THE CHAMELEON SUIT — A LIBERATED FUTURE FOR SPACE EXPLORERS

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ABSTRACT

Mankind's spacefaring future demands the ability to work freely and frequently in space. Traditional spacesuit systems burden both the spacefarer and the mission, limiting the extent to which this is possible. The spacefarer is burdened by a pressure suit designed for isolation from the environment and a life support system designed to replace everything our environment normally provides. The space mission is burdened by this equipment and the expendable materials to operate and maintain it. We aren't free to work in space as frequently, as long, or in all of the locations envisioned. The NASA Institute for Advanced Concepts (NIAC) has sponsored research on an alternative concept, the "Chameleon Suit", that seeks to liberate future explorers and missions from these limitations. The Chameleon Suit system works with the environment in an adaptive fashion to minimize hardware and expendable materials. To achieve this, functions of the life support system are integrated with the pressure suit using emerging materials and design technology.

Technologies under study include shape change polymers and electroemissive materials to modify heat transfer characteristics of the spacesuit "skin" achieving thermo-regulation analogous to that in natural biological systems. This approach was shown to be feasible for many space missions during the Phase 1 study program. The current Phase 2 program is investigating more aggressive concepts aimed at eliminating most of the hardware currently included in the spacesuit's life support backpack. This paper describes the concept, study results to date, and possible impacts on future human space exploration.

INTRODUCTION

Picture yourself journeying through space for months as part of the first human crew to explore a new planet. With what eager anticipation would you wait for the days after arrival when your forced confinement in a tiny spacecraft ends, and you can at last roam freely over an untouched world and slake your thirst for discovery. How precious would you consider every minute when you could apply the skills you had worked so hard to polish to wrest the secrets of an unknown past and untapped potential from the vast unexplored terrain that met your gaze. How cruel then would be the knowledge that only a fraction of your days could be spent out on the planetary surface. Even more bitter would be the awareness that during those precious moments you would have to divide your attention between exploring and safely managing a massive spacesuit near the weight bearing limits of a body weakened through months of weightlessness.

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If we were to mount such a mission today, this is the reality the crew would face. Even though we have walked in space for over 30 years (Portree and Trevino, 1997), explored the moon and made a good start on building the international space station, the spacesuits we use today and those we could build tomorrow remain too heavy and cumbersome for effective use in planetary gravity much greater than the moon's 1/6 *g*. Even worse, they continue to rely on technologies and components that will require large amounts of material from Earth to support their use, severely limiting the number and duration of the excursions (ExtraVehicular Activities or EVAs) that could be supported. This is the case despite many years of operational experience and system refinement, and extensive research into the underlying technologies. Over the years, we have made progress in reducing expendables, increasing the reliability and service life of the system, and increasing the mobility and comfort of the pressure suit, but on back system mass has actually grown as these improvements were made. Reversing this trend while achieving the dramatic further increases in system capability required by future missions will demand changes in our system design approach as well as advances in component technology.

THE EVA CHALLENGE

The challenge of Extravehicular Activity is to create a complete spacecraft with all of the equipment and supplies required to keep an astronaut alive, and to articulate the pressure hull of the spacecraft so it can conform to and move with his or her body. Then all of the equipment and supplies must be packaged so they can be used without interfering with mobility, manipulation, or vision. What's more, this one person spacecraft will need to fit through the hatches of other spacecraft, be easily entered and exited, and recharged and reused may times during an extended mission in space. If our mission is to a planet with a surface gravitational acceleration approaching that of earth, the spacecraft must also have a very low mass so its weight can be easily supported and moved over the surface while the occupant works and explores.

The life support systems for our spacecraft must supply oxygen, drinking water, and food; remove exhaled carbon dioxide, and water vapor from breathing and perspiration; and manage both liquid and solid bodily wastes. It must also remove the waste heat generated by the wearer's metabolism and its own equipment while maintaining internal temperatures at which the body can achieve stable thermoregulation.

The pressure hull of our spacecraft must provide the same protections as the rigid hull of the Shuttle, or Space Station. It must protect against temperature extremes between –150˚C and 120˚C, radiation, and micrometeoroids and orbital debris impacting at up to 20 km/sec as well as against noxious chemicals like nitrous oxide and hydrazine. It must sustain the pressure difference between a breathable atmosphere inside the suit and space vacuum outside, and must leak almost nothing. It must also resist punctures and tears as it moves over, brushes against, manipulates, and even falls on a planetary surface littered with irregular and often sharp edged rocks.

Each of these needs represents a significant challenge as illustrated by a brief example. In order to allow exploration of a significant area or the accomplishment of complex tasks, the spacesuit needs to provide life support capability for periods comparable to a normal, 8 hour, work day during which sustained hard work may be required. For a representative average work rate of about 275 watts (Thomas and Trevino, 1997), approximately 0.55 kg of oxygen will be consumed and 0.7 kg of carbon dioxide generated by the wearer through respiration. They are exchanged through the lungs from a much larger mass of tidal gas within which a narrow range of partial pressure conditions must be maintained to allow the body to sustain acceptable concentrations of dissolved gases in the blood stream. As a result, at least 7 m^3 of gas will be inhaled and exhaled over an 8 hour period. At normal sea level atmospheric pressure, this would have a mass of nearly 8.5 kg and must be either stored and supplied or processed to replenish the oxygen and remove the carbon dioxide during the EVA. Less than ideal flow through the oro-nasal region of the spacesuit helmet will necessitate even higher gas flow through the suit further increasing this mass. At demonstrated helmet washout efficiencies, maintaining acceptable inhaled gas composition for an astronaut working hard in his spacesuit requires approximately 170 l/m flow through the helmet (Hodgson and Guyer, 1998), a total of over 100 kg of gas over 8 hours! When the added penalties of tankage and valves for storing and delivering this gas are considered, the challenge of supporting a practical EVA and the reasons for today's complex system design becomes clear.

CURRENT SOLUTIONS – PROTECTIVE TECHNOLOGIES AND WHAT THEY COST

The current solutions to this challenge reflect a design paradigm rooted in our first forays into the relatively unknown space environment. In the midst of great uncertainty about what would be encountered and how the human system would respond, it was recognized that the environment was harsh, dangerous, and very different from earth surface environments to which we are accustomed. The prudent response, which guided the development of the first EVA systems and all that have come after, was to protect the astronaut as thoroughly as possible by isolating him from the space environment and to provide within the system all that he would need to sustain life and allow him to work effectively. The result was a design concept that divided the spacesuit system into two nearly independent subsystems: a protective pressure garment that provided the desired isolation, and a life support subsystem that provided all the necessary services we take for granted in our earthly environment. This paradigm is visibly reflected in the spacesuits we used to walk on the moon and in those in use on the International Space Station today (Figure 1).

