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A Chameleon Suit to Liberate Human Exploration of Space Environments

Final Report

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Introduction

The direct operation of humans in space environments must become commonplace if the goals of the HEDS enterprise are to be achieved. This transition from rare and expensive Extra-Vehicular Activity (EVA) to normal and expected "going outside" can be enabled by a system concept in which the walls of the protective clothing work with the space environment to provide required thermal control functions. This will liberate future space workers and explorers from reliance on cumbersome mechanisms and consumable resources currently used for thermal control. It will be achieved by providing the ability to tune the heat transmission characteristics of the outer garment from highly insulating as in present spacesuit designs to highly transmissive. This will allow heat flow from the body to be modulated to match varying metabolic activity levels in any environment and permit selective control on different garment surfaces to take advantage of the most advantageous thermal conditions at any work site. This study has evaluated the implications of the "Chameleon Suit" system concept which integrates emerging technologies for varying conductance / convection insulation with controllable radiation emissivity surfaces. We have assessed concepts for its implementation and required technology development beyond currently emerging and projected technologies to make it a success. The results of our study show that the concept can address most of the operating environments and missions envisioned in NASA's HEDS Strategic Plan and, if developed, will provide substantial savings over present system concepts.

Working in space exposes humans to temperature extremes well beyond the earthly norms for which evolution has adapted our bodies. Direct solar radiation without the moderating influence of earth's atmosphere, hydrosphere and lithosphere can create lethal surface temperatures above 400 K, while radiation to deep space can chill exposed surfaces to near 0 K. NASA goals for human exploration and work in space add the challenges of operation in the frigid atmosphere of Mars and in interplanetary space. (Figure 1)

Figure 1. HEDS Missions will demand revolutionary thermal control solutions.

In all of these environments, it is not sufficient to simply protect the human from temperature extremes. The body's waste heat must be continually removed to enable effective work, and indeed life itself, to continue. Widely varying levels of activity demand an extremely flexible system dealing with metabolic heat loads from less than 100 watts to over 600 watts in addition to tremendous variations in the environment.

Historically we met these challenges by

- thermally isolating the body from the environment using a protective garment,
- collecting the waste heat using a circulating fluid (water in a liquid cooling garment in US operational systems), and
- using expendable water to reject the heat by evaporating ice into the space vacuum environment.

This approach has been effective on the moon and in earth orbit, but carries a high price in consumable water loss (about 4 kilograms for eight hours of work in space by one person) and in equipment complexity, weight, and volume. NASA is currently planning much more demanding missions with the ultimate goal of robust, sustained human residence and work on other worlds and in interplanetary and interstellar space. These demand a different, revolutionary, solution that will eliminate the need for consumable resources and dramatically decrease the impacts of thermal control on the space suit system design. This study has explored a system concept that meets this need.

Summary

The Chameleon Suit concept in its essence is to reverse the prevailing design paradigm for EVA systems that views the pressure suit walls as a means of isolating the wearer from the hazardous space environment that surrounds him. We attempt, instead, to view the pressure suit walls as an interface to allow beneficial interaction with the surrounding space environment. Because that environment can present hazardous extremes, that view requires that the characteristics of the suit walls change in response to the environment, much as a Chameleon's skin changes color, to meet the wearer's needs and ensure his safety.

In this study, we have evaluated the formative elements of this concept, its application to maintaining the wearer in a comfortable thermal state while working in space. We began by studying the feasibility and technical performance requirements of a proposed architectural concept that included:

- Multiple insulating layers that could be separated or brought into contact to modulate conductive heat loss through the pressure garment.
- Electrochromic coatings on the surfaces of these layers to control radiant heat transport through the garment.
- Integrated sensors and control elements to permit both local and temporal control of these processes to maintain the wearer's comfort.

This confirmed that the concept has the potential to eliminate the need for water or other consumable heat sink materials in most EVA scenarios. Potential savings of several kilograms in EVA suit system mass and of as much as several thousand kilograms in mission consumables requirements were estimated.

Several concept adaptations required to achieve these goals were identified. In the process, a new approach to using MEMS devices to directionally shield a thermal radiation surface for improved performance near hot surfaces was conceived and characterized. Preliminary analyses indicate the ability to operate at or above average EVA work rates without heat rejection expendables on the lunar surface at nearly all solar elevation angles.

The status and potential performance of enabling technologies for the concept including:

- Electroactive plastic actuators
- Thermal infrared electrochromic systems
- Conductive plastics, wearable electronics, and distributed control systems

were investigated through literature searches and direct contacts with active researchers. The results indicate that substantial progress in all of the key enabling technology areas is likely prior to the expected use of a Chameleon Suit EVA system. However, it is unlikely that all requirements for the concept's success will be met without direct NASA involvement or sponsorship of research activity in each area.

In the course of the study, a number of extensions of the original concept emerged leading to a potential implementation of the concept in which every aspect of life support would benefit from the use of the suit walls to communicate with the space environment. Based on the favorable results achieved in examining the original, more limited, thermal control application of he

architecture, broader applications are believed to offer significant promise. Further study along these lines is recommended.

The balance of this report presents the principal results of the study in greater detail.

Concept Analysis

Concept Description and Analysis Approach

Our study addressed a revolutionary space suit system concept, the "Chameleon Suit" in which thermal management is accomplished without the use of consumables by rejecting metabolic and equipment waste heat through the outer surface of the space suit. Active control over the heat transmission characteristics of the space suit's protective outer garment to meet the needs of varying environmental conditions and widely varying activity levels is the key to this concept. Emerging technologies including infrared electro-chromism and new materials like electro-active polymers will make it possible.

Control is provided by varying both conductive/convective and radiative heat transfer characteristics of the garment. Conduction and convection are controlled by varying the physical thickness or loft of the insulating garment, while radiant heat transfer is varied by controlling the infrared emissivity of the layers of material which comprise it. This is illustrated in Figure 2 which compares the outer garment of the envisioned system under conditions demanding maximum and minimum insulation.

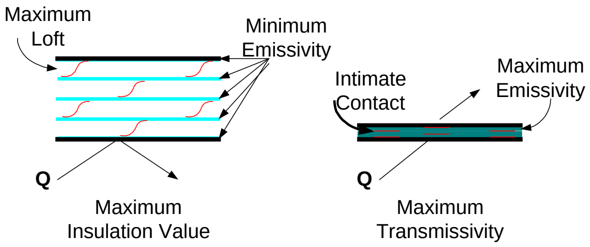


Figure 2. Both physical and electro-optical control will modulate space suit insulation.

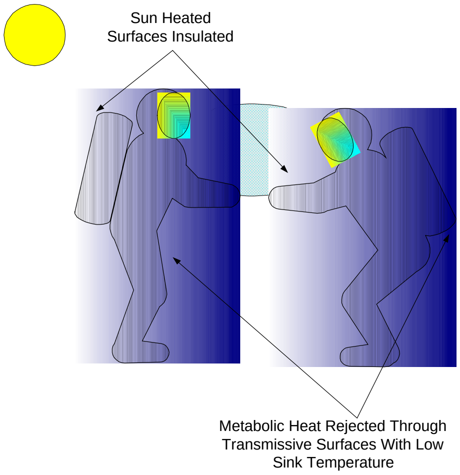


Figure 3. Local control of insulation properties supports operation in any environment without constraining activities

A typical operational scenario for the proposed system is illustrated in Figure 3. Local control of insulation loft and layer emissivity enable directional response to conditions like incident sunlight making some surfaces of the spacesuit insulating and others transmissive to automatically optimize system thermal conditions while the wearer moves freely to accomplish planned tasks.

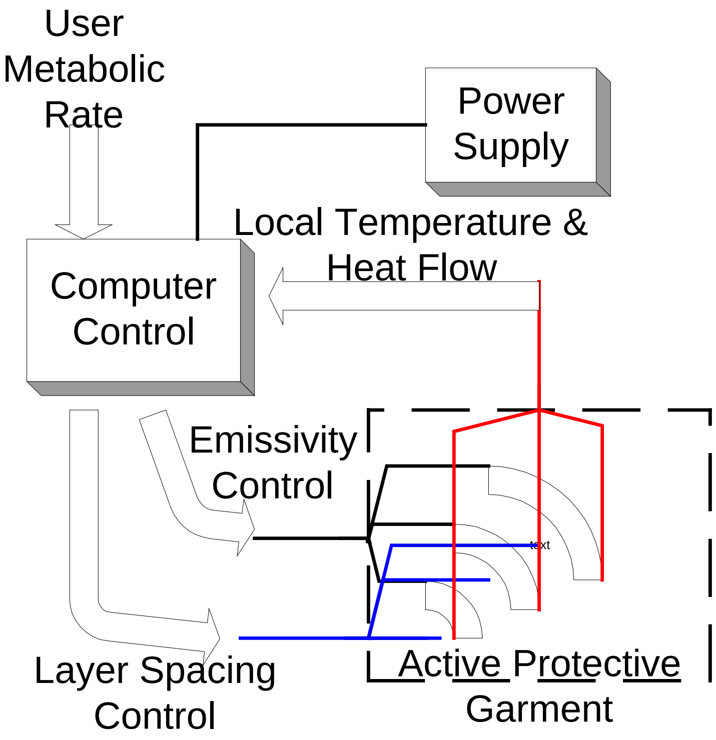


Figure 4. The proposed system concept responds actively to wearer activities and changing environments to maintain thermal comfort.

The complete thermal control system is envisioned as combining measurement of the wearer’s metabolic activity and garment thermal conditions, computer control logic, a power source, and control mechanisms integrated with the protective garment as illustrated schematically in Figure 4. Measured metabolic rate will define the heat flux and suit wall temperatures required to maintain the wearer in a state of thermal comfort. Measured garment temperatures will reflect external conditions including directional variations and allow closed loop control for the desired internal thermal environment. A computer model will integrate these data and determine the desired insulation characteristics on each segment of the garment. Actuation signals will be routed to each segment and active layer in the garment. Both suit layer spacing and emissivity can be controlled by low power, low voltage signals consistent with personal safety and practical portable power sources. The control elements will be minute, flexible, solid state constructs integral to the layers of the protective garment addressed through a conductive matrix analogous to systems used for addressing electronic arrays in sensors and other integrated circuit devices.

Our analysis of the Chameleon suit system concept was intended to confirm its feasibility based on physical principles and the potential performance of the underlying technologies and to quantify the requirements for their development in order to enable concept success. It included:

- review and analysis of relevant requirements associated with future NASA missions to confirm initial assumptions,
- derivation of required system performance characteristics,
- assessment of concept feasibility over the identified suite of missions based on fundamental physical limits,
- evaluation of physiological limits and implications of the concept,
- derivation of implied component and subsystem requirements.

Because the concept under analysis relies on components that do not currently exist but are only beginning to emerge as nascent technologies and research areas, these analyses necessarily relied upon a combination of known quantities and estimates of future component characteristics. We believe the results are realistic projections of what will be feasible because we have used values that are consistent with fundamental physical and chemical limitations and with prior experience in developing and applying materials and components in space life support systems. For example, infrared and visible spectrum emissivity values used in analysis have not been outside the range that has proven practical for extended use of surfaces on space systems in prior operational experience. Although materials are known which provide emissivity values outside this range, exposure to the space environment under conditions appropriate for EVA quickly degrades exceptionally low or high emissivity surfaces through a variety of weathering and contamination processes. These will most likely affect the components and materials in the Chameleon suit similarly.

Mission Requirements

Determining the mission requirements which the Chameleon suit must address required first that we assess the missions which NASA is likely to undertake within the 10 – 40 year horizon targeted by the advanced concepts developed under NIAC sponsorship. In general these are reflected in the NASA's Human Exploration and Development of Space (HEDS) Strategic Plan (Reference 1.) This plan sets out goals and activities for near-term, mid-term and far-term horizons. Although the mid-term nominally extends slightly beyond 10 years from the inception of this study, NIAC's focus is primarily on the period identified with the far-term goals in the HEDS Strategic Plan. These focus on 500 – 1000 day missions with design reference points including Mars and the asteroids. A major goal is the ability to operate independent of earth based logistics for extended periods. The far-term goals also include expanding activities at existing and additional "key sites"

Specific mid and far-term goals in the plan make it clear that these "key sites" will encompass a variety of locations within the earth – moon system. As examples:

- "Initiate Government - commercial partnerships in research, development, and infusion of new technology to extend ISS life beyond 2012, as needed."
- "Test and validate technologies and systems that can reduce the overall mass of the human support system by a factor of three (compared to 1990's levels)."
- "Complete research and technology validation (including demonstrations on the ISS) of competing technologies for 100- to 1000-day human missions."

- “Complete the transition of ISS to a customer-driven commercial operation and work with industry to identify and implement major upgrades as needed to extend ISS life expectancy and/or expand capability to meet user community needs, while improving safety.”

Continuing and more aggressive activities in LEO as well as mid-term design reference point missions to the earth-sun and earth-moon libration points and the lunar surface must be addressed by a successful design concept for the 10 – 40 year time frame.

Further definition of the missions that would be undertaken was obtained from prior experience, published design reference mission scenarios where available and from direct contact with NASA personnel engaged in advanced EVA mission planning studies. Design requirements for missions in low earth orbit were inferred from past experience and from the stated goals of future activities. NASA’s published design reference mission for the human exploration of Mars together with the scientific results from the Viking and Pathfinder missions provides a clear picture of both the thermal environments and EVA missions for Mars exploration activities within the targeted time frame. Numerous published lunar base and lunar mission studies as well as Apollo program experience also provide useful data. Libration point missions are currently under study and are not yet described in publicly available reference documents. Direct contact established the outlines of several potential missions from which likely EVA system design requirements could be derived for use in the analysis.

Characteristics of these missions which are of primary importance for this study include the thermal environments in which EVA will occur, the number and duration of EVA’s to be performed, the gravity environment in which the EVA’s must be accomplished, crew work rates during those EVA’s, and the mission duration and launch mass penalties. EVA thermal environments include the presence or absence and intensity of direct and reflected sunlight, the infrared flux from surrounding objects and surfaces (often represented by the black body equivalent sink temperature), and the presence or absence, temperature, and convection characteristics of a planetary atmosphere. Together, these define the energy transport from the outer surface of a space suit with given characteristics and are the primary factor in determining how much waste heat can be rejected to the environment through the suit. The number and duration of EVA’s to be performed determine the mass penalties (both on-back and resupply) associated with system operation by determining the individual and cumulative time during which it must operate. This was of primary importance in evaluating comparative benefits of the Chameleon Suit. The gravity environment determines the importance of system on-back mass for NASA EVA missions.

Crew work rates determine the rate at which metabolic waste heat must be rejected from the system. Maximum work rates set the highest heat rejection that must be accomplished. Minimum work rates (resting conditions) define a maximum level of insulation which the system must be capable of providing for crew safety and comfort. Average work rates determine the total heat rejection required during an EVA and are of primary importance in determining system mass penalties for use with EVA number and duration in assessing comparative benefits. Typically crew work rates are considered in terms of one or more representative metabolic rate profiles as illustrated in Figure 5. When available, these permit a complete analysis or test of system operational characteristics and interactions with the body’s heat storage and thermoregulatory characteristics that was considered beyond the scope of this study since both the system and the missions are at a very preliminary stage of development.

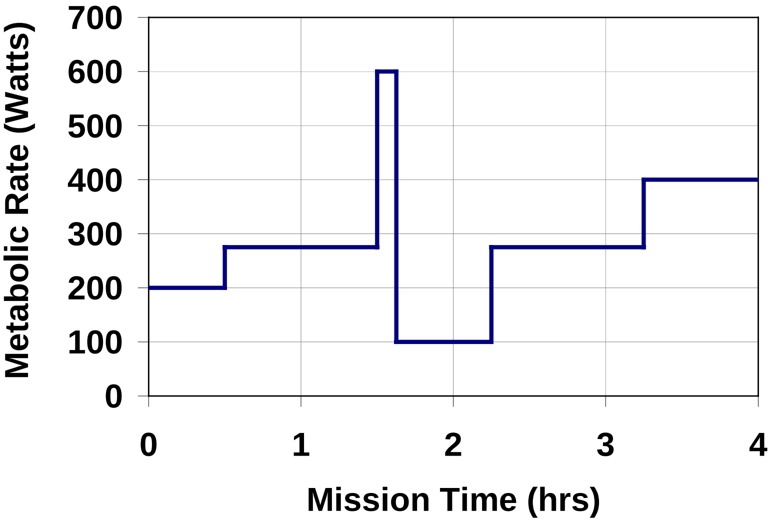


Figure 5. A representative EVA mission design reference metabolic rate profile

The mission duration and mass penalties for the mission (i.e. relative value or cost of a kg of mass delivered to the EVA site or returned to earth) are of primary importance in determining the relative value of competing concepts. These values will differ dramatically among the missions considered in this study; the cost of delivering a kilogram of mass to the Martian surface is much higher than that of delivering it to near earth orbit or even to one of the earth moon libration points. However, these costs must be expected to change dramatically from present values in the NIAC time frame. Next generation launch systems are currently targeting a ten-fold reduction in costs per kilogram to near earth orbit, and advanced systems under study though NIAC like the space elevator and tether launch systems may produce even greater changes. Comparison on a cost basis other than in purely relative terms appear to involve substantial uncertainty.

Missions in low earth orbit require EVA operations in a variety of thermal environments depending on orbital parameters and characteristics of the host vehicle(s). Design requirements are well established for present EVA systems and are unlikely to change dramatically although shifts in emphasis have occurred as missions and platforms have evolved and are sure to continue. Thermal environments are governed by the intensity and spectrum of incident sunlight at the Earth's position and by the reflected sunlight and emitted infra-red radiation from the earth. Substantial and rapid changes typically result from orbital motion into and out of earth's shadow. The orbit's inclination and its orientation with respect to the sun as well as the configuration of the host vehicle drive variations in the timing and magnitude of these swings. Incident sunlight at the earth's orbit carries a total energy density of approximately 400 W/m^2 in a spectrum that peaks at visible wavelengths. Significant incident sunlight levels can also result from reflection from the earth's surface with an albedo (reflectance) ranging from .3 - .42 depending on cloud cover and local surface conditions such as snow or ice cover. Infrared emissions from the earth's surface also provide appreciable incident energy in a radiated spectrum that peaks in the same thermal infra-red wavelength region (2 – 20 microns) in which the spacesuit assembly radiates its thermal energy. Typically this radiation corresponds to a source temperature of approximately 275 – 295 K. Its intensity varies inversely with the albedo. Together, these factors create a highly directional thermal environment in which some surfaces of the space suit assembly can be very cold while others are extremely hot. The effective radiation sink temperature for individual surfaces of an isolated object in earth orbit range between deep space at nearly 0 K and 260 K.

The situation is further complicated by other nearby objects in earth orbit. These can either shade the EVA astronaut decreasing incident sunlight or thermal radiation from the earth's surface or add to the incident energy by reflection and thermal radiation from their heated surfaces. Extreme cold environments result from activities on the space facing side of insulated vehicles during orbital night passes. This can yield over all effective radiation sink temperatures approaching deep space values. Specified extreme hot environments result from highly inclined orbits nearly normal to the sun – earth vector which eliminate or minimize shadowed intervals coupled with EVA operations in sun facing cavities like the Shuttle orbiter cargo bay. Operational experience has tended to de-emphasize extreme hot environments. Anticipated manned polar orbit missions have not materialized, and it has generally been practical to manage Shuttle orientation to avoid extreme EVA thermal environments. The design of the MIR and international space station do not provide sun oriented hot cavities like the Shuttle payload bay in which EVA is performed.

Other aspects of future low earth orbit missions are inferred from past experience. It appears unlikely that EVA duration will substantially exceed that experienced in recent Shuttle or ISS missions, (about 8 hours). This reflects not only the current system design capabilities, but also reasonable limits on crew endurance for a single day's work. It seems unlikely that future near earth orbital systems will be configured with markedly higher EVA egress / ingress penalties or with an increased probability that vehicle return within eight hours might be impossible. Therefore, it is unlikely that there will be any compelling need for greater system endurance for these missions. Similarly, other factors seem likely to ensure mission duration or resupply schedules consistent with present operational practice. The number of EVA's per flight is expected to range from 3 or fewer to a maximum of approximately 25. The usage time for a given EVA suit assembly on orbit may exceed two years (Orlan experience on MIR), but is typically much shorter and is normally supported by resupply of consumables (and potentially replacement parts) during the longer usage intervals. EVA in all of these missions is in a microgravity environment making on-back weight relatively insignificant.

Libration point missions differ from those in LEO in several important aspects. Thermal environments are different because EVA occurs at a much greater distance from the planetary surface and because orbital day-night cycles are absent or of much longer duration. Because the distance from the earth is large, the effects of the earth's albedo and infrared emission are minimal; thermal environments are generally colder than those for LEO. Current concepts for these missions generally entail relatively short duration and limited numbers of EVA's. Manned libration point mission concepts include use of the earth-moon L1 libration point for assembly and maintenance of large systems (e.g. space telescopes) for autonomous operation and possibly transfer to other, more remote, earth-sun libration points. Other mission concepts include lunar surface excursions from libration point way stations. In all cases, current mission concepts envision a duration less than three months with fewer than 10 EVA's (Reference 2). EVA at the libration points, like that in LEO, occurs in microgravity making on-back system mass a minor consideration. Launch mass penalties are appreciably greater than for LEO missions, but substantially lower than those for Lunar surface operations or missions to Mars and the asteroids.

