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Heat Balance Model to Inform Requirements for Martian Spacesuit Architectures

Gabriella Schauss[1],
University of Colorado Boulder, Boulder, CO, 80303

and

Allison Anderson[2]
University of Colorado Boulder, Boulder, CO, 80303

Limitations of our current spacesuits may pose operational challenges during Martian surface exploration. Alternative pressure systems, such as mechanical counter pressure (MCP), may provide potential advantages to overcome these limitations, but development and demonstrated capability is lacking. Progress has been stalled in the development of novel spacesuit architectures due to a lack of informed design requirements. It has been identified that research in the field of thermoregulation and heat transfer for MCP is a critical stepping stone in the road map to making MCP a feasible technology for spaceflight. Thermal modeling has been an effective method to analyze designs for gas pressures (GP) spacesuits in the past as well as used in other high performance safety industries. Past research has explored alternative heat rejection technologies and material layups for exploration thermal systems, but do to not considering sex, body segmentation, and garment architectures. In addition, some thermal modeling has used software which is not readily accessible. Improving the fidelity of human thermal models allows for rapid development and comparison of thermal requirements across alternatives spacesuits such as MCP. In this research, thermal models are developed to analyze novel spacesuits and evaluate the effects of architecture and thermal properties on local skin temperature of a female simulated astronaut. Models evaluated hot and cold conditions of a Martian day in the summer and winter for the constant metabolic rate of 400 W. This work builds on past research by adding gender and body segmentation, increasing the model fidelity and allowing for both segmented and layered spacesuit architectures evaluation. Future results can be used to inform designs and develop requirements for life support systems that can be tailored to operational tasks, environment, and gender specific considerations to minimize consumables as well as provide a comfortable environment for our future astronauts.

Nomenclature

C = Celsius
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
GP = Gas Pressure
LEO = Lower Earth Orbit
MCP = Mechanical Counter-Pressure
mmHg = millimeters of Mercury
METMAN = Metabolic man computer model
NASA = National Aeronautics and Space Administration
P = Pressure

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[1] Graduate Student, Ann and H.J. Smead Aerospace Engineering Sciences, gasc4080@colorado.edu.
[2] Assistant Professor, Ann and H.J. Smead Aerospace Engineering Sciences, apanders@colorado.edu.

psi = pounds per square inch
Q = Heat flux
TMG = Thermal and Micrometeoroid Garment

I. Introduction

Extravehicular activity (EVA) is a core pillar of human space exploration and will continue to play a pivotal role in future planetary surface missions. With a shift towards surface exploration, many subsystems of the current spacesuit will need to be reimagined to facilitate operational tasks within the Martian environment. While active cooling through sublimation has long served as the primary heat rejection mechanism during EVAs, it will not be feasible for Martian exploration due to planetary protection guidelines, consumable mass considerations, and the presence of an atmosphere[1-3]. Furthermore, with the anticipated increased number of EVAs being performed the amount of consumables traditionally used for EVA thermal regulation is not sustainable as water will not be as readily available as in microgravity or Lunar environments[2]. Alternative spacesuit architectures, such as leveraging mechanical counter pressure (MCP), may trade favorably compared to heritage systems[4]. The thermal considerations and the design requirements associated with MCP is relatively understudied[4-5]. Current architectural design use natural thermoregulation mechanisms, such as evaporation, to simplify MCP thermal system, but with the cost of significant water loss to the environment. To address these gaps, thermal computational models are a tool that can be used to understand a variety of operational envelopes for spacesuit systems and establish requirements for future thermal spacesuit regulation[6]. Prior work has used computational models to investigate passive radiative technology through variable emissivity films to maintain comfort in the dynamic environment of the Moon and Mars but often use low fidelity human models for primarily evaluating simplified single layer garment systems[7-9] . Other studies have used high fidelity comfort models developed by industry, which while complex in modeling human thermal control systems, are inaccessible making it restrictive for academic use[10] . Ultimately, these studies have progressed the body of research in passive cooling systems for Mars, but the limitations and requirements across different spacesuit designs are not well understood due to the disconnect in modeling techniques. When integrated into knowledge of operational designs, insight into the thermal limitation of passive cooling for different spacesuit architectures can help design future life support systems which optimize physical and mental performance with little to no loss in consumable mass. This work will help to address these gaps by improving computational thermal models to analyze trades across current and novel spacesuit architectures, ultimately allowing for the development of requirements for softgood layups properties and additional active heating or cooling systems.

