1 Introduction

The Bio-Suit System: A Synopsis

The Bio-Suit System is designed to revolutionize human space exploration by providing enhanced astronaut extravehicular activity (EVA) locomotion and performance based on the concepts of a ‘second skin’ capability and of biomechanically and cybernetically augmented human performance capacity. The novel Bio-Suit concept provides an overall exploration system realized through symbiotic relationships between a suite of advanced technologies, creative design, human modeling and analysis, and new mission operations techniques. By working at the intersection of engineering, design, medicine and operations, new emergent capabilities and interrelationships could expand NASA's future mission possibilities, potentially allowing new directions for future NASA missions. In many respects, the Bio-Suit System mimics Nature (biomimetics). For example, a second skin is envisioned, capable of augmenting our biological skin by providing mechanical counter-pressure (MCP). Perhaps the ‘epidermis’ of such a second skin will be a ‘spray-on’ layer offering protection in extremely dusty planetary environments. Incorporated into the second skin will be electrically actuated artificial muscle fibers to enhance human strength and stamina. Locomotion and performance are further enhanced by implementing biomimetic locomotion algorithms to actuate performance-enhancing hardware. Wearable technologies will be embedded throughout the Bio-Suit System to place the explorer in an information-rich environment enabling real-time mission planning, prediction, and visualization. Human-in-the-loop modeling algorithms will be developed to calculate metabolic exploration costs and to plan and dynamically update optimal astronaut traverses that account for changing mission requirements. The Bio-Suit System addresses the feasibility of further augmenting human capabilities by coupling human and robotic abilities into a hybrid of the two, to the point where the explorer is hardly aware of the boundary between innate human performance and robotic activities. The proposed Bio-Suit System contributes to four NASA Institute for Advanced Concepts (NIAC) areas: human space flight, life sciences, information systems and software, and biology. The Bio-Suit System concept is relevant to NASA's strategic plan and stated vision for exploration. Additionally, the Bio-Suit System is essential for NASA to realize its technology road map development for journeys to L1, Moon/Mars, Near-Earth Objects, and eventually for a ‘go anywhere’ capability.

Objectives of the Bio-Suit System Study

The primary goal of the Phase II Bio-Suit System effort was to provide a sound basis for NASA to consider the feasibility of the concept for future missions (NIAC, 2002), and our ultimate study goal was to produce a Bio-Suit System concept for human survival and enhanced performance in extreme, hostile environments. The main objectives of the proposed effort were to study the major feasibility issues, perform necessary research, and design a revolutionary concept for human exploration missions, namely the Bio-Suit System, which is envisioned as a locomotion enhancing, life support system for astronaut extravehicular activity (EVA) based on the concept of providing mechanical counter-pressure (MCP). The Bio-Suit System concept is in stark contrast to the incremental space suit design approach and improvements witnessed over the history of human spaceflight in both the NASA and Russian programs, including the International Space Station. Our Phase I study concentrated on the conceptual exploration of numerous technologies and designs that could potentially be utilized in a Bio-Suit System. Phase II continued our illustrative design process by updating the suite of
advanced technologies, modeling and testing the most promising Bio-Suit System candidates, and developing new mission operations techniques. Detailed objectives for the Bio-Suit System study included providing: 1) a novel design concept through symbiotic relationships in the areas of biomimetics, wearable and advanced technologies, innovative design, human modeling and analysis, and mission operations and 2) a synergistic multidisciplinary approach combining expertise from the fields of engineering, design, medicine, and space operations to assess the major feasibility issues associated with performance, key technology issues, implementation, and development cycle of the proposed Bio-Suit System. Imagine astronauts on Mars utilizing the Bio-Suit System for their search to find the definitive proof of life, which requires them to repel cliffs, perform geology and real-time data analysis in extreme environments where Olympus Mons and Valles Marineris dwarf Mount Everest and Grand Canyon terrains, all the time working in extreme temperatures and storm conditions.

Motivation for the Bio-Suit System Concept

LOCOMOTION AND MOBILITY: Locomotion is a top priority for exploring terrestrial environments and performing useful planetary work. Since the Apollo era only a few space suit concepts have been designed to provide locomotion, and all current NASA designs as well as the Apollo suits do not enable the human explorer, but rather hinder their performance. In an environment such as Mars, astronauts will need the ability to traverse loose terrain, steep grades, and possibly scale, if not repel, down cliff sides. These activities place new requirements on advanced suits in the areas of mobility and dexterity, which can only be attained through implementing designs that facilitate natural locomotion and minimize energetic expenditures. Due to the activities mentioned above as well as the evaluation of samples and the maintenance of equipment, manual dexterity is also a very high priority.

STRATEGY - WHY MCP? As suggested by Annis and Webb [1971], Clapp [1983] and others, mechanical counterpressure (MCP) suits have the possibility of greatly improving astronaut performance. The first MCP design, namely, the Space Activity Suit (SAS) [Annis and Webb, 1971], was a very creative idea before its time. The SAS used seven layers of highly elastic material in order to squeeze the wearer and implemented a gas-filled helmet and chest bladder to provide adequate breathing pressure [Annis and Webb, 1971]. While the SAS initiated the MCP concept and demonstrated advantages of mobility, low energy costs, and a simplified life support system, the difficulty in donning/doffing the SAS was the largest limitation. NASA did not pursue MCP suit development. A few additional MCP investigations such as those by Clapp [1983], Korona [2002], Tourbier et al. [2001], and Waldie et al. [2002] have advanced the state of the art of MCP glove design. These studies have investigated elastic materials or low-modulus MCP. The work of Tanaka et al. [2003] investigated important physiological issues such as blood flow and fluid distribution as well as pressure distribution. Tanaka and colleagues provide important evidence that MCP can be realized with no adverse physiological effects.

Given the performance characteristics of our biological skin, it seems reasonable to envision a second skin suit capable of augmenting our biological skin to the point where it can withstand the absence of a pressurized environment. If designed properly, Webb showed that a MCP suit could expose regions of skin no larger than 1 mm$^2$ to vacuum. There are two major advantages suggested by this result. First, this result suggests the
improved safety of a MCP suit design. Especially on planetary surfaces where the astronaut will be exposed to highly abrasive environments and activities, tears become an issue of increasing concern. In a gas-pressurized suit, a small tear not only means the loss of pressure, but also the loss of breathable oxygen. In an MCP suit, however, this would not be the case. Webb’s result suggests that should a small hole appear in a MCP suit, the user would be unharmed. There would be no loss of breathable oxygen, and the skin would not suffer any damage. Should the hole be larger than 1 mm², the wearer would still have sufficient time to return to a pressurized environment due to the fact that the effects of the reduced pressure would be highly localized. The second advantage suggested by Webb’s result is that of thermal cooling. In a MCP suit, normal thermal cooling, including evaporation of sweat, is enabled by using air-permeable fabric.

The Bio-Suit initiative at MIT returns to the concept of MCP, leveraging new technologies in modeling and materials to envision future possibilities for the use of MCP in locomotive extravehicular activity suits. Design concepts are conceived to allow the explorer the same ease of donning as experienced with clothes. Conceptually this is achieved by creating a suit that shrinks around the wearer once it is donned: the wearer slips into the MCP garment and then the suit slowly shrinks to provide adequate body-surface pressure. During our Phase II study we have developed several concepts that demonstrate decoupled donning/doffing and pressure production processes, as described below.