Lunar surface mission concepts include aggressive lunar base and resource utilization concepts as well as the libration point excursions discussed above. These may entail large numbers of EVA's and longer duration as well as extremely challenging thermal environments. The moon's 29-day rotation period results in long days and nights. Together with a relatively low albedo, this causes extreme variations in surface temperature, especially in locations like craters near the lunar equator where the sun can be nearly overhead and radiation to deep space is partially inhibited. Here, surface temperatures can be well above a tolerable human core temperature for the entire duration of an EVA, posing one of the most severe challenges to the Chameleon Suit concept. Recent evidence for ice deposits in lunar craters near the lunar South Pole makes this a probable target for extended lunar surface missions. These missions would present a relatively cold EVA environment minimizing the difficulty of heat rejection from the Chameleon Suit surface, and would result in the availability of significant quantities of water somewhat reducing the advantages of the Chameleon Suit over current EVA heat rejection concepts. They would also be associated with rapid local changes in the thermal environment between shaded and sunlit locations and strong directional variations which would challenge Chameleon Suit control systems. For all of these missions, EVA will occur in lunar surface gravity (1/6 g) making the reduction of EVA on-back mass below current values desirable.

The 500 – 1000 day class missions to Mars and the asteroids will introduce a new set of EVA system design and operational challenges. Thermal environments encountered during asteroid missions will be predominantly cool to cold due to the reduced intensity of incident sunlight at greater distances from the earth and will change the total design envelope for EVA thermal environments little. Mars surface missions, however will require operation within the Martian atmosphere. Even though, it is only about 1% as dense as earth's atmosphere, the atmosphere of Mars is sufficient to create substantial conductive and convective heat loss making it necessary to adopt different insulation configurations from those presently used in space vacuum. This makes the Chameleon Suit design for Mars missions particularly challenging despite the fact that ambient temperatures are well within the range encountered in LEO, libration point, and lunar missions. In addition, Mars surface gravitation (0.38 g) makes substantial reductions (at least 50%) in EVA system on-back mass essential.

The duration and EVA intensity of these missions result in large penalties for consumables required by current system concepts making the pay-off for the Chameleon Suit concept particularly high. For example, NASA's published design reference mission for the human exploration of Mars (Reference 3), envisions nearly 1000 person-days of human activity outside a Mars habitat during a single exploration mission. With current systems that evaporate water as the heat sink, this would require consumption of over 3.5 metric tons of water for thermal control. Whether delivered from earth as water or created in-situ from transported hydrogen, this represents a major mission impact.

Based on the potential missions and characteristics discussed above, a set of hot and cold case boundaries were selected for the evaluation of concept feasibility and impacts as summarized in Table I.

Table I. Chameleon Suit base mission analysis points.

Operating Condition	Hot Case	Warm Case	Cold Cases	
Environment	Lunar Surface	Space	Deep Space	Mars Surface
Ambient Temperature	253°F	-9.7°F (250K)	-460°F	-220°F
Gravity	1/6 g	0 g	0 g	3/8 g
Atmosphere	none	none	none	8 mm CO_2
Incident Sunlight	Yes	No	No	No
Wind Velocity	0 ft/s	0 ft/s	0 ft/s	49.2 ft/s
Heat Loss Requirement	600 W min	600 W min	100 W max	100 W max

Feasibility Assessment

Analyses have shown that there are substantial advantages to the Chameleon Suit concept over conventional design approaches. Figures 6 and 7 below show a preliminary comparison of radiated heat load from the spacesuit surface area and from the life support backpack surface area which has traditionally used for this purpose as a function of surface temperature and thermal environment.

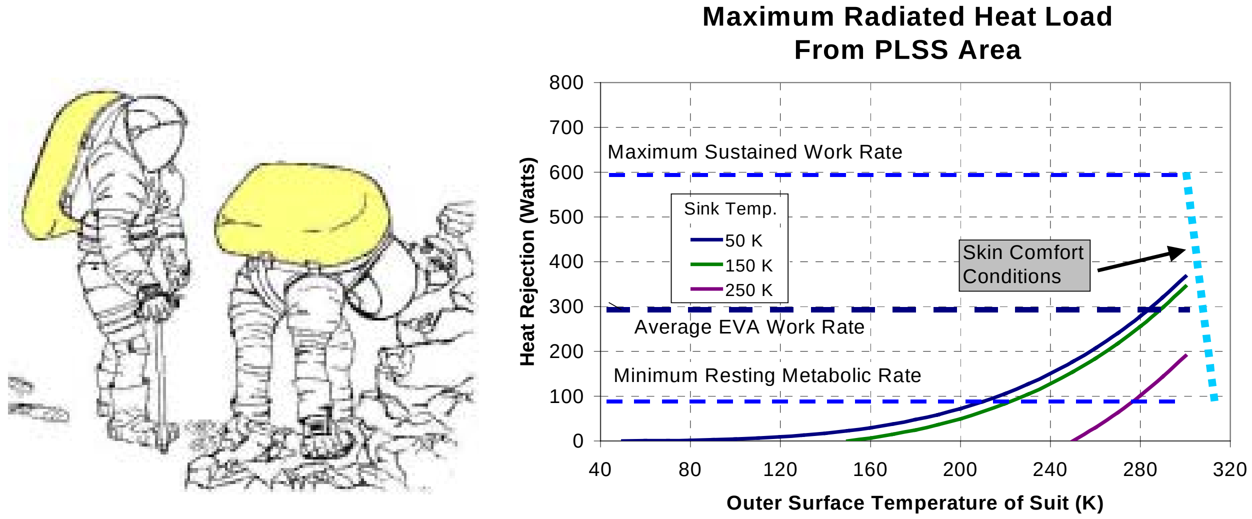


Figure 6. Maximum Radiated Heat Load From PLSS Area

Figure 6 illustrates the maximum radiated heat load from a traditional design approach which uses the surface of the portable life support system. For sink temperatures between 250 K and 50 K and a suit outer surface temperature of 300 K, this approach can reject only 200 Watts to 400 Watts, respectively. This configuration provides the opportunity to reject less than half of the maximum waste heat load in all but the most favorable environments. Radiating surface temperatures must. be very close to the wearer’s skin temperature to provide any useful heat rejection capacity in even moderately warm environments. This, coupled with the added temperature decrease incurred in transporting waste heat from the wearer's skin to and through the life support system, accounts for the failure to develop a practical EVA heat rejection system which does not depend on expendables to date.

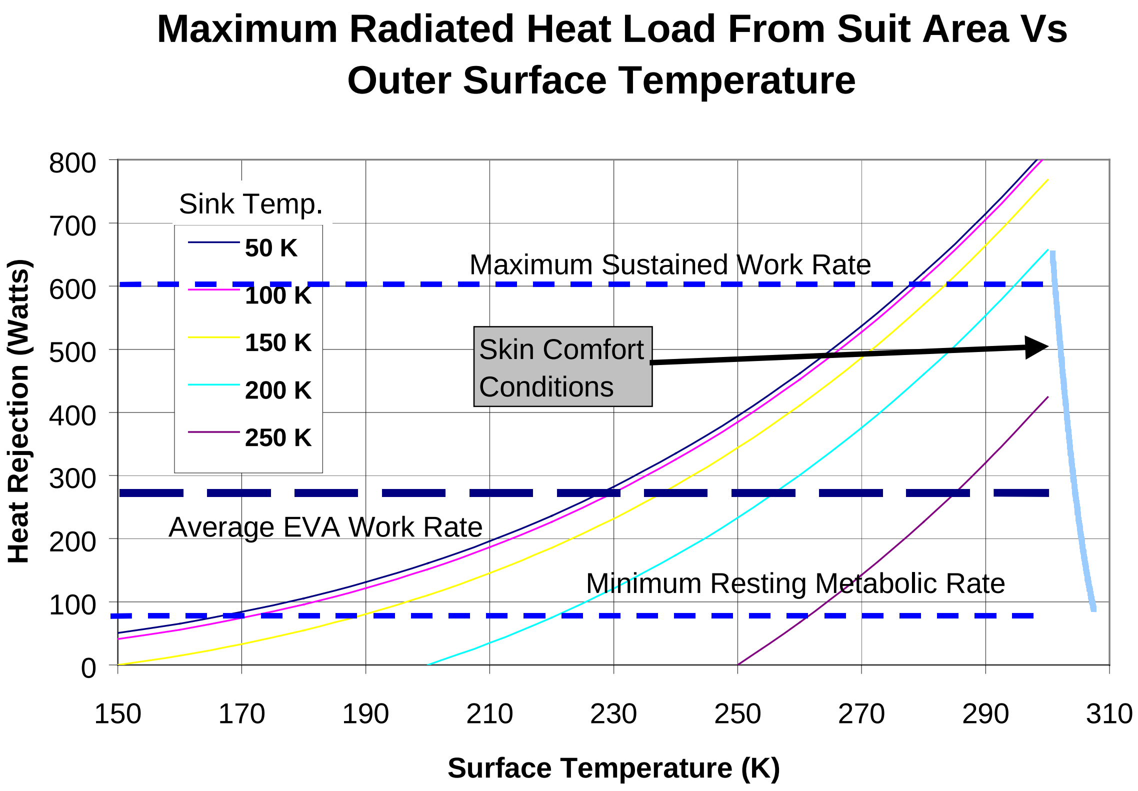


Figure 7. Maximum Radiated Heat Load From Spacesuit Surface Area

Similar analyses for the Chameleon Suit concept show much improved results. Figure 7 illustrates the maximum radiated heat load using the surface area of the pressurized suit. Even for the highest sink temperature represented above, 250 K, this approach allows heat rejection well in excess of metabolic waste heat at average EVA work rates. The maximum sustained metabolic waste heat loads can be radiated directly to space in many thermal environments. Under most conditions, the permissible difference between skin temperature and the required suit outer wall temperature is substantially increased reducing the difficulty of achieving the required heat transfer to and through the suit walls. However, this design is sensitive to suit surface coverage by the life support system back pack and other added items that may cover radiating surface area and it does not provide the capability to reject maximum waste heat loads with radiation sink temperatures appreciably above 200K. This lead us to consider an extension of the original Chameleon Suit concept.

More demanding conditions are presented in NASA missions and will require augmenting the system. Increased heat rejection in moderate environments may be accomplished by increasing the available surface to include the exposed surface of the life support system. This requires effective heat transfer from the crewman’s torso to the exposed surface area of the portable life support system. To achieve this, a liquid cooling vest similar in concept to the liquid cooling garment used in current systems is envisioned. Because it will be smaller and will not cover the arms and legs, it will be lighter and simpler than current garments, and will have essentially no effect on suit fit or mobility. The increased radiating surface area makes it possible to achieve the overall performance reflected in Figure 8. This will permit maximum sustained work rates in warm environments, and substantially greater flexibility in system operation. Increased temperature difference between the wearer’s skin and radiating surface is possible in all environments. The performance margin provided by this option may be very important in successfully dealing with thermally challenging mission scenarios.

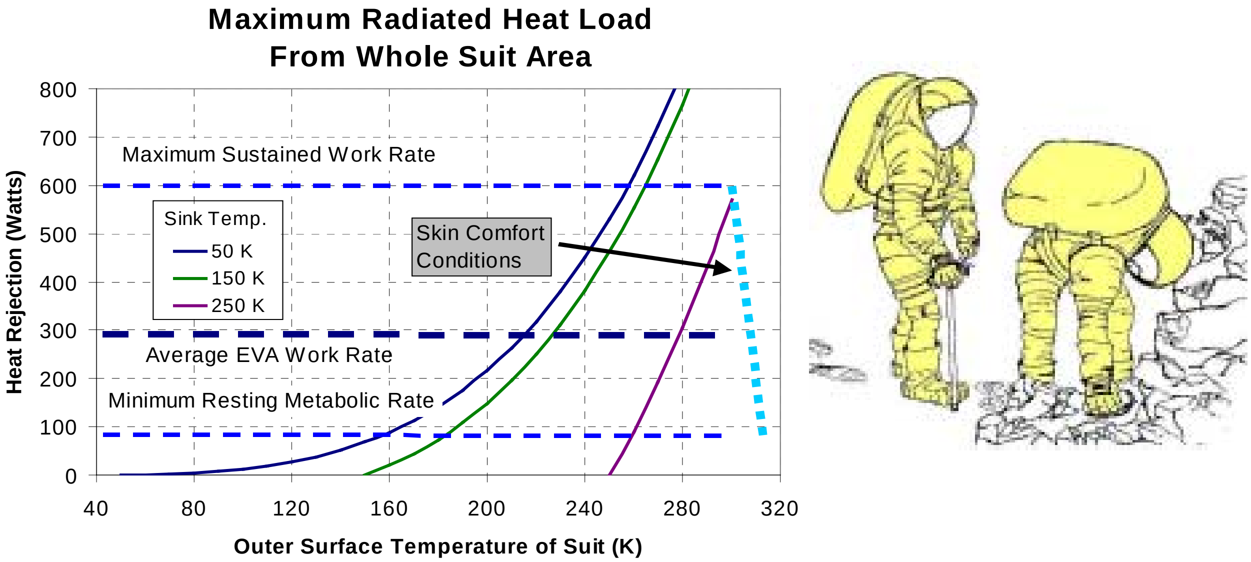


Figure 8. Maximum Radiated Heat Load From Combined PLSS and Pressurized Suit Area

These figures also show the requirement to modulate heat transfer characteristics in the Chameleon Suit. The substantial increase in the difference between skin temperature and suit surface temperature as the waste heat load decreases from the maximum to the minimum values can only be maintained if the thermal insulation of the suit can be dramatically increased. Calculations determine that the operating range between minimum resting metabolic activity in an extreme cold environment, and moderate activity (400 Watts) in a relatively warm environment (representative of the earthward side of a low earth orbital satellite) requires the ability to control the insulation value of the suit over an approximate range of 130:1 if only the suit area is used for radiation. This is within the estimated capabilities of the combined variable geometry and emissivity technologies which have been investigated. A somewhat lower required control range is estimated for the same conditions with the augmented configuration that adds heat rejection from the life support system surface since the maximum heat load can be rejected at much lower surface temperatures (lower required maximum suit conductance).

The concept as described above was found to perform well in cold and moderate environments, but cannot address hot environment cases most or all surfaces of the suit are exposed to effective radiation sink temperatures at or above skin comfort temperatures (i.e. 27 to 34 C or warmer). Such conditions are represented by operations in cavities or near large surfaces facing direct high angle sunlight. Examples include working on the lunar surface near lunar noon or in the Shuttle Orbiter payload bay when it is facing the sun. In these cases, the EVA suit is subjected to direct incident sunlight, reflected sunlight from the adjacent surfaces and infrared from the surrounding surface heated by the sun. The lunar surface, for example, has a relatively low reflectance in the solar spectrum (low albedo). While this means that the reflected sunlight on the surfaces of the suit that are not directly illuminated is not high, it also means that the moon's surface absorbs most of the solar energy and re-radiates it as infrared radiation. Under these conditions, most of the suit's outer surfaces "sees" the hot lunar surface in at least half of its field of view. Only suit surfaces that face upward (e.g. the top of the helmet and shoulders) escape this influence. Estimated equilibrium temperatures for the suit and lunar surfaces corresponding to level ground conditions are shown as functions of solar elevation angle in Figure 9.

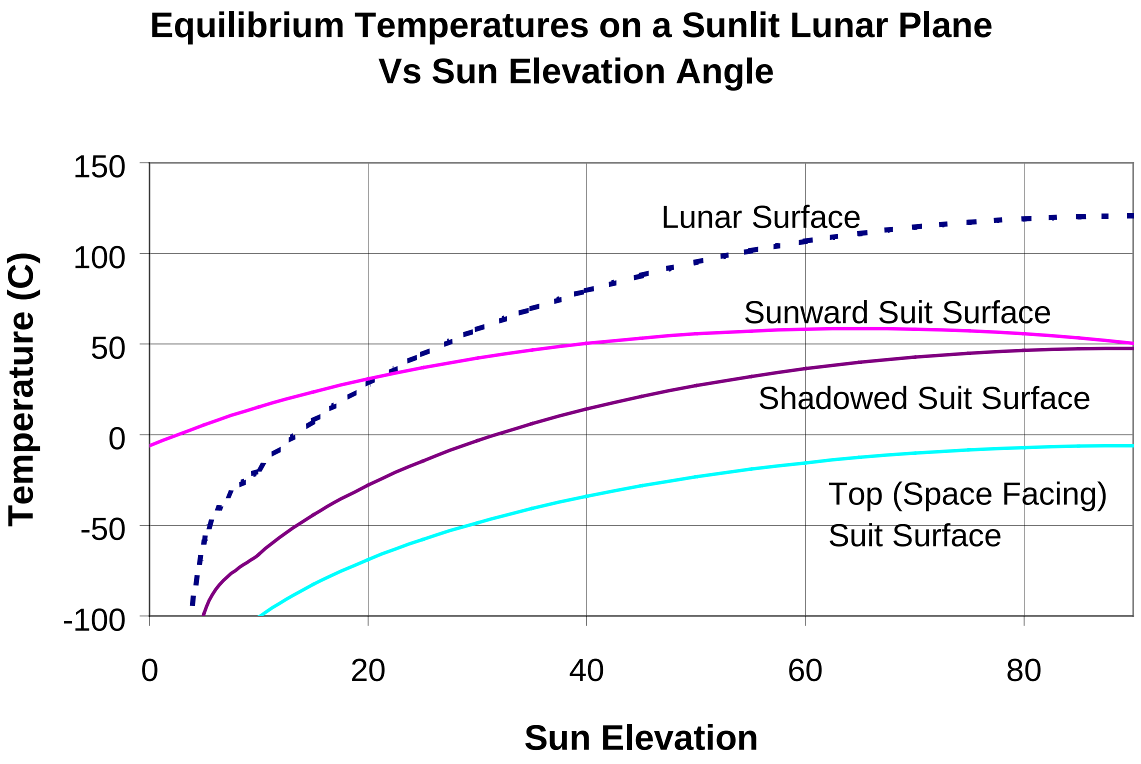


Figure 9. Adiabatic equilibrium temperature for lunar and suit surfaces exceed skin temperature at many sun elevation angles.

As the figure shows, only the space facing surfaces of the suit remain below skin temperature at all solar elevation angles in this scenario. When the adiabatic surface temperature in any region of the suit exceeds skin temperature, no net heat can be radiated to the environment. This posed a severe challenge to the concept since NASA mission goals will require the ability to operate on the lunar surface throughout the lunar day. Figure 9 shows that even at low solar angles the combined effect of direct and scattered sunlight and heat radiated from the lunar surface will significantly reduce heat rejection capability. At high solar angles, almost no metabolic load can be rejected.

Effects are similar or even worse in a sun facing Shuttle payload bay or in a Crater on the lunar surface. In these cases, a greater part of the field of view is filled by the heated surfaces (Figure 10). In addition, the temperature of those surfaces is further increased in these cavities by the influence of radiation emitted and reflected from other parts of the surface.

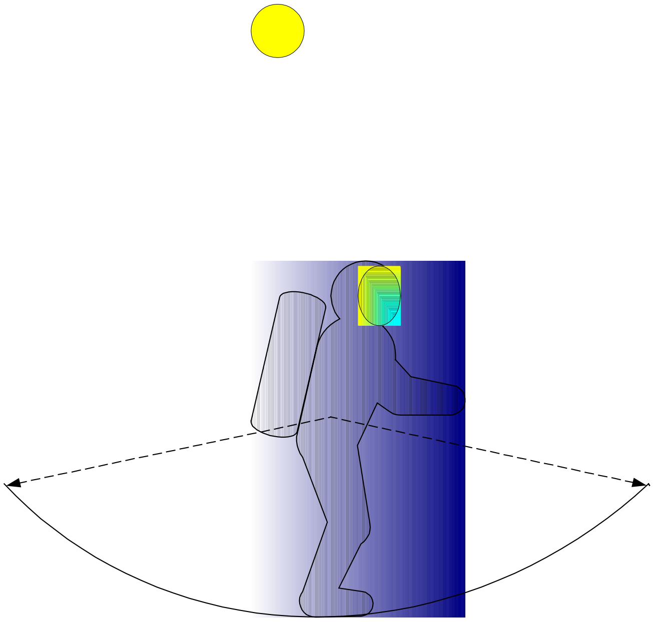


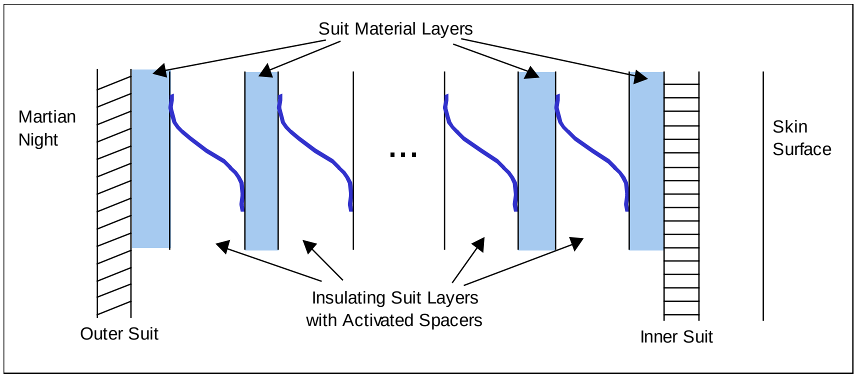
Figure 10. Operation in lunar craters near midday will require directional shading on active radiating portions of the suit.

