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Material Choices for Mars

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The environment on Mars presents many unique challenges when designing a space suit for use during human exploration. These include a micro-vacuum atmosphere of mostly carbon dioxide, wide temperature fluctuations, and physical hazards ranging from dust storms to micrometeoroids and radiation. Previous NASA suits were analyzed prior to choosing new materials for a Mars suit, using Ashby criteria where applicable, and specific commercial information where necessary. Liquid cooling and ventilation, pressure, and thermomechanical garments were developed, using multiple materials and layers in each. Further materials choices were made for bearing materials to allow movement while ensuring sealing integrity of the suit. The overall mass for the design (without life support systems) is just less than 21 kg, significantly (and necessarily) less than earlier designs for lunar and orbital applications.

Keywords Mars environment, material selection, space suit

1. Introduction

During the last half-century, the United States and Russia (former Soviet Union) have pioneered designs, innovations, and material selections during the development of space suits for lunar and orbital exploration. The next challenge is exploration of Mars. The red planet, Mars, has unique factors, which complicate the design process and challenge the limitations of current space suit design and materials selection. The goal of this design project was to develop and use a detailed design process for a potential Mars exploration suit.

A space suit consists of several layers of materials that together provide an airtight, breathable enclosure capable of resisting most micrometeorite impacts (tears and punctures) while keeping the astronaut at a comfortable temperature and pressure.

The spacesuit must withstand extremely cold temperatures, low gravity, low atmospheric pressure, and dust storms. It must also provide external protection against several types of radiation and be flexible and light enough to allow for a wide range of motion. The suit must contain a breathing apparatus and an internal environmental system, which will allow the astronaut to function independently for up to 8 h.

Mars is further from the sun than the Earth and experiences significantly lower surface temperatures. The maximum, minimum, and mean surfaces temperatures are 20, −120, and −63 °C, respectively. Materials must behave in a non-brittle manner at these subzero temperatures. In addition, the suit will need to provide thermal insulation to maintain the body at a comfortable temperature. The atmosphere is significantly different—on the Earth's surface, the atmospheric pressure is 1.013 bars, while on Mars the surface pressure is only 0.007 bars. The Mars atmosphere is composed mainly of CO_2, N_2, and Ar at 95.3%, 2.7%, and 1.6%, respectively. The oxygen content of the low-pressure environment is only 0.13%. Therefore, no breathable environment exists, and the suit must provide one. Materials that are non-permeable and non-degradable in the largely CO_2 environment are necessary. The gravitational pull on Mars is approximately 1/3 of that felt on Earth. The relatively high surface gravity, in comparison to the moon (1/6 of Earth), requires new suit design and material selection. For a highly mobile suit for use during an 8-h mission, current designs would require a significant weight reduction.

Preliminary studies have shown that Martian dust is extremely electrostatic, magnetic, and adhesive.[1] Material selection must reduce contamination from Martian soil, especially for rotational components. Unlike Earth, Mars does not have a global magnetic field to shield it from solar flares and cosmic rays. Scientists have estimated that Mars once had a strong magnetosphere but about 4 billion years ago this was disrupted, and essentially "turned off."[2] Since that time, solar winds have gradually eroded the Martian atmosphere to its present state in which the atmosphere is less than 1% of that on Earth. This leaves Mars susceptible to three sources of space radiation: galactic cosmic radiation (GCR), radiation trapped in belts, and solar energetic particles (SEP). GCRs are generated during explosions of supernovas and other galactic events. SEPs originate from the sun, mainly during solar flare events. The main radiation types include electrons, protons, alpha, and heavy nuclei particles.

Early NASA space suits, known as Mercury Spacesuits, consisted of an inner layer of Neoprene-coated nylon, with an outer restraint layer of aluminized nylon. These suits were "non-pressurized," and they were not designed to provide for any degree of mobility if pressurized and relied on the spacecraft for physical protection.[3] The next NASA generation, the Gemini Spacesuits, were developed to improve mobility. The design improvements included a pressure "gas containing" bladder that was covered with a link-net woven restraint layer, composed of Dacron (polyester) and Teflon (fluoropolymer) cords. The Apollo Spacesuit represents one of the major milestones in suit development. The major functional components included a liquid cooling and ventilation garment (LCVG), a

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pressure suit (PS), and a multilayer thermomechanical garment (TMG). The Apollo suit was custom-made to fit each astronaut. The LCVG, PS, and TMG were composed of various materials in multiple layers; each performed a specific function. Each layer was designed and materials were selected to optimize functionality while reducing weight and ensuring mobility. Mobility was achieved by foamed rubber with built-in restraint cables at bending points, e.g., the elbows. These "soft" joints allowed for human movement for lunar surface exploration activities.

The Shuttle Suit or Extravehicular Mobility Unit (EMU) is the current suit used by NASA on "shuttle-type missions" (e.g., Hubble telescope repairs or constructing the international space station). The suit has been designed, engineered, and tested for only orbital-type activities. The major components also include the LCVG, PS, TMG, and a primary life support system. Unlike previous designs that were custom-fit suits, the Shuttle Suit is highly modularized, facilitating interconnected parts for repeated use.

2. Materials Choice Methodology

The general stages of design were as follows.

2.1 Reverse Engineering of Existing Suits

This stage included considering existing identifiable materials and why they were used. A relative comparison of the important mechanical and material properties was considered. Each design section includes the results of the reverse engineering and its influence on the final design.

2.2 Derivation of Material Index

Based on the design process derived by Ashby[4] and the results of the reverse engineering stage, the controlling material performance indices were derived. This involved modeling each component and manipulating fundamental equations to derive indices for the governing material properties.