2 Bio-Suit System Requirements

Our Bio-Suit System requirements analysis is motivated by the need to design for uncertainty by incorporating flexibility into the Bio-Suit System design, to understand skin deformation in order for the Bio-Suit to provide a “second skin” capability, and to design for the specific demands dictated by planetary field exploration. The following sections describe our Phase II research in these areas.

2.1 Flexibility in spacesuit design

The need to design for uncertainty increases with the development time and service life of a system. In the context of a mission to the Moon or Mars, changes in the physical, technical, political, and economic environment surrounding the spacesuit are likely to result in considerable requirements and design changes.

In light of this we have striven to follow a systematic process in Bio-Suit development by defining and attacking the Bio-Suit design challenge from a systems engineering perspective. In doing so we have not only focused the direction in which Bio-Suit development is proceeding but, along the way, contributed to fundamental knowledge in systems engineering.
In our design lifetime research we have uncovered evidence that lifetime is a fundamental component of system architecture that cannot be seen or touched. We have subsequently developed a framework that identifies optimal design lifetimes for complex systems in general, and space systems in particular, based on an augmented diachronic perspective of system architecture. Using this framework we found that an optimal design lifetime for a satellite exists, even in the case of constant expected revenues per day over the system's lifetime, and that it changes substantially with the expected Time to Obsolescence of the system and the volatility of the market the system is serving in the case of a commercial venture. The analysis then shows that it is essential for a system architect to match the design lifetime with the dynamical characteristics of the environment the system is/will be operating in. We also show that as the uncertainty in the dynamical characteristics of the environment the system is operating in increases, the value of having the option to upgrade, modify, or extend the lifetime of a system at a later point in time increases depending on how events unfold (Figure 1) [Saleh et al. 2003].

In attempting to maximize the flexibility of the Bio-Suit design to cope with the inevitable requirements and design changes mentioned above, we also realized that flexibility is a word rich with ambiguity. While it is being increasingly used in various fields, few attempts have been made to formally define, quantify, and propose ways for achieving flexibility. We therefore synthesized a clearer and more consistent definition of flexibility by reviewing the usage of the term in various fields of inquiries, and showed that it is indeed possible to clearly and unambiguously characterize flexibility, and to disentangle it from closely related concepts [Saleh et al. 2004].

We then used this definition of flexibility to study the evolution of requirements for the Extravehicular Mobility Unit (EMU) as a case study in the need for flexibility in system design. We explored a fundamental environmental change, using the Shuttle EMU aboard the International Space Station (ISS), and the resulting EMU requirement and design changes. The EMU, like most complex systems, has faced considerable uncertainty during its service life due to changes in the technical, political, or economic environment. These have resulted in requirements changes, which in turn have necessitated design modifications or upgrades. We provided evidence that flexibility is a key attribute that needs to be embedded in the design of long-lived systems to enable them to efficiently meet the inevitability of changing requirements after they have been fielded [Jordan 2005].

We examined how environmental changes for the EMU caused requirements changes, which lead to EMU design changes. We begin with the political decision to use the Shuttle EMU aboard the ISS and then explore the resulting requirements and design changes.
changes. We then look at the change in the physical environment surrounding the EMU and a change in the technical environment and trace the resulting requirements and design iterations. Table 1 summarizes these changes. Despite the large number of environmental changes, the basic capabilities of the EMU, to support life in space and enable useful work, remained unaffected, and a number of EMU components such as the cooling garment, helmet, external visors, Display and Control Module housing, and the Communications Carrier Assembly headset have remained unaltered. The next section describes the changes that did happen as a result of using the EMU for the construction and operation of the ISS.

Table 1. Summary of EMU changes

<table>
<thead>
<tr>
<th>Environment Change - Use Shuttle EMU Aboard ISS</th>
<th>Requirement Change Design or Procedure Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make EMU sizable on-orbit</td>
<td>Adjustable cam sizing in softgoods</td>
</tr>
<tr>
<td></td>
<td>Sizing rings in arms and legs</td>
</tr>
<tr>
<td></td>
<td>HUT replaceable on-orbit</td>
</tr>
<tr>
<td></td>
<td>HUT redesign from pivoted to planar</td>
</tr>
<tr>
<td>Increased EMU life</td>
<td>Recertification of EMU components</td>
</tr>
<tr>
<td></td>
<td>Change in static seal material</td>
</tr>
<tr>
<td></td>
<td>Noise muffler redesign</td>
</tr>
<tr>
<td></td>
<td>Flow filter redesign</td>
</tr>
<tr>
<td></td>
<td>Coolant water bladder material change</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environment Change - Physical Environment of ISS</th>
<th>Requirement Change Design or Procedure Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. metabolic rate lowered</td>
<td>LCVG Bypass Designed</td>
</tr>
<tr>
<td>PNP &lt;0.995 over 10 years</td>
<td>Heated Gloves Redesigned</td>
</tr>
<tr>
<td>Different radiation exposure</td>
<td>Track Orbital Debris</td>
</tr>
<tr>
<td></td>
<td>Define Allowable Penetrations</td>
</tr>
<tr>
<td>Risk of propellant exposure</td>
<td>Carefully plan all EVAs</td>
</tr>
<tr>
<td></td>
<td>1-hr bake-out procedure</td>
</tr>
<tr>
<td></td>
<td>Lengthen SCU</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environment Change - Technical Environment Advances</th>
<th>Requirement Change Design or Procedure Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance in joint technology</td>
<td>Joint patterning and materials changed</td>
</tr>
<tr>
<td></td>
<td>Bearing design and materials changed</td>
</tr>
<tr>
<td>Delicate assembly tasks</td>
<td>Glove design and materials changed</td>
</tr>
<tr>
<td>Increased EMU life</td>
<td>Battery redesign</td>
</tr>
<tr>
<td></td>
<td>CCC upgrade to regenerable canister</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide sensor upgraded</td>
</tr>
<tr>
<td></td>
<td>SAFER</td>
</tr>
</tbody>
</table>

Table 2 lists the requirements that should serve as the guiding principles in the design of an advanced locomotion MCP suit [Bethke et al., 2004]. For quantitative completeness, Table 3 shows the tension per unit length that must be generated and maintained by an MCP suit at various locations on the leg of one female subject, for a 23 kPa (170 mmHg, 3.3 psi) desired body surface pressure, or $MCP = 23$ kPa.

2.2 Body and skin strain field requirements
Table 2. Requirements for an advanced locomotion mechanical counter pressure suit.

<table>
<thead>
<tr>
<th>Suit Function</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Production</td>
<td>Continuously maintain fabric tension to apply at least 23 kPa (170 mmHg, 3.3 psi) of pressure at body surface.</td>
</tr>
<tr>
<td>Pressure Production</td>
<td>Locally expose no more than 1 mm² surface area of the skin [Webb, 1968].</td>
</tr>
<tr>
<td>Pressure Distribution</td>
<td>Distribute pressure evenly, with no more than 20 mmHg spatial variation in pressure [Carr, 2005].</td>
</tr>
<tr>
<td>Mobility</td>
<td>Require no more than 2 N·m of extra work (joint torque) against the suit to flex the knee to 90 degrees. (Current EMU requires 3.74 N·m to bend the knee to 72 degrees [Schmidt, Newman, &amp; Hodgson, 2001]).</td>
</tr>
<tr>
<td>Mobility</td>
<td>Allow full unsuited range of lower body joint rotations.</td>
</tr>
<tr>
<td>Operational</td>
<td>Feasibility Don and doff times of less than 10 minutes</td>
</tr>
<tr>
<td>Operational</td>
<td>Feasibility Don and doff by an individual wearer.</td>
</tr>
</tbody>
</table>

Table 3. Required circumferential fabric tension per unit longitudinal length to create 23 kPa of body surface pressure on female subject, as a function of position on leg. Subject’s body mass and height are 59 kg (130 lb) and 168 cm (66 in), respectively.