In order to meet these challenging daylight mission scenarios, the Chameleon Suit concept was further adapted to incorporate a directional shielding capability that allows suit surfaces to radiate selectively in some directions while rejecting incident radiation from hot surfaces at other viewing angles. This required the conception of a new combination of optical and micro-electromechanical systems MEMS) that is explained in more detail in a subsequent section of this report.

Design Analyses and Component Requirements

The Chameleon Suit concept utilizes variable geometry insulation to meet the extreme demands of both hot and cold mission environments. When high levels of insulation are required to limit heat loss or gain, active spacers between suit material layers create insulating gaps that reduce heat loss. Adjustment of the emissivity of gap surfaces to low values using electrochromic material on each layer further increases insulating performance. When high heat transfer is required, the same active spacers adjust so the suit material layers are in contact with each other providing heat conductive heat transfer through the suit wall. These configurations allow very large variations (300:1 or more) in the suit's conductivity which enable the wearer to retain heat during periods of low metabolic activity and during use in cold environments and reject heat during periods of high metabolic activity and during use in hot environments.

Figure 11 depicts the suit layers in their expanded position to provide protection against the coldest of surroundings such as nights on Mars and deep space. The minimum expected metabolic rate of 100 Watts was considered for this analysis to determine the Chameleon Suit's maximum insulating thermal properties requirements. The insulation provided by the suit in this configuration is determined by many factors including the emissivity of the outermost layer, the thermal conductivity and thickness of the suit layers and the insulation provided by the gaps themselves. The active control concept for the suit requires that the gap thermal resistances predominate. In space vacuum, the gaps will be evacuated, and consequently become highly effective insulators even with a very small gap width. Heat transfer cannot occur by conduction or convection across the gap and so is limited by the thermal radiation properties of the facing surfaces and by the heat conduction characteristics of the actuators that necessarily bridge the gap and create a heat leakage path. In planetary atmospheres, as on Mars, the gaps will fill with the local atmosphere requiring greater gap height to limit heat loss by gas conduction, and the arrangement of the actuators will limit convection within the gap.

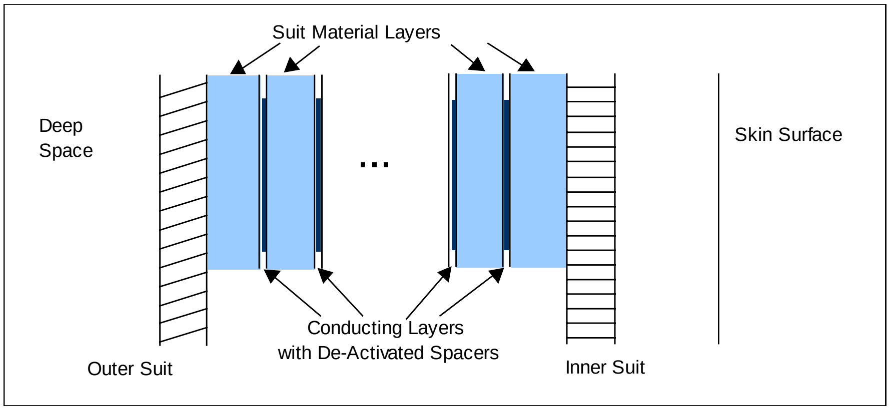


Radiation transport can be limited to acceptable loss for resting conditions

Figure 11. Expanded Suit Layers for Maximum Insulation

Assuming six insulating suit layers, each layer must have a conductivity of 0.53 W/m^2-°C to provide adequate insulation while working in cold environments at metabolic rates as low as 100 Watts. This arrangement has a combined conductivity of less than 0.09 W/m^2-°C to protect the wearer from losing too much heat in these conditions. The analyses were performed for two cold cases: deep space and Mars night. The requirement was derived from the Mars night case even though the ambient temperature is much higher than that for the deep space case. The Mars night operating point requires increased insulation because of convection due to wind. In fact, the convection accounts for about 70% of the heat loss and radiation is only responsible for the remaining 30%.

The wearer must also be protected against heat stress in hot environmental conditions while working at increased metabolic rates. In these situations, the suit outer surface temperature must be maximized to allow heat rejection by radiation. This requires highly effective heat transfer through the suit to bring the outer surface temperature as close as possible to the wearer's skin temperature. This is achieved by collapsing the actuators so the suit layers lie against each other in intimate contact and heat can be conducted directly through the whole stack. The overall heat transfer achieved is determined by the emissivity of the outermost surface of the suit, the conductivity of the suit layers, and by the thermal contact achieved between them. Figure 12 illustrates the Chameleon Suit layers in this collapsed configuration.



Thermal resistance
Can be minimized
to increase radiation
transport for hot
environment

Figure 12. Collapsed Suit Layers for Maximum Heat Rejection

Again assuming six suit layers, the conductivity of each layer should be 157.2 W/m^2-°C, resulting in an overall conductivity for the six layers of about 26.2 W/m^2-°C. The conduction through each layer includes both the layer material itself and associated contact resistances between the layers. The layers were assumed to have a conductivity of 0.05 W/m-°C which is a nominal value for plastics. This set the required contact resistance between layers to 3.6 W/m^2-°C to achieve the necessary overall heat transfer through the collapsed suit layers. Because the actuators do not provide much contact pressure between the layers, this value may be difficult to achieve. Therefore, interlayer thermal contact will be enhanced by the use of carbon felts. The performance and benefits of using these felts is discussed in more detail later.

The removal of waste heat occurs by radiation from the outer suit layer. The emissivity is assumed to be 0.787 for cold environments, and 0.85 for warm and hot environments. These values are consistent with the properties of the current space suit. It is unlikely that much higher values can be expected in the future due to the degradation that occurs with repeated use and extreme environments. Similarly, the existing values for solar and infrared absorbtivity were assumed for all analyses: 0.18 and 0.85, respectively. The electrochromic layers must have a maximum emissivity of 0.4, as discussed later, to prevent radiation heat loss at low metabolic activity rates.

The geometry and arrangement of the low force actuators were also considered as they relate to the overall heat transfer capability through the suit layers. When the layers are expanded, it is desirable for the actuator material to be insulating so as not to provide a substantial heat leak path. Conversely, when the suit layers are collapsed, the actuators should not prevent maximum heat transfer to the outer layer. The effects, in either case, are minimized by reducing the contact surface area between the actuators and the suit surface.

There will be approximately 1200 actuators total covering the 3 m^2 suit area to provide a consistent gap thickness. The total contact area of the actuators in the collapsed position is assumed to be 5% of the total suit area. This is small enough to mitigate any substantial heat transfer loss in hot environments. Each actuator is 0.02 cm thick and 0.42 cm wide. The insulating gap between layers should be 1 cm, and the actuator length to provide that gap is 3 cm. The gap distance is set based on conduction through the carbon dioxide between suit layers during use on Mars. A distance of 1 cm is sufficient to prevent heat loss above the minimum expected metabolic rate. The defined geometry will produce a conduction heat leak in the expanded configuration of less than 1%. The actuators will be placed throughout the suit to minimize convection in planetary environments.

Human Interface Implications

The Chameleon Suit concept introduces a new type of heat transfer interface in the spacesuit system with a new set of human interface issues. Unlike normal shirt sleeve human thermal control on earth, the system is intended to maintain thermal comfort at all work rates without appreciable reliance on sweating and evaporative cooling. This is similar to conditions in cold environments on earth and in current spacesuits with the use of a liquid cooling garment to provide sensible heat transport away from the wearer's skin. However, in the Chameleon Suit concept, heat transfer varies substantially over different parts of the wearer's body in response to the local environment, and these patterns can vary widely and shift rapidly over time as the wearer moves and changes orientation. To evaluate the feasibility and effectiveness of the concept, our study included a review of human thermo-regulatory mechanisms and the limits of local heat transfer.

Thermal Comfort

It is essential for a human body to maintain a stable internal environment, **homeostasis**. The body's natural homeostasis includes several factors: blood pressure, body temperature, fluid and electrolyte balance, and body weight. They work within homeostatic processes to regulate to a set point for each. For the Chameleon Suit, the body's temperature regulation processes and mechanisms are a central focus and an essential design interface. The suit must operate to support the body in maintaining the nearly constant internal temperature which is required for health over a wide range of activity levels and external environments. In doing this, it will interact directly with the local skin temperature of the wearer. It must achieve removal of the metabolic waste heat generated by the wearer at skin temperatures which are considered to be "thermally comfortable." Under these conditions, the body is able to transport the waste heat from the muscles and internal organs to the skin while maintaining the core temperature at the control set point. The control set point, although nearly constant is a weak function of the metabolic rate. In addition, the skin temperature can slightly alter the set point for core temperature control; i.e. the set point temperature increases as the skin temperature decreases.

The bounds on these conditions are shown in Tables II and III which summarize normal and limiting conditions for the body core and skin temperatures, respectively. As these tables show, while an appreciable thermal range is survivable for limited periods of time, only a small range of core temperatures are well tolerated. The range associated with "thermal comfort" is narrower still and rises slowly from the resting value as the work rate increases. As shown in Figure 13, experimental data show that the average skin temperature for thermal comfort also varies in a predictable way with metabolic rate. This "comfort band" occupies a small portion of the "normal" skin temperature range at any given work rate although the ideal comfort curve exhibits appreciable individual differences based on sex, age, conditioning, build, and other physiological factors. In the Chameleon Suit, this skin temperature is the source temperature from which heat must be transported through the suit walls and rejected to the environment. This is the primary driver for the design implementation of the concept. The control of suit wall heat transport must allow removal of the heat load with average skin temperature very near the ideal comfort value in widely varying environments.

Table II: Body (Core) Thermal Range (Reference 4)

Temp °C	Temp °F	Effect
>42	108	Fatal
41	106	Coma, convulsions
39.5	103	Upper Acceptable Limit-drowsiness
37	98.6	Normal Resting Value
35.5	96	Lower Acceptable Limit-mental dullness
34.5	94	Shivering diminishes-extreme mental slowness
33	91	Coma
<33	91	Deep coma. Death
27	81	Hart Stops. Death

Table III: Skin (Shell) Thermal Range (Reference 4)

Temp °C	Temp °F	Effect
>45	>113	Burns
42	108	Pain
40	104	Uncomfortably hot
25	77	Uncomfortably cold
5	41	Numbness
0	32	Frostbite
-0.6	31	Skin freezes

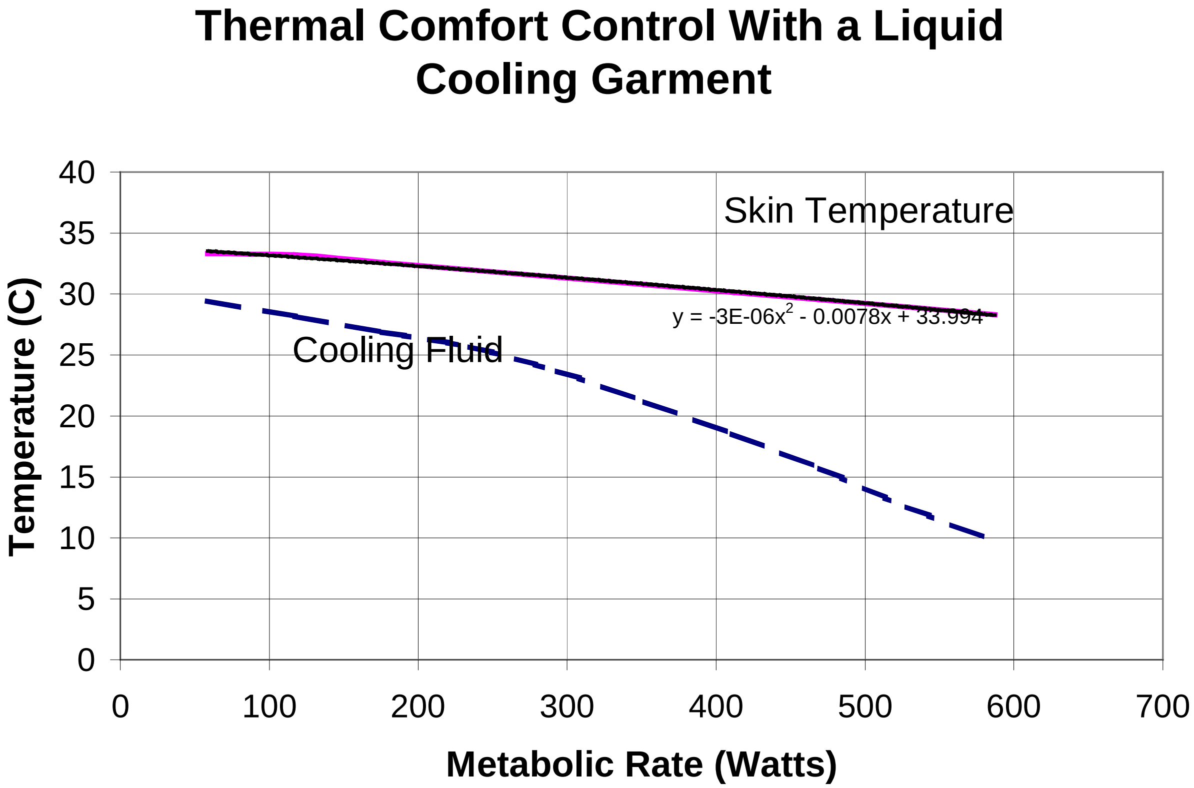


Figure 13. Comfortable human average skin temperature falls with increasing activity.

Under normal earth surface conditions, the body interacts with a variety of ambient factors including air temperature (dry bulb temperature or DBT), humidity (absolute humidity or AH), air movement (velocity v in m/s), and radiation (mean radiant temperature of surfaces or MRT). Homeostatic mechanisms modulate body processes including blood circulation patterns and sweating to achieve the required heat rejection with skin temperatures as close as possible to the comfort curve (Reference 5).

Temperature Regulation and Metabolic Rate

The waste heat which must be rejected from the body reflects the sum total of the body's activities. This includes external work performed and internal processes for the body's own maintenance. The minimum resting value is the **basal metabolic rate** (BMR) which is comprised entirely of the body's internal maintenance processes such as respiration, digestion, heartbeat, and brain function. BMR is affected by the individual's general activity level, genetic makeup and surrounding environment. It is directly proportional to lean body mass and surface area. BMR increases with the amount of muscle tissue a person has, and generally decreases with age. This represents the minimum heat rejection rate at which the system must function for any given wearer. Increased waste heat generation will result from activities associated with task performance, locomotion, etc. Human metabolic rate varies anywhere between 280 Btu/hr (4.2 kcal/min) during sleep to 30,000 Btu/hr (449kcal/min) during a 19mph run (Reference 6). As a practical matter for system design, only heat generation rates up to approximately 600 watts (2000 BTU/Hr) are sustained long enough to be significant for thermal comfort.

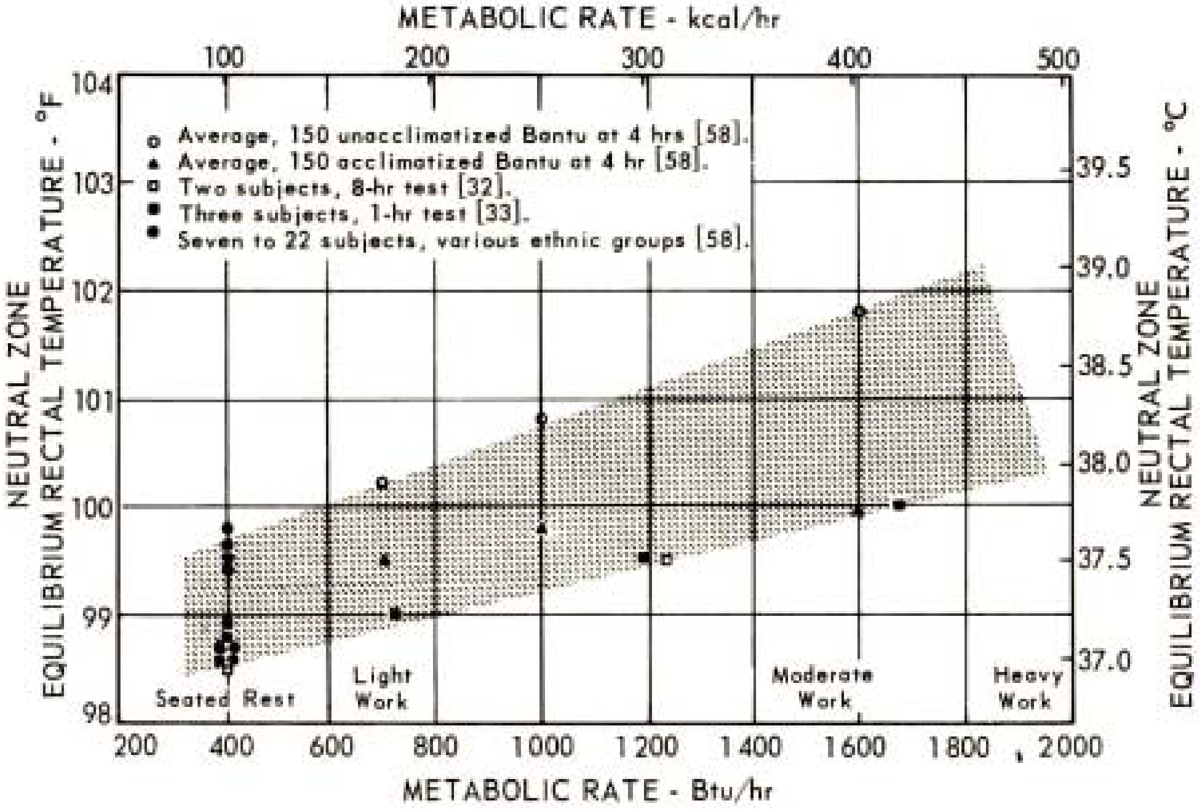


Figure 14. Body core temperature is regulated to increase slightly with increasing work rate. (Reference 5)

The body's core temperature set point generally shows an increasing trend with work rate as illustrated in Figure 14. The characteristic internal temperature for a particular workload varies among individuals; both physical training and training for work in the heat (*acclimatization*) produce lower values. These differences are related to the efficiency of the body's heat transport and control mechanisms as described in subsequent paragraphs and reflect the interaction of sensed core temperature at the hypothalamus and local skin temperatures sensed by cutaneous receptors. While, in general, the core temperature responds to the metabolic rate which is primarily controlled by conscious activity, cold skin temperatures when the core temperature is below the set point value trigger an involuntary increase in metabolic rate through the mechanism of shivering. This response is inhibited when the core temperature is above the set point value (Reference 7). This is illustrated in Figure 15 which shows conditions for the onset of shivering with varying core temperature values. In the Chameleon Suit, local skin temperatures colder than normal comfort conditions may be required in highly directional environments. The control will ensure that cold discomfort is avoided and shivering is not triggered by regulating the heat flow to ensure that the average skin temperature and core temperature are not too low.

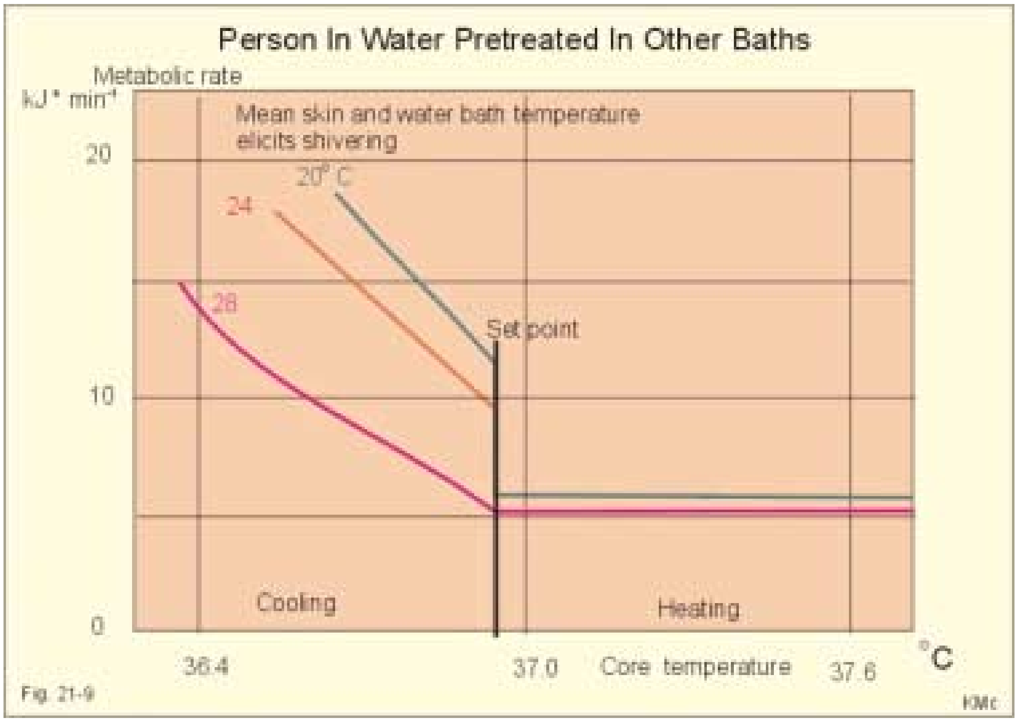


Figure 15. Shivering is triggered by cold skin temperatures and suppressed by warm core temperature. (Reference 8)

For the study of the Chameleon Suit concept, it is convenient to consider metabolic waste heat production in terms of normalized values adjusted for body surface area. One commonly used system for doing this expresses metabolic activity in "Met's" (Reference 9). 1 MET is equal to 1 calorie burned per kilogram of body weight per hour; or, alternatively, 1 Met = 58.15 W/m^2 of body surface (Reference 10). Our study used a representative body surface area and considered 13 separate body zones for heat transfer.

