MECHANICAL COUNTER PRESSURE SPACE SUITS: ADVANTAGES, LIMITATIONS AND CONCEPTS FOR MARTIAN EXPLORATION

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ABSTRACT

Gas-pressurised space suits have been highly effective as a life support system, but are a severe hindrance to astronaut function and capability. They are rigid, heavy, bulky, costly, leaky, and require high maintenance due to the complexity of constant volume joints and associated bearings and restraint layers. For future planetary exploration, revolutionary suit designs must be developed to satisfy requirements for a light, durable, puncture resistant, low leakage suit with excellent full-body flexibility. An alternative suit pressurisation technology called Mechanical Counter Pressure (MCP) may provide these required advances by utilizing tight, form-fitting garments to physically compress the body rather than pressurise it with a gas. The only limitations to the MCP approach is the donning, pre-breathe protocol and IVA adaptability characteristics. An active MCP suit, which can relax or tighten as necessary independently on all areas of the body (except the head), effectively addresses these drawbacks without compromising the inherent MCP advantages except for cost. With the advancement of shape-changing materials, an active suit may be produced with electro-active polymer fibres integrated circumferentially into the elastic weave, or shape memory alloy bands aligned in the longitudinal directional. A small, light and flexible suit based on active MCP elastics could be worn for all extravehicular operations, but also during launch and entry.

Keywords: Spacesuit, flexibility, Mars, mechanical counter pressure, MCP, elastic, EVA

INTRODUCTION

The ability to work outside the space craft became crucial to mission success soon after humans began flying beyond the atmosphere and into space. Such extravehicular activity (EVA) has taken the form of constructing and maintaining space stations, repairing satellites, or exploring the lunar surface. To survive during EVA, astronauts must wear spacesuits for life support and protection against the hostilities of space. To be effective, EVA spacesuits must also allow the astronaut to move and perform the required operational tasks.

Thus far, all flown spacesuits have been anthropomorphic balloons pressurised at low levels with the breathing oxygen, but despite over 40 years of development the suits are still heavy, bulky, relatively unsafe, costly, leaky, and require high maintenance and lengthy pre-breathe protocols. The greatest limitation, however, is that the suits are highly fatiguing to the wearer and a severe hindrance to normal mobility [3,9,10]. Astronauts must train for many months to build strength to articulate the rigid garments, and develop (and practice) new strategies for performing the relatively simple required motions.

An alternative approach to EVA spacesuit design uses form-fitting garments to physically compress regions of the body with elastics, instead of pressurisation with a gas. A full elastic (or ‘skin’) suit would pressurise the body with tight garments except the head, which would be enclosed in a standard gas-pressurised helmet for breathing. The compression of the elastics would be the same as the pressure of the breathing gas in the helmet (currently 222mmHg), and so a uniform loading is produced over the entire body. This approach is called Mechanical Counter Pressure (MCP), and potentially produces a light, flexible, cheap and safe compression suit. Performance studies with a simple MCP glove found task times to be only 1.37 slower than barehanded [5]. MCP has been investigated for almost as long as gas-pressurisation, but limitations in materials and tailoring technology have prevented a practical development [1,5,31].

In recent times, considerable advances have been made in elastics, weaves and seamless tailoring techniques. Due to these advances, the continued drawbacks of gas-pressurised suits, and the potential of MCP technology, Honeywell and NASA have produced a revolutionary prototype MCP EVA glove. The flexibility of the Honeywell MCP glove was qualitatively explored in a hypobaric chamber by wearing the MCP glove on the right hand and a NASA series 4000 shuttle glove on the left (see Fig. 1). Tactility and dexterity were dramatically improved. Small objects with a diameter of ~10mm could be handled with the MCP glove, but could not be grasped with the shuttle glove. Mobility studies in the US and Australian deserts have shown that MCP gloves increase EVA task time by only 65% compared to the naked hand, instead of 232-500% for gas-pressurised gloves (unpublished data).