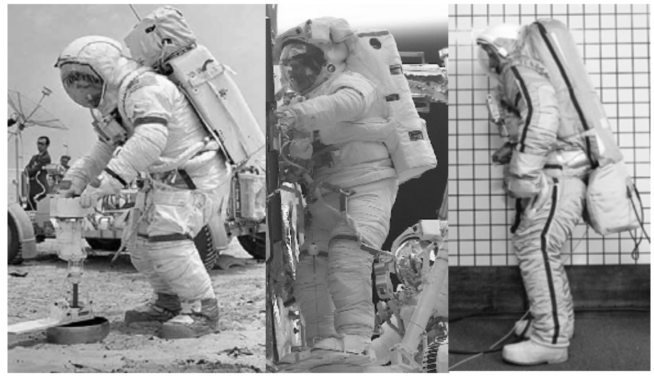

Figure 1. Current spacesuit systems are partitioned into protective garments and large life support backpacks.

The protective pressure garment evolved from high altitude pressure suits used by aircraft pilots as the need for substantially greater mobility to work outside a spacecraft or on a planetary surface was recognized and the resultant design challenges were solved. A gas tight pressure bladder and a strong patterned restraint layer evolved to create joints that could be flexed while producing almost no change in the internal volume of the suit. This minimized the work required to bend single axis joints like the knee and elbow. Sealed bearings were added to allow more complex motions like wrist and arm rotations without applying excessive force. The torque required to move all of these pressurized joints as well as the mass of the suit was minimized by reducing the operating pressure to the lowest value consistent with the wearer's health and safety. The range of motions enabled was limited by the bulk of the garment and the extent to which its dimensions necessarily exceeded those of the occupant's limbs and torso. The use of aluminized multi-layer insulation under tough layers of protective fabric, as shown in Figure 2, provided mechanical and thermal isolation while minimizing the bulk of the lay-up.

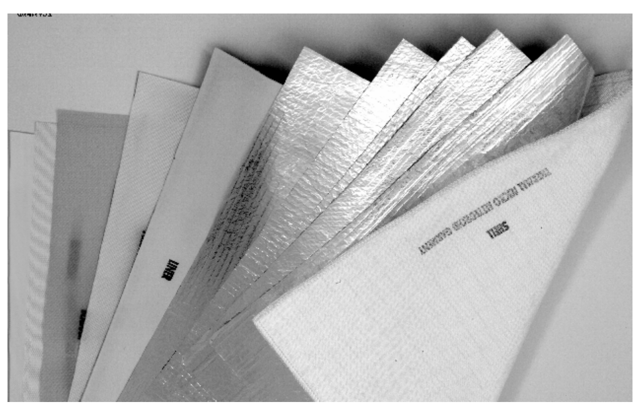

Figure 2. Spacesuit soft-goods use multi-layer insulation to provide thermal and mechanical protection and minimize bulk.

Sizing systems evolved to make the garment as conformal to each user's body as possible: through custom-made suits for Apollo, a modular design for the EMU, and integral adjustment features in the Russian Orlan. This proved especially difficult and critical for gloves where the use of custom-fit items is still common. The need to don and doff the spacesuit repeatedly during a mission added an important constraint to these efforts to improve mobility. As the number of uses for a spacesuit increased, Apollo's zippered entry gave way to a waist flange connecting the upper and lower parts of the suit in the EMU (waist entry) or a large rear hatch in the Orlan and in some US advanced concept prototypes (Dionne, 1991). For all of these donning approaches, the bulk and ultimate mobility of the suit is constrained not only by the entry closure itself, but also by the need to slide some parts of the body (e.g. the hands and feet) through the suit on their way to the final destination (Figure 3).

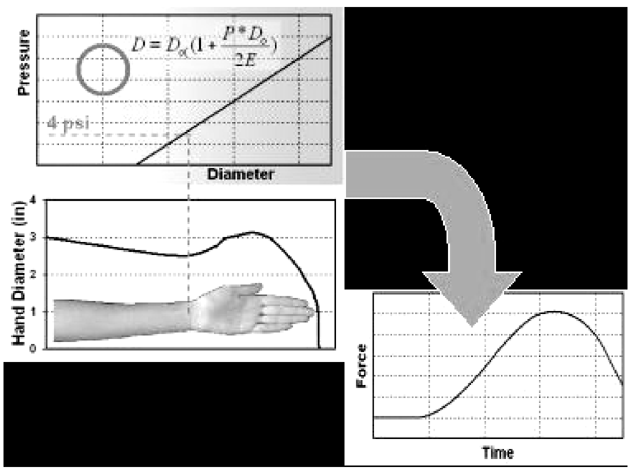

Figure 3. The challenge of donning clearances - wrist -hand clearance as an example.

The result of extensive and continuing (Ross, 2000a), (Hatcliff and Ross, 1996), (Ross, 2000b), (Ross *et al.*, 2002) development has been the evolution of highly protective pressure garment designs that can keep astronauts safe and comfortable in space while enabling most normal body motions with modest losses in joint torque capabilities and range of motion (Morgan *et al.*, 1996). The price to be paid, beyond the mass and encumbrance of the pressure suit itself, is the life support back-pack that must replace all of the environmental interactions that have been carefully eliminated and upon which our life processes usually depend.

The life support backpacks of current EVA systems contain an enormous number of components (Figure 4) and are comparable in mass to the astronauts who depend on them. An integrated set of subsystems:

- stores, delivers, and regulates oxygen for pressure control and metabolic consumption,
- circulates the oxygen to transport exhaled carbon dioxide and water from the pressure suit to the life support backpack,
- separates the carbon dioxide from circulating oxygen,
- condenses the water vapor to dry the circulating gas and prevent fogging on the spacesuit helmet and separates the condensate from the circulating oxygen,
- cools the circulating gas to remove heat released by the astronaut, the circulation system, and the carbon dioxide separation process,
- transports heat from the astronaut's body to the life support backpack,
- rejects the waste heat collected from the astronaut's body and from the life support equipment to space by evaporating water ice,
- stores water for use in heat transport and rejection and regulates its delivery to the heat rejection and heat transport subsystems and the collection and use of separated condensate,

