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Spacesuits and EVA Gloves Evolution and Future Trends of Extravehicular Activity Gloves / SEYED MOUSAVI, MOHAMAD MEHDI; Ambrosio, Elisa Paola; Appendino, Silvia; CHEN CHEN, Fai; Favetto, Alain; Manfredi, DIEGO GIOVANNI; Pescarmona, Francesco; Soma', Aurelio. - ELETTRONICO. - (2011). (Intervento presentato al convegno International Conference on Environmental Systems tenutosi a Portland, Oregon nel 17 - 21 Luglio 2011).

Availability:

This version is available at: 11583/2460635 since:

Publisher:

Published

DOI:

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Spacesuits and EVA Gloves Evolution and Future Trends of Extravehicular Activity Gloves

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The total time of Extravehicular Activity (EVA) performed by astronauts has increased significantly during the past few years. On the other hand, the bulk and stiffness of the suit itself and in particular of the gloves generate some difficulties for the astronauts to perform their tasks in space. Therefore, it is necessary to improve the EVA glove technology for future needs. Since a lack of categorized information for those who want to improve EVA gloves is evident, in this work a survey on related literature has been carried out and fundamental data has been categorized. The paper starts with an overview on the historical and chronological progress of EVA suits and EVA gloves followed by a review of the previously demonstrated EVA gloves including American and Russian ones. The remaining part of the paper is dedicated to the characteristics of current EVA gloves and to present and future trends in research for further improvements.

I. Introduction

ONE of the most promising topics in space related research is the astronaut's Extravehicular Activity (EVA) spacesuit. In particular, this is true for the glove, which is one of its most important parts. There are many published texts that describe the research of space agencies in different countries which cover the phases of basic and detail design, quality control and development of the final product.^{1,2} During the past decades, due to the political and economic importance of space science, most of the related information remained concealed. Recently, after declassification of part of this material, a huge amount of information has been made available for independent research centers. Subjects such as glove parts and number of layers, thickness and material of each layer, material properties and specifications and many other issues can be found in literature but not in a classified manner. Those aspects are discussed and reviewed in this paper, which gathers the related data from different sources.

In the first part of this paper, some manned space programs in which the spacesuits were used are described. Furthermore, a chronology regarding the spacesuits and the EVA gloves is presented, thus allowing readers to better understand the paper.

II. Spacesuits History

Spacesuits have developed over many years from the early prototypes used in the first space missions to the complex and highly technological suit worn by today's Space Shuttle and Space Station astronauts. Tasks such as the Hubble Space Telescope maintenance and the International Space Station assembly and servicing show the importance of spacesuits. As many as 154 EVAs were conducted from March 1965 to April 1997 in different U.S.

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and U.S.S.R./Russian projects.³ Being a critical component, the EVA spacesuit has continuously been under development. The following sections illustrate the development of the spacesuits briefly.

A. A Brief History of U.S Spacesuits

Before NASA's current shuttle program officially called Space Transportation System (STS), other important manned space programs were carried out by the United States: Mercury, Gemini, Apollo, Skylab and Apollo-Soyuz, each one consisting of several missions.

The Mercury project was the first U.S. manned space program and had six missions between 1961 and 1963. However, the first U.S. spacewalk was done during the Gemini Program, which consisted of a total of ten missions between 1965 and 1966. In 1967, the Apollo program, one of the most important achievements in aerospace history, started. The main goal of this project was to fulfill the request of President John F. Kennedy to land a man on the moon and return him back to Earth. Between 1967 and 1972 twelve missions were performed and Neil Armstrong was the first person ever to walk on the moon. The fourth important U.S. manned space program was Skylab during which the first space station was launched in 1973. Until 1974, four missions were carried out in this project. A joint program between two space agencies from different countries with different languages was the fifth manned space program, Apollo-Soyuz. The main objective of this project was to safely dock together an Apollo spacecraft and a Soviet Soyuz spacecraft. The Apollo-Soyuz mission was completed in 1975.^{4,5}

Much effort has been made since 1933 in order to create a proper suit at first for plane pilots and later for astronauts and this effort led to United States Shuttle Extravehicular Mobility Unit (EMU) and the Russian Orlan-M, two EVA suits that are currently in operation.

