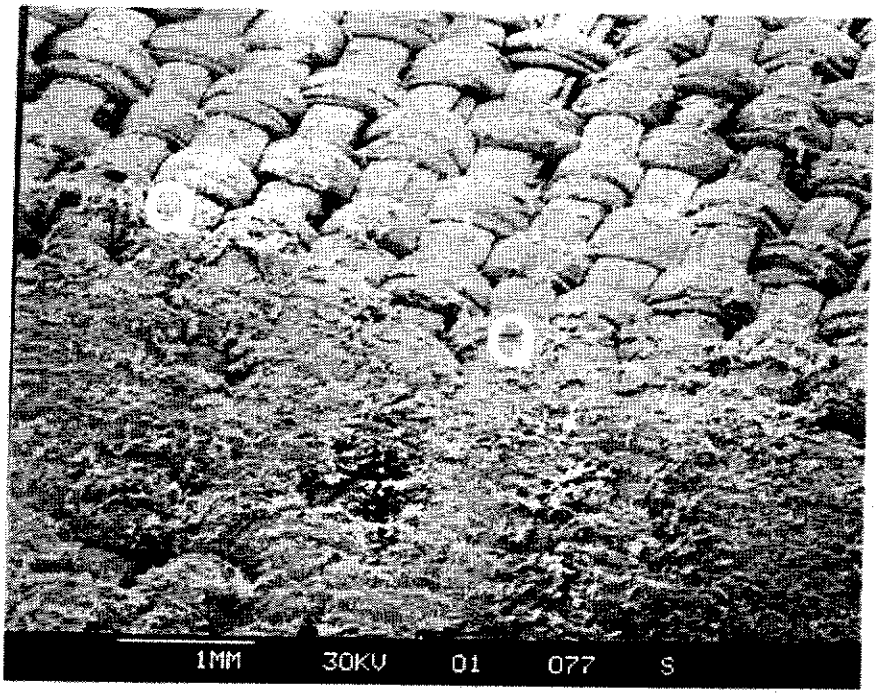


Figure 23

Sample: 1
View: Front
Condition:
Fold, Tumbled
Ref: 20 microns
Mag: 910x

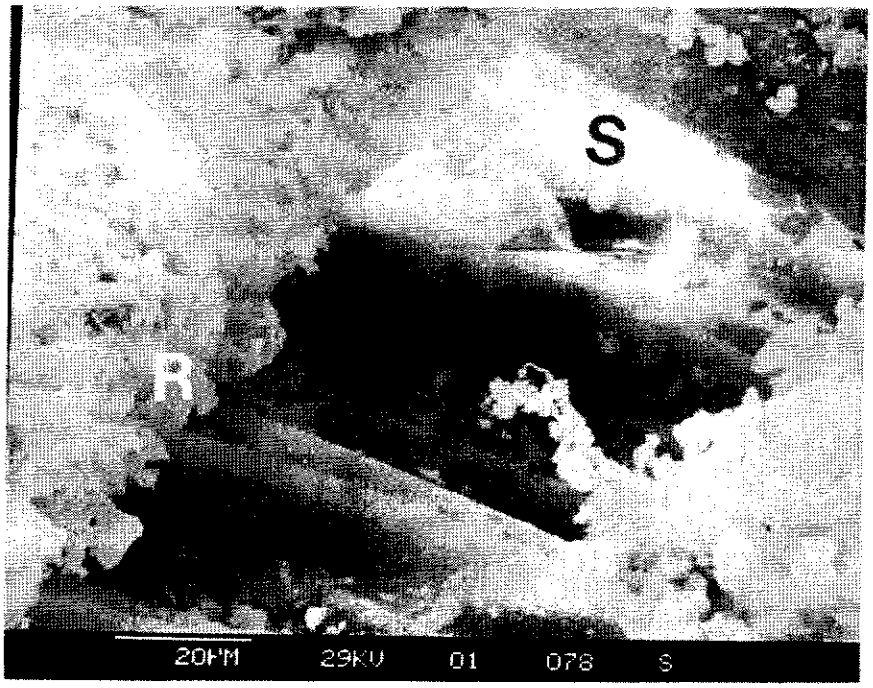


Figure 24

Sample: 1
View: Front
Condition:
Fold, Cleaned
Ref: 20 microns
Mag: 890x

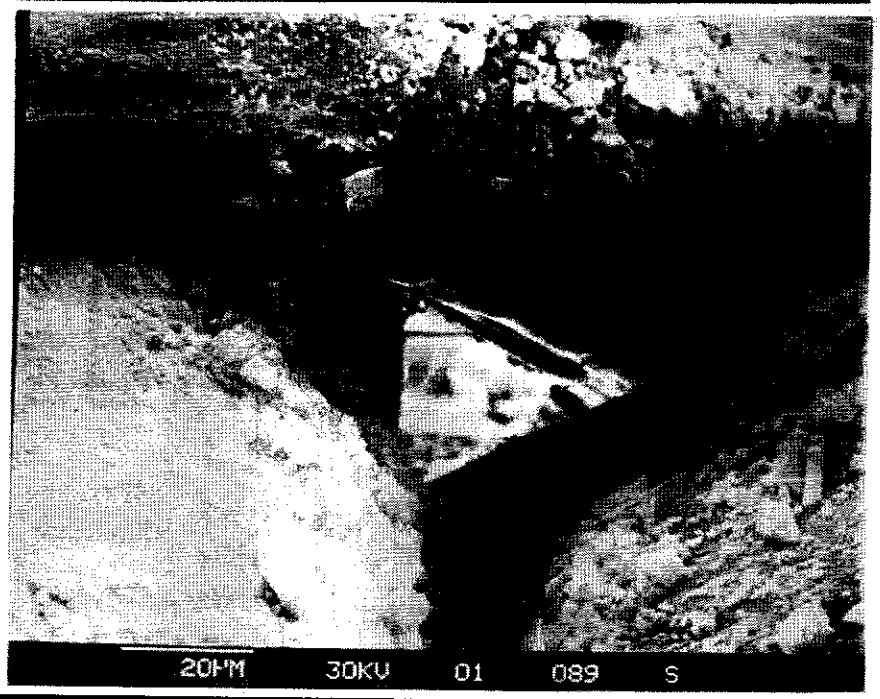


Figure 22

A fold (Q) on the front face of this specimen of tumbled Orthofabric is clearly distinguished by the difference in abrasion seen by the two sides. The fibers on one side of the fold show hardly any abrasion, whereas the other side is so heavily abraded that the weave is indistinguishable. Most of the fibers on the top side are intact and there is an even distribution of small dust or fiber debris particles covering the fibers. The bottom side shows the characteristic heavy abrasion seen in previous figures 15, 17 and 18 where the Gore-Tex fiber surface has been shredded. The abrasion seen in this micrograph appears worse than that of the previous photos; this is probably due to the lower magnification of the micrograph which could exaggerate the extent of the damage.

Figure 23

This view is a close-up of the fold (Q) shown in Figure 22. This is a good example of dust penetrating the fabric; lunar dust simulant particles adhere to the fiber on the left side of the micrograph (R) and more particles can be seen as the viewer looks through the fiber weave (S). Due to the number of particles covering the fibers, it is impossible to tell how much fiber damage has occurred.

Figure 24

Here is a micrograph of the same view and magnification of the fold as shown in Figure 23 after the ultrasound cleaning procedure. There are still quite a few particles on the surface of the fibers; the ultrasound procedure did not clean off enough particles to help in determining the extent of damage. There is not too much difference between the view of the previous figure and this one.

Figure 25

Sample: 1
View: Back
Condition: New
Ref: 400 microns
Mag: 48X

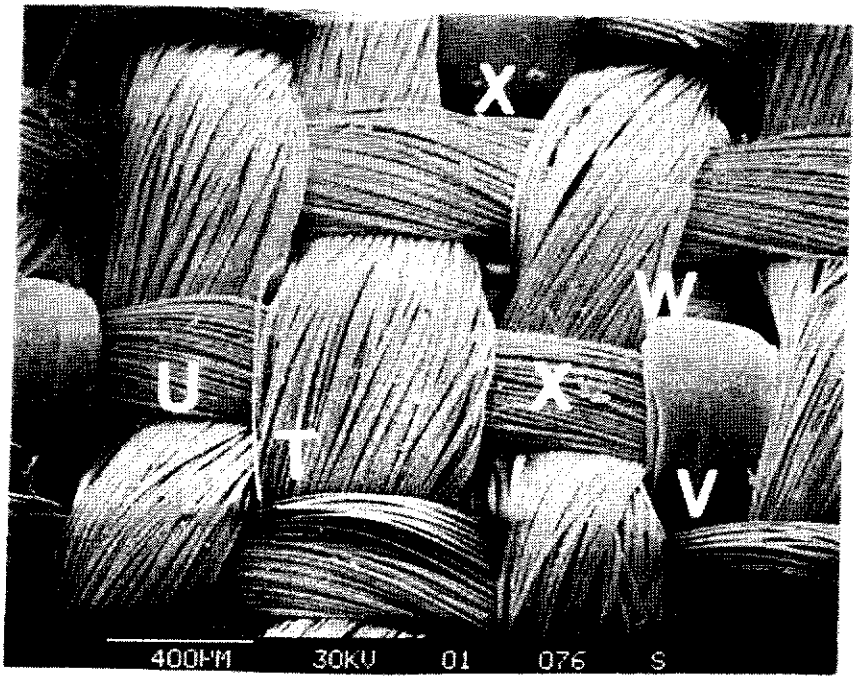


Figure 26

Sample: 1
View: Back
Condition: Tumbled
Ref: 400 microns
Mag: 45x

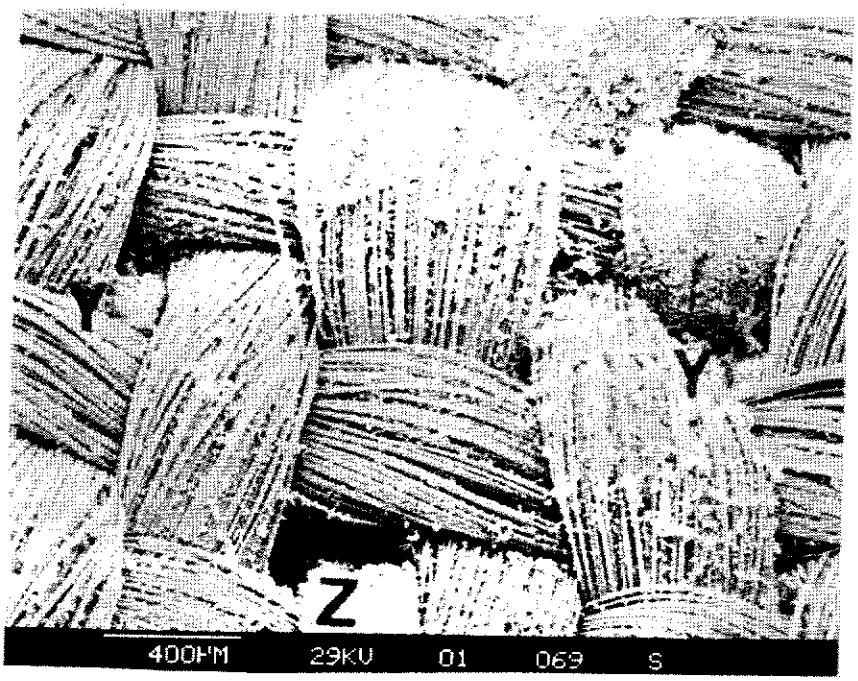


Figure 27

Sample: 1
View: Back
Condition: Cleaned
Ref: 400 microns
Mag: 44x

Figure 25

All three fibers, Gore-Tex, Nomex and Kevlar are visible on the back face of Orthofabric. In this micrograph, the bundles of thicker fibers are Kevlar (T) while the bundles of thinner fibers are Nomex (U). The broad Gore-Tex fibers (V) are woven through to the back face every third fiber just as the Nomex bundles were on the front face, creating a large gap in the weave (W). There is a small amount of particles (X) on the new fabric; as with the front, these are most likely pieces of dirt that got on the fabric during the weaving process or during handling. The fiber weave on the back face is much looser than on the front face; there is more room in the interstices of the weave for dust migration.

Figure 26

After tumbling, there is an even layer of fine particles covering the back face of the Orthofabric. These particles are in between the fibers of the Nomex and Kevlar bundles; they have also filled up the gaps in the fiber weave (Y) indicating migration of the lunar dust simulant from the front to the back face of the fabric. The gap (W) in the weave seen in Figure 25 is visible here (Z) but is not completely filled with dust. Unlike the front, it appears that there is little fiber damage to the back face; this is most likely because the back was not directly exposed to the tumbling.

Figure 27

The ultrasound cleaning procedure has removed nearly all of the particles from the back face of the fabric. Compared to Figure 25, the specimen is as clean as the new fabric. This view illustrates that there was little, if any, damage to the Nomex, Kevlar or Gore-Tex fibers on the back face of the fabric.

Figure 28

Sample: 1
View: Back
Condition: New
Ref: 100 microns
Mag: 200x

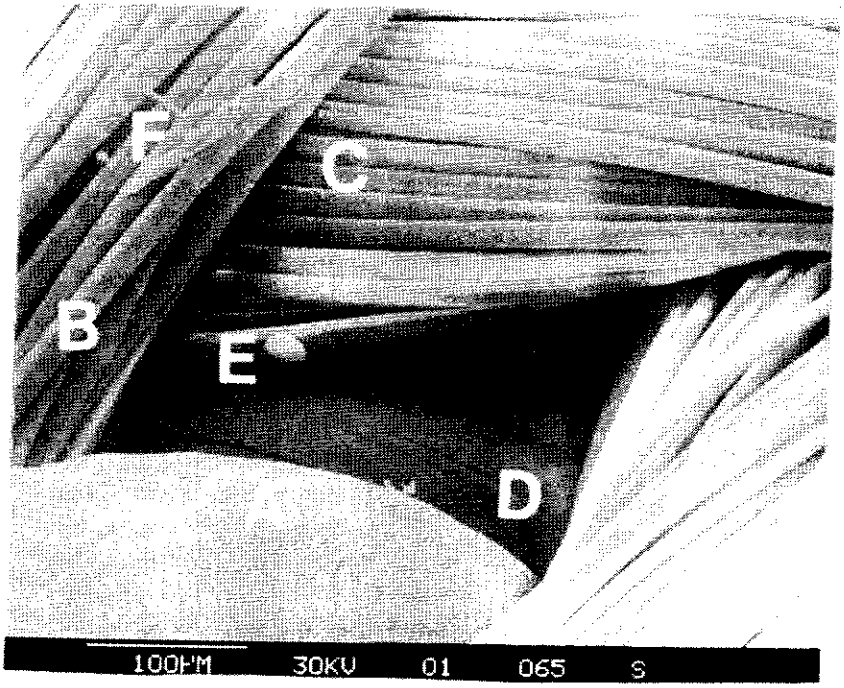


Figure 29

Sample: 1
View: Back
Condition: Tumbled
Ref: 100 microns
Mag: 230x

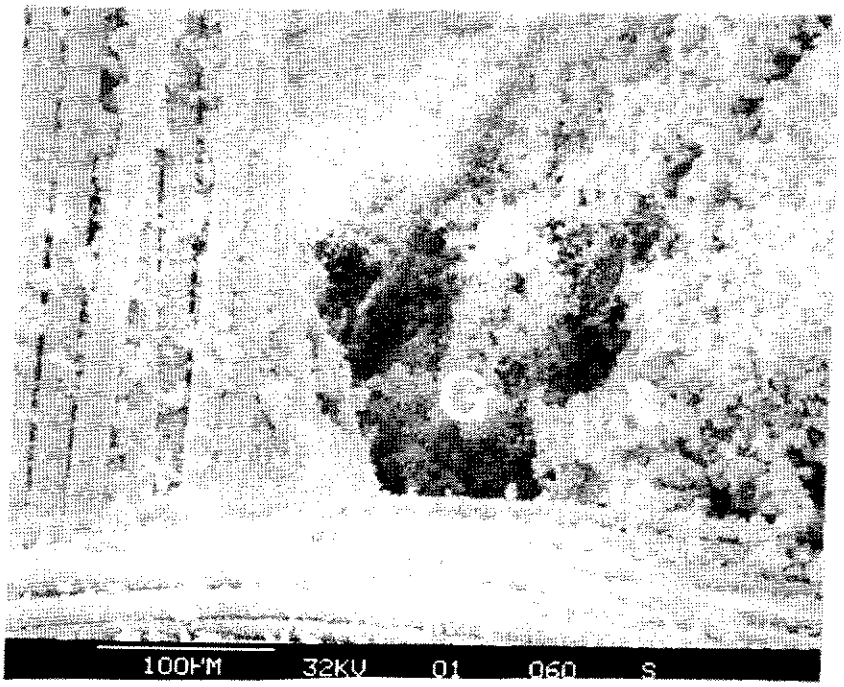


Figure 30

Sample: 1
View: Back
Condition: Cleaned
Ref: 100 microns
Mag: 90x

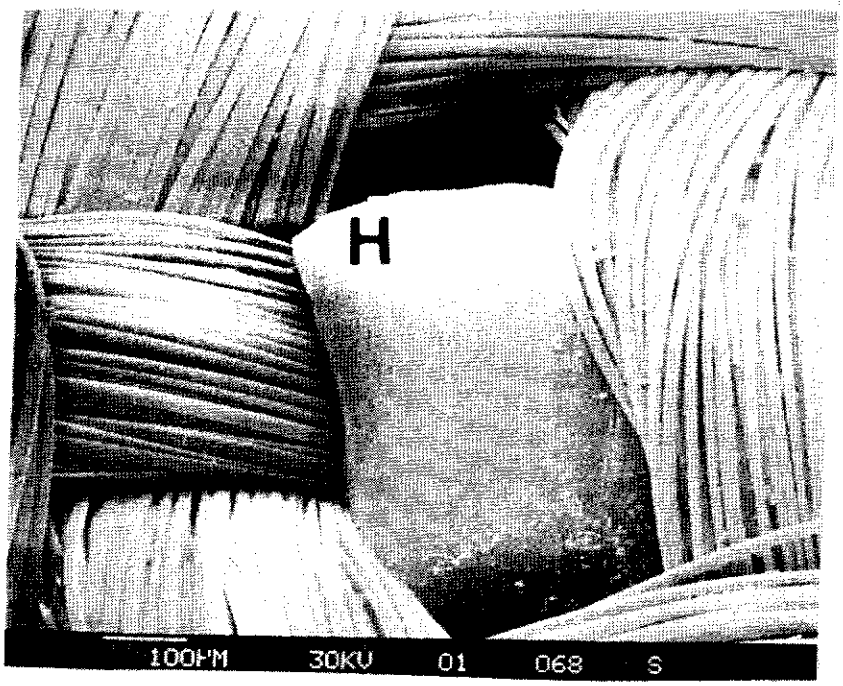


Figure 28

This micrograph is a close-up of the gap between the new Gore-Tex (A), Kevlar (B) and Nomex (C) fibers in the weave on the back face. The gap is nearly 300μm across and an average of 90μm wide. The front face Gore-Tex weave can be seen through the gap (D). A foreign dirt particle (E) can be seen clinging to the Nomex bundle at the edge of the gap. The Kevlar fiber bundle (B) has experienced some particulation (F) of one fiber through either handling or manufacturing processes.

Figure 29

After eight hours of tumbling, the lunar dust simulant has traveled through the gap between the three Orthofabric yarns. The high concentration of dust particles in the gap (G) confirms this area as a direct path for dust to travel from the front to the back face of the fabric.

Figure 30

All of the dust that had collected in the gap between the yarns is gone after the ultrasound cleaning procedure along with almost all of the dust on the rest of the fibers. The Gore-Tex fiber (H) near the gap has been abraded slightly by the lunar dust simulant which includes the sharp, refractory glass and volcanic rock passing through the fabric. The Kevlar and Nomex fibers have not been abraded.

Figure 31

Sample: 1
View: Back
Condition:
Seam, New
Ref: 1 mm
Mag: 8x

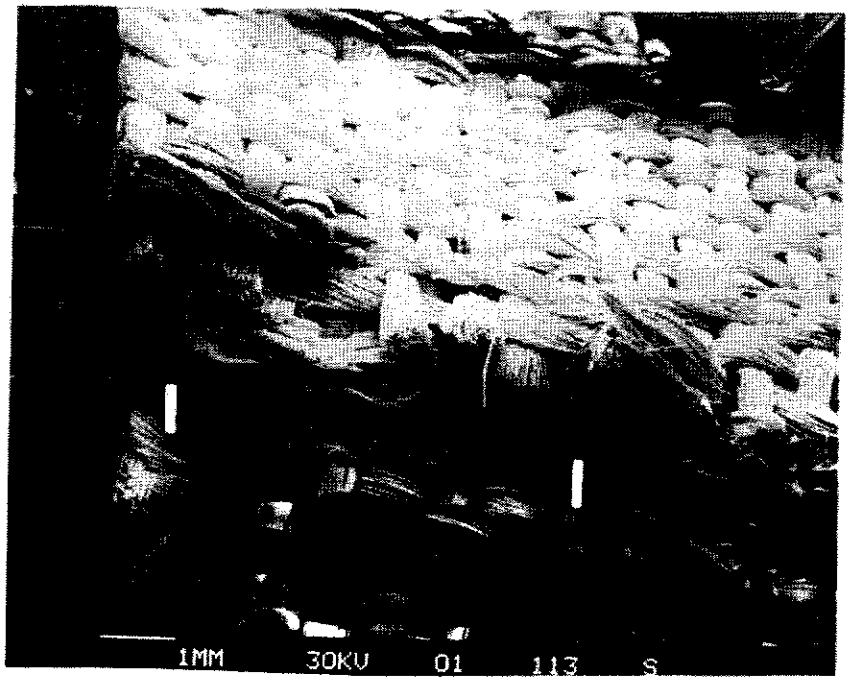


Figure 32

Sample: 1
View: Back
Condition:
Seam, Tumbled
Ref: 1 mm
Mag: 8x

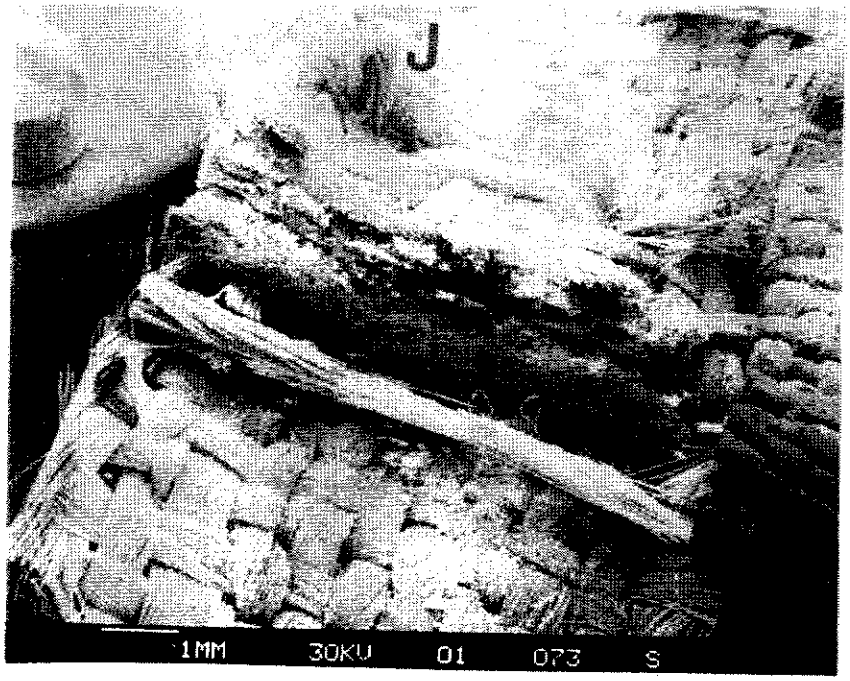
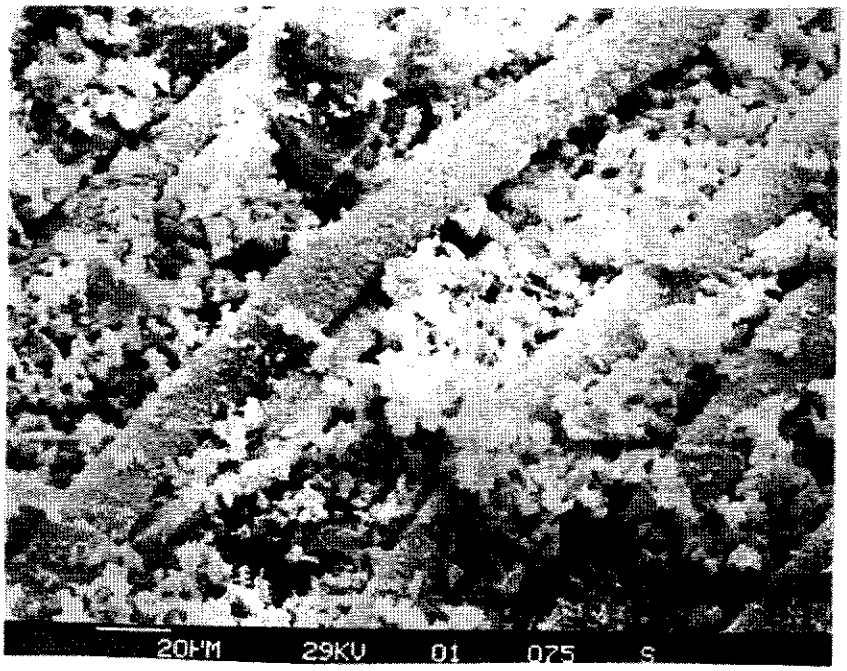


Figure 33

Sample: 1
View: Back
Condition:
Seam, Tumbled
Ref: 20 microns
Mag: 460x



Mag: 460x
Figure 31

This micrograph shows the back face view of a new Orthofabric seam. It is not a neat, flat seam like on the front face; the fibers of the cut fabric have started to fray and the weave is starting to separate (I). There are also large spaces between the bulky layers of fabric that have been sewn together at the seam.

Figure 32

Looking at the back face after tumbling shows a high concentration of dust at the seam (J). When obtaining the seam sample from the tumbled test cylinder, it was visually observed that there was a significant amount of dust on the insulation layers of the test article underneath the seams. As with the gaps in the back face of the fiber weave, this micrograph is evidence that there is an unobstructed path at the seam for the dust to follow through the fabric. The cut fibers have frayed a little more; but like Figure 29, there is not any evidence of fiber abrasion at this magnification, only a lot of dust on the fabric.

Figure 33

Micrographs of a tumbled seam that was cleaned with ultrasound did not contain useful information. Instead, it was decided to include a higher magnification of a view from the back face seam. This micrograph illustrates how the dust has gathered in the spaces between the fibers of a Nomex bundle. Notice the angular refractory glass particles (K) and the amorphous volcanic rock pieces (L).

