The "Space Activity Suit" – A Historical Perspective and A Primer On The Physiology of Mechanical Counter-Pressure

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Since the 1950s, mechanical counter-pressure [MCP] has been investigated as a possible alternative design concept to traditional extra-vehicular activity [EVA] space suits. While traditional gas-pressurized EVA suits provide physiological protection against the ambient vacuum by means of pressurized oxygen to at least 3.1 psia (160 mmHg), MCP provides protection by direct application of pressure on the skin by a fabric. In reviewing the concept, MCP offers distinct potential advantages to traditional EVA suits: lower mass, reduced consumables, increased mobility, increased comfort, less complexity, and improved failure modes. In the mid 1960s to early 1970s, Dr. Paul Webb of Webb Associates developed and tested such a suit under funding from NASA Langley Research Center. This "Space Activity Suit" [SAS] was improved many times while testing in the laboratory and an altitude chamber to as low as 0.3 psia (15 mmHg). This testing, and the reports by Webb documenting it, are often presented as evidence of the feasibility of MCP. In addition, the SAS reports contain a wealth of information regarding the physiological requirements to make MCP work at the time, which is still accurate today. This paper serves to document the Space Activity Suit effort and analyze it in today's context.

Nomenclature

EMU	=	Extra-Vehicular Mobility Unit
EPG	=	Environmental Protection Garment
EVA	=	Extra-Vehicular Activity
IVA	=	Intra-Vehicular Activity
JSC	=	Johnson Space Center
LCVG	=	Liquid Cooling and Ventilation Garment
MCP	=	Mechanical Counter-Pressure
mmHg	=	millimeters of Mercury
NASA	=	National Aeronautics and Space Administration
PPB	=	Positive-Pressure Breathing
psia	=	pounds per square inch absolute
psid	=	pounds per square inch differential
SAS	=	Space Activity Suit
SMA	=	Shape Memory Alloy
TMG	=	Thermal Micrometeorite Garment
TRL	=	Technology Readiness Level

I. Introduction

MECHANICAL counter-pressure [MCP] is a concept that has been around for some time. It has been evaluated by advocates and skeptics alike over the past 50 years. For the purpose of this paper, a mechanical counter-pressure suit is any space suit intended for extra-vehicular activity [EVA] in a vacuum (low Earth orbit, Moon, etc.) or near-vacuum (Mars) environment which employs, at least in part, direct contact pressure imparted onto the body instead of a

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gaseous pressure surrounding it. While this historically has been defined as a tight-fitting elastic garment from the neck down, it could also include architectures using pressurized air bladders to impart the contact pressure in more challenging areas. Note that this is distinctly different than so-called "hybrid" MCP architectures that might, for example, use gas pressurization for the head and torso, but MCP for the limbs. This type of hybrid architecture is not within the scope of this paper but will be evaluated more closely in upcoming work.

Gas-pressurized EVA suits have been used exclusively over the history of human spaceflight. Yet despite this MCP still calls for attention because it offers the possibility for a potentially improved space suit design concept. The hypothetical advantages of an MCP suit compared to traditional gas-pressurized suits are summarized in Table 1 below.

Table 1: Hypothetical MCP Advantages

Hypothetical Advantages
Reduced suit mass
Improved biomechanics
Increased mobility
Reduced consumables
Reduced production cost
Natural thermoregulation
Reduced stowage volume
Fewer failure modes
Safer failure modes
Increased comfort
Reduced and easier maintenance
Reduced spares/logistical overhead

As a theoretical comparison, MCP appears to offer many substantial advantages as an architecture compared to the state-of-the-art gas-pressurized suit. It is for this reason that NASA has continued funding many dedicated MCP development efforts over the past several decades. One such effort was the "Space Activity Suit" of the mid 1960s through early 1970s. To date, this work, funded by NASA Langley Research Center and completed by Dr. Paul Webb, is the only comprehensive evaluation of a full MCP suit, and the only evaluation period, of a full MCP suit at relative vacuum. It is for this reason that it is important to fully understand the design, fabrication, and results of this testing. Only then can one begin to accurately assess the feasibility of MCP as a concept and ultimately determine where resources should be expended to improve the technology toward viability. Subsequent efforts since the SAS, the current technology readiness of MCP today, and a detailed assessment of these hypothetical advantages also call for detailed examination, but are not addressed here and will be covered in a future paper.

II. History

Mechanical counter-pressure as a space suit design concept has a much longer history than many may realize. To fully appreciate the historical context of MCP, it is important to consider the history of early aviation.

As early as the mid 1920s, high-altitude balloonists realized their bodies could not long withstand the temperature or reduced pressure of high ascents, often up to about 40,000 feet (~12,000 m) – even with supplemental oxygen[1]. Even before this, as early as the mid-1800s, experiments at lower altitudes and on the ground in altitude chambers had suggested the need for supplemental oxygen if dwelling for more than a couple hours at 10,000 feet (3,048 m); above that altitude, oxygen was required even sooner.[1] The correlation between survivability and partial pressure of oxygen was, by this time, well established.

Also during the 1920s, new engine technology enabled higher altitude plane flights up to around 35,000 feet (~10,700 m). Similarly, pilots realized an altitude limit that could not be exceeded for long without losing consciousness. With human physiology now the limiting factor in achieving higher altitudes (and therefore, distance and speed records), work began in earnest to design suits that would protect the aviator. The early 1930s saw nearly parallel and presumably independent development of full pressure suits both for Wiley Post (in coordination with Russell Colley of B.F. Goodrich) and by Mark Ridge (in coordination with John Haldane of Oxford University and Sir Robert Davis of Siebe Gorman[1-5]. A test flight by Post in 1935 set a new altitude record of over 50,000 feet (~15,200 m).[5] By the early 1940s the Goodrich XH-5 full pressure suit achieved 80,000 feet (24,384 m) in an altitude chamber [3] and both the United States Air Force and Navy were funding development significantly. However, it soon became apparent that fully pressurized suits inhibited pilot mobility too significantly for military applications, and therefore, the Air Force decided to further develop what was termed "partial pressure" suits.[1]

Around this same time, to mitigate the effects of blood shift when breathing supplemental oxygen at high altitude and loss of consciousness during high-G maneuvers, pilots had been wearing newly-developed "anti-G suits" or "G suits" which consisted of a close-fitting garment with rubber bladders or tubes ("capstan tubes") that could be inflated with a gas to stretch the garment fabric, thereby exerting pressure to the lower extremities.[3] Realizing the need for increased intra-vehicular activity [IVA] mobility at even higher altitudes, Dr. James P. Henry at the University of Southern California developed a full-suit version of the G-suit in 1944 called the S-1.[3] Subsequent iterations, by this point coined "partial pressure suits" were developed in the mid-1950s by the David Clark Company and they were very effective up to about 100,000 feet (30,500 m);[6] however, there were some drawbacks. They were designed to only be tightened during an emergency when cabin pressure was compromised, and even then, for only short periods of time. In addition, the tight-fitting fabric made thermal regulation challenging[1].

The MC-3 partial pressure suit (Figure 1 at right, detail in Figure 2 below) was perhaps a harbinger of the eventual decline of the partial pressure suit – it used capstan tubes and a full torso bladder to exert pressure on the body. This facilitated higher altitudes, up to 198,770 feet (60,585 m) and for longer periods of time (several hours in an altitude chamber up to 100,000 feet or 30,500 m);[3] however, the bladder inhibited moisture ventilation and therefore, the pilot's thermal regulation. It was at this point that partial pressure suit development started to slow down, eventually shifting back toward full pressure suits to enable long-duration use as was needed in specific military applications at the time. Eventually, the military position on suits in general became more pragmatic, in that except for "special projects" like the U-2 that required routine stays at high altitude, cockpit pressure was deemed sufficient and any enemy action that depressurized the cabin would probably be sufficient to render a suit futile.[3] Therefore, other than unique cases like the U-2 or SR-71, cabin pressurization supplanted the full-body flight suit in military applications and only G-suits were worn on the lower half of the body going forward.

Figure 1: Francis Gary Powers wearing a David Clark MC-3 partial pressure suit


Figure 2: Detail of MC-3 partial pressure suit; capstan tube at left

Dr. James P. Henry, who built and tested the first partial pressure IVA suit in 1944, may have also been the first to conceive of the mechanical counter-pressure suit concept, in the form of an elastic-fabric version of his S-1 partial pressure suit[7]. However, this was in concept only and was not fabricated. Some time later, Wayland E. Hull at the Aeromedical Laboratories at Wright-Patterson Air Force Base reportedly had a form of an MCP suit constructed and tested. However, he apparently did not pursue the concept further because breathing was uncomfortable and the elastic material available at the time was too stiff. [7] Note that several attempts were made to verify this version of events, through literature search and speaking with Dr. Hull's family. To date, Dr. Webb's acknowledgement that he was not the first to fabricate and test a mechanical counter-pressure suit has yet to be independently verified.

In 1959, the United States Air Force contracted with Hans Mauch of Mauch Laboratories to develop something similar to an MCP or partial pressure suit. This design used closed-cell foam sandwiched between two layers of fabric, and the concept was that under reduced atmospheric pressure the closed cell foam would expand and provide a compressive force against the skin. Although initial development was intended for the X-20 Dyna-soar program, NASA later added funding looking to determine if bulk could be reduced compared to the Mercury suit development at the time. The suit, shown in Figure 3, was tested in a vacuum chamber and was effective, but it did not have the mobility or reduction in bulk they were hoping for.[5] In addition, the closed-cell foam concept would have almost certainly inhibited thermal regulation of the wearer.

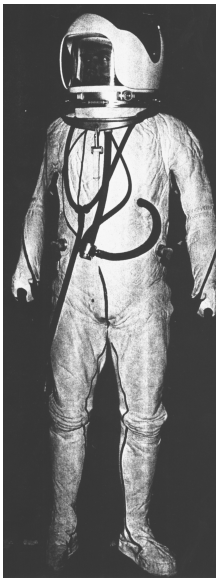


Figure 3: Mauch Suit, ca. 1962.

This brings us to 1967 and Webb Associates, headed by Dr. Paul Webb, who by this time was already an acclaimed researcher in physiology and supported many NASA and United States military efforts including production and editing of the NASA Bioastronautics Databook in 1964. Also during this time NASA was heavily funding space suit development not only for initial Lunar surface missions, but later planned long-duration Lunar habitat stays as part of what was termed Apollo "Block III". During this development phase, there were dozens of various contractors and smaller research institutions working on various space suit development efforts. It was during this time that NASA funded the Webb Associates to first, fabricate an MCP glove/arm assembly prototype and subsequently, a full true mechanical counter-pressure suit.