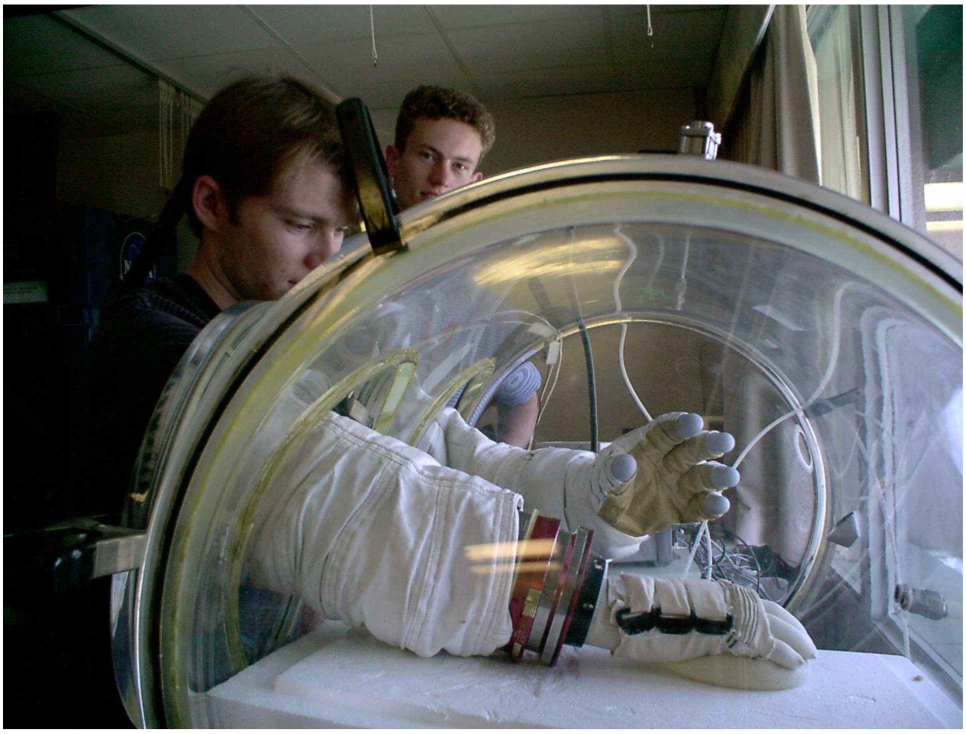

Fig.1: Qualitative comparison of MCP and shuttle gloves in a hypobaric chamber

The glove was very comfortable when worn at design hypobaric conditions in the chamber, and so would be similarly comfortable in space. Skin irritation was not discovered, despite minor waffling impressions on the skin. Unlike the gas-pressurised glove, the MCP glove did not require the fingers to be splayed to reach down into the bulky glove fingers. The thinner

MCP materials allowed the hand to rest in a more natural position, with the fingers close together. Donning the glove was, however, a consistent problem and took several minutes.

MARTIAN EXPLORATION

The major space agencies are not content to remain stagnant and continue with only LEO operations. The Russian, European and US space agencies are now actively planning for human missions to Mars. All of these programs propose a return to the Lunar surface, and initial Mars missions of approximately 1000 days with surface EVA operations of 500 days or more.

The long-term duration and physical nature of proposed Martian field operations are several orders of magnitude more demanding than any and all previous EVAs. An EVA suit (and life support system) for Martian exploration will therefore need to be greatly advanced over anything currently in use, particularly in robustness [10,11]. The operational and environmental requirements of a Martian EVA suit are outlined below.

Operational Requirements

A planetary suit for a Mars mission must safely and efficiently accommodate and support an astronaut for hundreds of hours during rigorous activities on jagged surfaces of significant gravity and dust [17,28,11]. At the most basic level, the design is driven by scientific exploration and so requires high mobility for geology, core sampling, instrument set-up etc. The suit must also be flexible enough to deploy structures and habitats, perform maintenance and repairs, and allow exploration over rugged terrain [23]. Even the basic act of walking must be accommodated, which involves mobility of the feet, ankles, knees and hip as well as controlling the centre of gravity, ground tactility and visibility [21]. It is important for the suits to be cheaper to produce than current suits, and to be stowable into a small volume for transport/storage [6]. The extended duration of demanding surface activities also requires a highly robust suit which is easy to maintain [10].

Rouen (1996) lists further specific operational criteria for Mars EVA suits:

- The suit must have no pre-breathe impact on the mission;
- The suit should be alterable to accommodate the lunar surface, and have technology that is transferable to a microgravity environment EVA suit;
- The suit must be capable of extra- and intravehicular activity (EVA and IVA), but optimised for surface operations;
- The suit must only require 10 minutes to don the suit and exit the airlock; and
- The PLSS volume must be no more than 70% of the Shuttle EMU PLSS volume;

Environmental Requirements

The design of planetary suits must also consider the Martian surface environmental conditions that are vastly different to those elsewhere. These conditions include dust, temperature, pressure, dust, sharp or jagged edges and physical hazards, gravity, micrometeoroids, radiation and potential biological contamination issues [17,28]. In general, the suit must make use of the natural environment (such as atmospheric gases) as much as possible [23]. The following briefly explores Martian conditions and any influences they may have on suit design.

Dust

Dust proved to be extremely hazardous on previous EVA missions, and Apollo astronauts found that it quickly abraded suit coverings, scratched helmet visors, covered external displays, degraded outer layer absorptivity and emissivity and contaminated seals and bearings. After two EVAs, astronauts reported that the outer layers of their spacesuits were "severely worn by lunar dust abrasion". On Apollo 17, Jack Schmitt had trouble securing his gloves and found that outer layer and worn through after 3 EVAs.

