N93-26060

# COMPOSITE MATERIALS FOR THE EXTRAVEHICULAR MOBILITY UNIT

Final Report
NASA/ASEE Summer Faculty Fellowship Program--1992
Johnson Space Center


| | |
|---|---|
| Prepared By: | Enrique V. Barrera |
| Academic Rank: | Assistant Professor of Materials Science |
| | Hector M. Tello<br>Graduate Student and NASA-ASEE<br>Summer Student Participant |
| University & Department: | Rice University<br>Department of Mechanical Engineering and Materials Science<br>Houston, TX 77251-1892 |


NASA/JSC

| | |
|---|---|
| Directorate: | Engineering |
| Division: | Crew and Thermal Systems |
| Branch: | Systems Engineering Analysis Office |
| JSC Colleague: | Dr. Frederic S. Dawn |
| Date Submitted: | August 7, 1992 |
| Contract Number: | NGT-44-005-803 |

## ABSTRACT

The extravehicular mobility unit (EMU), commonly known as the astronaut space suit assembly (SSA) and primary life support system (PLSS), has evolved through the years to incorporate new and innovative materials in order to meet the demands of the space environment. The space shuttle program which is seeing an increasing level of extravehicular activity (EVA), also called space walks, along with interest in an EMU for Lunar-Mars missions means even more demanding conditions are being placed on the suit and PLSS. The project for this NASA-ASEE Summer Program was to investigate new materials for these applications. The focus was to emphasis the use of composite materials for every component of the EMU to enhance the properties while reducing the total weight of the EMU. To accomplish this, development of new materials called fullerene reinforced materials (FRM's) was initiated. Fullerenes are carbon molecules which when added to a material significantly reduce the weight of that material. The Faculty Fellow worked directly on the development of the fullerene reinforced materials. A chamber for fullerene production was designed and assembled and first generation samples were processed. He also supervised with the JSC Colleague, a study of composite materials for the EMU conducted by the student participant in the NASA-ASEE Program, Hector Tello a Rice University graduate student, and by a NASA Aerospace Technologist (Materials Engineer) Evelyne Orndoff, in the Systems Engineering Analysis Office (EC7), also a Rice University graduate student. Hector Tello conducted a study on beryllium and Be alloys and initiated a study of carbon and glass reinforced composites for space applications. Evelyne Orndoff complied an inventory of the materials on the SSA. Ms. Orndoff also reviewed SSA material requirements and cited aspects of the SSA design where composite materials might be further considered. Hector Tello spend part of his time investigating the solar radiation sensitivity of anodic coatings. This project was directed toward the effects of ultra-violet radiation on high emissivity anodic coatings. The work of both Evelyne Orndoff and Hector Tello is of interest to the Engineering Directorate at NASA/JSC and is also directed toward their research as Rice University graduate students.

## INTRODUCTION

For the most part, the extravehicular mobility unit is already a composite in itself, the separation of the EMU into major components such as the arm assembly, lower torso assembly, glove, and etc; combination of flexible to non-flexible materials; the arrangement of numerous layers where each plays a different but important roll; and even the layers themselves like the outer layer of the Thermal Micrometeroid Garment (TMG) which is a composite of Gore-tex fiber, Nomex fiber, and Kevlar fiber. The total design is well engineered and the long time work of Dr. Frederic S. Dawn, NASA/JSC, and the numerous contractors of which Hamilton Standard, and ILC are the current contractors, deserve our recognition in this report.

In this research, a study was initiated to further extend the use of composite materials on the EMU. To accomplish this a new material was proposed by Rice University and accepted by NASA/JSC for development, an inventory of the existing materials on the EMU was completed, studies of the EMU requirements and of new composite materials were initiated, and design synthesis was accomplished. In this report the details of the various tasks will be elaborated. Task I, the development of the new materials of fullerene reinforced aluminum and stainless steel, is a multi-year project. The premise of the design will be given, as will the status of the project and the future plans for the material development. Task II is the inventory of the materials used on the space suit assembly (SSA), the SSA properties requirements and the design synthesis is also a multi-year project and this will be discussed. And Task III is the study of the new and available composite materials, this too will be the subject of a continuing study, which will be discussed in this report.

