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MASS LOSS OF SHUTTLE SPACE SUIT ORTHOFABRIC UNDER SIMULATED
IONOSPHERIC ATOMIC OXYGEN BOMBARDMENT

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SUMMARY

In the last few years there has been increasing awareness that many polymeric materials used for thermal protection and insulation on spacecraft degrade significantly under prolonged bombardment by ionospheric atomic oxygen. The covering fabric of the multilayered shuttle space suit, termed "orthofabric" by its designers, is composed of a loose weave of GORE-TEX fibers, Nomex and Kevlar-29, which are all polymeric materials. Suit exposure to the ionosphere will be much greater than at present on proposed extended shuttle missions and in the construction of the space station. Hence, the complete evaluation of suit fabric degradation from ionospheric atomic oxygen is of immediate importance in reevaluating suit lifetime and inspection procedures.

In the present study, pieces of the orthofabric were exposed to a simulated atomic oxygen environment using a microwave-driven plasma "barrel asher." Mass measurements and microscope examinations were made before and after each test to determine the mass loss and visible physical changes of each test sample. Kapton control samples and data from previous asher and flight tests were used to scale the results to reflect ionospheric conditions at about 220 km altitude.

The results of this study predicted that the orthofabric loses mass in the ionosphere at a rate of about 0.25 amu/atom, or about 66 percent of the original orthofabric mass/yr, assuming an atom flux of $7.44 \times 10^{22} \text{ cm}^{-2} \text{ yr}^{-1}$. A significant observation was that the outer layer of the two-layer orthofabric test samples (composed of GORE-TEX fibers) showed few easily visible signs of degradation, even when observed at 440X. It was thus concluded that the orthofabric could suffer significant loss of performance after much less than a year of total exposure time, while the degradation might be undetectable in post-flight visual examinations of space suits.

INTRODUCTION

Oxygen atoms at space shuttle altitudes impinge upon the surfaces of an orbiting spacecraft with velocities of about 8 km/sec and energies on the order of 5 eV. During the last few years there has been increasing awareness that many polymeric materials used for thermal protection and insulation on spacecraft and space hardware degrade significantly due to prolonged bombardment by ionospheric atomic oxygen (ref. 1). Flight and ground tests (refs. 2 to 5) have provided information as to the rates of decay and extent of physical damage suffered by many commonly-used plastics. The covering fabric of the multilayered shuttle space suit, termed "orthofabric" by its designers, is composed of GORE-TEX fibers¹, Nomex² and Kevlar-29², which are all polymeric materials.

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It follows that the assessment of the orthofabric's decay behavior when exposed to the space environment at shuttle altitudes is important in reevaluating suit lifetime and inspection procedures.

In the present study, pieces of the orthofabric were exposed to an atomic oxygen environment using a microwave-driven plasma "barrel asher." Mass measurements and microscope examinations were made to determine the mass loss and visible physical changes of each test sample. Kapton² control samples and data from previous asher tests were used to scale the results to reflect ionospheric conditions at about 220 km altitude.

ORTHOFABRIC DESIGN AND MATERIAL SPECIFICATIONS

There exists little or no published literature concerning the design and construction of the orthofabric. Hence, all such information presented in this study was gained through private communication between the author and people with intimate knowledge of the fabric. A list of persons contacted for information appears in appendix A. Through these communications it was also learned that no tests prior to the present study were performed on the orthofabric or its constituents to determine its degradation behavior due to atomic oxygen bombardment.

The orthofabric was designed to provide high abrasion resistance and snag minimization, high reflectivity to minimize heat absorption into the suit and an extra measure of thermal insulation. In all respects, the orthofabric was designed to out-perform and replace the external material used on the earlier Apollo mission suits. The resulting woven material was manufactured solely for use on the currently operational shuttle space suits.