After tests performed during the Mercury project, it was found that a pressure of 3.5 psi (24.13 kPa) is a sufficient internal pressure for the suit if the wearer breathes pure oxygen. However, the Mercury suit was worn only inside the spacecraft.⁶ It contained a gas bladder layer that confined 5 psi (34.47 kPa) of pure oxygen inside the suit, along with an aluminized nylon film to prevent inner layers of the suit from expanding. Since this suit was designed specifically for the case of pressure loss inside the Mercury capsule, later designers tried to improve the suit to serve not only as a pressure back up but also as an escape and EVA suit for the Gemini project. By substituting the fabric joints with a new construction of bladder layer and a nylon netting layer, the new suit had better flexibility and was more comfortable.

Walking on the moon in the Apollo mission required some new features to be added to the design of previous spacesuits. Also, in this case, the suit was a backup pressure system and had to be worn not only during the EVA but also in the space capsule. The wearer had to be able to pick samples up from the surface of the moon and this could not be achieved without a more flexible suit. Moving around freely without dragging an inconvenient oxygen line to the capsule would have been impossible without a self-contained Primary Life Support System (PLSS). To solve the problem of removing heat and moisture from the suit, a water cooling system was used instead of the former gas one. The Apollo suit was also a protection against heat and cold, micrometeoroids, wear and tear. Its bellow-like joints provided a better mobility than ever.

About six months after the last Apollo mission to the moon, NASA launched its first space station, Skylab. The suit that was used for the Skylab program was a simplified version of the one used in the Apollo missions. Since in Skylab crewmembers were connected to the station during EVA, there was no need to add a PLSS to their suit.

After Skylab, NASA decided to change its launching vehicles in space exploration from expendable launch vehicles (Rockets) to reusable ones (Space Shuttle Systems). According to this new approach a reusable EMU was also considered as a suitable option for spacesuits. Moreover, in the Shuttle program, spacesuits were composed of many standard size parts suitable for a wide range of body sizes. Furthermore, in comparison to the previously developed multi-function suits, single task shuttle spacesuits caused designers to concentrate on a single function of the spacesuit, EVA.^{4,5}

B. A Brief History of Soviet Union/Russian Spacesuits

On the other side of the World, the Soviet Union manned space activities started in the late 1950s. At that time, the Zvezda factory, a provider of safety equipments for the crews of aircrafts, was also directed to spacesuit development.

The first EVA ever was performed by the soviet astronaut Aleksey Leonov in 1965. His suit was called Berkut and it was an improved version of an Intravehicular Activity (IVA) suit that was called Vostok Sokol-1. It had the dual purpose of protecting the crew in case of cabin decompression during IVA and to support EVA periods. In this suit pressure could be set at either 5.88 psi (40.54 kPa) or 3.97 psi (27.37 kPa). An incorporated dual bladder was used in Berkut to protect astronauts if one bladder got punctured. In this case the second bladder would automatically inflate.^{7,8}

Yastreb is the name of the suit that was used for the Soyuz program. This pressure suit was planned for the Soyuz docking project in 1965. The most important differences between the Yastreb and Berkut spacesuits were the functions of these two suits. The Yastreb was designed for just the space walk and had to be donned aboard an orbiting vehicle therefore it was improved to ensure unassisted donning in orbit before an EVA.^{8,9}

In 1965 work also started on the development of hardware for the new lunar program, and the next generation of the soviet EVA suits (Orlan) that were designed to be used on the surface of the moon. This type of suit was never used for walking on the moon but was later adopted to work in the Soviet space station. This adoption was made in four phases in which the first Orlan lunar suit changed to Orlan-D, Orlan-DM, Orlan-DMA and finally Orlan-M.

The Orlan-D was used for an EVA in December 1977. In comparison to the lunar EVA suit, Orlan-D was designed to remain in the space station for 2 years and for several missions while the Orlan lunar suit was planned to be used only in a single mission. The inside pressure of this series was 5.8 psi (40.54 kPa). The most distinctive features in comparison with the Orlan lunar suit were a hard torso, adjustable soft limbs, and simple self-donning via a hatch in the back.

The Mir space station was a Soviet and later Russian space station, which was operational in the Earth's orbit from 1986 to 2001. The station was the first consistently inhabited long-term research station in space and was operated by a series of long-duration crews. For this station, Orlan-DM spacesuit series was used. Some improvements in control, material strength and mobility of the Orlan-D led to the Orlan-DM.

