NASA Technical Memorandum 102158

Development and Application of Nonflammable, High-Temperature Beta Fibers

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National Aeronautics and
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ABSTRACT

Recent advances in fiber technology have contributed immeasurably to the success of the U.S. space program. Some of the textile fibers which have been developed for the space program have also had commercial and household applications. The inorganic fiber named "Beta" has proved to be one of the more outstanding textile fibers of this century.

The challenge to develop an extra-fine inorganic fiber was initiated in 1962. This materials development program contributed significantly to the successful lunar landing on July 20, 1969. After the Apollo fire in January 1967, the demand for firesafe fibrous structures increased many fold. The crew bay area of the spacecraft was of foremost consideration since it was pressurized with an enriched oxygen atmosphere which increases the flammability potential of materials. But there are other requirements besides being fire safe. For example, outside the spacecraft, textiles are exposed to a hard vacuum, the deep-space thermal environment, bombardment by micrometeoroids, and impingement by the total electromagnetic spectrum. Meeting these requirements and obtaining the lowest possible cost are equally important.

The result of this inorganic fiber development was "Beta." Beta fiber is nonflammable in a 100-percent-oxygen environment. It possesses phenomenal tensile strength as compared to other common textile fibers. Also, the Beta fiber exhibits outstanding thermal properties and resistance to deep space deterioration.

Beta fiber is unique among inorganic and organic fibers. It has been developed into woven, nonwoven, knitted, braided, coated, and printed structures. All of these were used extensively for the Apollo, Skylab, Apollo-Soyuz Test Project, Space Shuttle Orbiter, Spacelab, and satellite programs. More than 10 000 pounds of Beta fibers have been used in various space programs up to the present time.

In an effort to spinoff space technology for commercial applications, Beta fibers are being used as firesafe fabrics such as safety suits, drapes, decorative hangings, overhead and wall coverings, upholstery and floor coverings, bed and seat covers in houses, hospitals, institutions, public buildings, aircraft, and public transportation wherever total nonflammability is required. One of the most unique applications of the Beta composite structure is the roofing material for the 80 000-seat Detroit Lions' Silverdome and 5 square miles of roofing for the Jeddah International Airport, in Saudi Arabia. This fiber has successfully been incorporated into 165 major public construction projects around the globe. The United States alone has used more than 12 million square yards of this material.

Although Beta has been very successfully used to date, it has a promising future with its potential unlimited. Efforts are being continued to further improve

Beta fiber for the U.S. space programs in order to meet the new requirement for 30 years service life for Space Station Freedom, lunar outpost, and Mars exploration programs.

INTRODUCTION

Never before have textile fibers played such a major role in technological advancement as in America's manned spaceflight programs. Since its inception, a primary objective of NASA's manned-space flight program has been to ensure the safe return of its crewmembers from the hostile environment of outer space. Recent advancements in fiber technology have contributed immeasurably to the success of the space program, not only in the astronaut's space suit but also throughout the spacecraft.

The purpose of this report is not to laud the NASA accomplishment in space but rather to make it known that some of the textile fibers which have been developed to satisfy space program requirements may also have commercial and household applications. Specifically, in this category is the inorganic fiber Beta, which has proven to be one of the outstanding textile fibers of this century. It has made significant contributions to aerospace applications as well as, through NASA spinoff technology, to commercial applications.

This document would not have been possible without the support and guidance of Walter W. Guy, Chief, Crew and Thermal Systems Division. His interest in this fiber and his technical review of the report are deeply appreciated. The author also wishes to thank H. R. Bob Herman of Hamilton Standard Management Services for his outstanding technical contributions and editorial services in the preparation of this document. The technical assistance of Debra A. Schaller and Donna J. Mays is gratefully acknowledged by the author and their contributions to this document has been of significant value.

BACKGROUND

The objective of this developmental effort was to develop a fiber from which fibrous structures could be made that would protect the Apollo crewmembers in an oxygen-enriched spacecraft cabin environment as well as in an alien lunar-landing environment. The fiber that resulted was extra fine, white, nonflammable, high-temperature and thermal-radiation resistant, nontoxic, low smoke, durable, flexible, lightweight, and low cost. The challenge to develop an extra-fine inorganic fiber was initiated in 1962. Although there were no organic fibers in existence with a flame-resistant property in a 100-percent oxygen environment, success was achieved through an intensive research and development effort, making this fiber available early in the Apollo Program. At the time of the Apollo 204 fire accident in January 1967, Beta fiber had successfully undergone the stringent requirements of qualification tests such as flammability, offgassing, carbon monoxide, and dermatological reaction. Following the incident, the demand for firesafe fibrous structures increased manyfold, ranging from space-suit application to fire-protective or fire-barrier covers for the flight equipment in order to render the Apollo spacecraft essentially nonflammable. The production of this fiber was expanded to meet all the planned flight schedules. The success of the materials development program contributed significantly to the successful lunar landing on July 20, 1969.

Following is a brief description of the aerospace requirements for this fiber development program along with a brief introduction of the unique properties of the fiber and of its applications in space programs as well as in NASA technology spinoff programs. Also, further improvements of this fiber being planned for future long-term applications in space are discussed.

AEROSPACE REQUIREMENTS

Many unique requirements were placed on textiles used in space flight as well as in the lunar environment. Advances in technology were required to develop new or to modify existing materials to meet these requirements. This task, which posed a formidable challenge to NASA and to industry, spurred technological achievements which seemed unattainable only a few years before.

Of foremost consideration in the crew bay area of the spacecraft, of course, is the enriched concentration of oxygen described in table 1 and its effects on flammability.

Outside of the spacecraft, described in table 2, textiles are exposed to a hard vacuum, to the deep-space thermal environment, to bombardment by micrometeoroids and impingement by total electromagnetic spectrum, as well as to the solar-wind particulate flux.

A number of screening tests, in addition to selected full-scale tests, are conducted to verify the capability of every textile material to perform in its intended applications. For example, the general screening tests imposed for safety considerations on every nonmetallic material used in the crew bay area of the Apollo spacecraft and the Space Shuttle Orbiter are listed in table 3.

