Thermal Modeling of Mechanical Counterpressure Spacesuit EVA

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Mechanical counterpressure (MCP) spacesuits offer several theoretical advantages over traditional gas-pressurized suits including lower energy cost of transport, reduced risk of decompression due to suit tear or puncture, and increased astronaut comfort. They may also simplify thermoregulation by allowing perspiration to evaporate and cool an astronaut, eliminating the need for a Liquid Cooling and Ventilation Garment (LCVG) and other life support system hardware currently used in NASA's Extravehicular Mobility Unit (EMU) suit. The BioSuit™ is an MCP concept being developed at MIT primarily for planetary extravehicular activity (EVA) on the Moon and Mars. In this paper we simulate the thermoregulation system of the BioSuit™ to assess the feasibility of relying on perspiration to provide cooling. Thermal modeling of EVA on lunar and Martian surfaces was conducted to assess the performance of MCP spacesuit garments in protecting astronauts from the extreme temperatures and harsh radiation environments of those locations. This modeling included new proposed radiation protection and insulating materials as well as a passive elastic compressive layer. Results were computed for both male and female astronauts, helping to identify suit design differences that will be needed to accommodate both men and women who will conduct future EVAs. This work is used to inform future design requirements for the suit's thermal management system. Overall, this research advances the development of life support systems for a full MCP spacesuit and lessons learned can be applied for future engineering prototypes.

Nomenclature

MCP = Mechanical Counterpressure
PLSS = Portable Life Support System
EVA = Extravehicular Activity
SAS = Space Activity Suit
xEMU = Exploration Extravehicular Mobility Unit
LCVG = Liquid Cooling and Ventilation Garment
BNNT = Boron Nitrite Nanotube
TMG = Thermal Micrometeoroid Garment
SMP = Shape Memory Polymer

I. Introduction

The MIT BioSuit™ is a mechanical counterpressure (MCP) spacesuit concept that has been in development since the early 2000s. MCP is an alternative method of providing pressurization to traditional gas pressurized suits. In an MCP suit, tight fitting elastic garments provide direct contact pressure on the human skin. It is thought that this approach could improve astronaut mobility during extravehicular activities (EVAs), eliminate the risk of small tear and puncture-associated depressurization, simplify thermoregulation for the astronaut inside, and reduce overall suit and life support mass[1]. The idea has been explored since the 1950s, most prominently in Webb and Annis's Space Activity Suit (SAS), a NASA Langley funded project in the late 1960s and early 1970s[2]. More recently, research has been ongoing at the MIT Human Systems Lab since 2001 on a suit architecture led by Professor Dava Newman called the BioSuit™.

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The BioSuit^{TM} system aims to use patterning along the lines of non-extension to apply constrictive force without inhibiting movement and active shape memory polymers to ease donning and doffing. The lines of non-extension first investigated by Arthur Iberall in the 1964 allow non-elastic pressure application without inhibiting mobility by taking advantage of contours on the skin that rotate but do not deform or stretch during joint movement[1,3]. This would theoretically alleviate some of the problems of the SAS which used only elastic layers to provide pressure and was very difficult to don and doff. Recent work has shown that shape memory polymers may be able to actuate and relax along these lines to tension the suit after it is donned[4].

Figure 1. Conceptual rendering of a BioSuit^{TM} PLSS. *Next generation MCP suits could include a modular portable life support system backpack with reduced mass and improved ergonomics. Image from Ref. 5*

Little research has been dedicated to investigating the life support system for a BioSuit^{TM}. Kracik et al. developed concepts for a conformal helmet and modular PLSS with components that could easily be replaced and consumables that could be swapped out during EVA[5]. One of these renderings is shown in Figure 1. Kracik envisioned a conformal helmet to provide a more natural feel and more freedom of movement, but one of the biggest challenges is creating a sufficient pressure seal with the rest of the suit. Kracik sketched out a design with a rubber neck seal inspired by diving dry suits that lay underneath a helmet locking ring and provided an airflow connection to a torso breathing bladder. The helmet mounting ring had a joint that swung open during donning and doffing because it was too small to fit directly over the head.

The aim of this paper is to advance and refine these concepts of a life support system for the BioSuit^{TM}, specifically the thermoregulation system. Thermal modeling of an astronaut wearing different combinations of potential MCP suit materials during a lunar and Martian EVA was conducted to help define thermal regulation needs and requirements for the BioSuit^{TM}.

II. Evaporative Cooling in a Mechanical Counterpressure Suit

A mechanical counterpressure suit may simplify the process of thermoregulation during EVA by eliminating the need for a Liquid Cooling and Ventilation Garment (LCVG). Instead of using water pumped through rubber tubing to draw latent heat away from the astronaut's skin, the astronaut may be able to sweat directly through the layers of the suit similarly to how one may sweat through moisture-wicking athletic apparel worn on Earth. It is possible that this would reduce the amount of life support system mass needed to support an EVA, perhaps even on the order of 30%[6].

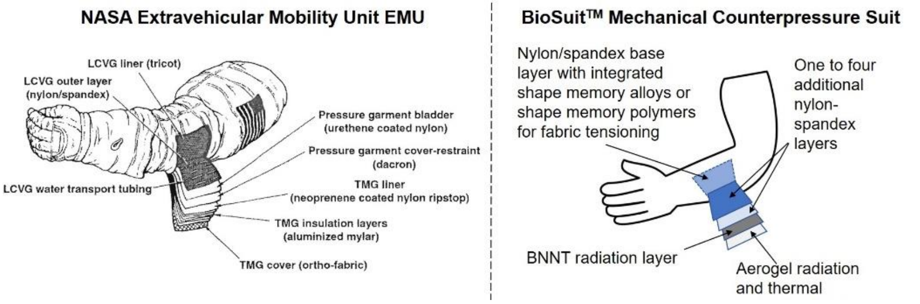

Figure 2. Spacesuit layering comparison. *A layering comparison of the EMU (left) and a possible BioSuit^{TM} layup (right). The MCP garment may require multiple nylon/spandex layers for incremental pressure application. Note that the MCP suit does include the Liquid Cooling and Ventilation Garment (LCVG) which is the primary cooling mechanism in current spacesuits. The reduction in the number and density of suit layers in an MCP suit offers potential mass savings.*

Figure 2 shows the difference in garment layering between the EMU and a potential BioSuit^{TM}. The BioSuit^{TM} could consist of many fewer layers, reducing the mass of the suit. The current EMU relies on a Liquid Cooling and Ventilation Garment to circulate cool water around the astronaut to draw heat away from the body. Additional ventilation tubes draw warm, moist air from the extremities for dehumidification, adding bulk to the suit. A feedwater circuit in the PLSS backpack freezes and evaporates water into space, removing heat from the water in the cooling line[7]. This method of cooling, using a sublimator, has a long flight history.