The Orlan-DMA was the third model of the Orlan spacesuit. Like other models of Orlan suits it had a hatch in the back of its hard aluminum alloy torso. Better mobility was achieved by using a new composite fabric that was lighter and tougher. It had some adjustable belts that could be adopted for different body sizes. It had improved gloves for better hand mobility. The minimum and maximum operating pressure of this suit was 3.8 and 5.8 psi (26.20 and 40.54 kPa) respectively. Like the Orlan-D and Orlan-DM suits before it, the Orlan-DMA had dual polyurethane rubber pressure bladders, one inside the other. The inner bladder inflated only if the primary layer got punctured. Like earlier Orlan models, the Orlan-DMA cooling garment used a liquid-cooling system.

The final variant in this series is the Orlan-M, first used at the Mir space station in 1997 (Fig. 1). The Orlan-M constituted a modest upgrade of the Orlan-DMA. The most noticeable additions were a second visor on the top of the helmet, and bearings in the upper calf area of the legs. Its slightly higher operating pressure (5.9 psi; 40.7 kPa) was not a hindrance, nor did the crew report any increase in fatigue. Crews also reported that the new Orlan-M gloves (Fig. 2) were easier to use than the Orlan-DMA gloves.¹²



Figure 1. Orlan-M spacesuit system¹⁰

C. An overview of Mechanical Counter Pressure (MCP) Spacesuits

Recently, the Mechanical Counter Pressure (MCP) approach has been considered as an applicable solution for problems of EVA suits. This new approach that has been suggested by some researchers can dramatically reduce the problems of conventional full-pressure EVA suits and gloves. The idea is to deliver oxygen only to the isolated helmet, while pressure is applied to the torso mechanically by utilizing tight, form-fitting garments to physically compress the body rather than pressurize it with a gas.

In 1968, Paul Webb first demonstrated a complete elastic MCP suit.⁴ This MCP suit had seven layers of highly elastic material and showed major advantages. However it was never fully developed, it had more mobility and dexterity and less metabolic costs for movement. Its excellent heat dissipation quality alone promises significant reductions in the mass and complexity of PLSS in comparison with the current EVA suits that require a cooling garment. While it saves weight by eliminating stored coolant and cooling tools, it is inherently safer because punctures and tears will not cause the loss of pressure that is a risk with current EMUs.^{4,13} Between 1967 and 1971, several journal articles were published by Webb and Annis but this line of study was cancelled with the demise of the Apollo Program.^{4,14,15}



Figure 2. Orlan-M EVA Glove¹¹

During the evolution of U.S. EVA gloves, improvement basically focused on changing the materials, whereas the basic design of the gloves remained unchanged. This improvement started from the Mercury program and later led to the 1000 Series, the first Shuttle EVA gloves. This process continued until the Phase VI gloves when the procedure of creating the EVA gloves changed completely. These changes were basically due to the high-tech facilities that did not exist before. Stereo lithography prototyping, laser cutting and laser scanning technology, 3D computer modeling and CNC machining were all new technologies that helped designers to produce better products.

There is not much information in literature about the EVA gloves prior to the 4000 series. The 4000 series were introduced into the flight program in 1985 as an improved version of the 3000 series glove. At first the 4000 series (Fig. 3) had nine standard sizes but later custom-sized gloves were produced for some special cases. The current EMU glove is based on the 4000 series and the fundamental approach has remained the same.

After the 4000 series the Phase IV gloves were developed. By the refinements of bladder and restraint designs, tactility of the fingertips was improved and a better fit was achieved. However, the Thermal Micrometeoroid Garment (TMG) remained basically unchanged from the 4000 series glove. In addition, the glove hand design included a custom formed, high strength palm bar and a segmented palm plate to make the palm of the pressurized glove match the natural shape of the hand. This provided a more conformal fit and still allowed some flexibility in this area due to the palm plate segmentation. The wrist of the Phase IV glove was developed as a four ring rolling convolute joint; this configuration provided a nearly constant volume during manipulation of the joint thus promoting a low torque and stable motion.¹⁸