The significant accomplishments which will be discussed in this report include: the attainment of fullerene reinforced material samples, the inventory of the materials used on the EMU, the findings of a study of beryllium and Be alloys, the findings from a study on composite materials which are carbon and glass reinforced polymer matrix materials, the findings from the design synthesis, and a plan by which the work initiated here will be continued. Other findings obtained during this study, such as the preliminary findings of a study of anodized coatings, which is a side effort, will also be contained in this report for completeness. The detailed findings of that discussed in this report can be obtained from the authors.

## COMPOSITE MATERIALS: DEVELOPMENT, SELECTION, DESIGN, AND EVALUATION

### Composite development

In the early Spring of 1992 Dr. E. V. Barrera and D. L. Callahan started development of a material which would have as a second phase or reinforcing phase the recently discovered fullerenes, the most famous of which, the Buckminsterfullerene $C_{60}$ called "Bucky balls" [1,2]. The premise of the design was that the fullerenes, which are nanometer size molecules, would serve as a strengthening and toughening agent in structural matrices such as aluminum and stainless steel. Use of the fullerenes would lead to substantial weight savings. Aluminum has a density of 2.7 $gm/cm^3$ (0.1 $lb/in^3$) and iron in the stainless steel has a density of 7.87 $gm/cm^3$ (0.285 $lb/in^3$) while carbon has a density as high as 2.22 $gm/cm^3$ (0.08 $lb/in^3$) compared to the $C_{60}$ with a density of 1.2 $gm/cm^3$ (0.043 $lb/in^3$). Strengthening would come from fullerene properties including, the soccer ball shape of the $C_{60}$ (see Figure 1), their capability of being deformed, and their proven chemical stability as reported in numerous papers including that by R. E. Smalley of Rice University who was a principal discoverer of fullerenes [3].

The project is at a stage where composite samples have been made and a fullerene production chamber has been assembled. The processing of composite samples was conducted by Hector M. Tello and E. V. Barrera. The first generation sample of fullerene reinforced aluminum was produced with a concentration of fullerenes not exceeding 1%, yet enough to show that mechanical deformation processing would lead to a final sample. NASA's interest in this material sparked by Dr. F. S. Dawn, E. S. Orndoff, and Dr. C. Lin, occurred early in this development process and soon the sample development was directed toward materials to be used on the astronaut primary life support subsystem (PLSS). The material now had a well defined and highly visible application whereby further fullerene composite research by other researchers was sure to follow.

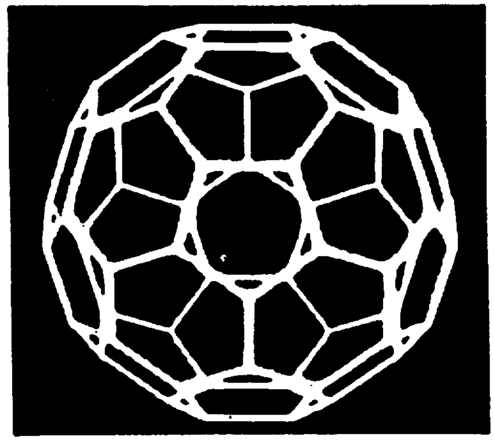

Figure 1. The truncated icosahedron soccer ball structure of the fullerene $C_{60}$.

Fullerene reinforced material (FRM) development was set and has followed a well defined plan. Dr. Barrera conducted the material processing while at the Johnson Space Center as a NASA/ASEE Summer Faculty Fellow. The Rice University student participant in the NASA/ASEE Summer Program, H. M. Tello would was partly involved in this work. During this time, fullerenes and fullerene containing soot [4] were purchased from Polygon Enterprises in Waco, TX, matrix materials were obtained without cost and processing was continued with appropriate experimental analysis. Early samples were processed with a pure aluminum matrix, processing was conducted during the NASA/ASEE summer term using a 7075-O matrix where the final properties of the composite were expected to surpass that of a 7075-T6 material. This material was obtained at no cost to the project. 2219-T851 aluminum will be used as the project continues because this is the material used by Hamilton Standard for fabrication of the current PLSS. The results to be discussed here will be directed toward that of the pure Al and 7075 matrix fullerene reinforced materials.