However, a single eight-hour ISS EVA burns through about 3.6 kilograms of water (approximately 1 gallon), making water the single largest EVA expendable by mass[8]. For long missions to Mars lasting around 575 surface days, water consumed during EVAs could amount to 2,500 kg, or over 30% of the total ECLSS mass[9]. An MCP suit could circumvent the need for an LCVG and sublimator by allowing perspiration to evaporate directly into the surrounding atmosphere. Two types of water loss would occur: loss through passive skin diffusion and active perspiration.

Suit System	Number of Layers	Cooling System	Cooling Hardware Mass	Water Loss
EMU	14	LCVG and Sublimator	5.5 kg	3.6 kg per 8-hour EVA
SAS	8-10	Evaporative Perspiration	0 kg	7-9 kg per 8-hour EVA
BioSuit^{TM}	3-10	Evaporative Perspiration and Radiators	Unknown	~1.4-2 kg per 8-hour EVA

Table 1. Comparison of metabolic cooling systems for the EMU, SAS and BioSuit^{TM}. *The cooling hardware mass for the EMU refers to the wet LCVG (3.9 kg) and the sublimator (1.6 kg)[7]. Water loss rates for the SAS are projected based on small sample testing data and based on the simulation results presented in this chapter for the BioSuit^{TM}*

This idea was described in Webb and Annis's report on the Space Activity Suit. They predicted an astronaut would lose approximately 360 mL of water through skin diffusion to a vacuum over the course of a 4-hour EVA (50 $g/m^2/hr$ for 1.8 m^2 of body surface area). Based on prior physiological experiments, they noted that total sustained water loss rates should not exceed 2 liters per hour, but peak sweating rates of up to 4 liters per hour can be tolerated for short periods[2]. For each gram of water evaporated, 2.4 kilojoules of heat are removed. At a nominal water discussion rate of 100 g/hr for human skin in a vacuum, 67 watts of heat will be removed, about half of resting metabolic heat. This is before sweating and conductive cooling are even introduced. At a sweat rate of 2 liters per hour, the body rejects heat through evaporation at a rate of 1350 watts, well above requirements. Vacuum or near vacuum environmental pressures would cause moisture to instantly vaporize, preventing sweat or ice buildup on the suit surface. Physiological feedback and vasoconstriction would prevent overcooling[2]. The evaporative resistance of the clothing layers adds another variable to actual water loss rates. It is important to note that all of this analysis is theoretical and would need to be verified in human testing. During actual SAS human testing, water loss rates of 97 to 185 grams (0.097 to 0.185 liters) per hour were recorded, with higher rates experienced during low pressure altitude chamber testing. These data points suggest total water loss during an 8-hour EVA in near vacuum could amount to between 7 and 9 liters, necessitating the need for a reserve of drinking water in the suit. However, the data gathered was small in sample size, inconsistent between tests and therefore not likely reliable[6]. A summary of these parameters can be found in Table 1.

It is also worth noting that the extreme radiation environments of space would still necessitate the need for a thermal micrometeoroid garment (TMG) to prevent the temperature of the MCP suit outer layer (and by extension the skin) from reaching extreme hot or cold values. The TMG would also offer protection from dust on the Moon and Mars[6]. Discussion on sweating in an MCP suit has emerged in other suit proposals as well. Hodgson included water transport in several of his Chameleon Suit Architectures, noting the potential to remove a significant amount of PLSS mass. He also noted it may be possible to vary the evaporative resistance of clothing layers to adapt to different thermal environments[10].

III. EVA Thermal Modeling

Historically, whole body human thermal modeling for space applications has been done using computer programs developed by Wissler, Hardy and Stolwijk in the late 1960s and early 1970s[11,12,13]. During the Apollo program, NASA relied primarily on the 41-node METMAN model developed by Kuznetz[11,14]. For the Shuttle and ISS EMU, NASA relied on an improved Wissler model with 225 nodes. In thermal modeling, the number of nodes represents the number of point solutions calculated and can be representative of model complexity. Incremental improvements for the last 40 years produced updated whole human models by Wissler and Fiala[11,13,15]. These models consisted of cylindrical elements representing body segments and considered countercurrent heat transfer between blood flows. Despite the history and volume of research built into these models, they still are run with Fortran code, a programming language not as commonly used today.

For the work in this thesis, a modern industry software called TAITherm$^{\text{TM}}$ developed by ThermoAnalytics, Inc. (Calumet, MI) was used[16]. The goal was to evaluate the feasibility of using perspiration for thermoregulation in an MCP spacesuit by running several simulations of EVA in lunar and Martian environments with different garment configurations in the Human Modeling extension of TAITherm$^{\text{TM}}$. TAITherm$^{\text{TM}}$ incorporates both the Fiala and Wissler model into its structure but provides a robust user interface with visualizations. This work built upon previous modeling completed by Vadhavkar, also using TAITherm$^{\text{TM}}$. Vadhavkar simulated human heat loads during a four-hour Martian EVA for an astronaut wearing a simulated clothing layer and found that evaporative cooling can keep an astronaut comfortable up until the very end of the EVA[17]. This project aimed to refine and expand upon the modeling performed by Vadhavkar. An updated metabolic activity profile was simulated in the environmental conditions of both a Martian and lunar EVA.