2.3 Ashby Selection Charts

Utilizing the Cambridge Engineering Selector (CES) 4.0 software (Cambridge, UK), general search regions were graphically determined for each component. Although the Ashby charts provided excellent information for general material selection, the various layers were often too complex to rely on graphical search regions alone. The graphical method facilitated identification of "families" of materials and narrowed down the search region from thousands of materials to a few hundred. In later stages of the design process, materials were identified that had not originally been options in the Ashby charts, or the final material selected did not appear on the Ashby plot in the optimum region of the plot.

2.4 Property Limit-Based Search Criteria

Following the identification of important properties and "families" of materials, a limit-based search was completed utilizing the CES 4.0 software. The search limits (i.e., a maximum value, minimum value, or specific range) were based upon either existing suit materials or similar engineering applications.

2.5 Tabular Comparison and Weighted-Selection Criteria

Many properties not previously considered were now compared in this iterative design process. Often, these properties were not apparent earlier, or they became important due only to interactions among layers. New objectives or constraints were incorporated to ensure continuity of design along the entire suit cross-section. A relative comparison-ranking table and a "weighted" ranking table were constructed for each component, and the results were analyzed. The "weight" set for each property was based on the layer's function, objectives, constraints, and material index (from stage 2.2).

2.6 Final Selection

Final selection of the material was based on the results of the relative ranking criterion (stage 2.5) and practical assessment (processing methods, availability, etc.).

3. Results and Discussion

3.1 Liquid Cooling and Ventilation Garment (LCVG) Design

The Apollo LCVG was a bilayered fabric with a network of tubes for transporting cooling water and a "duct" system for ventilating air. This layer was closest to the skin, and heat was transferred directly to the water-cooling medium. The duct system was ineffective during actual surface activities and ended up being a weight burden. There were also concerns of excessive perspiration build-up in the LCVG. Since nylon spandex (Spandex) has poor water-vapor transportation properties, water vapor would often condense (sweat) in the layer itself near the skin. Such accumulations lower cooling efficiency and provide added discomfort to the astronaut; furthermore, large collections could damage the suit.

3.1.1 Wicking Thin Film. To address the poor wicking properties, a very thin (25 μm) thermoplastic elastomer (TPE) film was added to the Mars suit closest to the body to allow for water vapor (perspiration) to travel out, away from the skin. The TPE film, which is a monolithic membrane, was selected over common microporous fabrics (e.g, Gore-Tex) due to superior permeability, water-vapor transmission, and tear strength properties. The TPE film will not allow water to penetrate in the opposite direction, back to the skin. Thus, the thin film's function was to allow for a one-way water transport and to maintain a comfortable microclimate between the fabric's surface closest to the skin.

Sources from the medical[5] industry (among others) were used to complete a tabular comparison of the most specific mechanical and material properties of interest, which are summarized in Table 1. Determining TPE resin chemistry is critical for determining the permeability and mechanical strength of the layer. The TPE is composed of a multi-block co-polymer with hard and soft-segments that act semi-independently and can be individually engineered, designed, and selected. The soft segment largely determines the water-vapor transmission

Table 1 Liquid Cooling and Ventilation Garment (LCVG) Selection Parameters

Layer	Constraints	Objectives, Properties
TPE Film	One-way water-vapor transport "wicking" material	Maximize: tear strength, toughness, water-vapor transmission Minimize: density
SAP	Compatible with other layers	Maximize: shear modulus, swelling ratio (absorbency) Minimize: density
LCVG Fabric	Compatible with other layers	Maximize: thermal conductivity and capacity Minimize: density, linear expansion Optimize: strength, stiffness, water-vapor/gaseous transmission

(WVT) properties, while the hard segment dominates the mechanical properties.

The final TPE film selection was a co-polymer composed of a polyethylene-oxide (PEO) soft segment and polyether-ester block amide (PEBA) hard segment. A common industrial example is a TPE film brand called Walotex, manufactured by Epurex Films (Bayer) (Epurex Films GmbH & Co., KG, Walsrode, Germany). For this particular application, the film will be manufactured via melt printing lamination processing, resulting in a tough, high quality, and repairable film designed for multiple uses.

3.1.2 Super-Absorbent Polymer—Absorbent Core. Working in tandem with the TPE film is a super-absorbent polymer (SAP) that promotes wicking and increases comfort for the LCVG. The SAP is manufactured into a physical blend with fibers, such as cellulose or thermoplastic, forming an absorbent core. The core's function is to trap any condensed sweat and pull it away from the skin. This new design concept is not common to any previous suits. Super-absorbent polymers are a unique pseudo-family of polymers characterized by very high molecular mass and cross-linked with a polyelectrolyte to absorb more than ten times their mass in water.[6] Due to the uniqueness of this layer, a full Ashby-based derivation was not completed; rather, sources were used to complete a tabular comparison of the properties of interest (Table 1).[6]

A unique feature of SAPs is that the processing and synthesis essentially controls the two main properties of interest, specific absorbency (swelling ratio) and shear modulus.[6] These properties are established during polymer synthesis and are proportional to the mole percent of neutralizer used; therefore, the controlling material property for material selection became density. Final selection yielded a methacrylic acid monomer with a triallylamin cross-linker. A common industrial example is Drytech, manufactured by DOW (The Dow Chemical Company, Midland, MI).

3.1.3 LCVG Fabric Layer. Previous suits used a spandex-nylon (Spandex) bilayered fabric in the LCVG to provide a form-fitting garment, control perspiration, and allow for heat transfer. This layer could not possibly perform all these combined functions at once. Thus, earlier LCVG garments were marred by poor wicking, water absorption, and ventilation properties, which have now been addressed by the TPE thin film and SAP absorbent core. The fabric layer must perform its own desired function of conducting heat to cool the body, while providing a structural network for adhering the other LCVG components together. The fabric layer must, therefore, be compatible with the TPE and SAP. Derivation of material indices from mechanical models was performed, followed by Ashby charts analysis and tabular comparison (Table 1) of the important material and mechanical properties.