During the summer term Dr. Barrera also started work on the assembly of a fullerene production chamber based on carbon arc generation of fullerenes [4]. The chamber was assembled yet fullerene production was not started until after the summer program was over. The purpose of the production chamber or "bucky ball factory" was to allow for production of the fullerenes rather than continuing to buy the fullerenes at a price of \$20/gm (\$9000/lb). A site visit is planned for August 24, 1992 to observe the Bucky Ball Factory in use.

Sample processing by a mechanical deformation method involved rolling of sheets and foils with fullerenes sandwiched in between. The foil surfaces were roughened to insure mechanical bonding. The fullerenes were suspended in toluene and applied to the surface using an eye dropper. The toluene would evaporate leaving the fullerenes on the surface of the foils. The foils with the fullerenes on the inner surfaces were laid up between steel patents and rolled to a reduction where the limit was the formation of edge cracks. Careful hardness measurements and annealing treatments were used to minimize edge cracking. Additional materials analysis was in the form of x-ray diffraction (XRD) conducted by D. L. Callahan and E. V. Barrera. XRD of the fullerenes and the soot show distinct differences in the x-ray powder patterns. The soot had peaks for that of graphite while the fullerenes showed peaks for a crystalline carbon structure. Even though the soot contained fullerenes of a percentage of 2-5% the powder pattern did not show this, indicating that the fullerenes were well dispersed in the soot and not in a crystalline form.

The following abstract has been submitted to the Fall 1982 TMS Conference in Chicago: E. V. Barrera, H. M. Tello, D. L. Callahan, E. S. Orndoff, and F. S. Dawn, "Emerging Composites with Fullerene Reinforcements" and was well received. The work is in progress and Dr. Barrera will present this paper at the conference.

## Selection and design

In this section the inventory of the non-metallic materials, which includes the nonflexible materials, will be discussed. This study by E. S. Orndoff was to be the first stage of her Rice University graduate research. It also has served to better familiarize herself with the EMU of which her NASA responsibilities are focused. The inventory discussed here will focus on the SSA only and not on the PLSS [5]. In this study each component of the suit including the arm, lower torso assembly, glove, Hard Upper Torso (HUT), liquid cooling ventilation garment, helmet, extravehicular visor assembly, and urine collect device were reviewed. The review was directed toward investigating the current materials used, to determine the requirements (project conditions) and potential areas where composite materials could be used or designed to reduce weight [6].

Thermoplastic and thermoset materials

The major groups of non-metallic materials used in the Space Shuttle EMU (this was the subject EMU of the inventory) which are on the SSA are thermoplastic polymers, elastomers, fluorocarbons, fiberglass, adhesives, and lubricants [5]. Some general requirements are imposed on the entire SSA. The suit must be lightweight, resistant to wear, abrasion, and tear. They must resist fungi and bacteria growth, and be nontoxic. They must resist extreme temperatures, be nonflammable, and protect against impact of orbital debris and micrometeroids. However, these requirements vary from one component of the suit to another.

Among the thermoplastic polymers, two groups are prominently represented in the SSA: polyamides and polyesters. The polyamides are nylon and two aramids: Nomex and Kevlar. The polyesters are woven Dacron fiber and mylar film. The properties of nylon and Dacron are similar, differences occur in that where both melt and drip at around 250°C (482°F), they can be distinguished from one another by the odor and the smoke. They have excellent fatigue properties, the same modulus and strength, with the exception of the high tenacity polyester. They differ in elongation properties, moisture regain and overall chemical resistance. Nylon can elongate twice as much as a polyester and regains ten times more moisture than the polyesters. The aramids used in the space suit are in the form of flexible fibrous woven structures to cover and protect the astronaut's body and accommodate body mobility (another requirement). Nomex and Kevlar have similar molecular structures, they both contain aromatic rings which contribute to their increased thermal stability. Both polyamides and polyesters satisfy the general requirements previously mentioned. However, for the components of the suit where flammability resistance is an essential criterion, only the aramids can be used.