TABLE 1.- SPACECRAFT CABIN ENVIRONMENT

Program	Gas composition, percent		Pressure, psia
	Oxygen	Nitrogen	
Mercury	100	0	5
Gemini	100	0	5
Apollo			
Command module Prelaunch	60	40	16.5
Command module Postlaunch	100	0	6.2
Lunar module	100	0	5.8
Skylab	65	35	5.2
Space Shuttle			
Normal	25.9	74.1	14.3
Preparation for EVA[a]	30	70	10

[a]Extravehicular activity.

TABLE 2.- SPACE AND LUNAR SURFACE ENVIRONMENT

Environment	Condition
Pressure, mm Hg	10^{-14}
Temperature (lunar surface), °F Upper .... Lower	 250 -250
Electromagnetic radiation	X-ray, ultraviolet, infrared
Solar-wind	particulate flux: proton, electron, alpha, etc., at 500 km/sec
Micrometeoroid density, gm/cm^2	0.5 at 20 km/sec

TABLE 3.- NONMETALLIC MATERIALS TEST CRITERIA

Test Description	Unit	Limit	Test condition	
			Apollo[a]	Space Shuttle[b]
Flammability				
Major exposures		S.E.[c]	5 psia, 100% O_2 Bottom ignition	10 psia, 30% O_2 Bottom ignition
Minor exposures	in/sec	0.3	5 psia, 100% O_2 Top ignition	10 psia, 30% O_2 Top ignition
Offgassing				
Total organics	μg/g	100	155 °F, 72 hr, 5 psia, 100% O_2	120 °F, 72 hr, 14.3 psia, 25.9% O_2
Carbon monoxide	μg/g	25	155 °F, 72 hr, 5 psia, 100% O_2	120 °F, 72 hr, 14.3 psia, 25.9% O_2
Odor	--	2.5	155 °F, 72 hr, 5 psia, 100% O_2	120 °F, 72 hr, 14.3 psia, 25.9% O_2

NOTE: Tests are defined in the following documents:

[a]Apollo Spacecraft Nonmetallic Materials Requirements. MSC-PA-D-67-13, Feb. 9, 1968.

[b]Flammability, Odor and Offgassing Requirements and Test Procedures for Materials in Environments That Support Combustion. NHB 8060.1A, Feb. 1974; NHB 8060.1B, Sept. 1981.

[c]Apollo Program
S.E. = Self-extinguish
Space Shuttle Program
S.E. = Self-extinguishing under 6 in. of 12 in. test specimen

Basically, these tests set limits on the capability of the material to propagate fire, and on the quantity and nature of the offgassing products of the materials if they are inadvertently overheated. Of course, the whole series of Federal test methods, American Society of Testing and Materials, and special textile tests are conducted as required to assure compliance with the more general textile properties delineated in the following listing as well as the specific functional properties mandated by each "end item" application.

General Requirements:

1. Durability
    - Breaking strength
    - Abrasion resistance
    - Wear resistance
    - Tear resistance
    - Puncture resistance
    - Pilling resistance
    - Dimensional stability
2. Flexibility
3. Permeability
4. Thermal and vacuum compatibility
5. Physiological compatibility (clothing requirement)
    - Dermatological compatibility
    - Comfort and aesthetic
    - Moisture transmission
6. Low offgassing
7. Low smoke

8. Low volatile condensable material

9. Obtaining the lowest possible cost concomitant with meeting the listed requirements is an equally important challenge.

10. Other requirements for specific functional properties dictated by "end item" applications

RESULTS AND DISCUSSION

The chemical structure of Beta fiber is a lattice of inorganic oxides formed at a temperature at which no known organic material could exist. The formation of the fiber requires a great deal of thermal energy. The fiber will not burn because it is already a product of the oxidation process. Beta fibers are almost perfectly elastic. Even when stressed almost to the point of rupture, the fiber will return to its original length. To cause this fiber to yield, the fiber would have to be heated to 945 °F (It melts at 1550 °F.) Because of these inherent properties, this fibrous structure has outstanding dimensional stability; neither heat, moisture, nor physical stresses can cause shrinkage or stretching.

Table 4 serves to illustrate the phenomenal tensile strength of Beta fiber as compared to some of the other common textile fibers. Figure 1 shows a demonstration of the flame resistance of the Beta fibrous structure.

The results of the qualification tests on flammability and offgassing properties of Beta fiber along with other high-temperature and flame-resistant textile fibers are shown in table 5.

The flammability test results indicate that the Beta fiber shows no ignition in 100 percent oxygen environment up to 16.5 psia with silicone ignitor. Table 6 identifies the physical and thermal properties of Beta fiber as compared with other high-temperature and flame-resistant textile fibers. The Beta fiber exhibits outstanding properties.

Beta fiber is unique among inorganic or organic fibers because of its fineness. It is 0.25 denier per filament or 3.8 μm in diameter. A comparison of cross-sectional areas of textile filaments is illustrative of the fineness of the fiber as shown in figure 2.

TABLE 4.- COMPARISON OF PHYSICAL PROPERTIES OF TEXTILE FIBERS

Fiber	Tensile strength, psi	Tenacity, GPD[a]	Yield point, GPD[a]
Beta	500 000	15.3	15.3
Polyester	92 000	5.2	4.0
Polyamide	88 000	6.0	5.0
Polypropylene	80 000	8.0	4.0
Acrylic	39 000	2.6	1.3
Modacrylic	70 000	4.2	1.0
Rayon	50 000	2.6	.9
Acetate	28 000	1.5	.9
Cotton	97 000	4.9	.5
Wool	28 000	1.7	.4
Silk	88 000	5.1	1.5

[a]Grams per denier.

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Figure 1.- Flame resistance demonstration on Beta fiber.