Mars dust and dirt is less abrasive and finer grained due to weathering than Lunar regolith, but will still contaminate seals and bearings. However, Mars is the only environment in which winds will be experienced. Martian winds may gust to 15m/s, but in the low pressure of the atmosphere these winds would exert little pressure on the astronaut [20,13]. Global dust storms obscure visibility and aid contamination as Martian winds are entrained with terrestrial particulate.

Rouen (1996) states that a Martian suit must be 'unaffected' by dust and dirt. To minimise such problems, suits should have a minimum of seals and bearings to prevent susceptibility to dust damage and reduce inspection and cleaning tasks [28,17]. NASA has already removed zippers from suit designs due to these concerns [10].

Gravity

On the surface of Mars, the gravitational acceleration is 0.38g. The mass of all suit systems therefore becomes significant. Since Apollo, gas-pressurised suits have actually got heavier due to added reusability (to reduce costs) and sizing rings (to increase size range) [18]. However, for future planetary missions, the reduction of mass will be critical.

An Apollo suit weighed 100 kg on earth, but only 17 kg on the lunar surface. Schmitt (2002) noted that the total weight of the suit was acceptable, however Apollo astronauts were not subject to the physical deconditioning expected to occur on long-duration Martian missions. The NASA EVA project office therefore calls for a planetary suit of reduced burden, with a suit only (no life support systems) Earth mass of 18kg and a life support system mass of 12kg [17,10]. This total mass is about one-quarter the current NASA spacesuit mass. The mass of the suit should also be distributed over the body to aid stability, maximise mobility and reduce fatigue in counter-balancing a lopsided suit [25].

Pressure/Temperature

Mars has a significant CO_2 atmosphere of 7.6mmHg (0.01atm) which serves to moderate temperatures at the surface. Thermal conditions tend to vary by latitude, seasons, time of day and elevation, but range from -140 to +20°C, with an average of approx –63°C. Suits will clearly be required to protect the wearer from the tenuous atmospheric pressure and maintain a comfortable internal temperature. The Martian atmosphere, though thin, will cause heat loss through conduction, convection, and wind-induced evaporation. Further, the life support system must have an automatic thermal control that benefits from in-situ resources utilisation (ISRU) [23].

Radiation

Outside the geomagnetic field of Earth, the most significant radiation risk is from a solar particle event (SPE) or Cosmic Background Radiation (GCR). Although Mars has no geomagnetic field, the atmosphere offers 27 g/cm2 equivalent aluminium atmosphere protection, and shields the surface from almost all of the solar particles, but is relatively ineffective against galactic radiation [2]. The planet provides hemispheric protection, as the planet blocks galactic radiation from below and solar particles at night. A suit cannot reasonably protect against this particulate radiation, but both types are predictable and detectable, and a retreat can be made to a shelter constructed of the surface regolith or spacecraft shelters surrounded with water. Electromagnetic radiation, such as UV and IR, reaches the surface and can cause degradation of EVA suit materials and should be considered in the outer layers and for helmet visors [17].

Micrometeoroids/Jagged Surfaces

The atmosphere of Mars essentially protects the surface from micrometeoroids, however, once at the surface, significant physical hazards can be found. All EVA missions must avoid sharp surfaces on orbital or landing spacecraft, but on Mars the surface environments often feature a vast collection of jagged pebbles, rocks and boulders. These surfaces will be encountered on virtually every planetary traverse. Rugged suit layers and safety systems must therefore be incorporated into the suit design to prevent puncture or failure due to any of these hazards [23].

Contamination

It may be necessary to avoid any contamination of the Mars surface with human biologic material, and also vice-versa. The biological contamination issues of a manned Mars mission have yet to be fully understood or addressed. As the Mars environment may harbour current or past life, a Mars suit should provide some measure of quarantine against human/bacterial contamination of the surface (and indeed vice-versa). It will be necessary to minimise human contamination of the surface so that samples (or Martian life) are not compromised.

It may be more important to contain Martian material from being introduced into the habitable environment due to the high oxidation state of the regolith. It is possible that small quantities of hexavalent chromium exists on the surface, which is toxic to humans. The presence of sulphur and chlorine also implies that the soil and airborne dust is acidic, which could be dangerous to both equipment and crew [19].

Planetary suits therefore may require a rigorous procedure to prevent the ingress of surface materials inside the airlock and habitat when returning from EVA. This may take the form of special cleaners or a suitport concept, in which the dirty outer layers remain outside, and the astronaut enters the habitat through a door in the rear (like the Orlan) [17]. Leakage from suits must also be minimised to save consumables and reduce or prevent contamination of the surface.

Table 1 below gives an overview of all the Martian suit requirements mentioned above.