In general woven polyamides and polyesters have been used successfully in the different areas of the space suit. Some consideration has been given to making changes where a single layer will be used to replace two or more layers. This would only be of interest if a weight loss occurs and if the astronaut's mobility is increased. One problem was cited in that the aluminized mylar used for its thermal radiative properties can tear easily even with the nylon scrim reinforcement. The nylon scrim has also been shown to separate from the aluminized mylar. It is also prone to blocking of the adjacent layers. Research has shown that these conditions have not effected the thermal radiative properties of the material. As EVA time is increased and suits become non retrievable, it may be necessary to further consider these physical properties.

## Elastomers

The different elastomers used in the space suit are spandex, polyurethane, neoprene, and silicone rubber. The critical properties for these materials are strength and moderate elongation. The applications are diverse and include using polyurethane and neoprene for coatings on woven nylon, flocked polyurethane film used as the pressure bladder on the glove, and patterned silicone rubber RTV 157 used on the palms and fingers to provide non-skid surfaces. The gloves are designed with excess material which forms folds when pressurized and this aggravates the bulkiness of the glove. Research indicates that the astronaut's hands become too cold when at rest and easily overheat when at work. Increased mobility and improved thermal management are on going research topics for the glove.

In addition to the glove and pressure bladder, elastomers are also used for micrometeroid protection. A neoprene-coated nylon woven fabric provides some protection against small particle impact but this protection is minimal and does not substantially reduce the risk of injury. As EVA time is increased as will occur with the building of the space station and lunar bases, etc., the potential of micrometeroid collisions increases therefore better protection becomes more important.

## Fluorocarbons

Teflon fluorocarbon fibrous structures are used on the TMG as the outermost material exposed to the environment. It was chosen for its unique combination of properties which are relatively independent of fabrication conditions; stability at high temperatures, low coefficient of friction, and flexibility at low temperatures. Chemically it is also resistant to corrosive reagents, nonflammable, nonsoluble, and nonabrasive. Teflon has proved to be a good outer layer of the suit for occasional and short duration EVA's. However, since Teflon is not resistant to atomic oxygen, it is a less likely candidate for long duration EVA's. Therefore, more research is needed to develop a suit protection with atomic oxygen exposures in mind.

Fiberglass

Fiberglass molded with epoxy resin is currently used as the Hard Upper Torso (HUT). In combination with the metal bearings on the suit, the HUT contributes to most of the weight on the EMU with exception of the PLSS. Presently materials are being developed (see the section on fullerene reinforced materials being designed for the PLSS but also useful on the HUT), and other are considered (Be and Be alloys and carbon or glass reinforced composites, see the next section on Evaluation) to replace the fiberglass/epoxy currently used.

Summary

In summary, with the exception of the adhesives and the lubricants, eight components of the suit were researched where the following five points are suggested for further consideration.

1. Materials development for thermal protection of the suit in general could be considered.

2. Improvement of micrometeroid protection of the suit especially as the number and duration of EVA's increase.

3. Reduction of the bulkiness and improved mobility of the glove by considering different or developing new elastomeric materials.

4. Development of a material for protection against atomic oxygen bombardment.

5. Reduction of the total weight of the suit by considering FRM's, beryllium and Be alloys and carbon and glass reinforced composites.

## Evaluation

### Rigid materials for possible EMU use

In this section an evaluation of rigid materials for possible EMU use, which include beryllium and Be alloys and polymer matrix composites, will be discussed. This review was the subject of the NASA/ASEE project set aside for the Student Participant, Hector M. Hello. Included in this section will be brief comments on anodized coatings ultra-violet (UV) radiation sensitivity.

### Beryllium and Be alloys

Perhaps the reason a study of Be and Be alloys for space applications comes up every so often is attributed for the most part to their high specific mechanical properties. Beryllium has a density of 1.85 $gm/cm^3$ (0.067 $lb/in^3$) compared to Al with a density of 2.7 $gm/cm^3$ (0.1 $lb/in^3$) and Ti with a density of 4.5 $gm/cm^3$ (0.160 $lb/in^3$). The low density attributes to a specific modulus approximately 4.5 times that of Al, Ti, and Fe. The fact that the Be materials can be rolled into sheets or extruded into bar, rod or tubing is also attractive. Beryllium can also be machined to close tolerances and can be joined by brazing and adhesive bonding. The disadvantages are anisotropic properties, forming constraints and of course the toxicity hazard. While Be materials have high specific strengths they are still inherently brittle and have a low fracture toughness [7,8]. This is important from the standpoint of impact loading where even small defects in the material will lead to crack advancement. Still they exhibit good fatigue properties and a coefficient of thermal expansion well matched to that of stainless steel, nickel and cobalt. It is also clear that these materials can withstand continuous operation at temperatures up to 260°C (500°F) depending on the strength requirements.