III. Physiology

To assess the utilities of a mechanical counter-pressure suit, and by extension the Space Activity Suit, let us first consider the physiological implications of human exposure to vacuum and the ways in which any suit, and specifically an MCP suit, must mitigate them.

1. *Skin Exposure to Vacuum*

The human skin is indeed an attractive starting point for a pressure suit to be exposed to vacuum: it is mostly gas-impermeable, elastic and by its nature does not impede natural motion. Many studies over the past century have demonstrated that the entire body can be exposed to vacuum for short periods of time. Tabling the clear issue of lack of breathing oxygen for a moment, the first issue to consider is swelling; as the skin is exposed to below the vapor pressure of water, vapor bubbles form in the skin and visible swelling of the skin occurs.[8,9]

Therefore, the first order of business for any space suit is to provide a restraint which would prevent the skin from being distorted by the formation of bubbles in the underlying tissues. A typical gas-pressurized space suit provides this restraint by means of a pneumatic pressure, while an MCP suit would provide a direct contact pressure using a fabric or other means. At sea level on Earth, the human body feels 760 mmHg (14.7 psia) of pressure on the skin. This magnitude is much larger than is needed for the purpose of skin retention as the skin itself provides some degree of inherent pressure.[10] Adding some nominal amount of pressure, on the order of 100 mmHg (1.93 psia) based on previous studies and experience of altitude tolerance, is sufficient to prevent swelling of the skin for extended periods of time.[10] In theory this minimum pressure must be applied everywhere, including the crotch, back, and armpit; if not, swelling and "blood pooling" (heretofore referred to as cardiovascular congestion) will occur. As it turns out, both experimental and analytical techniques have shown that in terms of providing even, sufficient pressure, more cylindrical body segments are easier than flatter or concave ones, and that smaller cylinders are easier than larger ones.[7,8]

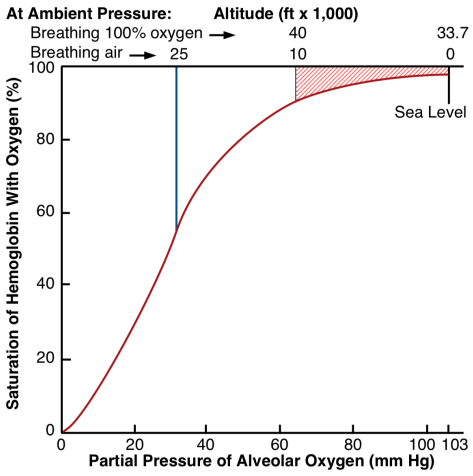


Figure 4: Oxygen Saturation Curve.

2. *Preventing Hypoxia*

On Earth at sea level, humans breathe 160 mmHg (3.1 psia) partial pressure of oxygen. Less oxygen pressure is acceptable as evidenced by large populations living at elevation and extensive experience in aviation. To prevent mild hypoxia, especially during exercise, a minimum design value of 150 mmHg (2.9 psia) is required which corresponds to breathing 100% O_2 at approximately 40,000 feet (12,200 m).[8,11] However, studies have shown cognitive deficit at this elevation (Medical aspects of harsh environments).

To provide a nominal safety factor and ensure adequate oxygen alveolar exchange and cognitive function, a breathing pressure of at least 180 mmHg (3.5 psia) is recommended, which corresponds to breathing 100% oxygen at 35,000 feet (10,668 m). Figure 4 at left shows oxygen saturation decreasing from right to left with increasing altitude for both breathing air and 100% oxygen. Physiologically, breathing oxygen at 35,000 feet (10,668 m) would correspond to breathing normal air at 2,000 feet (610 m).[9]

Note that the current NASA nominal suit operating pressure is defined as 4.3 psia (222 mmHg), which provides additional safety factor and also reduces pre-breathe time in stepping down from the 14.7 psia (760 mmHg) atmosphere of the International Space Station to avoid decompression sickness. An MCP suit would presumably conduct EVAs from a surface habitat on the Moon or Mars. If this future habitat, like the International Space Station, operates at a high standard pressure, a higher suit breathing pressure would also be required to not adversely affect operations through increased pre-breathe time. However, for the academic purposes of this paper, it is assumed that pre-breathe time is not a factor, or alternatively, that habitat pressures will be sufficiently low so as to decrease or eliminate EVA pre-breathe entirely. Therefore, for the purposes of practical use of a full MCP suit, 180 mmHg is an acceptable minimum breathing pressure, ignoring any impact to the rest of the EVA system.

3. *Circulatory System*

Regardless of the ambient pressure, a space suit needs to provide an external counterpressure against the human's internal physiological cardiac pressure at all times. A significant difference between the breathing pressure and the external counterpressure would leave the circulatory system functioning at a significant differential above the body's ambient environment. While the elasticity of most veins, arteries and skin would be able to withstand this pressure differential, smaller capillaries near the skin may burst into adjacent tissue, causing petechiae. The body would likely swell much larger than its usual size. Any localized areas of lower contact pressure will see relative swelling and edema.

Ebulism will occur by means of formation of water vapor bubbles in the blood. After a short period of time, without intervention, these bubbles will inhibit cardiac flow and pulmonary function, resulting in death.

In a traditional EVA space suit, the pneumatic suit pressurization provides an intrinsic balance between the body's pulmonary system and circulatory system. In this case, nominal metabolic function is achieved first because the body is receiving sufficient oxygen to the lungs, and subsequently a perfectly equivalent external pressure to the skin.

In an MCP suit, the direct contact pressure will need to at least roughly match the breathing pressure of at least 180 mmHg (3.5 psia). As previously discussed, skin physiology requirements alone might demand a counterpressure on the order of 100 mmHg (160 psia); doing so with the required 180 mmHg breathing pressure however, would almost certainly be too significant of a difference (80 mmHg) and would result in significant swelling, cardiovascular congestion and ultimately lack of venous return to the heart, resulting in failure of cardiac output.

Furthermore, while a slightly lower pressure differential of 50 - 60 mmHg (1.0 - 1.2 psia) may be sufficient to ward off circulatory problems, it would still place the crewmember in a significant positive-pressure-breathing (PPB) scenario. Positive pressure breathing simply means that the breathing pressure exceeds the body's ambient pressure and is the basis behind CPAP machines, although these operate typically no higher than the range of 3 – 15 mmHg (0.06 – 0.29 psia) differential. Positive pressure breathing has been used for years in aviation to support short excursions at elevations greater than 40,000 feet (12,200 m), as well as transient high-G maneuvers; however, PPB at this level (greater than 30 mmHg or 0.6 psia delta) is only intended to be used for short periods of time and even then, requires training, is uncomfortable, and makes communication difficult.[3] As Donn Byrnes describes in the book *Blackbird Rising*,

> This pressure breathing is conducted under very low mask pressure, usually equivalent to the weight of a column of water about five inches high. Imagine blowing a five-inch plug of water out of your snorkel in the swimming pool each time you exhaled, and doing that for a couple of hours or more. It is hard work and represents a complete reversal of a human being's normal physiology with respect to breathing. Essentially, nobody can function well under pressure breathing for any prolonged length of time, even with specially designed suits that assist with exhalation.[3]

Consequently, an MCP suit, to provide acceptable oxygen to the blood and prevent sustained positive-pressure breathing, needs to provide a counter-pressure at the same level or slightly above the breathing pressure (itself is at least 180 mmHg). This counter-pressure would preferably be slightly above the breathing pressure and slightly increasing distally along the limbs to prevent cardiovascular congestion and aid in venous return. Note that there is still a great deal to be learned about the physiological tolerance of under-pressure or over-pressure, something which is also affected by the gravity environment, human variability, and other factors. A future paper will summarize work completed to-date in this area and address these knowledge gaps in greater detail.

It is also important to note that the "ideal" MCP suit would apply this necessary pressure predominately or entirely in the circumferential direction, while exhibiting little or no tension longitudinally. This will be discussed in more detail in the context of the Space Activity Suit specifically in Section V.

4. Breathing Cavity

For the purposes of this paper it is assumed that any viable MCP suit architecture will use a pressurized helmet to deliver the necessary breathing gas. This breathing cavity poses a few complications that must be addressed.

During ventilation in an MCP suit, the change in volume of the torso is significant, which thereby increases tensile stress of the fabric and correspondingly, counterpressure on the skin. This change in counterpressure would cause circulatory problems if not addressed. Therefore to provide adequate and consistent counter-pressure to the torso, this change in volume must be counteracted. For any feasible MCP architecture in the near future, the consequence is the incorporation of a torso volume-compensating bladder ("counter-lung"). This counter-lung would be on the chest, would be pneumatically continuous with the pressurized helmet, and allow for a consistent circumference of the wearer's torso area during all phases of ventilation, resulting in a consistent tissue pressure. Note this provides a different function than a rebreather-type counter-lung, which typically does not need to physically expand and contract during respiration and is instead used to capture and reuse the expired oxygen.

The helmet, delivering pressurized breathing gas to the wearer, could be otherwise comparable to a typical pressurized suit helmet, with the exception that it also must facilitate a transition from the pneumatic pressurization scheme of the head to the mechanical pressurization of the body. This transition, likely in the form of a seal, dam or donut, would not only need to provide a relatively seamless pressure gradient between the two regimes to avoid cardiovascular congestion, vacuum exposure, or blood constriction to the head, but do so while minimizing air leakage against the 180 mmHg (3.5 psia) air pressure differential, and providing a continuous pneumatic path to the counter-lung on the chest.

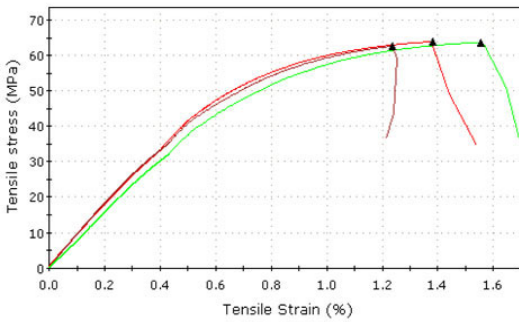


Figure 5: Typical textile stress-stain curve.

Note that the need for a counter-lung assumes passive materials; i.e., fabrics that exhibit an increase in tensile strength as they are stretched. For reference, shown in Figure 5 is a standard curve output from ASTM 5034, Textile Strength and Elongation. As the fabric is stretched, the tensile stress increases. However, an MCP garment needs to apply a consistent hoop stress to the body. During inhalation, the lungs and torso expand, which correspondingly increases critical dimensions such as chest circumference. A tight-fitting elastic fabric on the torso would also increase circumferentially, and a fabric such as is illustrated in Figure 5 would then exhibit increased tension and therefore increased pressure onto the skin, inhibiting breathing and ultimately, blood flow. Anecdotally, this matches personal experience of what it feels like to breathe while wearing a very tight garment. Any typical material would have a similar strain-stress curve and would therefore exhibit this same phenomenon, which is why a counter-lung is assumed. It may be possible for a fabric's stress-strain curve to contain a flat section in the region needed for sufficient tissue pressure, and over a domain that encapsulates the length change during respiration; although so far, no such fabric has been developed nor is it definitively known to be achievable.