Figure 34

Sample: 1
View: Back
Condition:
Fold, Tumbled
Ref: 200 microns
Mag: 50x

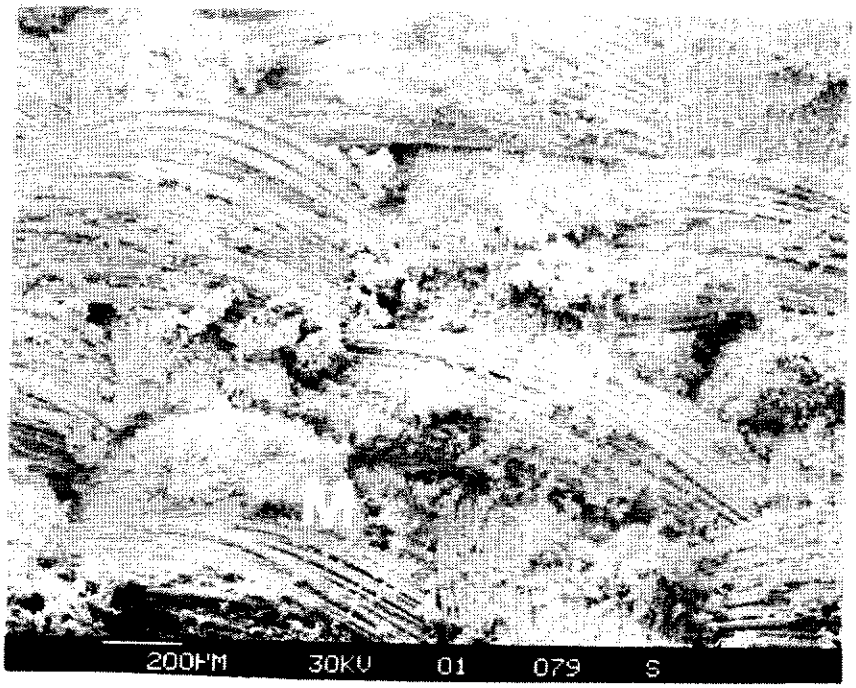


Figure 35

Sample: 1
View: Back
Condition:
Fold, Tumbled
Ref: 40 microns
Mag: 230x

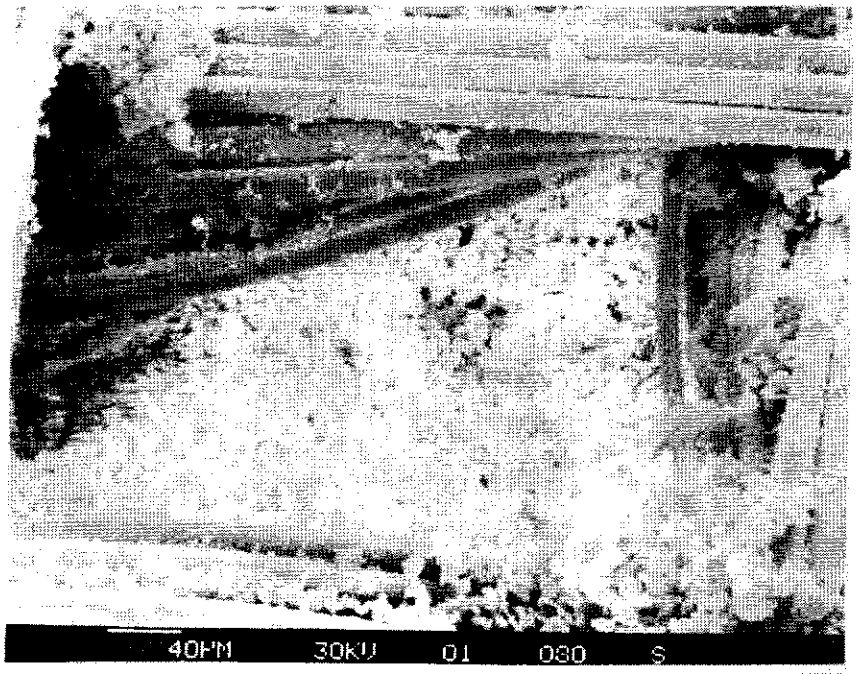
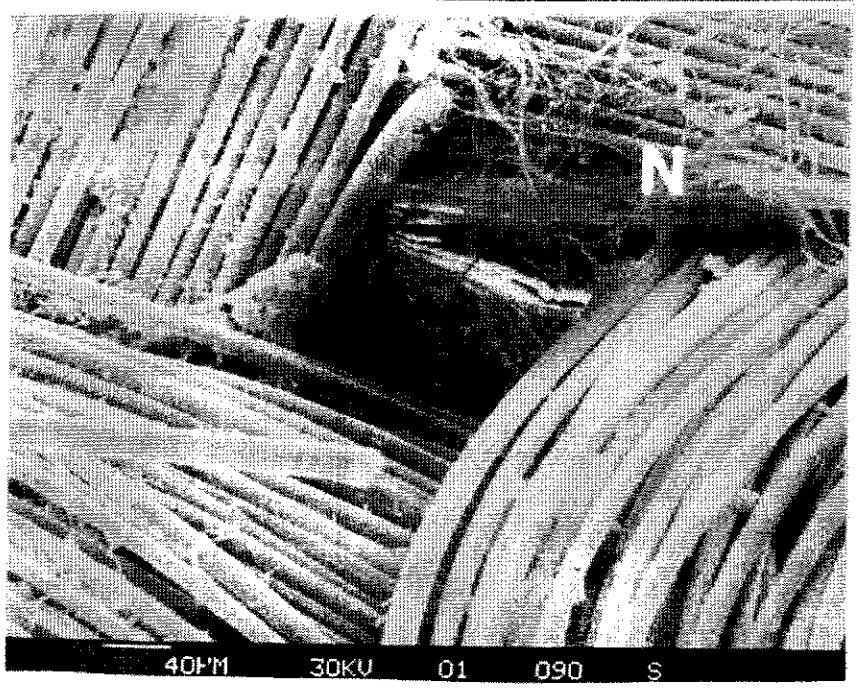


Figure 36

Sample: 1
View: Back
Condition:
Fold, Cleaned
Ref: 40 microns
Mag: 200x



Mag: 200x
Figure 34

Unlike the front face of the fold shown in Figure 22, there is no clear distinction where the fold is in this view from the back face. Both sides of the fold are covered with a thick, even layer of dust simulant that practically hides the weave pattern. The dust has completely filled the gaps in the fabric weave (M). There is much more dust on the back of this fold than there was on the representative back face, tumbled area of fabric seen in Figure 26.

Figure 35

This is a close-up view of the back face fold, showing the gap in the weave where the Gore-Tex fibers are visible from the front. The fine glass and volcanic rock particles cascading through the fabric have filled up the entire gap.

Figure 36

After the ultrasound cleaning, the gap shown in Figure 35 is essentially free of dust. The surrounding Kevlar fibers show evidence of abrasion; at the entrance to the gap, Kevlar fibrils (N) are present. This abrasion is probably due to a combination of the large amount of lunar dust simulant migrating through the fabric at this location along with possible fabric to fabric friction along the fold during the tumbling process.

Figure 37

Sample: 1
View: Front
Condition:
Gore-Tex Fiber
Ref: 10 microns
Mag: 2500x

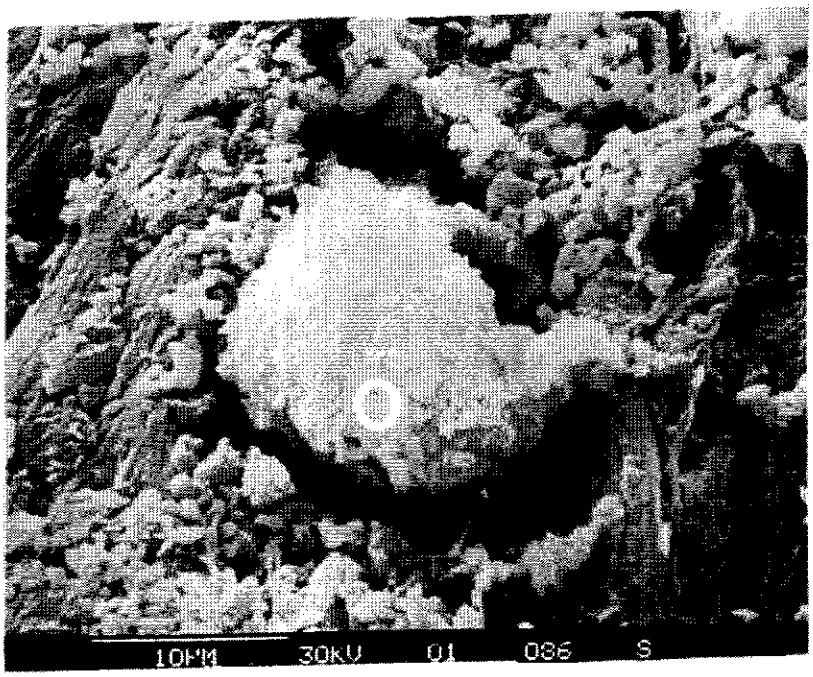


Figure 38

Sample: 1
View: Front
Condition:
Nomex Fiber
Ref: 10 microns
Mag: 5800x

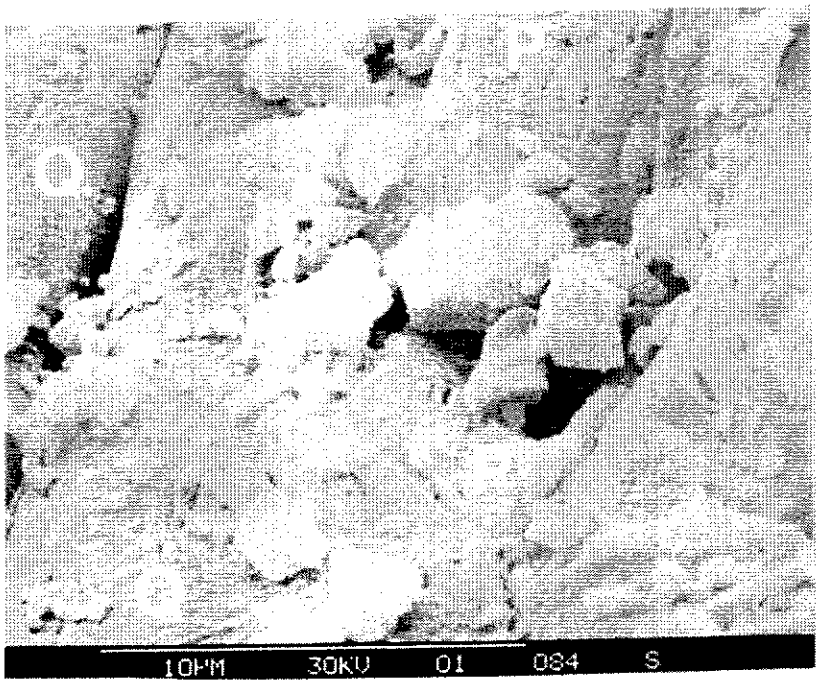


Figure 39

Sample: 1
View: Back
Condition:
Kevlar Fiber
Ref: 10 microns
Mag: 2400x

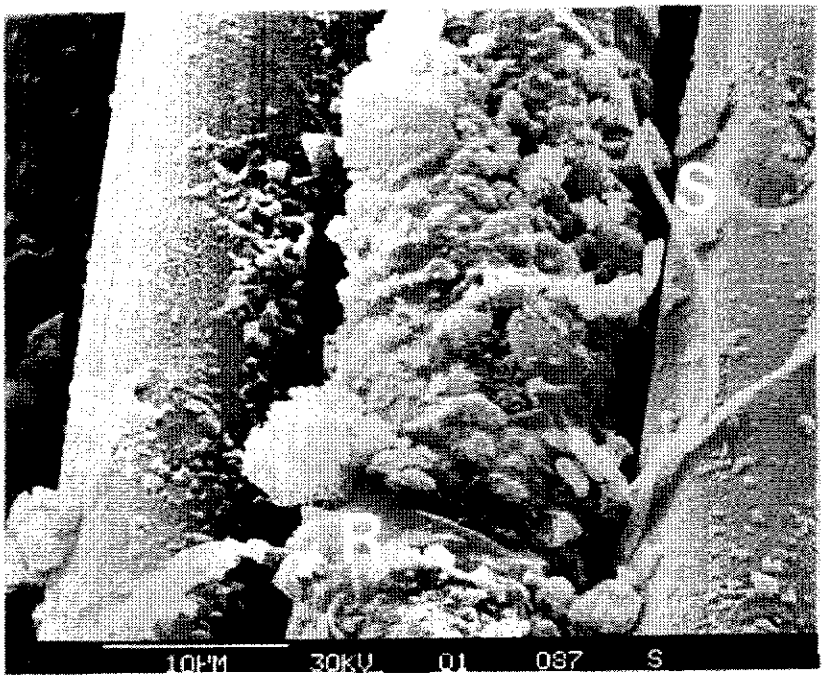


Figure 37
This figure is a close-up view (2500x) of a single Gore-Tex fiber. The fiber was found on the front face of the Orthofabric weave after tumbling where the Gore-Tex received the most severe damage. In the center of the micrograph (O) is a large dust simulant glass particle covered with volcanic rock and fiber debris. The particle has rolled back and forth, tearing away at the fiber and has created a large crater on the surface. This action describes a wear mechanism similar to plowing along with cyclic microcutting. Plowing is the action of a particle moving across a surface and scratching a groove; here the particle stays in one place after the inital penetration. Cyclic microcutting involves scooping the excess material out of the groove and releasing the material as a particle(s) of fiber debris. There is a significant amount of debris on the rest of the fiber, probably from the described wear mechanism and from the tumble test abrading particles of the lunar dust simulant.

Figure 38
Shown is a single Nomex fiber found in a depression on the front face Gore-Tex weave of Orthofabric after tumbling. This fiber shows signs of abrasion caused by both plowing and scaling wear mechanisms. There is evidence of the abrading particles plowing both large and small grooves (P) in the Nomex, although it is difficult to tell from this view whether or not fiber debris is being released by microcutting. Grooves are formed when a particle strikes at a low angle of incidence and plows along the fiber surface. The exposed surface of the fiber has a scaly appearance; these scales (Q) are formed by cyclic bending fatigue. This occurred when the fiber was compressed and bent during the tumble test. There are also a large number of small cracks in the fiber surface (R). These cracks could have formed during the impact of abrading particles during tumbling or they could be stress cracks from the cyclic bending fatigue experienced by the fibers.

Figure 39
This view is of four Kevlar fibers seen from the back face of the fabric. These fibers were not directly exposed to the tumbling process; they were abraded by the lunar dust simulant that had migrated through the fabric. Wear mechanisms present here include plowing (S). Also observed are the fiber surface lips (T). Lips form when a particle strikes a surface at a high angle of incidence. Notice the particle (U); this is a chip of fiber debris that was cut away from the fiber when the lip below it (T) was formed.

SEM ABRASION ANALYSIS RESULTS
SAMPLE 1
ORTHOFABRIC

Following are the answers to the questions posed in Section 7.5.1:

A. How do the three conditions of the sample compare?

The characteristic fancy draw, six harness, split basket weave was easy to identify on new Orthofabric specimens. In comparison, the tumble test abrasion made it extremely difficult to distinguish the weave on the front face of the fabric. After ultrasound cleaning, the original weave of the front face was still difficult to see due to the abrasion of the Gore-Tex fibers. As for the back face, the tumbling resulted in a lot of lunar dust simulant covering the fibers which was cleaned off with the ultrasound procedure, revealing little fiber damage.

B. On the tumbled samples, is the viewer looking at abrading particles or at fiber debris?

Abrading particles (glass and volcanic rock) and fiber debris were present on both faces of this sample.

C. How much of the dust can be cleaned off of the samples with the ultrasound procedure?

The ultrasound procedure was successful in cleaning essentially all of the lunar dust simulant off both the front and back face of the sample.

D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

The front face Gore-Tex and Nomex fibers did experience abrasion. The Gore-Tex fibers were heavily damaged. The wear mechanisms responsible for the Gore-Tex abrasion included plowing, and the action of a particle impacting the surface and creating a crater

through cyclic microcutting. The Nomex fiber abrasion was much less severe. This is due to the fact that the Nomex fibers were located in depressions in the Gore-Tex weave and were somewhat protected. The identified wear mechanisms affecting the Nomex fiber were plowing and scaling along with cyclic bending fatigue. Numerous small cracks were also found in the Nomex fibers possibly from particle impact or stress cracks from the cyclic bending fatigue.

E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

A key observation in this SEM study is that the lunar dust simulant did successfully migrate from the front to the back of the fabric. Migration routes include 1) depressions in the weave where the Nomex and Gore-Tex fibers crossed, joining the front and back face of the fabric 2) spaces in the interstices of the weave 3) needle holes for thread to travel from one face to the other at the seams 4) gaps between the two pieces of fabric joined at the seams 5) along folds in the test cylinder induced by tumbling.

F. Did the back face of the fabric abrade? If so, what was the abrasion mechanism and what was the extent of the damage caused by the abrasion?

The ultrasound cleaning of the back face revealed that there was little damage to the Gore-Tex and Nomex fibers. The Kevlar fibers were damaged by the lunar dust simulant that had migrated through the fabric. Wear occurred by the glass and volcanic rock particles plowing the surface of the fiber. Also observed was the formation of lips.

G. How do the results of the SEM analysis compare with the tumble test visual inspection?

The results of the SEM analysis confirm that initial visual conclusions made after the tumble test were correct. There was an even layer of dust on the front face of the fabric after tumbling and the lunar dust simulant does migrate through the seams in large quantities.

CHAPTER 10

SAMPLE 2

ORTHOFABRIC - Back Face Coated with 10 mil. Silicone

10.0 SAMPLE 2: ORTHOFABRIC - BACK FACE COATED WITH 10 mil. SILICONE

The primary design feature that is being evaluated in this study is the abrasion resistance of the candidate fabrics. A secondary design feature that is desirable is the ability of the outermost layer to keep the dust from penetrating the fabric, leading to the contamination of the underneath layers of the protective outergarment. In an attempt to satisfy this secondary design requirement, a small amount of Orthofabric (Sample 1) was prepared for this study by coating the back face with a 10 mil. layer of silicone. Silicone was chosen as the coating due to its compatiblity with the fabric, its ability to withstand the necessary temperature range extremes, and to provide protection from chemical propellants. Orthofabric was originally designed for Shuttle SSA use where dust abrasion and penetration is not an issue; in addition to its original purpose, the added coating is being considered as a possible enhancement to make the fabric more adaptable to planetary SSA outer-layer dust protection applications.

The Orthofabric was constructed in the same manner as described in Chapter 9; Gore-Tex, Nomex and Kevlar fibers were woven together in a fancy draw, six harness, split basket weave configuration. The back face was then knife coated with 10 mil. silicone, sealing the fabric from the inside.

Following are the specifications for back face silicone coated Orthofabric:

1.	Weight	10.8 kg/m^2	(35.3 oz/yd^2)
2.	Physical Properties:		
	a. Specific Gravity	1.9 g/cc	(1.10 oz/in^3)
	b. Breaking Strength	Warp: 4980 kg/m	(278.4 lbs/in)
		Fill: 3238 kg/m	(181.0 lbs/in)
	c. Ultimate Elongation	Warp: 16.3%	
		Fill: 12.1%	
3.	Mechanical Property:		
	Tear Resistance	Warp: 45.54 kg	(100.2 lb.)
		Fill: 38.18 kg	(84 lb.)

Figure 40 (NASA-JSC photo #S91-25160) and Figure 41 (NASA-JSC photo #S91-26394) illustrate the before and after tumble test appearance of the coated Orthofabric sample.

Note: The identifying labels in Figures 40 and 41 were incorrectly printed. The Orthofabric evaluated in this test was coated with 10 mil. of silicone, <u>not</u> 2 mil. as written on the photo label.

Figure 40 is a photo of the unpressurized, coated Orthofabric test article. The photo illustrates the weave of the new, clean fabric; however, the coating on the back is not visible in this view. The stitching is even and neat, all seams have been finished, and the end plugs are securely attached with Velco closers.

Figure 41 is a photo of the unpressurized test cylinder after eight hours of tumbling with the lunar dust simulant. As with the test cylinder from Chapter 9, the excess dust was shaken off the test article and the outside of the fabric cylinder was vacuum cleaned before this photo was taken. The lunar dust simulant is evenly distributed on the body of the cylinder with a high concentration of dust in areas of high relief and a low concentration in areas where the fabric has been indented. After tumbling, the fabric seems to be in good condition; there are no tears or any other types of visible surface damage evident in this photo.

Following the tumble test cylinder photos are the Micrograph Figure Arrangement Chart (Figure 42) and the analysis of the individual coated Orthofabric micrographs.

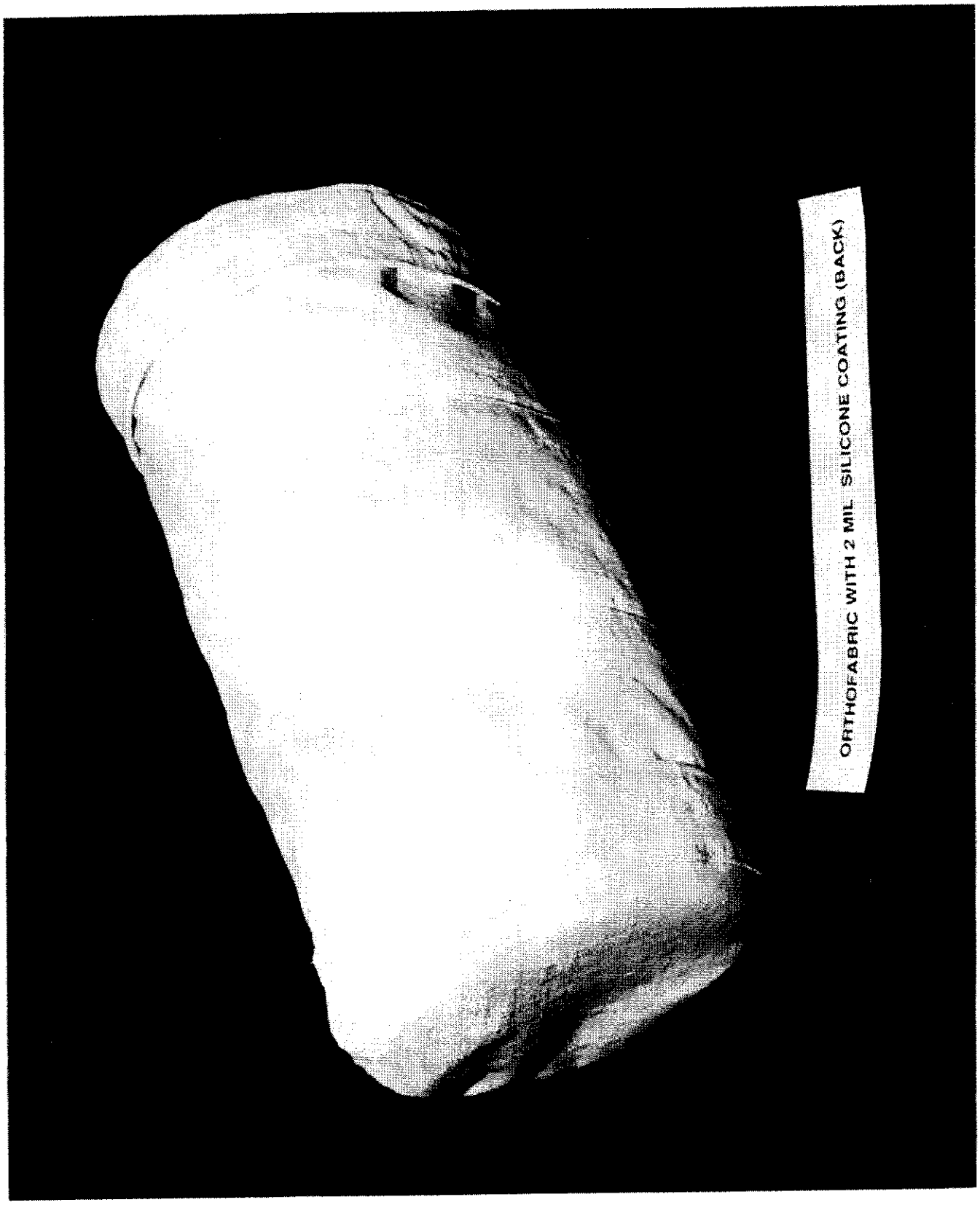


Figure 40

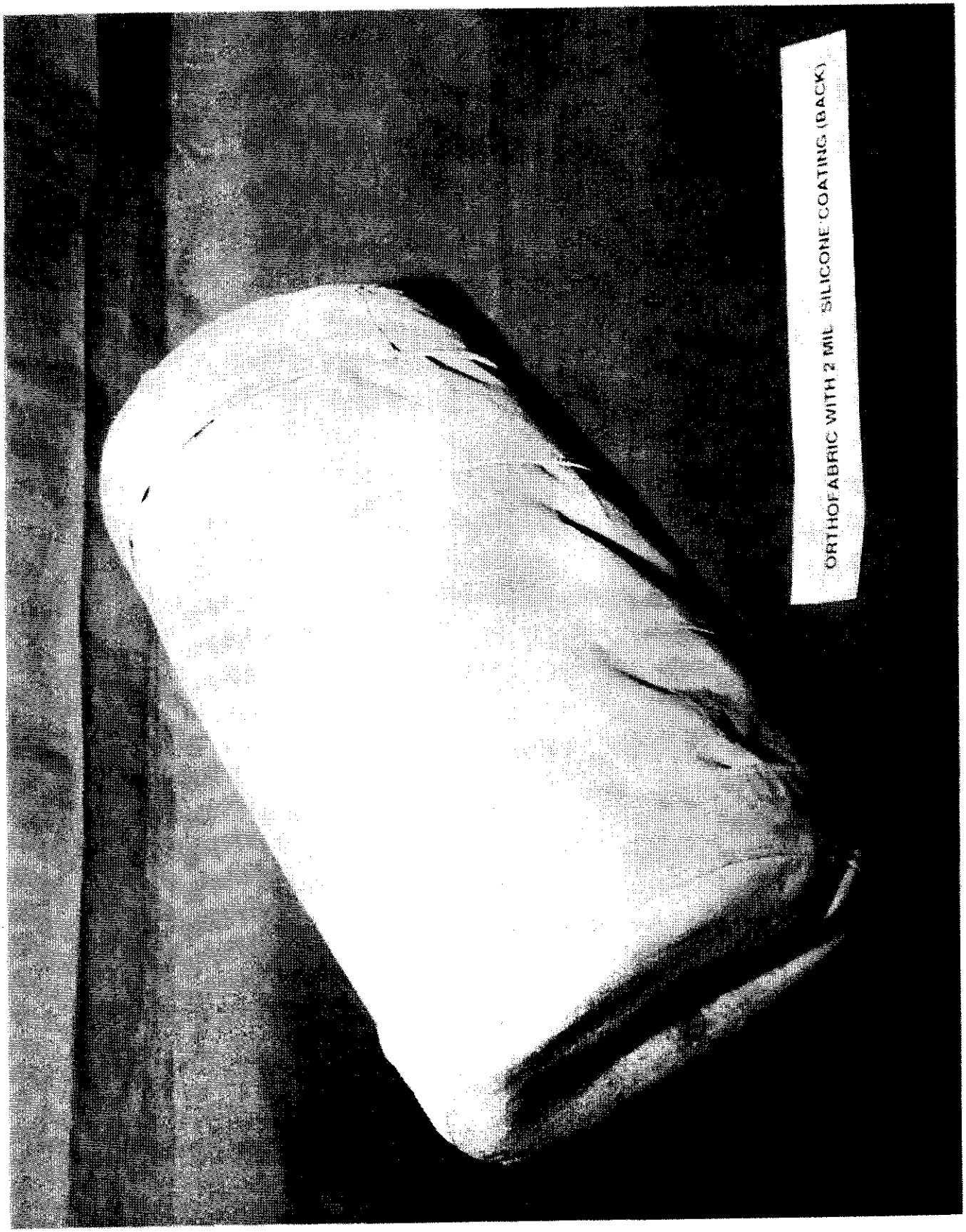


Figure 41

SAMPLE 2: ORTHOFABRIC-BACK FACE COATED WITH 10 mil. SILICONE

Micrograph Figure Arrangement Chart

Fig. 43 NEW Front	75x 400µm
Fig. 44 TUMBLED Front	79x 400µm
Fig. 45 CLEANED Front	76x 400µm
pg. 76	

Fig. 46 NEW Front	7600x 2µm
Fig. 47 TUMBLED Front	7500x 2µm
Fig. 48 CLEANED Front	7700x 2µm
pg. 78	

Fig. 49 NEW Back	130x 100µm
Fig. 50 TUMBLED Back	150x 100µm
Fig. 51 CLEANED Back	150x 100µm
pg. 80	

Fig. 52 NEW Back	14,700x 2µm
Fig. 53 TUMBLED Back	14,000x 2µm
Fig. 54 CLEANED Back	14,100x 2µm
pg. 82	