The final selection was polypropylene (PP). This material had superior moisture transport characteristics, while being low in density and adequately conductive. PP can be readily processed for this new application. For example, Quartermaster (Cerritos, CA) currently produces PP thermal uniforms for the military. The PP fabric, to the best of our knowledge, is completely compatible with the TPE film and SAP selection. Since PP exhibits some "wicking" characteristics, it will aid the TPE film and absorbent core in keeping moisture away from the skin, which helps keep the astronaut comfortable and facilitates proper functioning of the cooling system.

3.1.4 Cooling Medium and Heat Exchanger Design. The final component of the LCVG considered was the cooling system, since the micro-vacuum Mars environment would render current design for cooling sublimators useless.[7]

Cooling Medium. The function of the cooling medium is to transfer heat away from the body and reject the energy to space. The design objectives were to use a fluid with maximized heat capacity, conductivity, and minimum density. The groups of fluids analyzed included refrigerants, glycol-based coolants, and water. Due to possible health risks from leaks, both refrigerants and glycol coolants were eliminated from the material selection. Based solely on thermal and physical properties, glycol may be a viable alternative, but the non-toxic constraint eliminated the option. Water, which was used in previous suits, proved to have the best combination of thermal and physical properties, while exhibiting no toxicity concerns.

In previous suits, Tygon tubing was used. Although an exhaustive material selection and comparison was not completed, it was found that this material adequately performed the desired function and was readily available. No change is recommended.

Heat Exchanger Design. Various sources were sought for alternatives in heat exchanger design, with the patented process of Bayes et al.[8] being the most viable cooling strategy. The system is a non-venting, long-lasting, economical, and efficient heat exchanger device. It appears to be suitable for the Mars spacesuit. A phase change material (paraffin) isothermally absorbs heat energy as it changes from a solid to a liquid and is analogous to a heat sink. Subsequently, since the paraffin is housed in a special metal matrix "exposed" to the space environment, heat energy is radiated efficiently into space.

3.1.5 Final LCVG Design. The final selections for the LCVG garment are shown in the Fig. 1. The compatible PP fabric layer will be used as a backing substrate for the TPE film and is combined with the SAP to form the absorbent core. The tandem effect of the TPE film and SAP should substantially improve wicking, absorbency, and comfort of the LCVG layer. Although no changes or improvements were made in the water-cooling medium, significant changes were made in the heat exchanger assembly.

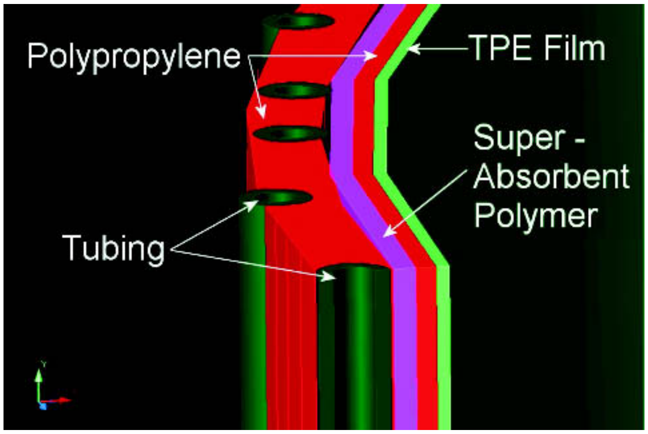

Fig. 1 Three-dimensional cross-sectional view of LCVG

Table 2 Pressure Suit (PS) Garment Selection Parameters

Layer	Constraints	Objectives, Properties
Pressure (Balloon)	Excellent barrier properties	Maximize: strength, flexibility, gaseous barrier properties
	Compatible with other layers	Minimize: density
Dampening	Compatible "backing-layer" for thin films	Maximize: strength, flexibility, heat dissipation Minimize: density
Structural	Compatible with other layers	Maximize: high strength, rigidity Minimize: elongation, density, gaseous permeability

3.2 Pressure Suit Design and Materials Selection

Several improvements have been made to the pressure suit, including the incorporation of the dampening protective layers, which were found in the TMG in previous suit deigns. A barrier material has been incorporated in the pressure suit to minimize gaseous and moisture losses to the environment.

The garment includes three layers performing three distinct functions. The inner layer (closest to the body) includes an ethylene vinyl alcohol (EVOH) film to provide a barrier to oxygen and moisture losses. This layer essentially acts like a balloon. The middle-dampening layer is made from a silicone elastomer. This material is present in case of impact and can help to absorb any external energy. The outer layer functions as a structural member to stop the balloon/ barrier and dampening layers from continued expansion, maintain a constant volume within the suit, and provide the pressure to keep the body at a comfortable level. This garment is modeled as a pressure vessel.

3.2.1 Internal Pressure Layer (Balloon Layer). The internal pressure layer functions as a barrier to eliminate gaseous and moisture losses and resists permeation of contaminants such as carbon dioxide. Polyurethane was the material formerly used. Urethanes have fairly good barrier properties to most fluids, except carbon dioxide.[9] Ethylene vinyl alcohol (EVOH) was chosen as the material for the bladder/balloon layer based on the objectives and properties outlined in Table 2. EVOH is a copolymer of ethylene and vinyl alcohol and is used as a barrier polymer in several medical and food applications.[10] Its resistance to permeation of gases is excellent, largely due to its highly crystalline structure. It is a fairly tough polymer with good flexibility and adheres easily to other layers. Commercially, it is often found in combination with a structural layer that provides strength for the EVOH film. One of the main manufacturers is Kuraray (Kuraray Holdings USA, Inc., NY), under the trade name of EVAL. A grade with high ethylene content would be recommended as ethylene increases crystallinity, which, in turn, decreases permeability.[11]

3.2.2 Dampening Layer (Shock Absorption). The function of the dampening layer is to absorb and dissipate the energy incurred from micrometeoroid impact. As shown in Table 2, the objectives of this layer include providing sufficient strength to avoid puncture from impact and acting as a "backing" layer to which the barrier (balloon) and structural layers may be adhered. The layer must be flexible to allow for mobility and dissipation of the build up of heat generated from impact.