Table 1: Mars Planetary suit requirements

Property	Mars Suit
Safety	High
Glove/arm flexibility	High
Leg/torso flexibility	High
Cost	Low
Bulk	Low
Robustness/ Maintainability	High
Pre-breathe impact	Low
Adaptability	IVA/EVA use for Mars, Moon and Microgravity
Donning	10 mins
PLSS size	70% EMU PLSS
Thermal regulation	ISRU
Susceptibility to dust/dirt	Low
SSA Weight on Earth (kg)	<18
Weight location	Distributed
Radiation Protection	Electromagnetic resistant
Puncture Resistance	High
Dust/contamination control	High
Gaseous leakage	Low/none

ADVANCED PLANETARY GAS SUITS

Initial prototypes of advanced planetary gas-pressurised suits were developed at the end of the last century to explore new ways of reducing suit mass, cost and bulk while improving flexibility [6]. ILC Dover (who produce the current NASA suits) modified the existing suit garments (called the space suit assembly, or SSA) by primarily replacing the hard upper torso structure with lightweight fabrics and inserting two bearing hip joints. The design (called the 'M' suit, see Fig. 2) saved about 21kg from just the SSA to give a total Mars weight of 42kg [10,6]. The design had improved flexibility primarily as the suit was pressurised at the minimum physiological acceptable level of 194mmHg. It also had high leakage from the increased number of bearings. David Clark produced the 'D' suit, a full soft suit that also operated at 194mmHg. The SSA predominantly used flat pattern convolutes, and weighed 12kg. However, the modified fabric joints were found to give unsatisfactory flexibility. The total Mars weight of this suit was about 40kg [10,6]. Improvements to the life-support systems could further reduce this mass, however huge advancements must be made in order to achieve similar in-situ weights as the Apollo suits on the lunar surface. The Hamilton Sundstrand suit incorporated a semi-autonomous navigating cart to transport various consumables. The cart was central to the design as it was required to reduce the mass of the suit [10].

Fig.2: Apollo, Shuttle EMU and 'M' Suit [24]

A further investigation into advanced planetary suits is the Mark III, which utilises a mix of soft joints, hard joints and bearings (see Fig. 3). The suit demonstrated improved flexibility by optimisation of joint selection and design. The suit is normally pressurised at 430mmHg for zero pre-breathe protocols, and weighs 58.5kg (up 8.5kg on the current suit) [24]. If modified for the lower pressure of 194mmHg, the SSA mass could drop to 36kg.

Fig.3: Mark III in simulated hypogravity [24]

Limitations of Gas-Pressurised Suits

While the designs of advanced gas-pressurised suits are an improvement over the current NASA space suit (called the Extravehicular Mobility Unit, or EMU), many characteristics of these designs can be shown to be unsuited to Martian conditions. Gas-pressurised suits are inherently heavy due to the bulky, air-tight layers of the SSA and the multiple number of seals and bearings to allow a freedom of movement. The Personal Life Support System (PLSS) is also large and complex, and must include the storage tanks, fans, pumps, contaminant-control cartridges/filters, regulators and valves to manage the oxygenation and pressurisation of the whole suit.

The greatest limitation of gas-pressurised suits is therefore the balance of weight and flexibility. The Mark III, for instance, has relatively good flexibility for gas suits, and allows the astronaut to touch the ground. However, the minimum mass of the Mark III SSA is approximately 36kg; lighter prototypes are unacceptably rigid [6]. Furthermore, most of the suit mass is located in the PLSS on the back. The centre-of-gravity of the suited astronaut is therefore shifted higher and behind the heels, forcing a forward hunch or lean to achieve standing balance. The suits also have high bulk. The Mark III utilises several hard components, increasing bulk even more than the predominantly soft components of the current EMU. This reduces stowage capability, but also the ability to act as an IVA suit as interior space (particularly at seated and piloting positions) is highly restricted. The all soft components of the ‘D’ suit, however, may be more suitable for dual IVA and EVA roles.

Gas-pressurised suits have a good safety record, but they are susceptible to puncture and abrasion failure. As the suit is a full body balloon, a puncture would be a catastrophic failure. They also have high cost, require lengthy and frequent maintenance, and are easily damaged by dust/dirt. The high leakage of suits may contaminate the surface, but also represents a significant wastage in oxygen supplies. If Martian habitats are pressurised at 1 atm (760mmHg), zero pre-breathe suits (such as versions of the Mark III) would need to be pressurised at 430mmHg, further increasing the pressure differential between the interior of the suit and the ambient environment, and driving a higher suit leakage. A solution to this waste of oxygen may be to pressurise the body with the Martian atmosphere, leaving only the head pressurised with oxygen [8]. A sizable compression and pump system would, however, be required to be carried along in the PLSS.