TABLE 5.- COMPARISON OF FLAMMABILITY AND OFFGASSING PROPERTIES OF HIGH-TEMPERATURE AND FLAME-RESISTANT TEXTILE FIBERS

[Silicone ignitor, 100 percent oxygen]

Material	Flame spread rate, in/sec					Offgassing		
	Top ignition		Bottom ignition			Total organics, µg/g	Carbon monoxide, µg/g	Odor
	16.5 psia	6.2 psia	16.5 psia	16.5[a] psia	6.2 psia			
Beta	NI[b]	NI	NI	NI	NI	0	.6	1.3
Teflon	SE	SE	.55	.30	.30	34	.7	.9
PBI	.20	.16	.41	.35	.30	.4	1.7	1.5
Asbeston	SE[c]	SE	SE	SE	SE	1.3	1	1.7
Nomex	.33	.16	1.00	.60	.60	1	.4	.7

[a]60 percent oxygen, 40 percent nitrogen.
[b]NI = no ignition
[c]SE = self-extinguishing

TABLE 6.- COMPARISON OF PHYSICAL AND THERMAL PROPERTIES OF HIGH-TEMPERATURE AND FLAME-RESISTANT TEXTILE FIBERS

Property	Beta	PBI[a]	Teflon	Nomex
Tensile strength GPD[b]	15	4.5	1.4	5.5
Elongation, percent	4	12	15	17
Specific gravity, g/cm3	2.1	1.34	2.1	1.38
Service temperature, °F	-300 to +900	-65 to +800	-400 to +500	-65 to +500
Degradation temperature, °F	1550	1000	700	700
Thermal radiative properties:				
Solar absorptance	.17	.51	.17	.22
Infrared emittance ...	.90	.75	.88	.88

[a]Polybenzimidazole
[b]Grams per denier

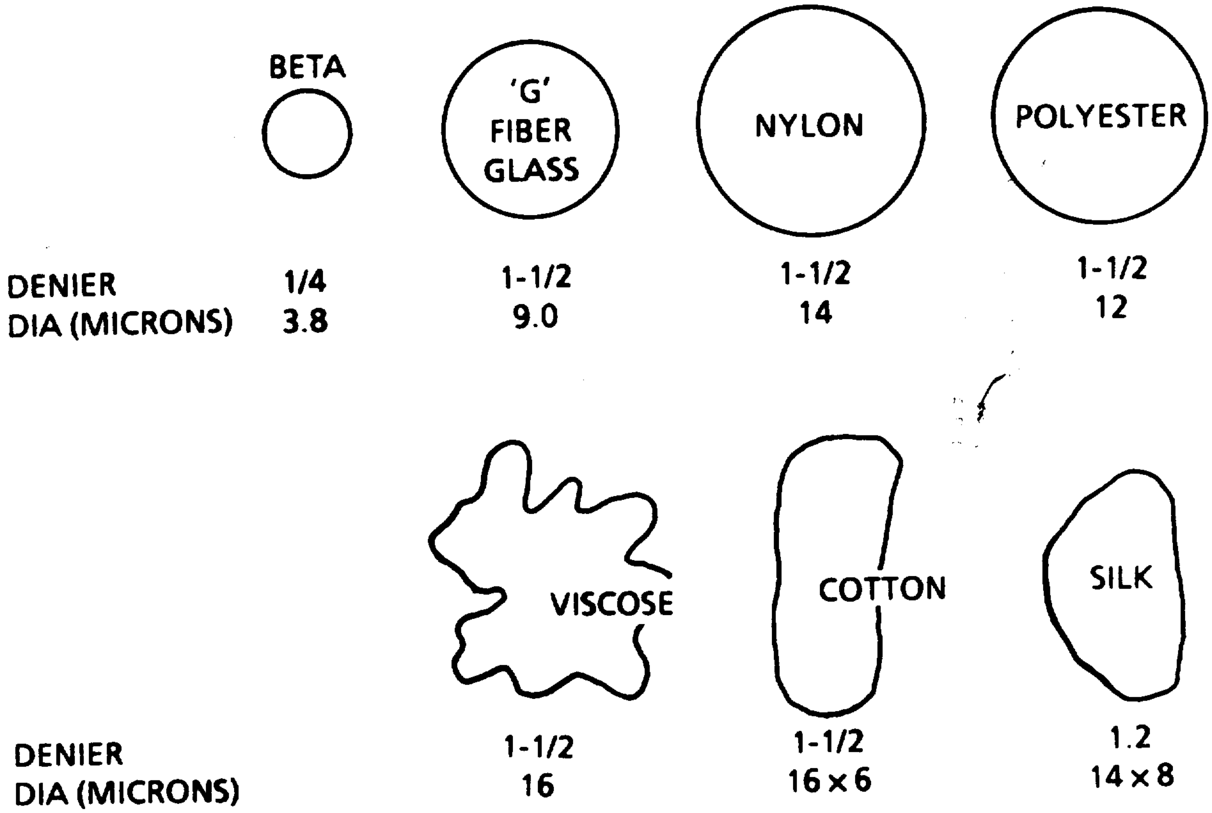

Figure 2.- Comparative size of fibers.

Beta fiber is one-sixth the denier of common organic fibers. However, because it has a much greater density than organic materials, the fineness of the filament is even greater than that indicated by the denier comparisons. For example, for similar weights of fiber, the actual cross-sectional area of a Beta filament would be nine times smaller than that of nylon, polyester, or viscose. Shown in table 7 is the comparison of relative stiffness of the fibers.

TABLE 7.- COMPARISON OF BENDING STIFFNESS OF FIBERS

Fiber	Relative bending stiffness[a]
Beta	1
Acetate	5
Viscose	7
Silk	7
Cotton	8
Nylon	11
Polyester	14
Glass fiber (G)	36

[a]Bending stiffness was calculated from formulas for stiffness of a cantilever beam and critical buckling load of a column with one end fixed and the other end free.

It is known that the radius of bend at rupture varies with the diameter. The small diameter of Beta fiber provides low stiffness value; therefore, the fiber is more flexible, more pliable, and softer. Some of the other physical characteristics of the Beta fibers are listed in table 8.