The material is officially named ST11G041-01, SHELL TMG two-layer plain weave "orthofabric." It is 14 oz/yd², and 23 mil (front surface to back surface) in thickness. Although the orthofabric is unique to the space suits, it consists of commercially available "off-the-shelf" polymeric yarns: Nomex, GORE-TEX fibers and Kevlar-29. The outer (space side) layer consists of woven white GORE-TEX fibers. The inner (suit side) layer is composed of white Nomex yarn. Single yellow Kevlar-29 threads are interwoven at regular intervals in the Nomex for the purposes of ripstop. The chemical structures for these polymers are shown in figure 1. While the chemical structure of GORE-TEX fiber is the same as that of Teflon³, differences in formation and processing lead to two materials with differing properties.

The orthofabric's weaving specifications are:

Style 116 (116 tightwoven);
Two-layer plain weave; 14 +/-0.35 oz/sq yd

¹GORE-TEX is a registered trademark of W.L. Gore and Assoc., Inc.

²Nomex, Kevlar-29 and Kapton are registered trademarks of the E.I. Du Pont de Nemours Co., Inc.

³Teflon is a registered trademark of the E.I. Du Pont de Nemours Co., Inc.

Construction of face: 52 x 43 +/-2 ends/in. and picks/in. GORE-TEX fibers.
Warp and fill on face: 400 denier 3.2 turns/in. (z) GORE-TEX fibers, twist two ends as one;

Face Pattern: solid;

Construction of back: 39 x 34 +/-2 ends/in. and picks/in. Nomex
Warp and fill on back: 200 denier 2/ply 5 turns/in. (z) Nomex
400 denier 5 turns/in. (z) Kevlar-29;

Back pattern: warp 16 Nomex to 2 Kevlar-29

Fill direction: 14 Nomex to 2 Kevlar-29

Weight measurements of separated layers of orthofabric revealed that the GORE-TEX layer makes up about 74 percent by mass of the whole fabric. Figure 2 shows the sample configuration/examined in this test.

TEST APPROACH AND EXPERIMENT CONFIGURATION

The approach taken in the present study was to place pieces of the orthofabric and Kapton control samples in a simulated atomic oxygen environment for about 17 hr, and then determine the mass loss rate and observe the physical changes of each sample tested. The mass loss rates were then scaled to reflect the ionosphere at about 220 km.

Figure 3 shows the experiment configuration and test sample mounting configuration. An SPI Plasma Prep II barrel asher provided atomic oxygen ions. The asher uses microwaves at a frequency of 13.6 MHz to ionize residual air molecules after most of the atmosphere has been pumped out of the test chamber. Air pressure in the asher during the tests was about 140 μ m, and was determined with a pressure gauge attached to the pump hose. There were no diagnostics available to measure either the plasma density or ion temperatures in the asher, nor to know whether the density and temperatures fluctuated during a test run. A lamp/photodiode apparatus did provide an idea of the stability of the plasma output from the asher. A Mettler number H315 scale was used to measure the masses of the test samples before and after each asher run.

PROCEDURE

Samples were cut with scissors from a sheet of orthofabric. Sample sizes were about 1.0 by 1.2 cm. In some test runs, the GORE-TEX layer was carefully separated from the Nomex and Kevlar-29, and tested alone. It was not possible to separate out an intact layer of Nomex and Kevlar-29 for use as a test sample, as these threads tended to come apart. Untested control samples of orthofabric were weighed before and after each test run to account for possible weight change of the tested samples due to moisture loss.

Test runs were performed according to the following procedure:

1. Observe and photograph test sample with microscope (50 to 440X used).
2. Weigh test sample and control sample.

3. Mount test sample on microscope slide and affix with Kapton tape. Place mounted test sample in asher.
4. Activate the asher and maintain test conditions for about 17 hr.
5. Remove test sample from the asher and leave exposed to the air for about four days to allow for possible moisture reabsorption. (Care was taken to avoid dust collection on the sample).
6. Observe, photograph and weigh samples again.

RESULTS

Observations

A thin film of dried oil or solvent appeared under microscope inspection as patches on the surface of several areas of the orthofabric, most noticeably between weaves. According to Cheryl Gomes (appendix A, number 5), there may have been some oil used to facilitate the weaving process, and a soap solution was used to wash off the orthofabric before use on the suits. This film disappeared upon testing in the asher.