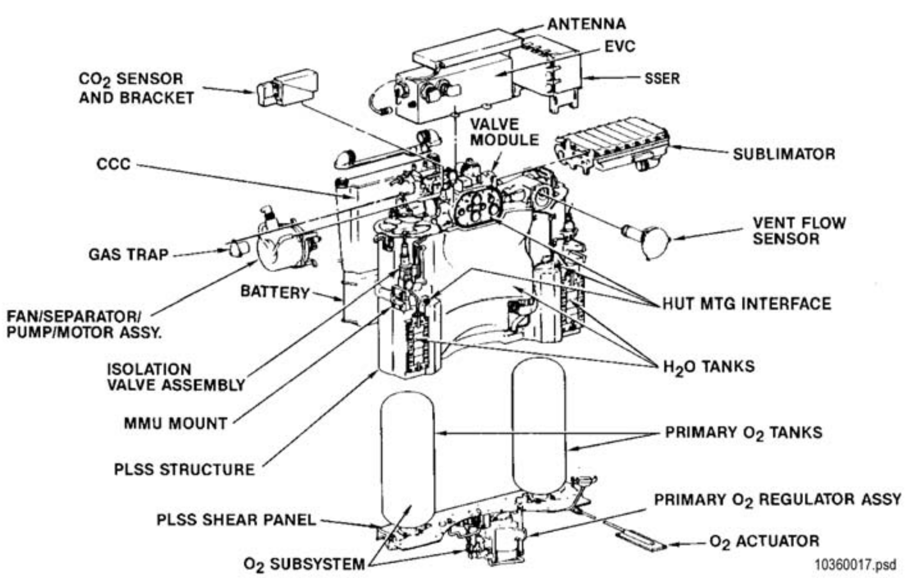

Figure 4. A Spacesuit life support assembly using current approaches is complex, large, and heavy.

- controls system functions, monitors them for failure, and generates appropriate warning and diagnostic messages for the astronaut,
- provides radio communication among EVA astronauts and between EVA astronauts and support personnel,
- stores and conditions electrical power to operate all of these subsystems throughout the EVA,
- stores and delivers at a high flow rate, if required, an additional, emergency, supply of oxygen in case of suit puncture or system failure.

The packaging of this assembly must be tightly constrained to keep its center of gravity as close to the wearer's body as possible and to limit its impact on the hatch size required to accommodate suited astronauts and other penalties on their mobility. As a consequence of this tight packaging and the concentration of all life support functions in this tightly packaged assembly, the surface area available for life support interactions with the environment are only about half the surface area of the spacesuit itself. This has had a substantial impact on efforts to develop alternative systems like heat rejection radiators (Bayes *et al.*, 1988) to reduce system complexity and weight and expendables consumption.

Practical considerations of balance, visibility, and useful work envelope have dictated placement of the life support system behind the astronaut's back like a conventional hiker's backpack. Requirements for convenient access to operating controls and information about the system led to the development of another, smaller, chest mounted assembly to place these elements where they can be seen and reached during spacesuit operations. This assembly, the Display and Controls Module (DCM, Figure 5.) also provides the interface point for fluid and electrical connections to the host vehicle or habitat to recharge the system and support its operations while in the airlock before and after an EVA.

CHAMELEON SUIT - AN ALTERNATIVE PARADIGM

Natural biological systems suggest an alternative paradigm and design approach that may reduce the difficulty of dramatically reducing the mass and mission penalties for future EVA systems. Biological systems thrive through a strategy of adaptive interaction with their environment using multi-functional materials and systems. Thus, protective and structural materials also mediate heat and material exchange processes, and energy from the environment is harvested to drive the processes that make this possible. This is the case in even the most extreme environments using a wide variety of mechanisms that adapt to changing environmental conditions and needs of the organism.

The evolution of manned space systems and technologies and our growing understanding of the space environment and human responses to it have resulted in the conception and exploration of many ways in which EVA systems could beneficially exploit facets of the space environment. It is now practical to revisit the fundamental design approach to EVA systems and explore this alternative, biologically inspired, paradigm.

Figure 5. The chest mounted DCM provides accessible operator and vehicle interfaces.

To do so, we must consider the walls of the spacesuit as much more than a barrier between a hostile environment outside and a fragile human inside. The essence of the Chameleon Suit concept is viewing the spacesuit walls as an extension of the wearer's skin and membrane tissues to better match their already robust adaptive capabilities to a new and challenging set of conditions. In the process, a wide range of potential functions of the membranes and fabrics in the suit wall and mechanisms for their control are considered. The objective is to move life support processes from an external back pack into the spacesuit itself and to connect them more closely and naturally to the biological processes of the person wearing the suit. Benefits which can be derived from this approach include:

- reduced penalties for mass and energy transport between the human and the life support process locus – less plumbing, pressure drop, temperature difference, parasitic heat loss or gain, etc.,
- increased use of and benefit from inherent adaptive capabilities of human systems,
- increased available surface area for desirable environmental interactions,
- increased diversity of access and flexibility for orientation dependent processes,
- decreased complexity, mass, and volume of life support equipment and supplies,
- inherently better system center of gravity management,
- greater radiation shielding benefits from life support systems and materials.

This concept shifts the role of the backpack from that of the sole focus of life support activity to that of an enabling supplement to life support processes focused primarily at the point of need within the spacesuit itself.

To make this possible, it is necessary not only to make the suit walls functional, but also to make them controllably so. The extent to which they transport heat or metabolic waste products or capture energy must vary as the wearer works at varying rates or the environment changes. This requires materials that can change shape, thermal or optical properties, pore sizes, or chemical activity in response to the application of a control signal such as a voltage or a magnetic field. Since space environments and the wearer's needs may vary locally, it also requires the ability to apply the control signals and effect these changes differently over different segments of the suit. To make the control effective, it is also necessary to monitor conditions at many points within the spacesuit and over its surface and integrate the results to derive the appropriate control actions for the wearer's well-being and comfort. Thus, the walls of the suit, while remaining light weight, thin and flexible, will become complex multifunctional structures integrating actuators, sensors, information processing, and signal and power transfer. This can be envisioned as a very large scale integrated circuit Micro-Electro-Mechanical Systems (MEMS) device implemented primarily or totally in flexible polymeric materials. Although the overall size is much larger than current integrated circuits (IC) or MEMS, the number of devices will be modest by modern standards making relatively low resolution production techniques effective.

As Figure 6 illustrates, the Chameleon Suit concept could be implemented in many different forms with varying degrees of impact on the design and size of the life support backpack and on the need for expendable supplies for EVA. These range from replacement of one major subsystem in the life support backpack by implementing controlled heat rejection capabilities in the spacesuit walls to visionary replacement of essentially all functions in the current life support backpack with regenerative processes in the suit walls powered by harvesting incident solar energy. To realize these possibilities, the Chameleon Suit will rely on the application of breakthrough technologies that are beginning to emerge from the convergence of exponential growth in information technologies and a revolution in our understanding of materials and biological systems.