Figure 42

Figure 43

Sample: 2
View: Front
Condition: New
Ref: 400 microns
Mag: 75x

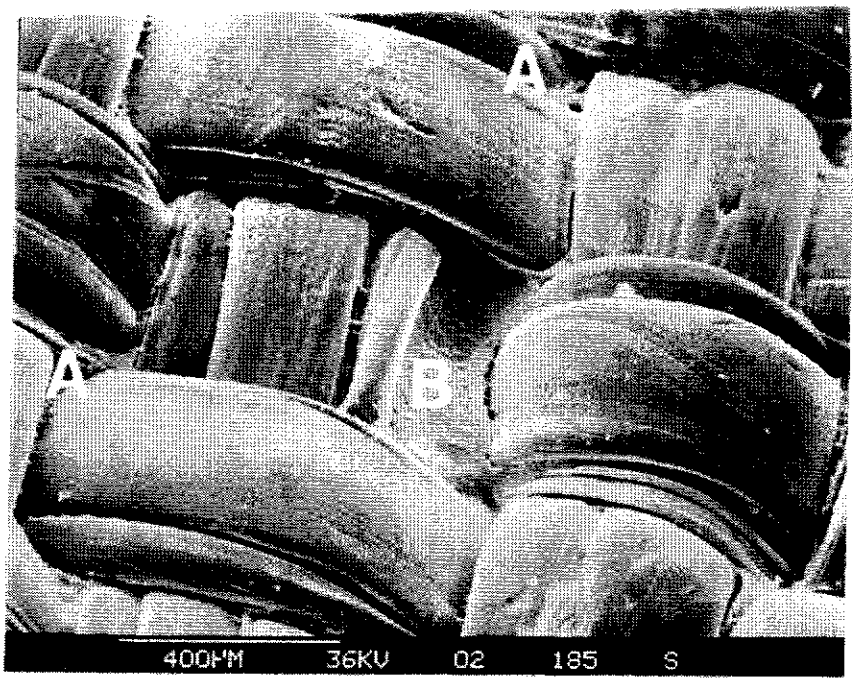


Figure 44

Sample: 2
View: Front
Condition: Tumbled
Ref: 400 microns
Mag: 79x

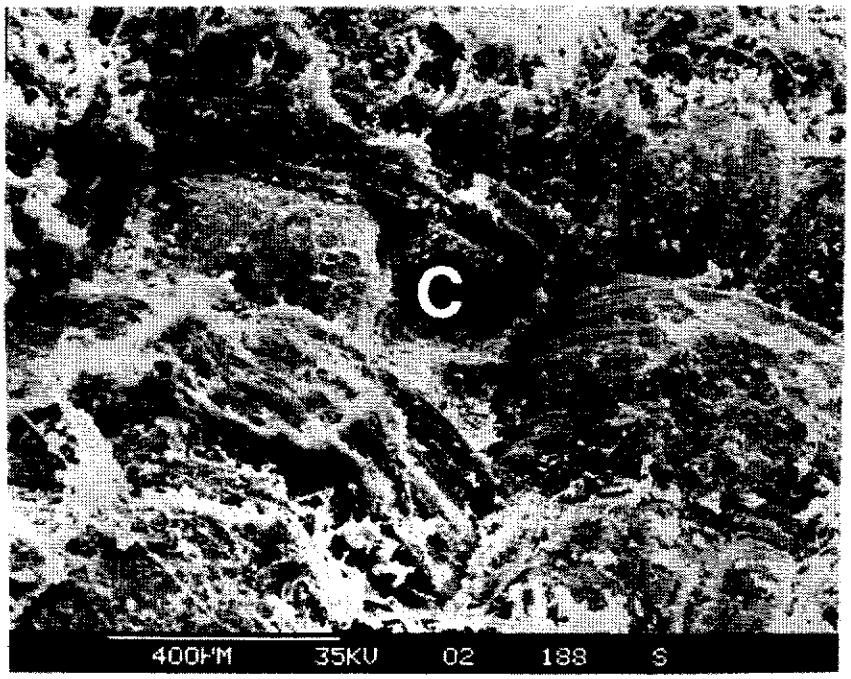


Figure 45

Sample: 2
View: Front
Condition: Cleaned
Ref: 400 microns
Mag: 76x

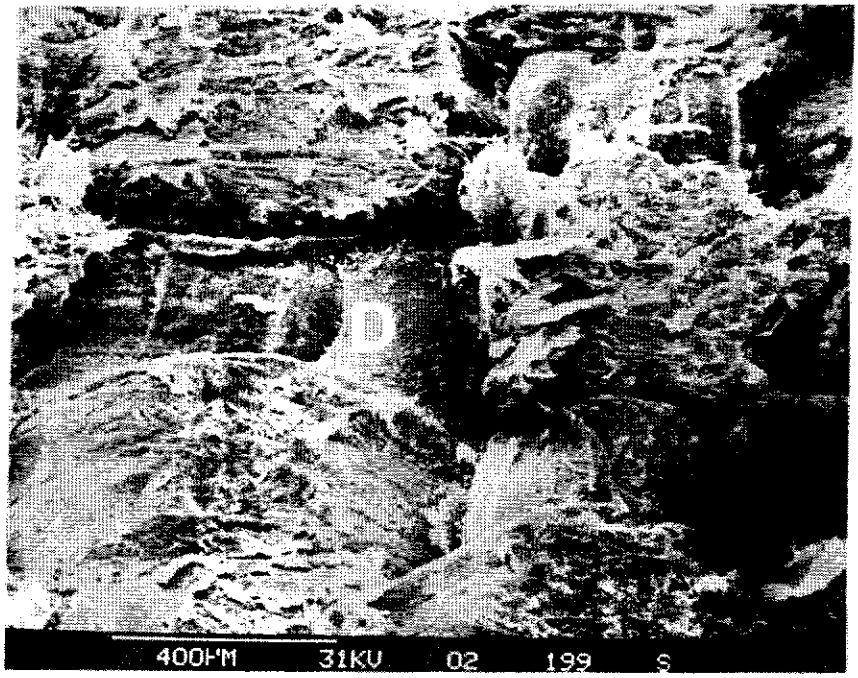


Figure 43

This is a representative view of the front-face of new, coated Orthofabric. The Gore-Tex weave is the same as that of the uncoated fabric. The difference in appearance is due to the back-face coating saturating through to the front which fills up the interstices of the weave (A). Notice that the Nomex fiber bundles are no longer visible; the depression in the weave (B) where these fibers would normally show through has been completely filled with the coating. Two dust migration routes that were identified for regular Orthofabric are through the interstices of the weave and through the depression in the weave. As seen in this micrograph, both of these routes are blocked on this sample due to the coating. There is some random pitting on the new Gore-Tex fibers, possibly from manufacturing or weaving processes.

Figure 44

Tumbling has caused a lot of damage to the coated fabric. The weave is almost indistinguishable; it is also difficult to tell the abrading particles and fiber debris apart. The depression in the weave is barely visible (C).

Figure 45

After the ultrasound cleaning procedure, all of the loose debris has been removed from the specimen. As with Sample 1, the Gore-Tex fibers have been heavily damaged. The original weave pattern is obscured by the Gore-Tex fibers that have been shredded into tufts from repeated dust particle impacts. Notice the depression in the weave (D) - the coating is still intact although it appears that there are some small particles embedded in the surface of the coating.

Figure 46

Sample: 2
View: Front
Condition: New
Ref: 2 microns
Mag: 7600x

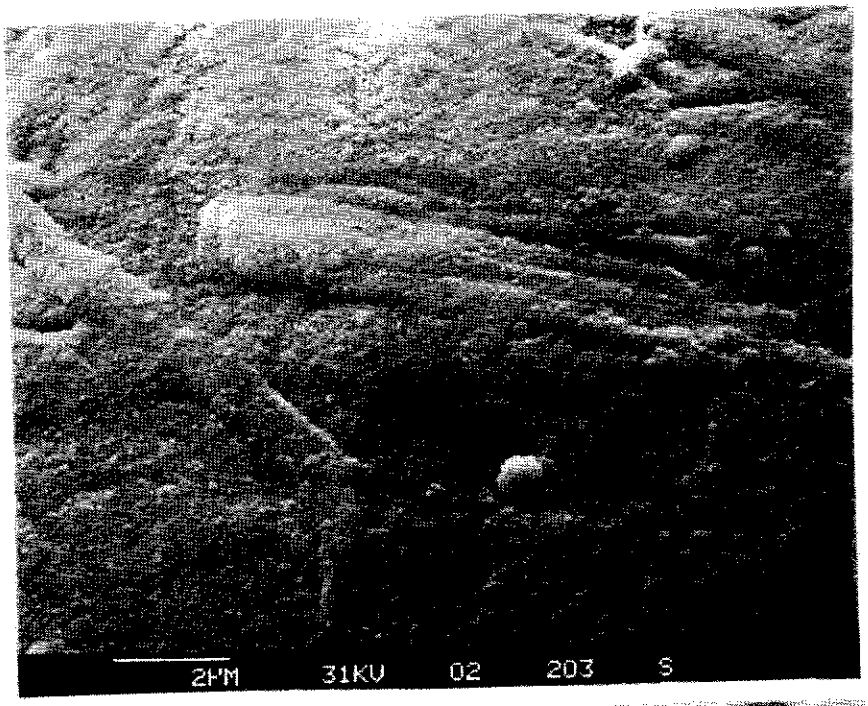


Figure 47

Sample: 2
View: Front
Condition: Tumbled
Ref: 2 microns
Mag: 7500x

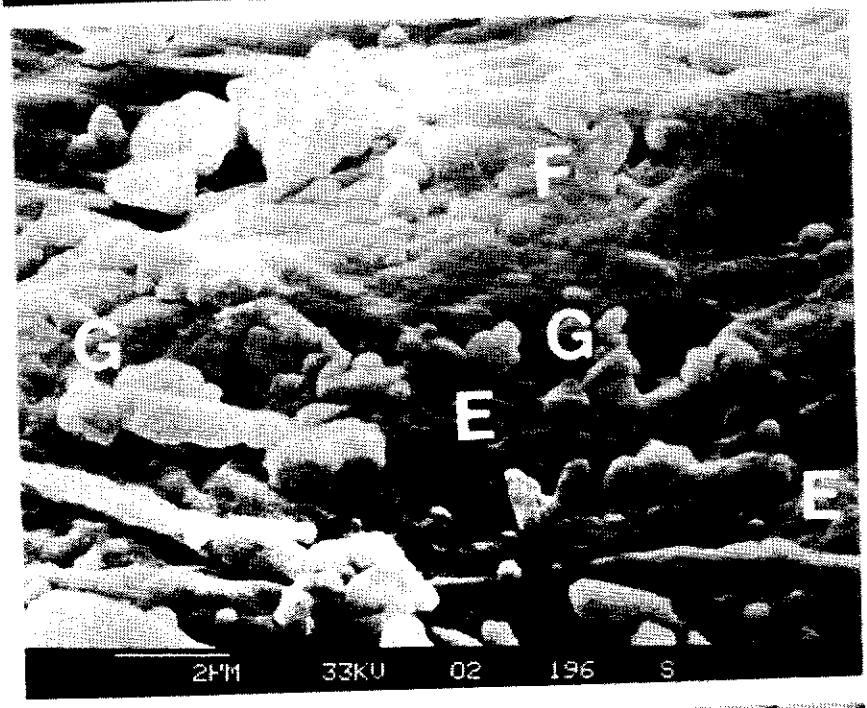
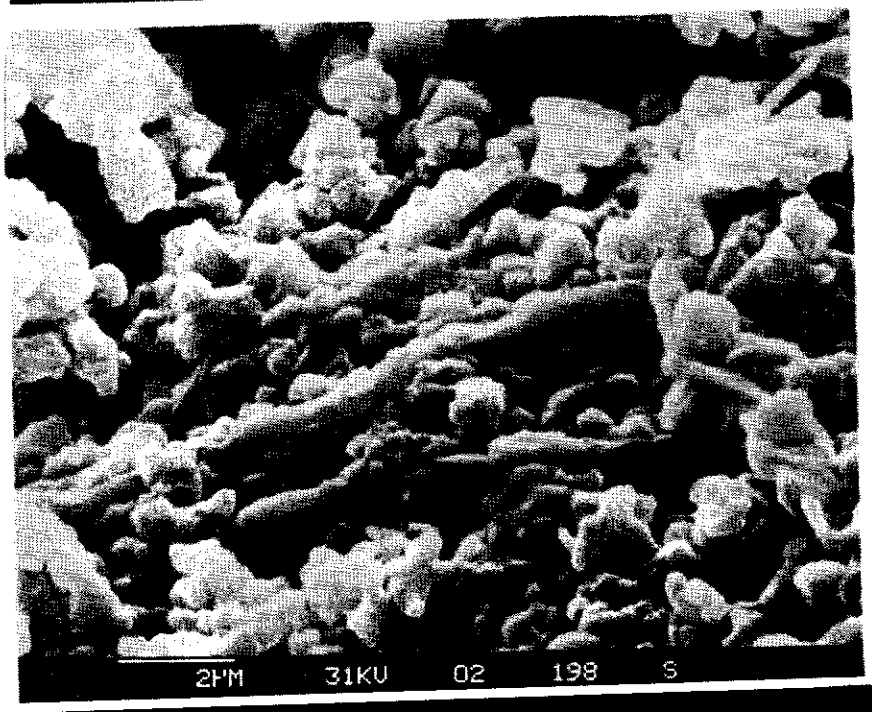


Figure 48

Sample: 2
View: Front
Condition: Cleaned
Ref: 2 microns
Mag: 7700x



Note: Since the front face Gore-Tex fiber abrasion was studied in detail in Chapter 9, the front face analysis in this chapter concentrates on the abrasion of the coating that saturated through the fabric from the back.

Figure 46

This micrograph is a closer look (7600x) at the new coating found in a depression in the front-face weave (Figure 43 at B). The coating has saturated through the fabric weave resulting in a self-formed surface that is fairly smooth.

Figure 47

Here is the same view presented in Figure 46 after tumbling. It is difficult to determine which particles are the lunar dust simulant and which are fiber debris. The dust particles have become partially embedded in the coating during the tumble test; this is the reason the particles are difficult to identify. Even with the large amount of particles present in the micrograph, it is obvious that the smooth surface seen in the previous figure has been severely abraded. The extensive abrasive wear includes the formation of grooves (E), with and without the release of silicone debris (F), and particles impacting the surface forming craters and lips (G).

Figure 48

The partially embedded lunar dust simulant particles could not be cleaned off the fabric with the ultrasound procedure. (It is of no significance that the particle density is higher in this figure than the previous one; this is only the consequence of an incidental choice of specimen areas to observe with the SEM.)

Figure 49

Sample: 2
View: Back
Condition: New
Ref: 100 microns
Mag: 130x

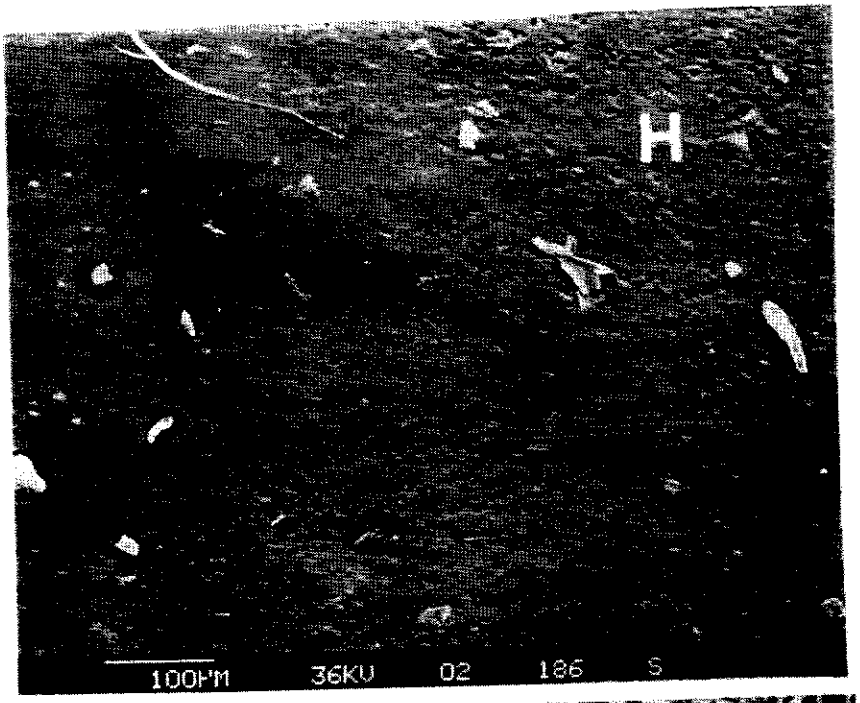


Figure 50

Sample: 2
View: Back
Condition: Tumbled
Ref: 100 microns
Mag: 150x

Figure 51

Sample: 2
View: Back
Condition: Cleaned
Ref: 100 microns
Mag: 150x

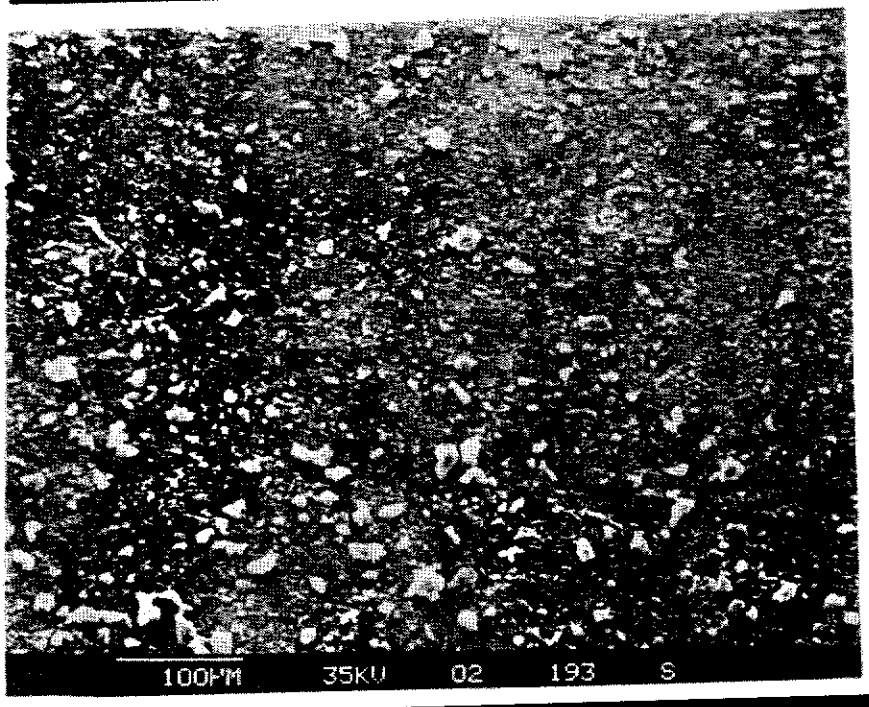


Figure 49

No features of the back face Orthrofabric weave (illustrated in Figure 28) are visible beneath the 10 mil. silicone coating. The surface of the new coating is fairly smooth; however, there are small pits (H) and several foreign particles randomly located on the specimen. Both the pits and foreign particles are most likely from fabric manufacturing or handling process.

Figure 50

There is a heavy, even distribution of lunar dust simulant particles on the back face coating after tumbling. The particles range in size from less than 5μm to 75μm. This is evidence that the dust has migrated through the fabric; migration paths through the coated fabric are at the seams. These paths include needle holes for thread to travel from one face to the other and gaps between the two pieces of fabric that are joined at the seam. Other dust migration paths observed on the uncoated Orthofabric which the coating blocks on this sample are depressions in the weave where the Nomex and Gore-Tex fibers cross, spaces in the interstices of the weave, and along folds induced by tumbling.

Figure 51

The ultrasound cleaning procedure has removed the large pieces of lunar dust simulant. Particles less than 30μm remain on the surface of the coating. This phenomenon is due to the following; particles that had migrated through to the back face of the fabric became sandwiched between the fabric and the pressurized test cylinder during the tumble test. The tumbling of the test cylinder resulted in the trapped particles being pressed into the coating. The embedded area of the large particles was small compared to the particles themselves; hence, the ultrasound procedure was able to shake the large particles loose from the surface. The embedded area of the small particles was a large portion of the particle's surface area; this is the reason that the ultrasound procedure was unable to detach the small particles from the coating. Although hard to tell from this magnification, it appears that there is little, if any, damage to the back face coating.

Figure 52

Sample: 2
View: Back
Condition: New
Ref: 2 microns
Mag: 14,700x

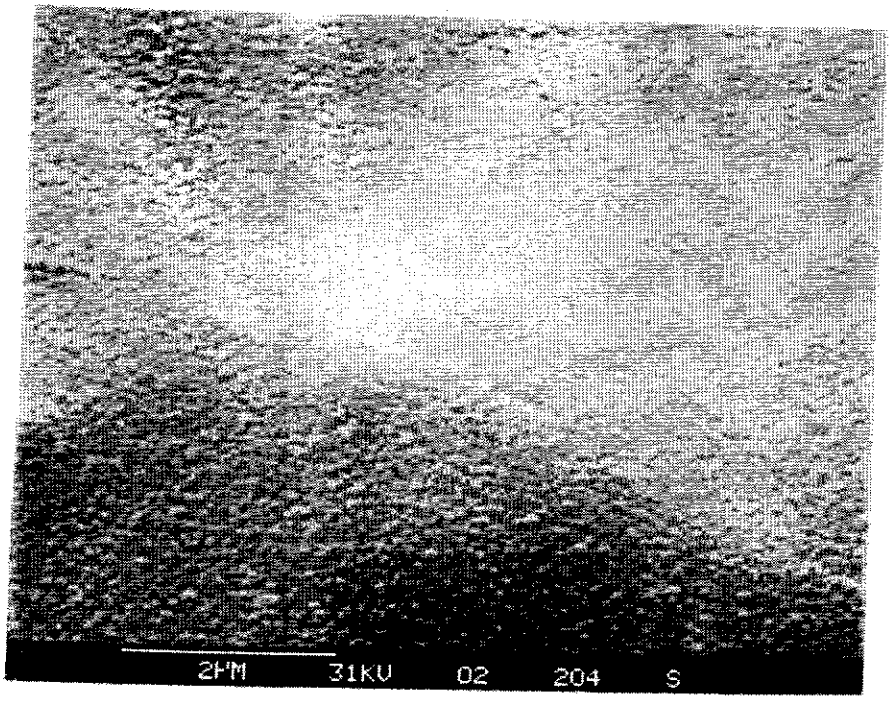


Figure 53

Sample: 2
View: Back
Condition: Tumbled
Ref: 2 microns
Mag: 14,000x

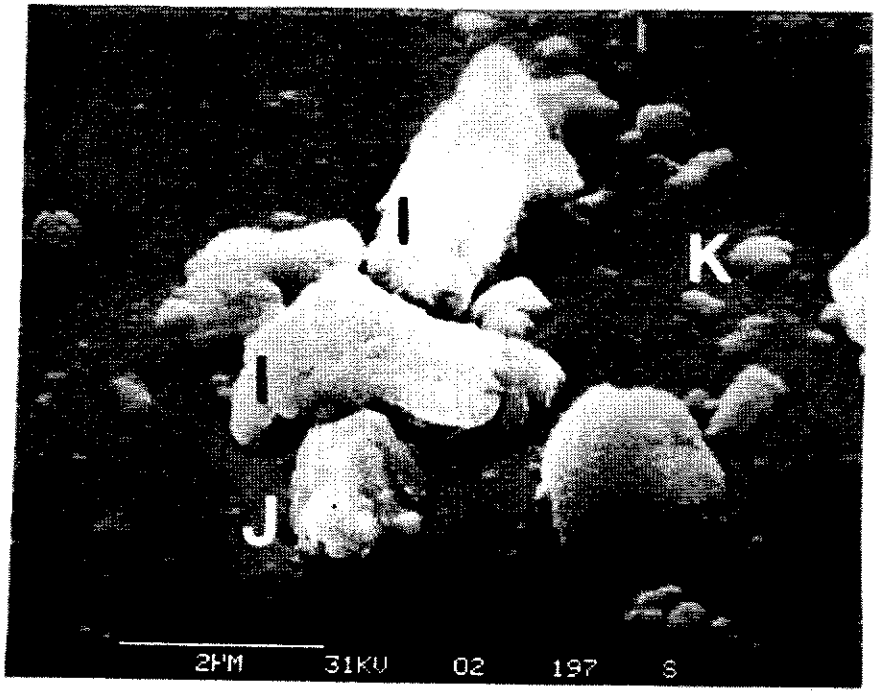


Figure 54

Sample: 2
View: Back
Condition: Cleaned
Ref: 2 microns
Mag: 14,100x

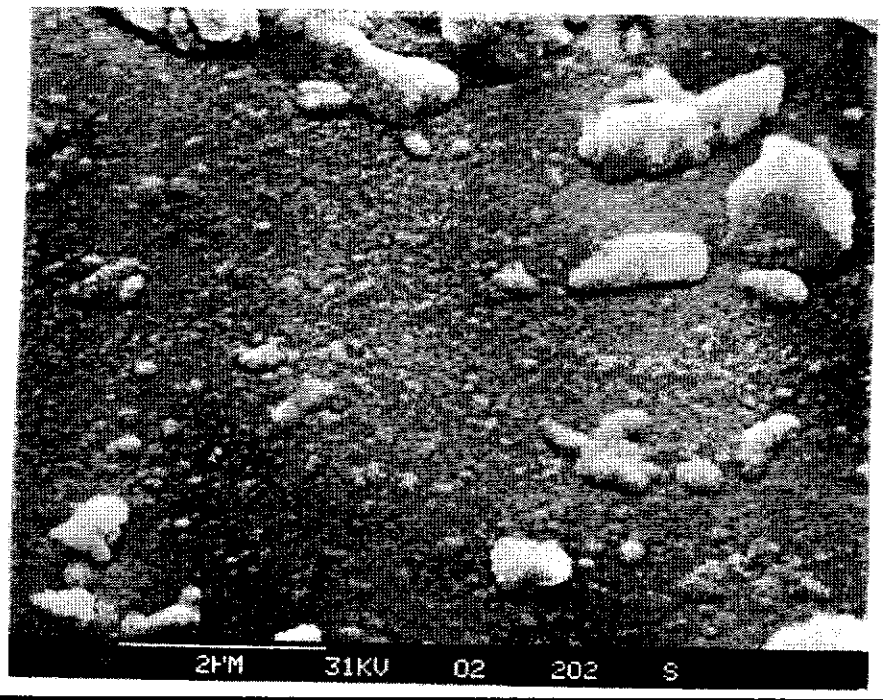


Figure 52

This micrograph is a close-up (14,700x) view of the new silicone coating on the back face of Orthofabric. (Notice that this is one of the highest magnification micrographs seen so far in this study.) The coating is very smooth. Disregard what appears to be a bump under the surface of the coating in the center of the micrograph. This is an anomally caused by the heat of the SEM electron beam focusing on the sample.

Figure 53

The particles in this micrograph are a result of the tumble test. The largest particles (I) are of lunar dust simulant glass partially covered with volcanic rock. Nearby, is a piece of volcanic rock (J). The smooth particle (K) is a piece of coating debris. As described in Figure 51, the large particles have not penetrated too deeply into the coating.

Figure 54

The cleaning procedure has removed the large particles. Figures 53 and 54 clearly demonstrate that the abrasive wear to the back face coating is minor. Only a few lunar simulant particles remain with a small amount of silicone coating debris.

SEM ABRASION ANALYSIS RESULTS
SAMPLE 2
ORTHOFABRIC - BACK FACE COATED WITH 10 mil. SILICONE

Following are the answers to the questions posed in Section 7.5.1:

A. How do the three conditions of the sample compare?

It was easy to identify the silicone coating filling the gaps in the characteristic Orthofabric weave on the front face of the sample. As with uncoated Orthofabric, the front face weave structure was indistinguishable after tumbling; it was still difficult to identify the weave after cleaning due to the abundance of shredded Gore-Tex fibers. The new back face coating was fairly smooth. Due to the presence of seams in the sample test article, tumbling resulted in a high concentration of lunar dust simulant particles covering the surface of the back face coating. Ultrasound cleaning removed the large particles while the smaller ones remained partially embedded in the surface.

B. On the tumbled samples is the viewer looking at abrading particles or at fiber debris?

Abrading particles (glass and volcanic rock) and fiber debris were present on both faces of the tumbled sample.

C. How much of the dust can be cleaned off the samples with the ultrasound procedure?

All loose debris (both lunar dust simulant particles and pieces of fiber debris) was cleaned off the front face Gore-Tex weave of the sample; however, small particles remained embedded in the coating that had saturated through the weave from the back, filling the depression in the Gore-Tex weave. On the back face, the dust simulant particles ranging from 30μm to 75μm were cleaned off by the ultrasound procedure. As with the front, the small particles less than 30μm in size remained trapped in the coating.

D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

The front face of the fabric, namely the Gore-Tex weave, was severely abraded. The extent of the damage was identical to that of Sample 1; the coating had no effect on the abrasion resistance of the front face Gore-Tex. As previously mentioned in Chapter 9, the responsible wear mechanisms included plowing along with cyclic microcutting which formed the 'tufts' on the shredded Gore-Tex fibers.

E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

Even with the back face coating as a barrier, the lunar dust simulant did successfully migrate from the front to the back of the fabric. The coating was a successful barrier to particles that normally would travel through the interstices of the weave and through the depressions in the weave of the uncoated Orthofabric. However, the migration routes through the needle holes and between the two pieces of fabric joined at the seams were still available here on this sample.

F. Did the back face of the fabric abrade? If so, what was the abrasion mechanism and what was the extent of the damage caused by the abrasion?