After all tests, most or all of the Kevlar-29 and much of the Nomex were observed to have disappeared, indicating a high rate of decay for the inner (Nomex and Kevlar-29) layer relative to that of the orthofabric as a whole. Although each test sample was mounted on a glass slide, thus leaving only one face "exposed," it was apparent that both sides of the test samples were receiving comparable atomic oxygen impingement. In all test runs, the GORE-TEX layer was not visibly changed (up to 400X) in apparent color or smoothness. The ends of many Nomex strands often appeared to have been singed (fig. 4).

Mass Loss Rates Resulting From Asher Tests

Table I shows the average mass loss rates (D1 and D2) for the test samples were defined as:

$$D1 = \frac{\text{mass loss}}{(\text{original mass})(\text{test time})}$$

$$D2 = \frac{\text{mass loss}}{(\text{area})(\text{test time})}$$

The GORE-TEX layer alone showed a slightly lower mass loss/unit area than did the complete orthofabric samples, while the GORE-TEX layer's mass loss/unit mass was essentially the same as that for the complete orthofabric samples. Since the test samples were small, and the GORE-TEX layer makes up about 74 percent of the orthofabric, the Nomex layer's effect on D1 for the complete orthofabric samples was negligible in these results, while it added slightly to D2. The actual rates of decay of the Nomex layer in the present study are not known, although from the above observations they are probably much higher than those for the GORE-TEX layer and complete orthofabric.

Conversion of Mass Loss Rates to Shuttle Altitude Environment

Appendix B lists the conversion factors and atom flux used to derive mass loss rates for the orthofabric in the ionosphere at shuttle altitudes, based on those found with the asher. Information on these conversion factors was gained through private communication with Bruce Banks at NASA Lewis Research Center (appendix A, number 1). The conversion factors are based on comparisons of the results of past asher tests to experimental data gained on STS-8 (ref. 5) and other similar-altitude shuttle missions (ref. 3). They are representative of polyimides like Kapton, and fluoropolymers like Teflon and GORE-TEX fibers. Conversion factors for Nomex and Kevlar-29, which are polyamides, were unavailable.

Table II shows the orthofabric mass loss rates converted to those expected in the ionosphere at an altitude of about 220 km. R1 and R2 were defined as:

$$R1 = D1 \times \text{Conversion factor} \times 1 \text{ yr} \times 100 \text{ percent}$$

$$R2 = D2 \times \text{Conversion factor/flux}$$

The decay rate of the complete orthofabric test samples again assume that the mass of the Nomex and Kevlar-29 were negligible.

Significance of Results

According to Bill Hall (appendix A, number 6), the orthofabric has been proposed for use on a new generation of NASA space suits now under consideration. Since the new suits will be put to much use on proposed extended shuttle missions and in the construction of the space station, suit exposure to the ionosphere will be much greater than at present. Hence, the complete evaluation of suit fabric degradation in space is of immediate importance.

The present study predicted that the orthofabric as a whole degrades at a rate of about 66 percent of original mass/yr, and the Nomex layer alone degrades at some higher rate. It is thus clear that the orthofabric could suffer significant loss of performance after much less than a year of total exposure time. In particular, the Nomex layer, responsible for much of the strength of the material and for ripstop, could lose most of its usefulness after a much shorter period of time. Thus, an in-depth examination of orthofabric loss of strength and other performance characteristics with mass loss is currently needed.

The observations of the tested orthofabric samples highlight the ineffectiveness of performing post-flight visual examinations of the space suits as a method of guarding against degradation. Given the high rate of inner (Nomex) layer mass loss, which would be hidden to the observer of a space suit, and the difficulty of visually observing physical changes on the outer (GORE-TEX) layer, nearly complete degradation of both layers of the orthofabric would be undetectable in visual examinations of the suits.