THE FOUNDATIONS FOR THE CHAMELEON SUIT – ADVANCED TECHNOLOGY INFORMED BY BIOLOGY

The Chameleon Suit, although a technological construct, may, in many ways, be considered a product of space biology research. It is possible to consider it now because we have developed a good understanding of how humans respond to space environments and how they can work effectively in them. The concept is biologically inspired; it seeks to emulate the way in which living organisms effectively meet their needs for survival in harsh and varied environments. This pursuit is encouraged by recent studies of extremophile life forms on earth in conjunction with our pursuit of astrobiology. Finally, successful implementations of the Chameleon Suit, when they occur, will be enabled by biomimetic technologies potentially including artificial muscles, biomimetic membranes biocatalysis, and artificial photosynthesis.

The application of these and other emerging technologies in this concept will be feasible because of rapid changes in materials technology and our understanding of biological processes made possible by

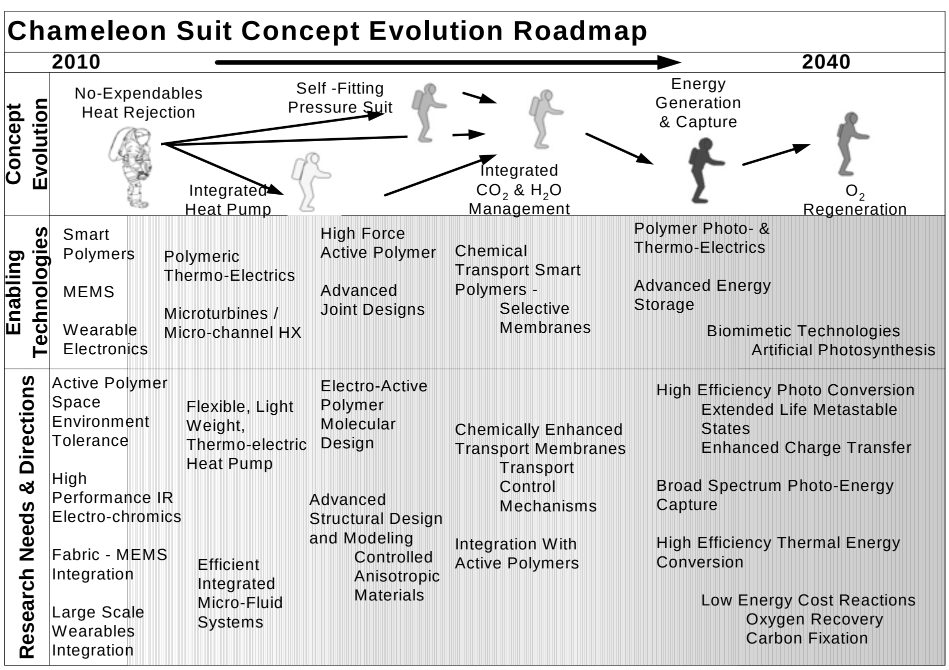

Figure 6. Candidate Chameleon Suit implementation concepts and supporting technologies.

the revolution in information technology we are presently experiencing (Figure 7.). Each of these areas is presently undergoing explosive growth in capabilities and fundamental change in the tools and approaches available to investigators and developers. Together, they have already made practical devices and discoveries that were unimaginable when the current EMU was designed. Patterns of further development that are discernible in active research today are reflected in the Chameleon Suit implementation concepts under study.

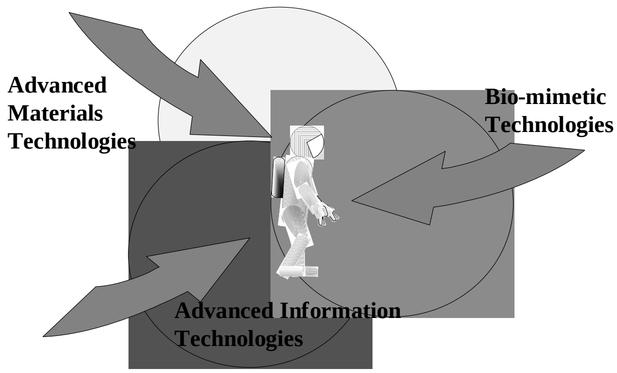

Figure 7. The convergence of materials, information, and biomimetic technology revolutions enables the Chameleon Suit concept.

Information technology capabilities have grown exponentially over the past several decades. This growth, expressed in the familiar Moore's law (http://www.belarus.net/Intel/MUSEUM/moore.htm), has made it possible to deal easily with levels of complexity that would never have been attempted a decade ago. This is true at several levels. The incredible growth in the amount of data that computers can process and the speed at which this is possible is well recognized. It is an essential enabling element in our progress in unraveling the fundamental secrets of materials and biological processes. (The recent completion of the human genome (U.S. Department of Energy, 2003) is an excellent example.) Across a broad front, it is also enabling dramatic gains in our ability to design and analyze increasingly complex structures and systems and to apply sophisticated control techniques to achieve new and better results with the systems we create. On a deeper level, the information revolution has blazed new paths in the creation of increasingly complex systems with amazing efficiency. The processes that have evolved for the mass production of integrated circuits containing millions of components and for their successful design using the products of previous applications of these techniques are extensible to many needs and have pointed the way to a broad array of emerging and future capabilities. Immediate examples are seen in the manufacture of a growing number of Micro-Electro-Mechanical Systems (MEMS), rapidly advancing Computer Assisted Software Engineering (CASE) tools, and proliferating systems and devices for rapid prototyping directly from computer design data bases. Finally, increasingly sophisticated techniques for transporting and integrating data among multiple sources and processing sites have emerged as a consequence of the proliferation and ubiquitous presence of computers and "smart" devices of all sorts making it practical and even easy to integrate large complex networks of active devices and distributed control systems. All of these expanding capabilities have a direct impact on the viability of the Chameleon Suit concept.

Armed with the power of modern computer systems and the insights resulting from imaging technologies extending down to molecular and atomic scales, materials scientists are rapidly developing the ability to engineer materials at the molecular level and the manipulation techniques to practically create what they have engineered. The results are becoming apparent in a growing array of functional materials combining optical, electrical, mechanical, thermal and chemical functions with the structural characteristics for which they have historically been selected and applied. In addition to the liquid crystal devices we now see everywhere, optically active polymers are under study for active visible and infrared camouflage for the military (www.ee.ucla.edu/~eamuri/vu-graphs/yablonovitch/yablonovitch1.html) and for controllable radiators for space heat rejection (Braig *et al.*, 1995). The number and capabilities of polymeric materials which are capable of substantial controlled dimensional or shape change in response to applied electrical, magnetic, thermal or even optical stimuli are rapidly growing (Bar-Cohen, 2001); the creation of practical artificial muscles in the near future is a real possibility. Polymeric nano-composites offering significantly enhanced heat transport properties are being researched (Chibante, 2002), and electrically conductive polymers and polymeric photovoltaics (Samuelson, 2002) are also undergoing rapid development. While few of these materials are currently mature and supported by the rich sets of design data characteristic of operational aerospace materials, a rich set of design choices for the Chameleon Suit is becoming a reality.