The next series of EVA gloves was the 5000 series. The main difference with the previous design was in the wrist joint. Although this new glove needed low torque to follow the astronaut's wrist, its steel components made it heavy in the wrist in comparison to the previous series. In this period new technologies such as Laser scanning and Stereo Lithography Apparatus (SLA) were used to some extent in developing the 5000 series. With this advancement, the reproducibility of the glove design was greatly enhanced. Later, in developing the Phase V glove these technologies were used more and more to improve the design and fabrication process; more accurate scanning was possible and data output became more readily useable by advancing computer aided design (CAD) softwares. More complex surface models were made possible as a result of 3-dimensional modeling and Non-Uniform B-Spline capabilities including in the new CAD softwares. Weight was reduced by using titanium and graphite/epoxy composite materials and



Figure 3. 4000 Series Glove Assembly¹⁸

III. EVA Glove History

Among different parts of a complete EVA suit, gloves have significant effects on the ability of astronauts to perform various tasks. Although other spacesuit parts such as the helmet, boots and PLSS are also important, we have to consider that most tasks that astronauts have to perform require the use of their hands. Many comments received from astronauts show their desire for a glove that stays in place, allows gripping without significant extra effort, and provides an acceptable level of dexterity and feedback.¹⁶ Much effort to improve EVA gloves has been performed during the evolution of EVA suits and these attempts have led to some results but more work is needed to meet the increasing demands of space exploration.

ILC Dover is the name of a U.S. company that started designing suits and gloves in 1961 and delivered its first suits for use by the Apollo astronauts in 1966. This company is still the main provider of spacesuits and EVA gloves for NASA.¹⁷



Figure 4. Phase VI Glove Assembly¹⁸

bearings were replaced with bushing assemblies.

Subsequently, a new request in basic design of astronaut suits caused a change in the main structure of the glove and led to the Phase VI gloves that are in operation now (Fig. 4). The wrist of the glove is fabricated from soft materials. By reducing unneeded insulation, overall TMG performance has been further increased. The use of lightweight polyester fabric has enabled the design of fingers and thumb mobility joints as in all fabric assemblies to decrease torque and increase fingertip tactility. By closely fitting the hand, finger and thumb joint torque is reduced and overall comfort is achieved.¹⁸ Furthermore, the glove TMG has incorporated features to allow on-orbit replacement of a damaged or worn-out TMG.

Phase VI gloves were used in a real space mission in 1998 for the first time and good results were reported. Under the Phase VI Implementation Program, Phase VI flight gloves are currently being fabricated and have been delivered for 57 EVA crewmembers.¹⁸

Finally, it should be mentioned that the Phase VI glove program represents the culmination of glove development efforts proceeding the Mercury and Gemini programs. Moreover, lessons learned from the Apollo program have had many effects on this improvement. A number of companies such as ILC Dover and David Clark Co. (DCC) have tried to push EVA glove technology forward. Phase VI gloves are the outcome of improvement in the 4000 series, the Phase IV, the 5000 series and the Phase V and the result of all these efforts is that Phase VI gloves are in space today.

IV. EVA Glove Construction and Details

According to ILC Dover, the thickness of a spacesuit is approximately 3/16 inches (4.8 mm) and it is fabricated by sewing and cementing 11 layers of different materials. Moreover, some metal parts are used to join different parts of the suit together. This is very similar for the EVA gloves, but nevertheless some layers of the gloves are different from those of the suit; for example the cooling garment does not extend on to the hands. Furthermore, there is not a unique cross section for different parts of the glove TMG.¹⁷

Basically, the glove includes three elements. Starting from the hand, we can find the bladder, the restraint and the TMG. The bladder is the first layer of the glove and is designed to maintain the pressurized environment of the glove. The restraint is the next layer of the glove and is responsible for carrying all pressure and man-induced loads during operational use. The TMG is the final, outer layer of the glove and its function is to provide a buffer from thermal swings and to guard against the impact of hyper-velocity, micrometeoroid particles. Wrist movement is possible by using a rotary bearing for rotation and a wrist joint for the flexion and extension of the wrist. Finger movement is allowed by using fabric joints for all fingers. Some fingertip heaters and also a heater pad are used to protect the hand from extreme hot and cold extravehicular conditions. Gloves are attached to the arms at the wrist disconnects.¹⁹