TABLE 8.- PHYSICAL PROPERTIES OF BETA FIBER

Characteristic	Single filament	Multifilament
Breaking tenacity, GPD[a]	15.3	9.6
Breaking elongation, percent	4.8	3.1
Tensile strength, psi	500 000	313 000
Elastic recovery, percent	100	100
Average stiffness, GPD[a]	320	310
Specific gravity, g/cm^3	2.5	2.5
Water absorbency, percent (70 °F, 65 percent relative humidity	None	None

[a]Grams per denier

The Beta fiber exhibits high values of breaking tenacity and tensile strength; however, it should be noted that there are losses in the strength values obtained with a single filament. This strength loss is caused by interfiber friction. To overcome this problem, a special Teflon coating was developed in which the individual 150 single-ply Beta yarns were coated, then woven into a 65 by 62 construction fibrous structure. This process provided a material that had the improved abrasion, tear and puncture resistance, and porosity to serve as the outer protective layer of the space suit and other applications in space. The Apollo extravehicular space suit and intravehicular flight suit are shown in figures 3 to 5.

Figure 3.- Apollo EVA space suit – Beta fibrous structures for outer layer.

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Figure 4.- EVA space suit worn by Apollo astronauts.

Figure 5.- Beta fibrous structures for Apollo intravehicular flight suit.

Another Teflon-coated fibrous structure developed is a 150 single-ply Beta yarn with a dense 90 by 65 construction. This fibrous structure is principally in use as a fire barrier in thermal and contamination control, and in containers that are designed to hold flammable flight items such as the tissue dispenser box shown in figure 6.

Figure 6.- Beta fibrous structures fabricated as tissue dispenser box.

AEROSPACE APPLICATIONS

Beta fiber is a unique material which is used in the spacecraft far more than any other textile fiber. It has developed into woven, nonwoven, knitted, braided, coated, and printed structures. All of these were used extensively for the Apollo, Skylab, Apollo-Soyuz Test Project, Space Shuttle, Spacelab, and satellite programs. As shown in figures 7 to 11, the Beta fibrous structures and bags were used as fire-protective covers for potential ignition sources (such as electrical assemblies, harnesses, wire bundles, connectors, and oxygen hoses) in the interior of the Apollo command module and lunar module in order to eliminate a flammability hazard.

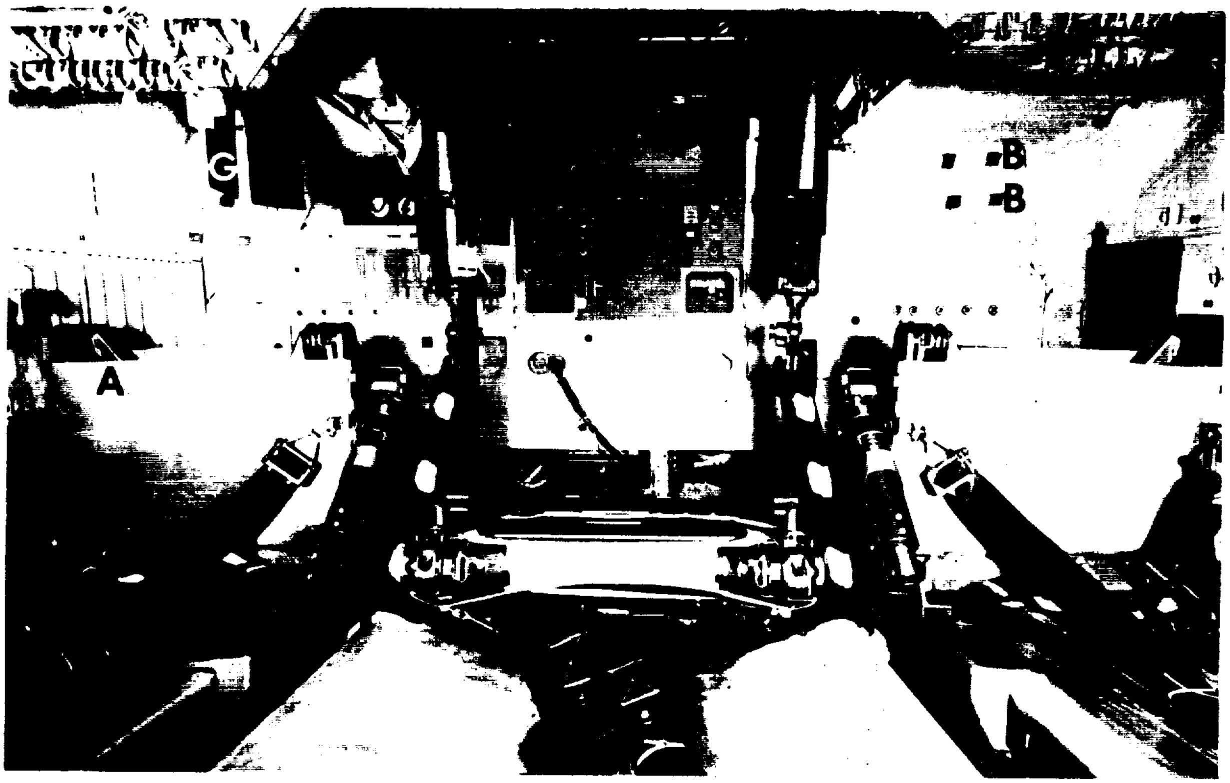

Figure 7.- Beta fibrous structures shown in the interior of Apollo command module.