Based on our growing ability to characterize and understand materials and their interactions, life scientists are making rapid progress in unraveling the key processes by which we and other organisms make use of our environment. This is opening up rich possibilities in biomimetic design. Research into bio-membranes is isolating the mechanisms by which selective and active transport are accomplished and may provide the key to gains in carbon dioxide transport and selectivity that are required for the Chameleon Suit, but have eluded researchers pursuing conventional physical / chemical approaches so far (Sirkar *et al.*, 2000). Improved understanding of biological reaction systems promises to unlock the secrets of bio-catalysis that achieve useful reaction rates for many processes at substantially lower temperatures than those required in conventional chemical practice. This, with the results of current research into artificial photo-synthesis (AIST, 2001), could enable the recovery of metabolic oxygen in practical quantities using the sunlight energy incident on the surface of a future Chameleon Suit — a break through possibility that would truly liberate future space explorers from many of the limitations imposed by present systems.

BUT WILL IT WORK? – CURRENT STATUS AND OUTLOOK

The Chameleon Suit concept is still very much in its infancy. It is applicable to future NASA missions and EVA systems that will not be operational for a decade or more. Studies to date are promising, but incomplete, and necessarily somewhat speculative in some areas. Based on the completed Phase 1 study sponsored by the NASA Institute for Advanced Concepts (NIAC), we believe the fundamental concept is sound and valuable. There is considerable confidence that some of the more limited implementation concepts under study can be realized within the target time frame and will provide real benefits to future astronauts and the missions they serve. With respect to the practical implementation of some of the other, more ambitious, possibilities, the jury is still out pending the completion of the current study and, likely, the results of future research efforts.

The Phase 1 study of this concept (Hodgson, 2002) focused on its application to EVA thermal control and showed that this new paradigm could make it practical to achieve thermal balance by radiating waste heat from the outside of the spacesuit. This eliminates the use of expendable water as an evaporative heat sink and allows the elimination of many components and substantial mass from the life support backpack. The feasibility of this approach is based on the application of technologies that allow that heat transport of the spacesuit walls to be controlled over a wide range by altering the structure between a compact conductive wall and multiple spaced layers with intervening gaps providing insulation as illustrated in Figure 8. Electro-active polymer materials currently provide sufficient force and motion amplitude to provide the required control over layer contact and spacing (Shahinpoor *et al.*, 1998). They are inherently thin and flexible materials suitable for use in a fabric lay-up and compatible with suit motion requirements. Continuing research is expected to resolve current issues of compatibility with the space environment for some of these materials and make emerging alternatives available. High conduction between layers when in contact, even in vacuum, can be achieved through the use of fibrous carbon velvet materials (Seaman and Knowles, 2001).

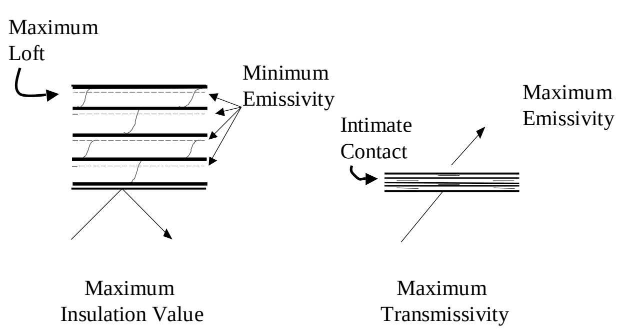

Figure 8. Chameleon Suit thermal control is achieved by varying loft and optical characteristics of the suit lay-up.

Further modulation of heat transfer when the layers are separated is provided by the use of infrared electrochromic materials being developed for use in controllable space radiators (Trimble *et al.*, 2000). These are used to modulate the emissivity of the surfaces within the lay-up by approximately a factor of two and vary the amount of heat transferred by radiation. This lay-up is illustrated in Figure 9.

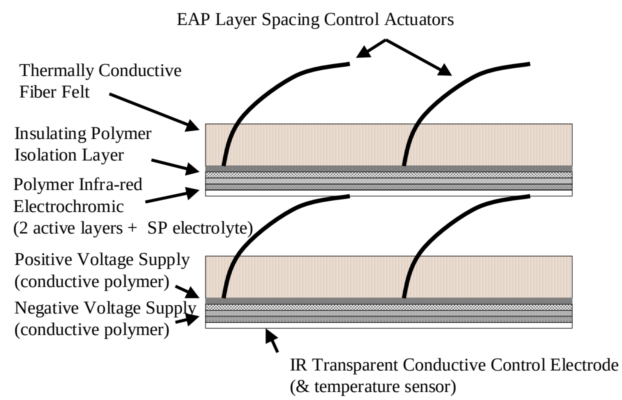

Figure 9. The Phase 1 study lay-up includes provisions for varying loft and optical properties, supplying power, and ensuring good thermal contact when desired.

As shown in Figure 10, the use of the full spacesuit surface area for heat rejection that it allows makes it possible to achieve thermal balance solely through radiation for most EVAs, a goal that has long eluded designers trying to implement radiators as part of the EVA life support back-pack.

In order to apply the concept effectively in space environments where radiative heat balance may be strongly directional, it is necessary to provide local control over the suit's heat transport. During the Phase 1 study, analysis showed that on the order of 150 independent control zones will be required as identified in Table 1. Each will respond to centrally determined metabolic rate information for the wearer and locally determined suit surface temperature to maintain the wearer's skin temperature at a comfortable value for his or her work rate. A typical relationship based on previous spacesuit experience is illustrated in Figure 11.