<table>
<thead>
<tr>
<th>Cross Section Location</th>
<th>Knee Angle (deg)</th>
<th>Estimated Crosssectional Radius (cm)</th>
<th>Required Tension per Unit Length for 23 kPa Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top of thigh</td>
<td>0</td>
<td>8.6</td>
<td>20 N/cm (4.5 lb/cm)</td>
</tr>
<tr>
<td>Bottom of thigh</td>
<td>0</td>
<td>6.1</td>
<td>14 N/cm (3.1 lb/cm)</td>
</tr>
<tr>
<td>Top of calf</td>
<td>0</td>
<td>5.5</td>
<td>13 N/cm (2.9 lb/cm)</td>
</tr>
<tr>
<td>Bottom of calf</td>
<td>0</td>
<td>3.8</td>
<td>8.6 N/cm (1.9 lb/cm)</td>
</tr>
</tbody>
</table>

2.2.1 Laser scanning techniques for measuring body shape changes

For the design of a skintight Bio-Suit garment it is critical to investigate the changes in volume, surface area, and three-dimensional (3D) shape that occur as the body bends and moves its joints. Our proposed second skin garment must mimic the stretching, deforming skin as the astronaut explorer moves about.

We developed techniques for quantifying the changes in volume, surface area and shape that occur during body movement using a 3D laser scanner (the Cyberware™ 3D full-body laser scanner at the U.S. Army Soldier Systems Center in Natick, MA). We then demonstrated these techniques on a human lower leg since...
much of our work focuses on leg mobility and locomotion. The scanner was used to scan the right leg of four subjects at each of four knee angles: 0, 30, 60, and 90 degrees (Figure 2). Zero degrees corresponds to a fully extended straight leg; 90 degrees corresponds to the leg bent so that the thigh and calf long axes are perpendicular.

Surface area and volume measurements of the entire leg, excluding the foot and hip, were calculated from the laser scan models of one female subject, at each of the four knee angles. Then reference marks fixed to the skin were used to define four cutting planes dividing the leg into the ‘thigh,’ ‘knee,’ and ‘calf’ segments. The surface area and volume of each isolated segment were calculated for the repeated measures at each knee angle.

Results show no significant change in the surface area or volume of the entire leg for increasing knee angle from 0 to 90 degrees (p = 0.58, 0.64). Results for the isolated knee segment show statistically significant changes in both knee surface area and knee volume (p < 0.01 for both measures). On average, the knee surface area decreased by 16% as the leg flexed from 0-degree full extension to 90-degree flexion. The knee volume decreased by 18%, on average, as the leg flexed from 0 degrees to 90 degrees. Since muscles are isovolumetric during contraction, the results of constant volume and surface area of the overall leg were expected. However, muscle motion underneath the skin causes significant shape changes in isolated leg segments. The results for knee surface area and volume have important implications for MCP suit design: as this subject bends her leg, an MCP suit fitted to her skin would ideally match the 16% decrease in surface area and the 18% decrease in volume in the knee region.

2.2.2 Digital techniques for measuring skin strain

To improve our understanding of the deformation of the body’s soft tissue during locomotion, we developed a repeatable, quantitative technique for mapping the strain field on the skin surface of the human body in motion. The results specify in which directions and with what magnitudes the “second skin” Bio-Suit pressure garment must stretch or contract at each location on the body surface.

To measure the strain of the human skin in vivo, we applied the non-invasive strain measurement technique of Digital Image Correlation to data sets gathered by a 3D laser scanner rather than by optical cameras. In this pilot study, knee flexion from 0 to 90 degrees, for one subject, was used as the representative movement for human locomotion. The leg surface was marked with 156 position trackers that could be identified in the laser scanner’s 3D virtual reconstructions of the leg surface. Each tracked point was separated by approximately 3 cm from adjacent points, and each triad of points defined a local surface reference frame with a longitudinal and a circumferential direction. Normal strains emanating from each tracked point were estimated by comparing the initial separation of each pair of

Figure 3 - Circumferential strain of the leg skin during knee flexion. A snapshot of a 3D reconstruction of the deformed position of ~150 tracked points. Light green represents zero strain, while yellow represents about 20% stretch, and cyan represents 20% contraction.
adjacent points to the deformed separation of each pair. Then, using strain gage rosette
equations, the strains were transformed from extension/contraction along arbitrary axes
to the normal and shear components of the orthogonal strain tensor, with respect to the
longitudinal and circumferential axes. Eigenvalue analysis of this strain tensor provided
information about the directions and magnitudes of principal strain and of minimum
normal strain.

For the one subject in our pilot study, the largest stretch of the leg skin in the longitudinal
direction occurred 3cm to 9cm below the patella; longitudinal normal strain magnitudes
in this region ranged from 0.3 to 0.7 (Figure 2). The largest stretching in the
circumferential direction occurred on the anterior surface 3cm below the patella and on
the medial surface of the mid-calf, with normal strain values of 0.6 and 0.5, respectively.
Angular distortion of the skin was found to be near zero for most of the anterior and
posterior surfaces of the leg.

Eigenvalue analysis transformed the orthogonal strain components into principal strain
and minimum strain directions. The set of minimum normal strain directions suggests the
orientation, or “weave” direction, of the tensile fibers for “second skin” Bio-Suit design
(Section 3.3).

2.3 Traverse Planning for Planetary EVA

Future planetary surface extravehicular activity (EVA) systems require the ability to
support the replanning requirements of field exploration. We developed a traverse
evaluation process to improve real-time re-planning that enables predictive parametric
analysis of planned traverses. Data sources included a digital elevation model (DEM), a
metabolic cost model, traverse waypoints, landmarks, and sun ephemeris data. Rules,
such as maximum slope, metabolic rate, or walk-back distance were evaluated. Output
metrics could include metabolic cost, maps of surface slope, accessibility or visibility, a
low-energy-cost direction of travel heuristic, sun-relative angles, and the sun score, a
metric of ability to sense surface features and assess distance as determined by surface
contrast differences due to the sun angle.

The traverse evaluation process was implemented in MATLAB and applied to the Apollo
14 2nd EVA traverses (planned, actual, and our own modified traverse). A major (unmet)
geologic goal of this traverse was to sample ejecta from the rim of Cone
Crater. Limited visibility of the crater and navigational difficulties prevented positive
identification of the crater during the Apollo 14 mission, even with an EVA time
extension.