The thermal requirements for Martian EVAs are a challenge for current technologies. NASA's Mars Design Reference 5.0 identifies the need for a spacesuit that is lightweight and allows for increased mobility in comparison to the current extravehicular mobility unit (EMU) as to decrease the amount of metabolic work needed to perform tasks which in turn reduces the amount of heat needed to be rejected by the thermal management system[11]. In order to fulfill this requirement, the amount of expendable mass will need to dramatically decrease as currently up to 4.6 kg of water is expelled into the environment through the sublimator during an 8-hour EVA[2]. In addition, the expelled water has the potential to contaminate the environment and scientific instruments. The anticipated thermal system for the Moon uses evaporation in a closed loop water recovery system which reduces the amount of consumables lost, but these systems still rely on water as the mechanism of transporting heat from the astronauts skin to a heat rejection system. For this reason, the new systems will still be very heavy. Additionally, current analysis suggests that the EMU LCVG would not meet the requirements of crew heat storage for the xEMU[5]. Alternative thermal management solutions need to be explored to address the specific needs and requirements for a Martian surface operation.

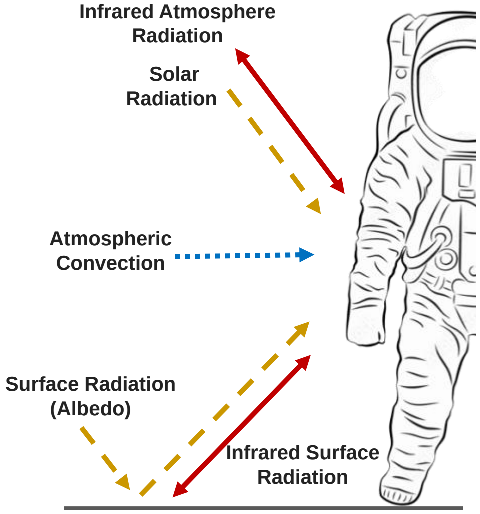


Figure 1. External heat flow between the environment and the spacesuit. *External heat flow is composed of radiation from the Sun, surface, and sky as well as atmospheric convection. This figure is adapted from Junker[9].*

Alternative concept spacesuits may be of interest to overcome the challenge of gas pressure (GP) suits for Martian exploration[4]. MCP is the concept of applying pressure to the body through the use of normal forces applied by an elastic structure. First proposed in the mid-60s by Dr. Paul Webb and James Annis, MCP offers a number of theoretical advantages which could address chronic challenges associated with GP spacesuits[12]. Over the last 20 years, as we shift our focus towards surface exploration, there has been a significant push to improve the state of the art for MCP to try to achieve an operational technology readiness level (TRL). Still, MCP remains a relatively under studied area of research.

Thermoregulation, and specifically the use of natural thermoregulation, has been identified as a critical technical gap for MCP which needs to be addressed in order to get MCP from an experimental proof of concept to an environmentally relevant system prototype[5,10]. Many conceptual architectures for MCP use breathable fabric layers instead of an ideal insulation, which decouples the astronaut from the environment[10]. This allows for heat management to occur using natural thermoregulation mechanisms such as evaporative cooling, atmospheric convection, and surface radiation. With any open loop thermal system, water loss and planetary protection restrictions are considerations that need to be defined, understood, and addressed through design solutions. It has been identified that to close the gap between theoretical advantages and operational feasibility, the development of MCP-specific physiological thermal models is required. This includes models that incorporate and evaluate the merit of natural thermoregulation in relevant environments and consider novel softgood layups to provide sufficient pressure and protection from the environment. Through the development of thermal models, requirements can then be defined to guide architecture design, explore material thermal characteristics and define requirements for active thermoregulation systems. From this basis, steps can be taken to improve current MCP spacesuit performance to push humans outside of the confounds of lower Earth orbit (LEO) and on to more remote and extreme environments.

II. Thermal Modeling of Spacesuits

In its simplest form, the human thermal system can be modeled as a heat exchange between the body's skin surface and the environment, as shown in Figure 1. Metabolic heat moves through the tissue layers of the body via conduction from the core to the skin. The 41-node metabolic man computer model (METMAN) developed by Kuznetz is currently used to determine thermal comfort for the liquid cooling and ventilation garment (LCVG) and exploration mobility unit (EMU)[13-15]. This model is composed of multi-layered cylinders representing the head, trunk, and extremities. Developed in FORTRAN, the METMAN model is relatively inaccessible to general researchers and has not been applied to the Martian environment in literature. Thermal modeling for Martian specific environments have been done in the past. Vadhavkar et al., 2018 analyzed thermal limitations of an MCP spacesuit during a Martian surface transverse to explore the extent of sweat evaporation[16]. While this was a significant contribution to the advancement of MCP spacesuit design, the modeling software used for the analysis is incredibly expensive and highly computational extensive making it limiting to a wide body of future work.