To extend the applicability of the concept to challenging thermal environments like the sunlit lunar surface, a new directional shading approach illustrated in Figure 12 was developed. It can be implemented as MEMS devices on the outer surface of the suit. Analysis results, shown in Figure 13, indicate that it can provide dramatic increases in the ability to reject waste heat during EVAs on a hot planetary surface. The Phase 2 study that is now underway is examining the broader application of the concept to all aspects of EVA life support. This study evaluates a broad range of emerging technologies and their application to enable the suit walls to mediate additional life support processes including the

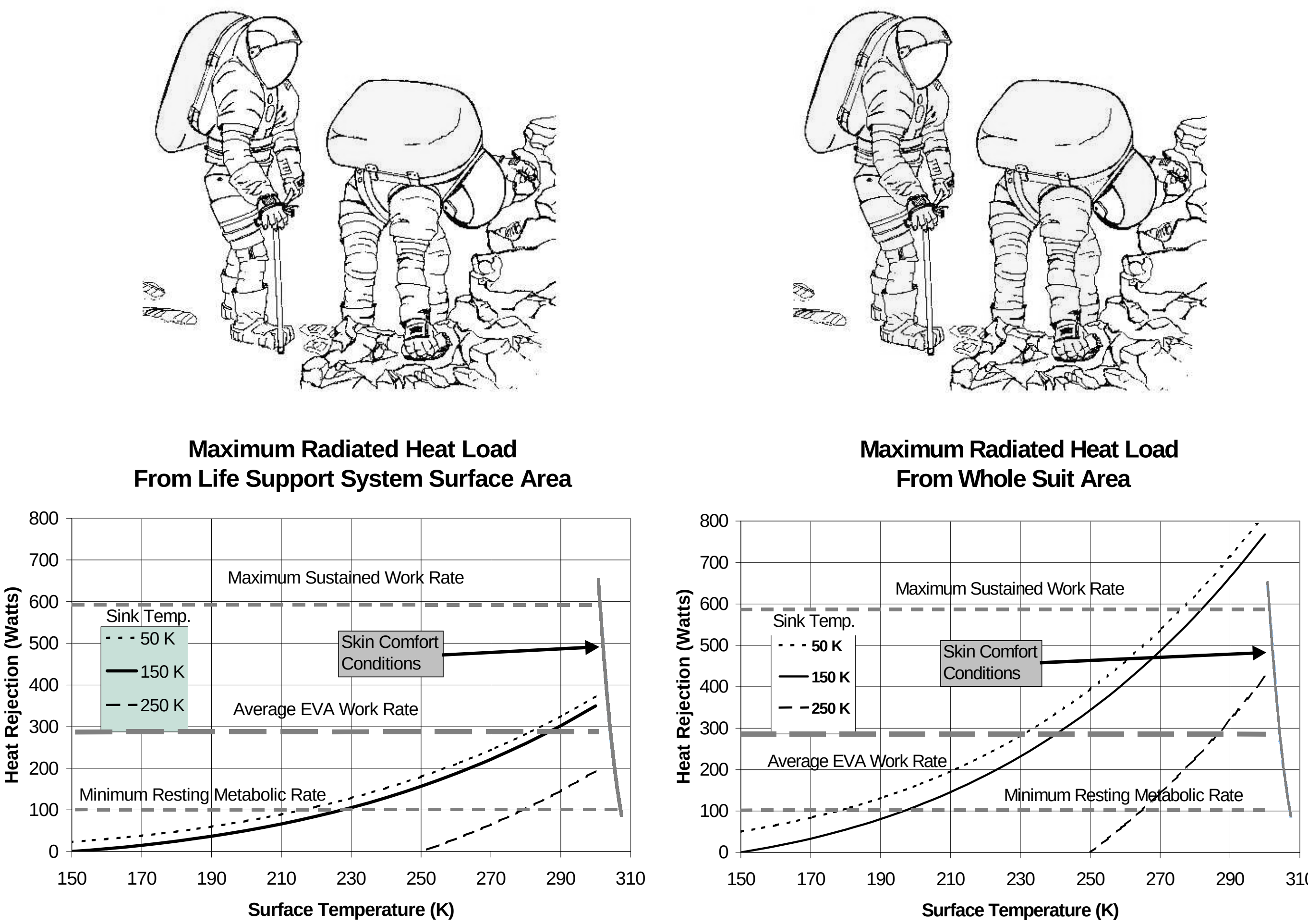

Figure 10. Heat rejection without consumables becomes possible if the full suit area can be used.

Table 1. Local control zones required to achieve effective system thermal control in direct solar illumination environments.

Control & Sensing Zones		Inactive Zones	Comments
Head	11	Gloves	45 degree cap on top, 5 ~45 degree zones, 45 degrees up from equator (excludes visor area), 5 ~45 degree zones, ~45 degrees down from equator to suit interface
Torso	32	Elbows	8 45 degree circumferential zones, 4 vertical divisions, encompasses torso and PLSS
Upper Arm	24	Knees	8 45 degree circumferential zones, 3 vertical divisions
Lower Arm	24	Boots	8 45 degree circumferential zones, 3 vertical divisions
Upper Leg	24		8 45 degree circumferential zones, 3 vertical divisions
Lower Leg	24		8 45 degree circumferential zones, 3 vertical divisions
Shoulders	7		2 subdivisions on top of each shoulder, 3 segments on top of PLSS
Total	**146**		

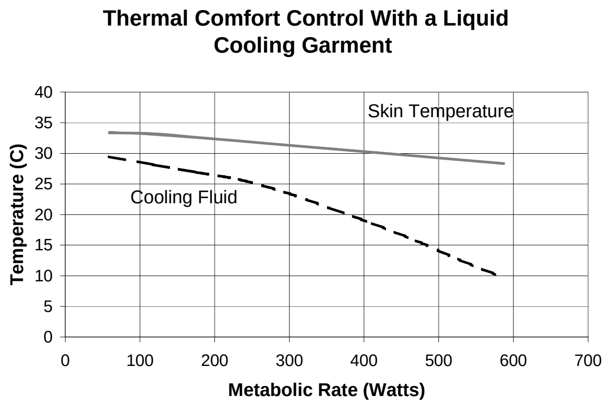

Figure 11. Skin temperature for thermal comfort varies with work rate.

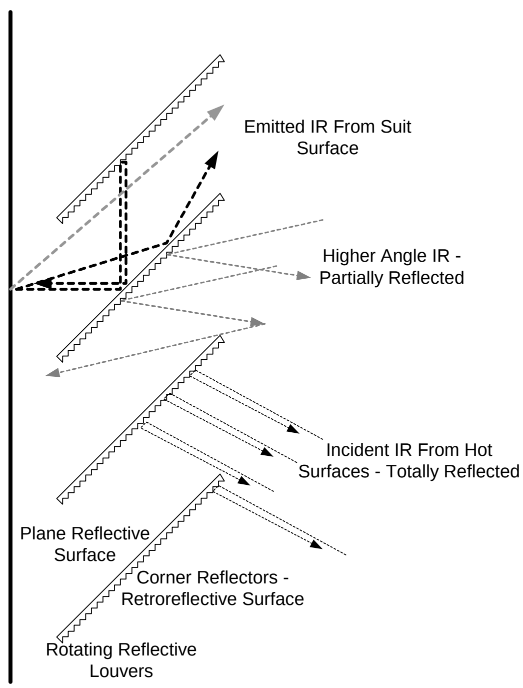

Figure 12. Directional shading louvers were conceived to allow operation on hot planetary surfaces.