It is also theoretically possible that in the future, a "smart" material, possibly a nano-material, biomechanical or shape memory material, could actively maintain a constant tension through a large increase in strain. Although it did not focus on the issue of breathing volume compensation specifically, some work was conducted by Holschuh et al on shape memory alloys, which could be integrated to a fabric and change length or stiffness as a function of voltage. The work demonstrated the basic feasibility of using shape memory alloys to provide a change in length of 40% with as little as 2V.[12] Although this change in length was shown to enable counter-pressure of greater than 200 mmHg (3.9 psia) around a sample rigid cylinder (demonstrating feasibility to improve ease of donning), future improvements may enable a constant counter-pressure around a cylinder of changing diameter.

That said, a garment such as this would likely require a complex network of tension sensors and power transmission to provide a feedback loop capable of measurement of individual fabric hoops (the required spatial resolution of which is not currently known) and then apply a corresponding per-hoop voltage in real time. Such active materials or others as mentioned may possibly eliminate the need for a breathing bladder in the future, but as of this writing they are many years off. Therefore, currently advanced textile development appears to be the best approach, which would be paired with a compensating breathing bladder. Note that these advanced textiles may be able to solve yet another potential problem with MCP, which is insufficient pressure application after a microgravity-induced deconditioning of the wearer, manifested specifically in reduced muscle mass, therefore body segment circumference and ultimately tissue counterpressure. A yet-to-be-developed advanced fabric could solve this issue as well. These materials and solutions will be discussed in greater detail in an upcoming paper investigating MCP technology gaps and a NASA strategy to best address them in the future.

5. Thermoregulation

One of the key hypothetical advantages of the MCP architecture is better characterized as a disadvantage of gas-pressurized suits: being constructed of an air-tight bladder surrounding the skin, traditional space suits significantly undermine the human body's natural mode of thermoregulation via convection and sweat evaporation. Therefore traditional EVA suits employ liquid cooling garments that carry cold water through tubing near the skin as a means of transporting heat away from the wearer; this heat is subsequently removed by specific components in the portable life support system backpack. Partly in an attempt to improve ventilation near the skin and provide some means of latent heat removal, large tubes pull warm, moist air from the extremities. These tubes add additional bulk and pose occasional comfort and mobility issues.[13] This is what is required, however when encapsulating the human body in what is effectively a balloon.

An MCP suit would not need to deal with these complications. As long as an MCP suit is constructed of a material that permits transmission of water (as would nearly any fabric, even those with poor "breathability") the vacuum of space will provide the means to evaporate perspiration and other diffused water directly from the skin, furnishing a significant cooling potential. Not only would this eliminate the need for the liquid cooling garment and the ventilation tubes used in gas-pressurized space suits, it would also abolish the necessity of heat removal from the water system, and potentially the

entire water system completely. As a result the portable life support system is reduced in complexity, mass and potential failure modes. Estimates for the reduction in mass are on the order of 1/3.[14]

However, there is a problem to consider, and that is water loss. Between diffusion losses of water directly from the body through the dermis to vacuum, sweat losses, and respiratory losses due to breathing dry air, the amount of water loss by the crewmember could be significant. Analytical calculations of diffusive and sweat water loss in literature for MCP suits suggest an excess of 0.5 L/hr, or 4 Liters (8.8 pounds) of water during a full 8-hour EVA. Addding in respiratory losses increases these estimates to 2 L/hr or higher – corresponding to 16 Liters (35.2 pounds).[7,8] Both of these estimates, if remotely accurate, suggest an unsustainable physiological state resulting in severe dehydration and cognitive deficit. Humidifying the breathing gas could help reduce the respiratory losses, but poses design complications with the need to add water back into the system. Of course, this issue could be eliminated by making the MCP fabric or one of the other outer protective layers impermeable to water vapor, but naturally this would result in completely losing MCP's advantage of natural thermoregulation, thereby adding in an LCVG which may be a very difficult challenge in an MCP architecture; therefore this is not considered a credible solution.

Note that eliminating the liquid cooling garment and leveraging the human body's natural thermoregulation does not eschew the need for thermal protection in extreme hot or cold environments. The thermal micrometeorite garment (TMG) on the current EMU provides thermal protection from incident solar infrared radiation, while also providing ballistic micrometeorite and cut/abrasion protection. Even if, when in direct sunlight the wearer of an MCP suit could maintain thermal equilibrium via sweat evaporation to ambient vacuum, the skin temperatures alone would be a problem as the outer fabric sees a sink temperature of +120 °C (+250 °F) and conducts that heat directly to the skin. Therefore, some manner of a TMG will be required, one which would presumably provide dust protection on the Moon or Mars as well.

Also worthy of mention is that fact that the inherently open structure of an MCP suit fabric may cause accumulation of ice on the suit as perspiration water freezes in cold sink temperature environments. To the author's knowledge, there has been no work to validate or retire this as a risk of an MCP architecture. Lastly, consideration may need to be made for planetary contamination implications of a suit architecture which, by its very nature allows free exchange between the crewmember's skin and the planetary body. While this is not within the scope of this paper, it is important to note and perhaps, others to consider in the future.

To conclude the physiological implications of MCP, the theory behind mechanical counter-pressure suits is that, a breathable atmosphere is provided by means of a pressurized helmet, and a comparable external counterpressure is provided using a tight-fitting, elastic garment covering the rest of the body. If the garment could apply pressure to the skin at a magnitude so as to prevent physiological issues associated with vacuum exposure, and sufficiently uniform so as to prevent circulatory failure, such a garment could be used in lieu of a fully pressurized space suit. This is the core basis behind the concept of mechanical counter-pressure suits: to provide a physical contact pressure against the body instead of a pneumatic one. It was upon this basis that Dr. Paul Webb devised of the concept of the Space Activity Suit and sought NASA support to develop and test it.

IV. The Elastic Sleeve-and-Glove

Under NASA contract NAS l-6872, Dr. Paul Webb and James Annis developed and tested a mechanical counterpressure glove and arm, the detail of which was provided to NASA Langley Research Center in contractor report CR-973 in December 1967.[8] In the report, titled "*The Principle of the Space Activity Suit*", Webb and Annis deftly lay out the basis of the MCP concept and its theoretical advantages over fully pressurized space suits of the time, then discuss the physiological implications and potential issues of concern. What follows next is documentation of a prototype development and testing effort whereby Paul and Annis designed and fabricated an MCP glove and arm with a torso interface, then tested this hardware in a relative vacuum glovebox at both ambient and sub ambient conditions. This section serves as a comprehensive summary and analysis of the work completed under this contract, which was primarily documented in CR-973; however, some additional context as noted has been taken from *The Space Activity Suit: An Elastic Leotard for Extravehicular Activity*, published in *Aerospace Medicine* in April 1968.[15]

A. MCP Physiology and Design Guidelines

Much of report CR-973 serves to explain the underlying principles of the mechanical counter-pressure concept, address the varied physiological concerns of note, and define the general design guidelines that would follow in fabricating a prototype. In addition to many of the topics already discussed here previously, Webb and Annis also discuss the possible need for "soft joint" designs for the elbow, shoulder and other areas where providing sufficient counter-pressure would be challenging. These joints would be composed of bags of lubricated balls or silicone oil that aid in transmitting pressure while maintaining a consistent body segment circumference through the range of motion.

For the sake of brevity, we can summarize the general design guidelines to say that a minimally acceptable theoretical breathing pressure of 150 mmHg was selected (as noted, corresponding to 8,000 feet or 2,438 meters elevation) as well as a minimally acceptable mechanical counter-pressure of 100 mmHg (1.9 psia). This pressure configuration, if used on an entire MCP suit, would reflect the absolute minimum of what could be considered acceptably safe, and also would place the crewmember in a positive pressure breathing scenario at 50 mmHg (1.0 psia) which has been shown to be possible for trained individuals, but uncomfortable and unsustainable for any significant length of time.[9] However, as a proof of concept of MCP, it was in retrospect, an appropriate place to start.

B. Design

Various materials were evaluated for the SAS glove concept, and ultimately a "bobbinet" weave was selected which used cotton-covered rubber in the warp and 100-Denier Nylon in the fill. The fabric had two-way stretch, but more power in the warp, and for that reason the arm sleeves were cut such that the warp ran circumferentially up the arm. Of note is the fact that this material was developed in conjunction with the Jobst Institute, local to Dr. Webb at the time, and the predominate manufacturer of fabric-based compression stockings (colloquially referred to as "Jobst stockings").

Also of interest is that vacuum compatibility was a key driving requirement – many fibers lose elasticity or strength as a result of vacuum off-gassing. The final material selected was exposed to vacuum for a short time (48 hours) and deemed to have no deterioration. Future work should evaluate candidate fabrics for longer periods of vacuum exposure to ensure long-term acceptability, but for the scope of NAS 1-6872, the compatibility assessment conducted was quite adequate.

The SAS sleeve was sized by taking circumference measurements of the subjects every 1.5" (38 mm) and applying an arithmetic modifier based on the known fabric stretch and power characteristics to provide the targeted pressure. Flatlock seams were used in the final design, which used two layers to cumulatively apply a targeted 100 mmHg pressure. It was reported that the glove fingers did not require two layers, which is likely due to the fact that the small, cylindrical anatomy made it easier to provide the prescribed counter-pressure.

"Soft joints" as previously discussed, were explored by evaluating a 100-mL bag of 1/8" (3.2 mm) Lucite spheres and a thin-walled silicone oil-filled rubber tube strategically placed at the elbow under the elastic fabric. Visually these approaches seemed to be successful in providing a constant convex surface at the elbow joint, which would prevent gaping of the bobbinet fabric. Ultimately, it was determined that such joints were not necessary with this prototype. Given the low pressure application of the SAS glove, coupled with the small surface area, this conclusion is not incredibly surprising, but a full-pressure garment may have been different. Certainly, even more concave areas like the shoulder, crotch, small of the back and armpit would have been more challenging still and would have likely required some form of special treatment.

Otherwise the glove used molded silicone pads on the palm and back of the hand. Early testing indicated capillary damage of the skin adjacent to the metacarpals on the back of the hand without the pads due to fabric gaping. Interestingly enough, despite the fact that the fabric also gaped over the palm and therefore saw no exerted pressure, there were no such petechiae at this location. It was surmised that the palm dermis is both thicker and better bonded to underlying structures, which provided more inherent protection against vacuum. Still, in order to provide some degree of palmar counter-pressure, a silicone pad was used.