TAITherm$^{\text{TM}}$ has a robust built-in human model consisting of 28 body parts, each of which has 16 distinct layers of bone, fat, muscle and skin tissue with unique thermal properties. The body parts include limb segments, and subsections of the head, torso and pelvis. The program's inputs include human geometry; thermal, optical and evaporative properties of clothing; air temperature, wind speed, relative humidity, solar irradiation, activity level, and activity type. Clothing is added as additional layers on top of the human. Figure 3 shows a schematic of all the thermal processes included in TAITherm$^{\text{TM}}$'s human model. TAITherm$^{\text{TM}}$ outputs the time varying temperature of each layer of the model as well as a comfort metric for each segment of the model based on a formula developed at the University of California Berkeley (referred to as the "Berkeley Comfort Model"). This model is based on literature as well as human subject testing and uses skin temperature, temperature rate of change, mean skin temperature, and core temperature rate of change to assess overall comfort[18].

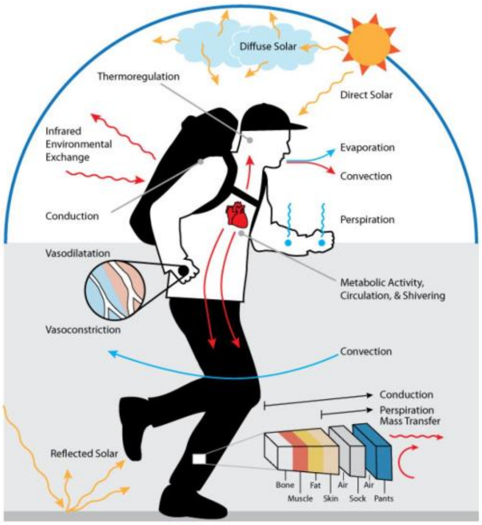

Figure 3. An overview of all of the natural processes and elements included in the TAITherm$^{\text{TM}}$ Human Modeling program[16].

In total, the model built for this analysis consists of 5636 individual thermal elements used in the thermal finite element solver. The time step was set at 2 minutes, and the physiological results were saved at each time step. This small time step allowed for high resolution of thermal changes and helped the model converge on a solution with fewer errors.

IV. Using TAITherm$^{\text{TM}}$

A. Human Model

The astronauts modeled are a 50th percentile male and a 50th percentile female. As described in the previous section, the human model consists of 16 layers of bone, muscle, fat and skin. Sweating and vasoconstriction were enabled in the model. The metabolic profile used is the standard profile used by NASA for qualifying elements, of the PLSS for the next generation xEMU. It includes 20% margins on the high and low heat outputs expected during xEMU EVA[19]. A graph showing the activity level over the course of an 8-hour EVA is shown in Figure 4. The activity profile used in this model was the first 240 minutes (4 hours) of the NASA model. This was done to both limit computation times and because the entire range of human metabolic potential is encapsulated in the first half of the profile.

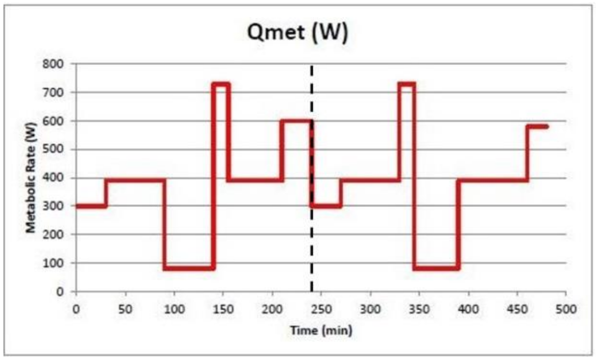

Figure 4. EVA Metabolic Profile. *Human heat production profile used by NASA to define operational requirements for the next generation PLSS system[19]. The dashed line at 240 minutes indicates the ending point of the portion of this profile used in this simulation (0-240 minutes).*

B. Spacesuit Model

Suit garments are added to the model as layers applied on selected surfaces with assigned material properties including thickness (mm), density (kg/m^3), lateral conductivity (W/m-K), specific heat (J/kg-K), whole body evaporative resistance (m^2-kPa/W), surface area augmentation (factor of surface area change from garment compared to bare skin) and whole body thermal resistance, also called thermal insulance (m^2-K/W). Three different clothing layups were simulated: a single nylon-spandex skinsuit layer, a skinsuit base layer with a Boron Nitrite Nanotube (BNNT) infused jacket for radiation shielding, and the skinsuit with the BNNT and an Aerogel fabric layer for radiation and thermal protection. Boots were also worn in all simulations. The nylon-spandex skinsuit layer was based on prior research done by Holschuh and Kothakonda[22,23,4] [70, 71, 37] as well as the material layers used in the Space Activity Suit. Webb and Annis used between 8 and 10 layers of fabrics named "bobbinet" and "powernet". The bobbinet fabric was composed of cotton wrapped spandex fiber cores interlaced with nylon. The powernet fabric was composed of 75% nylon and 25% spandex[2]. Holschuh and tested a variety of MCP tourniquets using shape memory alloy coils to provide active tension to fabric samples. He found the best performing passive material for MCP among those tested was a fabric called "jumbo spandex". This material was composed of 0.7 mm thick layers of 90% nylon and 10% spandex. Holschuh recommended the skinsuit portion of a BioSuit^{TM} be less than 5 mm in total thickness. Therefore, he recommended between 3 and 7 layers of jumbo spandex for the best performance[23]. Kothakonda is currently developing a single layer design with shape memory polymer (SMP) actuators to tension an inelastic fabric across the skin[4].