The back face coating showed little sign of abrasion. Any abrasion experienced was minimal; after ultrasound cleaning, the coating was intact with only a few, small pieces of lunar dust simulant partially embedded in the surface. No abrasion mechanism was identified.

G. How do the results of the SEM analysis compare with the tumble test visual inspection?

The results of the SEM analysis confirm that the visual inspection conclusions made after the tumble test were correct. There was an even layer of dust on the front face of the fabric after tumbling and the lunar dust simulant does migrate through the seams in large quantities.

CHAPTER 11

SAMPLE 3

GORE-TEX - Back Face Laminated with 2 mil. FEP Teflon

11.0 SAMPLE 3: GORE-TEX - BACK FACE LAMINATED WITH 2 mil. FEP TEFLON

Samples 1 and 2 are of Orthofabric, which was designed for Space Shuttle EVA use. Sample 3 is the fabric that is being considered as the outermost layer of the future Space Station Freedom 8 psi EVA space suit.

Sample 3 is a single fiber fabric. The Gore-Tex fiber used is a 100 denier, slit fiber of expanded PTFE. (Recall that the Gore-Tex fiber used in the Orthofabric weave was a 400 denier, slit fiber also of expanded PTFE.) The fabric is a plain weave assembled in a one-up, one-down configuration repeating on two warp and two filling yarns. This is the simplest and most common way to manufacture woven fabrics. The yarn count of the fabric in the warp direction is 93 ends and in the filling direction is 90 picks. A 2 mil. laminate was added to the back face of the fabric.

Following are the specifications for woven Gore-Tex with a 2 mil. FEP back face laminate:

1. Weight		3.21 kg/m^2	(10.5 oz/yd^2)
2. Physical Properties:			
a. Specific Gravity		2.2 g/cc	(1.27 oz/in^3)
b. Breaking Strength	Warp:	4079 kg/m	(228.0 lbs/in)
	Fill:	3460 kg/m	(193.4 lbs/in)
c. Ultimate Elongation	Warp:	11.9%	
	Fill:	23.7%	
3. Mechanical Property:			
Tear Resistance	Warp:	45.50 kg	(100.1 lb.)
	Fill:	45.50 kg	(100.1 lb.)

Figure 55 (NASA-JSC photo # S91-25161) and Figure 56 (NASA-JSC photo # S91-26395) illustrate the before and after tumble test appearance of the back face laminated Gore-Tex sample.

Note: The labels in Figures 55 and 56 were incorrectly printed. The woven Gore-Tex evaluated in this test was laminated with 2 mil. of FEP, not 3 mil. as written on the photo label.

Figure 55 is a photo of the unpressurized Gore-Tex test article. The new, clean fabric appears slightly wrinkled (A). An obervation made when inspecting the new fabric was that the laminate makes the woven Gore-Tex somewhat stiff. When folded, a crease is formed in the laminate. The fabric of the test article became wrinkled during manufacture. All stitching is even and neat, the seams have been finished and the endplugs are securely attached with Velcro closures. The back face laminate is not visible in this view.

Figure 56 illustrates the effects of eight hours of tumbling on the test article. As with the previous samples, the excess dust was shaken off the test article and the outside of the cylinder was vacuum cleaned before the photo was taken. There is a significant amount of lunar dust simulant adhering to the fabric. The dust is uniformly distributed on the body of the test cylinder with a slightly higher concentration of dust in areas of high relief and a low concentration in areas where the fabric has been indented, such as the endcaps. There are no tears or any other types of visible surface damage evident in this photo.

Following the tumble test cylinder photos are the Micrograph Figure Arrangement Chart (Figure 57) and the analysis of the individual micrographs.

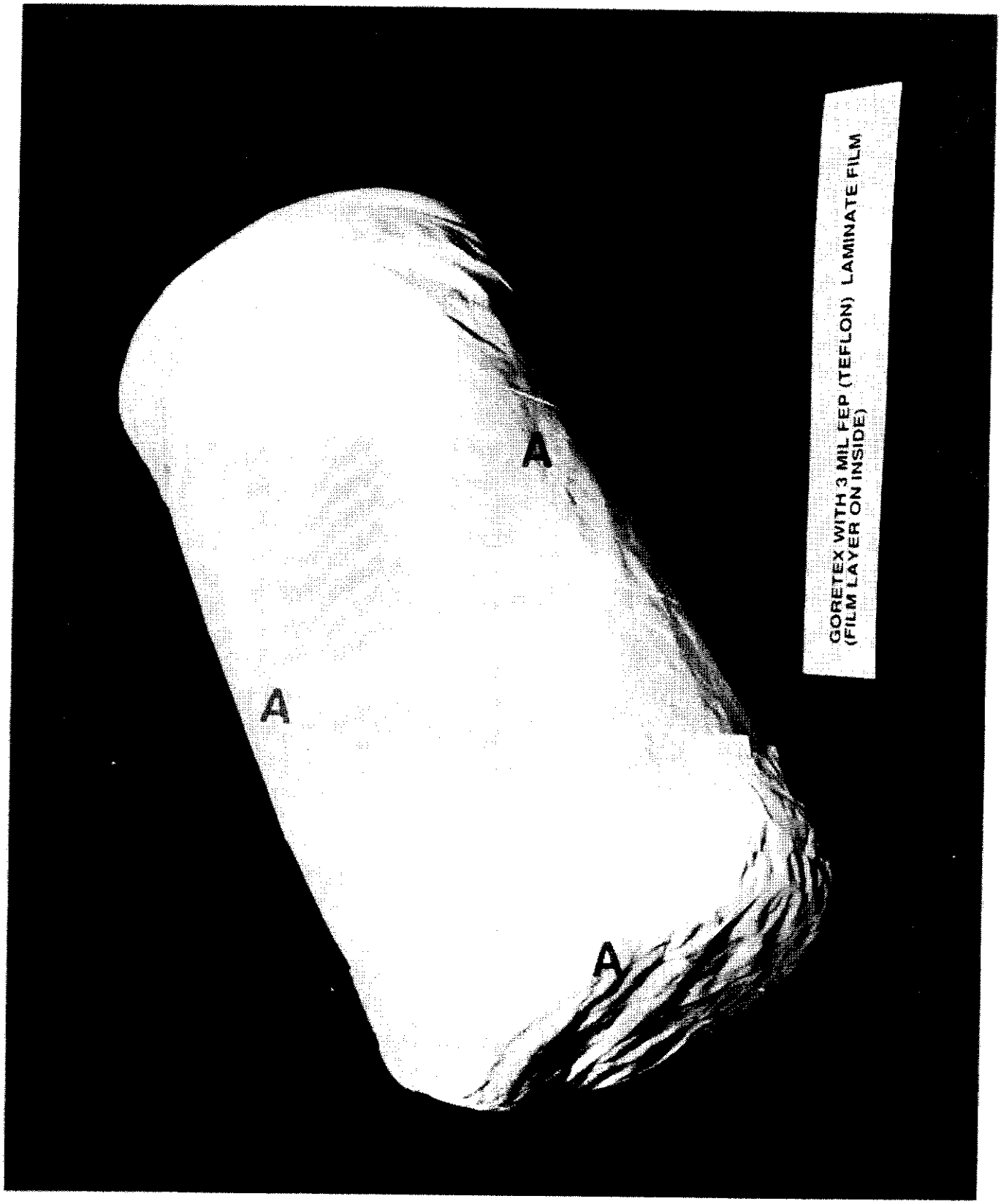

GORETEX WITH 3 MIL FEP (TEFLON) LAMINATE FILM
(FILM LAYER ON INSIDE)
A
A
A

Figure 55

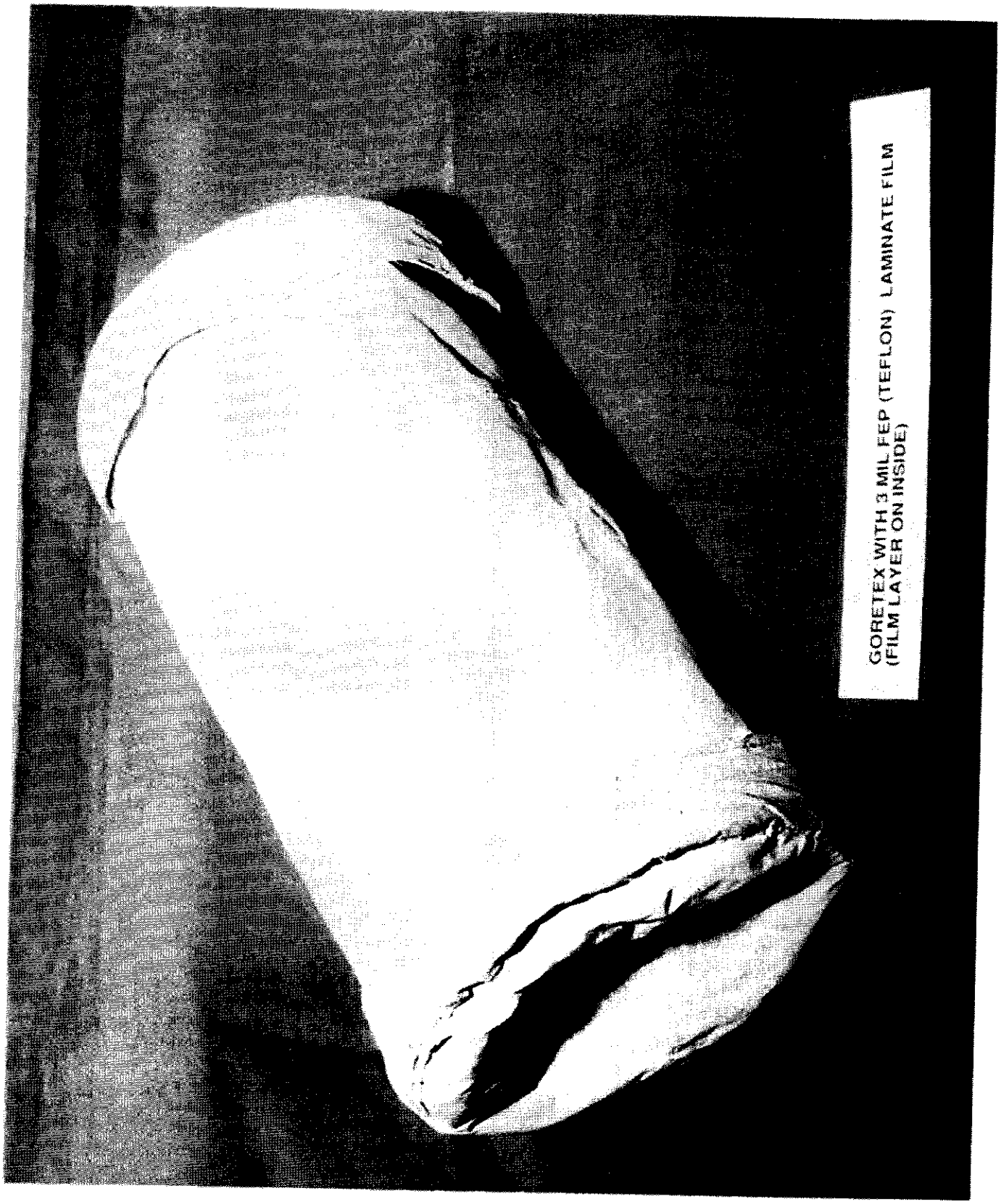

GORETEX WITH 3 MIL FEP (TEFLON) LAMINATE FILM
(FILM LAYER ON INSIDE)

Figure 56

SAMPLE 3: GORE-TEX - BACK FACE LAMINATED WITH 2 mil. FEP TEFLON

Micrograph Figure Arrangement Chart

Fig. 58	NEW	Front
50x		400µm
Fig. 59	TUMBLED	Front
50x		400µm
Fig. 60	CLEANED	Front
50x		400µm
pg. 96		

Fig. 61	NEW	Front
210x		40µm
Fig. 62	TUMBLED	Front
240x		40µm
Fig. 63	CLEANED	Front
250x		40µm
pg. 98		

Fig. 64	NEW	Back
50x		200µm
Fig. 65	TUMBLED	Back
50x		200µm
Fig. 66	CLEANED	Back
55x		200µm
pg. 100		

Fig. 67	NEW	Back
490x		40µm
Fig. 68	TUMBLED	Back
470x		40µm
Fig. 69	CLEANED	Back
570x		40µm
pg. 102		

Fig. 70	SEAM, NEW	Back
8x		1mm
Fig. 71	SEAM, TUMBLED	Back
46x		200µm
Fig. 72	SEAM, CLEANED	Back
47x		200µm
pg. 104		

Figure 57

Figure 58

Sample: 3
View: Front
Condition: New
Ref: 400 microns
Mag: 50x

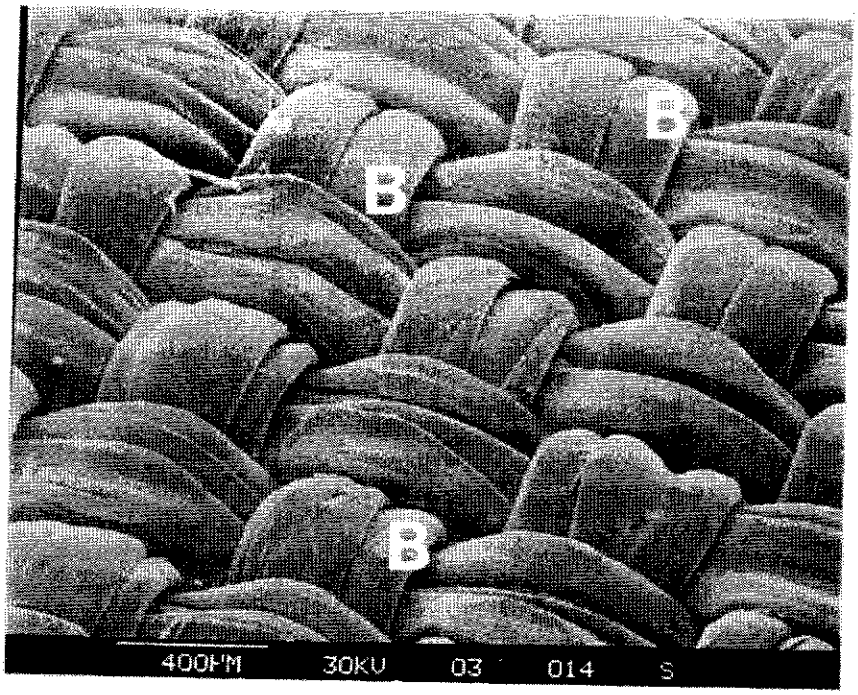


Figure 59

Sample: 3
View: Front
Condition: Tumbled
Ref: 400 microns
Mag: 50x

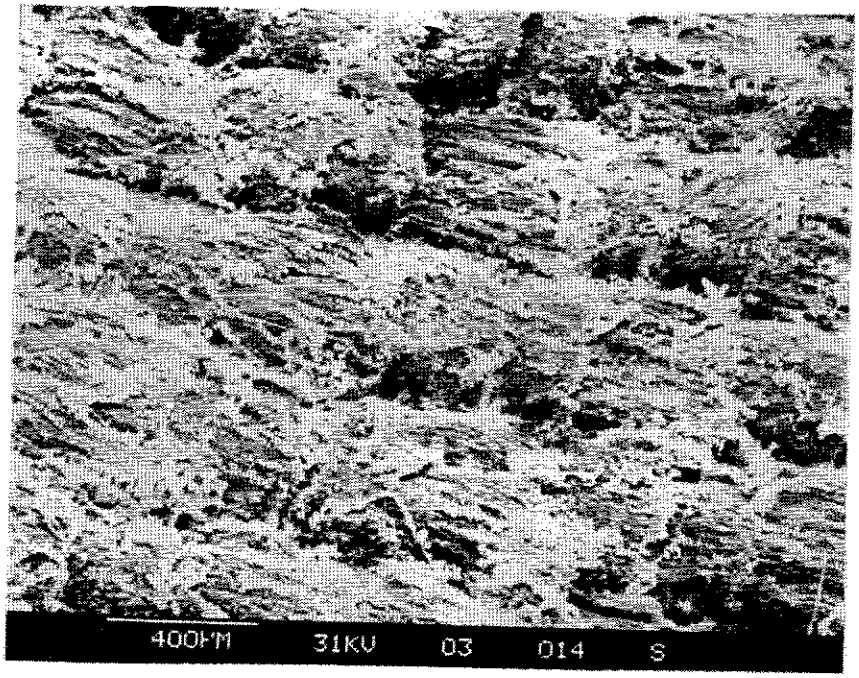


Figure 60

Sample: 3
View: Front
Condition: Cleaned
Ref: 400 microns
Mag: 50x

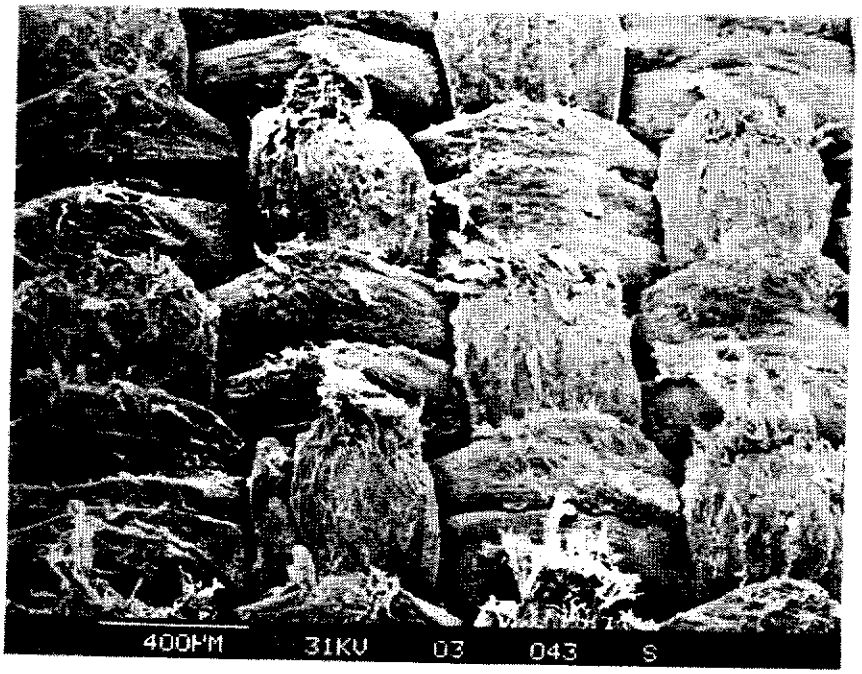


Figure 58

This is a representative view of the front face of the new Gore-Tex fabric. Notice the characteristic plain weave design of the familiar Gore-Tex fibers. The weave looks a lot like that of Orthofabric with the exception of the depressions where the Gore-Tex and Nomex fibers crossed. The weave is fairly tight, although there may be enough room in the interstices of the weave (B) for the lunar dust stimulant particles to penetrate the fabric. Again, there is random pitting on the new fibers from manufacturing or handling processes.

Figure 59

After tumbling, it is extremely difficult to distinguish the original fabric weave. There are both abrading particles and fiber debris present; however, it is impossible to tell which is which from this view. There are no new observations at this point about tumbled Gore-Tex fibers. As a reminder, this sample was vacuum cleaned before the photo was taken.

Figure 60

The ultrasound cleaning procedure did remove all the loose particles of lunar dust simulant and fiber debris from the tumbled fabric. As previously observed, the Gore-Tex fibers are shredded and heavily damaged.

Figure 61

Sample: 3
View: Front
Condition: New
Ref: 40 microns
Mag: 210x

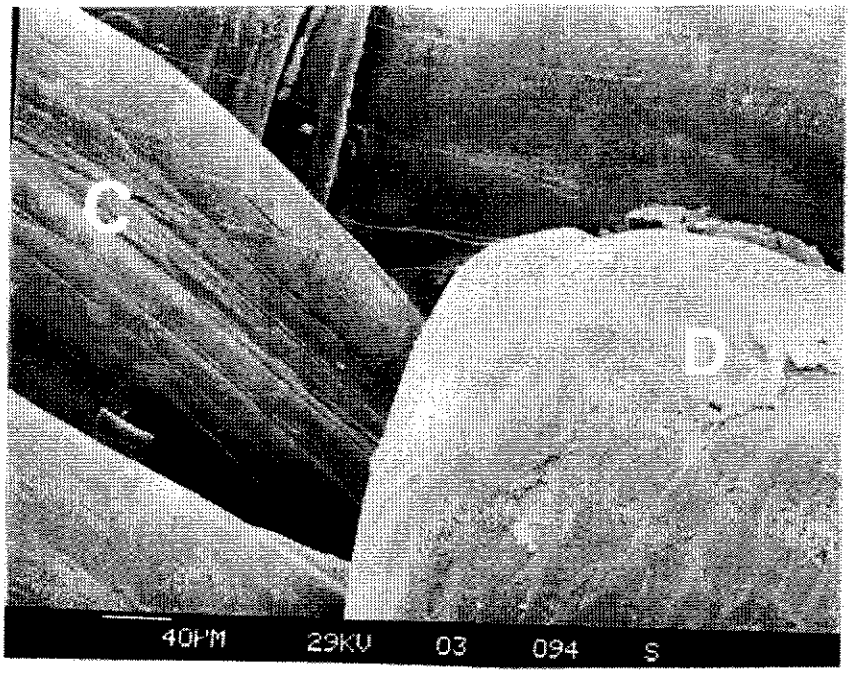


Figure 62

Sample: 3
View: Front
Condition: Tumbled
Ref: 40 microns
Mag: 240x

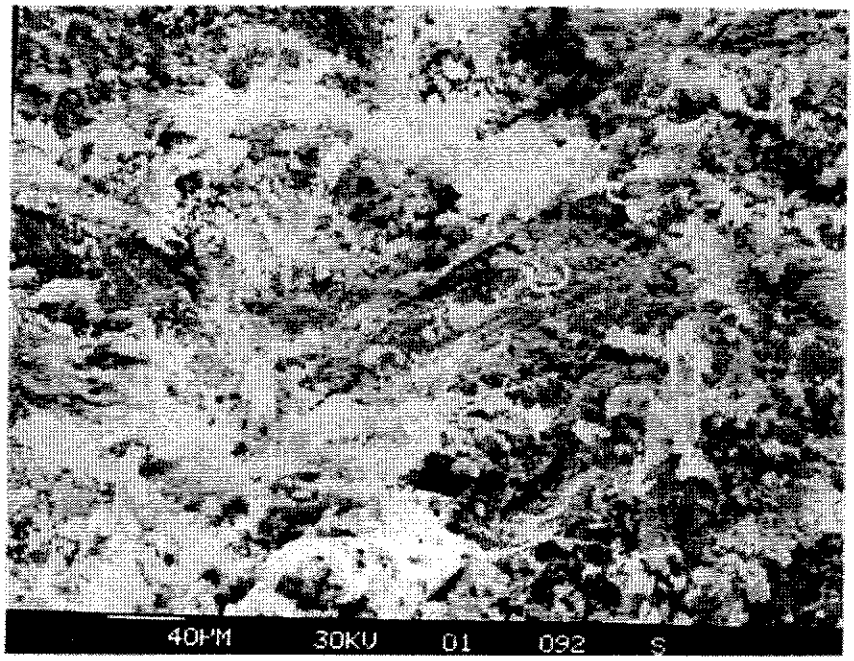


Figure 63

Sample: 3
View: Front
Condition: Cleaned
Ref: 40 microns
Mag: 250x

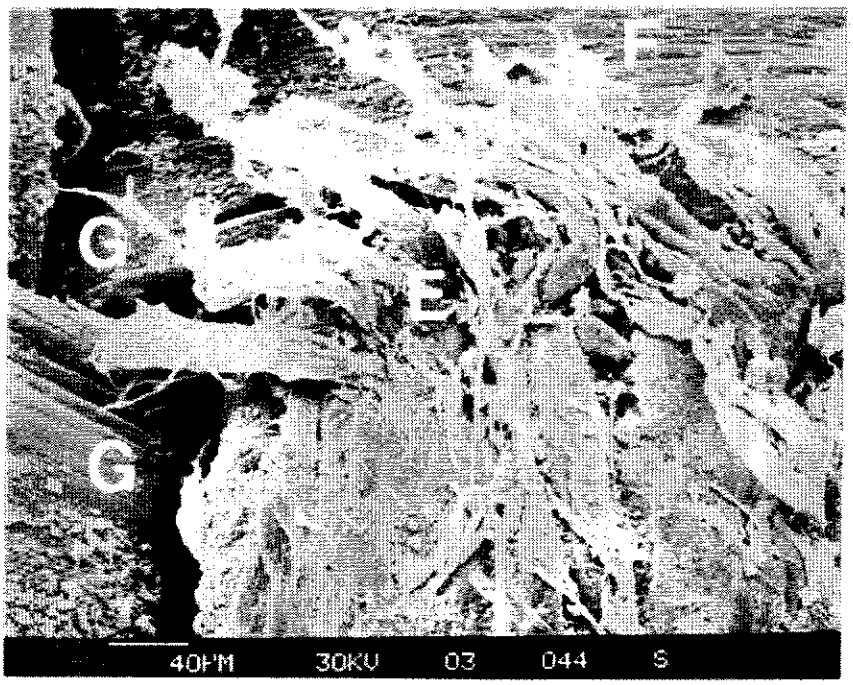


Figure 61

This micrograph illustrates the interstices of the front face Gore-Tex weave. There is little room for dust migration. Notice the parallel grooves (C) that run along the grain of the fiber; they are characteristic of new, expanded PTFE and are inherent to the material. The surface damage at (D) probably occurred during manufacturing. These features of new Gore-Tex fibers are noticeable at magnifications such as this (40μm).

Figure 62

Here is a micrograph of the same area of the fabric as shown in the previous figure after tumbling. There are no recognizable features of the original weave in this view. However, it is safe to say that there are lunar simulant particles of glass along with volcanic rock and fiber debris present.

Figure 63

After cleaning all the loose fiber debris and dust simulant off the specimen, the tumble test damage to the Gore-Tex fibers is apparent. The severe abrasive wear leads to the shredding of the fibers (E); this result can be attributed to the repeated impact of the dust particles which plow grooves in the surface of the fiber. These grooves may or may not cause the formation of fiber debris through microcutting. Along the top of the micrograph (F) is evidence that the abrasive particles have enhanced the original grooves found in the new Gore-Tex fibers. From this photo angle, it is difficult to tell if any particles are penetrating the weave through the interstices (G).