The transition from the mechanical counter-pressure regime of the arm placed inside the glovebox and the pneumatic pressure regime outside the glovebox, was problematic but ultimately solved by a combination of a rubber cuff, rigid plastic cuff, hose clamp and caulking compound. Practically speaking it appeared to be comparable to what we today call a vibration-isolating hose clamp, filled with caulk. While relatively crude, it was effective for the pressure differential tested and the purposes for which it was devised.

C. Testing

Evaluation of the SAS sleeve-and-glove consisted of negative-pressure glove box evaluations at -50, -100, -150 and -200 mmHg, with a final altitude chamber test where the ambient pressure was reduced to 155 mmHg and the glovebox was set at -150 mmHg, resulting in near-vacuum inside the glovebox and a mechanical counter-pressure matching that of ambient. Performance evaluations were primarily subjective in nature, with subjects demonstrating flexibility and tactility, while heart rate was used to evaluate metabolic cost (which has since been shown to be a poor indicator).[16] In addition to heart rate, other physiological parameters were also evaluated to gauge viability – skin temperature as a sign of decreased blood circulation, pre- and post-test water displacement to measure cardiovascular congestion, and arterial inflow and venous outflow using an ultrasonic flow meter.

Chamber testing confirmed a lower skin temperature, up to 7 °C cooler than the control hand and cooler than the glovebox or ambient environment. This confirmed what theory had suggested, that MCP provides a potential for very strong cooling through evaporative water and sweat loss from the skin.

There was moderate swelling of the arm, depending on the test up to 10%. It was noted that swelling below 5% disappeared within a few hours and not uncomfortable, while swelling in the 8-10% range took 24 hours to disappear and was typically associated with some degree of subject discomfort. A comparison with literature available at the time indicated that the volume of swelling observed in this pressure environment was commensurate with the sleeve delivering 50-100 mmHg of pressure, with additional pressure being provided by the skin itself and transient pressure provided by tensing of the muscles of the arm and hand. The degree to which the noted swelling was a result of cardiovascular congestion versus generally low pressure is unknown.[17]

Also interesting is that as part of this testing, unprotected arms and hands were exposed to various levels of vacuum to gauge physiological tolerance. While it is difficult to draw a definitive conclusion, it appeared that a 60 mmHg pressure deficit on the arm was enough to result in ischemic pain, with pain increasing as the pressure deficit increased, ultimately resulting in severe pain, petechiae and "circulatory collapse" (failure of cardiac output) with a very brief exposure of 175 mmHg.

By way of a conclusion, recounted here are excerpts directly from the original report's conclusion:

> The principle of the Space Activity Suit has been tested successfully with a full glove and sleeve garment designed to deliver 100 mm Hg pressure to the tissue, and which functionally appears to deliver between 50 and 100 mm Hg.…While it would be desirable to have an elastic sleeve which delivered 150 mm Hg of pressure to the tissue when the breathing pressure was 150 mm Hg, such a garment at present looks to be difficult to make, and heavy, and possibly limiting in mobility…There was no evidence of gas forming in the hand or arm when the arm was exposed to a near vacuum (less than 8 mm Hg). Circulation was adequate. Mobility, flexibility, and dexterity of the hand were excellent.
>
> There is no present hindrance to the construction of a full SAS for laboratory testing. Problems to be overcome include developing sufficient hoop tension in the larger diameter segments of the body, improvement in ease of donning and tensioning of the elastic material, and assuring adequate circulatory balance for a four-hour period. Since the SAS is designed for an active person, testing should be done with much physical activity, which will help venous return in the same way it may be aided in actual use by an active astronaut in space…A full SAS can be tested at ground level by using a regulator to deliver breathing gas at 150 mm Hg positive pressure; in this circumstance the protective effect of limb counterpressure can be measured, and the suit can be tested for mobility, metabolic cost, etc. Vacuum chamber testing for a full SAS suit can be deferred until a late stage in the development of the full suit.

To summarize, the SAS Sleeve-and-Glove was successful in that it verified at vacuum the underlying concept of mechanical counter-pressure. While the glove did not deliver the amount of pressure needed in a full suit to provide adequate respiratory function or to avoid extended positive-pressure breathing, the two-layer garment applied sufficient pressure to avoid significant physiological issues for the arm for up to 20 minutes. Taking the next step to another larger body segment or a full SAS suit seems like the most prudent approach given this success, and as Dr. Webb noted at the time, vacuum chamber testing could be deferred until later in development. Surprisingly however, based on the results of the sleeve-and-glove, NASA Langley Research Center funded development of an entire SAS assembly, with a breathing system, to be tested at vacuum.

V. The (Full) Space Activity Suit

Under NASA contract NAS l-8018, Dr. Paul Webb and James Annis developed and tested a mechanical counterpressure suit complete with helmet and breathing system, the detail of which was provided to NASA Langley Research Center in contractor report CR-1892 in November 1971.[7] In the report, titled "*Development of a Space Activity Suit*", Webb and Annis first restate and occasionally clarify the basis of the MCP concept and its theoretical advantages over fully pressurized suits, then discuss the physiological implications and potential issues of concern. Next, a prototype development effort is comprehensively documented whereby Paul and Annis designed and fabricated a series of ten Space Activity Suits. Testing of these suits began early and in parallel with development at ambient pressure in a laboratory environment. Final testing occurred in a vacuum chamber at The Ohio State University, where the goal was to evaluate the final SAS prototype for two hours at a pressure of 20 mmHg (80,000 feet equivalent). This section serves as a comprehensive summary and analysis of the work completed under this contract, which was primarily documented in CR-1892; however, some additional context has been taken from *The Space Activity Suit: An Elastic Leotard for Extravehicular Activity*, published in *Aerospace Medicine* in April 1968.[15]

A. MCP Physiology and Design Guidelines

In the beginning sections of CR-1892 Webb and Annis lay out a more detailed and refined assessment of the physiological implications and concerns associated with MCP, culminating in determination of driving requirements for the SAS fabrication and testing effort. Assuming that this report should supersede any small inconsistencies with the previous sleeve-and-glove report, the following are the primary conclusions:

- The inherent tensile strength of human skin is several orders of magnitude stronger than what is required to prevent unsupported skin exposed directly to vacuum from being extruded through the tensile mesh created by an MCP fabric under nominal tension.
- Gaseous percutaneous diffusion of O_2, CO_2 and N_2 are cumulatively on the order of a few hundred mL/hr, which could easily be made up in O_2 by the breathing system.
- Percutaneous diffusion and respiratory loss of water would likely not exceed 2 L/hr, which is admittedly high but was reportedly tolerable in thermal stress tests conducted around that time. This high water loss rate presumably drives a proposed EVA period of four hours, although that connection is never specifically stated.
- A breathing pressure of 170 mmHg O_2 is selected for the SAS to ensure safe respiratory function/
- Adequate counter-pressure against the 170 mmHg must be provided to ensure venous return and maintain circulating blood volume ; previous testing had shown that as little as 200 mL of circulatory blood volume loss due to pooling, coupled with the physiological stresses of positive-pressure-breathing may increase the risk of fainting.[9]
- A volume-compensating breathing bladder on the chest is necessary to provide adequate tissue counter-pressure during ventilation.
- 100g/hr of water loss will provide cooling sufficient to offset half of a resting metabolic load.
- Evaporation of sweat will provide sufficient total cooling capacity, with a peak 4 L/hr sweat rate associated with 2320 kcal/hr metabolic rate, well in excess of typical EVA metabolic rates.

In conclusion, a reasonable 170 mmHg was chosen for the SAS, which is minimally acceptable but the use of which may or may not be operationally challenging for pre-breathe depending on future habitat designs. The need to provide sufficient pressure was recognized; the use of a counter-lung aids in this during cyclic ventilation, and the use of PPB, while not acceptable or practical in a flight design, allowed the SAS prototype to provide sufficient breathing pressure while not always providing a matching tissue counter-pressure. Lastly, while evaporation can provide more than adequate cooling potential, water loss may be an issue during a multi-hour EVA. Extrapolation to a reasonable 500 kcal/hr metabolic rate suggests a sweat rate of 0.9 L/hr – still quite high. Presumably, as a result Webb proposed a 4-hour EVA period, although current EVAs typically last 6-7 hours in duration. Even then, a crewmember conducting a 4-hour EVA at an average metabolic rate of 500 kcal/hr could have a weight loss of 3.5 kg, which is not insignificant.

B. Design

It is difficult to briefly summarize the very lengthy iterative design process undertaken with the SAS, or the detailed documentation of such in the final report. For a more thorough and complete appreciation of the SAS design process and detailed fabrication, the reader is urged to read report CR-1892. Note, however, the high-level design philosophy that the SAS operated under at the time:

> The main garment design objective throughout the program was to retain the purity of the original concept of a form fitted leotard. The inclusion of special structures or other variations in the basic garment was considered only after physiological evidence indicated the absolute need. The development of joint structures, for example, had proven with the full pressure suit to be a difficult and costly task.

In terms of sizing, one item of interest is that a custom sizing tape was invented which allowed simultaneous circumferential measurements every 1.5" (3.8 cm) at a granularity of 1/8" (3.175 mm). In total, approximately 150 measurements were taken of each subject to fabricate the SAS prototypes. It is noted that any future MCP suit would likely leverage 3D body laser scanning, something that was not available to Webb at the time.

Three different elastic fabrics were used in the SAS prototypes. First, a bobbinet very similar to the bobbinet used in the sleeve-and-glove as shown in Figure 6. It was constructed of 50-60 gauge rubber cord, wrapped in 140-Denier cotton and filled with 140-Denier Nylon. The bobbinet was able to exert up to 15 mmHg of pressure on the torso (large radius) or 40 mmHg on the wrist (smaller radius) while not exceeding more than 50% of the available stretch to avoid plastic deformation – a general design guideline adopted when selecting fabrics and determining patterning.

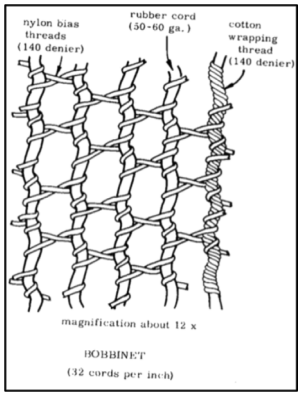


Figure 6: Bobbinet fabric.

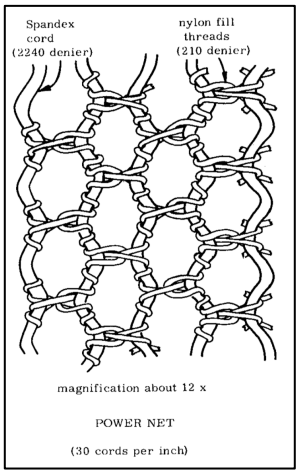


Figure 7: Powernet fabric.