Table 2. MCP Suit Thermal Modeling Material Properties. *Material property values used for different suit layers in TAIThermTM Modeling[20,21].*

Material	Layer Thickness	Whole Body Thermal Resistance	Whole Body Evaporative Resistance	Density	Specific Heat
Nylon-Spandex	4.2 mm	0.1 m^2-K/W	0.01 m^2-kPa/W	1150.0 kg/m^3	1600 J/kg-K
BNNT	2.0 mm	0.25 m^2-K/W	0.05 m^2-K/W	8000.0 kg/m^3	3500 J/kg-K
Aerogel	1.5 mm	0.5 m^2-K/W	0.01 m^2-K/W	900.0 kg/m^3	0.002 J/kg-K
Boots	5.0 mm	0.22 m^2-K/W	0.08 m^2-K/W	1500.0 kg/m^3	1600 J/kg-K

In general, the bulk thermal properties of the pressure layer will be dominated by the nylon-spandex fabric, even if there are embedded SMP actuators. Initial versions of the next MCP suit will likely require multiple pressure layers to achieve the required compression, but a single layer is the ultimate goal. Therefore, in this simulation, a single nylon-spandex layer 4.2 mm in thickness was added. A quick modeling comparison in TAITherm^{TM} was conducted to justify this decision. Martian EVA simulations were run with a nylon-spandex base layer of 4.2 mm in total thickness split into three layers, two layers, and a single layer. Core body temperature was not affected and mean skin temperatures varied by only 0.5°C after 4 hours, therefore the decision to use only a single layer was made. However, future simulations should include a multilayer analysis as this configuration is likely to be tested before a single layer suit can be realized. A sensitivity analysis of different fabric properties should also be conducted.

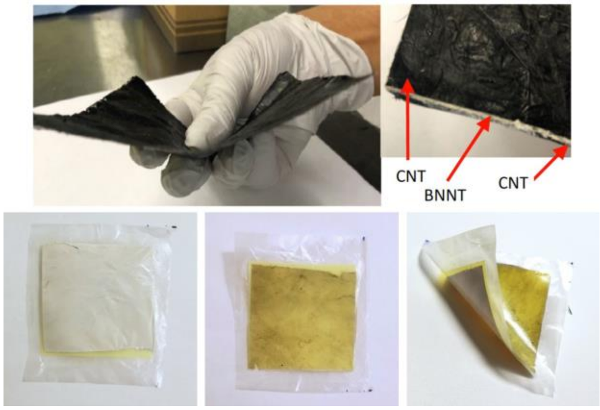

Figure 5. BNNT and Aerogel. *Test coupons of Boron Nitrite Nanutube (BNNT) and Aerogel radiation and thermal protection materials. On top is a BNNT sheet covered on both sides by a carbon nanotube (CNT) casing (for structural strength). On bottom is a combined BNNT Aerogel coupon encapsulated in polyethylene (a plastic with additional radiation shielding properties). The white side is the BNNT while the pale yellow side is the Aerogel. As evidenced by the image at bottom right, the product is flexible, meaning it could be incorporated into a suit garment[21].*

Thermal results are very similar, and a single layer decreases the computational time TAITherm^{TM} needed to run simulations. The BNNT and Aerogel materials are the subject of current research for their potentially beneficial protective properties[21]. Figure 5 shows several test coupons of these materials that have been manufactured previously and may eventually be incorporated into protection garments. Radiative emissivity coefficients were set at 0.9, slightly less than the value of 0.98 for human skin but comparable with many white coatings used to aid in heat rejection in space applications[24]. The material properties of the three garment types are summarized in Table 2.

C. Weather Model

TAITherm™ can simulate a complex weather environment if a user uploads the requisite data in the proper file format. Weather models in the program are meant for Earth conditions, but by changing the temperature, pressure, humidity, and radiation values, it is possible to model the surface of Mars or the Moon. Table 3 shows a high-level comparison of the weather conditions modeled for each planetary body.

Moon Weather

The lunar weather model was developed based on the expected average environmental conditions at the lunar South Pole, specifically Shackleton Crater, located at 89.8°S, 0.0°E. A South Pole landing site is specifically referenced in NASA's Plan for Sustained Lunar Exploration and Development[25]. This is a significant departure from Apollo program landing sites, all of which were located at near-equatorial latitudes. The Apollo EVAs were timed to occur during lunar mornings[26]. Astronauts avoided the high Sun elevation angles and the full heat of solar noon where surface temperatures can reach 400 K (127 °C) and the cold of lunar night when temperatures can fall to 100 K (-173°C)[27]. This was acceptable for short duration missions but a challenge for a permanent lunar base.

At polar latitudes, there is near constant sunlight for solar power production, relatively consistent surface temperatures, continuous direct to Earth communications capabilities, and potential access to water ice permanently frozen in shadowed craters[28]. These factors make the lunar south pole an intended target for future human landings. The average illuminated surface temperature of the Moon in polar regions is about 200 K (-73°C)[27]. Direct solar irradiance on the Moon is approximately1368 W/m^2. Diffuse radiation is calculated as only 2 W/m^2 using a lunar albedo (α) value of 0.08 and a solar zenith angle of 89.8°. The infrared heat flux from the lunar surface is about 5.2 W/m^2 at the south pole[29]. Because of the Moon's slow rotation rate and the extreme latitude, these values were held constant throughout the duration of the EVA. The direct radiation is the same as during Apollo EVAs, but the diffuse component is much less, creating slightly more hospitable conditions.

Table 3. Planetary EVA Weather Comparison. *A comparison of the average weather characteristics between the Moon and Mars used in the thermal modeling simulations. Average conditions for direct overhead sunlight at sea level on Earth are also included for reference.*

	Average Temperature	Atmospheric Pressure	Relative Humidity	Solar Irradiance	Diffuse Solar Component	Solar Position
Moon	-73 °C	0.0 kPa	0.0 %	1368 W/m^2	5.2 W/m^2	0.3° alt. 45.0° az.
Mars	-15 °C	0.65 kPa	0.01 %	504 W/m^2	98 W/m^2	86.0° alt. 10.0° az.
Earth	14 °C	101.3 kPa	20-100%	1000 W/m^2	1000 W/m^2	90.0° alt. 0.0° az.