Our metabolic cost estimate results for the Commander (CDR) and Lunar
Module Pilot (LMP) are within 11% of the NASA estimates for the planned
traverse (Table 4). This novel traverse evaluation process demonstrates that a
modified traverse could reduce total traverse distance and metabolic rate,
while improving visibility of Cone Crater, the sun score, and visibility of the lunar
module (important for judging position.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planned</th>
<th>Actual-CDR</th>
<th>Actual-LMP</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (hr)</td>
<td>2.975</td>
<td>3.347</td>
<td>3.347</td>
<td>2.975</td>
</tr>
<tr>
<td>Movement (hr)</td>
<td>1.009</td>
<td>1.395</td>
<td>1.395</td>
<td>1.039</td>
</tr>
<tr>
<td>Other (hr)</td>
<td>1.958</td>
<td>1.653</td>
<td>2.022</td>
<td>1.956</td>
</tr>
<tr>
<td>Total Distance (km)</td>
<td>3.064</td>
<td>3.345</td>
<td>3.234</td>
<td>2.716</td>
</tr>
<tr>
<td>Mean Slope Angle (deg)</td>
<td>2.7</td>
<td>0.9</td>
<td>1.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Metabolic Statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metabolic Rate (kJ/hr)+</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>2328</td>
<td>2256</td>
<td>2313</td>
<td>2326</td>
</tr>
<tr>
<td>Mean</td>
<td>1257</td>
<td>1025</td>
<td>1069</td>
<td>1137</td>
</tr>
<tr>
<td>Energy (KJ)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traverse (Movement)+</td>
<td>1292</td>
<td>1443</td>
<td>1430</td>
<td>1167</td>
</tr>
<tr>
<td>Other Metrics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall Sun Score</td>
<td>0.68</td>
<td>0.70</td>
<td>0.63</td>
<td>0.61</td>
</tr>
<tr>
<td>Accessibility (% surface)</td>
<td>99.31</td>
<td>99.31</td>
<td>99.31</td>
<td>99.31</td>
</tr>
<tr>
<td>LM Visible (% time)</td>
<td>74.55</td>
<td>45.00</td>
<td>43.33</td>
<td>93.64</td>
</tr>
<tr>
<td>Walkback Met (% time)</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Table 4 - Detailed results from traverse evaluation of the
second EVA of the Apollo 14 lunar surface mission
[abridged from Carr et al, 2003].
and distance) for the explorers. We recommend such a system be implemented using a wearable computer added to existing suits or integrated directly into the Bio-Suit system.

3 Prototype Development and Results

In our prototype development work we aim to demonstrate the feasibility of the MCP concept by developing comfortable, high-mobility prototypes that can protect the wearer from the effects of underpressure. We have focused on developing high-mobility MCP leg prototypes due to the relative lack of leg mobility in current and previous spacesuits, but the prototypes can also be applied to the arm with relatively few modifications. Section 3.1 describes some of the methods in which we assess prototype performance while Section 3.2 describes the numerous prototypes we have developed and tested.

3.1 Overview of prototype testing methods

3.1.1 Low pressure leg chamber

In order to assess the performance of a MCP prototype, a low pressure chamber (LPC) must be constructed around the body part of interest. Small, cylindrical LPCs have been used to conduct tests on forearm and lower leg prototypes. However, as our understanding of full-leg MCP garments advances it becomes necessary to build a LPC that can test larger prototypes that involve major joints.

For this reason a large (approx. 5'x1'x3') LPC was constructed to allow tests on an entire leg, including the knee (Figure 4). The box's sides were constructed from 3/4” clear acrylic sheet. Finite elements analysis was performed by Mide Technology Corp. to determine the size of the structural ribs that were required. The ribs were constructed of solid 2”x1” T6 6061 Aluminum and held together by steel machine screws. The box was made airtight with silicon sealant, and leaks were repaired with flexible quick-dry epoxy. Standard vacuum fixtures were added to provide an emergency quick-release, a manifold, and an atmospheric bypass. A 9” hole was cut in the top surface, and two parts were made to fit it: a 1” aluminum plug for validation, and a polypropylene adapter to a dry-suit gasket, used to form a seal to the body. Both parts are sealed with an O-ring.

The LPC was depressurized remotely to validate its performance. The box was tested for 3 failure modes: burst, fatigue, and repressurisation. Burst failure is a sudden and dramatic failure of the acrylic. Fatigue failure involved crack propagation at the screws and other problems related to cycling. Repressurisation failure would be a burst failure caused by the rapidly changing stress state as the emergency release was opened.
The box was determined to be structurally sound, however at a pressure approximately 20 kPa below operating pressure the seals would begin to leak. It was decided that this was advantageous, since if the box was ever under-pressurized the seals would allow the box to fail and relieve the pressure difference in a non-destructive and safe manner.

3.1.2  **Tekscan I-Scan sensors for measuring MCP distribution**

We currently use I-Scan resistive sensors (Tekscan Inc., South Boston MA) to measure the pressure distribution produced by our MCP prototypes (Figure 5). The sensors are thin Mylar printed circuit sheets consisting of individual 0.5”x0.5” pressure sensing elements called “sensels” arranged in rows and columns. Each sensel measures the pressure produced at its center; in this way, an I-Scan sensor produces a pressure distribution map using the measurements from its many individual sensels.

The principal advantage of I-Scan sensors is that they are among the thinnest commercially available (0.1mm) pressure sensors; this minimizes pressure points between the prototype and the skin. Many other sensors are more than 1mm thick; in using these, a person wearing an MCP garment would feel a pressure point and possibly discomfort at the sensor location. However, the I-Scan sensors exhibit numerous inaccuracies including false pressure spikes, hysteresis and slow response times. A literature review was therefore undertaken to ascertain whether these inaccuracies are caused by operator error or are an inherent property of the sensor, and how they could be minimized.

The review reveals that I-Scan sensors measure mean pressure to within 10% under ideal, flat-plate static loading conditions. However, the accuracy of individual sensels (individual sensing elements comprising the sensor array), especially for measuring pressure underneath a compression garment, is considerably poorer because the sensels suffer from creep, hysteresis, temperature and humidity sensitivity (e.g. when placed next to skin) and false pressure spikes when crimped (e.g. on a curved surface such as the leg). Unfortunately, there are few ways for the operator to minimize these inaccuracies except to minimize sensor crimping and follow calibration procedures as closely as possible.

Other pressure measurement systems were therefore investigated as potential alternatives for Bio-Suit work. The only reusable sensors capable of creating pressure maps in real time are capacitance-based arrays produced by manufacturers such as PPS, Novel and Xsensor. Although more accurate than I-Scan and other resistance-based sensors, capacitive sensors have been used less frequently for medical applications than I-Scan, especially for measuring pressure under compression garments, and are also considerably more expensive. In light of this we are continuing to use I-Scan sensors despite their inherent inaccuracies and, in doing so, are taking every possible step to minimize these inaccuracies.
3.2 Hybrid MCP prototypes

Hybrid prototypes produce MCP using a combination of fluid pressure and mechanical tension. The body surface is not enclosed in pressurized fluid; rather, pressurized fluid channels or bladders transduce MCP to the body via an inextensible restraint layer – conceptually similar to the pressure production in a fighter pilot’s g-suit or a blood pressure cuff.

Due to their reliance on fluid pressure, hybrid MCP prototypes are not final designs for a full-body MCP suit, but rather proof of concepts that yield data on pressures attained via MCP and illustrate some of the practical and physiological issues associated with using MCP garments.

3.2.1 Single channel hybrid prototype

The single channel hybrid MCP design implemented an inextensible, high-modulus garment that fits as closely to the skin as possible without initially applying pressure. Pressure production occurs when a longitudinal channel, placed between the body skin and fabric along the limbs, expands with gas. The expanding channel creates tension in the fabric, thus producing mechanical counter pressure along the body surface.

The prototype garment was constructed for the lower leg, using an 8-segment pattern for the lower leg form and a 10-cm polyurethane bladder as the expanding longitudinal channel (Figure 6a). A localized vacuum chamber was made so that the pressure surrounding the leg and garment could be reduced as the channel pressure was increased. Tekscan 9801 pressure sensors (Figure 5) were used to measure the mechanical counter pressure between the garment and body.