The second fabric was a powernet specified by Webb Associates and Jobst Institute, and developed by Liberty Fabrics in New York, NY. In an effort to reduce the number of layers required to apply the 170 mmHg pressure, this fabric was constructed out of the largest Elastane (Lycra, Spandex) fibers available, at 2240 Denier (25%) and a 210 Denier Nylon fill (75%). Early estimates of this fabric suggested application of up to 50 mmHg of pressure even on the large body segments such as the torso; however, comfort, closure and mobility issues were present with this degree of single-layer pressure application and therefore, layers constructed of the powernet were limited to about 35 mmHg. This fabric is shown in Figure 7 and strain-stress curves for the two fabrics is shown below in Figure 8.

The last elastic fabric was a lighter-weight powernet of 280-Denier Elastane and 100-Denier Nylon, used primarily as a low-power baselayer over which the more powerful fabrics were slipped. Henceforth this fabric was termed the "slip layer" and was not considered to contribute to the cumulative pressure applied to the body. This layer also contained prescribed bioinstrumentation.

All manner of various closure devices were evaluated or considered for the SAS, including the expensive and complex before settling on the simple – as discussed by Webb:

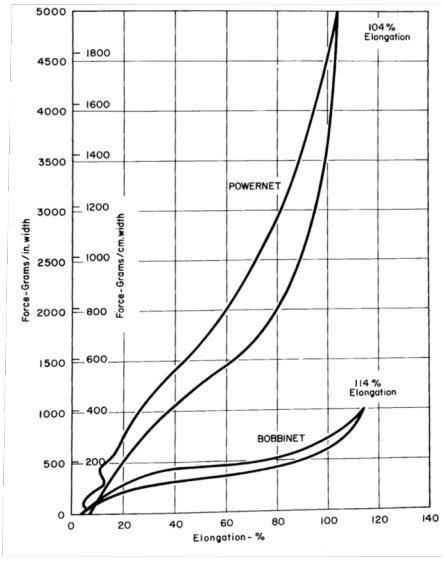


Figure 8: Stress-stain curve of two fabrics used in the Space Activity Suit

> More complex mechanical assistors were considered, such as compressed air driven clamps, exoskeletal frames, and hydraulic cylinders; however, investigation into the development and construction of complex devices proved that it would have been far too costly and time consuming at this stage in the development. Although these types of donning and closure machines are theoretically feasible for use in the laboratory, they would not readily lend themselves to use in space. Our design objective then became a garment assembly which could be donned and closed using fairly simple devices or none at all. Considered as the best compromise, the zipper was retained as the principal donning entry and closure device throughout the project. The development of motorized and/or elastic zippers was rejected by zipper experts as being infeasible, impractical, or too costly.

Note that there were many other fabrics and materials used in the SAS – rubberized fabrics, neoprene, and foam for sealing surfaces and transitions, creating or covering comfort or cavity pads, and the pressurized breathing bladder. A total of ten different garment assemblies were fabricated during this project, each different than the last and applying different amounts of pressures at different locations and using different solutions to solve problems.

In addition, multiple iterations of the helmet and improvements to the breathing system were made over the course of the SAS development; however, for lack of space here they are considered outside the scope of this paper and only mentioned as it relates to the overall physiology or general system acceptability. One item related to the potential for significant water loss is that 225 grams of water was measured out of the water trap of the breathing system after two hours of use; however the metabolic rate, nor the significance of this particular data point is not known.

Of special interest is the helmet and manner in which it provides a pressure transition from the pneumatic regime of 170 mmHg O_2 and the mechanical regime on the body. Shown at below in detail (Figure 9) a neck seal and dam were used to achieve this transition.

Also note the pressurized torso bladder, the interconnecting airway with the helmet, and the hard breastplate which served to hold the helmet in place and mitigate helmet rise. The reader is encouraged to read the full report which outlines the detailed design and development process for each of these hardware items.

As far as the SAS garment, a representative incremental layup is shown below in Figure 11. This figure outlines the various details of the SAS #7. More detail is available in Appendix A of CR-1892. Garments 8 and 9 differed in that they used one less power layer, but added webbing on the torso as a helmet pull-down strap.

Space Activity Suit #10, the final garment, was fabricated to provide 170 mmHg counter pressure and support positive pressure breathing at up to 200 mmHg. This design consisted of the following layers; some photos of this garment in various stages are shown below in Figure 10:

- Slip layer
- Torso pressurizing breathing bladder
- Helmet-bladder restraint garment – two full-body garments to aid in controlling helmet rise while providing up to 25 mmHg each to the arms and legs
- Arm balance layer – 30 mmHg added to the arms to balance counter-pressure with the legs
- Full-body bobbinet – Two garments, each applying 15 mmHg to the torso and 25-30 mmHg to the limbs
- Third bobbinet – optional bobbinet layer to support breathing pressures above 170 mmHg
- Girdles – Two powernet girdles, each with gradient pressure application on the upper thigh (35 mmHg) and lower torso (15 mmHg), shown to be needed when breathing pressure exceeded 140 mmHg.
- Gloves with filler/comfort pads and booties from earlier assemblies

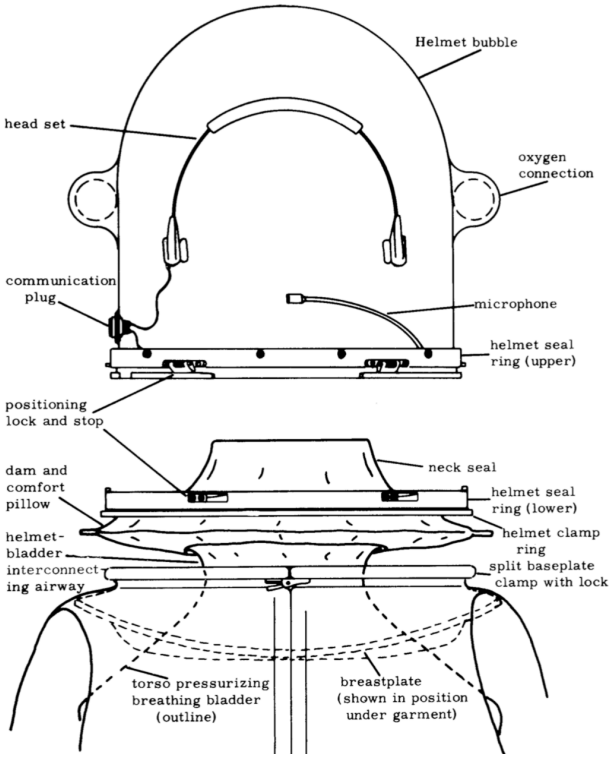


Figure 9: Final SAS helmet and integration thereof.

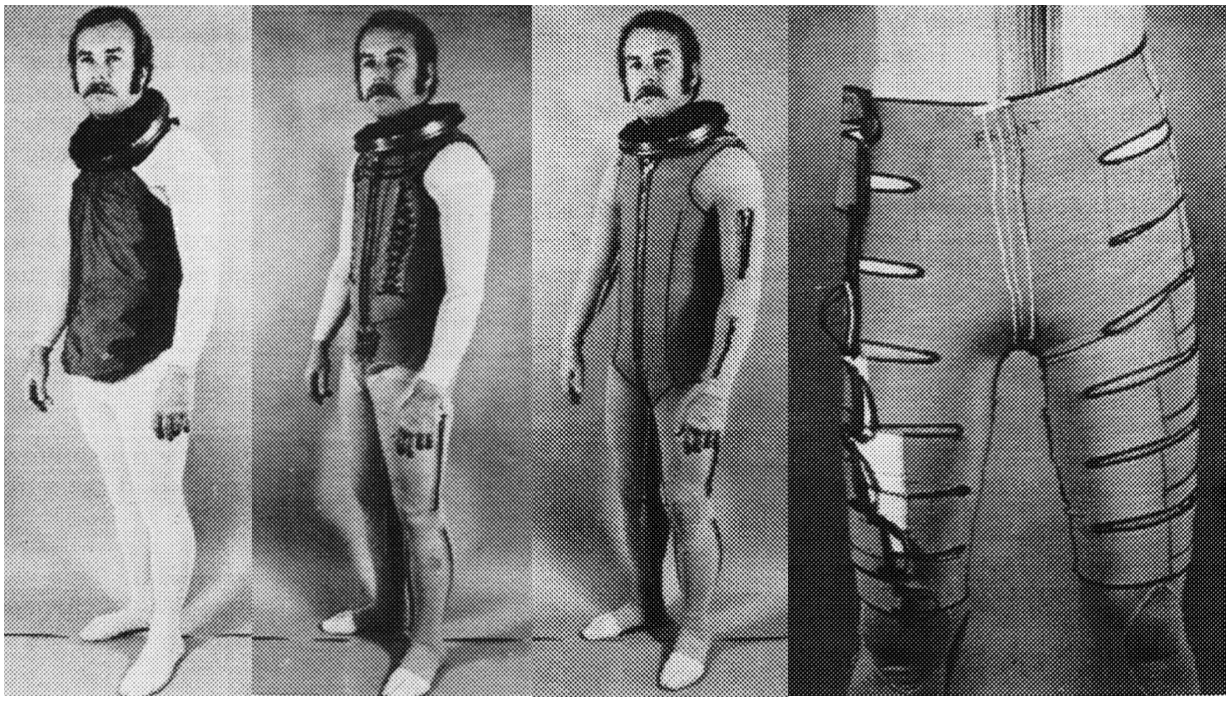
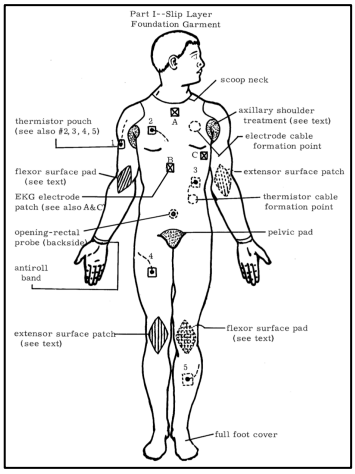
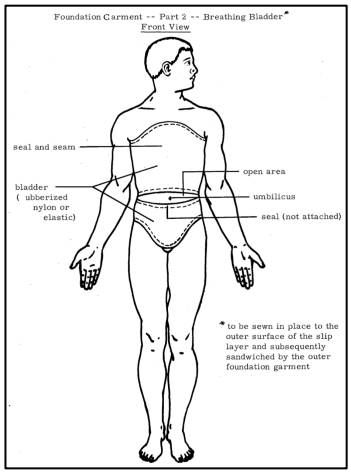


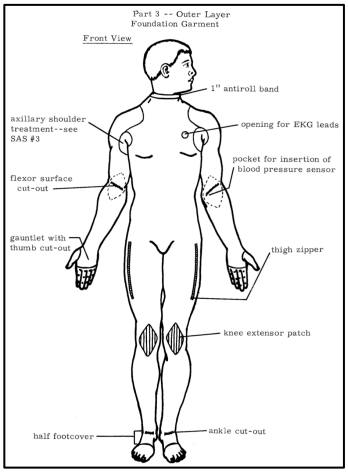
Figure 10: SAS #10 in various stages of donning. Note the counter-lung in the photo at upper left.