Silicone elastomer, the material selected for the dampening layer, is a thermoset elastomer that can be molded. Investigation revealed that silicone elastomers had better dampening properties than polychloroprene (sold as Neoprene) that was formerly used in this application.[3]

Silicone elastomers are stable at room temperature and do not degrade in most solvents. These elastomers are nonconductors of heat and electricity and are resistant to oxidation degradation.[9] Natural rubber appeared to have several of the properties that would have made a good material for the dampening layer, but was likely to degrade over time and under exposure to moisture, even at room temperature.[9] Dow Corning produces a silicone elastomer under the trade name Polysiloxane (Dow Corning Corporate Center, Midland, MI).

3.2.3 Structural Layer. The function of the outer structural layer is to provide the backbone for the pressure garment and stop the balloon and dampening layers from infinite expansion. The pressure in the garment is not excessively high, but selecting a high strength material would allow for a thinner layer.

To form the pressure garment, it became important to choose a film material that can be combined with the EVOH balloon layer. Polyesters are stiff, strong, and lightweight, have good barrier properties and can be made into a fabric.[3,12] Polyester was considered as the material for the structural layer until the idea was proposed to incorporate the dampening layer (formerly part of the TMG) into the pressure garment. With this molded silicone elastomeric material as part of the pressure garment, both EVOH and PI films could then be used by adhering them to the molded silicone elastomer. Thus, the polyester fiber would then not be required.

PI elongates very little (or slightly) before it yields (excellent for this application) and has good strength.[13] Polyimides also have low permeability to gases and moisture, which acts in tandem with the EVOH and the silicone elastomer to avoid losses of oxygen and water from the suit. A polyimide composite was chosen for the structural layer. Dupont makes a polyimide film available under the name Kapton (grade VN) (DuPont High Performance Materials, Circleville, OH),[14]

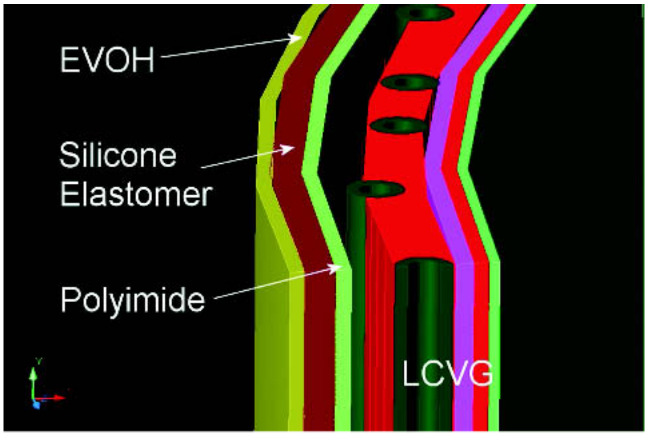

Fig. 2 Three-dimensional cross-sectional view of pressure suit (with LCVG)

which could be considered for this situation. Kapton film is very rigid if it encloses the entire bending joint (i.e., elbow), movement will be greatly impeded; therefore structural material would need to be selectively removed at the joints to allow for natural mobility. The completed structural layers for the pressure suit are shown in Fig. 2.

3.3 Thermomechanical Garment (TMG)

The TMG provides protection from excessively cold temperatures, impact, fire, heat, wear, abrasion, and chemical degradation. The insulation layer protects from thermal conduction and radiation heat losses and is composed of several thin layers of aluminized polyester. A thin layer of nylon, located between the polyester layers, allows for relative movement to avoid thermal stress buildup. A rigid-rod polymer called polyphenelyene benzobioxazole (PBZO) was found to be the best material to use for impact and fire protection. This multifunctional material replaces two separate layers on previous suit designs. A new polymer called Demron provides energetic radiation protection. Wear and abrasion protection is provided by a thermally stable nylon 6,6 (Radiation Shield Technologies, Coral Gable, FL). Finally, on the outside of the suit, chemical resistance and ultraviolet (UV) protection is provided by a fluoropolymer called PTFE that does not become brittle at low temperatures, is extremely inert, and does not degrade under UV radiation. The overall layer structure is illustrated in Fig. 3.

3.3.1 Insulation (Conduction and Radiation) Layer. The function of the insulation layer is to maintain a comfortable temperature range, even when exposed to the extreme Martian surface temperatures (down to about −120 °C). The microvacuum on Mars makes heat losses by conduction and convection less significant, and therefore, the major concern lies in radiation heat loss. Among the design objectives listed in Table 3, other important considerations included minimizing heat losses while ensuring dimensional stability through the large temperature gradients.

In the Apollo suit, three materials made up the insulation layer.[3] The thermal protection "layer" incorporated 5 pieces of aluminized polyester with 4 pieces of nylon scrim sandwiched between them. This provided protection from temperatures between −150 °C and +100 °C, as experienced on the lunar surface.[3] The astronaut on Mars has less thermal variation (between −120 °C and +20 °C), but due to the imperfect vacuum on Mars (unlike the hard vacuum on the Moon), conduction heat losses will need to be taken into account.