The mean MCP achieved from below the knee toward the ankle, averaged over all trials, had a root-mean-square deviation of 2.5 kPa (19 mmHg, 0.37 psi) from the desired value of 29.6 kPa (222 mmHg, 4.3 psi), excluding the areas close to the boundary of the low-pressure chamber. The MCP at the edge rows was slightly higher because of boundary effects at the edge of the test chamber. Despite this, the single channel hybrid achieves the desired level of pressure production for a future exploration spacesuit system.

3.2.2 Multi channel hybrid prototype

The multi-channel hybrid MCP concept lies in the design space between a single-channel suit (akin to a g-suit) and an EMU-lie, full gas pressure suit. A prototype was developed for the lower leg and consisted of two layers: an expanding layer with multiple gas-filled channels and an inextensible restraint layer. To create the expanding layer, a custom-patterned, RF-welded die sealed polyurethane to a high modulus rubber-like material along longitudinal lines that were 2 mm thick and separated from each other by 12 mm. The result was a garment embedded with a multi-chambered air bladder, with 12-mm wide channels running the length of the garment. The restraint layer was constructed by heating shrink-wrap polyester to fit precisely to a full-scale 3D replica of a human subject’s leg. The channels expand in parallel as gas is pumped into the bladder. The restraint layer prevents the channels from expanding away from the body and creates mechanical counter pressure on the body surface.
Figure 6b displays the expanding layer and restraint layer of the multi-channel prototype. To determine if the prototype produced adequate counter pressure with even pressure distribution, it was pressurized on a full-scale leg replica outfitted with pressure sensors. For an input channel pressure of 27 kPa (200 mmHg, 3.9 psi), the average output leg pressure was 14 kPa (105 mmHg, 2.0 psi), and the median standard deviation of the longitudinal pressures was 6.3 kPa (48 mmHg, 0.93 psi). The output-to-input pressure ratio of 1:2 and the large spatial variations in surface pressure did not satisfactorily meet the design requirements of the Bio-Suit System.

3.2.3 Open-cell foam prototype
As a further exploration of the hybrid MCP concept, we constructed a lower leg prototype out of open cell foam, urethane sealant, and restraining sailcloth. This urethane-foam prototype investigated the concept of spraying or painting on an MCP suit proposed in our Phase I study. Paper-thin layers of urethane were painted onto a full-scale leg replica, and laminated strips of open-cell foam were sandwiched in between the layers. The foam defines a flexible air space inside a skin-tight bladder. An outer restraint layer was custom-fit to the shape of the leg replica and constructed out of dimensionally stable sailcloth and a high pressure waterproof RIRI zipper. Leg surface pressure is created when the foam layer is filled with gas and prevented from expanding outward by the restraint layer. Upon pressurization, the overall thickness of the prototype is about 7 mm (0.25”).

Figure 6c displays the expanding layer and restraint layer of the open cell foam-urethane prototype. To determine if the prototype produced adequate counter pressure with even pressure distribution, it was pressurized on a full-scale leg replica outfitted with pressure sensors. Figures B and C show the results of testing on the full-scale leg replica. For an input channel pressure of 29 kPa (220 mmHg, 4.3 psi), the average output leg pressure was 33 kPa (248 mmHg, 4.8 psi), and the median standard deviation of the longitudinal pressures was 4.3 kPa (33 mmHg, 0.64 psi). The ratio of output pressure to input pressure was 1:1. The foam prototype produced more spatially uniform surface pressure than the multi-channel prototype in the previous section.

3.2.4 Hybrid prototypes for the foot and knee
Most of the other MCP prototypes we have developed are difficult to adapt for the foot due to its complex geometry. The elastic bands concept is most suited for cylindrical

![Image of hybrid prototypes](image-url)
shapes such as the arms and legs and would produce a highly uneven pressure distribution if applied to the feet. Hybrid bladders based on foam would be difficult to fabricate to suit foot contours.

We therefore developed hybrid foot bladders (Figure 6d) using commercially available waterproof socks. Not only is their shape appropriate *a priori* for producing a uniform pressure around the feet and ankles, but they are also extremely comfortable compared to other hybrid prototypes mentioned in this report.

The foot bladder consists of two Sealskinz Waterblocker Socks (Danalco Inc., Duarte CA) that are waterproof and impermeable to air, and have been pressure-tested before sale to ensure its integrity. A bulkhead port is located on one sock to act as the connector for an air line. The second sock is then turned inside out and nested inside the first. Finally, the two waterproof cuffs on the lower calf portion of the socks are then sealed together using waterproof marine glue sealant, creating a sealed bladder in the space between the two socks.

The bulkhead port is connected to the atmospheric port of the low-pressure chamber. This ensures that the MCP generated by the bladder on the foot is always equal to the negative pressure inside the chamber. A standard sneaker acts as the outer restraint layer.

The foot bladder has been used for up to one hour at –150 mmHg inside the low pressure chamber. The subject felt comfortable at all times and did not experience any sensations of underpressure. Post-test examination of the foot revealed no symptoms of underpressure.

3.3 Human modeling for a “second skin” spacesuit

“Second skin” spacesuit design requires an understanding of the dynamic body surface. To measure the stretching and rotating of the body surface, Iberall [1958, 1964, 1970] developed a method for mapping body surface curves that he coined the *Lines of Non-Extension*. The deformations of topically drawn circles are observed as the body moves, and lines of non-extension (LoNE) are found through these observations.

Iberall found these lines to flow continually over the entire body surface. He used the lines as patterns for pressure suit restraint layers constructed out of thin, non-stretchable cables; subjects who wore Iberall’s mesh garments found no loss in their mobility. Due to Iberall’s initial success we investigated the use of LoNE for an inextensible MCP mesh garment that allows full mobility and is capable of restraining the body’s internal inflation, consisting of a fine mesh of fibers or narrow fabric tape oriented along the LoNE. Unlike the hybrid prototypes of the previous section, these LoNE prototypes do not rely on any form of fluid pressure to produce MCP.

We began by determining the material properties requirements of the fibers or fabric as follows: The garment must provide 30 kPa of pressure on the leg surface, and the leg radius can be as large as 10 cm. Garment tension (per longitudinal width) is equal to the product of pressure and radius, so the desired operating tensile load is 30 N per centimeter of garment (30 kPa x 10 cm = 3000 N/m). Assume that one fiber or narrow fabric strip bears the load for each longitudinal centimeter, and assume a desired factor of safety of 2. The final tensile strength requirement is 60 N (2 x 30 N). The zero-
modulus portion of the force-displacement curve allows for the same level of tension to be maintained even when the leg shape changes slightly.

As such, an ideal Bio-Suit fiber or narrow fabric has a tensile strength of greater than 60 N (13 lbf) and an elastic modulus that is initially high but that approaches zero as the strain surpasses 30% and the load reaches 30 N. The target operating range for the fiber or fabric is at tensile loads of 30 N ± 5 N and strains of 50% ± 20%.

We fabricated some preliminary LoNE prototypes (Figure 7) to determine if a leg garment patterned by Iberall’s lines of non-extension would actually preserve knee flexion capability. Iberall’s lines were drawn on a 3D full-scale replica of the subject’s leg, using Iberall’s 2D drawings as a guide for the 3D recreation. Very high modulus Kevlar fibers (DuPont Kevlar 49 Aramid Fiber) were laid out on top of the lines, using doublesided tape to temporarily hold them onto a base of nylon stocking. To lock the fibers into place, a joint was formed at each fiber intersection by adhering the two crossing fibers together with urethane-epoxy. Kevlar fibers were chosen because they are virtually inextensible; if knee flexion demanded stretching of the fibers, the subject would not be able to provide the force required to stretch them.