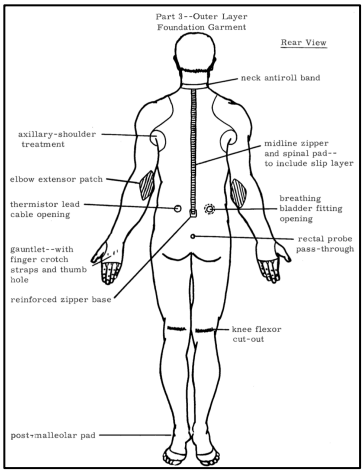
SAS Layer 1: Slip Layer



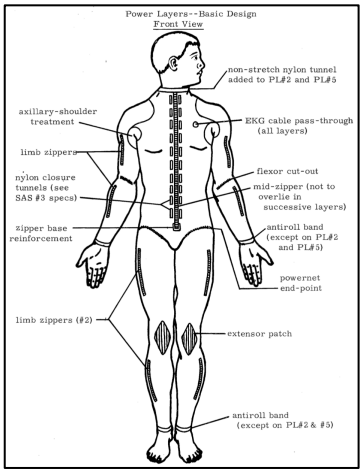
SAS Layer 2: Breathing Bladder



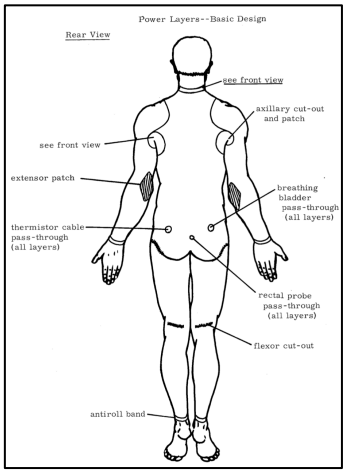
SAS Layer 3: Foundation (front)



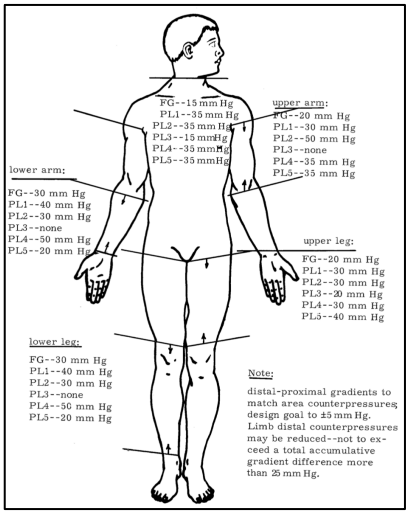
SAS Layer 3: Foundation (rear)



SAS Layers 4-8: Power Layer (front)



SAS Layers 4-8: Power Layer (rear)



Estimated pressure applied per layer and general anatomical area

Figure 11: Representative layup of an SAS prototype garment assembly with corresponding pressures

It is difficult to contextualize the design of the SAS without discussing it in tandem with the ongoing testing of the various SAS prototypes occurring concurrent with design. This testing was completed in two phases. The first phase consisted of 15 tests in the laboratory to verify the principle of the SAS at breathing pressures up to 170 mmHg, followed by five tests in the altitude chamber at 80,000 feet equivalent (20 mmHg). During Phase I, SAS garments #4-9 were used, with garments #8 and #9 being the primary test articles for the altitude chamber.

The objective of Phase II was to improve the SAS overall, in terms of safety and integration and to increase the possible breathing pressure to 200 mmHg. Similarly to Phase I, a laboratory phase consisting of 15 tests were followed by three tests in an altitude chamber. During Phase II, SAS garments #6-10 were used, with garment #10 supporting the latter half of the laboratory tests and all three of the chamber tests.

In general, the proceeding analysis of the SAS test campaign will not delineate between which garment was used for which test. Instead, given the significant amount of parallel testing conducted with development, it is assumed that the garment tested was the best available at the time, and that the final garment, SAS #10, which was used for the last 10 tests including the only altitude chamber tests in Phase II, represents the best possible SAS configuration and should be considered the most representative of the then-current state of the art. For specifics on which garment and configuration were used for each test, and more detail on the tests in general, the reader can refer to the NASA report CR-1892.

C. Testing

Three subjects were used for testing of the SAS for both Phase I and Phase II. All three subjects were employees of Webb Associates at the time. Subject A "developed a respiratory problem early in this test phase and was dropped from further testing as a precautionary measure" (no additional information is available).[7] The remaining two subjects were used evenly throughout the entirety of the test campaign; both had diving, test subject and altitude chamber experience; all were above average fitness. Subject C was a trained Navy diver.

It is also important to note that for all tests, test time was defined by "helmet time" and not fully donned time, chamber time or time at a particular altitude. Therefore stated test durations throughout the report should be considered in this context. For example, the final two tests completed in the altitude chamber are reported as lasting 145 and 125 minutes, respectively; however, a review of the chamber profiles reveals that each test lasted about 45 minutes above ground level, and only about 30 minutes above 30,000 feet (9,144 m). Furthermore, one test spent about 5 minutes at 60,000 feet (18,288 m) equivalent and the other, 5 minutes at 80,000 feet (24,384 m). More on this detail and how it relates to the success of the SAS overall will be discussed later in this section.

First, a great degree of instrumentation and measuring devices were used during testing to verify physiological safety and evaluate SAS performance. The following were used throughout most of the testing except where noted:

- Heart rate
- Limb volume change (H_2O displacement)
- Blood pressure
- Orthostatic intolerance (tilt table)
- Breathing pressure
- Respiratory rate
- Oxygen consumption (metabolic cost)
- Respiratory volume
- O_2, CO_2 and N_2 breathing loop sampling
- Skin temperature
- Rectal temperature
- Ambient temperature
- Water loss (nude weight change)
- Hemoconcentration
- Mobility (goniometry, flexometers)
- Dexterity (Purdue peg board)

During testing, subjects were also requested to engage in all manner of physical activity tasks, including walking, bicycling, rowing, and weight lifting. These tasks served two functions: first to evaluate overall mobility and metabolic cost in an attempt to compare against the then-current Apollo suit; second, as previously noted, a nominal degree of strenuous activity aids in increasing blood pressure and therefore in venous return, preventing circulatory failure. The fact that strenuous activity was prescribed as a safety measure to prevent syncope should be noted. It is expected that in addition to high-metabolic rate periods, future EVA crewmembers will be engaging in long periods of low-metabolic activity as well.

During early testing, various methods of directly measuring physical counter-pressure were evaluated, from strain gauges as used by the Jobst Institute to blood-pressure cuffs modified with electrical bridges to indicate loss of internal contact and therefore, a cuff pressure roughly matching that of the garment counter-pressure. The acceptability of these methods was mixed and seemed to be used to provide rough insight during early development, not as a constant monitoring device during testing.

Donning time for the various SAS assemblies ranged from 45-60 minutes, while doffing averaged six minutes. Donning multiple layers at once was attempted with varied techniques, none of which proved to be successful. In terms of high-level acceptability, Dr. Webb at one point states the following, from which the reader is free to draw their own conclusions:

> No conscious attempt was made to establish a maximum wear period for either partial or full SAS assemblies. There is little evidence from our studies that assemblies requiring up to 100 mm Hg breathing pressure for balance could not be tolerated indefinitely. Assemblies that theoretically require breathing pressures in excess of 130mm Hg appear to be time limited to approximately 3 hours wear by the moderately active subject. The limiting factor in the higher pressure experiments, in addition to generalized physical fatigue, usually manifested itself as an elevation in heart rate.

1. Laboratory Testing

Cumulatively, across the 30 ground-based test points in Phase I and Phase II, the SAS seemed sufficient at maintaining venous return and circulating blood flow so as to at a minimum, prevent syncope at breathing pressures up to 170 mmHg. However, mild tachycardia was prevalent above 110 mmHg breathing pressures, with heart rates increasing correspondingly with the breathing pressure. Powernet girdles were added to the final assembly to try to provide additional pressure to the upper thigh and lower torso areas. Hand and arm swelling were characterized to be approximately 26 cc/hr regardless of the breathing pressure, and was never eliminated completely despite concerted efforts. Tilt table testing indicated a marked difference between the SAS and unsuited control cases, although again, no major circulatory issues were prevalent and all test points were completed without incident.

Thermoregulation seemed positive in early laboratory testing, indicated by consistent core and skin temperatures, with the exception of thermocouples placed under the impermeable torso bladder. While water loss measurements were taken in these laboratory tests, they are not indicative of acceptability in a vacuum, where the skin is exposed below the triple point of water and no convective cooling can occur. Detailed discussion of thermoregulation potential will be investigated further in altitude chamber testing.

Metabolic testing indicated that the SAS was superior (less energy cost) to the Apollo suit, but perhaps not as much as originally hoped. When walking at 3.2 km/hr, the pressurized Apollo A7L suit at 1G was estimated to have a metabolic cost of 225% of unsuited, while the SAS cost the two subjects 150% and 117%, respectively. Note that the SAS did not include an environmental protection garment as would be required for dust and heat protection, while the Apollo suit did. Recent work at Johnson Space Center has indicated that the TMG is a significant contributor to overall mobility reduction and metabolic cost.[18] Second, as reported in recent extensive suited testing, the metabolic cost of carrying additional mass is exaggerated at 1G when comparing suits intended for partial or zero gravity environments.[18] The SAS was approximately 6.5 kg with an additional 18 kg breathing system (not worn for all tests) while the fully loaded A7L suit was 91 kg.[5] Comparative metabolic cost evaluations of these two systems in 1G would result in a significant disadvantage for the heavier system regardless of mobility. A review of metabolic cost of pressurized space suit assemblies of different masses was considered for this paper, to determine an estimated degree to which the A7L suit would be penalized in metabolic cost based on weight alone compared to the SAS. However, considering the poor heritage of the originally referenced A7L data, coupled with the low subject count and high standard deviation of the SAS data and the fact that different subjects and test methods were used, it was determined to be of limited value.

The SAS exhibited its own form of difficulty in motion as referenced throughout the final report due to the tight-fitting constricting layers of fabric. Suffice to say, while it appears that the SAS may have had a metabolic cost advantage in 1G over the state of the art pressurized suit at the time, the degree to which this is the case is unknown and will likely never be known. Meanwhile, since 1971 pressurized space suits have advanced tremendously in terms of mobility and metabolic cost, and fabrics and fabrication techniques to support an MCP suit have undoubtedly improved significantly as well; therefore undertaking further retrospective metabolic analysis comparing the SAS to the A7L would be an effort primarily academic in nature.