Previous studies have shown that **skin temperature** (*Ts*) provides a more important cue for perception of thermal sensations than core temperature (Reference 11 & 12). Thus, it is important to consider the variation in skin temperature among localized body zones when referring to thermal comfort. Also, it is important to note that temperatures vary within the localized body parts, such as torso and limbs. In Figure 16 we see that the external and peripheral parts of the body have a lower mean temperature than the internal parts and core, with temperature decreasing along the longitudinal axis of the extremities. This produces both axial and radial temperature gradients that interact with the Chameleon Suit's heat transfer and control mechanisms.

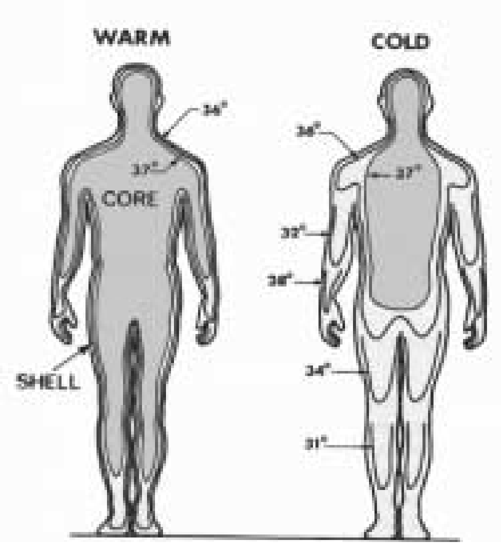


Figure 16. Thermal gradients within the body result in varying source temperature and heat transport requirements for different parts of the Chameleon Suit. (Reference 13)

The body's temperature regulatory system is centered in the hypothalamus (Figure 17). It is a small portion of a brain that is located below the thalamus (Reference 14). The hypothalamus works as a thermostat system in the human body [5]. It ensures that the body's core temperature (*Tc*) is kept at approximately 37°C (98.6°F), the hypothalamic set point (Fig.5x). Thermo-sensory impulses from the skin and internal receptors trigger the hypothalamus to raise or lower body temperature (Reference 15). The hypothalamus maintains homeostasis by regulating a variety of visceral activities and linking the nervous and endocrine systems.

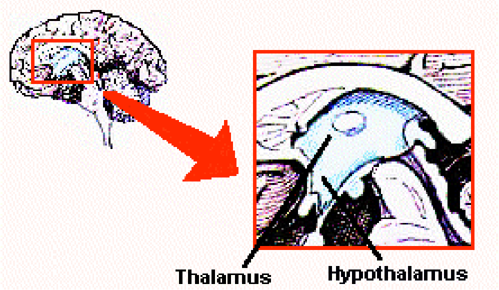


Figure 17. Hypothalamus (Reference 16)

The skin is also a vital contributor to evaluating the thermal environment. While the brain and blood vessels contain thermal receptors for sensing core temperature, the skin contains the thermal receptors for sensing skin temperature. Such receptors are not uniformly distributed in the skin: heat receptors are concentrated in the fingertips (note: the area most sensitive to heat conduction), nose, and elbows. Cold receptors are concentrated in the upper lip, nose, chin, chest, and fingers (Reference 4). Signals for cold and hot sensations are transmitted through different types of nerve fibers. Thermal inputs are integrated at numerous levels within the spinal cord and central nervous system, finally arriving at the hypothalamus (Figure 18).

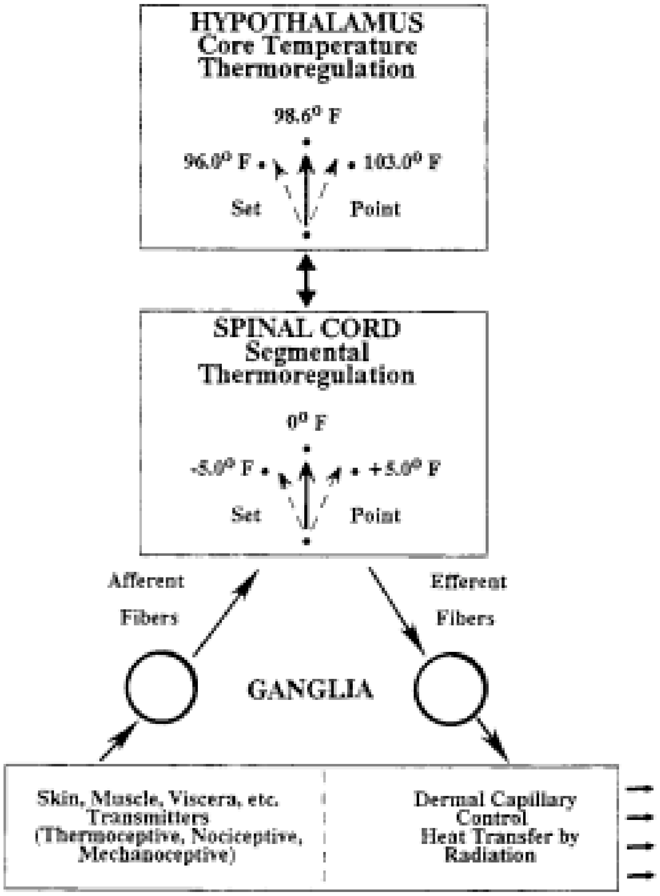


Figure 18. Simplified Representation of Thermoregulation (Reference 17)

Skin surface, deep abdominal and thoracic tissues, spinal cord, hypothalamus, and other portions of the brain each contribute very roughly 20% to autonomic thermoregulatory control. Behavioral responses, in contrast, depend more on skin temperature (Reference 18).

Responses to Heat

When the body temperature rises above normal, the nervous system signals dermal blood vessels to **vasodilate**, thus increasing the blood flow through the skin to increase heat loss. Secondarily, and at the same time there is an increased sympathetic stimulation of the sweat glands to increase sweat rate. Active sweat glands lead to the formation of *bradykinin*[*] in the local tissue, which stimulates local vasodilation. This ensures that sweating will not occur without vasodilation (Reference 19).

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[*] A biologically active polypeptide, consisting of nine amino acids, that forms from a blood plasma globulin and mediates the inflammatory response, increases vasodilation, and causes contraction of smooth muscle. (Reference 19)

Only a few tenths of a degree increase in the body core temperature can stimulate enough sweat production to quadruple the body's heat loss. The sweating process generates heat loss to the body's surroundings to maintain homeostasis, and the body temperature drops toward normal.

In current space suit systems, the circulating breathing gas flow is limited and the suit impermeable to water vapor. This means that only a small amount of sweat can evaporate, and the sweating mechanism for increased heat rejection becomes quite ineffective. The accumulation of unevaporated sweat in the space suit is not only uncomfortable, but it is also a source of excessive heat loss and potential hypothermic stress during subsequent periods of low metabolic activity. In addition, loss of substantial water to sweating during an extended EVA can lead to dangerous dehydration. For these reasons, the liquid cooling garment is normally controlled to maintain comfortably cool conditions with the core temperature at or below the set point and active sweating suppressed. The Chameleon Suit may be designed to have water permeable walls in its pressure garment enabling the evaporation of sweat directly to space. However, substantial reliance on this mechanism for cooling would still create the potential for dehydration and would represent an undesirable loss of water for the mission just as if it were evaporated as an expendable heat sink material in a sublimator. Consequently, operation with wall temperatures that will support thermal equilibrium at sufficiently cool skin temperatures to suppress sweating has been assumed in the analyses performed for this study.

Responses to Cold

Conversely, when body temperature drops below normal, the nervous system signals dermal blood vessels to **vasoconstrict**, thus reducing the blood flow through the skin. During this reaction, sweat glands remain inactive. The body heat is then conserved and body temperature rises toward normal. However, if body temperature continues to drop the nervous system signals muscles to contract involuntarily, creating shivering and dramatically increasing body heat production (Reference 10). Shivering consists of rapid muscle contractions, 10-12 per second and can increase heat production by 200-500%.

At maximum vasoconstriction the effective insulation of the core can be increased by 3-5 cm of tissue, however in cold temperatures even maximal vasoconstriction cannot reduce heat loss sufficiently to maintain thermal balance. Maximum vasodilation in response to warm conditions can increase the effective thermal conductivity of the affected tissues by as much as eight times. Mechanisms for this are illustrated in Figure 19. and discussed in the ensuing paragraph.

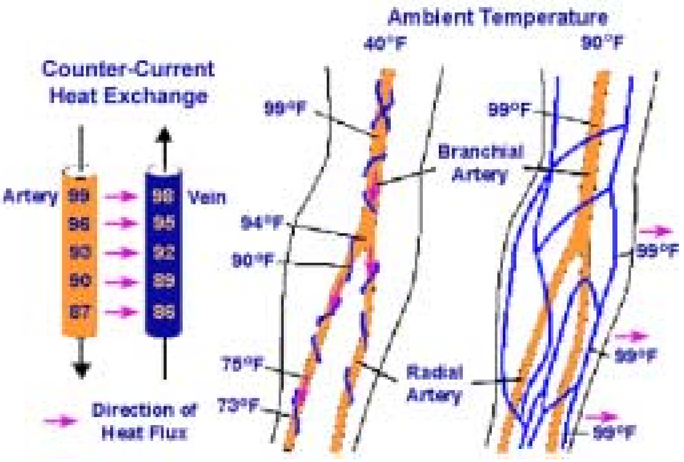

Figure 19: Vasoconstriction and Vasodilation of Vessels (Reference 20)

Effective Tissue Conductivity

Effective tissue conductivity is actually the result of a combination of conductive and forced convection heat transport. This accounts for the dramatic effects of vasoconstriction and vasodilation on heat transport and their effectiveness as thermoregulatory mechanisms. The body's tissues generally offer only modest thermal conductivity which varies over a narrow range. Effective heat transport and the fact that it can be controlled is enabled by the blood flow that perfuses these tissues exchanging heat with the surrounding tissue and transporting it from one location to the other. The body's total blood flow of 5 –30 l/min. together with observed thermal gradients as shown above creates the potential to transport over 15000 watts of heat, far more than any sustained work rate requires. This makes the boy's thermoregulatory mechanisms extremely robust as long as external conditions permit control of net heat loss within reasonable skin temperature bounds. It also accounts for the large tolerance for local variations in heat transport explored in Dr. Kosheyev's research at the University of Minnesota (References 8 & 10). The results of this research have shown that the body can support very large local heat transport. Further, with proper control of total body conditions, adverse thermoregulatory responses such as local vasoconstriction where skin is cooled to achieve high heat flux can be prevented. This is essential for the Chameleon Suit's ability to respond to directional environments by isolating some body surfaces and increasing heat transport from others in order to achieve the required net thermal balance. Initial results are promising and show that local heat flux substantially above the required average values can be achieved. However, further research in this area will be required, particularly with respect to the limits of perceptual comfort under these conditions.

Concept Refinement and Evolution

During the feasibility assessment and component requirements analyses for the Chameleon Suit concept several areas were identified in which the concept as formulated at the outset of the study was incomplete or could be significantly improved. These included:

- The surface of the life support system was not effectively used for heat rejection.
- Layer to layer contact thermal resistance was likely to be higher than desired
- No surface of the suit could provide effective heat rejection in some scenarios.

The concept was adapted and refined in response to each of these challenges to identify a solution path which offers a high probability that NASA's future missions can be supported effectively. As described in the ensuing sections, some of these solutions reflect straightforward engineering design adaptation of the original concept, while others involve further development and adaptation of emerging materials and technologies or the application of totally new design concepts.

Surface Utilization & Internal Heat Transport

In the Chameleon Suit concept as originally formulated and proposed, the system was intended to operate completely without the use of the liquid cooling garment and circulating coolant that serves to transport heat away from the wearer's body in current EVA systems. This was part of the system simplification and weight savings that will make the Chameleon Suit advantageous for NASA's challenging exploration missions in the future. However, concept feasibility studies showed that the surface area available for heat rejection to the external environment would be inadequate under some expected conditions even with the full suit surface area used. This is aggravated by the fact that a portion of the suit area will typically be covered by the life support backpack and unavailable for heat rejection (Figure 20). When directional environments in which the most favorable conditions for heat rejection are to the rear of the astronaut are considered, the impact of the life support system may be very significant.

Figure 20. The EVA life support system backpack can interfere with heat rejection from the suit surface or offer additional heat rejection opportunities.

This issue can be resolved by using a scaled down version of the liquid cooling garment in the form of a vest. With a pumped water circulation loop this can be used to collect body heat from the torso areas covered by the life support system and to transport it to the outer surface of the life support system. With the present life support system volume, this can provide as much as a 50% increase in the available heat rejection surface area significantly expanding the Chameleon Suit's operational envelope. The effect is even greater when directional environments are considered. In addition, this modification of the concept provides substantially increased flexibility in the pressure suit design in terms of the accommodation of lung expansion without introducing uncomfortable suit interference or degraded heat transfer from the wearer to the suit.

Since the most critical elements of the concept, especially elimination of expendable heat sink materials, are unchanged, the integration of the cooling loop can be significantly simpler than in present systems and extremely compact preserving most of anticipated gains in system simplicity and weight. Similarly, the cooling vest can be much lighter than a full liquid cooling garment. It will have essentially no effect on suit fit and mobility since it covers only the torso.

Thermal Contact Enhancement

An inherent characteristic of the Chameleon Suit is the use of multiple layers that are separated by gas or vacuum gaps to produce a highly insulating garment or brought into intimate contact to provide a conductive path for heat from the inside to the outside of the garment in response to changing system needs. The actuators used to change the system between these two states are conceived to be flexible, light, and to consume extremely little power. With all of the technologies envisioned for their implementation, this implies that they are also likely to produce relatively low actuation forces. This implies that the contact pressure between the layers of the Chameleon Suit will be modest when they are in their collapsed, conducting state. System performance demands that the temperature difference between the innermost and outermost layers of the suit must be minimized under these conditions. That is, the thermal resistance through suit, including contact resistance between layers must be low.

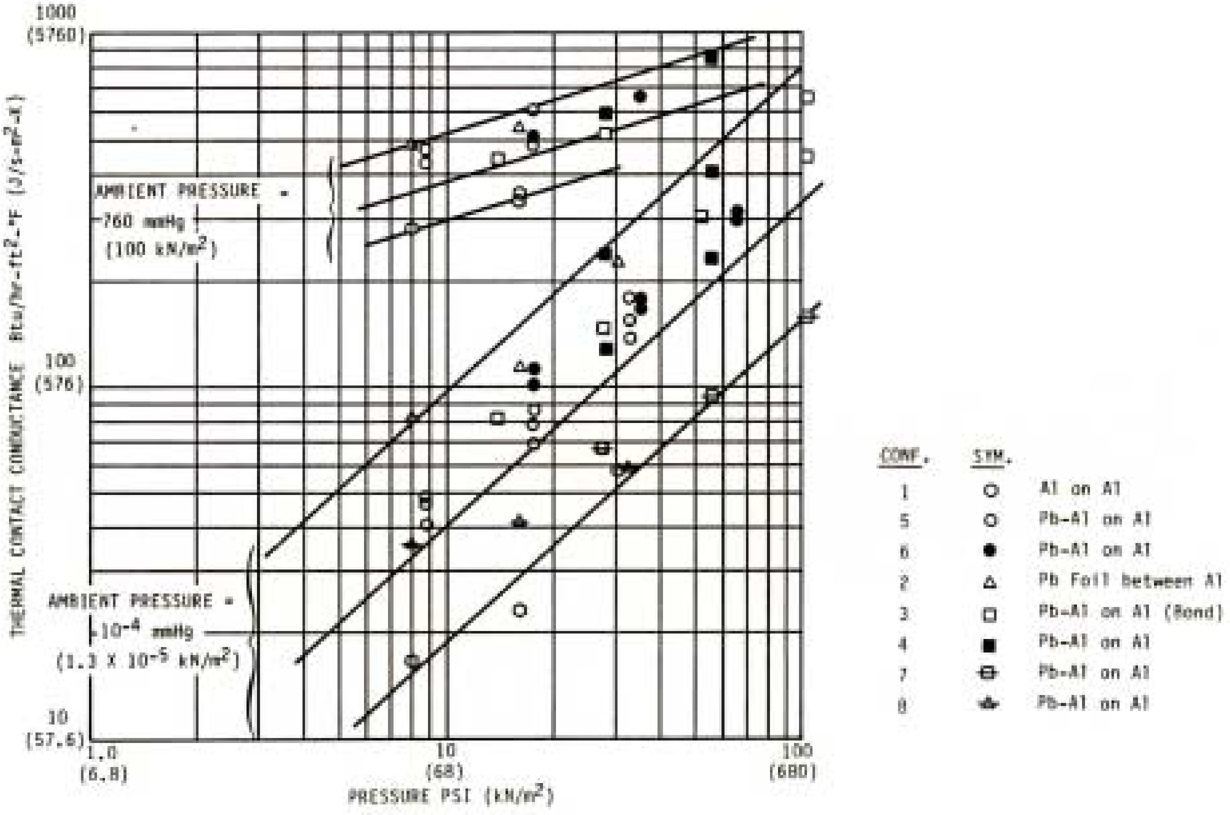

Figure 21. Thermal contact resistance at low contact pressures is a significant challenge for Chameleon Suit implementation.

As shown in figure 21, contact resistance for typical material configurations like the layers originally conceived to comprise the Chameleon Suit can become quite large at low contact pressure, especially in a vacuum environment. Typical solutions to this problem such as the use of thermal greases to enhance contact are unlikely to be acceptable in the Chameleon Suit. Not only would the adherence of the thermal grease interfere with the separation of the suit layers using low force actuators, but it is unlikely that they could be used without interfering with the low emissivity surface properties that are required for system insulating performance in the separated state. In addition, the effectiveness of these solutions through large numbers of cycles and prolonged exposure to EVA environments is very doubtful.

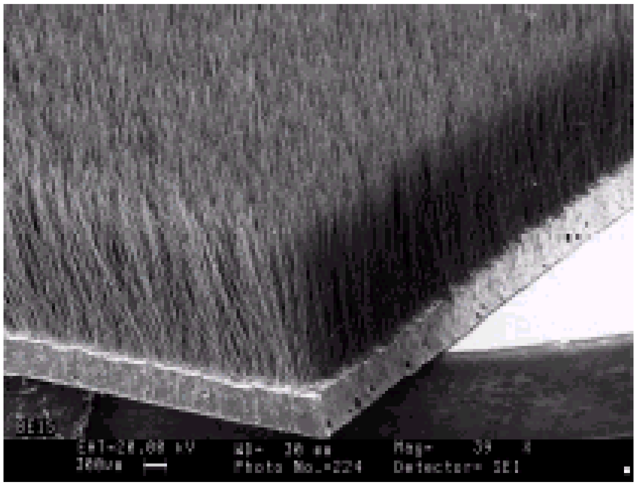

Figure 22. Fibrous carbon felts can provide substantially improved thermal contact between layers in the Chameleon Suit.

Recent technology development offers an attractive potential solution to this challenge. Fibrous carbon felts, (Figure 22.), have been produced which provide substantially improved thermal contact at low contact pressure and a high tolerance for surface irregularities. Published data for the performance of these felts illustrated in Figure 23 show that heat transfer can exceed 300 Watts/m^2 at very low contact pressures, especially when the fibers are sloped or curved to maximize effectiveness.

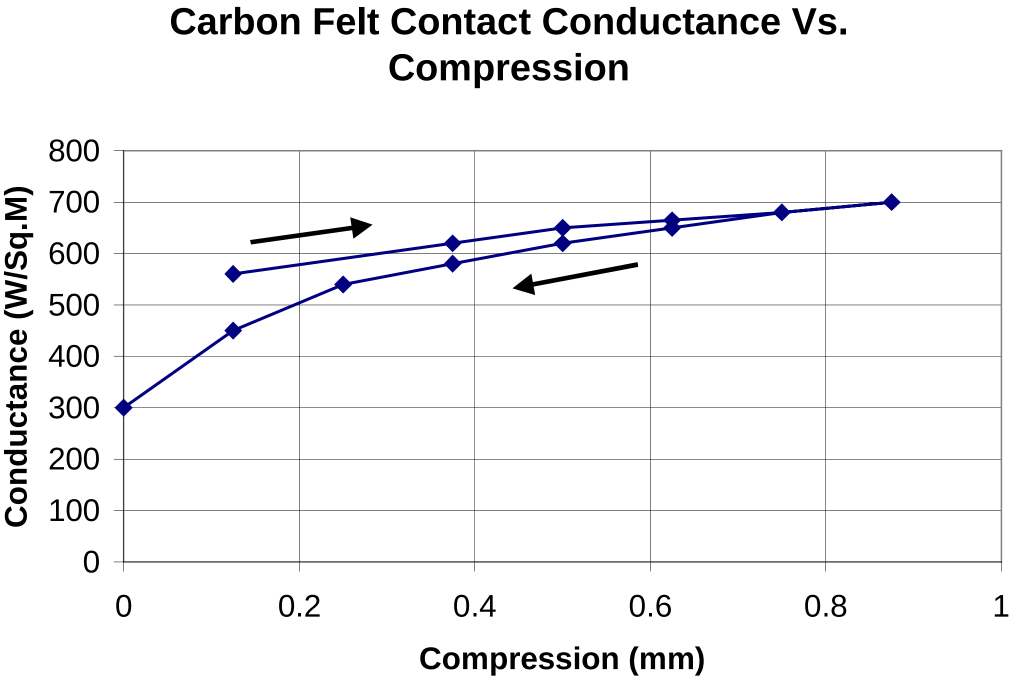

Figure 23. Effective heat transfer is achieved at low contact pressure.