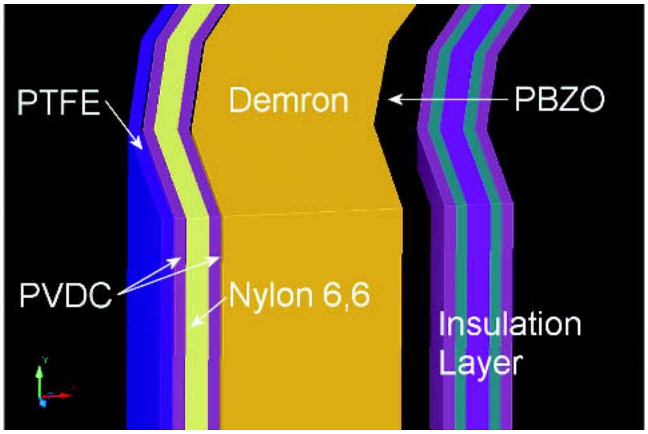

Fig. 3 Three-dimensional cross-sectional view of TMG

Researching a metal for thermal radiation protection yielded tin as the best material. Tin was reluctantly discounted because there are no referenced accounts of tin being vapor deposited on any kind of polymer; therefore, we were uncertain of the feasibility and practicality of processing tin is this manner. There are liquid precursors for depositing tin oxides on substrates,[15] so it may well be possible to coat polymers with tin via chemical vapor deposition (CVD) in the near future. Second to tin on the selection list was aluminum. Aluminum was chosen based on its high ranking, low density and because it was the only suitable metal found to be currently industrially viable for deposition on polymers.[12]

The polymer chosen as the "backing" material (and the conduction layer) must have the ability to be metallized (i.e., it must be able to accept a layer of deposited metal). The metal needs to be applied via physical vapor deposition (PVD), CVD, or sputtering to get the minimum thickness required for weight considerations. Polyethylene therephlalate (PET) was found to be the best material for the function. PET is strong, provides a good barrier to moisture and oxygen,[10] and can be extruded into a thin film of approximately 13 μm. It can be used in a wide range of temperatures (−250 to +200 °C) and is readily combined with a variety of polymers and other materials. It has good puncture resistance properties and also has good chemical resistance.[12]

Nylon was chosen to remain as the scrim material that creates a slight vacuum effect between the insulating layers to avoid heat losses (or gains) by conduction or convection. It acts like an adherent material by bringing the PET layers closer together (i.e., a vacuum), while still permitting some degree of relative movement. Because the nylon is not actually bonded to the PET, slip between the layers can slightly increase mobility. Due to the temperature gradient between the outside and inside layers of the insulating garment, linear material contraction becomes a consideration. The nylon allows layers to shift and slip across each other as temperatures change, reducing thermal stresses between layers.

Table 3 Thermomechanical Garment (TMG) Selection Parameters

Layer	Constraints	Objectives, Properties
Insulation	Stable over temperature range	Maximize: dimensional stability Minimize: heat losses, density, CO_2 permeability
Energetic Radiation	Protection for Martian radiation Stable over temperature range	Maximize: flexibility, radiation protection Minimize: density, low-temperature brittleness
Fire/ Impact	Stable over temperature range Both fire and impact protection	Maximize: projectile impact strength, fire protection Minimize: density, dimensional instability, low-temperature brittleness
Abrasion (wear)	Stable over temperature range	Maximize: dimensional stability, low-temperature ductility Minimize: density, coefficient of friction Optimize: hardness, strength
Chemical	Stable over temperature range	Maximize: chemical/UV resistance, low-temperature ductility, flexibility Minimize: density

PET might be a good barrier against most gases, but it does not provide a particularly good barrier to carbon dioxide.[10] However, PET can be co-extruded with EVOH (ethylene vinyl alcohol), which was used as the gaseous barrier on the balloon layer. Addition of a thin, 15 μm EVOH film on the outside of each layer of polyester would not increase the weight dramatically, but would reduce carbon dioxide permeation, and conduction and convection heat losses.

For safety, it was decided to use seven layers of aluminized polyester for the insulation layer. This will make an effective heat loss of about 1.5 W and the insulation layer approximately 0.6 mm thick. Dupont manufactures a polyester (PET) film called Mylar, which was used in earlier suits. Mylar (Grade M45 MC2)[16] is available from Dupont with a vacuum-deposited layer of aluminum on one side and a co-extruded layer of PVDC (polyvinyldiene chloride) for moisture protection. Ideally, minor modifications should allow for co-extrusion of EVOH (instead of PVDC) that would serve our purpose. The insulation layer overall cross section is shown in Fig. 4.

3.3.2 Impact, Puncture, Fire and Heat Protection Layer. The fire and impact layers have been incorporated into a single layer and will be discussed together. In the event of a micrometeoroid collision or a Martian dust storm, the function of the impact layer is to absorb the small projectiles, and along with the internal dampening layer dissipate the energy generated, and prevent puncture of the suit. The design objectives are listed in Table 3. Unique design considerations for this layer, which is not thermally protected by the insulation layer, include low-temperature ductility and dimensional stability. There is essentially no oxygen on Mars, but there is high oxygen content in the suit, and therefore, any contact with the oxygen, a spark, and a substance such as shuttle fuel may cause extensive damage. Protection from fire and heat degradation is the secondary function of this layer. The suit's low permeability to oxygen helps to avoid a situation where a fire may be encountered, but puncture from impact, wear or tearing might compromise this protection.