Mobility of the SAS was measured and compared to known literature of the time. Subjectively, mobility at 100 mmHg applied pressure was evaluated by Webb and Annis as “extremely good” while at 170 mmHg, “reasonable”. The reason for this mobility deficit compared to nude values was undoubtedly the constriction caused by multiple tight-fitting layers of fabric; specifically, the fabrics exerting circumferential pressure were also applying a longitudinal load. For example, during elbow flexion, these fabrics not only created bulk and bunching at the inside of the elbow, but also tension on the outside of the elbow. Therefore, an ideal MCP fabric would not only apply sufficient pressure circumferentially in as few layers as possible to eliminate this bunching, but also apply little or no

longitudinal load while doing so. In addition, hip mobility was remarkably reduced in the SAS and this was further explained by stiffening of the torso breathing bladder and pulling of the crotch by the pressurized helmet; essentially helmet pressurization axial loads were transmitted from the neck to the crotch, further stiffening the fabric in that area and decreasing mobility.

In the final report, a direct comparison against data from ongoing pressurized suit development at the time was referenced but not directly reported; henceforth the actual comparative mobility data is provided for the first time here. Direct measurements of joint angles provided in the SAS report as a percentage of nude mobility are repeated here, along with direct comparison of data from the referenced NASA report on evaluation of three suit assemblies from 1966.[19] Note that the percentage of nude values are reported instead of direct joint angles due to differences between the two reports in terms of direct joint angles for various joints. Reporting and comparing the percentage of nude ability reduces the confounding variables of difference in technique or subject variation between the two reports. Also note that the NASA report included five measurements which were not evaluated with the SAS: Wrist-forearm flexion/extension; Hip rotation; Ankle flexion/extension; Waist rotation and Shoulder adduction/abduction in the transverse plane. The reason for this omission is not known; based on available data, it is presumed that the SAS would have performed better than the pressurized suits on the wrist, ankle and waist rotation movement, while the same or worse on the hip rotation and shoulder adduction/abduction. However, due to the complexity of human movement and the intricacies of suit joint programming (both pressurized and apparently, the SAS to some degree) it is impossible to say for sure how the suits would have compared on these remaining measurements.

Lastly, note that the ILC AX5L was the suit that performed the best in the NASA report, both in terms of pressurized mobility and overall, but was not the final flight configuration that was used on the Moon in 1969. Presumably, between the publication of the 1966 NASA report and the 1971 SAS report, several improvements were made to the AX5L baseline in what would eventually become the A7L and finally the A7LB flight suits. That said, as a basis of comparison, all four suits compared here were early prototypes and therefore, a direct comparison of raw mobility provides valuable insight into how well the SAS (at 170 mmHg counterpressure) compared against the pressurized suit development (at 3.7 psid or 191 mmHg, no TMG) at the time.

Table 2: Mobility comparison of Space Activity Suit and three Apollo suit prototypes

Movement	SAS Sub A	SAS Sub B	ILC AX5L	HS AX6H	DC AX1C
Wrist flexion/extension	95	97	78	83	83
Forearm supination/pronation	75	71	99	100	97
Elbow flexion/extension	96	84	100	85	71
Shoulder adduction/abduction	62	61	75	55	61
Shoulder flexion/extension	60	60	67	56	76
Shoulder rotation	98	100*	100*	94	100*
Waist flexion/extension	90	52	65**	79**	100**
Waist adduction/abduction	39	43	41**	21**	64**
Hip adduction/abduction	67	36	8	19	18
Hip flexion/extension	41	54	54	52	33
Knee flexion/extension	64	52	100*	93	89
Foot flexion	--	82	--	--	100**

* Reduced from above 100% ** Measured at vent pressure (otherwise 3.7 psid)

Dexterity testing was also compared to the 1966 NASA report using a Purdue pegboard test where subjects were asked to place as many small pins as possible in 60 seconds. In this comparison, the advantage of the SAS is at first more pronounced than the preceding mobility comparison: subjects were able to complete 67-82% of barehanded performance, compared to the best of the three suits (again the ILC AX5L) at 32-53%. However, as noted in the SAS report: "The scores presented were obtained wearing a single pair of SAS gloves which provide a maximum of approximately 100mmHg over the fingers. Two pairs of gloves were sometimes worn by subjects during full suit runs. Dexterity, therefore, would be less in the two layers of gloves." As previously noted, 100 mmHg of pressure at the hands when breathing the required minimum 170 mmHg oxygen pressure would almost certainly result in significant cardiovascular problems. Secondly, while the NASA report does not explicitly state this, the dexterity testing of the Apollo prototypes was likely completed with a full glove TMG, while the SAS testing was not. The reader is urged to consider these factors when reviewing the data on dexterity performance.

2. Altitude Chamber Testing

The goal of the altitude chamber testing was to safely achieve a pressure of 20 mmHg (80,000 feet equivalent) for a duration of two hours. Before testing, a prebreathe period of at least two hours on 100% O_2 was enforced for denitrogenation, plus an additional approximately 45 minutes during test preparation and pre-helmet donning.

The first three chamber tests, conducted in Phase I, were relatively short by design in that they were training and checkout runs of 25-45 minutes each; approximately 30 minutes was spent cumulatively above 30,000 feet equivalent. In these short tests, everything seemed physiologically nominal except for a few items of interest: heart rates were elevated at higher breathing pressures; arm swelling averaged 34 mL across two tests; N_2 in the breathing loop was higher than expected and likely due to trapped gas in the system during donning.

The fourth Phase I chamber test lasted 51 minutes from ground level to ground level, with approximately 1.5 minutes at 80,000 feet (24,384 m) equivalent. The test was terminated early due to subject fatigue, increased heart rate, a dangerously high nitrogen level of 14% in the breathing loop, and abdominal pain. One cause was determined to be trapped gas in the gastrointestinal tract. Further examination of the subject indicated no physical signs of damage otherwise. It was noted that the water loss rate during the test averaged 97 g/hr, which on its face seems acceptable but also obscures the evaluation period. Given that water loss was measured by nude weight loss of the subject, it can be assumed that the test period was at least the 126 minutes advertised "helmet time" plus 60 minutes for pre-helmet and post-helmet doffing, as well as general overhead associated with testing of this nature (human subject in an altitude chamber). Conservatively assuming 186 minutes (3.1 hours) as the test period over which the weight was measured suggests a total water loss of at least 300 grams during the test. Additionally, the rate of evaporative water loss increases as the chamber pressure decreases; when the triple point of water is passed, it increases suddenly and significantly – this is evidenced by the sweat trapped under the impermeable breathing bladder suddenly "flash-boiling" at the triple point of water, providing a sudden and marked cooling effect on the relevant thermocouple. There is no way of knowing how much of the 300 grams minimum water loss occurred below the triple point of water, but it was likely a significant portion. For the sake of argument, if 50% of this test's water loss occurred during the five minutes spent below the triple point, it would suggest a transient water loss rate of 1804 g/hr during an EVA at reduced pressure. For the relatively short 4-hr stated EVA period of the SAS, at least 7.2 Liters of water would be lost due to diffusive water loss, sweat and respiratory losses. Diffusive water loss changes significantly with pressure, and both analytical and experimental techniques suggest that water loss at reduced pressure would be significant, especially below the triple point of water.[20]

The final chamber test in Phase I lasted 25 minutes at altitude, with one minute spent at 15mmHg chamber pressure (87,000 feet equivalent) before the subject collapsed without warning. The test was terminated, and subsequent investigation determined the cause to be a failure of the breathing system itself. While this failure does not directly condemn the concept of the SAS, other data collected during the test provides insight similar to the preceding chamber run. Arm volume increased by 33 mL per hour of pressure breathing, while leg volume held constant. Circulatory blood volume loss was estimated to be 5%, or assuming a 6 L total blood volume, about 320 mL – possibly acceptable for short durations but as previously noted, within the range to increase the risk of syncope. Water loss was 185 gm/hr, which was noted to be high, possibly due to "increase in evaporative (and diffusive) water loss while at reduced pressure." Adopting the same assumptions as the previous test point suggests a total water loss of 398 grams, a transient water loss of 2387 g/hr when at reduced pressure and a total water loss for an EVA of 9.5 Liters.

Phase II included three altitude chamber tests, the first two of which were checkout and training runs. The first test did not go above 30,000 feet (9,144 m) equivalent, was at a lower breathing pressure and detailed results were not provided. The second test reached an altitude of 63,000 feet equivalent (46 mmHg) for five minutes, but was ended abruptly due a failure of a heart rate monitor. No further data was provided on this test.

The final test in Phase II and of the SAS overall was conducted using Subject C and by all accounts, should be considered the best opportunity for the SAS to prove conceptual feasibility and safety. The altitude goal of 80,000 feet (24,384 m) equivalent was met, but the test was terminated after only five minutes at this altitude due to the subject developing a "bends" pain in his foot. The test lasted 42 minutes in total, with approximately seven minutes below the triple point of water and 25 minutes spent above 30,000 feet (9,144 m). The altitude profile and temperature readings are shown in Figure 12. This graph is similar to graphs for all prior altitude chamber runs in both Phase I and Phase II, and it should be noted that time-dependent graphs of other data such as heart rate, etc are not published.

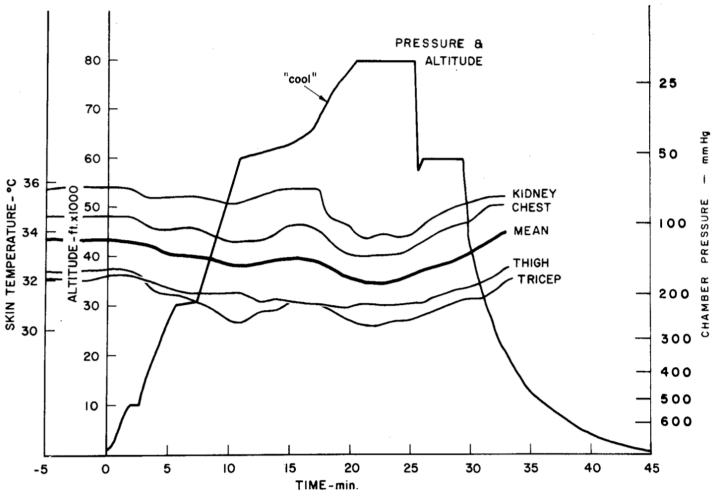


Figure 12: Altitude profile and temperature readings for the final test of the Space Activity Suit.