Research for future spacesuits is focusing on thermal management, as neither the Shuttle EMUs multi-layer insulation nor the water sublimation system will function in the thin atmosphere of Mars. Furthermore, these systems are heavy: water and associated pumps/plumbing systems would weigh as much as 9kg on Mars [18]. Current advanced space suit materials research is focused on insulating materials. Thin, light-weight, flexible, and durable insulation must be developed. One promising technology being investigated is that of aerogels [28]. Radiators are being considered, but they most likely will not be capable enough. The Chameleon suit uses electroactive polymers, thermal infrared electrochromic materials and wearable electronics to sense the internal and exterior environment and adjust heat conductivity of the suit layers accordingly [12]. In terms of insulation, Mars should not require exotic material development as radiation levels, temperature extremes and micrometeorite strikes are less extreme than on Earth orbit or Lunar environments.

Table 2 again lists the requirements of a Mars suit, but also shows the corresponding attributes of gas-pressurised suits.

Table 2: Attributes of gas-pressurised suits compared to Mars requirements

Property	**Mars Suit**	**Gas Suits**
Safety	High	Med
Glove/arm flexibility	High	Low
Leg/torso flexibility	High	Low
Cost	Low	High
Bulk	Low	High
Robustness/ Maintainability	High	Low
Pre-breathe impact	Low	Low
Adaptability	IVA/EVA use for Mars, Moon and Microgravity	EVA-High; IVA-Med
Donning	10 mins	2-20mins
PLSS size	70% EMU PLSS	?
Thermal regulation	ISRU	?
Susceptibility to dust/dirt	Low	High
SSA Weight on Earth (kg)	<18	12-36
Weight location	Distributed	Back
Radiation Protection	Electromagnetic resistant	Electromagnetic resistant
Puncture Resistance	High	Low
Dust/contamination control	High	Low
Gaseous leakage	Low/none	High

As gas-pressurised suits do not appear to be capable of providing the flexibility and weight balance, cost, bulk, robustness and leakage required for Mars exploration, the Advanced EVA Projects Office at NASA JSC believes that planetary exploration requires a new generation of suit [6]. Innovative spacesuit design is considered essential, given the increasingly complex and physically demanding tasks caused by the extreme environments and EVA goals of Mars missions [22].

MCP PLANETARY CONCEPT

A pure MCP Martian EVA suit would comprise of elastics garments over the whole body except for the head, which would be pressurised with the breathing oxygen (see Fig. 4). A dust/protection overgarment would be worn over the MCP layer which could be sealed or unsealed via a filter as necessary. This would allow cold Martian air to circulate and assist perspiration if necessary. Alternatively, heating elements could be incorporated into the MCP weave to serve as thermal heating control. No cooling garments would be required, and the life support system would be significantly reduced in mass, bulk and complexity without the need to manage the cooling water. Standard hiking boots could be worn over the MCP socks. A full MCP suit therefore moves the design concept away from personal space craft to a garment that augments the properties of the body in the Martian environment.

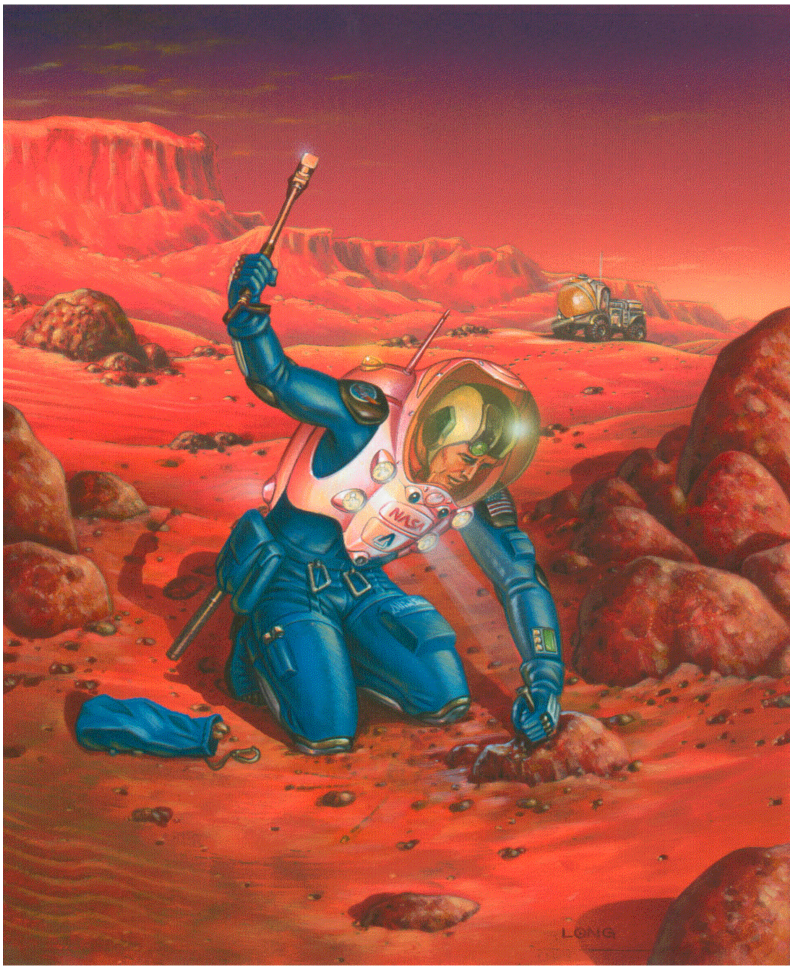

Fig.4: MCP EVA Concept [30]

Advantages of MCP

Flexibility

All research has shown that MCP garments and suits offer a significant flexibility enhancement over gas-pressurised designs. Annis and Webb (1971) found that MCP garments offered dramatic improvements to gas pressurized suits in flexibility, dexterity, reach and tactility due to the replacement of stiff joints and bearings with light, flexible elastics. Running, cycling and even crawling was possible in the MCP suit.