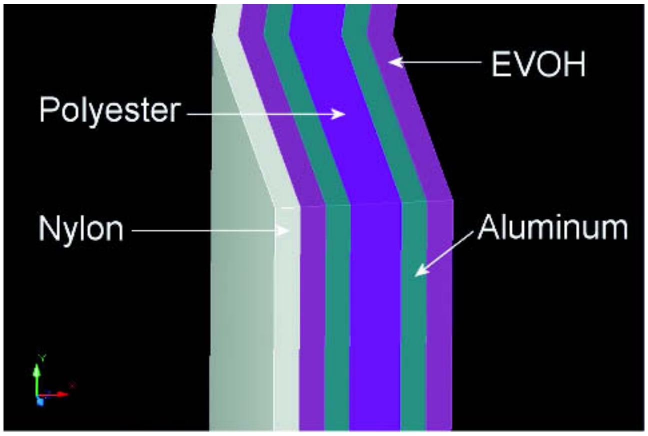

Fig. 4 Three-dimensional cross-sectional view of insulation layers

Kevlar, an aromatic polyamide or aramid, was the material of choice for the Apollo and Shuttle suits for impact protection. It has exceptionally strong fibers and the ability to dissipate great amounts of localized energy.[17] Nomex, an aromatic polyamide fiber, was used in the Apollo suit as a fire-protective layer. It has outstanding heat resistance properties, electrical resistance properties, and fairly high strength (for a polymer) and modulus, and therefore, can be used as reinforcing fiber.[17]

A family of polymers with enhanced properties has recently evolved. Rigid-rod polymers are a new innovation in the realm of high strength polymers. The polymer fibers have superior tensile properties, excellent thermal stability, flame resistance, barrier properties, low smoke generation, and low moisture sensitivity (compared with almost all other polymers). They have high dampening properties upon impact or vibration, and fatigue resistance as well.[18] PBZO (polyphenylene benzobioxazole) was chosen as the rigid-rod polymer for use in the Mars suit. It is the strongest (i.e., its fibers are almost twice as strong as Kevlar fibers) and most heat-resistant (i.e., almost twice as flame resistant as Nomex) polymer in its family. It is the only rigid-rod polymer available for industrial manufacturing. PBZO is made by the Japanese manufacturer Toyobo and sold under the name Zylon (Osaka, Japan).

3.3.3 Energetic Radiation Layer. The actual nature of the energetic radiation present on Mars remains relatively unknown, but the main radiation types believed to be present include electrons, protons, alpha, and heavy nuclei particles. Thus, this layer's function is to provide resistance to energetic radiation that may cause damage to the entire suit. Further, according to the objectives listed in Table 3, this must be a lightweight and flexible layer providing resistance to energetic radiation down to low temperatures.

Demron is a material developed by Radiation Shield Technologies (RST) (Coral Gables, FL), which not only protects against particle ionizing/nuclear radiation (such as beta and alpha), but also against x-ray and low-energy gamma emissions. In addition, Demron is non-toxic and poses no environmental disposal issues when compared with metallic lead.

While the exact composition is proprietary, this material is a polyethylene, polyvinyl chloride based composite. The metallic composition used in this composite material is unknown. Demron has a density of 2.43–3.14 g/cm^3, which is significantly lower than lead (11.34 g/cm^3) and tantalum (16.65 g/cm^3). The fabric has a rubbery appearance and has high thermal conductivity.

Shielding test results[26] indicate that two layers of Demron, with a density of 3.14 g/cm^3 and a thickness of 0.4 mm each, act as an effective radiation shield against a variety of sources. This would have equivalent shielding power as lead with a density of 11.3 g/cm^3 and a thickness of 0.2 mm. For adequate shielding effectiveness against highly energetic sources, as much as 4 mm of Demron would be required. This covers the range of radiation types that would be similar to those expected on Mars. The lower thickness of 0.8 mm would result in an overall mass of 5.024 kg, which seems reasonable when compared with the estimated mass of the overall suit, 20.88 kg. For a thickness of 4 mm, the mass contribution would be 25.12 kg to the overall suit, a considerable mass addition that would present significant weight and possible mobility problems.

Other materials used in the Mars suit offer radiation protection; for example, Kapton, Teflon, Nylon, and Mylar offer some protective value. This additive effect may lessen the amount of Demron required if implemented.

3.3.4 Abrasion (Wear) Resistance Layer. The actual nature of Martian dust remains relatively unknown, but dust storms do exist on Mars. Thus, resistance to flying debris must be considered for the abrasion layer. The function is to avoid wear due to abrasive dust that may cause damage to the TMG and the rest of the suit. Further, according to the objectives listed in Table 3, important considerations include low coefficient of friction and low-temperature toughness to avoid fracture.

In previous suits, this layer was polytetrafluoroethylene (PTFE).[3] PTFE has a very low coefficient of friction and does not degrade in almost all solvents. On the Apollo suit, PTFE was the outermost layer providing UV radiation resistance and will also be on the Mars suit to serve this purpose (see the Chemical Resistance section below). PTFE is not particularly strong and is very soft, which highlighted nylon as a viable alternative for the wear layer, should the PTFE layer be worn away. Nylon 6,6 has good strength, decent hardness (for a polymer), fairly good toughness at low temperatures, and a low coefficient of friction, and it provides good wear and abrasion resistance.[19] Nylons are hydroscopic, meaning that they readily absorb moisture. To avoid problems due to exposure to a vacuum (i.e., spontaneous boiling of absorbed moisture causing damage to the material) a layer of polyvinyldiene chloride (PVDC), an exceptionally good barrier to moisture, is suggested. This film would be adhered to both the outside and the inside of the nylon to avoid moisture absorption. PVDC can be produced in a film about 13 μm thick that would make a negligible thickness difference for the suit.[10] Nylon can be produced in several grades and by several methods. For low-temperature ductility, nylon 6,6 would be required. Dartek, a nylon 6-6 made by Dupont, should be able to provide these properties.[20] It is a readily available film, can be made into 25 μm thick layers, and can be co-extruded with other polymers.