Mars Weather

The Martian weather model was adopted from prior work by Vadhavkar, simulating a hot summer day in the southern hemisphere (-25°S) based on data from the Mars Global Surveyor and several Mars landers[17]. Temperatures range between -23°C and -6°C and atmospheric pressure is only 0.65 kPa. Solar irradiance values increase as the Sun reaches a higher elevation in the sky. This weather pattern is meant to simulate a "hot" EVA scenario during summer in the southern hemisphere. The latitude was chosen to maximize insolation, with 25 degrees corresponding to the axial tilt of Mars[17]. These conditions were chosen to simulate conditions that might be expected at a future Mars station built at a location with a climate warmer (and therefore more hospitable) than the Martian average.

V. Results

As discussed in the sections above, three separate simulations were run for each planetary environment: one with the astronaut wearing only a nylon skinsuit, one with a BNNT jacket on top of the skinsuit, and one with a skinsuit, an Aerogel insulation layer and a BNNT jacket. These test cases were run first with a male manikin and then a female manikin. The results recorded and analyzed included the time-varying skin surface temperature and corresponding thermal comfort sensation provided by the Berkeley Comfort Model. These results are also visualized on the human model. Area averaged skin temperature and body core temperature were also recorded, as well as the sweat rate in grams per minute and the amount of time spend in any state of shivering.

In normal conditions, the temperature of the human skin is between 33.5°C and 36.9°C[30]. The body's core temperature is between 36.5°C and 37.5°C[31]. Hypothermia occurs when the body's core temperature falls below 35°C[32], while hyperthermia occurs when the body's core temperature exceeds 38.3°C[33]. These are the values used to assess safe conditions. These values are summarized in Table 4.

Thermal State	Temperature Range
Healthy	Core: 36.5°-37.5°C Skin: 33.5°-36.9°C
Hyperthermia	Core: >38.3°C
Hypothermia	Core: <35°C
Cold Numbness	Skin: 20°-28°C
Cold Pain	Skin: 10°-20°C

Table 4. Summary of human thermal states. *Core and skin temperature ranges for a variety of thermal states. The goal is to maintain astronaut core and skin temperatures in the healthy range*[30,31,32,33,34].

Additionally, heat fluxes were recorded. TAITherm™ records the time varying heat flux from the following sources[16]:• *Qm (Metabolism)*: Total rate of energy generated by the virtual manikin in response to the environment and activity level.

- *Qconv (Convection)*: Rate of heat transfer to the virtual manikin's skin and clothing by air, wind, water or other fluids included as boundary conditions.
- *Qrad (Radiation)*: Rate of heat transfer to the virtual manikin's skin and clothing by infrared radiation exchange with the surrounding environment. It does not include solar loading, which is reported separately.
- *Qsolar: (Solar)*: Rate of heat gained by the virtual manikin's skin and clothing through direct, diffuse and reflected solar radiation.
- *Qevap: (Evaporation)*: Rate of heat transfer occurring through latent heat of vaporization of perspiration.
- *Qresp: (Respiration)*: Rate of heat transfer in the process of breathing. It includes both convective heat transfer and latent heat of vaporization when the breath increases the humidity of the exhaled air.

In the model created, the manikin also wore a pair of boots that was consistent between all tests. An enclosed climate-controlled helmet on the head could not be modeled. It was assumed that a helmet ventilation system (not modeled) would keep the astronaut's head comfortable during any of these EVA scenarios. The head and face were also modeled as being covered with fabric layers to match the rest of the body. If this has not been done, the head would have been extremely cold in all simulations and skewed overall results. However, this means that thermal results specifically for the head should not be the focus of attention. Readers should also refer to the author’s Master’s Thesis, *Design and evaluation of elements of a life support system for mechanical counterpressure spacesuits*, for a full dissemination of these results including the complete set of plots and figures[36].

A. Moon Modeling

The extreme radiation environment of the lunar surface dominated the results of the lunar EVA thermal model. When only the nylon-spandex base layer was worn, body surfaces facing the sun experienced skin temperatures exceeding 60°C while surfaces in shadow dropped to below -40°C. The result is more severe than would be realistically experienced because the astronaut does not move, meaning the sunlit and shaded halves of the body remain constant throughout the EVA. An actual astronaut would constantly be changing their orientation relative to the Sun while conducting EVA tasks, varying the exposure of different surfaces to the Sun. Nevertheless, the thermal load remains unsafely high. The heat loading is most extreme in the case of the astronaut wearing only the nylon skinsuit.

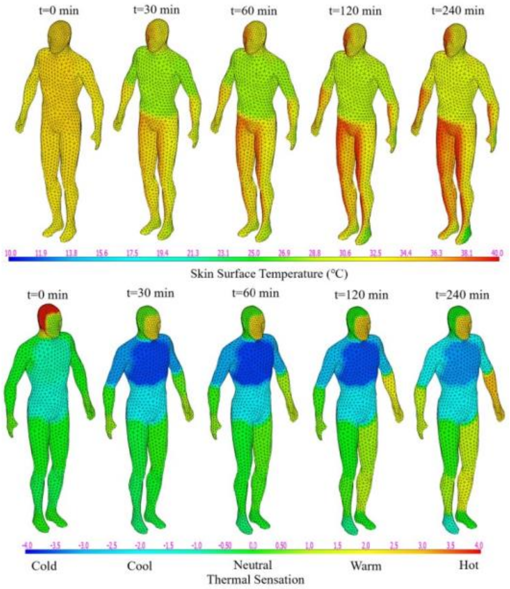

Figure 6. Lunar EVA Skin Temperatures. *Skin surface temperature (top) and Berkeley Comfort thermal sensation (bottom) for a Lunar EVA wearing the full clothing layup. Skin surface temperatures are much more uniform (lower on the hot side and higher on the cold side). However the astronaut still feels slightly chilled throughout the EVA.*

The addition of the BNNT and Aerogel protective layers began to add some shielding effects. Figure 6 shows a time-lapse of the skin surface temperature and the thermal sensation experienced by the astronaut wearing the nylon-spandex base layer, BNNT and Aerogel sampled at 0, 30, 60, 120 and 240 minutes. The astronaut is initialized with clothing temperature of 20°C, representative of a person exiting a habitat kept at a comfortable 20°C temperature. In all tests, the astronaut's core body temperature increases but remains below the point of hyperthermia.