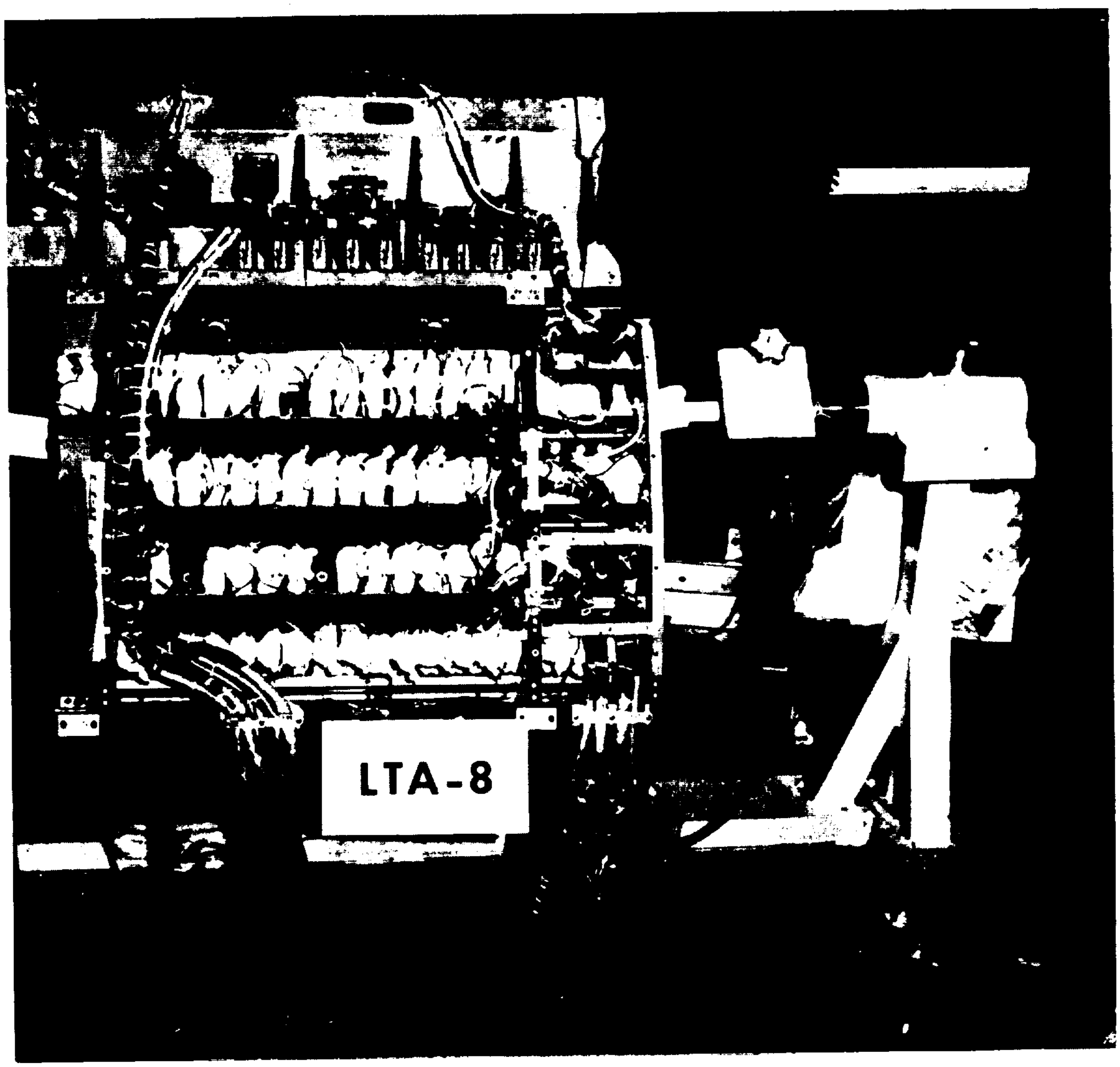

Figure 8.- Beta fibrous structure fire-protective bags on lunar module circuit-breaker panel.

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Figure 9.- Beta fibrous structure fire-protective cover for the lunar module suit loop.

Figure 10.- Beta fibrous structure fire-protective covers for silicone rubber oxygen hoses on lunar module.

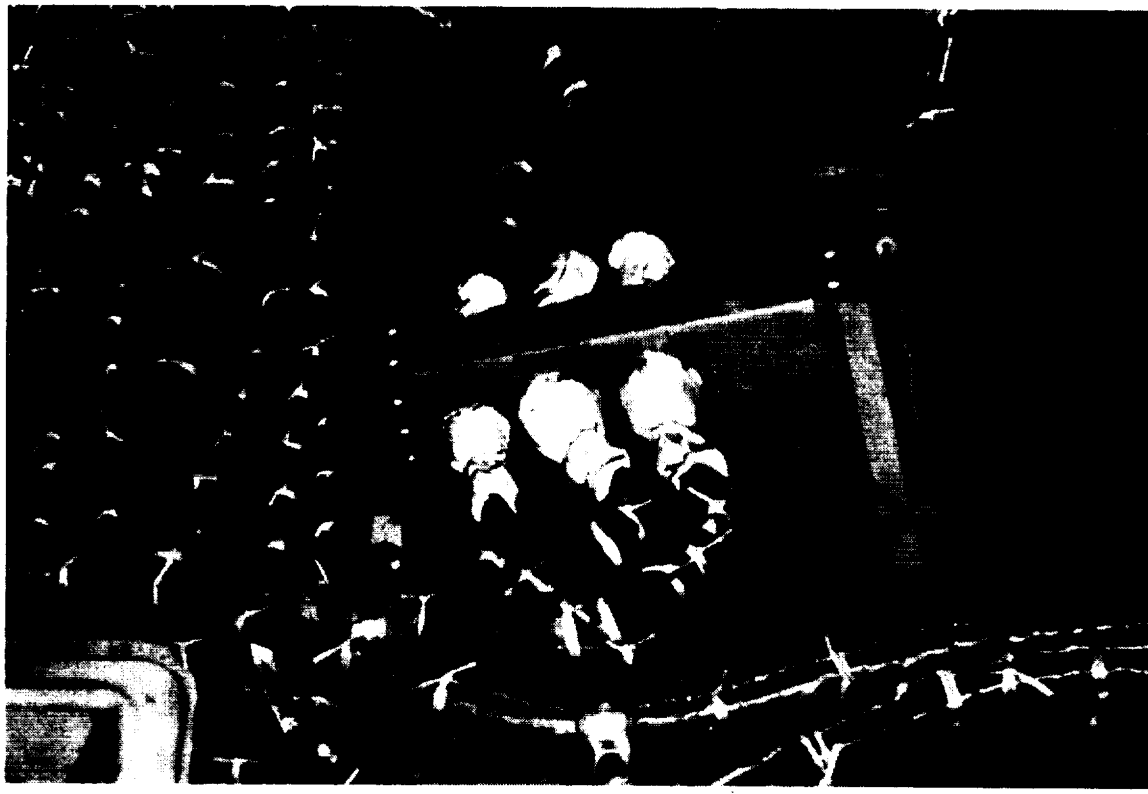

Figure 11.- Beta fibrous structure fire-protective bags for electrical connectors.