The data from this test paints a similar picture to previous tests: subject tachycardia was again observed above 150 mmHg of breathing pressure; near the end of the test, the heart rate was 160 beats per minute at a breathing pressure of 180 mmHg. Arm volume increased at 26 mL per hour of pressure breathing, and a water loss of 30 g/hr was measured.

Adopting the same assumptions as before suggests a total water loss of 93 grams, a transient water loss of 396 g/hr when at reduced pressure and a total water loss for an EVA of 1.6 Liters. If accurate, these values are more acceptable; however, given the lack of data provided in the SAS report it is difficult to say if these assumptions are correct and if so, why they are markedly different than previous tests. A probable explanation is that in the interest of safety, the subject was not conducting the same strenuous exercise as previous tests, resulting in less sweating. Another possible explanation is that the test duration over which the 30 g/hr was calculated, was longer than in previous tests; every additional hour of assumed test period translates into 0.5 L of estimated water loss over a 4-hr EVA. This said, it is also possible that the SAS Garment #10 used in Phase II was sufficiently different than #8 and #9 used in Phase I as it relates to water loss or metabolic cost resulting in sweating. While #10 used more layers to provide the higher pressures required in Phase II, which could explain some reduction in evaporative cooling power, it does not seem likely that this difference is enough to explain a 70% reduction in water loss compared to the next-lower data point.

At the time, the symptoms were not considered decompression sickness [DCS], because 165 minutes of oxygen prebreathe was believed more than sufficient to eliminate any risk of DCS; therefore, they were unable to explain why these symptoms occurred. To evaluate if DCS was a possible contribution to these symptoms, the authors consulted with NASA's Human Physiology, Performance, Protection and Operations laboratory to perform a cursory retrospective DCS risk analysis based on the relevant details of this altitude chamber profile as well as the fourth chamber test from Phase I where other possible DCS symptoms were reported. Across three decompression risk models, [21,22,23] the last exposure denoted in Figure 12 above had a range of DCS risk estimates from 5-13%, indicating a definite chance that these symptoms were possibly due to DCS. The exposure from Phase I had not only a higher DCS risk level (5-20%), but was further complicated by a very low breathing pressure (170 mmHg, 3.3 psia) and high breathing loop N_2 content, about 14%, indicating hypoxic stress (inspired oxygen partial pressure: P_IO_2 = 106 mmHg), which is similar to breathing air at an altitude of 9,000 ft (2,743 m).

D. Subsequent Analyses and Discussion

A thorough literature review was conducted on the Space Activity Suit subsequent to the 1971 report. The literature review found many interesting pieces of historical context:

- The Paul Webb Collection was located at Wright State University Library's Special Collections and Archives.[24] The collection includes experimental data, notes, correspondence, reports, publications, computer cartridges and hardware. Box 28 may contain minimal research notes relevant to the SAS effort but unfortunately, historical record of the work completed at Webb Associates in this collection seems primarily focused on the late 1970s-late 1990s. As such, test documentation, raw data, correspondence, and other data of interest from the SAS effort were not located. However, at least eight different SAS garments were located in this collection. A comprehensive set of photographs of these garments is available in Appendix A.
- Raw data from SAS testing may shed light on open physiological questions such as water loss during an EVA, among others. Speaking with Dr. Webb's estate, the author determined that full documentation from SAS may

have been transferred from Dr. Webb's estate to another researcher or possibly destroyed; efforts are still underway to locate this material.[25]

- Most textbooks on space suit design or development include a rather sparse or superficial discussion on the SAS or MCP in general. One exception is *The Origins and Technology of the Advanced Extravehicular Space Suit* by Gary Harris. After a brief summary of testing and the issues encountered, Harris writes, "everyone whom I interviewed for this book has commented that the SAS must await a materials revolution that has not yet arrived".[2]
- A Channel 4 Equinox documentary titled "Spacesuit" which aired on April 15, 1991 was located. The documentary was determined to be very accurate and detailed on the topic of space suits in general. The SAS is briefly discussed and the common criticisms of the viability of MCP are expressed by NASA engineers. [26]
- Reference to a NASA video conference from April 17, 1986 titled "EVA Development – Suit and Glove Review" at NASA Headquarters' Office of Spaceflight was discovered, which in some form documents a NASA position on the SAS or MCP in general. As of this writing, this tape has not been located or reviewed.
- An interview by Dr. Paul Webb on *The Space Show* podcast from September 17, 2006 was located and reviewed. In it, Dr. Webb is optimistic on the promise of the SAS in the context of upcoming Lunar EVA needs for the Constellation Program at the time. Highlights are as follows: [27]
  - Donning required "a great deal of effort" and was not possible without assistance of two people
  - Perhaps contrary to reports, Dr. Webb indicated that were no issues with providing sufficient counterpressure to the crotch, and there would be "no problem at all" in testing the SAS for "three hours or more" at vacuum
  - By this time, Dr. Webb began quoting a design breathing pressure of 222 mmHg, matching that of the current EMU suit which provides this pressure to reduce the occurrence of the bends when stepping down from the full atmospheric pressure of the International Space Station.
  - An unnamed Russian engineer reportedly told Dr. Webb that they had "tried that elastic suit idea a long time ago, and it didn't work". Subsequent investigation by the authors and discussions with a former employee of Zvezda revealed the anecdote that Zvezda developed and tested an MCP suit in ca. 1960, but due to difficulty in donning, as well as pain and swelling across the body from poor pressure uniformity, it was viewed negatively and was not further developed.
  - Dr. Webb felt that the culture of full pressure suits from aviation at JSC resisted the concept because it was not invented there and not due to technical merit (Dr. Webb's personal opinion documented for posterity)
  - Dr. Webb acknowledged moderate newfound support at JSC, where MCP glove work had been conducted in recent years (1999-2002; to be discussed in detail in a forthcoming paper)
  - Dr. Webb proposed that the SAS concept could be used for IVA suits as well as IVA/EVA combination suits, with mechanisms that tightly engaged the elastic fabric upon loss of cabin pressurization
  - Dr. Webb indicated that two or three years of dedicated development, primarily on enabling textiles is sufficient to produce a working prototype capable of meeting the necessary physiological requirements
- In 2011 Dr. Webb, Dr. Alan Hargens at the University of California at San Diego and Dr. Christine Cole at Clemson published a paper titled, "*The Elastic Space Suit: Its Time Has Come*".[28] Little additional technical detail was provided in this paper, which mostly serves to repeat the summary from the 1971 NASA report and call for continued development on textiles. It is left to the reader to determine if this paper accurately characterizes the work completed on the SAS.

VI. Conclusion

The Space Activity Suit has been touted as proof that mechanical counter-pressure is not only a feasible concept, but has been technically viable for some time, given only modest improvements made to pressure application and donning. The purpose of this paper is not to condemn the Space Activity Suit or MCP in general. In fact, the SAS and the Webb Associates' effort goes a long way to demonstrating that MCP is theoretically feasible and in the future, may supplant the use of fully pressurized suits for EVA. However, the current viability or Technology Readiness Level [TRL] of MCP is not within the scope of this paper. The purpose of this paper is to revisit the SAS effort, the testing that was completed and independently analyze it in today's context. As such, the primary conclusions are as follows:

- An MCP breathing pressure of at least 180-200 mmHg is required to ensure safe respiratory function
- A matching counter-pressure over most of the body is required to prevent cardiovascular congestion and subsequent failure of cardiac output, as well as to avoid positive pressure breathing
- The SAS sleeve-and-glove demonstrated conceptual feasibility and general promise of the SAS
- Webb Associates ultimately targeted a suit breathing pressure and counterpressure of 170 mmHg with a positive pressure breathing system, pressurized torso breathing bladder and neck dam
- The SAS used up to seven layers as well as various pads, slits and other features to apply the necessary cumulative target pressure.
- The SAS was quite difficult to don, not only in that it took 45-60 minutes but that it required two assistants and significant exertion to do so. Note that this is not ideal, but possibly not prohibitive compared to donning the legacy EMU (10-15 minutes in training; 55 minutes in flight);[29] that said, future rear-entry suit designs will likely reduce this significantly.
- The torso bladder of the SAS was leveraged more and more to provide counter-pressure as development matured, with less emphasis on fabric layers exerting pressure in this area; while this improved ease of ventilation, it also represents a design shift toward partial pressure suit design, which hinders natural thermoregulation.
- Fabric openings exposing up to 1mm^2 of skin to vacuum were well-tolerated physiologically for the periods tested.
- The SAS suit posed many design challenges related to providing sufficient pressure; this manifested itself in myriad ways throughout development including: cardiovascular congestion, syncope, poor circulation, pain, petechiae, fatigue, increased heart rate, decreased respiratory capacity and swelling. Many of these issues could not be eliminated over the course of SAS development.
- The SAS targeted a two-hour test at 80,000 feet (24,384 m) equivalent altitude but across multiple opportunities, failed to dwell at this altitude for more than seven minutes with highly trained Webb Associates subjects.
- The SAS, while possibly more mobile and dexterous than pressurized suits at the time in many ways, came with its own mobility restrictions due to constrictions of the fabric and was not as mobile, as dexterous or as improved on metabolic cost as originally hoped or theorized.
- Test subjects experienced very high water loss rates during chamber testing, which may be a significant issue for extended EVAs at vacuum
- The neck dam transition from the pressurized helmet to the mechanical counter-pressure regime had some issues related to cardiovascular congestion and poor circulation, but was otherwise successful and did not seem to be of concern compared to other issues
- In terms of high-altitude protection, the SAS was successful in that it was comparable to partial pressure suits of the time, but was still far from providing long-duration protection against a full vacuum.

In short, the Space Activity Suit demonstrated that the fundamental concept of the mechanical counter-pressure suit is possible. However, it also demonstrated that the design challenges associated with a full MCP suit were very significant at the time, and likely will continue to be for the foreseeable future. While materials, textile fabrication, anthropometry measurement capability, and other technologies have certainly advanced significantly since the Space Activity Suit report in 1971, there are still substantial technical gaps that require considerable enabling technologies that will likely not exist until some undetermined point in the future.

VII. MCP – 1972 to the Future

Significant and valuable work to advance the MCP concept has since been conducted by Honeywell, the University of California at San Diego, Clemson University, Paul Webb himself, the University of Maryland, Massachusetts Institute of Technology, NASA, Final Frontier Design, among others including too many individuals to mention. Almost every single one of these efforts was wholly or significantly funded by NASA. Cumulatively these efforts deserve a summary as well, as each one in its way has contributed to solving what is truly a very difficult problem. NASA considers mechanical counter-pressure suits to currently be unrealizable in terms of acceptability for flight; that said, NASA has also not taken the opportunity to document comprehensive rationale for this position. In addition, there should be a suggested development strategy to guide academia and industry when considering how to push the technology one more step toward flight. All of this will be fully detailed in a paper soon to follow.

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