To test the “non-extension” property of Iberall’s lines, the Kevlar garment and its nylon backing were removed from the leg replica and put on the subject’s leg. The subject performed a deep knee squat and easily achieved full knee flexion without extra work output or discomfort (Figure 7, right).

3.4 Elastic bindings prototype

We have investigated a novel MCP concept consisting of thin 1”-wide elastic bands wrapped around the limbs in a similar fashion to medical bindings to overcome the don/doff and mobility problems in previous MCP suits. Like the LoNE prototypes of the previous section, the elastic bands concept does not rely on fluid pressure to produce MCP. The bands create MCP through elastic circumferential stress only, thus minimizing longitudinal stresses and maximizing mobility at the knee joint. The force with which the binding is
stretched is varied as it is wrapped around the limb to achieve a uniform pressure distribution along the entire leg. Friction permits different sections of the binding to be stretched at different rates in order to create a uniform pressure distribution.

Several materials were investigated in order to find bindings with suitable elastic modulus and yield strain. Standard rubber inner tubes for bicycle wheels slit circumferentially to form a flat rectangular binding were found to be most practically suitable. In donning the prototype, the user’s leg circumference is first measured at 0.5” intervals between the ankle and upper thigh. The circumferential tension necessary to produce the target pressure at each limb circumference is then calculated. The binding is attached to a spring scale and stretched to the appropriate tension as it is wrapped onto the leg (Figure 8, top). Friction between the comfort layer and binding allows different sections of the binding to be stretched to different tensions, allowing a theoretically uniform MCP to be generated on limb regions with different circumference. The elastic bindings have proven to be extremely easy to don (less than 5min per leg) and provides almost no hindrance to subject mobility (Figure 8, bottom).

As before, measured the pressure distribution produced by the elastic bindings prototype on the calf using a Tekscan 9801 sensors. Measurements were taken at a range of knee flexion angles between 0°-90° at ambient conditions with the target mechanical counterpressure being 26.7kPa (200mmHg, 3.76psi).

The average MCP on the calf in ambient conditions was 23.3±10.0kPa at the anterior and 22.5±7.5kPa at the posterior. The friction between the binding and slip layer over the skin allows the tension to be varied along the length of the binding, allowing a single binding to provide uniform row- and column-mean pressure on leg cross sections with different radii. Furthermore, although the results show a non-uniform pressure distribution between columns due to the tension in the bindings being adjusted only once per revolution (i.e., each time the binding was wrapped around 360º), some preliminary experiments suggest that the uniformity is considerably improved by adjusting the tension up to four times per revolution.

3.5 Smart materials

One of the ways in which we envision decoupling the don/doff and pressure production processes is using smart materials. The wearer would activate the suit to stretch it into a loose-fitting suit for donning; once donned the suit would be deactivated to shrink around the user, thus creating MCP.

Of the numerous smart materials we have considered to date, shape memory polymers (SMPs) appear to be a promising candidate for MCP garments because of its large maximum strain (typically >100%), which facilitates easy donning and doffing; its elastic, rubber-like properties and texture above its transition temperature ($T_g$) that is conformable to and comfortable for the wearer’s body; and the potential for the $T_g$ of commercially available SMPs to be customized – to 37 degrees Celsius for the purposes of the Bio-Suit, so that the SMPs pressure production would be activated directly by the body.

We have thus been working with Mide Technology Corp. to demonstrate MCP using Veriflex, a SMP from Cornerstone Research Group, which is one of the few SMPs that is currently commercially available. Our aim is to use SMPs to demonstrate MCP, first on a
cylindrical surface and eventually on human limbs. We have demonstrated the ability of a cylindrical SMP sample to return from a highly deformed state into its memory state upon being heated above \( T_g \). We have also measured the material properties of the SMP below \( T_g \) and have found them to be comparable to other rigid polymers such as PVC and PET. Current work involves determining the material properties above \( T_g \) in order to ascertain the level of MCP that the SMP could potentially produce.

We are also investigating the potential for the Bio-Suit System to be used as a countermeasure to astronaut deconditioning in addition to allowing explorers enhanced mobility and life support. An intriguing consequence of using electroactive materials in the Bio-Suit – a potential alternative to SMPs – may be the ability to send biomechanical signals to the body’s tissues. This ability could allow the Bio-Suit to provide a countermeasure for the degenerative effects of microgravity on the musculoskeletal system.

Recent research by Rubin et al. indicates that bone cell deposition in the leg may be stimulated by longitudinal vibration at a much higher frequency (30 Hz) and much lower amplitude (5 microstrain) than experienced during normal walking on Earth (1 Hz and 3000 microstrain) [Rubin, 2001]. We have considered whether high frequency and low amplitude signals can be generated by active polymer materials. If such materials were incorporated into the boots or legs of the Bio-Suit, an electrical forcing function could drive them to vibrate the leg and mechanically stimulate bone growth. Conversations with researchers who study the material science properties of bone tissue have been encouraging – these researchers agree that low-strain mechanical signals may compensate for the absence of gravity on bone, and they suggest using waves to focus a mechanical signal of a desired frequency and amplitude on a specific bone site.

4 Physiological Considerations and Exoskeleton Development – Methods and Results

Our physiological research is driven by several motivations. First, it is well known that using gas-filled spacesuits significantly increases an astronaut’s energy expenditure and exertion compared to performing similar tasks without a spacesuit; this is a major driver of current microgravity EVA intensity and duration and will be even more so for planetary missions on the Moon or Mars (Sections 4.1-4.2). Additionally, wearing MCP suits for extended periods may induce some effects on the body, particularly if the MCP generated on the body is not uniform or does not equal the breathing pressure (Section 4.3).

4.1 Bioenergetics of walking and running in spacesuits

Metabolic requirements are significantly elevated in space-suited activity compared to unsuited activity and are thus are a major driver of the allowable duration and intensity of EVAs. To investigate how space suited locomotion impacts the energetics of walking and running we developed a framework for analyzing energetics data, derived from basic thermodynamics, that clearly differentiates between muscle efficiency and energy recovery. The framework, when applied to unsuited locomotion, revealed that the human run-walk transition in Earth gravity occurs when energy recovery for walking and running are approximately equal. The dependence of muscle efficiency on gravity – during
Figure 9 - A subject wears a lower-body exoskeleton designed to simulate the knee joint of the EMU.

Figure 10. A. Experimental apparatus used to determine stiffness of exoskeleton legs as a function of exoskeleton knee angle $\Phi$. The long horizontal rods constrain hip pin motion to approximately the vertical axis for small amplitude oscillations. Oscillations are measured using the accelerometer. B. Model of exoskeleton leg used to estimate stiffness $k$ and damping parameter $b$ as a function of the total mass $m$, which is the sum of the spring self mass and the mass of the relevant experimental apparatus elements, including the additional load (see figure label).
Evaluation of the exoskeleton legs revealed that they we achieved knee torques similar to the EMU in both form and magnitude. Therefore, space suit joints such as the EMU knee joint behave like non-linear springs, with the effect of these springs most pronounced when locomotion requires large changes in knee flexion such as during running.

Figure 11 shows that equivalent spring stiffness of each exoskeleton leg varies as a function of exoskeleton knee angle and load, and the exoskeleton joint torque relationship closely matches the current NASA spacesuit, or Extravehicular Mobility Unit, knee torques in form and in magnitude.