Accuracy of Simulation Using the Asher

While exposed fabric in the ionosphere is impinged upon by essentially unidirectional ram atoms and ions, test samples in the asher are surrounded completely by high temperature atoms and ions that have little directed motion. Thus, it might be thought that the Nomex layer of the orthofabric might receive a greater percentage of the total atom flux in the asher than in space. However, the difference in physics may be lessened in importance because the ionospheric ram atoms traveling at 8 km/sec can easily reach the Nomex layer through gaps in the weave of the GORE-TEX layer.

Purvis et al., (ref. 3) provide data on the mass loss rates of many materials in the ionosphere. The mass loss rates for Kapton and Teflon appear alongside the present results in table II, and confirm the validity of ionospheric atomic oxygen simulation using the asher. The factor of four difference between the results in reference 3 for Teflon and those for the GORE-TEX layer in this test may be due, in part, to a difference in the surface area/volume ratio of these two materials. Nonetheless, a factor of four is believed to be within the possible error of the simulation.

Finally, the degradation rates predicted by this test, using conversion factors based on shuttle experiments in ram atom conditions, may be greater than the actual degradation rate of the orthofabric on the space suits, since suited astronauts may continuously and randomly maneuver with respect to the direction of the ionospheric ram atoms.

CONCLUSIONS

Pieces of the plastic covering fabric of the astronaut space suits, called "orthofabric," were exposed to an atomic oxygen environment using a microwave-driven plasma "barrel asher," to simulate exposure to the ionosphere. The results predicted the mass loss rate of the orthofabric to be about 0.24 amu/atom, or about 66 percent of original mass/yr in the ionosphere at about 220 km altitude. The outer GORE-TEX layer of the two-layer fabric was not visibly changed (up to 400X) in apparent color or smoothness. The Nomex and Kevlar-29 (inner) layer, responsible for much of the strength of the material and for ripstop, was found to have a much higher rate of mass loss than that for the complete orthofabric. The results and observations suggest that extensive loss of performance of the orthofabric on the space suits could occur after a total exposure time to the ionospheric atomic oxygen of much less than a year, while the degradation might not be visibly obvious.

APPENDIX A

PRIVATE COMMUNICATION REFERENCES

1. Bruce Banks (asher tests)-NASA Lewis Research Center, Cleveland, OH. 44135, (216) 433-4000.
2. Fred Dawn (one of original designers of orthofabric)-Mail Code EC, NASA/Johnson Space Center, Houston, TX 77058, (713) 483-4931 (FTS 525-4932).
3. Fabric Development, Inc. (orthofabric weaver)-Quakertown, PA. 18951, (215) 536-1420.
4. Dale Ferguson (degradation in space)-NASA Lewis Research Center, Mail Stop 302-1, Cleveland, OH 44135, (216) 433-2298.
5. Cheryl Gomes, ILC Dover (contract designer and manufacturer of the space suits)-P.O. Box 266, Frederica, DE 19946, (302) 335-3911.
6. Bill Hall, (familiar with plans for new generation of space suits), Air Force Geophysical Laboratory, Hanscom Air Force Base, Mass. 01731, (617) 861-3989.

APPENDIX B

ASHER TO IONOSPHERE CONVERSION FACTORS

Assumptions

The following assumptions were made in converting the asher mass loss rate results to those expected in the ionosphere.

Altitude = 220 km (i.e., STS-8 type altitude)

Atomic oxygen flux = 7.44×10^{22} cm⁻² yr⁻¹.

Conversion factors

The conversion factors below were obtained through private communication with Bruce Banks (appendix A, number 1), and reflect the above assumptions of altitude and atom flux.

$$\frac{\text{Rate of polyimide mass loss in asher}}{\text{Rate of polyimide mass loss in space}} = 7$$

$$\frac{\text{Rate of fluoropolymer mass loss in asher}}{\text{Rate of polyimide mass loss in asher}} = 0.25$$

$$\frac{\text{Rate of polyimide mass loss in space}}{\text{Rate of fluoropolymer mass loss in space}} = 100$$

Thus,

$$\frac{\text{Rate of fluoropolymer mass loss in asher}}{\text{Rate of fluoropolymer mass loss in space}} = 175$$

In the present study, the polyimide control was Kapton. GORE-TEX fiber, a fluoropolymer (see fig. 1), comprised the outer (space side) layer of the two-layer woven orthofabric. Conversions for Nomex and Kevlar-29 (constituents of the inner layer), which are polyimides, were unavailable.