As for manufacturing, Be is available in pressed billets, sheet, plate, rod, bar, and tubing. Billet sizes are from 0.8 x 0.75 m (32" x 30") up to 1.8 m (72") diameters by 1.7 m (66") lengths [9]. Forming requires temperatures in the range of 700-732°C (1300-1350°F) where sheet bends up to 90° are possible. Chemical milling is typically required before forming to prevent microcracking. Machining is possible but damage is usually caused and must be removed. Beryllium can be anodized as well as plated with nickel, silver, gold or aluminum.

Where improved manufacturing is needed, Be alloys (Be-Al) are being developed. Alloys such as Lockalloy (Be 38 Al) have been around for at least twenty years [10] and similar alloys are being considered in the National Aerospace Plane (NASP). The Be alloys exhibit an elastic modulus much closer to that of aluminum and increased density but also offer superior forming and deformation characteristics compared to pure beryllium.

## Be design considerations and remarks

The properties of beryllium and Be alloys are directly related to its microstructure therefore precise controls must be used in all forming and machining operations. Fastening of Be to other materials is preferred compared to bolting. Match fit holes are usually required to minimize stress concentrations and because the anisotropic behavior of the Be does not redistribute applied stresses as well as aluminum or steel. NSTS 14046, Payload Verification Requirements, details specific requirements for use of Be such as:

1. machined/mechanically disturbed surfaces must be chemically milled to ensure removal of surface damage,

2. all Be components must be penetrant inspected for crack-like flaws,

3. provisions must be made for containment of unconstrained pieces of a failed part.

Evaluation of Be materials has been that even though they periodically are considered for aerospace applications, they are frequently not selected because of their low fracture toughness, their special manufacturing requirements and toxicity issues. The data base for beryllium within NASA dates back to pre-Apollo days. The typical cost of manufacturing a Be part is about 3 times that of the same aluminum component although the additional safety and verification requirements may increase the final cost substantially.

Polymer matrix composites

Reinforcements

Polymer matrix composites were considered in this study for replacement materials for metallic materials on the PLSS and HUT on the EMU, MKIII, and other prototype suits. The criteria were weight savings, impact resistance, good strength and modulus, meeting the requirements of flammability, toxicity, thermal vacuum stability, and manufacturing ease and flexibility. Reinforcement materials that were considered were carbon fibers, Kevlar, E-glass and S-glass. Coefficients of thermal expansion (CTE) are important when reinforcements are incorporated into a matrix. The CTE's of glass reinforcements are better matched to the matrices than that of carbon and Kevlar. The reinforcements have comparable strength levels as compared to their matrix counterparts. In comparison, glass and aramid reinforced composites exhibit 2 to 3 times the impact strength of the carbon reinforced composites [11] however, the compression after impact strength of the carbon reinforced materials is substantially greater for moderate impact levels. The density of the glasses are greater than that of carbon therefore weight savings is compromised. Aramids offer the most weight savings but also have the lowest compression strength. From an impact and CTE matching standpoint, S-glass appears to be the best candidate. For maximum weight savings carbon fibers are typically used yet hybrid materials such as mixtures of graphite and glass layered with Kevlar or graphite are seeing increasing usage. Stitching with aramid yarn has also shown to increase the impact resistance of polymer matrix/carbon reinforced composites.

Matrix materials

Three types of matrix materials were considered in this study: toughened epoxies, cyanate esters, and thermoplastics. Toughened epoxies are the most widely used, they offer good impact resistance, good hot/wet properties, and low moisture absorption. Maximum service temperature for these materials is typically in the 90-150°C (200-300°F) range. The material that was used in the prototypical hardware exhibits good impact resistance and was a good selection.