The human thermoregulatory system is a complex and efficient control system which regulates temperature in a changing external and internal environment[17]. While the human core temperature only fluctuates slightly in nominal operation, the skin temperature can vary greatly[17]. Heat loss from the skin surface to the environment is divided into two parts: sensible and insensible heat transfer. Sensible heat exchange is encompassed by dry heat transfer such as conduction through clothing, radiation, and convection of air. Insensible heat exchange are mechanism of heat transfer which uses perspiration or respiration to reject heat. In nominal spacesuit operations, insensible heat exchange is undesirable[18]. For the scope of this study, thermal control mechanisms which encompass insensible heat exchange were not considered. The primary factor for astronaut comfort is based off the core temperature, which is nominally around 37 C[19]. Outside of this temperature physical and cognitive performance quickly declines. For operational ease, thermal control requirements are often translated into a corresponding skin temperature. For most spacesuit architectures, a skin temperature of 30 C is considered comfortable but that value can fluctuate depending on metabolic output and location on the body[20].

III. Methods

This paper advances research from models developed by Massina[8] and Junker[9]. The model described has three components: Martian environmental inputs, spacesuit architecture, and human thermal system consideration. These three components were improved from past work to increase the fidelity of past models and develop a more complete understanding of the design space for exploration spacesuit thermal systems. A model was implemented with five body segmentations each composing of four cylinders representing the astronaut's skin, the interior of the suit, the ventilation gas, and the exterior of the suit. For this paper, we use the female body and corresponding segments in the Martian environment as a case study for the application and utilization of computational models for thermal system development. MCP and GP architectures were compared. While we are not investigating a dynamic method for thermal regulation, a range of environmental conditions establishes the boundaries of which material properties can provide adequate passive cooling as well as establish initial requirements for active heating or cooling systems.

A. The Martian Environment

The Martian environment is characterized by low temperatures (-128 C to 21 C), low pressures (7 mmHg), reduced gravity (0.38g), fine sand and dust, reactive surface chemistry, high ultraviolet levels, and elevated cosmic radiation compared to nominal conditions on Earth[21]. These parameters are all critical factors to consider when defining requirements for a thermal system.

In this investigation, we chose to model seasonal, wind, and local standard time (LST) environmental extremes to inform the bounds of design requirements. These environments are:

- Martian Summer, LST 12, with 0 m/s wind
- Martian Summer, LST 0, with 10 m/s wind
- Martian Winter, LST 12, with 0 m/s wind
- Martian Winter, LST 0, with 10 m/s wind

All values for the thermal extremes for summer and winter are in Table 1. Each condition is characterized with a direct solar flux, surface temperature, air temperature, and infrared (IR) radiation from the sky. Figure 2 provides the temperature profile of the sky, surface, and atmosphere for a Martian day as well as the time band where the fringe conditions were selected. The values used are results from Vasavada et al. (2012) from the Mars Science Laboratory to determine the Martian thermal environment at a latitude of 27.5 S[21-22].