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1. Leger, L.J.: Oxygen Atom Reaction with Shuttle Materials at Orbital Altitudes. AIAA Paper 83-0073, Jan. 1983.
2. Ferguson, D.C.: The Energy Dependence and Surface Morphology of Kapton Degradation Under Atomic Oxygen Bombardment. Thirteenth Space Simulation Conference, NASA CP-2340. J. Stecher, ed., 1984, pp. 205-221.
3. Purvis, C.K., et al: Environmental Interactions Considerations for Space Station and Solar Array Design. In preparation, 1986.
4. Ferguson, D.C.: Laboratory Degradation of Kapton in a Low Energy Oxygen Ion Beam. AIAA Paper 83-2658, Oct. 1983.
5. Banks, B.A.; Mirtich, M.J.; and Rutledge, S.R.: Sputtered Coatings for Protection of Spacecraft Polymers. NASA TM-83706, 1984.

(See Also Appendix A-Private Communication References)

TABLE I. - RATES OF MASS LOSS FOR TEST SAMPLES IN THE ASHER

Sample	D1, g/g-min	D2, g/cm ² -min
Kapton control	5.77x10 ⁻⁵	1.71x10 ⁻⁶
Complete orthofabric	2.17x10 ⁻⁴	9.78x10 ⁻⁶
GORE-TEX layer	2.21x10 ⁻⁴	7.50x10 ⁻⁶

$$D1 = \frac{\text{mass loss}}{\text{orig. mass (test time)}}, \quad D2 = \frac{\text{mass loss}}{\text{area (test time)}}$$

TABLES II. - RATES OF DECAY (IN TABLE I)
SCALED FOR THE IONOSPHERE

Sample	Conversion factor space/asher	R1 percent/ year	R2 amu/atom	Results from reference 3 amu/atom
Kapton control	1/7	433	1.05	2.6
Complete orthofabric	1/175	65.5	0.24	-----
GORE-TEX layer	1/175	66	0.186	0.042 (Teflon)

R1 = D1 x Conversion factor x 1 yr x 100 percent.
R2 = D2 x Conversion factor x 1 yr flux.

Flux = 7.44x10²² cm⁻² yr⁻¹ (altitude ≈ 220 km).

ORTHOFABRIC CONSTITUENTS

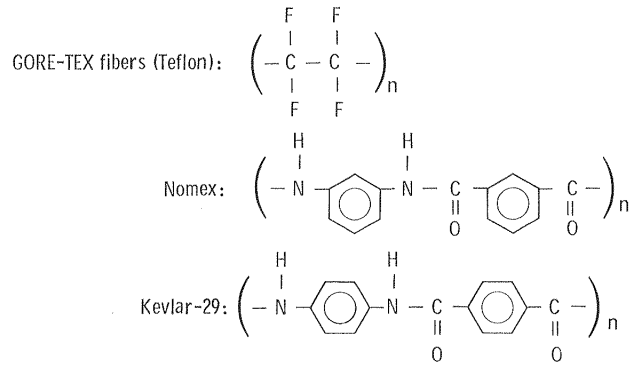


Figure 1. - Chemical structures of the constituents of Orthofabric.