As a measure of full body flexibility, oxygen demand during walking was reduced 66% when compared to the Apollo suit. Later studies by Clapp (1984) showed that MCP ‘skinsuit’ gloves were significantly better in mobility, dexterity, tactility and fatigue. The results of the flexibility studies of this research indicate that the MCP gloves inhibit movement and performance by one-quarter of gas-pressurised gloves. While the performance advantages of the MCP glove may be exaggerated by the multitude of finger movements of the hand, simple movements such as the elbow and knee would benefit from the mobility afforded by the lighter, thinner and more flexible fabrics.

Safety

A tear or hole in a gas-pressurised suit would result in a rapid and probably fatal decompression. Tears in a MCP suit would remain a local defect as the elastic weave prevents the tear from propagating. A tear, therefore, would cause symptoms of localised low pressure exposure at the site of the tear (such as bruising and edema), while the rest of the body remains protected. The severity of these symptoms is quite mild and dissipates within hours/days (depending on exposure time), especially when occurring on a small area.

Improved mobility, greater reach, better tactility and improved dexterity all contribute to the effectiveness of performing EVA tasks, reducing risk, fatigue and error. The MCP Martian suit would also utilise standard hiking boots to convey great advantages in moving over rough terrain, especially considering the bulky gas-pressurised boots of the current EMU. All of these performance improvements should also lessen concentration and physical fatigue for accomplishing a given task list, thereby reducing the tendency to make errors that are potentially harmful [32].

Weight

Both the suit and the life support system should be significantly lighter than a gas-pressurised suit. While both MCP and gas suits might share outer protective layers, the air-tight and cooling layers of gas-pressurised suits are replaced with the light MCP elastics, saving considerable weight. Comparisons between current gas and MCP gloves show the latter to conservatively weigh about one-quarter of the former. A MCP suit could therefore weigh about 14 kg or less (based on weight of shuttle suit, boots, gloves etc) [16].

The MCP life support system will also provide significant weight savings. As the oxygen demand is decreased, the total volume of required pressurised oxygen is drastically reduced and the oxygen leakage virtually eliminated, there is an associated scaling down in both the required oxygen and pressurisation/management hardware. Further, omitting the coolant loop means saving the weight of the water, the water pump, its battery, the connecting tubes and valves, and all associated control hardware. The MCP life support system could therefore be less than half the volume of the Apollo EMU [1].

Bulk

An MCP suit would also be comparatively small. With a suitably sized outer dust/protection layer, the suit could be no more bulky than winter clothes. Conceivably, the MCP garment could be stuffed within the helmet itself for stowage/storage. The less bulky torso of MCP suits also allows for improved walking and climbing vision of the feet. As the suit is worn by the body (rather than carried), many more loading points can be used to distribute mass over the body.

Cost

A full MCP garment will cost far less to make than the current EMU with its expensive mechanical joints and the relative simplicity and size of the PLSS. No liquid cooling garment will be needed. Weight and volume are greatly reduced with the MCP approach. Even though the elastics are durable, there could be many replacement garments available due to their small cost and storage size. A whole suit could be stored in the fishbowl helmet. Minimal maintenance is required for the SSA. There could be replacement SSA garments available for everyone scheduled for multiple EVAs that would be inexpensive, light weight, and easily stored.

Life Support System

The PLSS will be significantly smaller and lighter due to the savings in oxygen supply and omission of the cooling loop hardware. The required oxygen supply for a given set of tasks may be reduced by two-thirds, according to the energy cost ratio of slow walking in an MCP garment versus a pressurized Apollo suit. Omitting the coolant loop (because the astronaut cools naturally from sweating which evaporates instantly into the vacuum) means saving of the weight of the water pump, its battery, the water boiler, connecting tubes and valves, and associated control hardware. The PLSS should be less than half the weight and volume of current hardware. Advanced concepts, such as venting metal hybrid/hollow fibre membranes, and CO_2 and water vapour scrubbers may need to be employed, as they have low overboard loss of oxygen, no moving parts, and a long operating life [10].