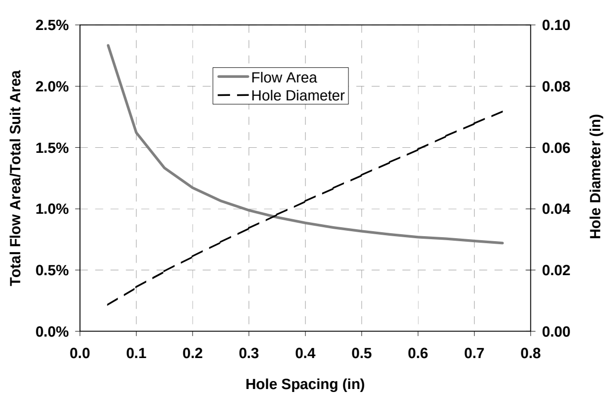

Figure 13. With directional shading heat balance can be achieved by radiation and without active heat pumping under most lunar mission conditions.

separation and rejection of metabolic waste gases, energy capture form the environment and from the user's waste heat to power life support processes, and the recovery of metabolic oxygen from metabolic waste processes or from ambient atmospheres. The study encompasses the development of concepts for various ways in which these functions may be implemented and combined and for analyses of those concepts to address the principle design issues they entail and to evaluate first order feasibility questions and potential benefits.

So far, the study has resulted in the development of a series of system design concepts with accompanying schematics and mass and energy balance estimates. The boldest of these, illustrated in Figure 14, would result in limiting the requirements for a distinct life support backpack to the provision of emergency back-up life support functions and a limited quantity of make-up oxygen for EVAs with insufficient solar energy availability.

First principles analyses of these concepts have addressed some of the most critical feasibility questions:

- Do the mass and energy balances make sense?
- Are the required mass transport paths feasible?

The results of energy balance calculations summarized in Table 2 lead to the conclusion that all of the Chameleon Suit implementations envisioned are within the realm of physical possibility, but some will prove very difficult to achieve. The energy required for active heat transport functions to address extreme thermal environments are easily recoverable from incident solar energy, and the energy theoretically recoverable from suit wall heat flows is comparable to current life support system power requirements. Energy balances for the recovery of significant amounts of oxygen remain theoretically achievable for EVAs conducted no farther from the sun than Mars orbit but demand efficiencies in energy capture and conversion that exceed current technology projections. Overall efficiency on the order of 50% in converting incident sunlight into chemical energy in the form of recovered oxygen from Carbon Dioxide will be required to allow complete closure of the Chameleon Suit oxygen loop. Comparing this to current projections for photovoltaic solar energy conversion (33% - Samuelson, personal communication, 2002.) and the uncertain performance of emerging biomimetic oxygen recovery processes leads to the conclusion that the risk is high that at most a fraction of the oxygen supply may be recovered.

Mass transport within an integrated Chameleon Suit wall presented a significant challenge to system concepts that use the suit wall to reject metabolic carbon dioxide and humidity to the environment. The outer functional layers required to control heat transport and to provide energy harvesting represent potential barriers to the flow of waste gases out of the suit walls. Resulting back pressure at the suit's pressure membrane would decrease the partial pressure driving the membrane transport processes. Since current membrane performance must be significantly improved to make the concept feasible, further increases in the challenge could be a serious concern.

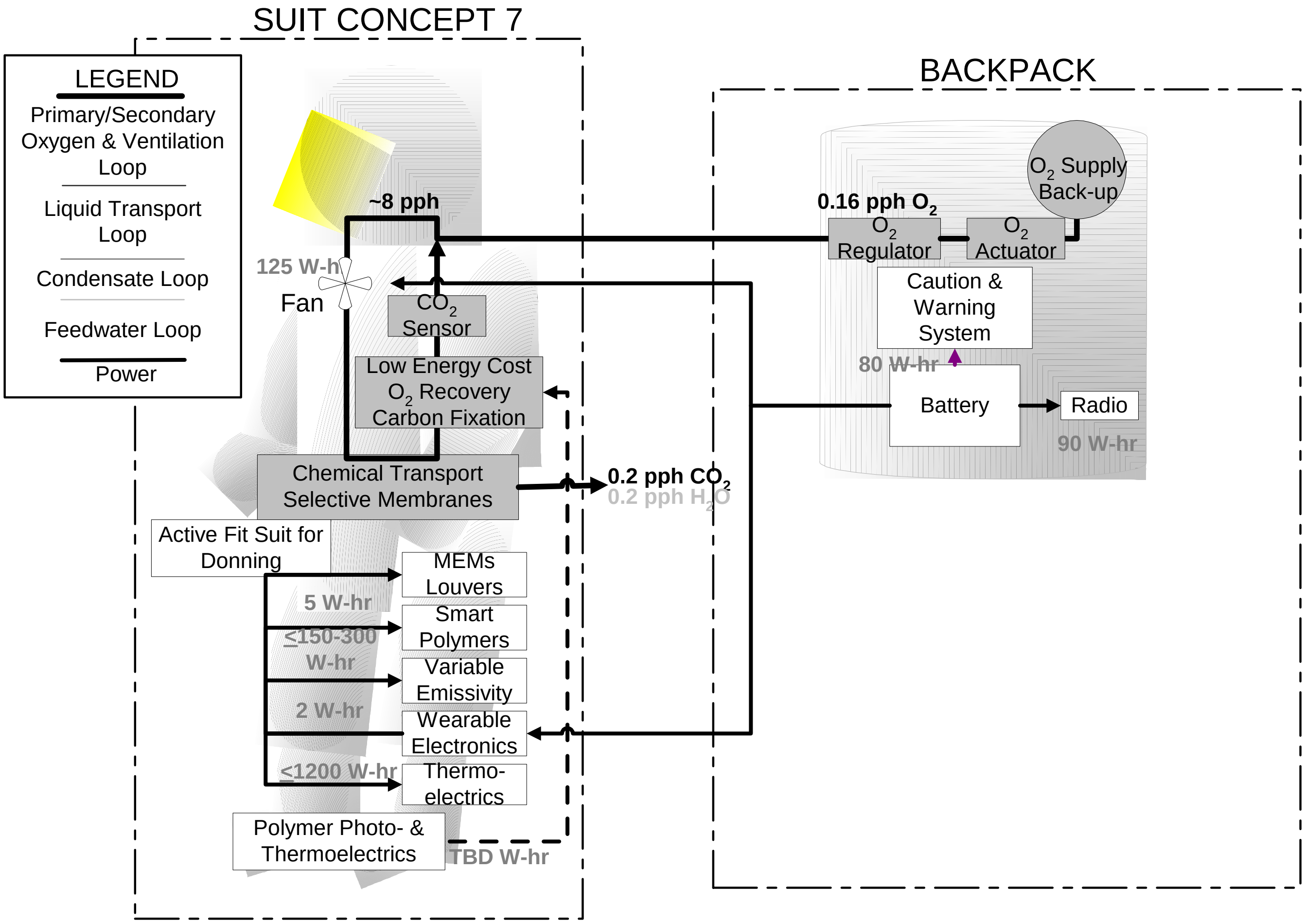

Figure 14. Biomimetic oxygen recovery in the spacesuit could result in a dramatic reduction in life support backpack equipment and materials.