The Phase VI glove principally differed from the 4000 and 5000 series in that it is the first EVA glove to be completely developed with the use of computer aided design. This has resulted in a faster development cycle, higher accuracy and lower costs. An ILC developed laser scan process provides a 3D data of crewmembers' hands, which can quickly and inexpensively produce molds for conformal fit. The 3D model can easily be adjusted to obtain an optimum fit. The conformal fit provides minimum volume, thus reducing the effort required to perform work. Utilizing pleated, lightweight polyester fabric, the fingers and thumb mobility joints are designed as all fabric assemblies to decrease torque and increase fingertip tactility. Moreover, the Phase VI glove uses a one-piece urethane bladder design that exhibits little to no wrinkling when integrated into the glove; thus it significantly improves the fit and performance. Mimicking the shape of the restraint, the bladder provides the conformal pressure-retaining layer of the glove. Furthermore, it features a lower torque wrist bearing and an enhanced rolling convolute wrist joint using a two gimbal ring system that is tightly integrated to the wrist softgoods for reduced effort in use.

Above all, it has improved reproducibility through its reduced wrist complexity as compared to the 4000 and 5000 Series wrist. Finally, it utilizes a revised attachment method for rapid on-orbit replacement of a damaged or worn-out TMG.

In order to meet the thermal challenges of ISS assembly, the Phase VI glove has also been designed to include improved insulation and an active heating system. Using the geometry of the subject's hand, felt insulation has been placed in areas of prime surface contact. This includes selective areas of the palm and the fingertips. By reducing unneeded insulation, overall TMG performance has been further increased. The Phase VI glove incorporates an active heating system that consists of resistive element heaters located at the fingertips. This system originated as a 3-volt system designed to operate off remotely located battery pack. A recent battery redesign has resulted in the evolution of the heater system to a 12-volt design.²⁰

As mentioned above, the inner layer of the Phase VI glove is the pressure-retaining bladder. The bladder is made of nylon that is dipped in rubber (urethane) at least six times to create an impermeable barrier between the inside pressure of the spacesuit and the vacuum of space outside of the suit. A layer of Dacron restrains the pressure bladder.

Nylon (Polyamides) can be drawn to fibers as fine as silk and was widely used as a substitute for it. There are many grades (Nylon 6, Nylon 66, Nylon 11), each with slightly different properties, but in all cases nylon is a good thermal and electrical insulator. Moreover it exhibits excellent abrasion resistance and high resilience, and it melts instead of burning. On the other side nylon is hygroscopic, and for this reason it must be coated with neoprene.²¹⁻²⁶

Dacron is a polyester fiber made from ethylene glycol and terephthalic acid. It can be made in all of the fiber forms and in the same denier ranges as Nylon. It can also be made into knitted and woven fabrics. The important physical properties of Dacron are high wet and dry strength, high abrasion resistance, high flex life and resistance to heat, chemicals and organic degradation.²⁷

The inner lining of the TMG is a layer of Neoprene, coated with Nylon Ripstop.

Neoprene (polychloroprene) is a family of synthetic rubbers and in general has good chemical stability, and maintains flexibility over a wide temperature range. Neoprene is a multipurpose elastomer that has a balanced combination of properties. All types of Neoprene have these inherent characteristics: resist degradation from sun, ozone, and weather, perform well in contact with oils and many chemicals, remain useful over a wide temperature range, display outstanding physical toughness, are more resistant to burning than exclusively hydrocarbon rubbers.²⁸

Ripstop fabrics are woven fabrics often made out of nylon, whilst using a special reinforcing technique that makes them resistant to tearing and ripping and are commonly used for camping equipment such as tents and the outer shells of sleeping bags. Ripstop nylon is a light-weight nylon fabric with interwoven ripstop reinforcement threads in a crosshatch pattern. Ripstop nylon may be waterproof, water resistant, fire resistant, or have zero porosity (will not allow air or water through). Ripstop nylon is the primary material used in hot air balloons. Advantages of ripstop are the favourable strength-to-weight ratio and that small tears can not easily spread.