Cooling

Current gas suits cool the astronaut via the Liquid Cooling and Ventilation Garment (LCVG), an inner layer containing a network of small tubes that circulates cool water around the body. The LCVG may be redundant in MCP suits due to the ability of the astronaut to sweat through the porous MCP garment. Evaporation cools the skin, body heat is dissipated, and the rate is controlled by the astronaut's normal physiology [32]. This natural cooling is further aided by conduction and convection. When sealed, the outer dust layer would trap metabolic heat and warm the astronaut. Heating elements could also be incorporated into the MCP elastics. When cooling is required, the outer layer is vented through a filter to allow filtered circulation of the Martian atmosphere over the porous MCP elastics. The dust/protection overgarment can be left unsealed to allow free circulation of the cold Martian atmosphere, however attention must still be paid to contamination issues. If an effective filter can be placed at the venting point, then most of the contaminants could be collected as the cooling gas is returned to the environment. The gaseous leakage from gas-pressurised suits is due to the high internal pressure and the number of joints and bearings. The leakage from an MCP outer layer would be considerably reduced as there are far fewer bearings and joints and because the interior gaseous pressure (except for the helmet) is equal to the outside environment – the leakage points are therefore reduced and the force for the gas to escape nullified.

If the cooling allowed by MCP in the Martian environment is too severe, then a filter valve in the outer layer may be closed to reduce or stop air circulation. In this way, the sealed interior of the suit warms with body heat. Adjustment of the filter valve may effectively serve to regulate the suit internal temperature. Heating elements could also be incorporated into the weave of the elastics, as is currently available in some thermal wear.

Contamination

It is unlikely that any suit concept could completely prevent any form of human or organic matter from reaching the surface. For MCP, perspiration and other gases around the body aren’t subject to the same high pressure expulsion and leakage as gas suits. The leakage of the environmental circulation proposed for cooling would be directed through select filters to minimise cross-contamination.

Another concept to reduce organic or dust contamination is the suitport. The suit utilises a rear hatch (like the Orlan) which connects to a port on the side of the habitat. The astronaut then opens the rear hatch to enter the habitat, while leaving the dust layers outside. For a MCP suit, such a hatch would be an unpressurised, non-critical seal in the dust layer; for gas-pressurised suits, the hatch represents a large and more complex airlock door, capable of withstanding large pressure differentials while still minimising leakage.

Limitations of MCP

The prototype MCP glove shows there are two main areas of MCP design which pose the most significant problems in producing an effective, practical suit: donning and doffing, and ensuring all areas of the body receive uniform or sufficient compression.

Donning/Doffing

The powerful elastics of the MCP garments are currently designed to exert the same pressure on the skin as the pressure found in the current shuttle EMU (i.e. about 0.3 atm). However, as donning and doffing will be required in the pressurised environment of the spacecraft/habitat, the combined pressure can be painful after only several minutes. The act of donning and doffing such a constrictive garment can also take considerable time and effort, especially as larger cross-sectional areas of the body require increased tension to produce the requisite skin pressure (according to the hoop stress relationship where pressure is equal to tension over radius). Such an increase in tension may produce larger voids and unpressurised regions between the fibres of the weave, but also reduce the flexibility of the material. The increase in tension would also hamper the donning and doffing process, as the elastics would need to be stretched more tightly to cover the larger area. The MCP elastics over the torso, for example, are required to be at a tension approximately 10 times larger than the finger, as the torso radius is approximately 10 times larger than the finger. Even though the glove could be donned in tests in only 3 minutes (after practice), it therefore seems likely that donning a full body MCP suit would demand about 30 minutes.

Uniform Compression

Applying uniform compression over the human body is difficult because it is a complex shape in some areas. As Annis and Webb (1971) discovered, flat or concave sections experiences reduced skin compression due to elastic ‘bridging’. Areas such as the back of the hand, the spinal trough, under the arms and the back of the knees all require some form of supplemental device in order to transfer the compression to the skin. In the Honeywell glove, an inflatable bladder was used, but gel packs and foam padding may also suffice in such areas. Providing extra compression under the arms and behind the knees is more difficult as these areas are required to be free for good mobility, and because the joint undergoes large amounts of articulation. However, the most challenging (and delicate) area to pressurise is the groin. It may be deemed more effective to create a gas-pressurised system for the groin, which would share the PLSS helmet pressurisation hardware. This would require seals above (abdomen) and below the groin (thigh) in addition to that around the base of the neck (for the helmet).

The Honeywell glove tests also revealed that some areas of the body are more resilient to low pressure (like the palm) and may not need the same compression as other areas. The characterisation of various regions of the body by hypobaric sensitivity is yet to be performed.

Summary of MCP Properties

The properties of MCP suits can now be added to the previous table of planetary requirements and gas-suit properties, as shown below in Table 3. The ability of MCP suits to address planetary requirements is clearly shown to be superior to gas-pressurised suits.