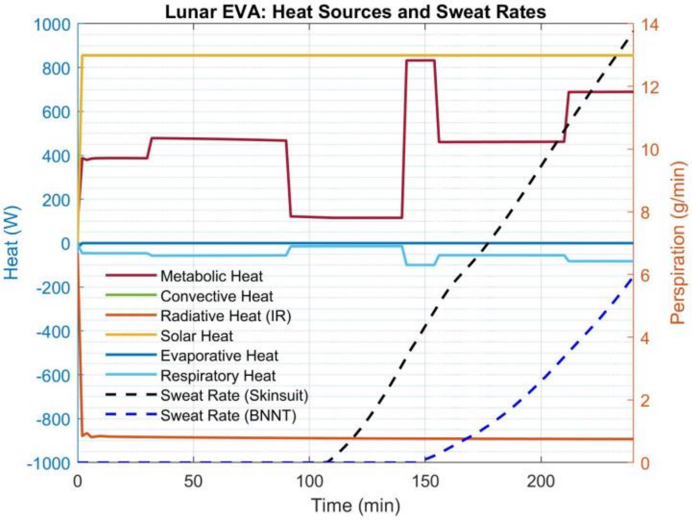

Figure 7. Lunar EVA Heat Sources and Sweat Rates. *Heat fluxes and sweat rate for a Lunar EVA wearing the full garment assembly (nylon skinsuit, BNNT and Aerogel). The manikin begins to sweat after portions of high activity depending on the amount of clothing insulation. Note that convective heat loss is zero because the Moon does not have an atmosphere.*

The addition of the BNNT jacket kept the torso at a lower and more comfortable average temperature. This suggests that its inclusion did not adversely affect the thermal properties of the suit. Skin temperatures remain the closest to normal with the full Aerogel insulation layer. Interestingly, the manikin began sweating to dissipate heat during both the skinsuit and the skinsuit with BNNT tests but did not sweat during the Aerogel clothing test. Even with higher mean skin temperatures, the Berkeley Comfort model also shows that while wearing Aerogel, the astronaut remains slightly cool, especially in the torso for the duration of the EVA. In contrast, while wearing only the skinsuit, the chest becomes extremely hot. This difference is likely caused by the ability of the insulation layer to prevent extreme hot and cold patches from developing on the body and allowing a more uniform temperature and thermal sensation. In the extreme case, once the body is insulated from the intense solar radiation environment, there is very little incoming heat flux and a very low ambient temperature, meaning that the challenge in this situation becomes keeping the astronaut warm.

The heat fluxes and sweat rates for the lunar EVA wearing the full Aerogel suit assembly are shown in Figure 7. This image shows that the two heat inputs are metabolic heat (modeled by the activity profile) and solar heat (modeled by the lunar weather conditions described in the sections above). Heat is dissipated via infrared radiation, atmospheric convection, respiratory exhaust and evaporation from perspiration. There is a delay between the beginning of physical activity and sweating, which is why sweat rates remain zero for the first parts of the EVA. The sweat rate reached a maximum of 14 grams per minute while wearing only the skinsuit, equivalent to 0.84 liters per hour, falling within the safe sweat rate limit of about 2 liters per hour[2]. Total water loss due to perspiration for the four-hour EVA was 0.891 liters. This water loss could easily be compensated by an in-suit drinking bag. Even for a full eight-hour EVA, a total sweated water loss of 2 liters would be less than the approximately 3.6 liters used per EVA on the ISS now[8].

The radiative heat dissipation is very large in this simulation, remaining at about 850 watts. This is certainly too large a value as the program also shows zero evaporative cooling despite a positive sweat rate that increases throughout the EVA. This is likely a program error stemming from the fact that convective heat transfer was set to zero. Radiative heat dissipation would also be limited by available surface area in a real suit. The model does not account for a PLSS backpack or helmet that would reduce the amount of heat emitted. Nevertheless, these results support the hypothesis that evaporative cooling can provide a large portion of the heat rejection needed for a lunar EVA. Though these particular clothing configurations resulted in uncomfortable thermal conditions for the astronaut, they were survivable. It is clear that a full MCP suit for lunar EVA would need a thermal micrometeoroid garment to block harmful solar radiation while allowing perspiration to evaporate. This system would keep the astronaut a comfortable temperature while still allowing heat to escape in case of high stress activity.

Male and Female EVA Comparison for the Moon

A female astronaut experiences lower skin temperatures than a male counterpart for each suit configuration. This results in increased cold discomfort as compared to the male astronaut. The female manikin produced less metabolic heat and less sweat than the male astronaut. The female manikin reached a maximum sweat rate of 5 grams per minute, much less than the male manikin's maximum rate of 14 grams per minute. This sweat rate falls within safe limits and only 0.369 liters of water were lost over the 4-hour EVA. The overall heat rejection requirements for a female astronaut are less than a male due to a lower metabolic heat rate. This means that supplemental cooling systems for a female suit such as radiators could be downsized as compared to male suits.