These characteristics show the potential to achieve the interlayer heat transfer performance needed to make the Chameleon Suit a practical reality. To incorporate a conductive fiber felt interface between layers, it is necessary to modify the original design concept as depicted in Figure 24. An active electrochromic surface on one side of each layer will face a felt surface on the adjoining layer. This somewhat reduces the heat transfer modulation achieved with the electrochromic layers as shown in Figure 25. However, the anticipated control authority remains more than adequate for the successful implementation of the concept

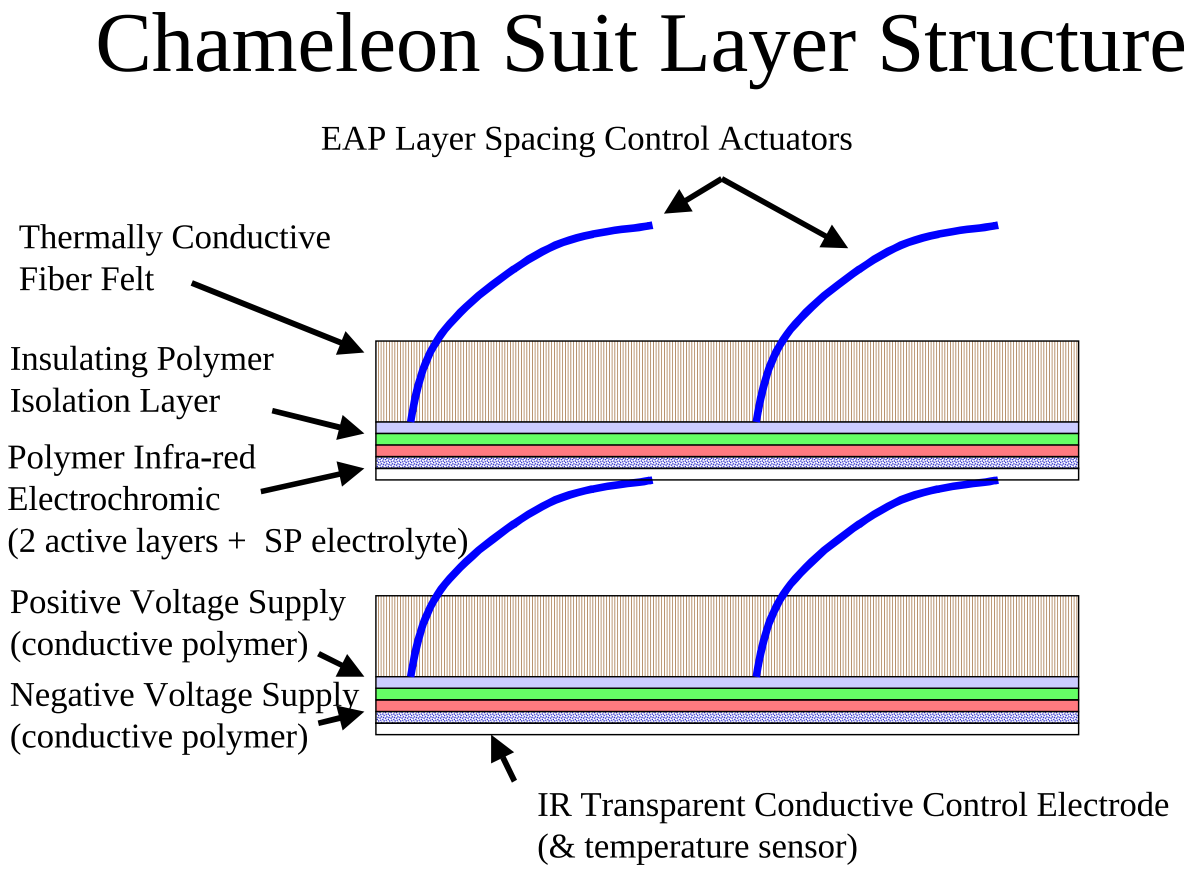

Figure 24. The Chameleon Suit layer structure is compatible with the use of thermal contact enhancement.

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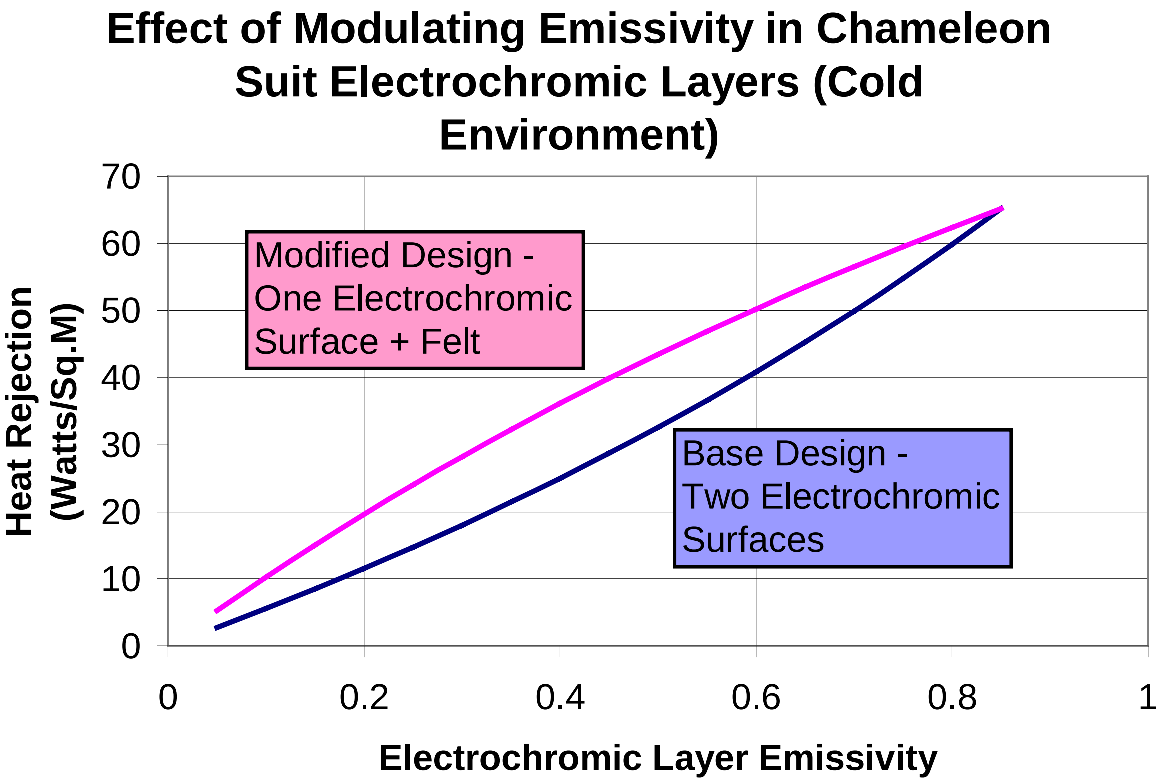

Figure 25. The use of thermally conductive felt interfaces to improve maximum Chameleon Suit heat transmission slightly reduces radiated heat loss control authority.

Directional Surface Shading

More demanding operating conditions, especially in hot environments where radiation sink temperatures for most or all of the suit surfaces are exposed to effective radiation sink temperatures at or near skin comfort temperatures (i.e. 27 - 34 C) will require augmenting the system. Sufficient heat rejection cannot be obtained in these environments by varying insulation and surface emissivity only. For these scenarios, a directional shading concept will be utilized. The directional shading can be implemented with MEMS technology as part of the garment and will substantially enhance heat rejection capability by reducing the effective radiation sink temperature in crater-type landscape or Shuttle cargo-bay situations. This concept is illustrated in Figure 26.

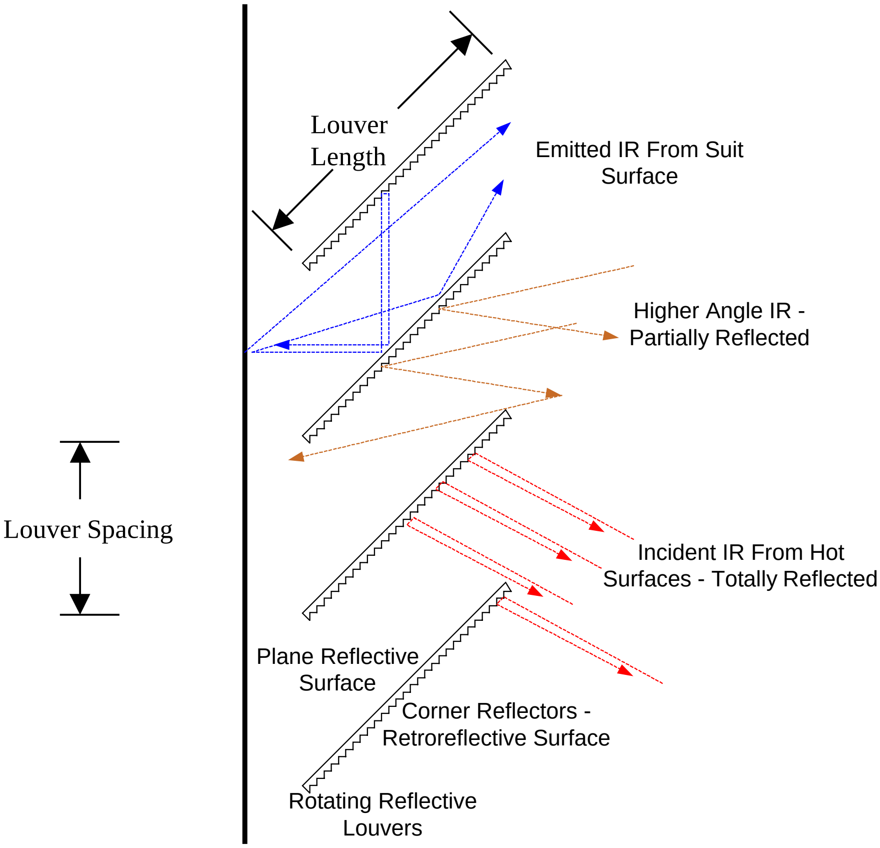

Figure 26. Directional Shading Louver Concept

The louvers can be very small while accommodating corner reflectors which are large enough (several wavelengths) for effective function. The length and depth must be consistent with corner reflector dimensions that are at least several wavelengths in the thermal infrared spectral region, i.e. ~50 microns in order to limit diffraction effects and achieve the desired angular performance. Louvers containing several corner reflectors along their length could therefore be as little as 100 microns (.1 mm) long and 40 microns (.04 mm) deep. Louver width (perpendicular to the plane shown in Figure 28) has only secondary effects on performance. It will not affect the radiation transport properties of the louvers, but will have some influence on the difficulty of achieving thermal isolation between the louvers and suit surface below. It will also affect the packaging efficiency that can be achieved and consequent fraction of open surface area available with the louver system. These parameters can be optimized during actual device development prior to or during the Chameleon Suit system development process.

The primary performance factors for the louver system are the ratio of length to spacing and the angle at which the louvers are inclined with respect to the surface normal. Together they determine the breadth of angular view into which radiation can be emitted from the surface below and its location. Based on our preliminary analyses, optimum length is estimated to be approximately equal to their spacing. A louver angle of approximately 25 degrees above horizontal was found to work well for level ground conditions. Greater louver angles would be desirable for operation in craters, but result in lower view factors. Smaller louver angles result in larger view factors. A louver angle of 25 degrees provides reasonable protection from incident thermal radiation from the surrounding surface while minimizing adverse affects on heat rejection. This combination of length, spacing, and angle were used to calculate an infrared radiation view factor of 0.53 times the total available without the use of louvers. A louver with the same spacing and angle, but a length of 1.4 times its spacing, has an infrared radiation view factor of only 0.44 times the unshaded total. This means that the louver will block more incident IR radiation; however, it also cannot reject heat as efficiently as a louver with a higher view factor. Figure 27 shows a comparison of estimated sustainable metabolic heat rejection for two different louver geometries on a lunar plane as a function of sun elevation angle.

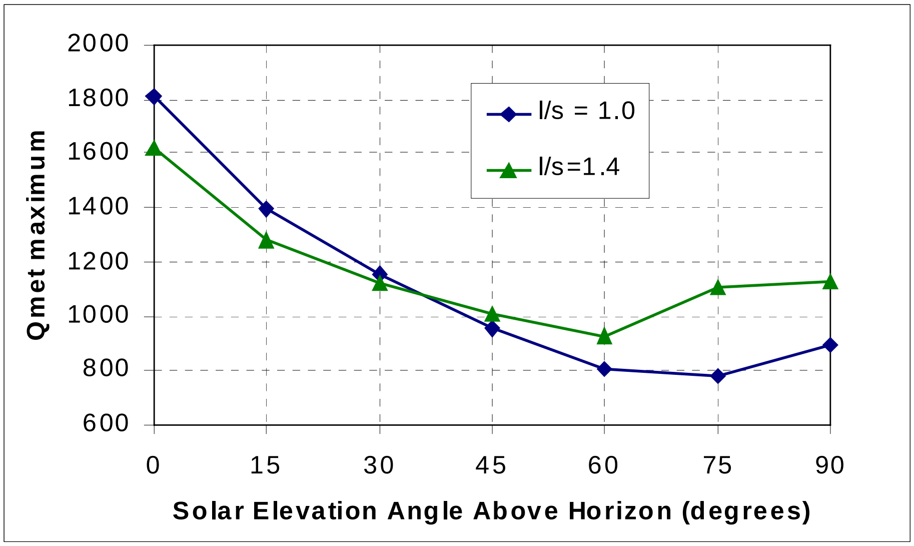

Figure 27. Comparison of heat rejection performance with different louver geometries (Metabolic rates in BTU/Hr)

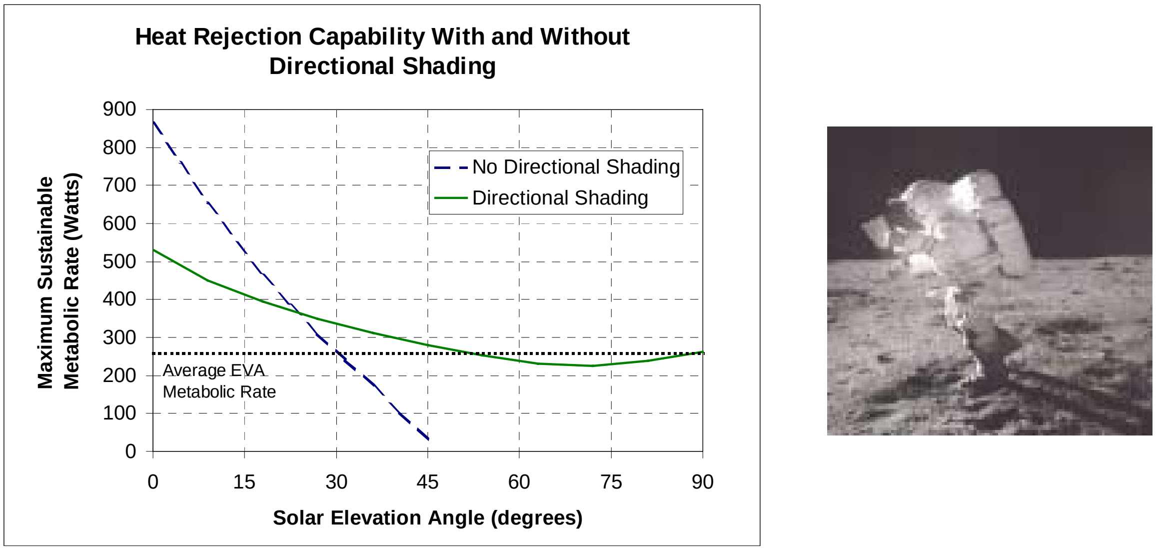

Figure 28. Heat Rejection Capability With and Without Directional Shading

Figure 28 illustrates the advantages of directional shading, especially at high solar angles. Without directional shading, it is impossible to reject even the minimum EVA metabolic rate without the use of expendables for solar angles above 30 degrees. Directional shading allows the suit to reject nearly the average metabolic waste heat without expendables for all solar angles. This makes it possible to use thermal storage to manage peak work rates. However, the louvers restrict heat rejection performance for low solar angles (less than 20 degrees), or in other environments that do not involve EVA near or on large, heated, surfaces. This makes it desirable to be able to control the louvers' effects depending on the operating environment. This is made somewhat difficult because the louver system performance depends on a high reflectivity on both surfaces of the louver in both the visible and the infrared and thermal isolation of the louvers from the underlying suit surface. Eliminating loss of heat rejection capacity will demand that the exposed surface can be made reflective in the solar spectrum and emissive in the infrared and coupled to the underlying suit layers. This could be accomplished with the basic technologies envisioned for the Chameleon Suit, but will require higher performance levels and integration with MEMS devices that is not essential for other aspects of system implementation. A simpler solution could be the use of distinct suit configurations for different mission demands.

Potential Concept Growth

The Chameleon Suit concept has numerous potential avenues for growth with even more significant implications for future NASA missions. Ultimately, it is foreseen that the implementation of this concept could allow integration of most (if not all) of the functions of the current life support backpack into the walls of the pressure garment. Technology evolution paths that will take advantage of mass transfer benefits of this distributed architecture in much the same way as heat transfer gains have benefited the present study have been conceived. These became apparent as the study proceeded, but could not be meaningfully explored within the scope of the present effort. They will be proposed for inclusion in a Phase 2 study program.

The range of concept growth possibilities encompasses:

- the integration of active heat pumping technologies to expand the operational regime
- incorporation of higher force actuators for improved pressure suit mobility
- selective transport of metabolic waste products through the pressure suit walls
- energy harvesting from both solar and waste heat sources
- recovery of breathing oxygen from metabolic byproducts using artificial photosynthesis or related processes.

Each is discussed briefly in the ensuing paragraphs.

Some of the missions that NASA will undertake will require EVA in environments that offer no effective heat sink that is substantially below the astronaut's skin temperature. Under these conditions, the Chameleon Suit, like any design that seeks to reject heat without the use of consumables, must be augmented to provide an alternative for the removal of metabolic waste heat. One approach that has been extensively studied in the past is the use of an active heat pump to allow the waste heat to be absorbed below the skin temperature and rejected at a higher temperature. In general, this has been found to require excessive equipment weight and complexity and a substantial weight penalty for the stored energy to run the heat pump system. The Chameleon Suit concept and emerging technologies provide an opportunity to significantly improve on this situation. In the Chameleon Suit, increased heat rejection surface area and the ability to select surfaces exposed to favorable heat sink conditions while isolating others provides the ability to substantially lower the temperature differential at which the heat pump must operate. This, in turn, can yield a much higher heat pump coefficient of performance reducing the amount of energy required for heat pump operation and the total heat that must be rejected. Emerging capabilities in active polymer technology include indications that it may be possible to produce high performance polymeric thermoelectric materials. These could be integrated into the Chameleon Suit layers to add active heat transport capabilities (and potentially electrical energy recovery from waste heat flow). The on-going development of nano- and micro-machinery including compressors and complete heat pump assemblies provides another alternative for the effective integration of heat pump capabilities into the Chameleon Suit that could be developed to a sufficient level of maturity within the time frame targeted by NIAC. If successful, this would yield an EVA system that is essentially completely independent of thermal environment without the need for consumables resupply.

The incorporation of variable geometry elements into an EVA pressure suit has long been considered a potentially attractive path for resolving the conflict between the need for sufficient easement for donning and an extremely tight fit for optimum pressurized mobility. To a limited extent, it has been implemented in operational systems, as in the pivoted shoulder assembly in the EMU. However, with existing technology, the penalties incurred have generally been found to outweigh the gains. As described by Dr. Newman at the recent NIAC meeting (Reference 21) emerging active materials technologies may provide the means to alter this situation making it practical to custom fit spacesuits in real time during the donning process. This is a logical extension of the Chameleon Suit's integration of active materials and extensive control capabilities in the pressure garment which will be enabled by further development of these materials to provide higher actuation force levels than is presently available or foreseen for most active polymers. It is highly attractive for any pressure suit design, and may prove to be an essential enabling technology for mechanical counter-pressure concepts like those described by Dr. Newman and under study elsewhere (Reference 22). In addition, the incorporation of higher force active polymers of this type would create the opportunity to provide assisted mobility in the pressure suit where ambitious future missions make it desirable.

Selective transport membranes for the removal of carbon dioxide and humidity from space suit breathing gas have been actively researched at Hamilton Sundstrand and elsewhere for many years. While this research has failed to achieve desired performance levels so far, progress has been substantial in recent years. Advancing polymer technology may make it practical to integrate this capability into the Chameleon Suit pressure garment walls. In this case, the system could benefit from the large surface area of the garment and mass transfer available from gas flow within the suit. When coupled with the Chameleon Suit's heat transfer capability, this could allow a system design in which no circulation of the vent gas outside the pressure garment is required substantially simplifying the suit – life support system interface, reducing gas circulation power dramatically, and greatly enhancing safety. This could potentially reduce the life support backpack to an energy storage device and an oxygen storage system and regulated supply for pressure suit oxygen replenishment enabling a drastic reduction in weight and volume.