Because spacecraft wiring is a potential ignition source, it was necessary to provide protection from any fire that might propagate significantly beyond the region of ignition. After extensive individual testing with Beta-covered components, a series of full-scale spacecraft mockup flammability tests was conducted. Interior mockups of the Apollo command module and lunar module were used in a series of 173 flammability tests, the results of which provided the final verification that the Apollo command module and lunar module were firesafe.

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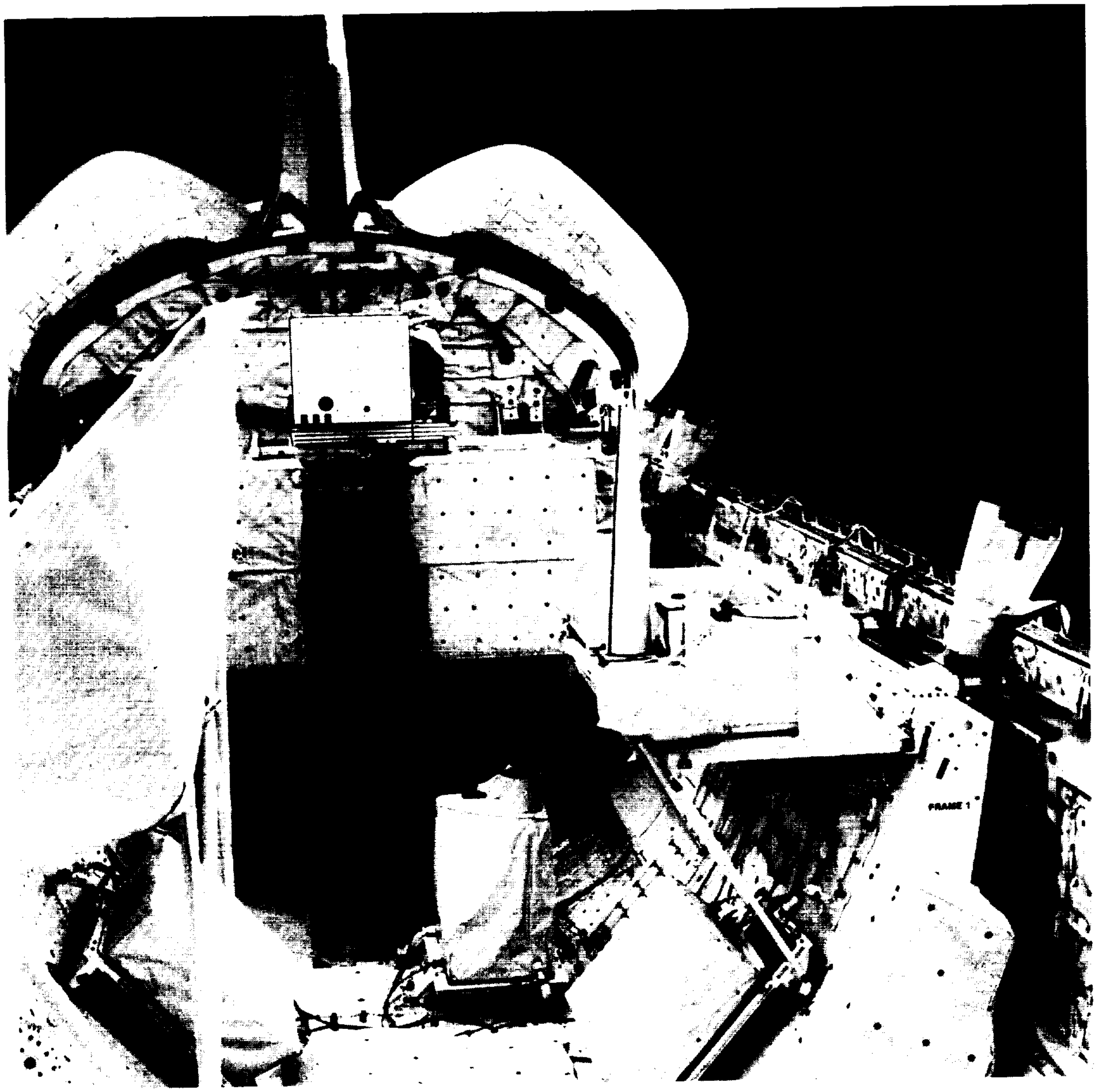
Beta fibrous structures meet thermal radiative property requirements; figure 12(a) shows the Beta fibrous structures as a thermal and contamination control cover layer for the entire Space Shuttle Orbiter payload bay area.



(a) As contamination control cover layer.

Figure 12.- Beta fibrous structures for the Space Shuttle Orbiter payload bay area.