Figure 64

Sample: 3
View: Back
Condition: New
Ref: 200 microns
Mag: 50x

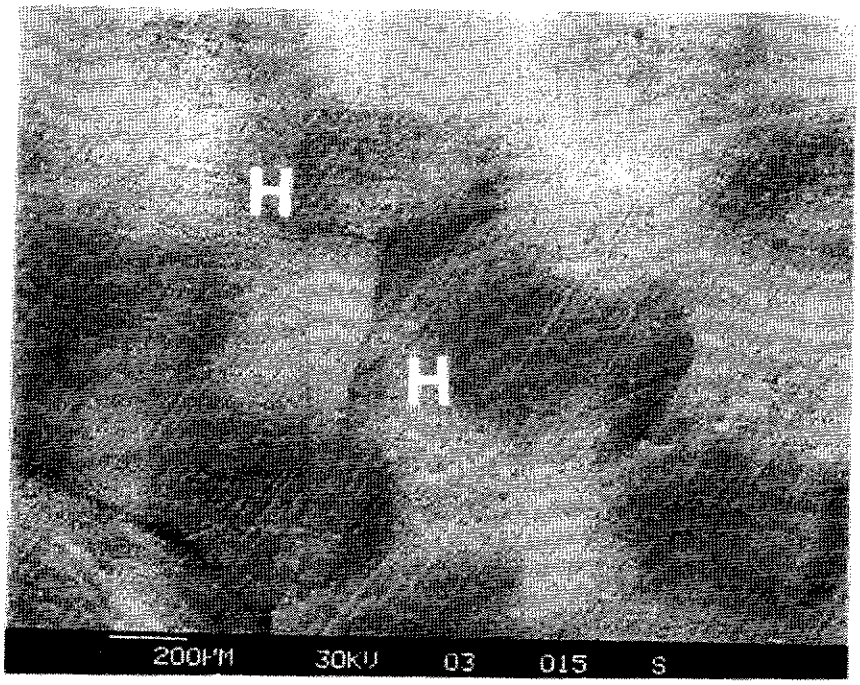


Figure 65

Sample: 3
View: Back
Condition: Tumbled
Ref: 200 microns
Mag: 50x

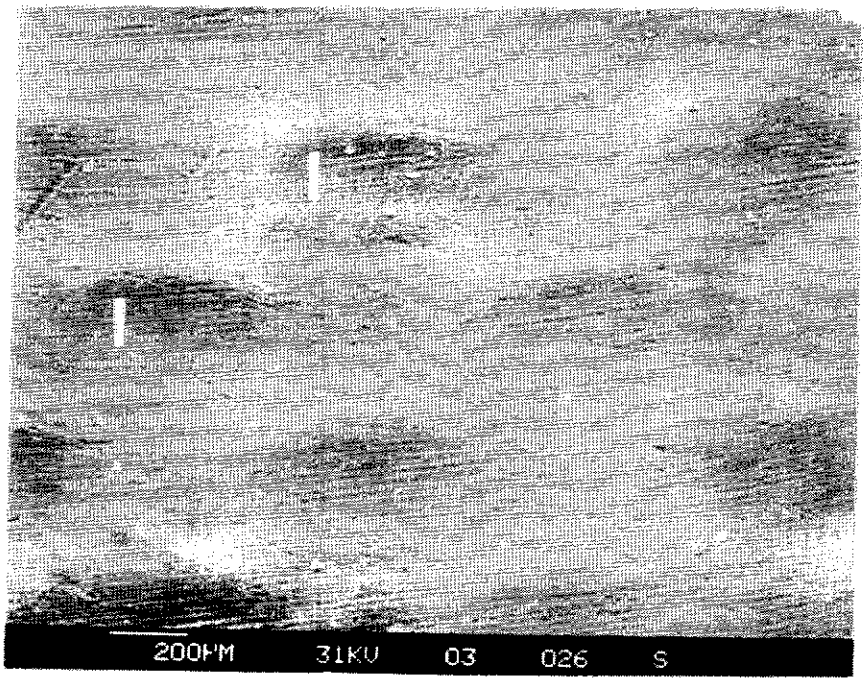


Figure 66

Sample: 3
View: Back
Condition: Cleaned
Ref: 200 microns
Mag: 55x

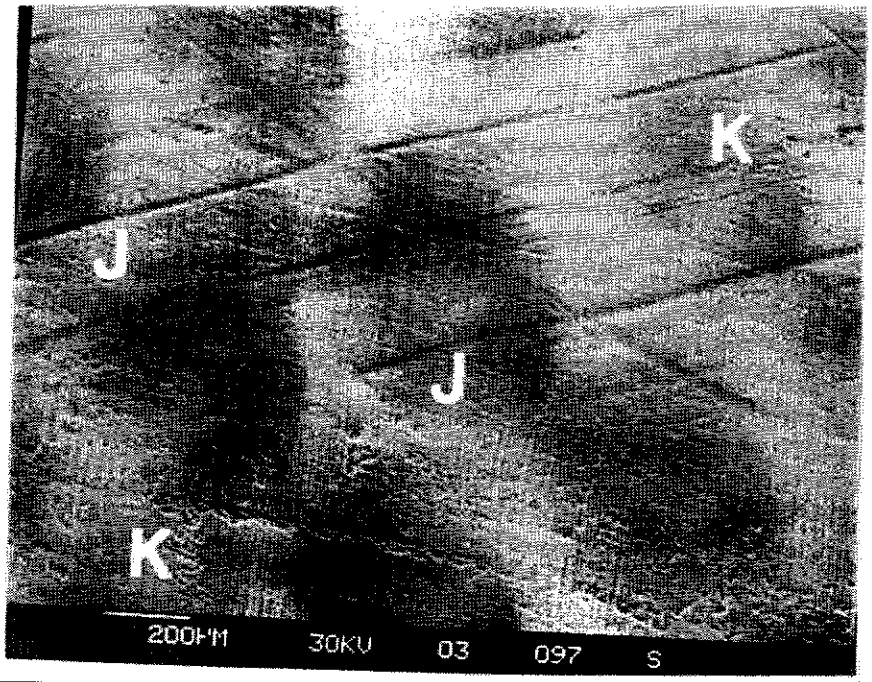


Figure 64

The laminate on the back face of the new Gore-Tex fabric is very smooth. The shadow-like, dark areas (H) on the surface indicate the weave beneath the 2 mil. laminate. There are very few pits or surface scars present from manufacturing or handling.

Figure 65

There is little debris on the back face laminate after tumbling. Particles present are an average of 30μm; it is difficult to tell if the particles are glass, volcanic rock or fabric debris. The Gore-Tex weave beneath the laminate is still visible (I).

Figure 66

The ultrasound cleaning procedure has removed all of the loose dust and debris particles. The most obvious wear mechanism present is grooving (J); there are several long, continuous grooves in the laminate. Also visible are sections where the laminate appears pitted (K).

Figure 67

Sample: 3
View: Back
Condition: New
Ref: 40 microns
Mag: 490x

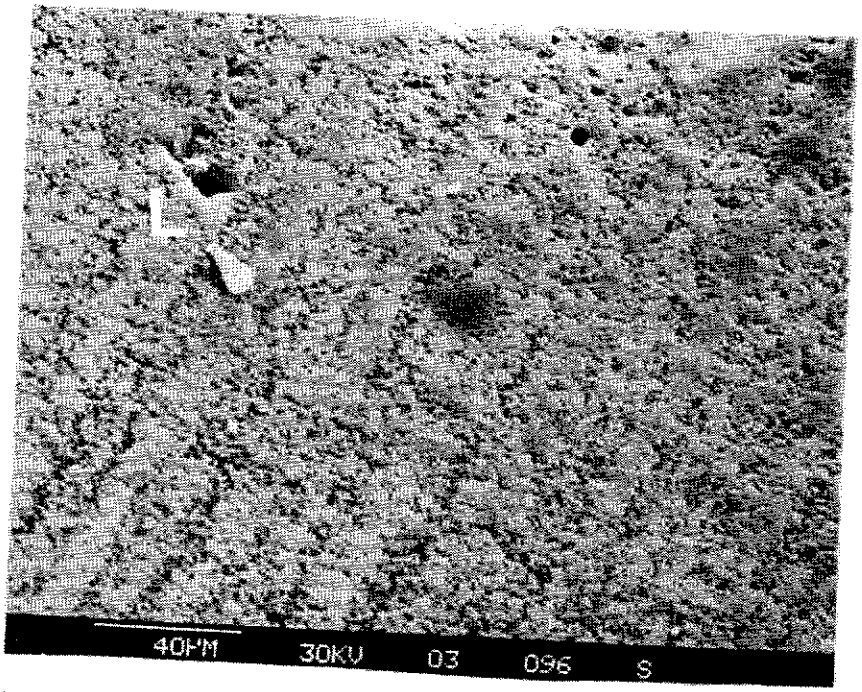


Figure 68

Sample: 3
View: Back
Condition: Tumbled
Ref: 40 microns
Mag: 470x

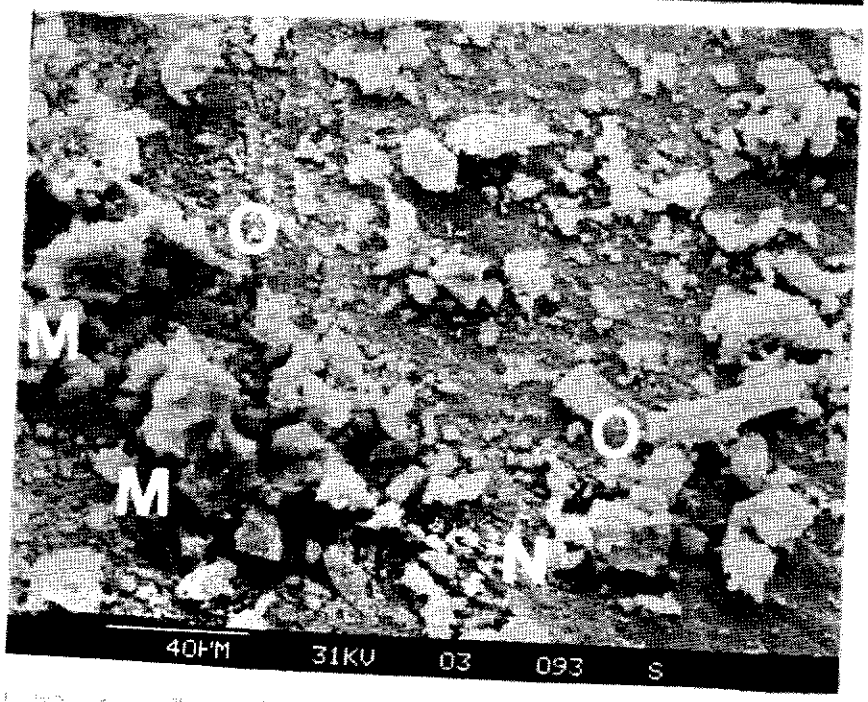


Figure 69

Sample: 3
View: Back
Condition: Cleaned
Ref: 40 microns
Mag: 570x

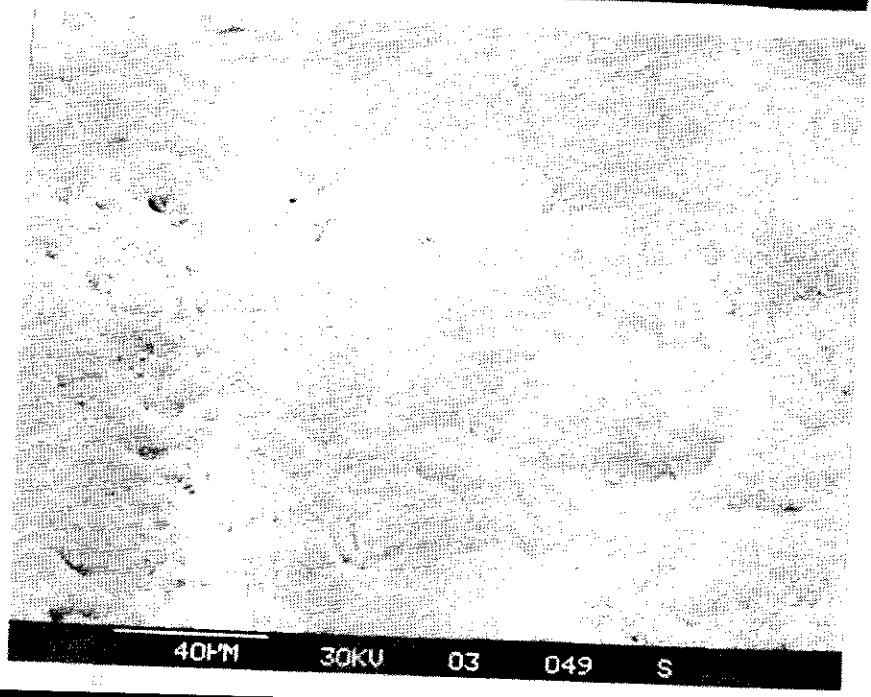


Figure 67

A closer look (490x) at the back face of the fabric reveals that the new laminate is essentially a membrane that resembles a dense, fishnet-like structure. There is a pattern of holes in the membrane. These holes are approximately 2-5μm which is too small for the lunar dust simulant particles to penetrate from the front face. The large hole (L) most likely occurred during manufacturing or handling.

Figure 68

The analysis of Figure 65 indicated that there were few particles on the back face laminate after tumbling. This higher magnification (470x) micrograph of the same view illustrates that, in fact there is a significant number of small particles on the laminate surface. Both glass (M) and volcanic rock particles (N) are present along with very small pieces of Gore-Tex fiber debris (O). To get to the back face of the fabric, these particles migrated through the needle holes and between the two pieces of fabric that are joined at the seams. (The analysis of Figures 61 and 67 has already determined that the particles are unable to migrate directly through the weave.)

Figure 69

The smooth laminate of Figure 67 now shows signs of heavy abrasive wear. As with Sample 2, particles that migrated through the seams became sandwiched between the fabric and the pressurized test cylinder during the tumble test. The tumbling pressed the particles into the laminate resulting in the cratered appearance of the laminate. However, the majority of the particles were not trapped in the laminate and the ultrasound procedure was able to remove nearly all of the particles. A few small particles are still present in the craters.

Figure 70

Sample: 3
View: Back
Condition:
Seam, New
Ref: 1 mm
Mag: 8x

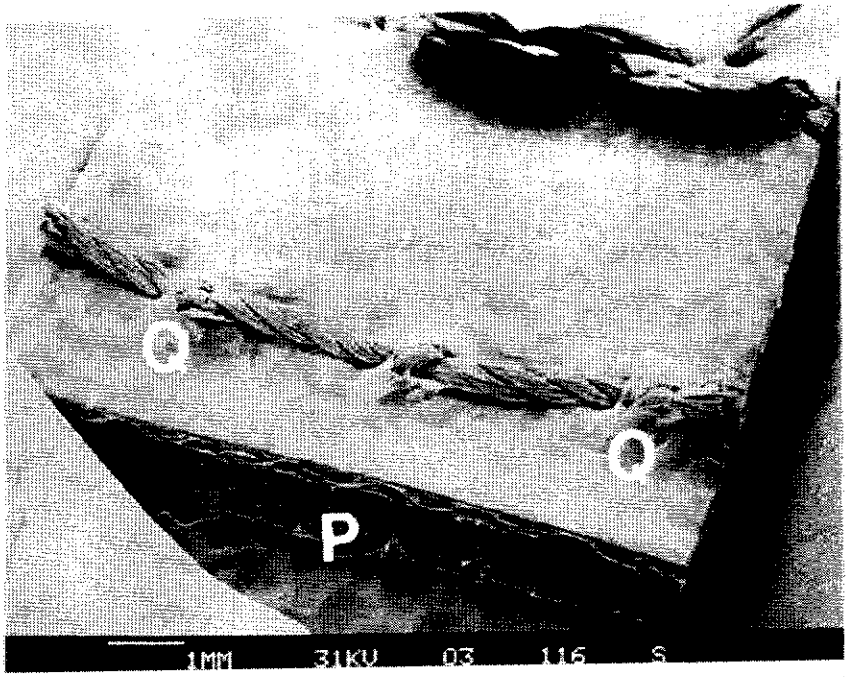


Figure 71

Sample: 3
View: Back
Condition:
Seam, Tumbled
Ref: 200 microns
Mag: 46x

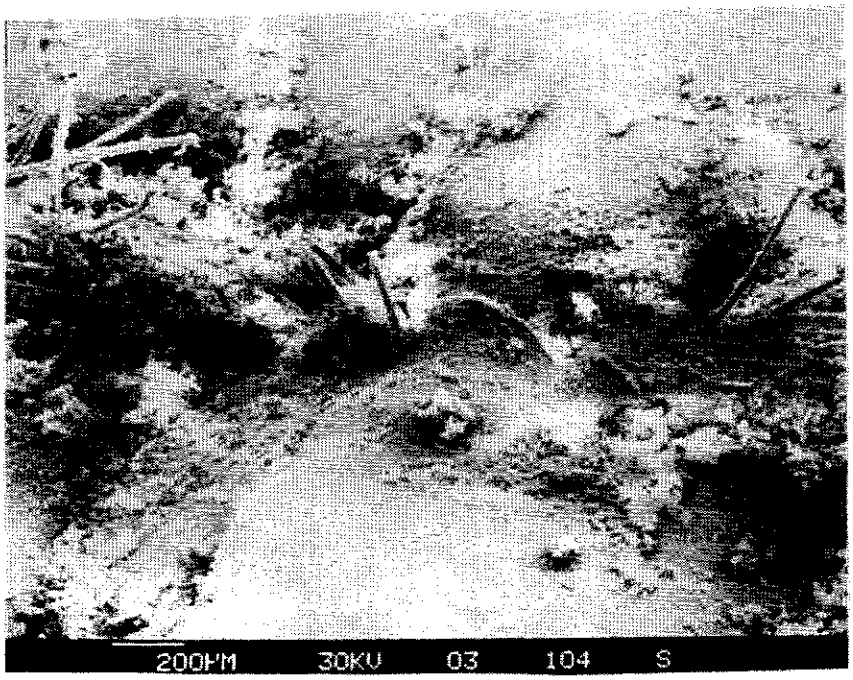


Figure 72

Sample: 3
View: Back
Condition:
Seam, Cleaned
Ref: 200 microns
Mag: 47x

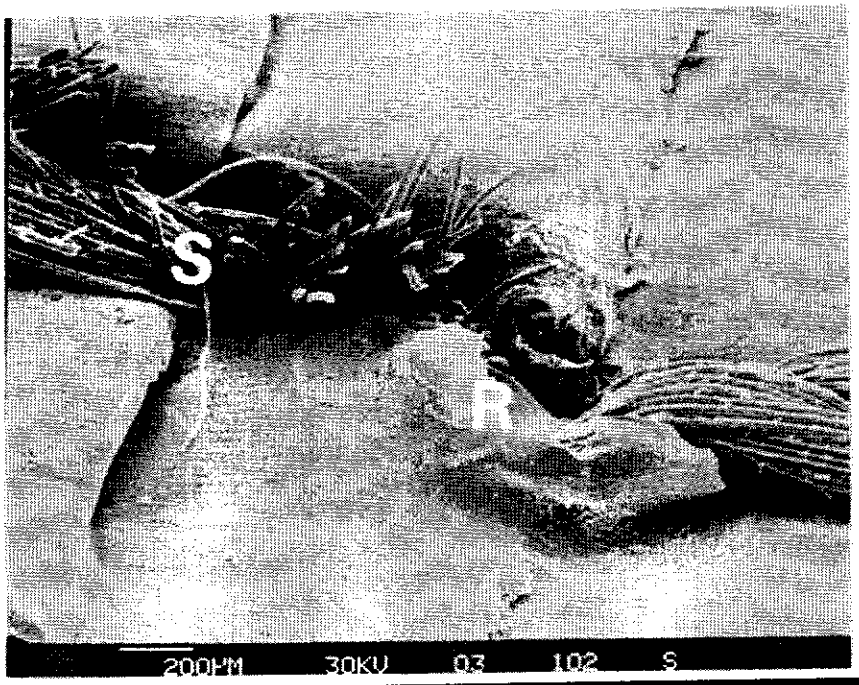


Figure 70

Here is a representative back face view of a new seam. Notice the smooth laminate which seals the Gore-Tex weave. As previously mentioned, there is a large gap (P) between the two pieces of fabric that are joined at the seam; this is the primary migration route of the lunar dust simulant particles from the front to the back of the fabric. Additional routes for particle penetration are the needle holes (Q) which pierce the back face laminate.

Figure 71

This figure illustrates the dust simulant particles cascading through the needle holes at the seam. This confirms that the seam construction technique of sewing is the major contributor to the problem of dust migration through the fabric.

Figure 72

The ultrasound cleaning technique has removed a majority of loose dust and debris particles, including all the particles that had filled gapping needle hole (R). The laminate on the back of the fabric was successful in preventing dust migration; however, this preventive measure was underminded by the seam construction technique. Note the Nomex thread (S) is frayed from the abrasive effects of tumbling and from the particles traveling through the fabric.

SEM ABRASION ANALYSIS RESULTS
SAMPLE 3
GORE-TEX - BACK FACE LAMINATED WITH 2 MIL. FEP TEFLON

Following are the answers to the questions posed in Section 7.5.1:

A. How do the three conditions of the sample compare?

The characteristic plain weave of the new Gore-Tex specimens closely resembled that of the front face of Orthofabric with the exception of the depressions where the Gore-Tex and Nomex fibers cross. The Gore-Tex fiber that was used to construct the front face of Orthofabric was that same type of fiber as in this sample; hence, the same observations were made both after tumbling and after ultrasound cleaning. The back face laminate was not visible from the front face but appeared smooth on the back face of the new sample; after tumbling the back face was covered with an even distribution of small particles. Ultrasound cleaning removed a majority of the particles.

B. On the tumbled samples is the viewer looking at abrading particles or at fiber debris?

Both lunar dust simulant particles along with pieces of volcanic rock and Gore-Tex fiber debris were present on both faces of the tumbled sample.

C. How much of the dust can be cleaned off the samples with the ultrasound procedure?

On the front face, all of the loose fiber debris and dust simulant particles were removed by the ultrasound cleaning procedure. Nearly all of the particles on the back face laminate were removed with the exception of a few small particles in the craters formed during tumbling.

D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

The front face of the fabric suffered the same type and extent of abrasion as was observed in the analysis of Samples 1 and 2. The Gore-Tex fibers were severely abraded; the back face laminate had no effect on the abrasion resistance of the front face. The responsible wear mechanism on the front was plowing along with cyclic microcutting which, after repeated impacts from the dust simulant particles, caused the formation of 'tufts' on the shredded Gore-Tex fibers.

E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

The dust migration route directly through the fabric weave is not available in this sample due to the following two reasons. First, this fabric is tightly woven which lessens the chance for particles to travel through the interstices. Second, the back face laminate acts as a barrier to any particles that do try to get through the fabric. However, the lunar dust simulant particles are successful in penetrating the fabric at the seams. Both needle holes from stitching and the gap between the two pieces of fabric joined at the seam are open doors for dust to travel through.

F. Did the back face of the fabric abrade? If so, what was the abrasion mechanism and what was the extent of the damage caused by the abrasion?

The back face laminate is considered heavily abraded if viewed at the 570x magnification (Figure 69), but only appears slightly damaged in the 55x magnification micrograph (Figure 66). The wear mechanism of grooving is evident along with the formation of craters and pits in the laminate surface.

G. How do the results of the SEM analysis compare with the tumble test visual inspection?

The results of the SEM analysis confirm that the visual inspection conclusions made after the tumble test are correct.

CHAPTER 12

SAMPLE 4

GORE-TEX - Front Face Laminated with 2 mil. FEP Teflon

12.0 SAMPLE 4: GORE-TEX - FRONT FACE LAMINATED WITH 2 mil. FEP TEFLON

The design of the previous sample included a laminate on the back face of the woven Gore-Tex. The main purpose of laminating the fabric was for this layer to act as a seal so that dust particles could not migrate through the weave. It has been shown in the previous chapter that the laminate was indeed an effective barrier to lunar dust simulant penetration.

It was also of interest to know how this laminate would stand up to the harsh abrasive effects of the tumble test. The Sample 3 fabric was reversed and given the name Sample 4. Sample 4 was include in the tumble test to answer the following question: Can the laminate acts as both a barrier to particle migration and improve the abrasion resistance of the woven Gore-Tex?

Figure 73 (NASA-JSC photo # S90-49806) and Figure 74 (NASA-JSC photo # S90-51411) illustrate the before and after tumble test appearance of the woven Gore-Tex with the front face laminated.

Figure 73 is a photo of the unpressurized test article. As with the previous sample, the new fabric is slightly wrinkled. The woven fabric cannot be seen beneath the front face laminate. All stitching is even and neat, the seams have been finished and the endplugs are securely attached with Velcro closures.

The tumble test damage to Sample 4 is immediately obvious as shown in Figure 74. The laminate has been peeled away from the fabric (A) at the seam and endcaps. However, the visual inspection of the areas beneath where the laminate was peeled away revealed that there was no visible damage to the woven fabric. Also noted was the absence of the even layer of dust on the surface of the test cylinder as was observed in the other tumble test samples. The visual inspection conclusion is that where the laminate remained on the fabric after tumbling, it was successful in keeping the surface of the fabric free from dust; however, the laminate itself was critically abraded in too many areas to be considered as a candidate fabric in this study.

As stated earlier in the report, a micrograph analysis of this sample was not done due to the extent of abrasion seen during the tumble test.

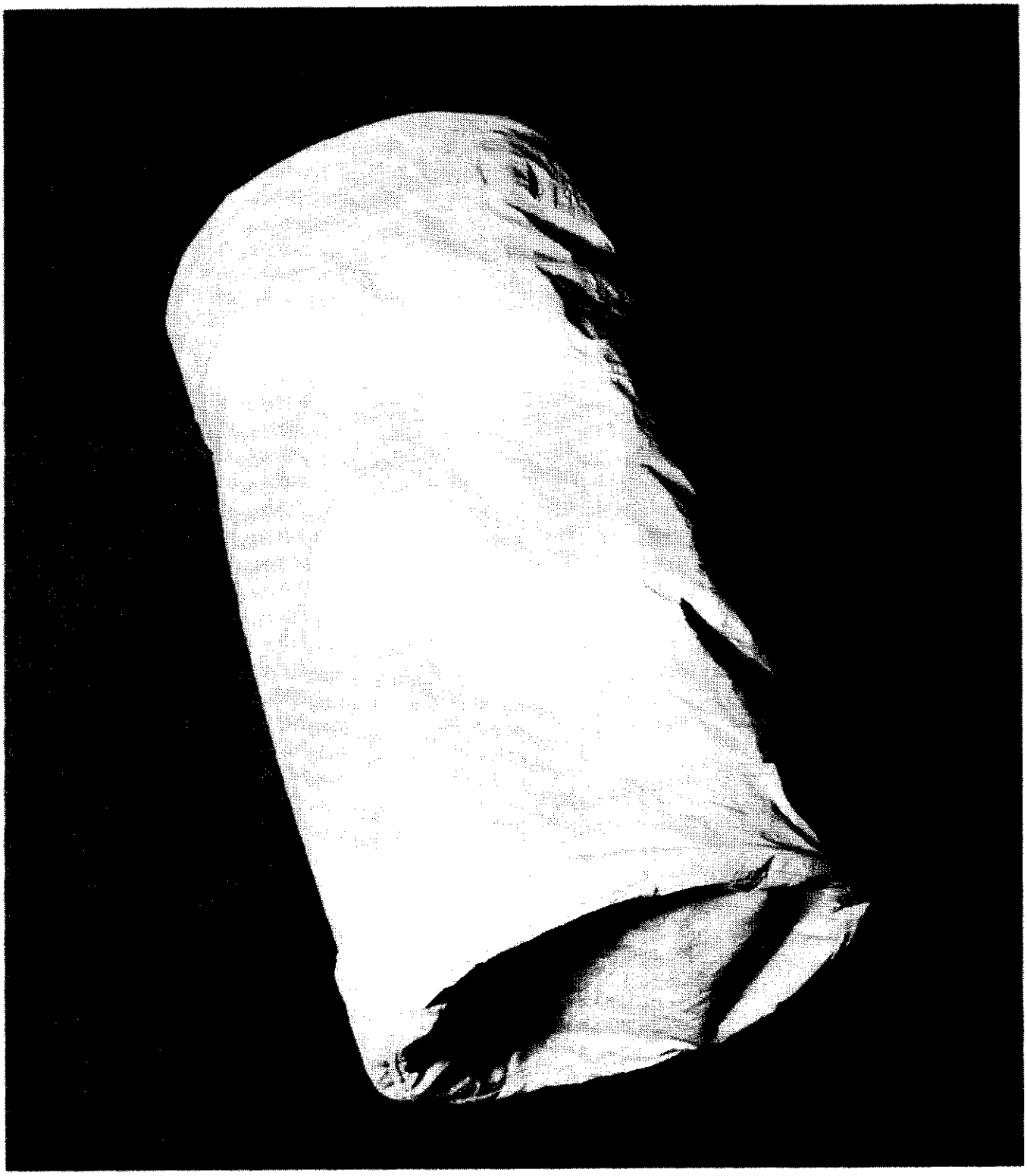


Figure 73

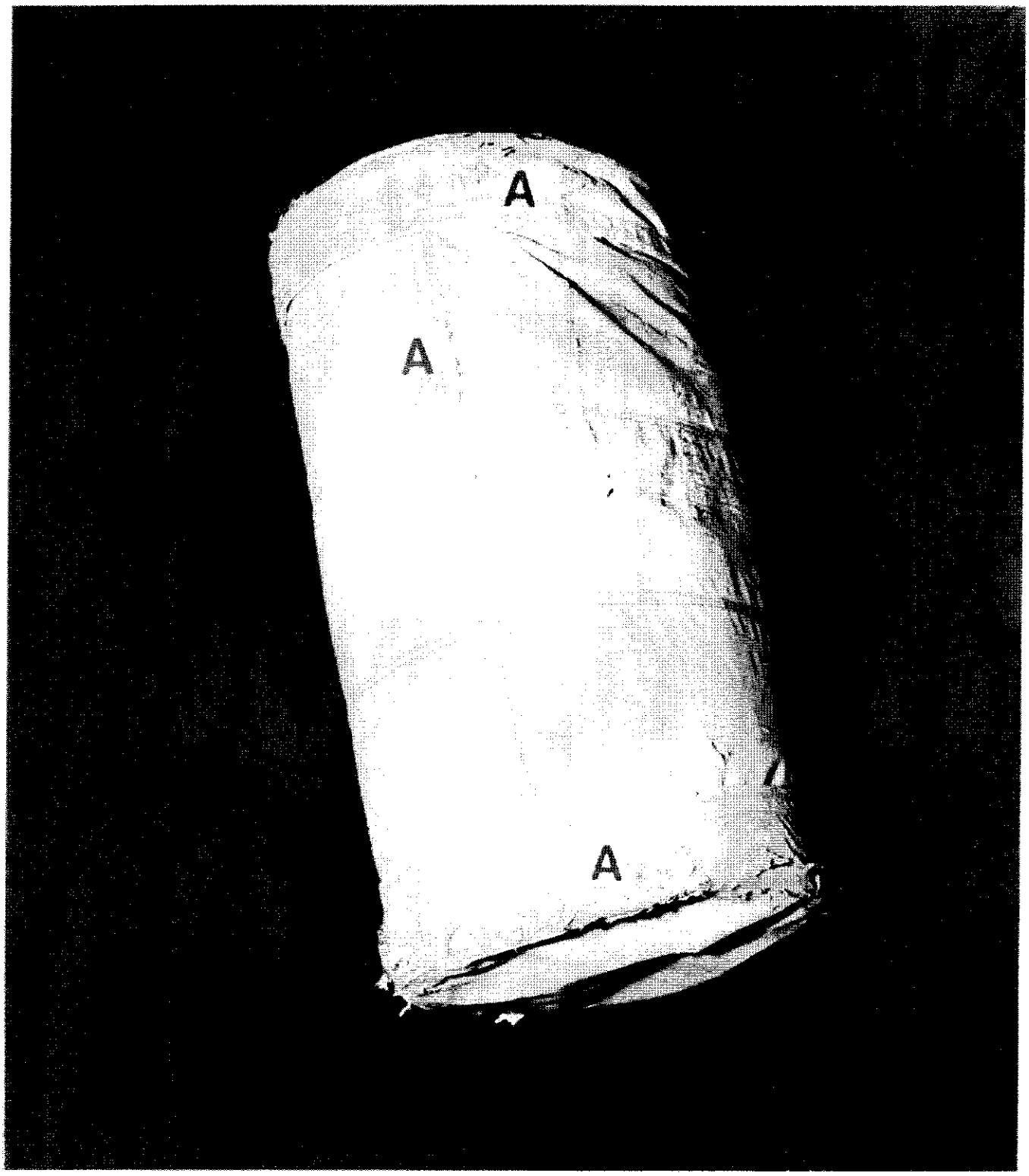


Figure 74

CHAPTER 13

SAMPLE 5

APOLLO TEST ARTICLE
Teflon (T162)

13.0 SAMPLE 5: APOLLO TEST ARTICLE TEFLON (T162)

In the Apollo program of the 1960's, the original fabric designed for the outermost layer of the lunar SSA was woven Beta. Beta fabric was unique in that it had a very low flammability potential in oxygen rich atmospheres (such as the crew cabin) along with satisfying the strict requirements necessary to protect an astronaut during EVAs on the lunar surface. After Apollo 11, which was the first lunar landing mission, it was quickly discovered that woven Beta was not able to successfully resist the abrasive effects of the lunar dust. Subsequent Apollo missions incorporated an additional fabric in the TMG design to protect the Beta from abrasion. This modified design resulted in an outermost fabric layer of woven Teflon (T162) which covered the Beta. Together these fabrics are considered the dual outer layer of the Apollo SSA.