TYPICAL ORTHOFABRIC TEST SAMPLE

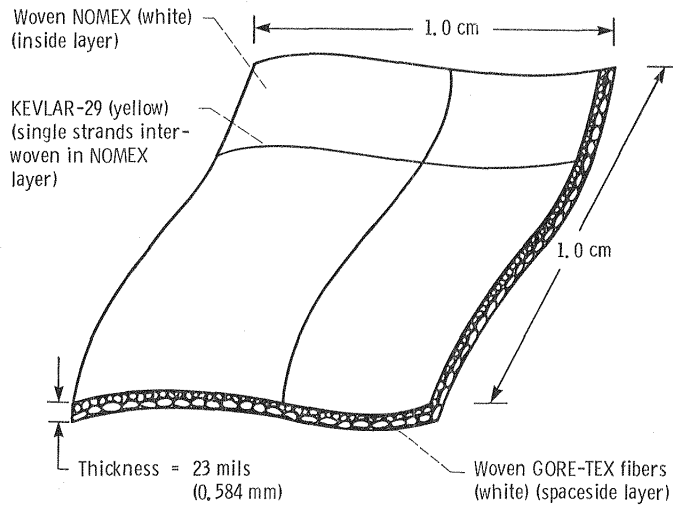


Figure 2. - Typical test sample of Orthofabric.

SPACE SUIT ORTHOFABRIC TEST CONFIGURATION

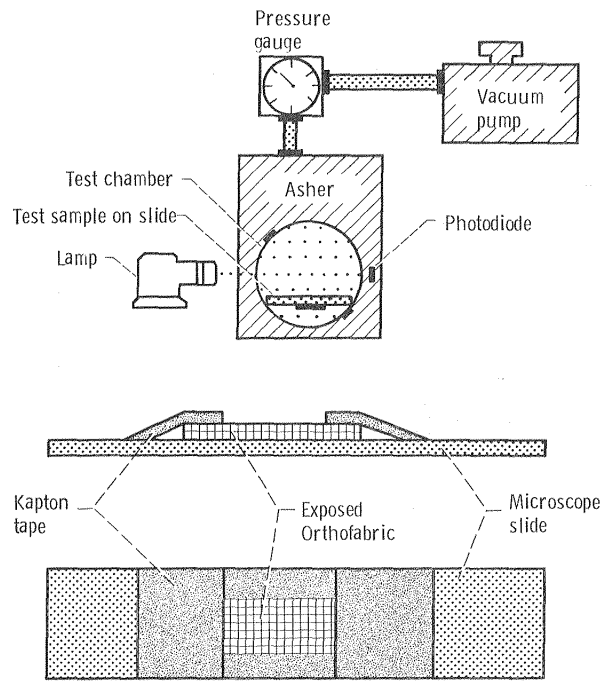


Figure 3. - Experiment configuration and test sample mounting configuration.

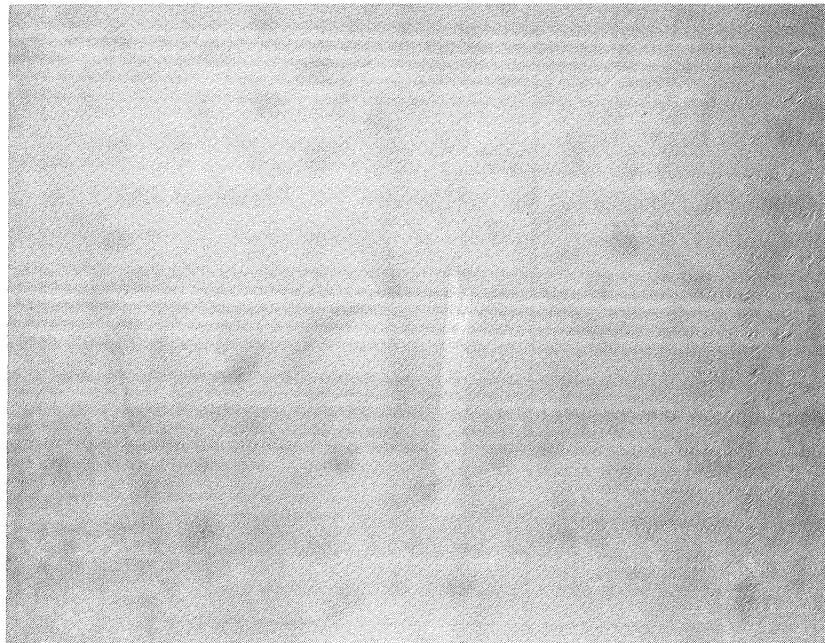


Figure 4. - Photograph of Nomex strand after asher test.

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