Five layers of aluminized Mylar for heat protection mixed with four layers of thermal insulator spacer fabrics of non-woven Dacron with low heat transfer coefficient are on top of the previous layers and offer thermal protection. When the TMG is used in the near vacuum condition of space, its several layers act like a vacuum flask. If an object with a surface temperature between -118° and 113° C presses the external surface of the glove with 1 psi (6.89 kPa) pressure for 30 seconds, the STS Extravehicular Mobility Unit glove can maintain the crewmen's skin temperature between 10° and 38° C.^{17,19}

Mylar is the trade name of Biaxially-oriented Polyethylene Terephthalate (BoPET) patented by DuPont in the early 1950s. Mylar polyester film exhibits good resistance to the action of many chemical reagents, solvents, impregnants, and varnishes. It is relatively insensitive to moisture absorption. It absorbs less than 0.8% moisture when totally immersed in water for 24 hr (ASTM D-570-63). Mylar polyester film retains good physical and mechanical properties over a wide temperature range (-70 to 150°C). However it can be aluminized by vacuum depositing to reduce its permeability, and to make it reflective and opaque. This was first developed by NASA in 1964 for the US space program, and it is able to reflect up to 97% of radiated heat.²⁹ Also, the stiffness, stability and strength of Polyethylene Terephthalate (PET) films increase when coated with Al.³⁰

Micrometeoroid/Tear protection layer is the outermost layer of glove TMG. It is an Ortho-Fabric which is a blend of Teflon/Gore-Tex, Kevlar, and Nomex. The Ortho-Fabric is particularly good for thermal control and for protecting the pressure bladder and the pressure restraint layer from micrometeoroids.

Teflon is a well known DuPont brand name for polytetrafluoroethylene (PTFE). Its tensile strength is up to 23.5 MPa, elongation 250 to 350% and melting point of 312°C. It is water resistant and highly chemical resistant. As a coating, it gives hardness and abrasion resistance.^{22,29} Also, Gore-Tex is a PTFE-based material. It is a waterproof but breathable fabric. Gore-Tex fabric is best known for its use in protective, yet breathable, rainwear.

Kevlar is the registered trademark developed at DuPont. This high strength material was first commercially used in the early 1970s as a replacement for steel in racing tires. Currently, Kevlar has many applications ranging from bicycle tires and racing sails to body armor because of its high tensile strength-to-weight ratio; by this measure it is 5 times stronger than steel on an equal weight basis. When Kevlar is spun, the resulting fiber has a tensile strength of about 3,620 MPa.³¹

Nomex is also a registered trademark developed at DuPont. Unlike Kevlar, Nomex cannot align during filament formation and has poorer strength. It has excellent thermal, chemical, and radiation resistance. Nomex products are well known for their excellent abrasion and flame resistance.²² This is due to a melting point above the decomposition temperature, an ignition point above 600°C and a flash point above 800°C. Since they char on exposure to a flame, they provide protection from the flame for a period of time for example in Formula 1 car race drivers suites.²⁴ As mentioned above, the glove TMG has different cross sections to allow better mobility of the hand, abrasion resistance, and thermal protection. Usually these different sections are Finger Tip, Finger Back, Finger Front, Palm, and Gauntlet areas. The Glove thermal garment is illustrated in Fig. 5.¹⁹

The Finger Tip is composed of Room Temperature Vulcanized (RTV) silicon 630, RTV 157, Nomex Fabric and Nomex Felt. RTV Silicone is a type of silicone rubber made from a two-component system, base plus curative. For abrasion protection, RTV 157 and to enhance fingertip tactility and also protection of the fingers RTV 630 are used for the glove fingertip. As mentioned above, the Nomex Felt is a thermal and abrasion protecting layer and the Nomex Fabric is a very strong, durable fabric that adheres to the RTV.

The Finger Back is made of these four materials: Teflon for abrasion and thermal protection, three layers of Mylar to reflect the radiations of the Sun which are separated with scrims as insulator, and finally Chiffon that is a abrading protection layer for Mylar.

The Finger Front is composed of RTV 157 and Nomex fabric; RTV 150 to enhance gripping capability, tactility and thermal resistance of the glove and Nomex fabric for its excellent wear and adhesion properties.

The Palm is made of RTV 157 as abrasion resistance to enhance tactility, the Nomex Felt as a thermal and abrasion protecting layer and the Nomex Fabric as a very strong, durable fabric.