Cyanate esters (CE's) generally exhibit the same mechanical properties as the toughened epoxies but are superior in toughness. Some of the newer materials are 2-7 times tougher than the epoxies. CE's have a higher service temperature where the glass transition temperature is higher than that of epoxies [12]. They are also capable of being used at much lower temperatures. They exhibit less outgassing and better dimensional stability.

Polyetheretherketone (PEEK) has become the thermoplastic matrix of choice in the aerospace industry. The density and mechanical properties of PEEK are approximately that of epoxies and its toughness is several times that of epoxies. The material ratings for PEEK are "A" for flammability in the cabin environment, "K" for toxicity (over 100 lbs usage is acceptable), and "A" for TVS after vacuum cured a few hours. Thermoplastics are favored to thermoset materials for repair and post forming operations. In fact, thermoplastics can be repaired by re-melting or by local heating (welding or ultrasonic welding).

Polymer composite considerations and remarks

Where the PEEK has pronounced superior properties to the other polymeric matrices mentioned, it has a lower glass transition temperature than the epoxies which limits its operating temperature. Furthermore, the percent crystallinity of the thermoplastics must be taken into consideration as well when it comes to long term operations. The data base for thermoplastics is large with extensive work having been done at Wright R&D Labs and by NASA-LaRC.

Further remarks on polymer matrix composites

1. The use of S-glass/epoxy may offer weight savings of 25% or more over aluminum.

2. Kevlar reinforced composites offer the best weight savings and good impact resistance. However, consideration must be given to the negative CTE (poor coefficient of thermal expansion matching with the matrix) and UV sensitivity in their design.

3. Thermoplastics matrices have superior impact resistance although their service temperatures may limit their use.

4. When designing hardware for a manned mission to the moon or Mars, consider the ability to repair damaged component.

5. This study is a continuous process since new materials are continually being developed for FAA and DoD applications.

Anodized coatings

Hector Tello and E. V. Barrera also worked with Steve Jacobs in the Structures and Mechanics Division (SMD) on anodized coatings, their UV radiative properties. Samples were obtained from McDonnell Douglas, Huntington Beach, optical properties were measured, x-ray photoelectron spectroscopy was conducted, and transmission electron microscopic samples are being made. An extensive literature search is underway.

## CONCLUSIONS AND FUTURE WORK

The significant accomplishments include the attainment of fullerene reinforced material samples, the assembly of the "Bucky Ball Factory", the inventory of the materials used on the EMU, the findings from the design synthesis, the findings from the study of beryllium and Be alloys and that from the study of composite materials which are carbon and glass reinforced.

The plan by which the work initiated here will be continued includes a Rice graduate student, John Sims to continue the research on the fullerene reinforced materials with Drs. Barrera and Callahan. Dr. Barrera will continue to work with the Systems Engineering Analysis Office in the continuing study of composite materials to be used on the EMU. It is likely that this may be on a consulting basis. Hector Hello will continue to be a part of the fullerene reinforced materials project but will direct a majority of his time toward the study of anodized coatings for space station radiator applications.

## REFERENCES


1. Kroto, H. W., et al., "$C_{60}$: Buckminsterfullerene", *Nature*, 318 (1985) 162-163.

2. Kratschmer, K., et al., "Solid $C_{60}$: a new form of carbon", *Nature*, 347 (1990) 354-357.

3. Smalley, R. E., "Great Balls of Carbon", *The Sciences*, Mar./Apr. (1990) 22-28.

4. Haufler, R. E., et al., "Carbon Arc Generation of $C_{60}$". Mat. Res. Symp., 206 (1991) 627-637.

5. Hamilton Standard internal publication, Space Shuttle Extravehicular Mobility Unit, Space Suit Assembly (SSA)-Mini Data Book.

6. *Textile World*, 138 (8) (1982).

7. Lemon, D. D. and Brown, W. F., Jr., "Fracture Toughness of Hot-Pressed Beryllium", *J. Testing and Evaluation*, 113 (2), Mar. (1985) 152-161.

8. MIL-HNBK-5.

9. Brush Wellman Catalog, (1989).

10. Final Report for Evaluation of Beryllium for Space Shuttle Components, LMSC-D159319, Sept., (1972).

11. *Eng. Mat. Handbook*, v. 1-Composites, ASM Intern., (1987).

12. *Adv. Composites*, 7 (3), (1992) 28-37.