3.3.5 Chemical Resistance Layer. The chemical resistance layer is found on the outside of the suit. The function is to protect the astronaut from hazards such as UV radiation and chemical contamination (organic and inorganic solvents) down to low temperatures (see Table 3 for all design objectives). The chemical resistance layer appeared to have been made of a polyimide film on a β-cloth in previous suits.[3] This layer also provided extra insulation and some energetic radiation protection. CES 4.0 indicated that polyimide chemical resistance is considered only "good." Polytetrafluoroethylene (PTFE) is thus, the material that was chosen for this layer. Along with being one of the most inert materials known, highly crystalline PTFE has several other useful properties. PTFE is a white (opaque) film that performs well even at temperatures of −200 °C and can shield the suit from UV radiation as the layer on the outside of the suit. To avoid dust collecting on the suit and wearing away at the surface layers, the PTFE layer provides anti-static protection and the dust merely falls off the suit instead of building up.[1] PTFE has a very low coefficient of friction, providing fairly good wear resistance. It therefore acts in tandem with the nylon wear layer beneath it.[21] A thin extruded membrane (approximately 25 μm thick) of PTFE, similar to a Gore-Tex material (Newark, DE) (PTFE processed by Gore and Associates), should be able to provide adequate protection.

3.4 Bearings for Motion

The Apollo, Gemini, and Shuttle suits achieved a reasonable range of motion by using a "soft suit," but these suits were still highly restrictive. A full range of motion is required for the Mars mission and bearings are necessary in facilitating this. The final bearing/joint design incorporates several positive attributes from various joining methods and bearing types commercially available, with a unique approach that will be suitable for the Mars atmosphere.

Bearings for the Mars suit must accommodate axial loads as well as radial loads. An axial load is required to maintain contact between the raceways and the balls so these bearings are usually fitted in pairs, either face-to-face or back-to-back.[22] The balls are contained in a cage, and each raceway has one high shoulder that supports the ball under axial load. The joint/bearing apparatus for the Mars suit makes use of a novel design approach to achieve weight savings while incorporating a disconnection point, to allow the astronaut to don the suit, and a rotational bearing all in one functional unit. The bearing/joint apparatus requires a suitable materials selection process for three individual components, an outer bearing ring, an inner bearing ring, and several inner compression rings, as shown in Fig. 5.

3.4.1 Compression Rings. The main function of the compression rings is to serve as the immediate joint connection between the fabric layers and the bearing apparatus. They are fitted into the bearing apparatus, under constant compression from the outer bearing ring, and feel a constant internal pressure of 25 kPa from the internal environmental system. Thus, among other objectives listed in Table 4, compression strength and fracture toughness must be maximized. The constraints are that the material selected should have low thermal conductivity and thermal expansion to allow for compatibility with the fabric layers while remaining impermeable to the internal O_2 en-

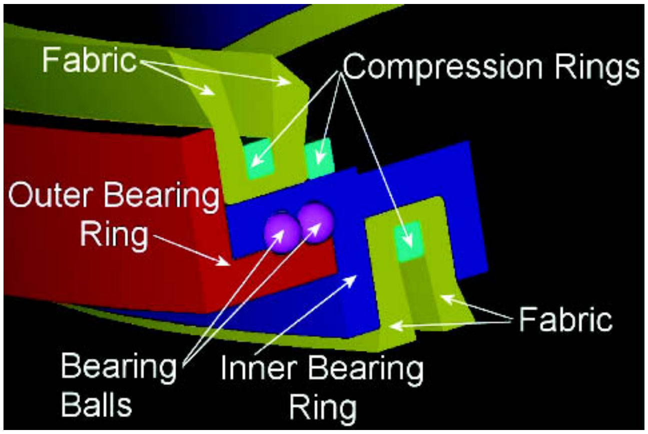

Fig. 5 Bearing apparatus

Table 4 Bearing Apparatus Selection Parameters

Component	Constraints	Objectives: Properties
Compression Ring	Impermeable to gases	Maximize: compressive and tensile strength, fracture toughness Minimize: density, thermal conductivity and expansion
Outer Ring	Austenitic transition finish temperature below −120°C Non-ferrous alloy	Maximize: yield strength, UV stability, flammable resistance Minimize: density, emissivity
Inner Ring	Low thermal conductivity and expansion	Maximize: yield strength, wear resistance, toughness Minimize: density, thermal expansion and conductivity

vironment. Polyetheretherketone (PEEK) + 60% carbon fiber (CF) exhibited the best overall property-based ranking. PEEK/CF composites are used for seal ring and bearing materials and have inherently good wear and abrasion resistance. This material has excellent corrosion resistance and very low moisture absorption, while O_2 permeation is not an issue with PEEK/CF.[23] The addition of carbon fibers in compression molding enhances the compression strength, stiffness, and coefficient of thermal expansion.

3.4.2 Outer Bearing Ring. The outer bearing ring serves three main purposes. The main function is to provide structural rigidity to the bearing apparatus by applying compression to the inner bearing components. Secondly, it serves as a joint connection between the fabric layers and the bearing assembly. Finally, it provides a disconnection point for all major components to allow the astronaut to don the suit. The bearing design incorporates a shape memory alloy (SMA) that utilizes a "memory effect" to recover a particular shape upon heating through the transformation temperature range. The ring is constructed to the desired size in the austenitic phase at room temperature. The ring is then trained, or expanded, in its soft, more ductile, martensitic phase. Upon heating through its transformation temperature range, or the hysteresis temperature loop, the SMA undergoes thermal shrinkage and recovers its previous size. The material will be used in the austenitic phase for the full range of Mars conditions.