The active walls of the Chameleon Suit provide the opportunity to take advantage of external energy flow to and from the suit. Incident sunlight provides an obvious opportunity for energy harvesting that could make a substantial impact on the EVA system energy budget if solar cell efficiencies are improved and cell technologies more suitable for use on the suit surface are developed. In earth orbit and at the earth-moon system Lagrange points, the incident solar power density is1350 watts/m^2. The power potentially available over the EVA suit's 1 m^2 projected area is substantial compared to current system power budgets of about 50 watts. Heat flow from the astronaut to space also provides a potential power source although only a fraction is expected to be recoverable. The Chameleon Suit concept substantially increases the potential benefits. The large radiating area it affords allows substantially lower radiating temperatures and increased temperature differences in the recovery device making useful efficiencies possible. As shown in Figure 29, energy recovery from metabolic waste heat can compare favorably to current system energy budgets if efficiencies approaching ideal Carnot limits can be realized. The incorporation of thermoelectric heat pump capability in the suit layers would make energy recovery from this source possible with almost no system penalties. Implementation of these energy harvesting technologies in the Chameleon Suit could dramatically reduce the size of energy storage elements in the life support backpack further reducing its size and weight. With continuing development of battery technology, especially polymer batteries, it may be practical to incorporate distributed energy storage elements within the pressure garment reducing the need for power distribution and completely eliminating the need for energy storage in the backpack and its associated interfaces. In addition, these energy harvesting possibilities may be enabling for still more ambitious extensions of the concept as outlined in the following paragraph.

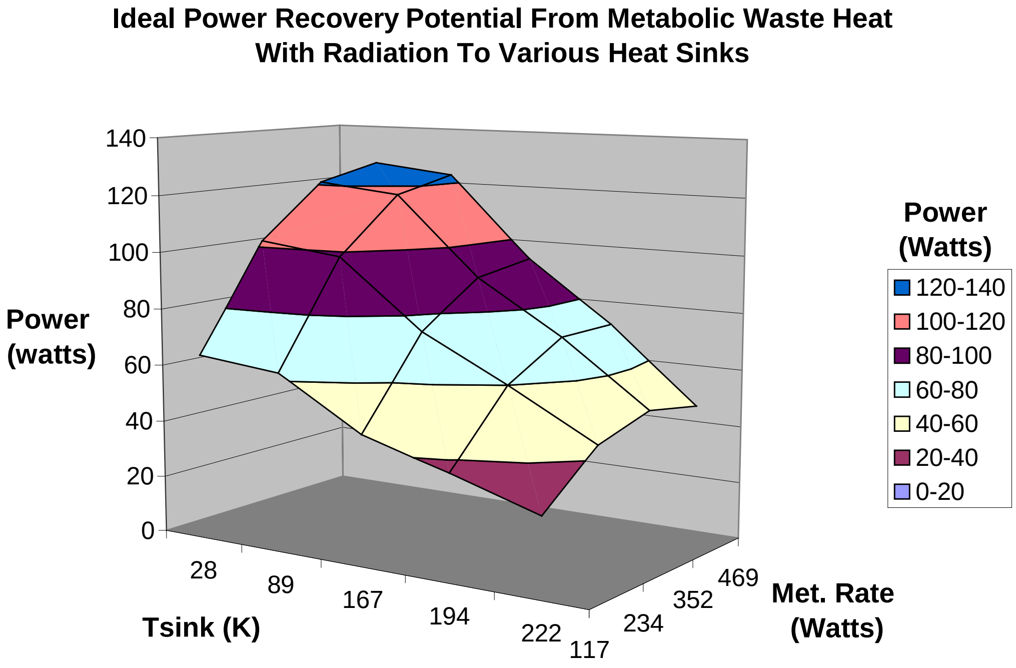

Figure 29. Energy recovery from metabolic waste heat could supply useful amounts of power to the Chameleon Suit EVA system.

An ideal EVA system, like any ideal space life support system, would reduce weight and volume and eliminate endurance limits by achieving closure on the major life support consumable materials. As outlined in the preceding paragraphs, implementation concepts have emerged for the growth of the Chameleon Suit from the thermal self sufficiency posited in this Phase 1 study to independence of external supplies for the control of metabolic waste CO^2 and humidity, and to at least a substantial degree of energy self-sufficiency. The final logical step for an EVA system is to reduce or eliminate dependence on stored or externally supplied oxygen by recovering respirable oxygen from metabolic byproducts. This has proven an elusive ideal since the processes are complex and the energy input required is at least comparable to the astronaut's metabolic energy expenditure. In practice, energy requirements are substantially higher at demonstrated process efficiencies, making the penalties for stored energy greater than those for storing the oxygen. The combination of the extended surface area use and energy harvesting potential in the Chameleon Suit architecture with emerging biomimetic technologies may make the recovery of useful amounts of oxygen during EVA possible within the foreseeable future. This would be accomplished by the implementation of higher intensity engineered processes based on the artificial photosynthesis research presently underway and integrating them as distributed processes integral to the outer layers of the Chameleon Suit. Like natural photosynthesis in some plants, they could operate independent of light exposure cycles using locally stored energy produced during periods of illumination. To maximize system benefit within the constraints of achievable process efficiencies, it is envisioned that the synthesis catalyst will be engineered for a product which optimizes oxygen yield per unit energy rather than the sugars and starches resulting from natural photosynthesis.

System Control and Electronic Integration

Control objectives and technical basis

The ultimate objective of the Chameleon Suit control is to maintain the wearer in a healthy and comfortable state independent of environmental conditions and the wearer's task activities. The control is also required to ensure that the system operates to minimize conditions under which supplementary resources, thermal storage, expendable heat sink materials, or heat pump energy are required. To achieve these top level objectives, the control must:

- maintain all of the suit's internal temperatures within safe limits,
- match the total heat flow through the suit walls to the wearer's metabolic waste heat production,
- locally adjust the heat transfer characteristics of the suit's walls to directional thermal environments, and
- adjust to changing thermal conditions as the astronaut moves.

In accomplishing these objectives, the control can draw upon the known relationships between metabolic activity and comfortable skin temperature, and make use of the human body's substantial capacity to regulate thermal comfort and transfer heat within the body in response to external environments. Operating experience with the use of liquid cooled garments in current and past space suit systems has established the ability to achieve a safe and comfortable thermal equilibrium without appreciable sweating over a wide range of activity levels if the average skin temperature is controlled to appropriate values. Established values using a liquid cooling garment that covers the torso and limbs, but not the head, neck, feet and hands as in the NASA EMU are reflected in Figure 13. As discussed previously, more recent research at the University of Minnesota has explored the body's tolerance for non-uniform heating and cooling (Reference 23). The results of this research support common experience that local variations are well tolerated. This allows several possible control strategies to be considered and makes system control based on locally measured temperatures and centrally determined metabolic heat generation a practical possibility. Based on the system implementation concepts developed during the study, required control functions to accomplish the system objectives were identified including:

1. Locally sense outer surface temperature and activate directional louvers to support heat rejection on warm planetary surfaces.
2. Locally sense outer surface temperature and adjust to maximize insulation where heat is gained from environment (unless temperatures below comfort conditions result).
3. Locally sense inner surface temperature and adjust insulation to eliminate touch temperature hazards.
4. Adjust heat flow through suit wall to maintain / achieve occupant thermal comfort at varying metabolic rates and environmental conditions.
5. Detect system failures and hazardous conditions, provide crew advisories / warning through EVA information system.
6. Fail safe to protective – insulating values

The fourth of these functions, adjusting heat flow to maintain thermal comfort implies matching heat flow closely to metabolic waste heat generation. This can be accomplished in several different ways:

- by directly measuring heat flux through different suit areas and integrating to derive the total for comparison to metabolic activity,
- by adjusting average skin (or suit inner wall) temperature to a predetermined comfortable temperature for the measured metabolic rate, or
- by tuning the system for thermal comfort as determined by physiological monitoring.

All were considered during the study. While the coordination of different portions of the suit is more evident in the first and third options, it is implicit in all three. Since the average skin temperature determines thermal comfort, the second control option requires the incorporation of some mechanism for the adjustment of local target temperatures based on actual temperatures achieved elsewhere in the suit.

Control action to achieve these functions can take several different forms. The largest effect will be achieved in the transition between the state in which suit layers are in contact and conductive heat transfer occurs, and that in which suit layers are isolated and heat transfer (in space vacuum) is primarily by radiation. Modulation in this effect is possible either by varying the number of layers separated to provide several steps in the control or by varying the number of spacing actuators excited to produce a fine patchwork of separated and conducting areas to achieve the correct averaged response. In a planetary atmosphere like that on Mars, modulation is also possible by varying the spacing between separated layers to alter the gas conduction across the gap. Continuous modulation over a smaller range of heat transfer between separated layers can be achieved by exciting electrochromic surfaces to vary their emissivity. This can be combined with the stepwise excitation of layer separation actuators to achieve essentially continuous control of the total heat transfer characteristics of the suit in any given region.

Control zones

One of the major strengths of the Chameleon Suit architecture is the ability to locally modulate the suit's heat transfer characteristics for the most advantageous heat rejection performance in directional thermal environments. To benefit from this capability, the suit control must be able to sense these directional variations and respond with appropriate local control actions. In the ideal, one could conceive of a system in which each square millimeter of the suit could independently sense and respond to conditions. However, such a system would require an enormous number of sensors for surface temperatures (on the order of 6 million for a 3 square meter suit area) and an equally large number of independent control decisions implying a large processing load whether implemented in a central or distributed control architecture. System coordination would also require a large signal transfer rate within the system. As a result, there is a trade-off between system performance which improves with increasing numbers of small independent control zones and system cost and reliability which favor a minimum number of independent zones.

To allow a realistic consideration of system control concepts and technology requirements within this study, it was necessary to develop some preliminary assessment of the number and arrangement of control zones that would make the concept successful. To achieve the system objectives, the control zones must be sized to make it possible to prevent the creation of inner surface touch temperatures which would be hazardous and to allow efficient over-all suit heat rejection performance. The first requirement implies that the zones must be sized to preclude very large temperature differences between a (presumably central) measurement location and any other point in the zone. The second implies that the zone sizing should minimize adverse heat flow allowed as a result of hot suit regions included in zones sensed as cool and lost heat rejection capability as a result of cool areas shut off based on hot sensed temperatures. These conditions can arise from two sources:

- directional energy flux – e.g. incident sunlight – which varies systematically with surface orientation
- shadowing which can introduce sharp boundaries between hot, illuminated and cool, shadowed surfaces in arbitrary locations and boundaries.

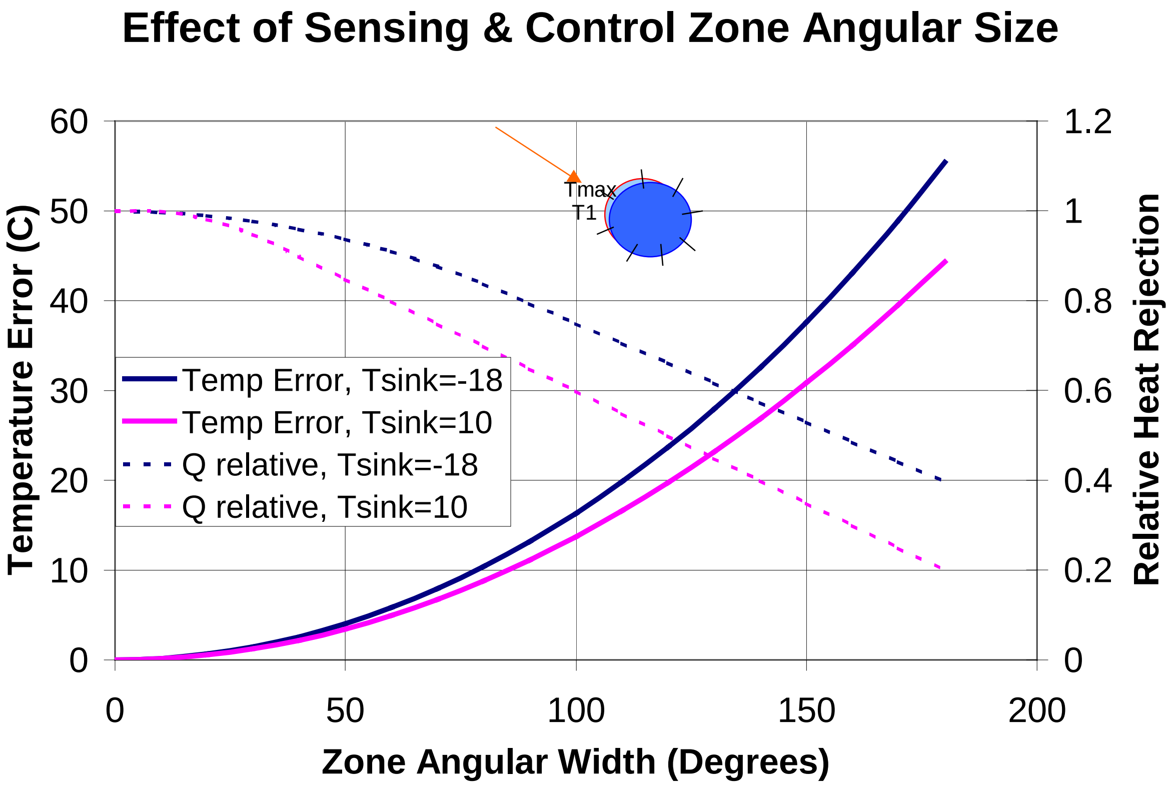

Figure 30. Control zones with 45 degrees angular width result in minor system performance compromise.

The effects of the first of these were analyzed by considering a representative cylindrical body segment radiating to a relatively warm sink temperature with incident sunlight normal to its axis. Variations in adiabatic surface temperature with angle from the incident sunlight vector were determined and a control assumed in which maximum insulation would be created where the surface temperature exceeded the skin temperature from which heat was to be removed. The difference between the temperature at the center and edge of the zone was then determined as a measure of the effectiveness of the control in protecting against hazardous touch temperatures. A large difference here implies that the control must provide a large margin between shut-off values and actual hazard conditions in order to ensure safety, substantially narrowing the system operating envelope. Heat rejection from the cylindrical segment was also calculated based on ideal control of the insulation as outlined above and based on control in zones of varying angular width. The results of these analyses for two different sink temperatures are shown in Figure 30. Based on these results, we concluded that an angular width of 45 degrees represented a good preliminary design value for Chameleon Suit control zones. At this value, temperature errors within a zone due to displacement from the sensed location will not exceed a few degrees Celcuis, and heat rejection capability will exceed 90% of the ideal maximum at most radiation sink temperatures.

The effects of arbitrary shadowing do not lend themselves to convenient analysis. However, as a preliminary response to this potential, the circumferential zones derived based on the above analysis were further divided longitudinally to achieve segments of comparable length and width. In general, three longitudinal sections were formed. In addition, four areas, the gloves, elbows, knees and boots were identified in which contact with hot and cold surfaces was likely making it desirable to preclude high conductivity at substantial contact pressure. These areas were designated as inactive meaning that permanent insulation would be used. The over all zone structure that results is summarized in Table IV. A total of nearly 150 active control zones were identified.

Table IV. Chameleon Suit objectives can be achieved with approximately 150 distinct insulation control zones.

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
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**			

Control Sensor Interfaces

Sensor requirements are defined on several different levels for the Chameleon Suit. The first sensor array required is used to control the local effectors in each zone of the suit to react to external stimulus. The second level of sensing will require an awareness of the crewmembers metabolic rate and skin comfort temperature to vary the amount of heat loss or insulation required for a particular or overall area of the suit.

Sensing of the various external and internal temperatures of the multiple zones may be best organized by local zone control with the information shared between zones using a network topology.

Both external and internal suit temperature measurements can be achieved through conventional surface temperature sensors based on thermocouple or RTDs (Resistance Temperature Detector). An integration of the sensing medium with the layers of the suit offers significant advantages with respect to size requirements.

Skin surface temperature sensing requires a less intrusive methodology, which could be based on an infrared technology. In recent years a common form of surface temperature measurements has been based on the use of thermopile sensors. The most prevalent use of these in the commercial market has been for the use of non-mercury body temperature sensors, which you point in the ear of a patient. Placement of optical sensors to remotely detect the temperatures of both the body skin and internal suit layer offers an approach again to reduce the overall size requirements of the sensors. Crewmember body core temperature can be derived from metabolic rate calculations. The metabolic rate is based on sensor information from the Primary Life Support System (PLSS) based on Oxygen rate use calculations. Figure 31 describes a possible sensor configuration for the suit system.

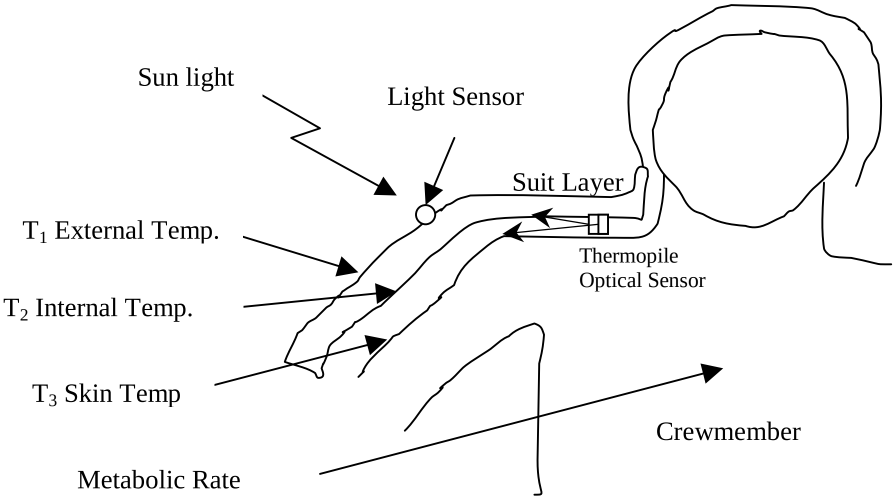

Figure 31 Potential suit/crewmember sensor arrangement

Again a topology of the control system which is based on a network of multiple processors is required to share the information from the PLSS and the various zones to enable active control of the independent layers. The layer’s control parameters are external temperature, internal temperature, skin temperature, and metabolic rate additional parameters such as incident sun light may be used to further enhance the control algorithm.

The challenge for the Chameleon suit will be sharing the sensor data between the multiple zones. Various architectures shall be discussed in the next section, which present different approaches to sharing data across distributed controllers.

Depending on the thermal contact of the suit material to the skin. Trade studies could be conducted to determine the need for local skin surface temperature sensors versus use of inner layer surface sensors. The goal in the study would be to reduce the overall temperature sensor count yet provide adequate redundancy to cover the loss of sensors.

An alternative for internal temperature sensing would be to locate the sensors on a garment warn by the crewmember before he/she dons (puts on) the suit. The challenge with this approach would be to determine a means for the data to bridge the gap between the two isolated suit structures.

Control architecture alternatives and trade-offs

An estimation of the total number of zones is approximately 150 for the entire suit. Within each zone there are 5 layers of material, which need to be individually activated. This configuration creates a high input/output requirement. Control Architecture options for control of the multiple zones and layers can be based on either a distributed or centralized scheme.

A centralized scheme reduces the overall processor count but increases the burden of handling the high I/O count in one location. This scheme also increases the overall complexity of signal flow in harnesses and requires larger interface connectors to handle the high pin counts.

A distributed scheme reduces the I/O count handled by each processor but increase the overall processor count of the system.

The trade-off between the two systems is best determined by calculating the overall power/weight and volume of each system and choosing and optimal system based on the lowest p/w/v solution, which still achieves adequate redundancy and safety.

The final solution is likely to be a hybrid of each approach. A distributed approach could be used to control zone grouping of the suit for the layers and to handle the local temperature sensors. The central processor would then act somewhat as a network controller and handle zone-to-zone data interaction and interface with the PLSS Caution and Warning System. An embedded controller and wireless network node for a solution of this type is shown in Figure 32.

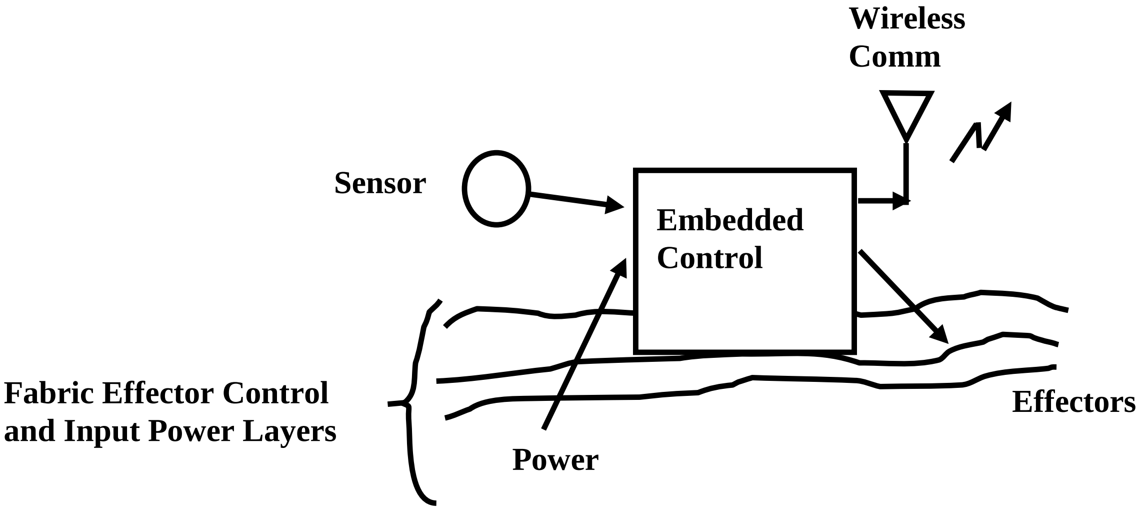

Figure 32. Sensor and distributed control integration concept.