Table 3: Attributes of MCP and gas-pressurised suits compared to Mars requirements

Property	Mars Suit	Gas Suits	MCP Suits
Safety	High	Med	High
Glove/arm flexibility	High	Low	High
Leg/torso flexibility	High	Low	High
Cost	Low	High	Low
Bulk	Low	High	Low
Robustness/ Maintainability	High	Low	High
Pre-breathe impact	Low	Low	Dependant on MCP compression.
Adaptability	IVA/EVA use for Mars, Moon and Microgravity	EVA-High; IVA-Med	EVA-High; IVA-Low
Donning	10 mins	2-20mins	30mins
PLSS size	70% EMU PLSS	?	50% Apollo EMU PLSS
Thermal regulation	ISRU	?	ISRU
Susceptibility to dust/dirt	Low	High	Low
SSA Weight on Earth (kg)	<18	12-36	14
Weight location	Distributed	Back	Distributed
Radiation Protection	Electromagnetic resistant	Electromagnetic resistant	Electromagnetic resistant
Puncture Resistance	High	Low	High
Dust/contamination control	High	Low	High
Gaseous leakage	Low/none	High	Low

REQUIRED DEVELOPMENT

This analysis of planetary EVA has shown that MCP suits satisfy most requirements considerably better than gas-suits, but several MCP limitations exist: donning time is increased, adaptability to IVA use is low, and the capacity to exert high compression effectively over the body impacts on the ability for short or zero pre-breathe protocols.

For planetary use, hybrid MCP/gas options are possible such as a ~100mmHg MCP layer under a ~100mmHg gas-pressurised layer. The reduced pressures of the MCP layer would be more conducive to easy donning/doffing than pure MCP designs, and the compression once donned would be more tolerable in ambient/spacecraft conditions. As the pressure in the gas tight layer is halved, so too would the actuation forces at the joints. If the pressure garments were tolerant of 222mmHg, the MCP layer could be removed for IVA use and allow the suit to function as a pure gas-pressurised garment in the event of emergency cabin-depressurisation.

Another hybrid option may be to pressurise the torso with gas, and incorporate a seal at the hips and shoulders for MCP limbs. This allows the efficiency of gas-pressurisation to function over difficult areas of the body to compress (for example the male groin, under the arms and chest expansion/contraction with respiration) and where flexibility is not as crucial. The MCP is supplied at the limbs where shapes are more cylindrical and flexibility is needed most.

However, any gas-pressurised elements would increase bulk, leakage, contamination, susceptibility to puncture, PLSS size and complexity, and still require the bulky LCVG or other cooling equipment. Table 3 clearly shows that any elements of gas-pressurisation should be minimised as the properties of the suit may fall below the stringent requirements. As the requirements are matched (and not exceeded) by MCP garments, a successful planetary EVA design is likely to be achieved by incorporating a minimum of gas-pressurised elements.

Another possible solution to the limitations of MCP may be to incorporate an electro-activated polymer into the weave of the garment, thereby allowing it to relax and compress at will. Other ‘activation’ options are shape memory alloy bands aligned in the longitudinal directional, capstan-like fluid channels or bunching/clasping mechanisms. Inflatable fluid channels could also be used to increase tension in the MCP materials for non-stretchable fabrics [7]. A Martian astronaut could conceivably don the MCP EMU in the airlock and feel it gradually compress on the skin as the pressure in the airlock decreases. Further, this approach could be used in intravehicular activity (IVA) suits used during launch and re-entry: the suit would be relaxed by default but triggered to compress in the event of a cabin depressurisation. As the compression over the various regions of the body is managed and more efficient and uniform as a whole, total compression levels may be increased so that a zero pre-breathe protocol could be feasible. As a pure elastic MCP suit assembly is approximately 4kg under the mass budget on Mars (or 10.7kg on Earth), this deficit is available for the weight of the activation mechanism. MCP activation mechanisms would, however, increase complexity, cost and power consumption of pure MCP designs, but ideally the mechanism would be fail-safe, such that power is required only to relax the suit. An active MCP suit would therefore satisfy IVA compatibility, donning/doffing protocols and pre-breathe requirements without significant ramifications to other properties except for cost, which would most likely increase above a ‘low’ rating.

CONCLUSION

For planetary missions, the properties of full-body MCP suits are ideally matched to the myriad of severe requirements for future planetary EVA. Gas-pressurised suits do not meet these requirements. The only limitation to the MCP approach is the donning, pre-breathe protocol and IVA adaptability characteristics. An active MCP suit, which can relax or tighten as necessary independently on all areas of the body (except the head), effectively addresses these drawbacks without compromising the inherent MCP advantages except for cost. With the advancement of shape-changing materials, an active suit may be produced with electro-active polymer fibres integrated circumferentially into the elastic weave, or shape memory alloy bands aligned in the longitudinal directional. The superiority of MCP over gas-pressurisation for future planetary exploration suits warrants the investigation into these activation mechanisms and other MCP/gas hybrid options.

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