Finally the Gauntlet is composed by two materials. The reinforced Mylar serves the same purpose as in the Finger Back, but is reinforced for greater durability and Teflon that provides abrasion resistance and protection.¹⁹

In August 2007, a cut glove incident, which caused an early end to an EVA, occurred during a spacewalk. The damage was later confirmed as being caused by contact with a sharp edge. In 2009, some protective layers, acting as a patch, were added to a new TMG glove in areas that receive the most wear and tear. This new TMG glove gives added protection against cuts with implementation of a new RTV 3145 and a special “Turtleskin” reinforcement layer which is sandwiched between molded palm and RTV coating on thumb and index finger. RTV 3145 exhibits greater peel adhesion than previous one and Turtleskin shows a significantly higher cut and puncture resistance than the knit Vectran currently used in the glove palm (two to four times more cut resistant than the Phase VI glove knit Vectran).

V. Future Trends

In subsequent interviews with astronauts who have returned from space missions, there is a consensus about several problems of their gloves such as reduced dexterity, lack of adequate tactility and feedback and hand fatigue. But these are not the only reasons for future improvements of the EVA gloves. According to a 2005 study, of the 350 EVA training injuries reported between 2002 and 2004, nearly half were hand-related. For instance, one of the most common types of injury reported by astronauts involved in EVA work is known as fingernail delamination, in which the nail completely detaches from the nail bed. Moreover, growth of bacteria inside the gloves can be a major problem during an EVA, which can last upto several hours each day.³²

Several suggestions are offered to solve such problems and these suggestions form the future characteristic of EVA gloves. The first step to overcome

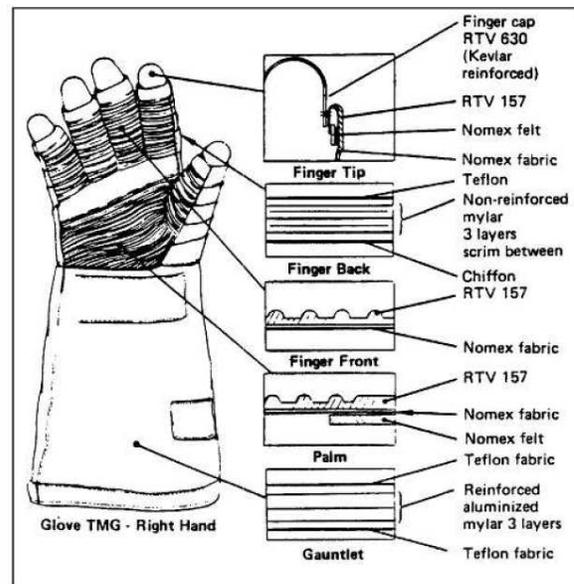


Figure 5. The Glove Thermal Garment¹⁹

the problem of reduced dexterity and hand fatigue is a more accurate evaluation of EVA glove effects on hand strength and performance. Even though some work has already been done in the past, literature from 2009 to the present has shown a growing interest in this subject in order to develop the requirements for improvements in the design of the next generation of EVA gloves.³³⁻³⁸ Furthermore, customization and careful fitting of the gloves or exercise and training of the hands before the missions to prepare them for extended-duration EVAs have also been proposed in some papers to solve this problem.¹⁶ Maybe the increased attention given to the MCP gloves in recent years is the outcome of these efforts to create dexterous and more carefully fitted gloves. In 1983 Clapp designed and tested an MCP glove and compared its performance to the Skylab gas pressure gloves.³⁹ In 2002, Korona et al developed a hybrid gas elastic glove and compared its performance to a 4000 series EMU glove.⁴⁰ Later Tourbier and Tanaka examined the physiological effects of elastic MCP gloves.^{14,15} However, MCP glove design has been limited by some factors, above all a difficulty in donning and doffing, a non-uniform pressure distribution, and an insufficient pressure on body concavities. Moreover, their mobility is still somewhat less than that of a bare hand. Attempts to overcome these problems are the current goals of some research centers.¹³

The fingernail delamination problem is another issue that is under evaluation by some researchers. Many potential injuries have now been prevented with the use of available countermeasures and an improved fit of the gloves. However, improvements can still be made in glove design in order to reduce fingertip loading. Since an average of six months is needed for an injured nail to fully re-grow, prevention is a key factor. Furthermore, research shows that a better gas flow around fingertips can prevent nail injuries inside the EVA gloves. Therefore, some new research to improve the ventilation inside the glove could be helpful.