Table 2. Energy balance summary for alternative system implementation concepts.

	Current Suit (W-hr)	Phase 1 Concept (W-hr)	Phase 2 Concepts 1 (W-hr)	2 (W-hr)	3 (W-hr)	4 (W-hr)	5 (W-hr)	6 (W-hr)	7 (W-hr)	8 (W-hr)
DCM/CWS	80	80	80	80	80	80	80	80	80	80
Radio	90	90	90	90	90	90	90	90	90	90
Pump	40	20	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fan/Separator Motor Ass'y	304	304	254	N/A	N/A	254	N/A	N/A	N/A	254
Circulation Fan	N/A	N/A	N/A	125	125	N/A	125	125	125	N/A
Electrochromics	N/A	2	2	2	2	2	2	2	2	2
Actuators	N/A	150–300	150–300	150–300	150–300	150–300	150–300	150–300	150–300	150–300
MEMS Louvers	N/A	5	5	5	5	5	5	5	5	5
Thermoelectrics	N/A	N/A	1200–80	1200–80	1200–80	1200–80	1200–80	1200–80	1200–80	1200–80
Photovoltaics	N/A	N/A	N/A	N/A	N/A	N/A	0 to 3456	0 to 3456	0 to TBD	0 to 3456
Oxygen Recovery	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2350	N/A	2350
Net Energy Balance - MAX	514	801	1931	1802	1802	1931	1802	4152	1802	4281
Net Energy Balance - MIN	514	651	501	372	372	501	3084	734	TBD	605

The results of analyses illustrated in Figure 15, have shown that a very small fraction of open area through each layer will support the required mass flow while imposing less than a 10% penalty on the membrane transport process. Further, the size of individual openings can be small. As a result, only minimal effects on the design and functional performance of the outer suit layers are anticipated.

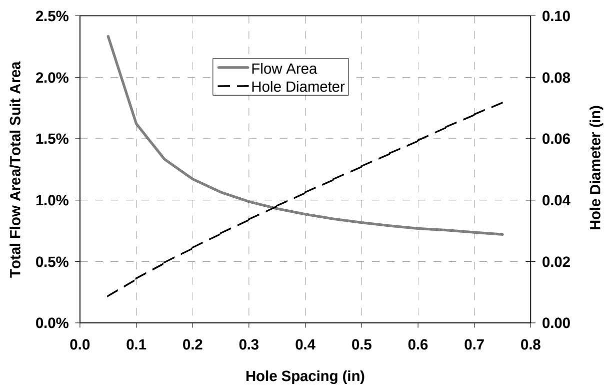

Figure 15 Metabolic waste carbon dioxide and water vapor can be passed through the Chameleon Suit lay-up without degrading thermal control or electrical integration.

Concept development and analysis has been supported by the investigation of research programs and results at universities, and in industrial and government laboratories around the world. In general, the results of these investigations and of direct contacts with many active researchers has supported the initial thesis that the technologies required for the Chameleon Suit are emerging and can be applied within the 10 – 40 year horizon targeted by the NIAC. Among the noteworthy highlights:

- Thermoelectric materials using both thin film (Vankatasubramanian *et al.*, 2001) and polymeric (Liu, 2001) construction have been reported to offer significant performance increases over present commercial materials. These performance gains together with the Chamaeleon Suit's operating advantgage of increased heat rejection surface area and their suitability for use on a thin, flexible substrate show great promise for successful implemetation of envisioned active heat transport and thermal energy harvesting functions.
- Photovoltaic materials have shown steady gains in performance. Based on recent developments in multi-spectral devices (Space Daily, 2002), theoretical limits have not yet been approached and continued progress can be anticipated. Thin film and polymeric photovoltaic materials and systems have been developed and are reaching practical conversion efficiencies (Zweibel, 2002). Driven by the demands of potential military and commercial applications, there is strong interest and investment in further developing these devices; considerable progress in the coming decade can be anticipated. However, conversion efficiencies consistent with the energy demands of in-suit oxygen recovery systems remain speculative.
- Flexible and light weight energy storage suitable for integration into the suit walls is fast becoming a reality with the development of high energy density lithium polymer cell designs in flexible formats (Cymbet Corporation) and of super capacitor designs using conductive polymer materials.
- Researchers are making significant progress in unlocking the secrets of natural photosynthetic processes and implementing key process steps in engineered systems in the laboratory (Ritz *et al.*, 2000; Earth Vision, 2000). While current capabilities fall far short of the ability to engineer the biomimetic systems envisioned for this purpose in the Chameleon suit, the necessary base science and technology are clearly emerging. It is far less clear that the capability to implement the processes with the needed end to end efficiency will result for either a fully biomimetic or electrochemically linked process.

CONCLUSIONS

The Chameleon Suit concept offers a new perspective on EVA systems design that could provide a key to unlock the challenges of ambitious future space missions. On-going research studies have shown that significant gains can be achieved by shifting the system design paradigm from one based in conventional space vehicle engineering practice to one inspired by biological systems. Traditional engineering approaches which partition the system into an enclosure that provides protection and isolation and a life support system impose performance penalties that disappear when the system is viewed as an organic whole in which the boundary surfaces actively mediate interactions with the environment in a manner analogous to the skin and mocosae of living organisms.

Real opportunities to significantly reduce system mass and resupply needs by providing for heat rejection and mass transfer from spacesuit surfaces and using those surfaces to harvest available energy have been identified. First principle analyses indicate that these gains are achievable, and investigation of emerging technologies supports the expectation that they could be implemented to support NASA missions within a 10 – 40 year horizon. The ultimate goal of this concept, a symbiotic interaction of astronaut and spacesuit like that between humans and terrestrial plants in which the astronaut's waste carbon dioxide and water vapor are converted back into respirable oxygen in the suit walls using environmental energy sources, remains a theoretical possibility, but requires energy capture and conversion performance beyond current technology projections.

Based on results to date, the Chameleon Suit concept continues to offer benefits that are worth pursuing and may suggest new avenues of attack on many EVA system design challenges. Research is continuing.

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