B. Mars Modeling

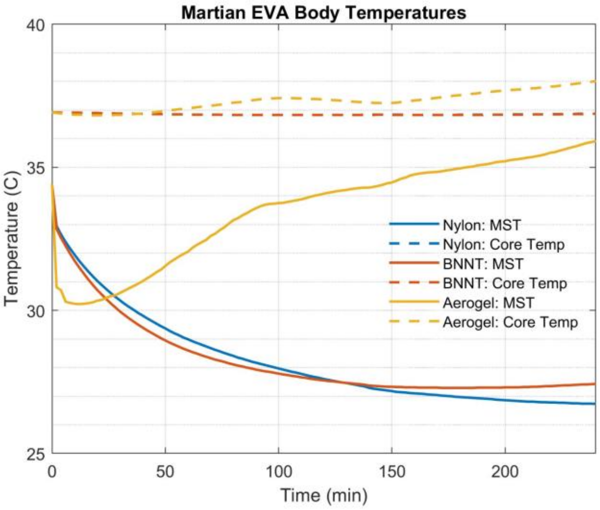

Figure 8. Martian EVA Body Temperatures. *A comparison of mean skin temperature (MSK) and core body temperature for a Martian EVA wearing three layering combinations: a nylon skinsuit only, a skinsuit with a BNNT radiation jacket, and a skinsuit with an aerogel insulation layer and the BNNT jacket. The nylon core temperature is nearly the same as the BNNT and is hidden behind the BNNT data in the plot.*

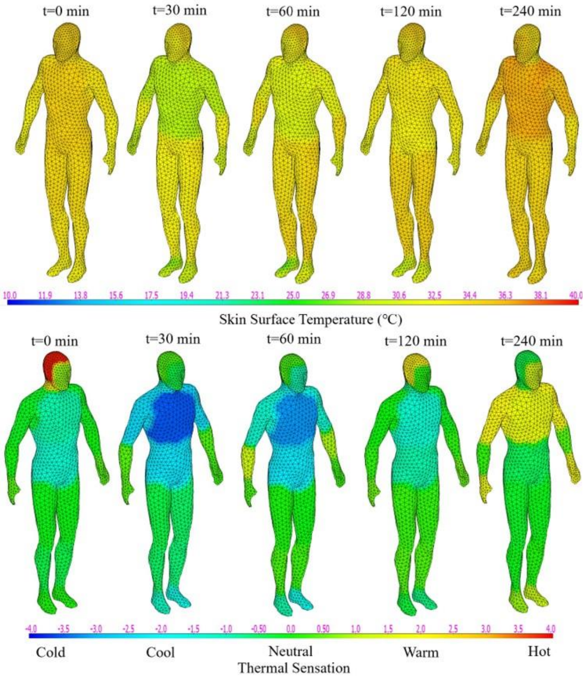

Figure 9. Martian EVA Skin Temperatures. *Skin surface temperature (top) and Berkeley Comfort thermal sensation (bottom) for a Martian EVA wearing a skinsuit, BNNT jacket and Aerogel insulation layer. The astronaut experiences slight cold discomfort, which gradually dissipates after the physically strenuous portions of the EVA. Compared to the skinsuit only EVA, the astronaut remains much warmer and more comfortable.*

It was found that all three garment configurations created survivable thermal conditions for an astronaut in a simulated Martian EVA. However, only when the Aerogel insulation was added did the astronaut avoid becoming uncomfortably or even dangerously cold. In the first simulation, with an astronaut wearing only a nylon-spandex skinsuit and boots, skin temperatures generally remained around 27°C, about 7°C below nominal. Core temperature remained at about 37°C, meaning the astronaut did not become hypothermic.

Figure 8 shows the mean skin temperatures and core temperatures compared for all suit configurations. Skin temperature quickly drops in the cold Martian atmosphere before increasing slightly during the phases of the EVA with a high metabolic load. This is also shown in the Berkeley Comfort Model thermal sensation. The astronaut is very cold for most of the four-hour EVA, and the model reporting that some form of shivering occurred about 90% of the time.

When a BNNT jacket layer is added to the suit, the astronaut experiences a very similar thermal load. The torso is kept slightly warmer, especially during the high activity portions of the EVA, but overall the astronaut remains very cold. Localized hot spots on the torso are similar to what may be experienced with a breathing bladder in place. Overall though, these results show that the radiation shielding jacket can be added to the suit assembly without significantly affecting the thermal properties of the suit.

Finally, with the addition of an Aerogel insulation layer to the suit, the astronaut exhibited much more stable skin temperatures and comfort. As seen in Figure 8, both the mean skin temperature and core temperature where higher than the previous tests. After an initial drop due to cold exposure, skin temperature rose close to normal values, even surpassing 35°C at the end of the EVA after more stringent activity. Figure 9 shows the time-lapse of the skin temperature and thermal comfort sensation for the Martian EVA wearing the full suit assembly with aerogel insulation. The amount of time spent shivering drops to only about 15% of the EVA, all of which occurs in the early minutes of the EVA before any intense activity. Still, an even thicker Aerogel layer is needed to prevent all shivering.

The full Aerogel simulation was the only suit setup in which the modeled human began to sweat significantly. By the end of the EVA, the astronaut reaches a sweat rate of 15 grams per minute and is rejecting over 250 watts through moisture-wicking through the garment and evaporative cooling. This rate, equivalent to 0.96 liters per hour is within the recommended safe limit of 2 liters per hour by Webb et al. The sweat rate was integrated to produce a total sweat volume of 0.691 L for the 4-hour EVA. While the environmental conditions are different on Mars than in Low Earth Orbit, the potential for water mass reductions and the elimination of bulky cooling loops from the suit make this a potential improvement.

Male and Female EVA Comparison for Mars

As with the results from the lunar EVA modeling, a female astronaut experiences lower skin temperatures than a male counterpart for each suit configuration. This results in increased cold discomfort as compared to the male astronaut. The female manikin produced less metabolic heat than the male astronaut. The maximum energy dissipation rate from evaporation is just under 200 watts, over 50 watts less than the male astronaut. This makes sense given the smaller sweat rate. The female manikin reached a maximum sweat rate of 5 grams per minute, much less than the male manikin's maximum rate of 15 grams per minute. This sweat rate falls within safe limits and only 0.238 liters of water were lost over the 4-hour EVA. The female manikin also spent slightly more time shivering than the male manikin in all suit configurations, illustrating the need for supplemental insulation in a female suit.