As previously mentioned, the warm, moist environment inside an astronaut's glove is highly conducive to the growth of bacteria. Growth of bacteria inside the gloves can be a major problem during an EVA, which can last up to eight hours each day. Several commercial organic and inorganic anti-microbial treatments have been studied by ILC and some have transitioned from research into application. Some coatings can prevent harmful microbial growth and control odor inside the glove. Specialty silver coatings have now been qualified in EVA glove comfort liners and will need more investigation in the future.^{32,41}

In a concept solicitation from the EVA development community in 2004, 89 individuals (researchers, engineers, etc.) at 38 different organizations that are active in EVA research and development were asked to suggest concepts that could lead to a realization of future EVA needs. ILC Dover which is one of the leaders of the EVA glove Industry suggested a hot research topic in the development of a new garment material that could integrate the pressure restraint and thermal control functions.¹⁶

The Astronaut Glove Challenge is a Challenge managed by NASA's Innovative Partnership Program to improve the next generation of EVA gloves. Volanz Aerospace Inc. manages this competition for NASA. The Astronaut Glove Challenge seeks innovative glove design concepts in order to reduce the effort needed to perform tasks during spacewalks. In a recent competition held on November 19, 2009, Peter Homer won the first prize of \$250,000. The key difference in Homer's glove and the Phase VI is Homer's finger joints. He crisscrossed one-eighth-inch craft ribbon into an "X" at each finger joint in order to create a hinge-like effect. The hinge helped to improve the fingers' dexterity. Therefore, construction improvement may still be a key issue for overcoming glove problems in the future.⁴²

To overcome the stiffness of the pressurized EVA gloves, a few research centers, among which the Italian Institute of Technology, aim to develop a prototype of a light weight hand exoskeleton designed to be embedded in the gloved hand of an astronaut. Also in the Man Vehicle Laboratory in MIT as part of an ongoing research on EVA performance, researchers and students are exploring how robotic technology can work in parallel with gas-pressurized suits and gloves, including ways to use actuators to help hand muscles fight against pressurized gloves. This system still needs more investigation to be able to provide force and precision to the hand grip. The exoskeleton should have a multi-finger design. The architecture and design of the actuation system needs to mimic the kinematics of the hand joints and electrical motors or artificial muscles will act as the system actuators.

VI. Conclusion

Future missions will require a spacesuit which is capable of performing zero gravity operations as well as varying partial gravity missions. The multi-role mission will require suit qualities which are not available in any currently operational EVA spacesuit. Future spacesuits will have to provide excellent full body mobility, be very lightweight, robust and comfortable.⁴³

As we mentioned above different problems during EVA especially regarding the hands are the most important reasons for improving astronaut gloves. Although several efforts have been made in this direction, much work is still

needed to improve these systems. This paper attempts to summarize the chronology of the EVA suit and gloves and to describe the components of an EVA glove and all the materials that are used in its construction. Information about layers of the glove and specification and properties of each layer has been collected. Moreover, future trends of investigation in this field as well as current problems that need more research were mentioned. Table 1 shows the issues that still need to be investigated by future research.

Table 1: Recommended Research Topics

Problems	Recommended Research Topics
<ul style="list-style-type: none"> • Low Dexterity (Topics 1, 2, 3, 4, 5) • Hand Fatigue (Topics 1, 2, 3, 4, 5, 6) • Donning and doffing difficulties of MCP suit and glove (Topic 5) • Non-uniform pressure distribution of MCP suit and glove (Topic 5) • Insufficient pressure on body concavities of MCP suit and glove (Topic 5) • Fingernail delamination (Topics 7, 8, 9) • Growth of bacteria inside the glove (Topic 9) • Hybrid MCP technology is still rely on fluid to transmit the pressure to the skin (Topics 5, 10) 	<ol style="list-style-type: none"> 1- Developing the requirements for improving the design of next generation of EVA gloves 2- More accurate evaluation regarding the effects of EVA glove on hand performance and fatigue 3- Developing a new garment material that integrates the pressure restraint and thermal control functions 4- New ways of customaization and better fitting of the gloves 5- MCP suit technology improvement 6- Research on embedding hand exoskeleton inside the EVA glove 7- More investigation of the exact reason of fingernail delamination 8- Design improvement to reduce fingertip loading 9- Improvement of gas flow around fingertips 10- True MCP suit development that does not use fluid to transmit pressure

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