Figure 11. Estimated exoskeleton knee joint-torques (17" fiberglass bars) as a function of exoskeleton knee angle $\Phi$. Space suit knee-torque data from the Extravehicular Mobility Unit (EMU) is shown as a reference.
To characterize the impact of space suit legs on the energetics of walking and running, we measured the energetic cost of locomotion with and without the lower-body exoskeleton in a variety of simulated gravitational environments at specific and self-selected Froude numbers, non-dimensional parameters used to characterize the run-walk transition. Exoskeleton locomotion increased energy recovery and significantly improved the efficiency of locomotion, per unit mass and per unit distance, in reduced gravity but not in Earth gravity. The framework was used to predict, based on Earth gravity data, the metabolic cost of unsuited locomotion in reduced gravity; there were no statistical differences between the predictions and the observed values.

The results suggest that the optimal space-suit knee-joint torque may be non-zero: it may be possible to build a ‘tuned space suit’ that minimizes the energy cost of locomotion (Figure 12). Furthermore, the observed lowering of the self-selected run-walk transition Froude number during exoskeleton locomotion is consistent with the hypothesis that the run-walk transition is mediated by energy recovery.

We have built a physical nonlinear exoskeleton, and demonstrated that this spring device achieves space-suit like joint torques; therefore, space suit legs act as springs, with this effect most pronounced when locomotion requires large changes in knee flexion such as during running.
4.2 Space Suit Energetics

We performed a cross-study analysis of prior suited and unsuited locomotion energetics studies to try to understand how space suits affect cost of transport. We hypothesized that space suit legs act as springs during running, thereby maintaining or lowering cost of transport relative to space-suited walking.

We transformed data from prior studies into a common format using non-dimensional parameterization (Figure 13). We developed a regression equation for the specific resistance ($S$), a non-dimensional form of metabolic cost, based on the Froude number, surface slope, earth-relative gravitational acceleration, and space-suit pressure. Acceptance criteria for regression factors included significance and a reduction in the residual variance. We divided suited data into running and walking or slow running groups and performed a group means hypothesis test and categorical regression of metabolic cost per unit weight (efficiency per unit time) and specific resistance (efficiency per unit distance).

The specific resistance regression achieved a DOF-corrected multiple $R^2$ of 0.83 (Figure 14); all four factors were significant ($p<0.0005$). No additional evaluated factors (for example, velocity, suit mass, leg length) met the acceptance criteria. The categorical regression, but not the hypothesis test, suggested that the running group had reduced efficiency per unit time; both tests suggested that the running group had increased efficiency per unit distance.

Variations in specific resistance across studies were largely explained by a simple regression model. Several findings suggest that gas-pressure suit legs function as springs during running, including the finding of higher efficiency per unit distance during running, despite the presumed increased work against space suit joint torques at higher velocities.
4.3 **Physiological effects of over- and under-pressure**

One challenge to realizing operational MCP suits is the potential for edema caused by spatial variations in the pressure applied to the body (dP). We thus determined a theoretical first-order requirement for these variations by using Darcy’s law, which relates volume flux of fluid from capillaries to the interstitial space, to transmural hydraulic and osmotic pressure differences; and albumin and fibrinogen levels, which determine, to first order, the capillary oncotic pressure (COP). We estimated dP, neglecting hydrostatic pressure differences, by equating the volume flux under MCP and under normal with the volume flux under abnormal variations in COP; then we compared these estimates to results from MCP garment studies.

Our model shows that normal COP varies from 20-32 mm Hg; with constant hydraulic conductivity, dP≈12 mm Hg. In comparison, COP may drop to 11 mm Hg in nephrotic syndrome, yielding dP≈15 mm Hg relative to mid-normal COP. Previous studies found dPmax =151 mm Hg (MCP glove; finger and hand dorsum relative to palm), dPmax=51 mm Hg (MCP arm; finger, hand dorsum, and wrist relative to arm), and dP=52, 90 and 239 mm Hg (three MCP lower leg garments).

We concluded, to first order, that MCP garments with dPmax≤12 mm Hg are unlikely to produce edema or restrict capillary blood flow; however, garments with dPmax>12 mm Hg will not necessarily produce edema. For example, the hydrostatic pressure gradient at the feet in 1g can range from 70-90 mm Hg. Current MCP garment prototypes do not meet our conservative design requirement.

We have also begun developing experimental methods for assessing edema in a human subject wearing an MCP garment using a Thermal Diffusion Probe (TDP) that measures heat conductivity as a surrogate for tissue water content. We have made preliminary efforts to calibrate this sensor for use in a non-invasive 2D mode, as opposed to its normal minimally invasive 3D mode.

To calibrate, we made TDP measurements using agar plates made with varied percent water content, varying the percentage by adding glycerol, while keeping the agar percentage constant at 2% for all of the plates. Surface (non-invasive 2D) and subsurface (simulating minimally invasive 3D) measurements were made in order to compare results to existing data. The agar plates were placed in a heated incubator for temperature stabilization. The TDP sensor was first placed on top of the agar mixture with the ultrasound gel and 3M-microfoam surgical tape in order to simulate the procedures that will be used for humans. Then the sensor was placed through the mixture to compare the two different geometries. In order to increase the reproducibility of the trials, we implemented saran wrap as a “skin” for the agar mixtures, allowing a greater accuracy of the 2D measurements.

The relationship between the measured thermal conductivity in 2D-geometry and the calculated thermal conductivity values can be used for the estimation of percent water content in the body, since thermal conductivity of pure water is known, and thermal conductivity of a specific tissue can be assumed based on the sensor’s location and the type of the tissue.
5 Bio–Suit Technology Roadmap

A Bio–Suit Technology Roadmap deliverable was developed for the culmination of our Phase II efforts. We recommend investment in the 11 technologies below:

- **3D Laser Scanning**
  - D 1980: Patented 3D rapid digitizing technology
  - M 1990: General purpose 3D scanning systems
  - P 2005: Bio-Suit analysis technique for skin strain field mapping

- **3D and Conductive Textiles**
  - D 1950: 3D knitting machine for gloves
  - M 2006: 3D knit stockings produced, wearable computing proposed
  - P 2008: 3D full body garments, conductive polymer wearable clothing

- **Electrospinning**
  - D 1940: Electrospinning proposed and patented
  - M 2003: Electrospun nano-fibers realized, anisotropic spray capability proposed
  - P 2015: 3D electrospun polymer Bio-Suit garment with specified mechanical properties

- **Design from Nature**
  - D 4 Billion B.C.: Evolution on Earth, Nature’s mysteries unfold
  - M 2000: Biomimetic design enthusiasm, multidisciplinary approaches
  - P 2020: Realization of giraffe counterpressure mechanism for g-suits & Bio-Suit

- **Smart Materials: Shape-Changing Polymers (Artificial Muscles)**
  - D 2000: Promising dielectric elastomers, electroactive (EAP), and mechano-chemical polymers
  - M 2010: Actuator success, polymerizing, & biologically conductive polymers available
  - P 2020: Human-like capable polymers, local control of suit fabrics, Bio-Suit (NCI) Integration

- **Ferromagnetic Shape Memory Alloys (SMA)**
  - D 1990: Shape memory effect observed in Ni-Ti alloy
  - M 2000: NiTi widely available, high-temperature alloy equators
  - P 2015: SMA technology demonstrated at human force equivalents

- **Smart Gels & Fluid-Filled Bladders**
  - D 1970-80: Radio frequency (RF) welding for polymer bladder, smart gel discovered
  - M 2005: Thermal control for divers, MEMS valves and actuators make pressure bladders practical
  - P 2013: Electronically activated smart gels and bladders for Bio-Suit (body coolant)