For the purposes of this report, only the Teflon (T162) fabric will be analyzed. This sample has been included in this study as a baseline fabric.

T162 is the Stern & Stern manufacture number for this woven teflon fabric. For the remainder of the report, this code will be used to identify the Sample 5 fabric.

T162 is a single fiber weave. The teflon fiber used is a 400 denier, drawn fiber of PTFE. (Recall that the Gore-Tex fibers in Samples 1-4 were slit fibers of expanded PTFE). As with Samples 3 and 4, the fabric is a plain weave assembled in a one-up, one-down configuration repeating on two warp and two filling yarns. The yarn count of the fabric in the warp direction is 77 ends and in the filling direction is 64 picks. Following are the specifications for T162:

1. Weight		2.60 kg/m^2	(8.5 oz/yd^2)
2. Physical Properties:			
	a. Specific Gravity	2.1 g/cc	(1.21 oz/in^3)
	b. Breaking Strength	Warp: 1109 kg/m	(62.0 lbs/in)
		Fill: 1064 kg/m	(59.5 lbs/in)
	c. Ultimate Elongation	Warp: 40.1%	
		Fill: 53.1%	

3. Mechanical Property:

Tear Resistance	Warp:	9.95 kg (21.9 lb.)
	Fill:	7.5 kg (16.5 lb.)

Figure 75 (NASA-JSC photo # S91-25162) and Figure 76 (NASA-JSC photo # S91-26393) illustrate the before and after tumble test appearance of the T162 sample.

Figure 75 is a photo of the unpressurized T162 test article. The new, clean fabric has been assembled with neat, even stitching. The seams have been finished and the endplugs are securely attached with Velcro closures.

Figure 76 illustrates the effects of eight hours of tumbling on the test article. This cylinder was treated in the same manner as all others after the tumble test. There is a significant amount of lunar dust simulant adhering to the fabric. The dust is uniformly distributed on the body of the test cylinder with a slightly higher concentration of dust in areas of high relief and a low concentration in areas where the fabric has been indented. The only evidence of surface damage is a small tear (A) on the endcap.

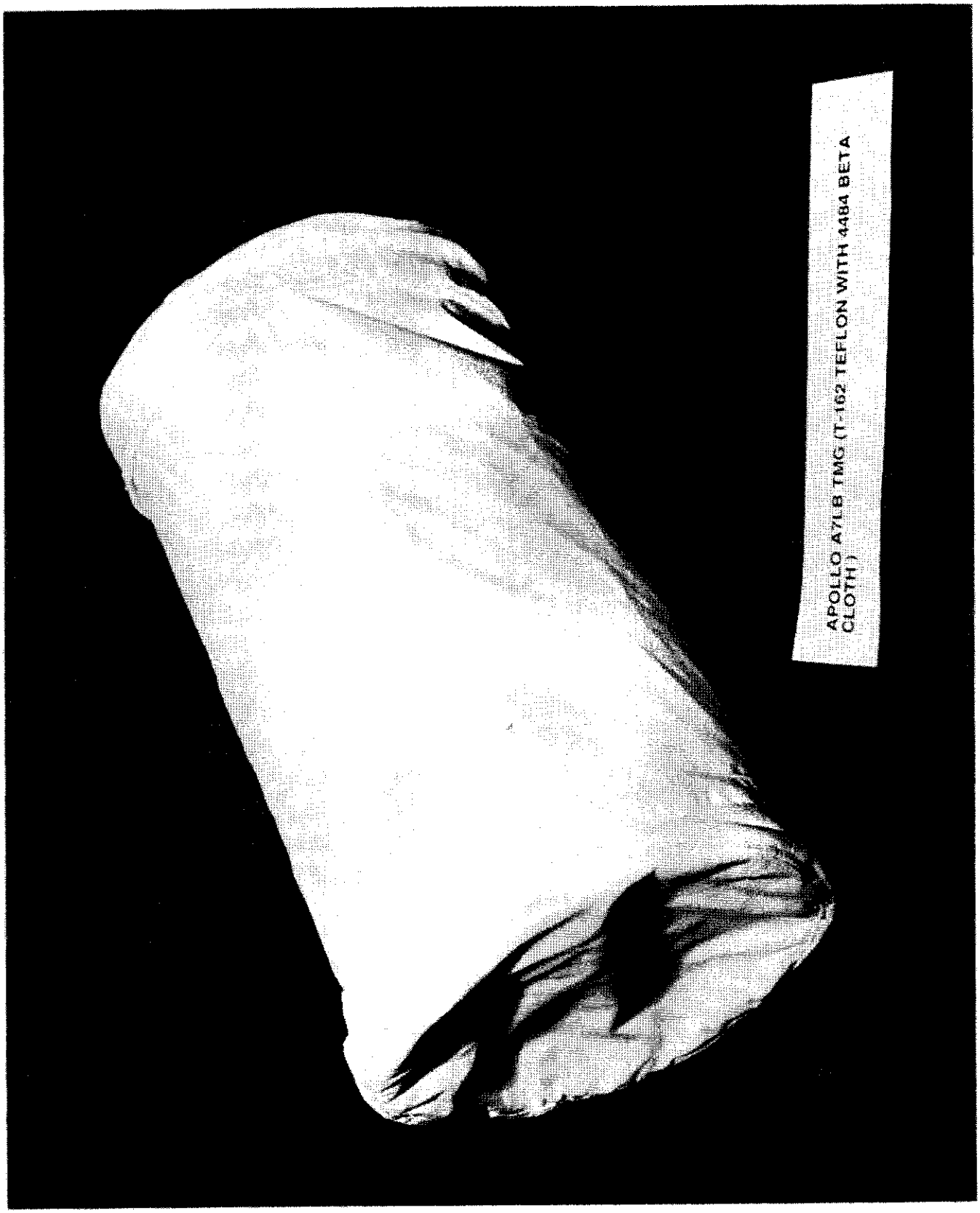


Figure 75

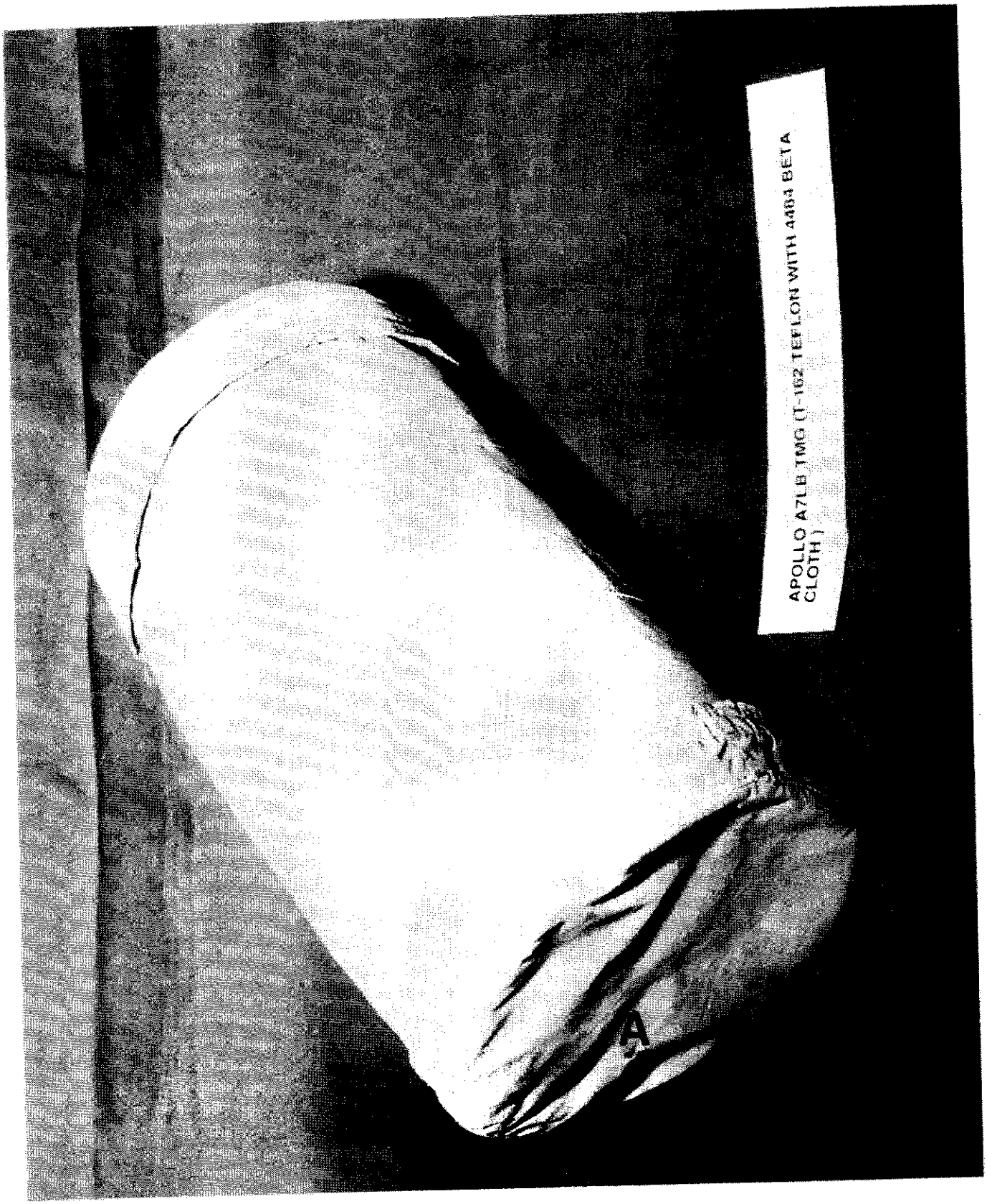


Figure 76

SAMPLE 5: APOLLO TEST ARTICLE TEFLON (T162)

Micrograph Figure Arrangement Chart

Fig. 78	NEW	Front
77x		200µm
Fig. 79	TUMBLED	Front
87x		200µm
Fig. 80	CLEANED	Front
75x		200µm
pg. 126		

Fig. 81	NEW	Front
380x		40µm
Fig. 82	TUMBLED	Front
230x		40µm
Fig. 83	CLEANED	Front
370x		40µm
pg. 128		

Fig. 84	NEW	Front
1400x		10µm
Fig. 85	TUMBLED	Front
800x		10µm
Fig. 86	TUMBLED	Front
7000x		2µm
pg. 130		

Fig. 87	NEW	Back
80x		100µm
Fig. 88	TUMBLED	Back
88x		200µm
Fig. 89	CLEANED	Back
62x		200µm
pg. 132		

Fig. 90	NEW	Back
380x		100µm
Fig. 91	TUMBLED	Back
360x		40µm
Fig. 92	CLEANED	Back
300x		40µm
pg. 134		

Figure 77

Figure 78

Sample: 5
View: Front
Condition: New
Ref: 200 microns
Mag: 77x

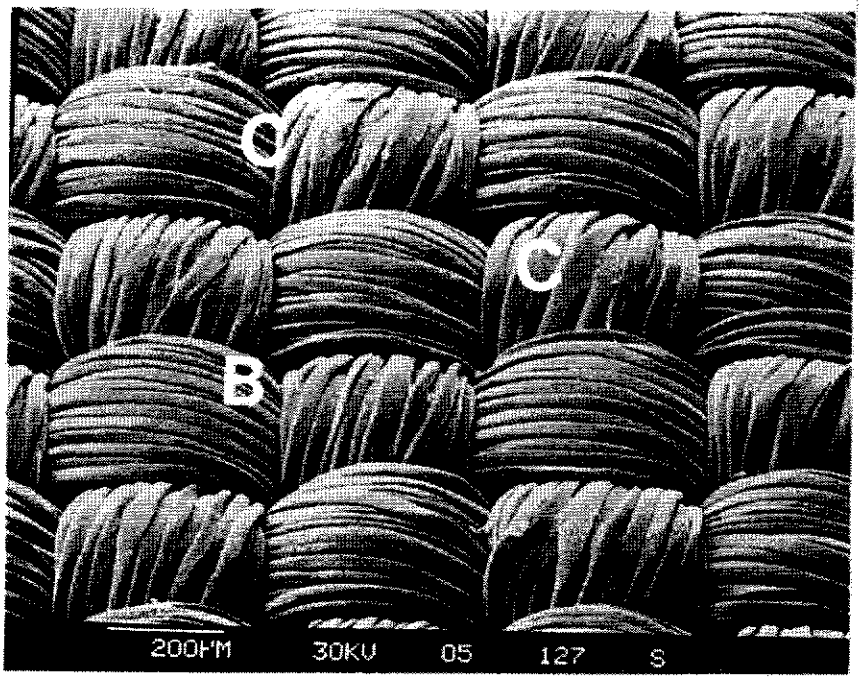


Figure 79

Sample: 5
View: Front
Condition: Tumbled
Ref: 200 microns
Mag: 87x

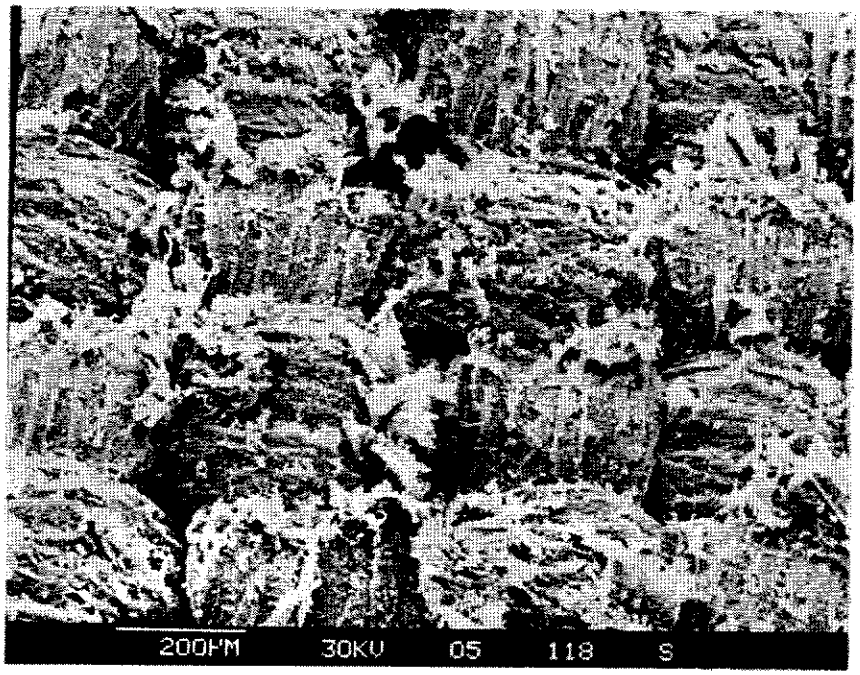


Figure 80

Sample: 5
View: Front
Condition: Cleaned
Ref: 200 microns
Mag: 75x

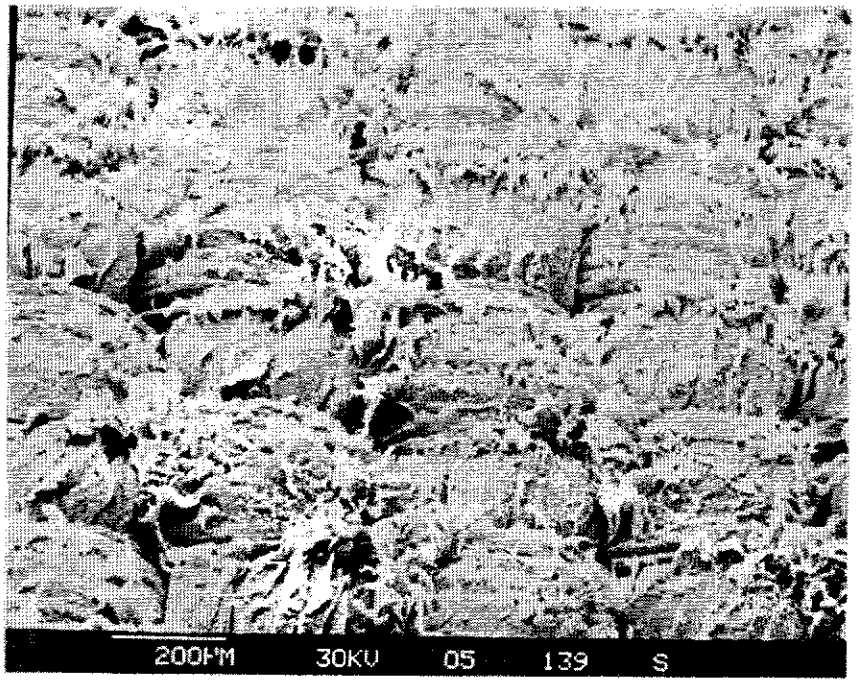


Figure 78

This is a representative view of the front face of new T162. The teflon fibers are smooth and have the ribbon-like appearance of the Gore-Tex fibers in Samples 1-4. However, unlike the two fiber Gore-Tex yarns (see Figure 16), the T162 yarns consist of many fine fibers. The characteristic plain weave is tight with little room in the interstices (B) for dust migration. There are a few fibers that are flattened (C); this damage occurred either during manufacturing or handling processes.

Figure 79

After tumbling, the severe abrasive wear of the T162 resembles the damage seen by the Gore-Tex fibers. There is a significant amount of both lunar simulant particles and fiber debris present. The original weave can be distinguished in this view.

Figure 80

The ultrasound cleaning procedure was successful in removing the loose simulant particles and/or fiber debris. The tumble test damage to the T162 fibers is evident; each fiber has been shredded causing the formation of tufts which are present all over the surface of the specimen.

Figure 81

Sample: 5
View: Front
Condition: New
Ref: 40 microns
Mag: 380x

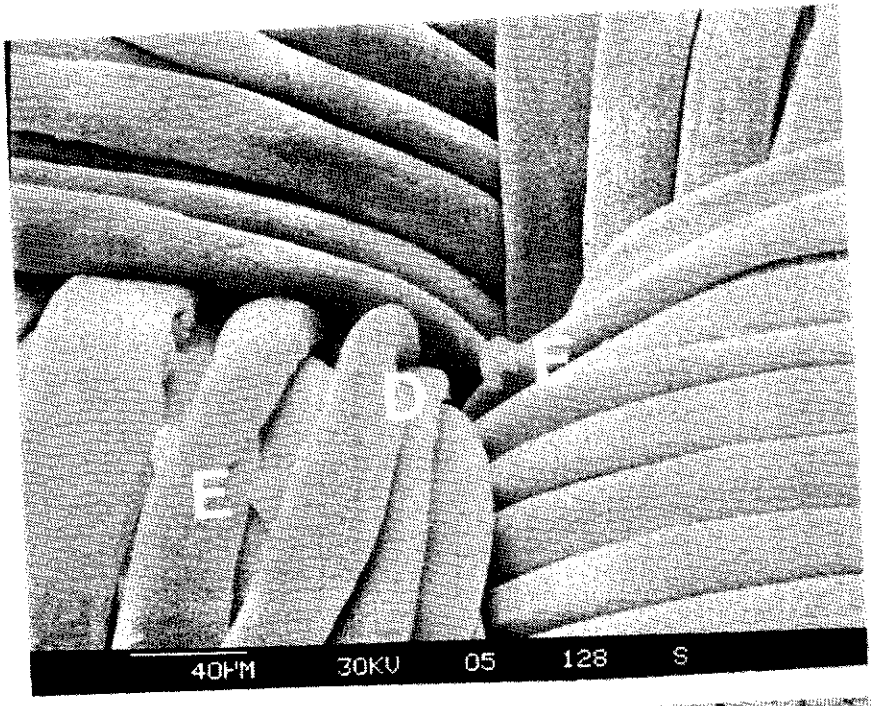


Figure 82

Sample: 5
View: Front
Condition: Tumbled
Ref: 40 microns
Mag: 230x

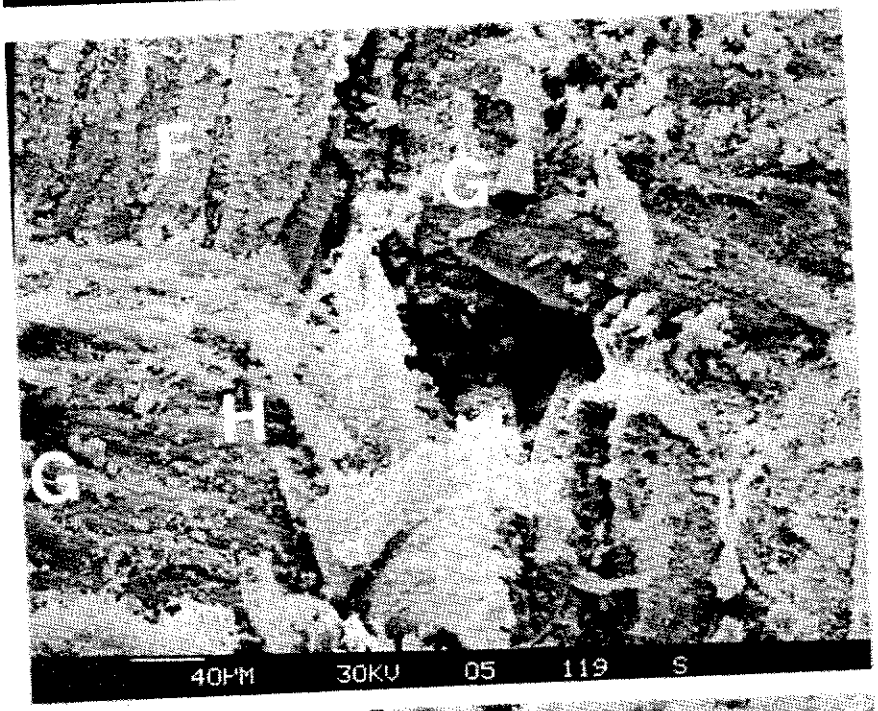


Figure 83

Sample: 5
View: Front
Condition: Cleaned
Ref: 40 microns
Mag: 370x

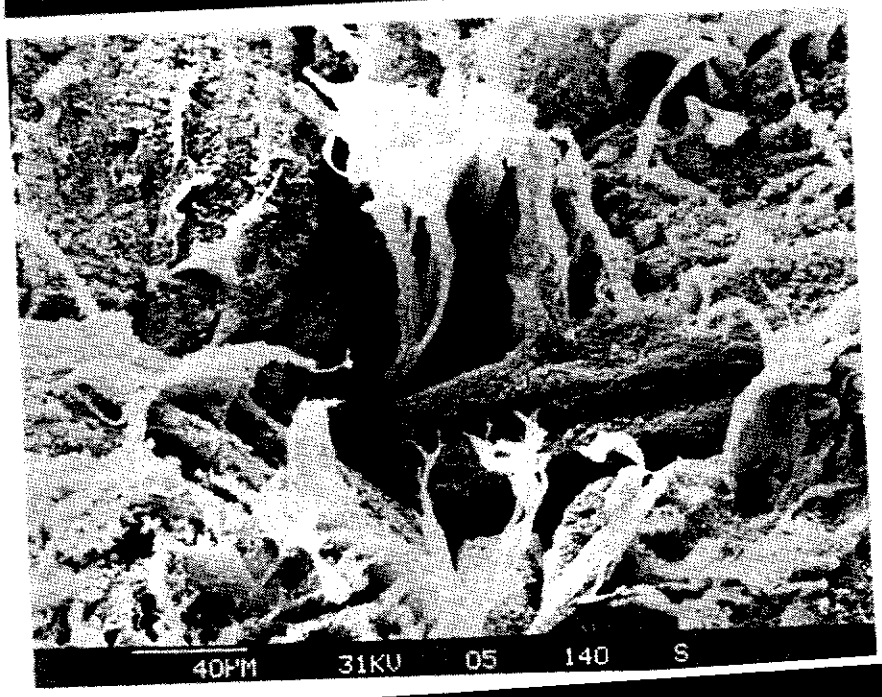


Figure 81

There is a 20μm gap (D) between the woven T162 yarns; this is a large enough path for small lunar dust simulant particles and fiber debris to travel through. Notice the smooth, thin, flat fibers of the fabric. There is little damage to this new specimen; the only anomalies are small pieces of fiber debris (E).

Figure 82

Extensive abrasive wear is visible in this micrograph of T162 after tumbling. The responsible wear mechanism here is the same as that of the Gore-Tex fibers. The abrasion includes grooves, with and without the release of teflon debris (F), along with the formation of tufts from repeated impact of lunar dust simulant particles (G) on the fiber surface. Here is an example of part of a fiber being peeled back (H); this is the beginning of the formation of a tuft.

Figure 83

This micrograph of tumbled T162 after the ultrasound cleaning procedure illustrates the damage caused by the abrasion of the of the T162 fibers. This view closely resembles Sample 3 Figure 63; it is no surprise that there is a resemblance between the abrasion seen by PTFE (T162) and that of expanded PTFE (Gore-Tex). The observations made about Figure 63 apply to this specimen.