Signal Flow and Power Distribution

Issues independent of the overall architecture that need to be addressed concern the myriad variety of interfaces to be handled. On the input side of the controllers there are sensors, power and data inputs. Each type of input signal has its own design concerns associated with it.

The sensors although predominately temperature may also be comprised of light and infrared. The sensor inputs can be partitioned into either low level or nominal level signals. The low-level signals require special handling in the area of EMI (Electro-Magnetic-Interference) to prevent cross talk and noise from higher level sources.

The power interface requires a different focus to provide over-current protection of the harness and items attached. The area of power distribution becomes an issue with the question of location, design and configuration of the protective features for the power bus. See Figure 33 for one example configuration. This is a factor in the trade off between a distributed processor approach versus a centralized approach. Each design will drive the power bus protection features in a different direction with respect to the PWV (Power/Weight/Volume) impacts.

The effector outputs shall provide built in overcurrent protection however the input power to the controllers will require additional protection at the distribution node or source. If a classical approach for power is used for the PLSS then a battery with a high power density will be used as the primary power source and current limiting at the output shall be a requirement (unlike today’s system). After the power leaves the battery there will be several nodes which further distribute the power. This is analogous to the circuit breaker panel in your house.

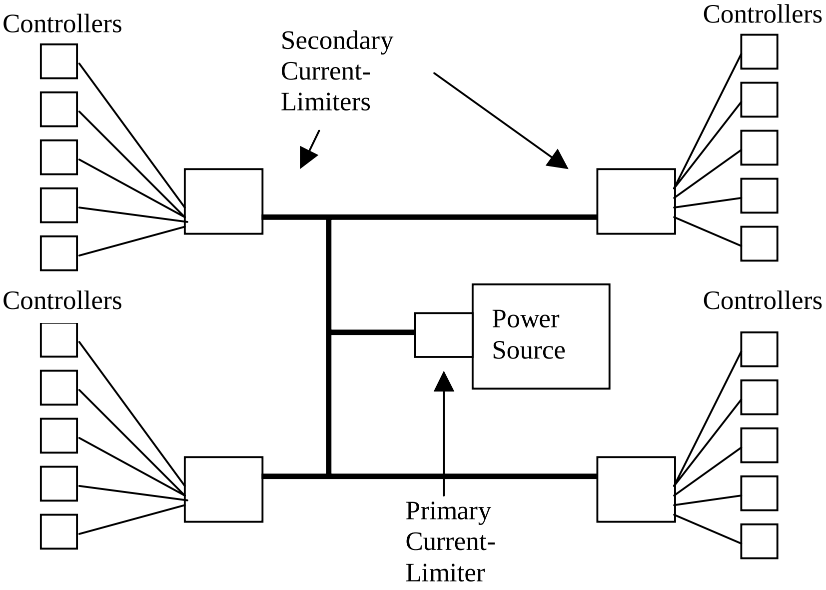

Figure 33 Power Distribution Current Limiting Scheme

If the fabric is used as a current carrying medium use of polymer fuses integral with the fabric conductors will achieve a reduction in size in complexity. The technical challenge with polymer fuses is that they have memory characteristics, which cause a significant increase in their series resistance after a high current event. This is an area which needs further technical development.

Effector Drive and Control

Given the high effector count resulting from the Chameleon Suit Layer Structure control of the effectors will require a novel control scheme. One possible approach within a zone may be accomplished by a scheme based on a common form of memory addressing.

Conventional memory address schemes provide a means to activate a high quantity of nodes via the use of rows and columns. An example is shown in Figure 34 of a memory map effector drive scheme. If we apply activating the effectors with the same approach a reduction in the overall drivers may be achieved.

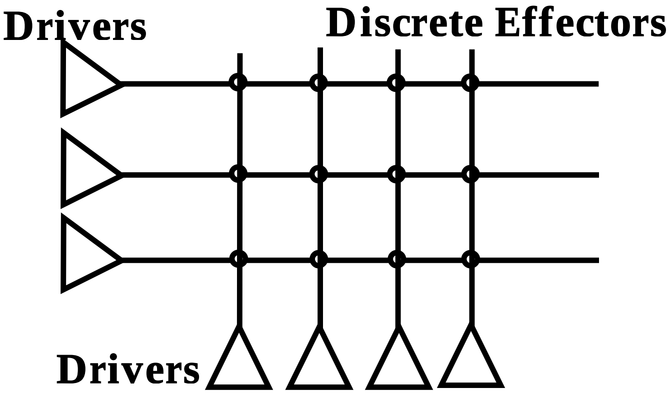

Figure 34. Effector Drive Memory Map Scheme

The next challenge in control of the effects concerns overcurrent protection in the event that an effector or fabric conductor fails short. Smart power MOSFETs integrate current sense and control with the switching MOSFET thereby providing a small form factor for circuitry, which has classically been implemented with separate circuits. Figure 35 provides an example of a Smart Power device.

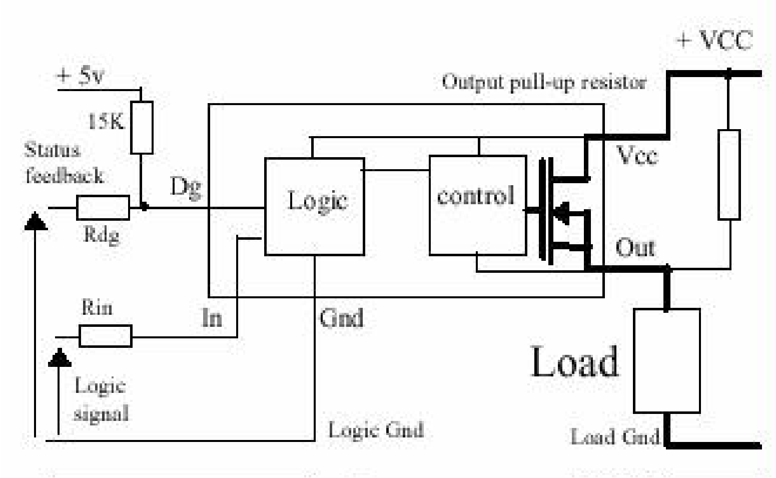

Figure 35 Effector Drive Memory Map Scheme

Technology Readiness, Development Needs and Outlook

Enabling technologies definition and required characteristics

Consistent with NIAC objectives and ground rules, the Chameleon Suit concept is well founded in scientific and engineering principles, but requires significant new technology in several areas if it is to be successfully implemented. Enabling technologies identified in the initial concept formulation and study proposal included:

- advanced, flexible, low power actuators for the controlled separation and contact of suit layers,
- polymer based infrared electrochromic devices offering a significant ratio between maximum and minimum emissivity, and
- light weight, flexible and robust sensing, signal transfer, and power distribution integrated with the multi-layer space suit pressure garment.

As the study has evolved, the challenges to these enabling technologies have become more clear and additional technology needs have emerged. Specific additional enabling technologies include:

- integrated conductive felt thermal contact enhancement
- MEMS directional shading louvers.

All of these enabling technologies are currently the subject of research study or in the early stages of development, and none can be said to be “available” for application in the Chameleon Suit today.

For all of them, the rigorous application environment of a space system, and especially an EVA suit presents one of the greatest development challenges. Ultimately, they must be implemented and integrated in a fashion that is compatible with operation in space vacuum and in a variety of vehicle, habitat, and natural pressures and atmospheres including:

- sea level air,
- hypothetical Mars habitat 8 psi oxygen-argon-nitrogen mixes,
- 4 psi pure oxygen,
- and Mars 1Kpa carbon dioxide atmosphere.

They will need to tolerate the temperature extremes and rapid temperature changes of deep space and space radiation exposure, and numerous mechanical challenges including extensive cyclic operation, bending and flexing, impact, vibration, and contact pressure. To support NASA missions to the surfaces of the moon, Mars, and asteroids, they will also need to function in the presence of ubiquitous, abrasive, and potentially corrosive dust. All of these environments must be tolerated for extended missions lasting up to three years to support the full suite of activities currently envisioned in NASA's HEDS Strategic Plan. To enable new mission concepts, they may need to provide even longer service. This alone represents an enormous development challenge for nascent technologies that are currently demonstrated to operate for days or weeks in controlled laboratory environments. Some of the other, more specific, challenging requirements for each of these enabling technologies are discussed in the ensuing paragraphs.

Suit layer spacing actuators are required to generate low to moderate forces over relatively large displacements with low power input. Layer spacing capability is currently targeted at approximately 1 cm and each actuator will be required to produce approximately .01 Newtons of actuation force to support the weight of the outer layers of the suit in planetary surface operations. They must be sufficiently flexible to accommodate suit mobility without damage and without impeding crew motion. They must tolerate prolonged and repeated exposure to space vacuum or the Martian atmosphere and remain fully functional in those environments since the suit insulation layers must be vented to ambient conditions for mobility and optimal insulation performance. They also must tolerate exposure to both hot and cold temperature extremes since actuators are required between the outermost pair of layers in the suit. They will approach outer surface temperatures when the suit is in its most insulating state. However, full function under thermal extremes, while desirable, is not essential since sequential activation of layers from the inside out could be used to achieve a narrower operating temperature range. In addition, the actuators must achieve the required force capability with a sufficiently small cross sectional area to minimize conductive heat transfer in the expanded state.

Polymer based infrared electrochromics are desired for the Chameleon Suit to ensure that emissivity control can be implemented without compromising system weight and reliability or suit mobility. The driving requirements are for flexibility and compliance to suit motions and for a substantial (i.e. 2:1 or better) broad band change in emissivity at thermal infrared wavelengths. To provide highly effective insulation performance, a minimum emissivity value below 0.4 is required. It is important to note that the electrochromic surfaces in the Chameleon Suit are internal to the suit lay-up and thus not exposed to direct solar UV. This substantially eases the challenge of adapting polymeric materials. Although inorganic salt infrared electrochromic materials could be integrated as discrete rigid platelets that could move relative to each other to accommodate flexure of the suit layers, this would complicate manufacture, create discontinuities and interfaces that would degrade reliability and necessarily degrade radiation control performance under some conditions.

Sensing and control elements must be integrated with the suit layers with minimal weight and flexibility penalties and without creating thermal short circuits between layers in the expanded, insulating state. In the ideal, many elements, power and signal conductors, temperature sensors, and possibly control switches will be formed directly within the active polymer layers in processes analogous to current manufacture of IC’s and printed circuit boards. More complex devices for control logic and wireless signal and power transfer will be required in extremely small packaging to mount directly to these “soft” circuits.

Integrated thermal contact enhancement is targeted to achieve contact resistance below approximately 0.0035 m^2-C/Watt at very low contact pressure. In addition, the thickness of the thermal contact enhancement layer must be small (1 mm or less) and its density low to minimize total suit weight penalties. Less than two kilograms of added weight over the total 3 m^2 surface area is presently anticipated. Durability is a critical requirement since the felt will not only see many compression / decompression cycles, but must remain effective through extensive suit flexure with associated shear motions between the suit layers.

Directional shading MEMS louvers are required to permit system operation in extreme thermal environments like the sunlit lunar surface. Operationally they are comparable to MEMS louver assemblies under development for vehicle based applications (Reference 24). Like those devices, they must achieve a high level of thermal isolation of the exposed louver surface from the mounting interface. Louver size is set to at least .2 mm width and .06 mm depth by the need to accommodate effective corner reflectors for thermal infrared wavelengths. Unique to this application is the need to interface the MEMS louver assemblies to the suit outer surface in such a way as to accommodate suit mobility and flexure. Small unit size is expected to be a significant asset in this regard.

Variable geometry insulation activation

In the last few decades, the role of polymers in our world has changed from being a simple, largely inexpensive commodity to becoming a highly engineered, multi-function material. Polymers having secondary valuable characteristics such as optical clarity or electrical conductivity are being developed under the global appellation of "functional polymers" or "smart polymers". A class of such polymers particularly relevant to this study are electroactive polymers that are capable of changing their shape upon electrical actuation. Upon integration in a fabric, such polymers would allow variable loft and therefore variable thermal conductivity of the overall structure.

During EVA, two extreme scenarios may occur: (1) low heat generation in a cold environment which calls for a well-insulated suit and (2) high heat generation which calls for a highly heat conducting suit. Therefore, the proposed garment should provide a large range of heat transfer rates. This can be achieved by controlling both conduction and radiation within the insulating garment. Conduction is controlled primarily by varying the physical arrangement of the layers which comprise the garment from a close packed configuration with direct contact between layers to an open stack with layers separated by small cross section insulating supports. When the layers are separated, increasing separation has little effect in vacuum environment, but further decreases heat transfer in a planetary atmosphere by increasing conductive path length and decreasing internal gas pressure (if the insulating garment is not porous). One attractive technology for this purpose, electro-active polymers, has seen rapid development in recent years.

Electro active polymers (EAP) are used in various fields, but are especially relevant to robotics and the manufacturing of artificial muscles. In essence, EAP change dimensions and configuration when a potential is applied. Ion-exchange polymer metal composites (IMPC) are active actuators that show large deformation in the presence of low applied voltage. They are manufactured by depositing a noble metal (Pt) within the molecular network of an ionic polymer (for example Nafion in the H+, Na+ or Li+ form). When an external voltage of 2 volts or higher is applied on a IMPC film, it bends towards the anode. When an alternating voltage is applied, the film undergoes a swinging movement. The movement is due to the shifting of mobile charges within the polymer. As one example, such properties have been used to manufacture artificial "grippers"(Reference 25). IMPC can actually be used both as muscles (applied current induces movement) or as sensors (movement induces current). A review of such applications is given by Shahinpoor et al. (Reference 26) and Sadeghipour et al. (Reference 27) used polymeric membranes as a pressure sensor. The dynamics of such systems have been studied in detail by Shahinpoor and co-workers (References 26, 28, 29, 30), and several patents have recently been issued. For example, US patent 6,109,852 (Reference 30) discloses a soft actuator made of Nafion ion-exchange membrane and a method of manufacturing. A disadvantage of such active polymers is their reliance on water or other conductive solvent for ion diffusion. Therefore, in order to stay hydrated, the polymers need to be wrapped in cellophane for example. During Phase 1, contacts have been made with Professor Shahinpoor at the university of New Mexico and collaboration has been discussed for the upcoming phase.

Contacts have also been made with the group of Professor Ian Hunter at MIT (Reference 31), which is developing polypyrrole-based active polymers. Such polymers are electron conductive (whereas Nafion is ionically conductive) and exhibit dimensional changes as oxidation and reduction occur within the polymer. Typical changes are 2% in length or 6% in volume. The activation energy is about 1 V although the dimensional changes may be accelerated by increasing the voltage up to 10 V. Such polymers can withstand high temperatures (up to 400 C). but, at low temperature, the speed of response decreases as the diffusion of ions through the polymer becomes slower.

Polypyrrole does not require as much water as Nafion to perform although it seems that encapsulation of both polymers is preferred in order to maintain their activity. Future work however could envision the use of solid electrolytes instead of liquid electrolytes; even though this would come at the expense of rate. The MIT group has produced electroactive polymers that are several meters in length in fiber form. Preliminary life characterization demonstrated no change in performance over 100000 cycles.

Professor Mazzoldi’s group at the University of Pisa actively working on incorporating active polymers into wearable hardware (Reference 32) and has been contacted as well.

Another type of electroactive polymers is being developed by SRI international (Reference 33). The polymers are formed of elastomers coated with a conductive polymer that acts as an electrode. Such materials exhibit a strain that is comparable to natural muscles (30% strain and higher). However they also require activation energies in the kV range, which may make them impractical for the Chameleon Suit application.

Based on the current state-of-the-art, the incorporation of active polymers to a space suit seems very possible but will require much development to ensure adequacy on all levels, that is compatibility with the expected environment especially temperature, repeatability and accuracy, and reliability and endurance.

Vacuum thermal contact technologies

The use of thermally conductive fiber felts is a developing technology that has shown considerable promise for the improvement of heat transfer between adjacent surfaces at low contact pressure (Reference 34). This is an essential capability for the Chameleon Suit. Based on published information and on direct experience at Hamilton Sundstrand with the use of this type of material in vehicle thermal control applications, it appears that the required performance characteristics will be achievable, but that considerable further development of this technology will be required.

The means by which this technology enhances contact heat transfer include the creation of an extremely compliant interface that eliminates lost contact due to irregularities in the mating surfaces and the creation of locally high contact pressure at the felt fiber contact points. To be successful, the fibers in the felt must have high thermal conductivity, sufficient flexibility to achieve the desired conformance to irregularities, and sufficient stiffness to produce reasonable local contact pressures at modest deformation. This combination of demands has lead to the use of carbon fiber felts with considerable success.

Published data for these materials show the ability to generate thermal contact resistance well above the Chameleon Suit requirements at modest contact pressure. However, data reflecting operation in a vacuum are sparse, and the published data do not reflect contact with the materials which will be employed in the Chameleon Suit. Since the contact resistance achieved is a function of the thermal conductivity and deformation of both materials at the point of contact, application specific evaluation is required. Together with the knowledge that loss of gas conduction in a vacuum environment will result in lower total contact heat transfer, this makes it highly probable that further development will be required to achieve Chameleon Suit performance goals.

Development experience to date provides guidance in the directions that this development may take. Low contact pressure performance is enhanced substantially by mounting the fibers in the felt at an angle to the plane of contact so compliance is made easier and a larger fiber contact area is achieved at low deflection. Higher compliance in the polymer layers in the Chameleon Suit may also provide significant gains in reducing contact resistance by increasing the area in intimate contact with the fiber. Generally, increased thermal conductivity in the contacted surface as well as in the fiber results in increased contact heat transfer. Increasing thermal conductivity within the Chameleon Suit layers is generally desirable for system performance and is expected to be a part of the system development process.

Recently, attempts to apply available carbon felt thermal contact enhancement materials in a vehicle thermal control application at Hamilton Standard were abandoned when severe problems with the durability of the carbon felt in vehicle vibration environments were discovered. This indicates that considerable further development for durability will be required before this type of contact enhancement can be applied in the Chameleon Suit. Our application will entail not only vibration and shock, but also repeated flexing and shear among layers of the suit that will deform the fibers significantly and in arbitrary modes. This implies the need for significantly greater toughness and durability than was evident in the carbon fiber felts we evaluated. Possible paths to achieving this toughness while retaining high thermal performance include the use of different grades of graphite or the use of composite materials combining carbon or graphite with a polymer matrix which is more tolerant of deformation.

An additional integration issue which must be addressed is the potential for abrasion of the electrochromic layers contacted by the fiber thermal contact interface. This will require research into the mechanical properties of the mating surfaces and the structural integration of the layers in the pressure suit to better understand contact forces and relative motions.

At the summary level, no fundamental barriers to success have been identified. Required levels of thermal performance have been reported, but are not demonstrated under Chameleon Suit usage conditions. There is evidence that considerable further development of the mechanical durability of these materials will be required for their successful use in the Chameleon Suit. Both of these issues are important for many potential applications. Since this is an emerging technology which is still developing, it is probable that considerable progress will occur prior to a commitment to development of an operational Chameleon Suit without specifically focused research activity. However, the Chameleon Suit application presents unique challenges to the technology and unique combinations of materials and geometry which will require specifically focused research activity. This should be further defined in collaboration with the current developers of the technology during a Phase 2 study to allow more complete definition of a Chameleon Suit technology development roadmap and assessment of likely development costs and risks.

Infra-red variable emissivity materials

Electrochromism is defined as a reversible and visible change in the transmittance and/or reflectance of a material as the result of electrochemical oxidation or reduction. . As the name implies, in this technology, the material assumes a colored state due to a change in composition when subjected to a potential. Examples of current EC devices are automotive rear-view mirrors and “smart windows” which work in the visible spectral region. Electrochromic rear view mirrors use the effect to reduce headlight glare automatically and are available in a number of car models. “Smart windows” are now being considered for commercialization after Sage Electrochromics, 3M and the Center for Ceramic Research at Rutgers University developed a process in which five thin layers of ceramic are baked onto glass panes. Application of electricity to the coating causes the window to tint: the higher the voltage, the darker it gets. Turning the dimmer knob all the way causes the window to block up to 95 percent of light. The National Institute of Standards and Technology's Advanced Technology Program supported the development with a $3.5 million grant. EC devices can consist of a galvanic cell with several layers: a glass substrate, an electrochromic layer , a solid or liquid electrolyte and a counter electrode. Alternatively, photovoltaic devices may be made by use of a dye-impregnated layer of titanium dioxide. Between the titanium dioxide and the electrochromic layer is a layer of either lithium iodide solution or a solid polymer containing lithium iodide. This entire device is sandwiched between two layers of transparent conducting oxide material. When sunlight strikes this device, the dye absorbs some of the sunlight and releases electrons, which are injected into the titanium dioxide. The electrons are then conducted to the adjacent conducting oxide layer, and pass through an external circuit to the conducting layer adjacent to the electric layer, on the other side of the device. This electron flow, in turn, causes iodide ions to migrate through the solution or solid polymer toward the titanium dioxide, and causes lithium ions to migrate into the electrochromic layer. As in a standard electrochromic device, the injection of lithium ions into the electrochromic layer causes it to color. When sunlight stops hitting the device, the charge stored in the electrochromic layer drives the process in reverse, ejecting lithium ions from the electrochromic layer and causing it to bleach. Thus, with no external controls, the window will color in sunlight and bleach in its absence. The external circuit can also be used as a control device; disconnecting the circuit will cause the window to remain in its current state regardless of the presence or absence of sunlight. In addition, an external voltage can be applied to the device through this circuit to drive the device to either the bleached or colored state.