Table 5. Summary of TAITherm^{TM} EVA Modeling Results

Moon							
	Suit Assembly	Ending Skin Temp	Ending Core Temp	Max Evaporation	Time Shivering	Max Sweat Rate	Total Sweat Loss
Male	NS	30.64 °C	37.54 °C	0 W*	0.0%	13.75 g/min	0.891 L
	NS & BNNT	31.57 °C	37.23 °C	0 W*	0.36%	5.94 g/min	0.226 L
	NS, BNNT & Aerogel	32.84 °C	36.88 °C	0 W	0.45%	0.0 g/min	0.0 L
Female	NS	28.30 °C	37.81 °C	0 W*	0.0%	5.41 g/min	0.369 L
	NS & BNNT	30.40 °C	37.44 °C	0 W*	0.33%	2.75 g/min	0.121 L
	NS, BNNT & Aerogel	31.68 °C	37.03 °C	0 W	0.41%	0.0 g/min	0.0 L
Mars							
	Suit Assembly	Ending Skin Temp	Ending Core Temp	Max Evaporation	Time Shivering	Max Sweat Rate	Total Sweat Loss
Male	NS	26.73 °C	36.87 °C	38.2 W	89.3%	0.0 g/min	0.0 L
	NS & BNNT	27.43 °C	36.87 °C	28.8 W	90.9%	0.0 g/min	0.0 L
	NS, BNNT & Aerogel	35.92 °C	38.01 °C	265.1 W	14.8%	14.5 g/min	0.691 L
Female	NS	24.54 °C	36.92 °C	31.7 W	94.2%	0.0 g/min	0.0 L
	NS & BNNT	25.84 °C	36.91 °C	24.3 W	94.2%	0.0 g/min	0.0 L
	NS, BNNT & Aerogel	35.02 °C	37.94 °C	176.9 W	16.5%	5.08 g/min	0.238 L

VI. Conclusion

The goal of this thermal analysis was to determine whether clothing representative of a mechanical counterpressure spacesuit such as the BioSuit^{TM} could provide adequate thermal regulation in the harsh environments of the lunar and Martian surfaces. Table 5 summarizes key thermal data from the simulations. The simulation results support the claim that with adequate material properties, an MCP suit can rely on natural cooling processes to help keep an astronaut safe and thermally comfortable for the duration of an EVA in these simulated environmental conditions. However, significant challenges remain to achieve thermoregulation for the full range of environmental conditions expected on the Moon and Mars. Even wearing the full insulated suit, the manikins spent up to 16.5% of the time shivering, especially in the Mars EVAs. This could be fixed with additional insulation on the suit, but this would also reduce the capacity of the suit to allow for evaporative cooling during high activity periods.

Perspiration provided up to 250 watts of cooling during a Martian EVA, all at sweat rates well within the established healthy limit. On Mars, convective heat loss to the thin atmosphere also provided close to 300 watts of cooling. Convection is not available on the Moon however. Additional heat rejection can likely be accomplished using radiating surfaces directly on the body (as in these simulations) or on a life support systems backpack. This idea has been explored in research both through NASA contract work and at the University of Colorado Boulder[8,9,35]. Still it is likely necessary to provide supplemental active cooling for extreme hot cases, especially on the Moon. A thermal protective garment like the TMG will definitely be needed during lunar EVAs to prevent large solar radiation fluxes that could damage the body and increase the heat stress on the suit's thermoregulation system.

On Mars, the challenge is to provide an adequate amount of insulation to keep an astronaut warm while not building up too much evaporative resistance so that the astronaut can easily sweat during intense activity. This was shown in the simulation. Only with proper insulation did the manikin avoid becoming very cold. But when adequate insulation was added to the suit, the manikin was able to remain at a mostly comfortable temperature throughout the EVA and reject heat through perspiration when the activity level became strenuous. The addition of convective cooling also lowers the amount of heat that needs to be dissipated directly through sweat evaporation.

Another key takeaway is the difference in thermal results between the male and female astronaut manikins. In both the lunar and Martian environments, the female astronaut experienced lower skin temperatures, meaning increased cold discomfort. Future designs of the BioSuit^{TM} or similar mechanical counterpressure spacesuits should include thermal and radiation protection in the list of design differences that should be made between male and female suits. Based on these results, female suits will need more thermal insulation than male suits. The sweat rates of the female astronaut were also less than the male astronaut. This means that a female suit may need to accommodate less drinking water, but this is not a certainty. The female astronaut manikins may have also sweat less than the male manikins because they were experiencing colder skin temperatures.

These results provide an interesting comparison to the results derived by Vadhavkar in his TAITherm^{TM} Martian EVA modeling. Vadhavkar's suit model (based on the Space Shuttle ACES flight suit) had much higher thermal and evaporative resistance properties. This caused the astronaut to experience higher levels of heat stress and lower rates of evaporative cooling than in the modeling of this paper[17]. The astronaut manikins in this work experienced more cold discomfort but maintained healthier core body temperatures and were able to achieve more cooling from sweating. We believe the spacesuit model used in these simulations is a more accurate representation of a true mechanical counterpressure suit.

Overall, significant thermal challenges remain before an MCP suit architecture like the BioSuit^{TM} can be implemented in planetary EVA operations. While acceptable thermal regulation appears achievable for the environmental conditions modeled here they represent only a small fraction of the temperature ranges a planetary EVA suit must be equipped to handle. However, the capacity for cooling via both perspiration and body radiation open up a wider possibility of methods for thermal regulation. The material properties of the clothing pieces modeled here support their usage in future spacesuit testing. The Boron Nitrite Nanotube (BNNT) infused fabric theoretically provided additional radiation shielding to the chest without inhibiting moisture transport. Additionally, the Aerogel layer proved to be a necessary addition to provide insulation to an astronaut. Without this layer, the astronaut was uncomfortably cold for the majority of the EVA duration on Mars and uncomfortably hot on the Moon. If these insulation layers can be engineered to have a low evaporative resistance, they are an excellent candidate to keep an astronaut warm but allow for heat dissipation under high activity loads in a variety of thermal environments.

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