Figure 84

Sample: 5
View: Front
Condition: New
Ref: 10 microns
Mag: 1400x

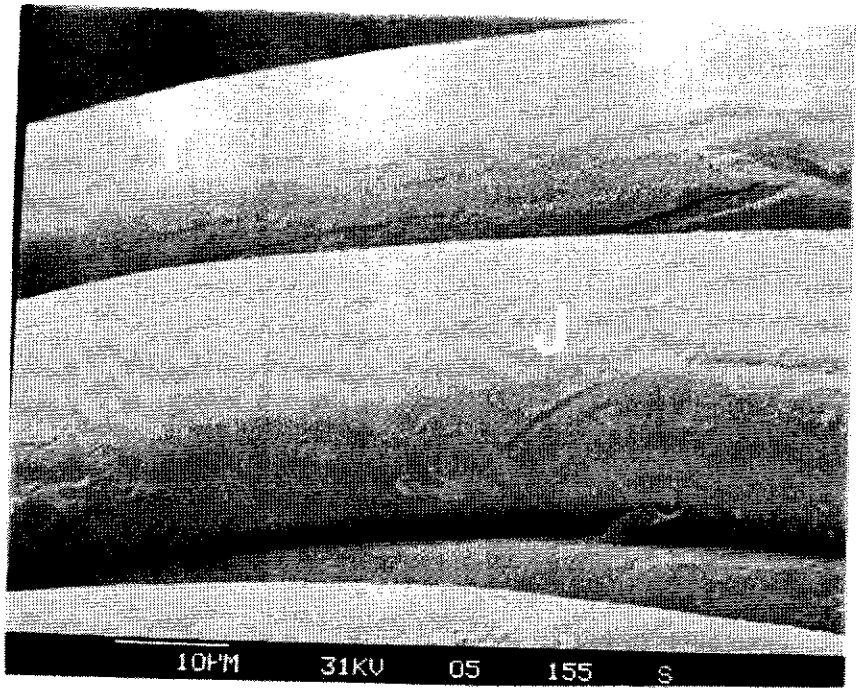


Figure 85

Sample: 5
View: Front
Condition: Tumbled
Ref: 10 microns
Mag: 800x

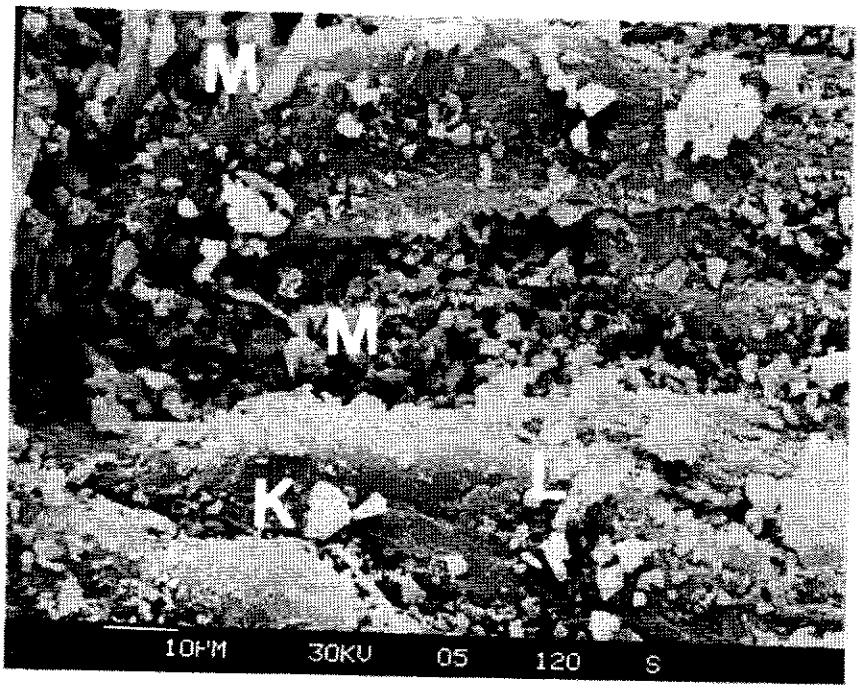


Figure 86

Sample: 5
View: Front
Condition: Tumbled
Ref: 2 microns
Mag: 7000x

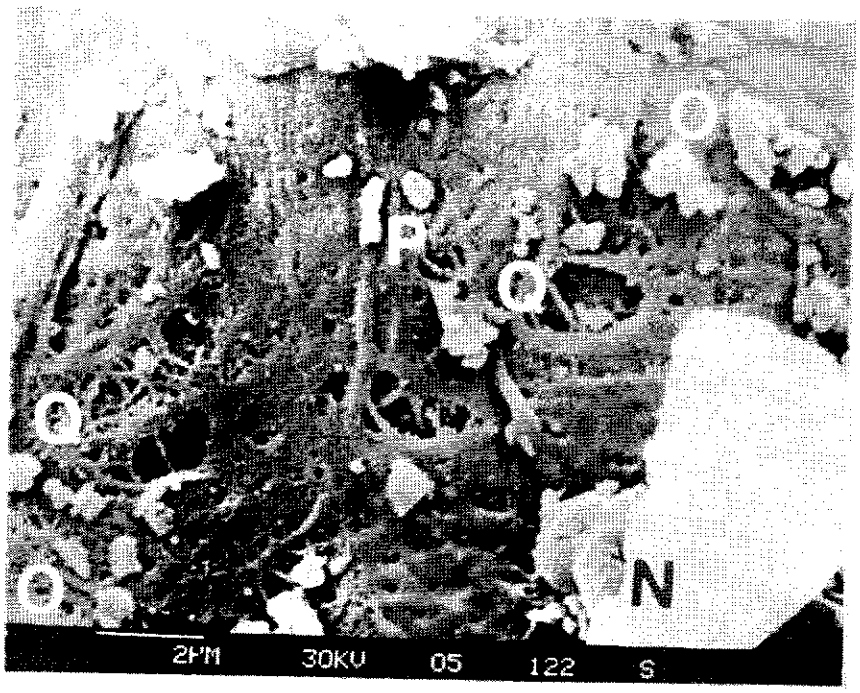


Figure 84

Here is a close look (1400x) at four individual fibers in a T162 yarn. The fibers are very smooth. The surface grooves (I) of the new fibers are not as deep as the scars on the new Gore-Tex fibers (Sample 3 Figure 61). The other surface damage (J) is due to manufacturing and handling processes.

Figure 85

This view confirms the tumble test abrasion of the T162 fabric. Both lunar dust simulant particles of glass (K) and volcanic rock (L) are present along with teflon debris (M). The abrasion mechanism of plowing along with cyclic microcutting is again responsible for the damage to the fibers.

Figure 86

This micrograph is a high magnification view (7000x) of a T162 fiber after tumbling. To give some perspective to the photo, notice the glass particle (N). Small particles of volcanic rock (O) and fiber debris (P) are scattered around on the surface of the fiber. The fiber itself has been pulled apart (Q) to reveal a web similar to the membrane of FEP laminate on the back face of Sample 3 (Figure 67). This pulling apart of the fiber is most likely due not to abrasion, but to shear forces and torsion of the yarns during the tumble test.

Figure 87

Sample: 5
View: Back
Condition: New
Ref: 100 microns
Mag: 80x

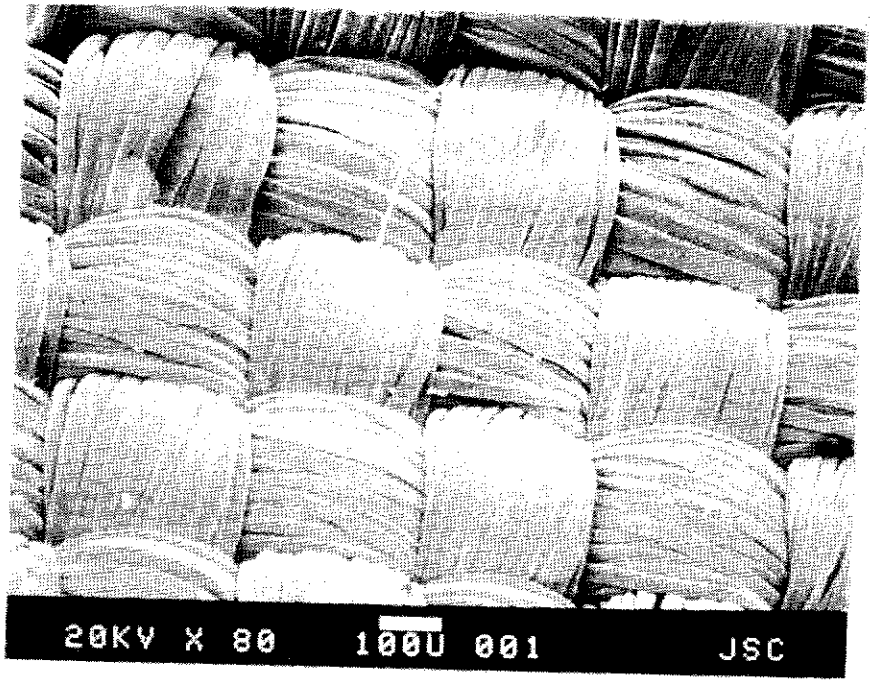


Figure 88

Sample: 5
View: Back
Condition: Tumbled
Ref: 200 microns
Mag: 88x

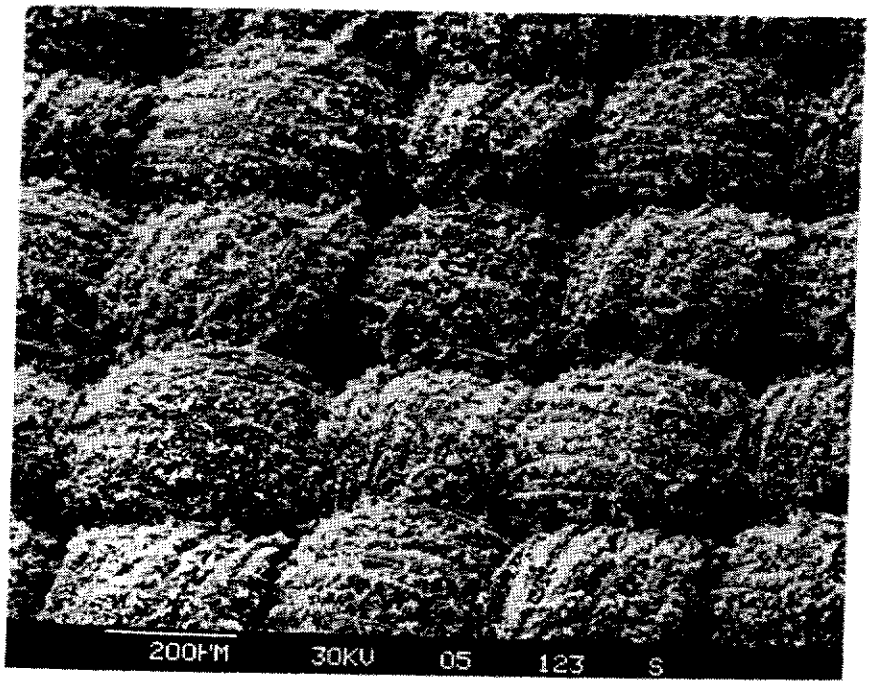


Figure 89

Sample: 5
View: Back
Condition: Cleaned
Ref: 200 microns
Mag: 62x

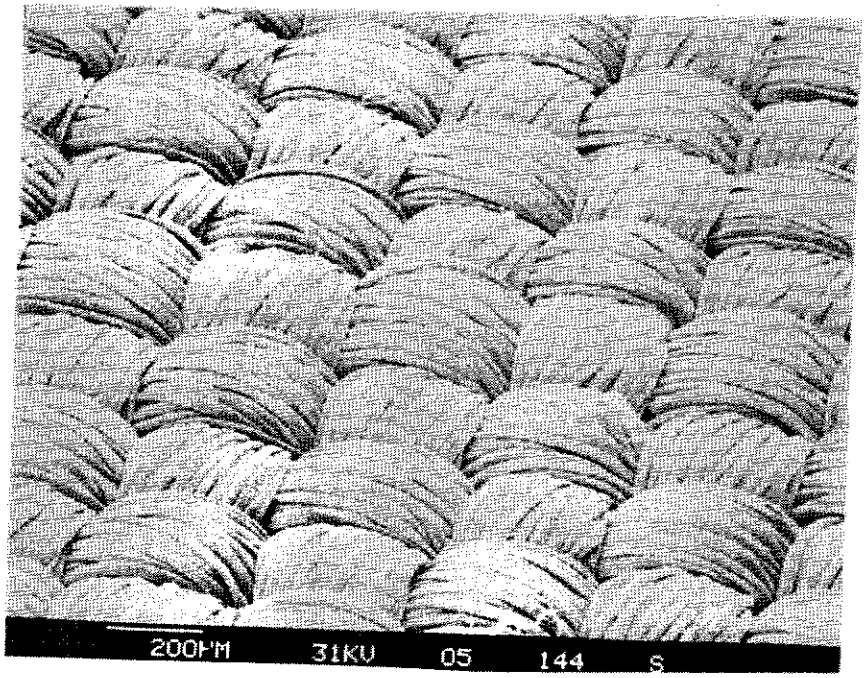


Figure 87

The back face of new T162 is identical to the front face (Figure 78).

Figure 88

After tumbling, there is an even layer of particles covering the back face of the woven T162. These particles are in between the fibers; they have also filled up the interstices of the weave. This confirms that not only do the lunar dust simulant particles and pieces of fiber debris migrate through the seams as described in Chapters 9-11, but the particles also travel through the interstices in the weave as observed in Chapters 9 with the Orthofabric sample. It is difficult to tell from this view if there is any fiber damage due to abrasion.

Figure 89

As with Orthofabric, the ultrasound cleaning procedure was able to remove nearly all of the particles from the back of the fabric. It is difficult to tell if there is any fiber damage from this view.

Figure 90

Sample: 5
View: Back
Condition: New
Ref: 100 microns
Mag: 380x

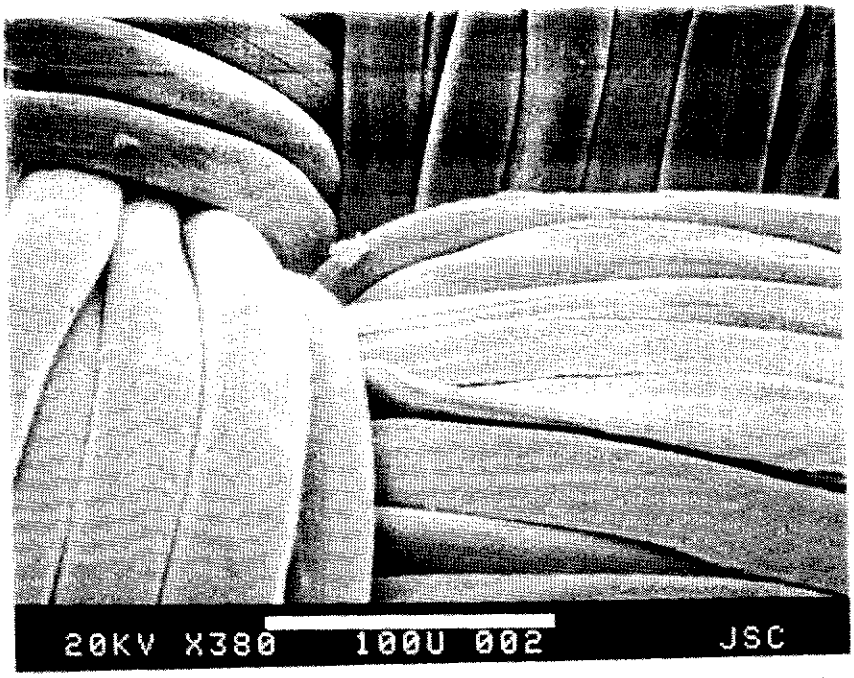


Figure 91

Sample: 5
View: Back
Condition: Tumbled
Ref: 40 microns
Mag: 360x

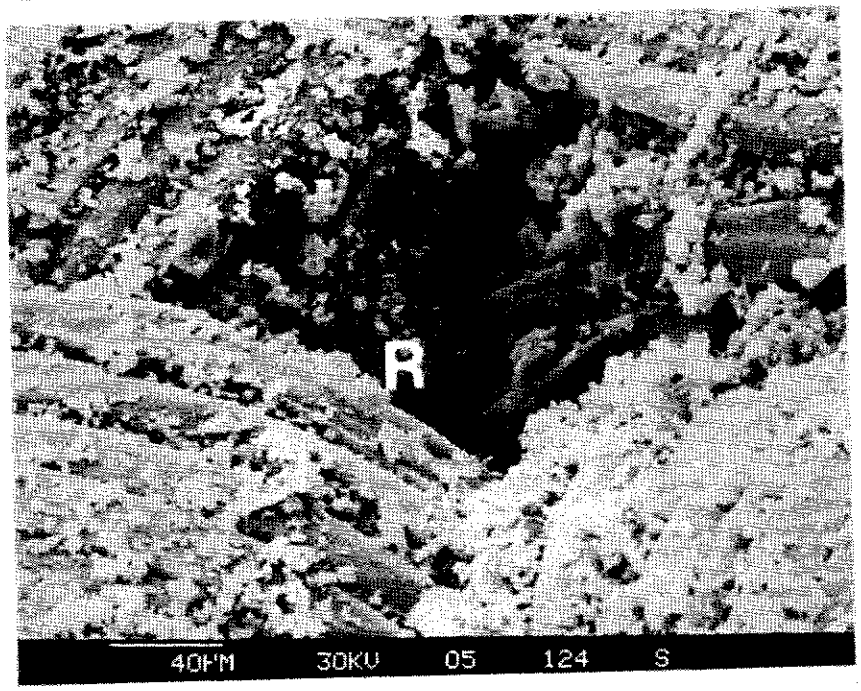


Figure 92

Sample: 5
View: Back
Condition: Cleaned
Ref: 40 microns
Mag: 300x

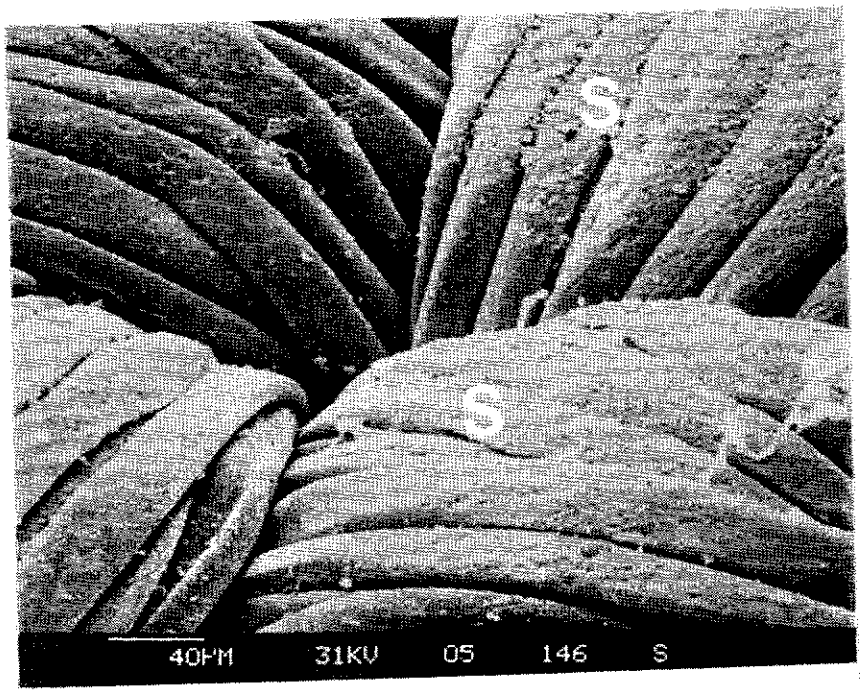


Figure 90

The back face of new T162 is identical to the front face (Figure 81).

Figure 91

The micrograph shows the lunar dust simulant particles migrating through the interstices of the weave (R).

Figure 92

After ultrasound cleaning, there is evidence that the back face fibers experienced abrasion (S) from the particles migrating through the weave. The particles have worn away some of the material from the surface of the fibers. The cleaning procedure was successful in removing all of the loose particles.

SEM ABRASION ANALYSIS RESULTS
SAMPLE 5
APOLLO TEST ARTICLE TEFLON (T162)

Following are the answers to the questions posed in Section 7.5.1:

A. How do the three conditions of the sample compare?

The characteristic plain weave of the T162 specimens closely resembles that of woven Gore-Tex. There were essentially no new observations to be made regarding the three sample conditions; this fabric behaved like Sample 3 throughout the test.

B. On the tumbled samples is the viewer looking at abrading particles or at fiber debris?

Both lunar dust simulant particles along with pieces of volcanic rock and Gore-Tex fiber debris were present on both faces of the tumbled sample.

C. How much of the dust can be cleaned off of the samples with the ultrasound procedure?

Nearly all of the loose fiber debris and dust simulant particles were removed by the ultrasound cleaning procedure from both the front and back faces of the fabric.

D. Did the front face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

The front face of the fabric suffered the same type and extent of abrasion as was observed in the analysis of Samples 1, 2 and 3. The

Gore-Tex fibers were severely abraded. The responsible wear mechanism was plowing along with cyclic microcutting which, after repeated impacts from the dust simulant particles, caused the formation of 'tufts' on the shredded Gore-Tex fibers.

E. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

There was a successful migration of particles from the front to the back face of the fabric through the intersticies in the fabric weave, through the needle holes and through the gap between the two pieces of fabric joined at the seam.

F. Did the back face of the fabric abrade? If so, what was the abrasion mechanism and what was the extent of the damage caused by the abrasion?

Abrasion did occur when the particles travelling through the interstices of the weave wore away some of the material from the surface of the fibers, but the back face abrasion was considerably less than that of the front face.

G. How do the results of the SEM analysis compare with the tumble test visual inspection?

The results of the SEM analysis confirm that the visual inspection conclusions made after the tumble test are correct.

CHAPTER 14

SAMPLE 6

APOLLO 12 - Teflon (T162)

14.0 SAMPLE 6: APOLLO 12 TEFLON (T162)

Samples 1 through 5 were abraded during the laboratory tumble test; this test was chosen to simulate worst case EVA abrasion of the candidate fabrics. However, it is a widely recognized fact in the textile industry that none of the various laboratory abrasion tests accurately simulate actual fabric abrasion. The decision to include a portion of Apollo 12 TMG in the SEM analysis was made so that a comparison could be done between Samples 5 and 6. The goal of the comparison is to determine if the abrasion seen by the Apollo test article from the tumble test (Sample 5) resembles the damage of the actual Apollo 12 outer fabric (Sample 6) that was abraded during real-time lunar EVA use.

The Apollo 12 lunar landing was in November of 1969. Alan Bean and Pete Conrad were the crewmen in the lunar landing module that touched down on the moon in an area called the Ocean of Storms. Two EVAs were conducted during the Apollo 12 mission; both astronauts participated in the exploration of the lunar surface, placement of scientific equipment and collection of geologic samples. The duration of the first EVA was 3 hours, 56 minutes and the second was 3 hours, 49 minutes, for a total of 7 hours, 45 minutes in which the TMG of the space suits was exposed to the effects of the lunar environment including the abrasive effects of the lunar dust.

As decribed in Chapter 13, the dual outer layer design of T162 and woven Beta was incorporated in the Apollo 12 TMG. Again, only the outermost layer of T162 will be analyzed in this chapter.

The fabric description and specifications for this sample are the same as those listed in the last chapter. T162 is a plain weave of 400 denier, drawn PTFE fibers. For easy reference, woven fabric specifications are repeated:

1.	Weight	2.60 kg/m^2 (8.5 oz/yd^2)
2.	Physical Properties:	
	a. Specific Gravity	2.1 g/cc (1.21 oz/in^3)
	b. Breaking Strength	Warp: 1109 kg/m (62.0 lbs/in)
		Fill: 1064 kg/m (59.5 lbs/in)
	c. Ultimate Elongation	Warp: 40.1%
		Fill: 53.1%

3. Mechanical Property:

Tear Resistance	Warp:	9.95 kg (21.9 lb.)
	Fill:	7.5 kg (16.5 lb.)

Figure 93 (NASA-JSC photo # S92-37196) and Figure 94 (NASA-JSC photo # S92-37194) illustrate the appearance of the Apollo 12 TMGs that were abraded by the lunar dust.

Figure 93 is a photo of Pete Conrad's SSA. This SSA has been preserved in a glass case and is on display at NASA-JSC; the suit is internally supported to show how it looked when worn by the astronaut. Although this TMG was not use in the SEM analysis, it illustrates where the suit was soiled by the lunar dust. The area of interest is the knee section (A) which was one of the most heavily abraded areas of the SSA; there is a significant amount of lunar dust present. The dust is uniformly distributed on the knee section with a slightly higher concentration of dust in areas of high relief and a low conentration in areas where the fabric has been indented. This is the same obervation that was made during the visual inspection of the tumbled test cylinders of Samples 1, 2, 3 and 5.

Figure 94 is a photo of Alan Bean's SSA TMG. Sample 6 was cut from the center of the left knee (B). The White Sands Test Facility performed a particle size range distribution test on this TMG in 1970; for this test, a sample was also cut from the left knee (C), approximately three inches below the area that was examined in this test.

Note: No photos or micrographs of new, woven T162 are included in this chapter. To compare the Apollo 12 abraded photos with photos of new T162 fabric, refer to Figures 75, 78, 81, 84, 87, and 90 in Chapter 13.

There are also no micrographs illustrating the effects of the ultrasound cleaning of Sample 6 in this chapter. When tested, the ultrasound procedure was unable to clean the Apollo 12 T162 specimens any further. The fabric had already been subjected to extensive cleaning activities both at NASA-JSC and during the White Sands test. Additionally, there has been an unknown amount of handling of the Apollo 12 TMGs over the past twenty-three years which also could have resulted in further removal of loose dust particles.