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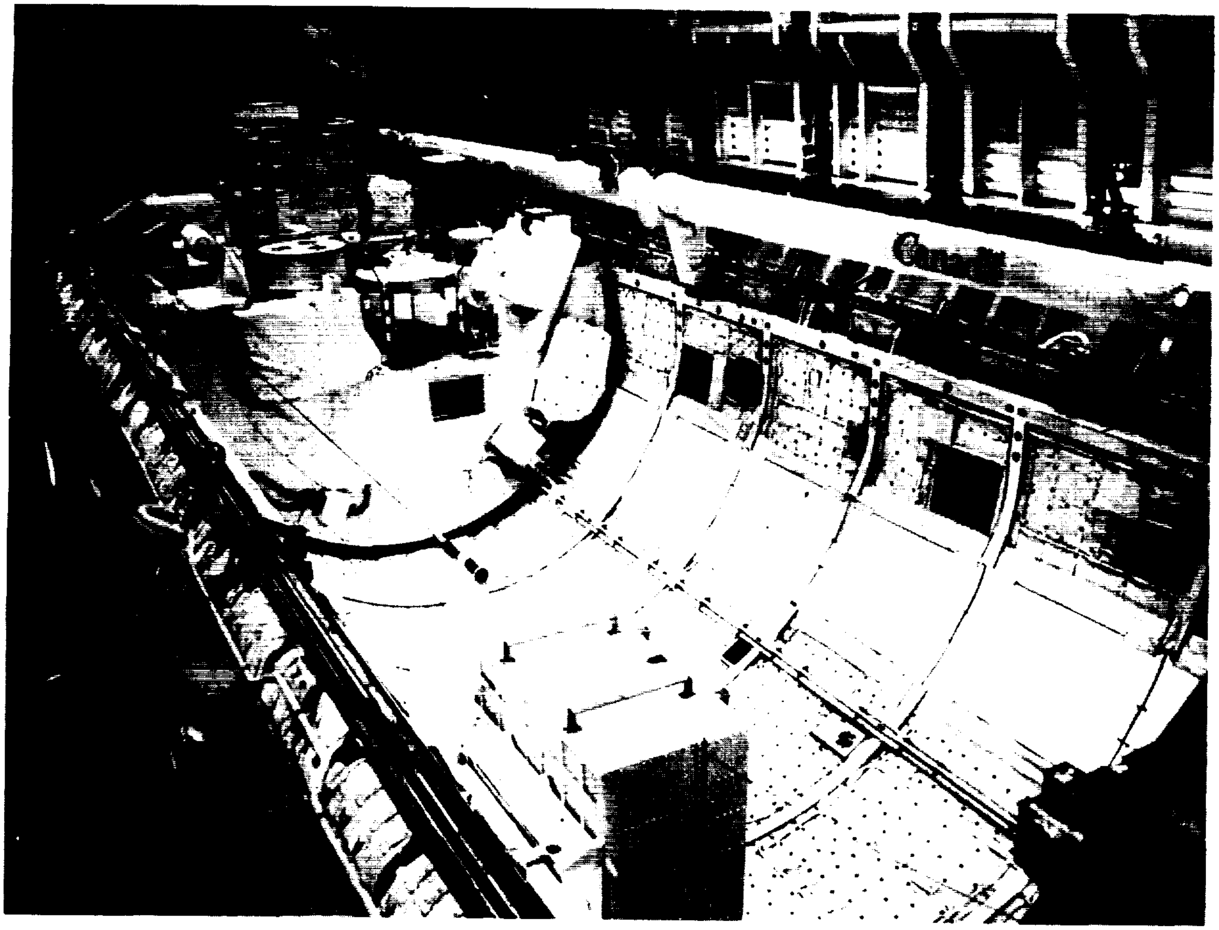
The flight experiment and crew equipment protected with Beta fibrous structures in the Shuttle Orbiter payload bay area are shown in figure 12(b).



(b) As thermal control cover layer for flight experiment and crew equipment.

Figure 12.- Concluded.

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All the satellites, such as Viking, Mariner, etc., launched by the NASA Jet Propulsion Laboratory in Pasadena, California, are also covered with Beta fibrous structures as thermal control material. As shown in figure 13, the Mariner X satellite is covered with Beta fibrous structures.

Figure 13.- Beta fibrous structure used for thermal control in Mariner X satellite.

The following is a partial list of the successful applications of Beta fibrous structures for the space program.

- Flame-protective layer of Apollo space suit
- Apollo space-suit thermal insulation spacer
- Apollo flight suit
- Apollo spacecraft window shade
- Medical kits
- Rucksacks
- Towel bags
- Space-suit accessories kit
- Life vest assembly kit
- Portable life support system covers
- Crew provision container
- Oxygen hose cover
- Containers for accessories of survival equipment and crew provision items
- NASA emblems
- Mission emblems
- American flags
- Nameplates
- Ground tape for Astro Velcro fasteners
- Astronauts' couch
- Fire-protective barriers

- Heat shields
- Spacecraft insulation
- Skylab shower enclosure
- Shuttle Orbiter payload bay and door liner
- Shuttle Orbiter remote manipulator arms cover
- IMAX camera cover

This partial list illustrates the wide variety of the end items which have been fabricated. The successful development of the Beta fiber and various types of Beta fibrous structures, as well as the adaptation and fabrication of the items listed, is considered a major technical achievement. Table 9 itemizes the quantity of a total over 10 000 pounds of Beta fibers which have been used in various space programs up to the present time.

TABLE 9.- U.S. SPACE PROGRAM USE OF BETA FIBER

Program	Each spacecraft or unit, lb	Total, lb
Apollo	450	4500
Skylab	600	1960
Apollo-Soyuz Test Project	450	450
Space Shuttle	500	2500
Spacelab	50	150
Payload assist module	50	250
Satellites	40	640

TECHNOLOGY UTILIZATION

As part of a NASA effort to spinoff space technology for commercial applications, Beta fibers are being used as firesafe fabrics, such as safety suits; drapes; decorative hangings; overhead and wall coverings; upholstery and floor coverings; bed and seat covers in homes, hospitals, institutions, public buildings, aircraft, and public transportation – wherever total nonflammability is required. Many racing car drivers wear Beta coveralls as fire-protection clothing. The fire-protective suits made from Beta are standard equipment at many airports in the United States. The first Beta roofing was erected for the United States Exposition Pavilion at Osaka, Japan.

One of the most outstanding applications of the Beta composite structure is the roofing material used for the 80 000-seat Detroit Lions' Silverdome shown in figure 14 and for the 5 square miles of roofing for the King Abdulaziz International Airport in Jeddah, Saudi Arabia shown in figure 15.

Applications have been found for this roofing material in all continents from Europe to South America and from Asia to Australia. The United States alone has used more than 12 million square yards of this material. This fiber has successfully been incorporated into 165 major public construction projects around the globe. Figure 16 shows the use of Beta fibrous structural roofing in a shopping mall. The reason for such wide usage is attributed to the durable, lightweight, low-cost, and nonflammable nature of this fiber. It will not decay, mildew, or absorb moisture when exposed to the outdoor environment. Its relatively low cost has resulted in widespread acceptance of fibrous roof structures in shopping malls, stadiums, field houses, schools, theaters, exhibit halls, and industrial facilities.