Table 5 Material Properties for Outer Bearing Ring [25]

Property	NiTi	CuZnAl	CuAlNi
Transformation Temperature (Low), °C	−200	−180	−140
Transformation Temperature (High), °C	110	200	100
Hysteresis Temperature	30	20	17
Melting Temperature	1300	970	1025
Density, g/cm^3	6.45	7.64	7.12
Corrosion Performance	High	Medium	Medium
Young's Modulus austenite, GPa	83	72	85
Young's Modulus martensite, GPa	35	70	80
Yield Strength austenite, MPa	443	350	400
Yield Strength martensite, MPa	120	80	130
UTS austenite, MPa	895	600	500

Along with the objectives listed in Table 4, the material selected must have an austenitic finish transition temperature below −120 °C to always remain fully austenitic. Also, the SMA needs to be non-ferrous so it does not attract the electrostatic and magnetic Martian dust.

Property evaluation performed on three SMAs (NiTi, CuZnAl, and CuAlNi) revealed that NiTi was by far the superior material for use as the outer bearing ring. It has superior corrosion resistance (comparable to an austenitic stainless steel), lower density, higher yield, and ultimate tensile strengths than both CuZnAl and CuAlNi, as shown in Table 5.[25] The SMA will be constructed and set to the desired shape in its austenitic condition and trained (or expanded) in its martensitic phase. While in the martensitic phase, the layers of the suit and the bearing assembly will be secured in place. Heating through its transformation hysteresis, the SMA will undergo thermal shrinkage, up to 8%. After this point the NiTi will be fully austenitic.

3.4.3 Inner Bearing Ring. The main function of the inner bearing ring is to serve as the connection point between the fabric layers and half of the bearing contact surface. This component will have two raceways in which the ball bearings sit. This is one half of the rotational surface, with the other half being the outer bearing ring.

The design objectives (Table 4) are aimed at maximum strength per unit volume, with design constraints to ensure compatibility with the fabric layers. Ti-Be alloy exhibited the best overall ranking, with Mg-CF coming in as a close second option. Ti-Be alloy density was almost double that of the Mg-CF composite. Weight savings are crucial to the overall design of the suit, and the Mg-CF alloy appears to have adequate properties in all other categories and is, therefore, considered the material of choice for the Mars spacesuit. The Mars atmosphere is void of any moisture, so corrosion should not be a concern.

3.4.4 Overall Bearing Apparatus. The final selection of the bearing materials included a PEEK-CF composite for the compression ring, a nickel-titanium shape memory alloy for the outer bearing ring, and a Mg/Al/CF composite for the inner bearing ring. A three-dimensional representation of the overall bearing apparatus is shown in Fig. 6.

To improve bearing capabilities, a Teflon coating is often

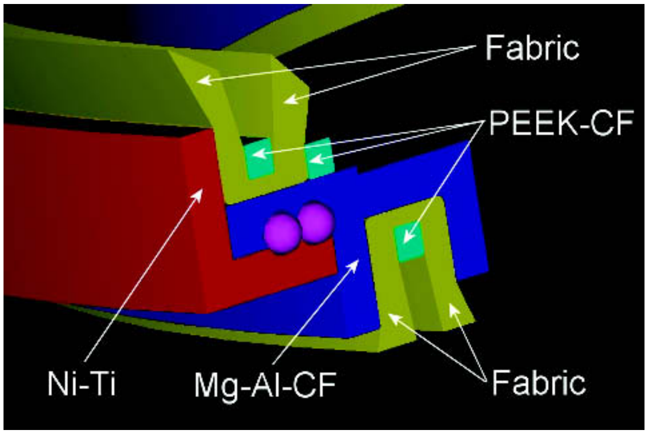

Fig. 6 Final bearings materials selection and three dimensional view of bearing

used to minimize the coefficient of friction. The coefficient of friction of Teflon is lower than that of graphite, MoS_2 or any other known solid lubricant, and it is also stable in vacuum conditions.[24] In addition, this outermost bearing Teflon coating could eliminate electro-static dust buildup, improving bearing performance.

3.4.5 Range of Motion Considerations. The design of the Mars spacesuit takes into consideration that the astronaut will need to perform surface activities. The range of motion required includes the ability to walk, bend over, and flex all major bodily joints, while expending a minimum amount of energy and muscular force. To allow for a wide range of motion, each layer in the spacesuit is optimized for flexibility, thickness, and mass. Rotational bearings are located at the following strategic positions: the waist to permit pelvic rotation and slight tilt, the shoulder to permit shoulder and upper arm rotation, the upper arm (located slightly above the elbow joint) to facilitate arm revolution and on the lower arm (located slightly above the wrist joint) to allow for wrist rotation. Pleats will be located at the following locations to allow for flexing of the major bodily joints: elbows, shoulders, knees, thighs, and ankles. The pleats allow for localized build-up and expansion of the fabric material, analogous to an accordion, thus facilitating natural movements. The innovative "constant volume joint design"[27] that utilizes unique interactions between the pressure suit balloon and structural layer also drastically improves the range of motion for space suits.

4. Conclusions

The design purpose was to facilitate walking and exploration on Mars. The scope included materials selection and design of three multilayered functional garments—the LCVG, PS, and TMG—and permitting motion via addition of joints, bearings, and pleats.

Few original Apollo or Shuttle suit materials remain for insulation and protection from micrometeorites, Martian dust storms, and energetic radiation. Innovative design and material selection and the use of a shape-memory alloys have facilitated development of prototype bearings.

The layers are compatible with each other and, hence, provide a cumulative effect to perform the required functions. For example, the pressure layer also provides dampening, the chemical protection layer also provides wear resistance, and the fire retardant layer also provides impact resistance.

The overall mass of fabric layers and bearings was calculated as 20.88 kg. This mass is reasonable compared with current prototype "concept" suits and represents a significant weight savings over previous Apollo and Shuttle suits. The total thickness of the Mars suit is estimated to be 4.81 mm (0.1893″). Current Mars prototype suits are estimated to be approximately 4.76 mm thick (0.1875″).

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