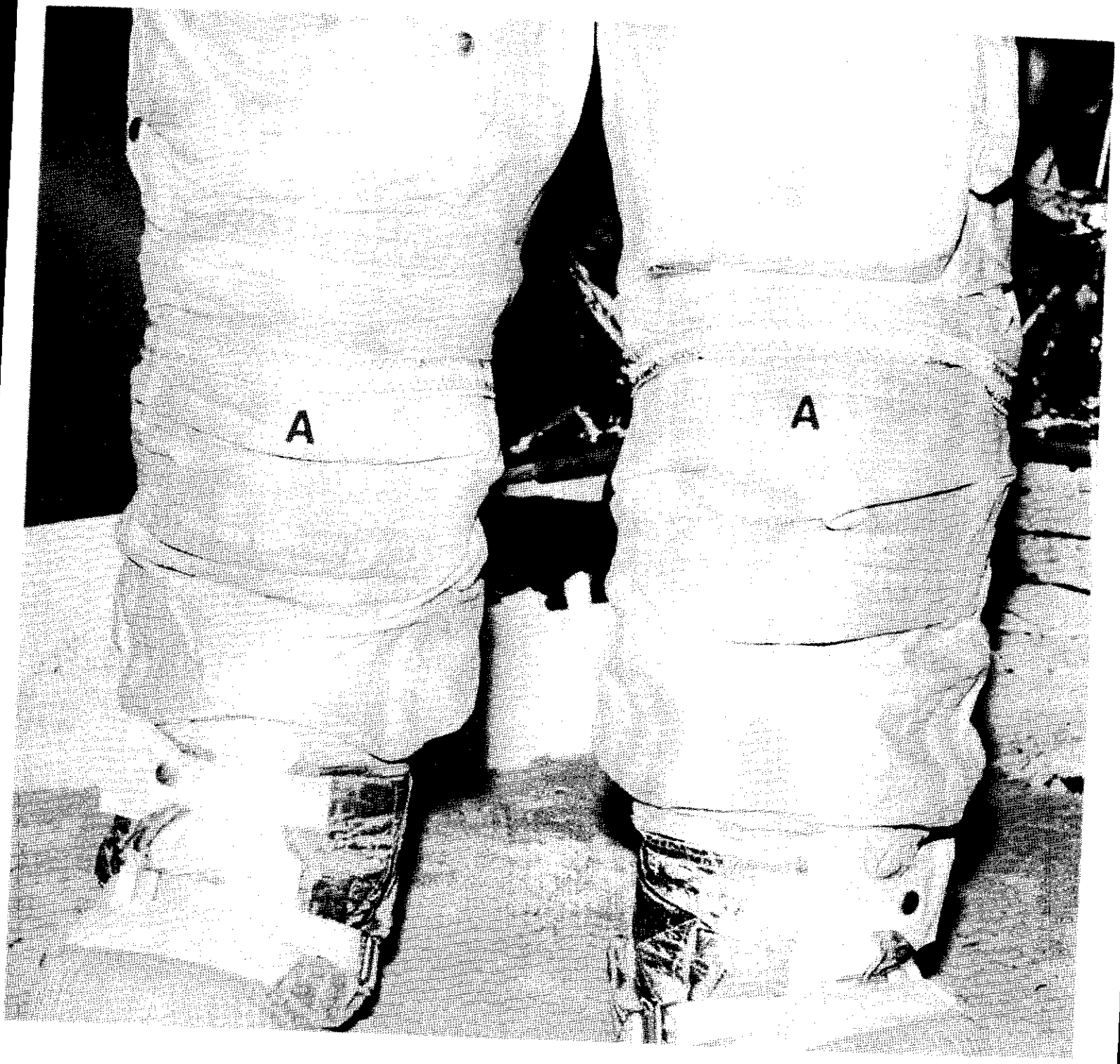


Figure 93

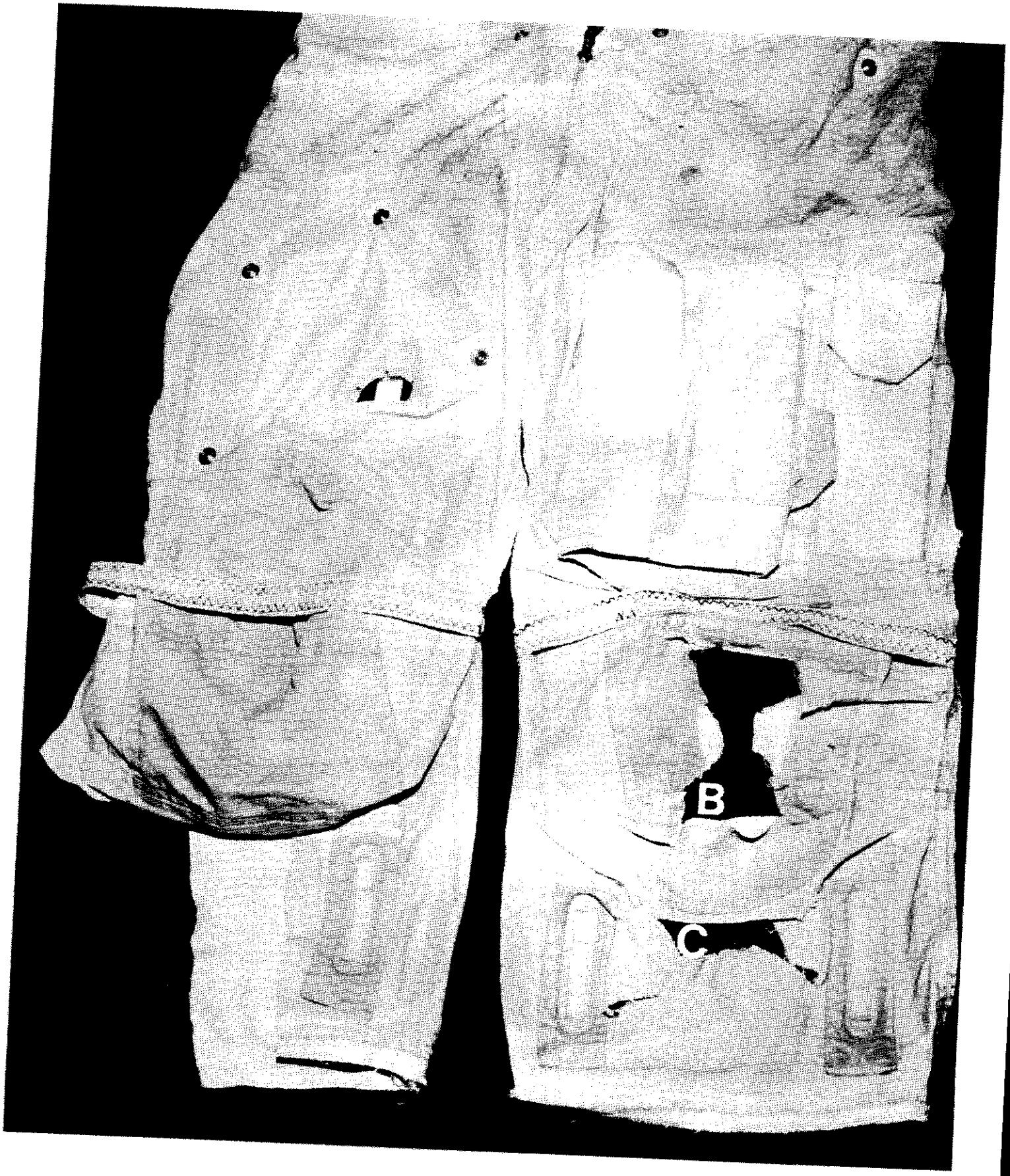


Figure 94

SAMPLE 6: APOLLO 12 TEFLON (T162)

Micrograph Figure Arrangement Chart

Fig. 96 Front LUNAR EVA USE 80x 100µm	Fig. 98 Front LUNAR EVA USE 160x 100µm	Fig. 100 Front LUNAR EVA USE 1600x 10µm
Fig. 97 Back LUNAR EVA USE 80x 100µm	Fig. 99 Back LUNAR EVA USE 160x 100µm	Fig. 101 Back LUNAR EVA USE 1600x 10µm
pg. 148	pg. 150	pg. 152

Figure 95

Figure 96

Sample: 6
View: Front
Condition:
Lunar EVA use
Ref: 100 microns
Mag: 80x

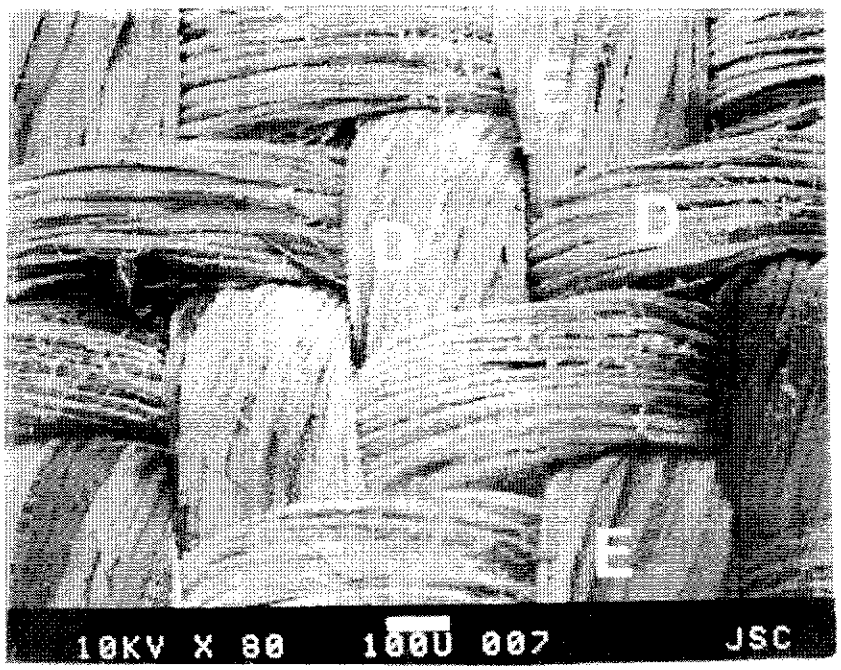


Figure 97

Sample: 6
View: Back
Condition:
Lunar EVA use
Ref: 100 microns
Mag: 80x

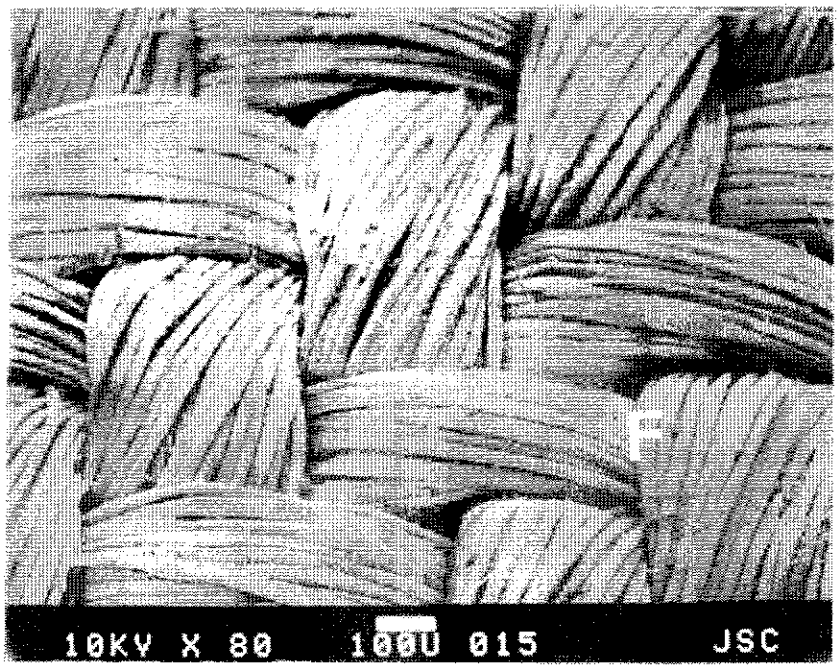


Figure 96

This micrograph is a representative view of the front face Apollo 12 T162 that was abraded during real-time EVA use. It is easy to see the characteristic plain weave in this micrograph, whereas the weave was indistinguishable on the tumbled samples. The abrasion damage to the fibers is minimal compared to the heavy abrasion that the T162 encountered during the tumble test (Figure 79). This was expected due to the following two reasons: First, the tumble test was designed to represent 8 hours of 'worst case' EVA exposure; whereas the Apollo 12 T162 did not experience 8 continuous hours of 'worst case EVA although it was exposed to the dust for about the same length of time (7 hours, 45 minutes). Second, the tumble test element was in constant contact with the lunar dust simulant; the Apollo 12 TMGs were not always in constant contact with the lunar dust. The shredding of the fibers that was observed on the tumbled samples is also starting to occur on the Apollo specimen. Interaction with the lunar dust has resulted in the formation of fibrils (D) which are present on all the front face yarns. Some of the fibers are also splitting apart (E). The formation of fibrils and the split fibers are the first steps in the formation of the tufts which were present on both the front face Gore-Tex and T162 samples after tumbling. The abrasive wear mechanisms responsible for the damage to the Gore-Tex and T162 fibers in the tumble test are also responsible for the damage to the Apollo 12 T162; these include plowing with the formation of grooves and impact damage from the lunar dust particles.

Figure 97

This micrograph view is similar to the laboratory T162 specimen shown in Figure 89. The back face of the Apollo sample shows slightly more abrasion damage than that of Figure 89; however, a direct comparison should not be made since both since neither the magnification nor the reference resolution of the micrographs matchs. It is difficult to tell if there are any particles of lunar dust on the fabric; however, small pieces of fiber debris (F) are easily identifiable. As with the laboratory T162 sample, the lunar dust is able to successfully penetrate the intersticies of the weave, and the needle holes and gap between the two pieces of fabric joined at the seams.

Figure 98

Sample: 6
View: Front
Condition:
Lunar EVA use
Ref: 100 microns
Mag: 160x

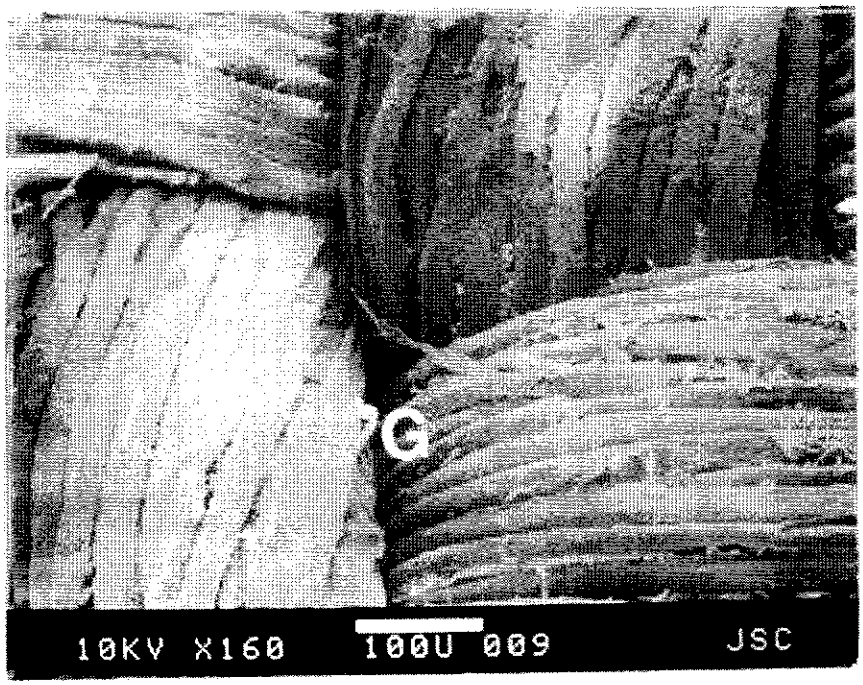


Figure 99

Sample: 6
View: Back
Condition:
Lunar EVA use
Ref: 100 microns
Mag: 160x

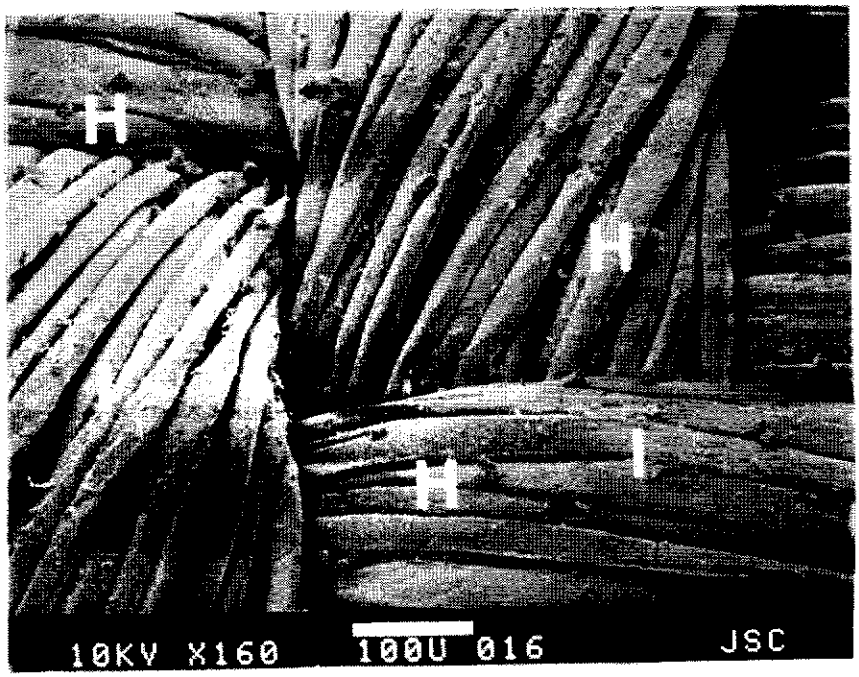


Figure 98

Here is a closer view (160x), of the interstices in the weave (G) on the front face of the Apollo 12 T162 sample. The minimal amount of abrasion on this front face specimen does not resemble the heavy abrasive damage seen on the tumbled and cleaned front face T162 specimen (Figure 83). However, the abrasion does resemble that of the back face laboratory specimen in Figure 92. This view illustrates the fibrils that were observed in Figure 96. No loose particles are present.

Figure 99

The fibers on the back face have experienced less abrasive damage than those on the front as shown in the previous figure. Lunar dust particles (H) have successfully migrated through the fabric. Fibril formation is starting to occur (I). The same wear mechanisms are present as described for Figure 96.

Figure 100

Sample: 6
View: Front
Condition:
Lunar EVA use
Ref: 10 microns
Mag: 1600x

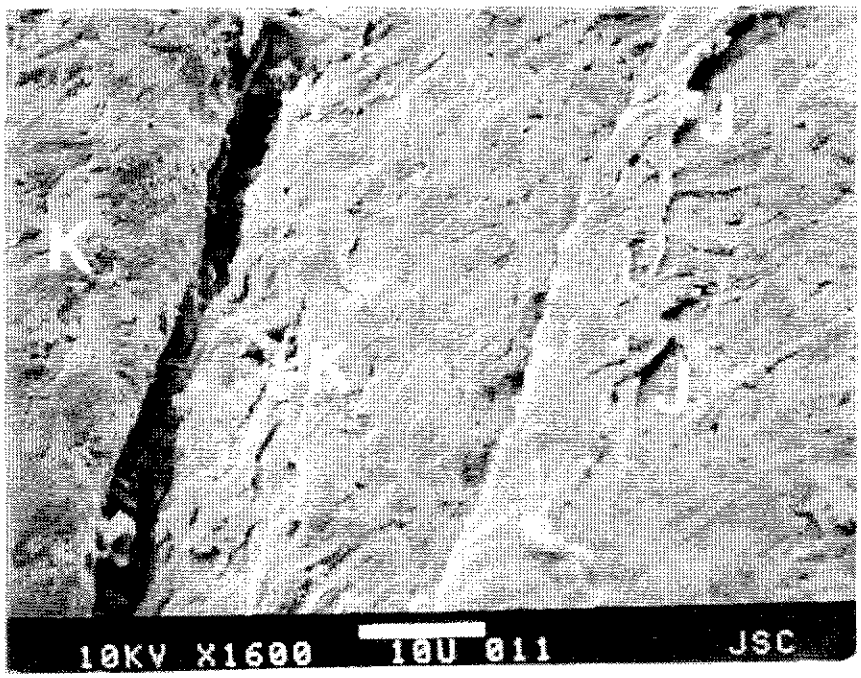


Figure 101

Sample: 6
View: Back
Condition:
Lunar EVA use
Ref: 10 microns
Mag: 1600x

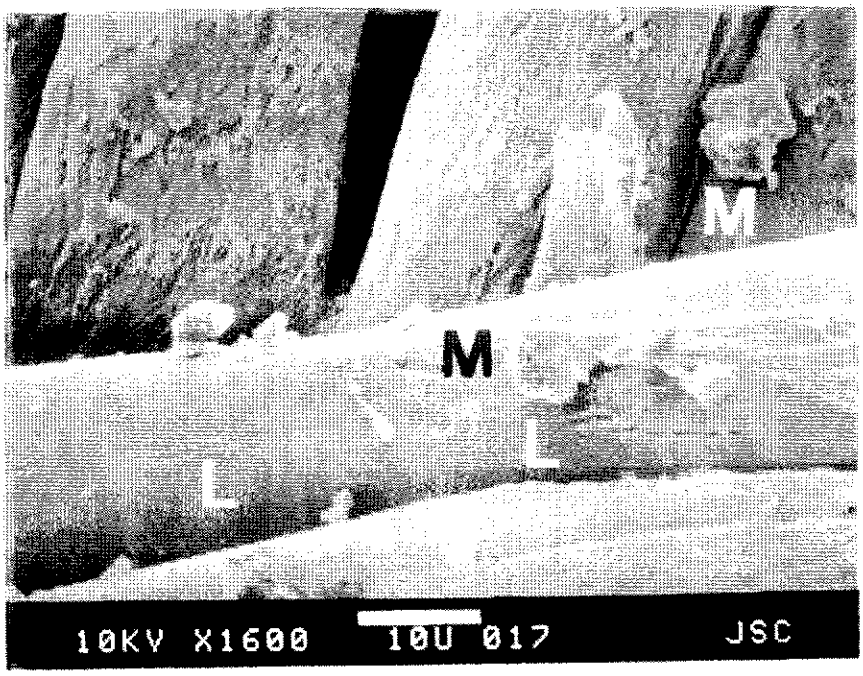


Figure 100

This high magnification view (1600x) is of the front face of the woven T162 illustrating the lunar dust abrasive damage to the fibers. Impacts from the dust particles have caused the formation of scales (J). Evidence of the tribofracture mechanism of microcutting is seen all over the fiber (K); this is where material has been cut away from the fiber surface. The interaction of the lunar dust particles with the T162 fibers, which has resulted in the scales and removal of material from the fiber surface, is the first step in the formation of fibrils and later on tufts that are observed on the laboratory T162 tumbled specimens. Note that there are no loose particles on the surface of the fibers.

Figure 101

This view of the T162 fibers reveals that the same scaling and removal of material from the fibers that was observed in the previous micrograph is occuring on the back face as well. Also present are cracks along the longitudinal axis of the fibers (L). These cracks are due to torsional shear stress experienced by the fibers during actual wear. Notice the pieces of lunar dust on the fibers (M); their size and shape is similar to that of the dust simulant glass particles used during the tumble test.

SEM ABRASION ANALYSIS RESULTS
SAMPLE 6
APOLLO 12 TEFLON (T162)

Following is a summary of the SEM analysis of the Apollo 12 sample. The questions posed in Section 7.5.1 were modified to be applicable to this sample:

A. On the tumbled samples is the viewer looking at abrading particles or at fiber debris?

Lunar dust particles were only found on the back face of the fabric. No pieces of T162 loose fiber debris were present on either face of the fabric; this is due to the mininal amount of abrasion seen by the Apollo 12 sample.

B. Comment on the amount of lunar dust that can be cleaned off the sample.

All of the lunar dust particles were previously cleaned off the front face of the fabric. A few particles were still present on the back face. Extensive cleaning was done of the sample during both the post-mission cleaning at NASA-JSC and during the White Sands Test in 1970; however, it is unknown if both faces of the fabric were cleaned or just the front face.

C. Did the front face or back face of the fabric abrade? If so, what was the abrading mechanism and what was the extent of the damage caused by the abrasion?

Both faces of the fabric suffered the same type of abrasion as was observed in the analysis of Samples 5; however, the extent of the damage was much less. This can be attributed to the fact that the T162 exposure to abrasive lunar dust was not continuous; whereas in the tumble test, the sample fabrics were in constant contact with the abradant. Also, the tumble test was designed to represent 8

hours of 'worst case' EVA; the Apollo 12 TMGs were not subjected to this harsh use. The abrading mechanisms were identical to those identified for the laboratory tested T162.

D. Did the dust migrate from the front to the back of the fabric? If so, how did it penetrate the fabric?

There was a successful migration of particles from the front to the back face of the fabric through the intersticies in the fabric weave, through the needle holes and through the gap between the two pieces of fabric joined at the seam.

The same types of abrasion mechanisms were identified in the analysis of both Samples 5 and 6. The migration routes through the fabric were also identical. Therefore, the results of the tumble test and electron microscopy analysis do adequately represent realistic worst case EVA abrasion damage to the candidate fabrics.

15.0 COMPARISON OF SAMPLES AND RECOMMENDATIONS

15.1 Comparison of Samples

A. Fiber Comparison:

Samples 1 and 2 are a woven blend of Gore-Tex (expanded PTFE), Nomex, and Kevlar fibers. Samples 3 and 4 are single fiber fabrics of the same Gore-Tex fiber as is used in Samples 1 and 2. Samples 5 and 6 are single fiber fabrics of Teflon (PTFE). Samples 1-4 have a front face of expanded PTFE fibers, while Samples 5 and 6 have a front face of PTFE fibers. (The front face of the fabric is significant because it is the side of the fabric that was directly exposed to the abrasive action of the lunar dust or the lunar dust simulant).

B. Weave Comparison:

Samples 1 and 2 are woven in a fancy draw, six harness, split basket weave configuration. Samples 3, 4, 5, and 6 are constructed in a plain weave design. The plain weave design offered less room in the interstices of the woven fabrics for dust to migrate through.

C. Tumble Test Comparison:

The tumble test articles of Samples 1, 2, 3, and 5 were covered with the powdery lunar dust simulant. The signifigant amount of dust simulant was distributed evenly on the body of the test article with a high concentration in areas of high relief and a low concentration in areas where the fabric had been indented. Sample 4 was eliminated from consideration as a candidate fabric due to the extent of abrasive damage that this sample experienced during the tumble test.

D. SEM Abrasion Analysis Comparison:

Particles of the lunar dust simulant and fiber debris were observed on both faces of Samples 1, 2, 3, and 5. There were no particles of lunar dust present on the front face of Sample 6 (Apollo 12 T162) due to the extensive cleaning of the TMG done post-flight by NASA-JSC, and at the White Sands Test Facility in 1970 as well as an unknown amount of handling over the past twenty-three years. However, a small amount of the lunar dust particles were observed on the back face of Sample 6.

The ultrasound procedure was able to clean all of the loose lunar dust simulant particles off both the front and back face of Samples 1 and 5. Particles bigger than 30μm could also be cleaned off the front face of Sample 2, but particles less than 30μm became embeded in the back face coating. The loose particles were also successfully cleaned off the front face of Sample 3; most were removed from the back face with the exception of very small particles in the craters of the laminate.

In all samples the particles were successful in migrating from the front to the back of the fabric. In all samples the particles were free to travel through the needle holes and through the gap between the two pieces of fabric joined at the seam. Samples 1, 5 and 6 had particles migrating through the interstices of the weave (and through the depressions in the weave in Sample 1). This path was closed to particle migration in Samples 2 and 3 due to the coating or laminate of the back face which acted as a seal.

The front face of Samples 1, 2, 3, and 5 suffered severe abrasive damage. The back face of Sample 1 revealed little damage to the Gore-Tex and Nomex fibers, whereas the Kevlar fibers experienced a fair amount of abrasion. The back face of Samples 2 showed little sign of abrasion. A small amount of abrasive damage was observed on the back face of samples 3 and 5. Both the front and back face of the Apollo 12 T162 were abraded, although the damage was minimal in comparison with the samples from the tumble test.

The same wear mechanisms were responsible for the damage on all the samples. The primary mechanism was plowing along with microcutting or cyclic microcutting. There were instances when microcutting produced a chip of fiber debris and instances where it

produced a lip on the fiber. There was evidence of particles impacting the surface of the fibers causing cracks and craters. The Nomex in Sample 1 also experienced scaling of the fiber surface by cyclic bending fatigue.

15.2 Recommendations

The final activity of the SEM analysis is to answer the following questions:

1. Is it possible to determine which tumble test sample was damaged the least?

Because the front face fibers in Samples 1, 2, and 3 were the same, these samples experienced very similar levels of heavy abrasion. Sample 5 also experienced heavy abrasion. It is not possible to determine which tumble test sample (1, 2, 3, or 5) was damaged the least; there was essentially no difference in the extent of abrasion between the PTFE fibers and the expanded PTFE fibers.

2. If so, what is the best-worst ranking with respect to abrasion resistance and which sample should be identified as the primary candidate fabric as selected in this analysis for further study?

Because it is not possible to determine which tumble test sample was damaged the least, there can be no best-worst ranking with respect to abrasion resistance. However, when considering the particle penetration of the fabrics, Samples 2 and 3 are most desireable. These two are equally good due to the back face coating/laminate that seals the fabric and prevents particle migration through the intersticies of the weave.

3. Does the comparison of Samples 5 and 6 indicate that the laboratory tumble test is representative of actual EVA abrasion?

The laboratory tumble testing of the fabrics was designed to represent 8 hours of worst case EVA abrasion. The Apollo 12 sample

experienced 7 hours, 45 minutes of exposure to the lunar dust. The damage of Sample 6 was much less than that of Sample 5; this is due to the following: The T162 exposure to the abrasive lunar dust was not continuous; whereas the tumble test articles were in constant contact with the lunar dust simulant. Also, the tumble test was designed to represent 8 hours of 'worst case' EVA; the real-time use of the Apollo 12 T162 did not subject the fabric to such extremes. The same types of abrasion mechanisms were active in both samples indicating that the laboratory tumble test was representative of actual EVA abrasion, although Samples 5 and 6 were not exposed to the same severity.

Other Recommendations:

Future development and testing of Samples 2 and 3 and other potential fabrics is recommended in the search for a protective outerfabric for next-generation lunar and Martian planetary SSA use.

Following, is a list of suggestions for the development of suitable fabrics:

1. Weaves, like Orthofabric, that are thicker are able to resist abrasion much more than thinner weaves, like the plain weave of Samples 3,5, and 6.

2. The abrasion of the back face of the outer layer can be eliminated completely by coating/laminating the back face and sealing the seams from the back. Sealing the seams and the fabric will also keep the under layers of fabric from becoming contaminated with the dust.

3. Fabrics that have a low coefficient of surface friction are able to resist abrasion much more successfully than those with a high coefficient of friction.

4. A common textile industry tactic when designing abrasion resistant fabrics is to blend fibers of high abrasion resistance with those that have a low resistance to abrasion.

5. The fabric should be easy to clean without the cleaning procedure contributing additional abrasion damage to the fabric.

6. If it is not possible to design a fabric that is both abrasion resistant to lunar dust and easy to clean, another idea that is being considered is a disposable outergarment. This outergarment would serve to protect the TMG from abrasion in the same manner as the T162 did in the Apollo SSA design. When this outer layer becomes soiled and abraded, it could be removed and replaced. This would extend the life of the TMG greatly.

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