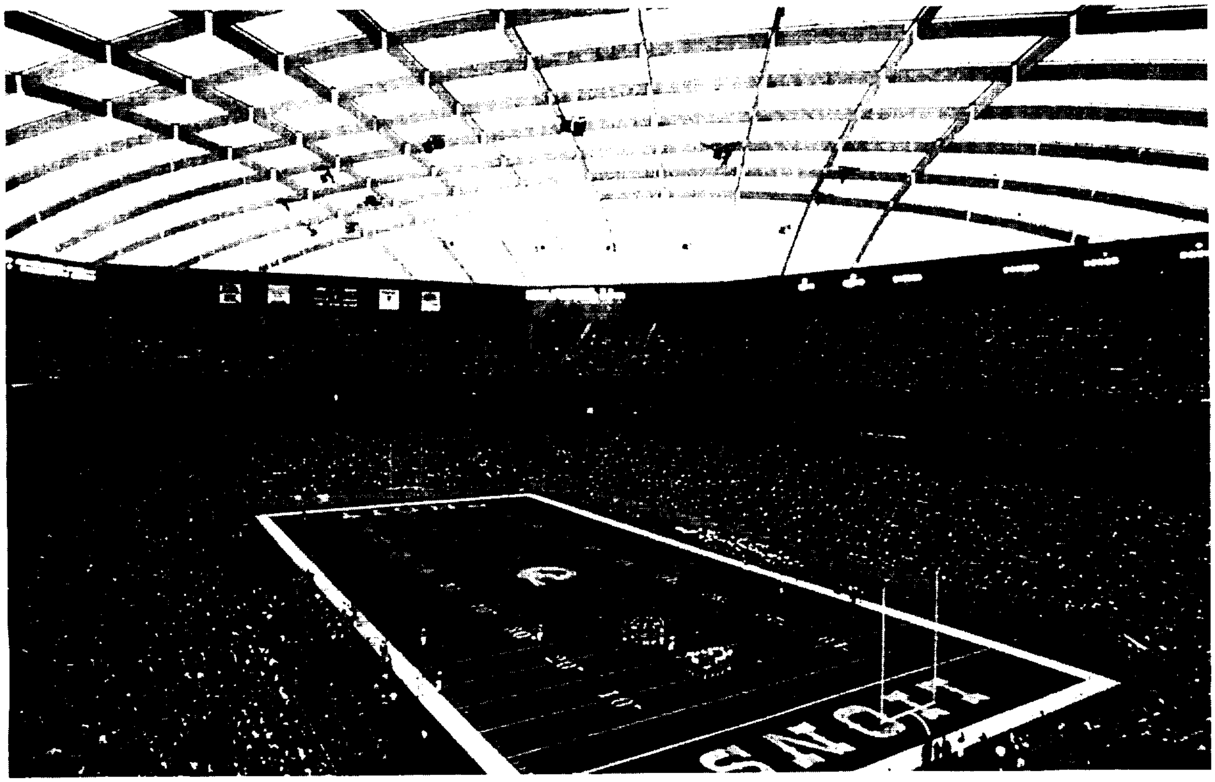

Figure 14.- Beta fibrous structures roofing for Detroit Lions' Silverdome in Pontiac, Michigan.

Figure 15.- Beta fibrous structures roofing for Haj terminal at King Abdulaziz International Airport in Jeddah, Saudi Arabia.

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Figure 16.- Beta fibrous structures roofing for shopping mall.

FUTURE PLANS

Beta is already a very successful fiber, but its future is promising and its potential is unlimited. Efforts are being continued to further improve Beta fiber for the space program as well as for spinoff applications. New requirements, such as a 30-year service life requirement for long-term space missions currently planned for orbital Space Station Freedom, the lunar habitat, and the lunar and Mars exploration programs are stimulating improvements.

To search for increased durability and long-term service life in the future, the following areas are being pursued:

- Decreasing fiber diameter to produce a finer and more flexible fiber
- Modifying chemical composition to achieve higher strength
- Modifying manufacturing technique/process for cost savings
- Developing a new coating to further improve performance characteristics

In addition, Beta fiber is being combined with other fibers to provide synergistic properties that are not obtainable by the use of the component fibers alone. These efforts will lead to a more durable textile fiber with even greater dynamic and long-term service life applications.

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15. Supplementary Notes

16. Abstract

Recent advances in fiber technology have contributed to the success of the U.S. space program. The inorganic fiber "Beta," developed as a result of efforts begun in the early 1960's and heightened following the January 27, 1967, Apollo fire, is unique among inorganic and organic fibers. It has been developed into woven, nonwoven, knitted, braided, coated and printed structures. All of these were used extensively for the Apollo, Skylab, Apollo-Soyuz Test Project, Space Shuttle, Spacelab, and satellite programs.

In addition to being used successfully in the space program, Beta fibers are being used commercially as firesafe fabrics in homes, hospitals, institutions, public buildings, aircraft, and public transportation, wherever total nonflammability is required. One of the most unique applications of the Beta composite structure is the roofing material for the 80,000-seat Detroit Lion's Silverdome and 5 square miles of the Jeddah International Airport in Saudi Arabia. This fiber has been successfully incorporated into 165 major public construction projects around the globe. The United States alone has used more than 12 million square yards of the material.

Beta fiber has been used successfully to date and has a promising future with unlimited potential for both space and commercial application. Efforts are currently underway to improve Beta fiber to meet the requirements of extended service life for the Space Station Freedom, lunar outpost, and Mars exploration missions.

17. Key Words (Suggested by Author(s)) Beta fibers; Micrometeoroid density; Electromagnetic spectrum; Spinoff space technology; Nonmetallic fibers; Flame resistant; Fibrous structure; Fire-protective	18. Distribution Statement Unclassified - Unlimited Subject Category: 54

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