- **Biomedical Monitoring**
  - D 1990: Prototype for “BioSuit medical ‘suit on a chip’
  - M 2000: Prototype monitors used in several prototypes to assess astronaut iron metabolism
  - P 2015: Astronaut specific miniaturized monitoring systems embedded in Bio-Suit

- **Human Power Harvesting**
  - D 1990: Shoe design incorporates piezoelectrics to generate 10 mW average power
  - M 2001: EAP energy harvesting boot generates 2 W of power
  - P 2013: Energy harvesting becomes more mature, integrated into Bio-Suit for power aids
6 Bio–Suit Visualizations

Our Phase I and Phase II efforts have been noted for our concepts and illustrations. Phase II culminates in a Bio–Suit Infographic that depicts the history of human extravehicular activity (EVA), describes past spacesuits, highlights our mechanical counterpressure Bio-Suit feasibility and research, and provides the previously mentioned technology roadmap. The following gallery shows a sampling of the Bio–Suit illustrations and graphics produced by Trotti and Associates, Inc. (TAI) as an integral member of our Bio–Suit team.
The Bio-Suit Infographic is shown below and can be downloaded at http://mvl.mit.edu/EVA/biosuit/biosuit_images/
In addition to our prototypes and scientific testing, we produced a Bio–Suit mockup to convey the look and feel of a future Bio-Suit System. Envisioning synthetic vision, wearable computing and a ‘second skin’ Bio–Suit we show a revolutionary concept for advanced spacesuit design to realize exploration-class missions to the moon or Mars.
7 Education and Outreach

We made significant progress to reach out to students and the general public. Specifically, we joined forces between MIT and TAI to design and build a Knowledge Station (KS), which is an interactive multimedia station implementing a high-impact design for 1-2 users. The KS will travel to museums across the US in 2006 and challenges kids to “Explore Space” by learning about life on the International Space Station, human exploration of Mars in a Bio-Suit to search for the evidence of past life, and human and robotic cooperation on a journey to Europa. The following images show the gestural interface design of the Knowledge Station and the Bio-Suit System animation.

Explore Space!
The Knowledge Station is an educational portal where you can Explore, Interact, and Learn.

*Explore* the International Space Station (ISS), Mars, and Europa.

*Interact* through the gestural interface to exercise on the ISS, explore Mars with Max in an advanced spacesuit, or teleoperate M. Tallchief (a robot) on Jupiter’s moon of Europa.

*Learn* about the world of NASA and NSBRI’s science and technology breakthroughs.

*Virtually Travel* in the Knowledge Station – an educational environment with freestanding mobility designed for museums and public outreach. Our outreach vehicle is designed for 1-2 users and shares a global vision for peaceful space exploration and hopes to inspire the imaginations of future astronauts.
8 Summary and Conclusions

Our Phase II research performance period was 1 Sept 2004 through 31 Aug 2005. We have accomplished significant research in three main streams: definition of Bio-Suit System requirements, prototype development and testing, and physiological considerations of MCP and planetary traversal. Our program received notoriety and extensive media coverage. We proved the feasibility of a MCP Bio-Suit System, tested working prototypes, delivered a technology roadmap and contributed to public outreach.

In our **Bio-Suit System requirements definition** we have studied the evolution and changes in requirements for the current EMU and the ways in which its design was modified to accommodate these changes; in doing so we have provided evidence that flexibility is a key attribute that needs to be embedded in the design of long-lived systems such as the Bio-Suit System to enable them to efficiently meet inevitably changing requirements after they have been fielded – critical in human missions to Mars where the planning and execution both have long timeframes.

To develop a second-skin capability for the Bio-Suit we have also developed techniques for quantifying these changes using 3D laser scanning and digital image correlation and have subsequently demonstrated these techniques on a human leg as it was flexed from 0 to 90 degrees.

Finally, we have developed predictive parametric analysis tools to plan and optimize planned planetary traverses in real-time. These have shown good correlation with NASA estimates of metabolic energy expenditure when applied to Apollo EVAs.

In our **prototype development** work we have developed MCP leg prototypes based on a variety of novel concepts. First, we developed several types of hybrid garment that provide MCP using a combination of gas pressure and mechanical tension including single- and multi-channel prototypes, conformal spray-on urethane layers with minimal suit profile and hybrid bladders for the knee and foot. Some of these hybrid concepts demonstrated an impressively uniform pressure distribution over their pressure-producing area.

We have also developed numerous elastic-only prototypes that do not rely on any form of gas pressure to produce MCP. One concept is patterned using the body’s lines of non-extension (LoNE) using Kevlar, Nylon and Spandex fibers; we demonstrated their ability to provide excellent leg mobility and are currently investigating techniques for increasing the pressure produced by these prototypes.

To overcome the don-doff and mobility problems in previous elastic-only MCP suits we have also developed prototypes based on a concept involving elastic bands wrapped around the limbs. These bands create MCP through elastic circumferential stress only, thus minimizing longitudinal stresses and maximizing joint mobility. The bands concept demonstrated both short don-doff times – less than 5 minutes per leg – and mobility comparable to an unsuited human; furthermore, we successfully demonstrated the use of this prototype in a low-pressure leg chamber at −150mmHg (−0.2atm) for periods of up to one hour, longer than any chamber tests of previous MCP garments.
Finally we have investigated the use of smart materials, particularly shape memory polymers (SMPs), to decouple the don-doff and pressure production processes. We have demonstrated the ability of a cylindrical sample of the polymer to return to its memory (cylindrical) shape after being deformed to an almost flat shape and are currently characterizing the polymer’s material properties to ascertain whether it would be suitable for use in an MCP garment.

In our **physiological considerations** research we have performed experimental studies to quantify the bioenergetics of walking and running in spacesuits at different gravity levels, and fabricated an exoskeleton to model the spring-like behavior of the legs of gas-filled suits. These studies have shown that running is more efficient than walking in a gas-filled spacesuit in reduced gravity but not at Earth gravity, and that spacesuits have the potential to improve the efficiency of running in reduced gravity. These results are important for planning and executing EVAs using both gas-filled and MCP spacesuits and suggest the potential for tuning spacesuit leg stiffness to minimize the metabolic cost of different activities such as long-distance traversal and climbing.

We have also investigated the effects of pressure differentials between different parts of the body, as it is unlikely that an MCP suit will produce a pressure distribution as uniform as that in a gas pressure suit. We have determined a theoretical first-order estimate of the differential that can be supported by the cardio-pulmonary system without causing edema; furthermore, we have also begun developing non-invasive experimental methods for assessing edema in a human subject wearing an MCP garment using a Thermal Diffusion Probe.

We have accomplished significant Bio-Suit System research requirements definition, prototype development and testing, and physiological considerations of MCP and planetary traversal. We published 34 papers in journals and conferences, and this effort has funded the graduate work of 6 Master’s theses and 2 doctoral dissertations at MIT. We hope to continue our research to realize this revolutionary concept for NASA and are very grateful for support from the NASA Institute for Advanced Concepts (NIAC).
9 References


10 Bio-Suit Publications (Phase I and II)

The following publications have resulted from our Bio-Suit System research effort. We have published 34 papers in journals and conferences, 6 Master’s theses, and 2 Doctoral dissertations. Please see our website for additional information and resources at http://mvl.mit.edu/EVA/biosuit


Saleh, J. H., Jordan, N. C., Newman, D. J., “Shifting the emphasis: from cost models to satellite utility or revenue models”, 56th International Astronautical Congress (IAC), Fukuoka, Japan, October 17-21, 2005.