This is a technology area which is in a very early stage of development. As the previous paragraph shows, the development of electrochromic materials has a considerable history, and has reached the point of widespread commercial application in some areas. Work is also underway on electrochromic sunglasses. However, most of this activity has been in the visible spectrum and has focused primarily on inorganic materials on glass substrates. Considerably less work has addressed the thermal infrared spectrum and polymeric materials more suitable for the Chameleon Suit.

While most effort and applications for electrochromism have been in the visible region, effective levels of control in the thermal infra-red where heat transfer at space suit temperatures will occur has also been demonstrated. The magnitude of the emissivity is dependent on the surface structure and on the specific properties of a material such as binding forces and concentration of free electrons. Non conducting materials generally absorb and transmit thermal radiation whereas conductive materials, especially metals, are infrared reflectors, the reflectivity increasing with conductivity. Therefore, one can alter the emissivity by altering the conductivity of a material.

As early as 1988, NASA published information identifying WO_3 based variable emissivity electrochromic coatings for thermal control as an available technology (Reference 35). Significant effort has been directed to the study of WO_3 as an effective infra-red electrochromic material (References 36-42). In these studies, research was directed specifically toward the development of suitable elctrochromic systems for thermal control of spacecraft by modulating emissivity in the 300K blackbody spectral region. A variety of structures and formulations exploiting WO_3 as the basic material were investigated and ratios of maximum to minimum emissivity as large as 3.5:1 were achieved. Other researchers (Reference 43) have studied the feasibility of integrating electrochromic coatings of this type with graphite composite structural elements for ultra-lightweight spacecraft. They concluded that such an arrangement will not only save weight and enhance thermal control, but also provide radiation shielding benefits. This is of considerable interest for the Chameleon Suit since EVA radiation shielding remains a significant concern for future NASA missions beyond low earth orbit. While WO_3 is typically applied to rigid substrates, infrared electrochromism has also been studied in polymeric materials more readily incorporated into a flexible protective garment.

Researchers at Dornier studied variable emissivity thermal control coatings for spacecraft radiators using both inorganic and polymeric electrochromic materials. In the “ESTHER” electro-emissive devices (References 44 & 45) they used polyaniline as an electrochromic material to enable the construction of “intelligent” spacecraft radiators. In the conductive state, it is green and may change its color and its conductivity on exposure to a variety of media. Researchers at Dornier showed that a potential as low as 0.2 V could change the emissivity of a conducting polyaniline film by a factor of two. The change could be repeated for up to 1000 cycles without significant degradation.

Most natural polymers (such as rubber and cellulose) and manufactured polymers (such as nylon, Teflon, and other plastics) won't conduct electricity. However, there are also man-made polymers that are able to conduct electricity like metals. Such intrinsically conductive polymers were first prepared by Alan J. Heeger, Alan G. MacDiarmid, and Hideki Shirakawa, who shared the 2000 Nobel Prize in Chemistry. Conductive polymers are formed by modifying a suitable non-conductive polymer by removing electrons via oxidation or by adding electrons via reduction. Polyacetylene and polyaniline (PAN) are such polymers whose conductivity can be modified by application of a small potential that triggers electron movement. As conductivity varies so does the emissivity.

Current research is expanding the base of conductive polymers and design structures which may be available to implement variable emissivity polymeric systems. For example, a team of researchers from UCLA, the University of Florida, Allied Signal and the Rockwell Science Center are working to develop technology for electrochromic, adaptive infrared camouflage (Reference 46). This work involves the investigation of engineered microstructure and a wide variety of low to medium band gap polymers to achieve improved and highly efficient modulation of infrared emissivity applicable to military uniforms and equipment in the field. Materials under investigation include polycarbazole, polypyrrole, polythiophene and PEDOT and its derivatives as well as polyacetylene. Although the focus of their research is camouflage rather than thermal control, its content is clearly highly relevant to the Chameleon Suit.

Further development is required to combine the desired electrochromic performance with the mechanical properties required for the envisioned space suit system. This may include combining the active polymers with appropriate supporting materials. For example, Lee et al. (Reference 47) prepared conducting PAN composite flat sheet membranes by using a porous nylon support and tested them for gas separation.

In summary, recent progress and demonstrated performance to date makes it clear that electrochromic variable emissivity systems adequate for use in the Chameleon Suit can be successfully developed. Current research activity appears likely to yield significant advances which will be directly related to Chameleon Suit requirements. This is a young technology area where rapid progress and change can be reasonably expected. However, none of the present research efforts truly addresses all of the Chameleon Suit needs together. Space thermal control research activities are vehicle oriented and focused on rigid constructs unsuitable for use in a space suit. Research focused on materials and structures with the requisite flexibility are primarily aimed at modulation of emissivity in narrower spectral bands and do not consider suitability for use in space environments. As a consequence, it is probable that directed research activity will be needed to address the specific requirements for this technology in the Chameleon Suit before system development commences. The Phase 2 study should include detailed assessment of this need based on further contact with current researchers to establish the appropriate timing and scope of this research.

Wearable sensing and control systems

The Chameleon Suit concept depends on the local control of characteristics of a flexible garment with appreciable surface area. Control actions are often in response to centrally determined needs and complex interactions of factors. Thus, there is a need for effective communication of data and coordination of control as well as robust integration with minimal overhead. To meet this challenge, the system will draw on emerging capabilities in wearable computers, distributed control and wireless networking as well as the underlying capability provided by conductive polymer advances. Developmental areas in electrical technologies concern control, interfaces, communications, advanced harnessing and sensors.

In general, this is a very active field of research and development. Intense interest in portable and wearable computers for commercial uses and military demand for robust portable data systems as well as aerospace applications are driving numerous academic, industry and government efforts. They are aimed at developing systems, components and enabling technologies to allow the collection, processing, communication and presentation of data to a mobile human. In these efforts, in addition to capitalizing on the rapid development of increasingly powerful processors in smaller and less power hungry packages, there is a general recognition that mobile human applications can be well served by an architecture that distributes electronic systems

The many significant initiatives in the field include an “E-textiles” program at the DARPA Information Technology Office (Reference 50). This broad based effort seeks to address the underlying technologies for extremely flexible and robust portable electronic systems from the perspective of basic materials and devices and at the level of architecture and integration concepts. Significant goals include smart uniforms for soldiers to provide multiple monitoring and support functions. Clearly this application shares many requirements with the Chameleon Suit, and progress at DARPA will be of direct benefit.

Commercial activities are already marketing or preparing to market a variety of “smart” garments including t-shirts deigned to monitor vital signs and garments that can communicate with washing machines to provide care instructions (Reference 51). Cloth keyboards and keypads have been produced using embroidered patterns of conductive yarn and applied as wearable control interfaces for music synthesizers (Reference 52). In these and other applications, considerable progress has been made in the integration of conventional microelectronic elements with flexible circuitry integrated with wearable garments.

These and numerous similar developments, together with the rapid emergence of new functional polymeric materials are expected to provide a strong technology base for the development of the Chameleon Suit. Because of the breadth of the activity, the pace of change, and the demonstrated ability for the electronic technologies to generate new and largely unanticipated markets, it would be presumptuous to predict at this point where there may be needs for the Chameleon Suit that will not be satisfied by the technology base driven by commercial market opportunities. This should be assessed as the concept is further developed and both the concept’s technology needs and available technology base are better understood.

Potential Benefits to NASA Missions

Benefits estimation methodology

The benefits of the Chameleon Suit in enabling future NASA missions result from the concepts impact on the operation of the EVA system itself and from the reduction of mission consumables and resupply requirements. Some of the benefits are readily quantified, direct reduction in on-back weight, reduced material resupply mass, etc. Others are more difficult to assess since they depend so strongly on other aspects of system evolution and on over-all mission parameters that are not yet defined. We have attempted to look at these benefits in both a concrete quantitative sense and in a broader qualitative context.

Quantitative estimates of benefits are based on the best current estimates for characteristics of the Chameleon Suit design implementation in comparison to existing technology EVA systems. These were evaluated parametrically over a range of mission variables reflecting human missions presently under study by NASA as derived from the HEDS strategic plan, from mission study documents, and from direct contacts with NASA personnel as described earlier in the report. Comparisons are made in physical units – on-back weight reductions and consumables weight savings since these can be directly related to the Chameleon Suit concept. However, the more significant impacts, launch weight reductions, cost savings, etc. have not been estimated since they will depend on the characteristics of larger systems which must be assumed to have changed dramatically from current conditions when the Chameleon Suit is operational.

Estimated quantitative benefits

The Chameleon Suit concept addressed in this Phase 1 study offers the potential to significantly change the nature of EVA and its impacts on future NASA missions. By creating an architecture in which it is possible to reject metabolic waste heat without the use of expendables, the Chameleon Suit liberates future EVA astronauts and NASA mission planners from one of the significant impediments to accomplishing challenging missions with present EVA concepts. This may be exploited in many ways, but the most direct and easiest to estimate are the reduction of the on back weight carried by the EVA astronaut, and the reduction of the weight of mission consumables.

Carry weight for the EVA astronaut is reduced as a result of the elimination of the water presently used for heat rejection in the sublimator and of the equipment required for its storage, management and use. These gains are partially offset by added weight in the pressure suit for the new functional elements required to implement the Chameleon Suit concept. The net gain is illustrated in Table V which summarizes system changes associated with the Chameleon Suit and their estimated weight impact. In the table, the current technology weights reflect present operational systems, Chameleon Suit values are preliminary estimates based on the design concepts and parameters evolved in this study. The potential for appreciable weight savings of over 3 kg is shown. The impact on the mass of the life support backpack is much larger, ~8 kg, but is partially offset by the anticipated increase in weight in the pressure garment due to the incorporation of the Chameleon Suit active elements. This shift in mass may prove highly beneficial since it will result in locating its center of gravity approximately at that of the human occupant of the suit, a more favorable location than the current backpack location behind the body.

Table V. Chameleon Suit comparison to affected current technology EVA system elements.

System Element	Current Technology		Chameleon Suit	
	Description	Mass (kg)	Description	Mass (kg)
Evaporative Water	~3.25 Kg/EVA	3.3	None required	0.0
Water storage	Water tank (estimated weight impact – integrated structural functions)	1.9	None required	0.0
Plumbing, Valves and Controls	Lines, manifold mass, regulating valves, flow control valves, etc.	1.0	Simple single loop to cooling vest and backpack	0.1
Sublimator	Three fluid, evaporative heat exchanger with metal porous plate	2.2	Non required	0.0
Pump	Pump and water separator integrated with vent fan	0.4	No separator, reduced pump flow and head	0.2
LCVG	Full body, full heat load, woven tubing	1.7	Upper torso only, partial heat load	0.3
Battery weight	For pump and separator power (estimated from combined total)	0.3	For lower power pump + actuator and electrochromic power	2.0
TMG	Outer (Beta cloth) layer + 5 – 7 layers aluminized Mylar with scrim	2.8	Similar Protective outer layer + 5 active insulation layers (see Table VI for weight estimate detail)	7.8
Total		13.6		10.4

The basis for the estimates of the Chameleon Suit pressure garment elements is shown in Table VI. These values are subject to considerable uncertainty since they represent a design implementation for technologies in such an early stage of development. Since the number of layers and base materials are essentially the same as in the current TMG, there appears to be a significant opportunity to reduce these estimates as the technology matures. Improvements in performance of the active layers which allow decreased thickness will result in large savings. Similarly, the present estimate of a 2 kg battery mass penalty to drive the active polymer actuators and electrochromic surfaces could prove to be conservative. It is noteworthy that the thermally conductive felt layers incorporated into the suit to minimize contact resistance between suit layers are estimated to comprise nearly half of the pressure suit weight growth. Research into the potential improvement of this technology and careful attention to its detailed design implementation for this application could have a sizable pay off

Table VI. Chameleon Suit Weight Estimate

Layer	Area 3 sq.m.		Cycles 150 avg		Time Powered 4 hr			
	Mat'l basis	**S.G.**	**No. Layers**	**Thickness mm**	**Pwr/cycle w-sec**	**Pwr/Time watts**	**Mass grams**	**Energy w-hr**
Outer cover	beta cloth	1.19	1	0.56	0	0	1999.2	0
actuators	nafion	1.5	5	0.01	0	15	225	300
felt	graphite	0.15	5	1	0	0	2250	0
inert support	mylar	1.3	6	0.03	0	0	702	0
conductor	pa	1.15	15	0.02	0	0	1035	0
insulator	mylar	1.3	6	0.02	0	0	468	0
reflective layer	Al	3	5	0.001	0	0	45	0
Electrochromic 1	pa	1.15	5	0.02	5	0	345	1.041667
Electrolyte	pa	1.15	5	0.02	0	0	345	0
Electrochromic 2	pa	1.15	5	0.02	5	0	345	1.041667
Total							7759.2	
Battery Weight Impact							2000	

Note: Actuator thickness 0.2mm with 5% area coverage

The reductions in the weight of mission consumables through the use of this system are a direct function of the number and duration of the EVA's performed during a mission. As discussed previously, this varies widely among the missions that will be performed by NASA during the NIAC target time frame. Lagrange point missions involving relatively few EVA's form one extreme while contemplated missions for Mars exploration involving 500 or more represent the other. In addition to the consumable water saved, the reduction in the weight of the EVA system itself also provides a savings in the weight that must be launched. These two factors were used parametrically to estimate savings in the weight that must be delivered to the mission destination if the Chameleon Suit is used in place of current technology systems. The results are shown in Figure 39. For long duration EVA intensive missions the mass that must be launched can be reduced by several thousand kilograms. In terms of science payload that could replace this consumable mass, this can have an enormous impact on the productivity of such a mission.

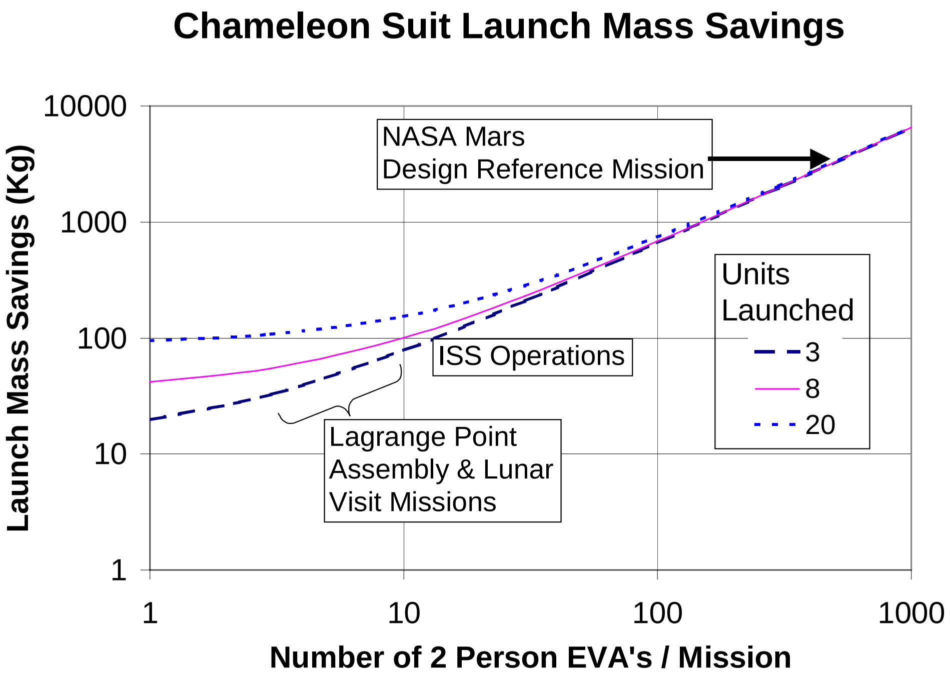

Figure 36. The Chameleon Suit concept offers consumables launch mass reductions for all of the missions studied especially for EVA intensive 1000 day class missions.

The mass shown on the figure is the direct mass of consumable materials and EVA equipment delivered to the mission destination and does not include any of the multiplying factors that will apply to account for packaging, vehicle weight impacts, propellant, etc. in any real mission. These penalties are typically large, but are specific to the mission design and must be expected to change significantly from present values for missions flown in the NIAC target time frame. Still, it can be seen that the when they are considered, the Chameleon Suit concept as studied during Phase 1 may prove to be not only significant, but enabling for EVA intensive missions. As discussed previously under “Potential Concept Growth”, more complete implementation of the Chameleon Suit architecture integrating more life support functionality could have even more significant effects.

Other considerations

Other significant effects of the Chameleon Suit concept include impact on vehicle and habitat systems, system reliability benefits, operational benefits, and benefits for crew safety. These are more difficult to quantify or extremely sensitive to specific mission context, but worthy of discussion.

The elimination of water as an evaporative heat sink for EVA cooling in the Chameleon Suit allows simplification of vehicle and habitat EVA support systems. Systems that presently provide for routine cooling water recharge and allow for water dump from the EMU water tanks will no longer be required. In addition, at the low activity levels typical of EVA preparation and pre-breathe (if any is still needed for some missions), the Chameleon Suit should provide ample crew cooling in the airlock by rejecting heat to ambient eliminating the need for EVA support heat exchangers. Finally, elimination of the sublimator removes a special water quality requirement resulting from the sublimate's known sensitivity to contaminants in the evaporative feed water. This can simplify the development of flight water processing and handling systems or eliminate the need for separate dedicated supplies for EVA use.

The EVA life support system and EVA support systems in the host vehicle or habitat can be significantly simplified with the Chameleon Suit architecture. The elimination of the sublimator, water storage tanks, and associated valves and plumbing eliminates many system failures. The net result is less certain. The reliability of the new technology elements used for the Chameleon Suit active control functions has not been determined. However, the concept incorporates a robust architecture embodying distributed systems and control and a high degree of inherent parallelism. Also, by analogy to integrated circuits which are conceptually similar in may respects, it seems likely that a high level of reliability will ultimately be achieved yielding a substantial net gain in total reliability.

Operationally, the Chameleon Suit eliminates reliance on one of the major consumable resources that currently limit the duration of EVA missions. This will give NASA's mission planners greater flexibility in planning EVA's for future exploration missions and especially in contingency management. The elimination of water as a consumable heat sink eliminates one barrier to extending EVA beyond the nominal endurance limits in the event of emergencies. Such a need has been considered in previous studies of EVA for Mars exploration missions and addressed by a preliminary requirement for a contingency "camp-out" capability (Reference 47). With the Chameleon Suit, extended thermal control endurance can be provided with only a battery swap out or supplementary power connection. There is no need for water recharge provisions or supplementary cooling loop support on an EVA support rover to meet this need. This represents a significant simplification and mission cost savings as well as an opportunity to increase science support capability on the rover. Operational benefits are also evident in comparison to earlier concepts for no-expendables thermal control. Because it provides increased heat rejection capability, the Chameleon Suit eliminates most metabolic profile restrictions implicit in those concepts. Because it provides actively controlled heat transfer from all surfaces of the spacesuit system, it avoids restrictions on work site and orientation based on maintaining favorable radiator orientation.

The Chameleon Suit also provides increased crew protection against two of the hazards of working and exploring in space. By distributing mass for heat transfer (and possibly other life support processes) over the surface of the suit, it increases the level of shielding between the crew person and incident micrometeoroids and orbital debris (MMOD) and radiation. Both have been a matter of concern from the outset of the space program, and are cumulative hazards such that the risks increase as more EVA is performed to accomplish challenging future missions. While MMOD hazards are relatively large in near earth orbit (Reference mmm.), radiation hazards grow as we venture outside the earth's protective magnetic filed and have been cited as limiting factors for Mars exploration missions. As indicated in one recent study of advanced satellite thermal control concepts (Reference 48), the incorporation of electrochromic devices in the pressure garment as well as the general increase in the shielding mass around the astronaut may help to reduce EVA radiation exposures and contribute to the solution of this problem.

Finally, it should be noted that the results of our study continue to support the applicability of the Chameleon Suit concept to systems other than EVA pressure suit systems. We have discovered nothing that diminishes the potential benefits of applying the same thermal control architecture to unmanned or manned vehicles, satellites, landers etc. to provide enhanced temperature regulation and to eliminate or reduce the need for dedicated thermal control systems. In addition, the broader implementation of the concept to encompass additional life support processes

Conclusions

Based on the results of our study, we conclude that the Chameleon Suit concept represents a viable architecture for future EVA systems that can be of significant value for future NASA missions. Specifically, we have found:

- The concept is feasible and can provide rejection of metabolic waste heat under most EVA scenarios without the use of consumable heat sink materials.
- Adjustments to the concept as originally proposed are required to increase the surface area available for heat rejection, to enhance the maximum heat transfer between the suit layers, and to allow effective heat rejection near large heated surfaces. These adjustments are also feasible.
- Implementation of the Chameleon Suit thermal control concepts we have studied could save future EVA intensive exploration missions several thousand kilograms of consumable supplies for EVA support, reduce system on-back weight, and enhance safety and operational flexibility.
- Required technologies are under development for many other applications and can be expected to advance significantly even in he absence of NASA research directed toward this concept.
- The Chameleon Suit places unique demands on each of these technologies that will make directed NASA research necessary before the design and development of an integrated system can be accomplished.
- The concept can be generalized to encompass many other and potentially all EVA life support functions as well as important aspects of the pressure suit mobility design. This broader implementation could totally change the nature of EVA systems and enable much more ambitious NASA missions.

Based on these results, we believe that further study should be pursued with an emphasis on the broader implementation and implications of the concept.

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