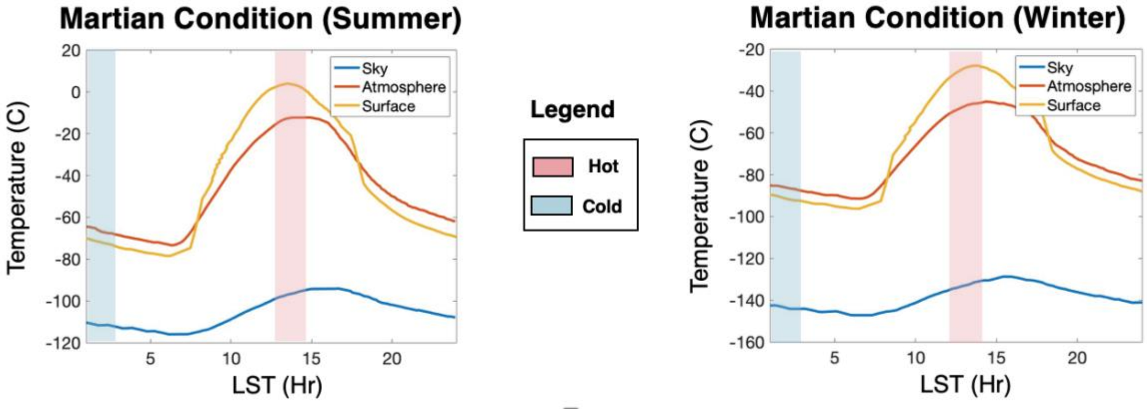


Figure 2. Summer and Winter Martian Conditions. *The blue regions are the areas that are considered the coldest during the Martian day and the hot are the areas that are considered the hottest. These two regions create the operational boundaries for an active thermal system*[21].

In vacuum, spacesuits only interact with the environment through IR radiation and solar radiation. On a planetary environment like Mars, which has a thin atmosphere, convective heat transfer has a significant impact of the thermal balance. The surface of a planetary body provides a surface for conductive heat transfer and reflected surface albedo. For the purpose of this analysis, the feet were not considered due to the significant amount of conductive heat transfer between the boots and the lunar surface.

Table 1. Environmental parameters for thermal extremes[21].

Season	Heat Flux	LST (hr)	Wind (m/s)	Direct Solar Heat Flux (W/m^2)	Sky Temp. (C)	Surface Temp. (C)	Atmo. Temp. (C)
Summer	Max	12	0	600	-100	2	-15
	Min	0	10	0	-115	-70	-60
Winter	Max	12	0	490	-130	-25	-50
	Min	0	10	0	-145	-80	-75

Solar flux is composed of two sources: direct and albedo, which are given in Eq. 1 [8,9]. Direct solar flux (Q_{Sun}) is affected by the absorptivity (α_{Rad}) of the suit's exterior, and the cross-sectional surface area that is in direct view of the Sun ($A_{Rad,cross}$), in addition to the solar heat flux density on Mars (q_{Solar}). Albedo (Q_{Albedo}), which is solar heat flux reflected off of the surface is dependent on the factors defined above as well as the albedo (α) of the planetary surface and the view factor (F_{Surf}). For the purpose of this research, it is assumed that the exterior of the modeled spacesuit has the same absorptivity and emissivity values of the current Ortho-fabric, 0.2 and 0.85 respectively. Under the assumption of a flat surface environment, the view factor, or the portion of radiative heat flux which leaves the surface and strikes the spacesuit, to the surface is 0.5.

$$\begin{gathered} Q_{Sun} = \alpha_{Rad} A_{Rad,cross} q_{solar} \\ Q_{Albedo} = \alpha \alpha_{Rad} A_{Rad} F_{Surf} q_{solar,norm} \end{gathered} \tag{1}$$

IR radiation comes from the planetary surface and the sky. The heat flux from the surface (Q_{Surf}) is affected by the spacesuit (ϵ_{Rad}) and surface emissivity (ϵ_{Surf}), surface area (A_{Rad}), the view factor of the suit (F_{Surf}), the temperature of the surface (T_{Surf}) and the exterior temperature of the spacesuit (T_{Rad}), as shown in Eq 2[8,9]. Surface temperature is an especially important driver for radiative heat flux due to the drastic change in the parameter between the day and night cycles. The Boltzmann constant is given by σ.

$$Q_{Surf} = \frac{\sigma k_{eff,Rad} A_{Rad} F_{Surf} (T_{Rad}^4 - T_{Surf}^4)}{\frac{1}{\epsilon_{Rad}} + \frac{1}{\epsilon_{Surf}} - 1} \tag{2}$$

Eq 3[8,9] describes heat flux from the sky (QSky) and is similar to surface heat flux but does not consider surface emissivity. Similarly to the surface view factor, the view factor to the sky is 0.5.

$$Q_{Sky} = \sigma \epsilon_{Rad} k_{eff,Rad} A_{Rad} F_{Sky} (T_{Rad}^4 - T_{Sky}^4) \tag{3}$$

The relevant mechanisms of heat transfer on Mars is unique in compared to the vacuum of space since Mars has a thin atmosphere. Because of that, convective heat transfer can occur. Convective heat transfer to the atmosphere (Q_{Atmo}) is given by Eq 4[8,9]. It is dependent on the convective heat transfer coefficient (h_{Atmo}), surface area, and the temperature of the atmosphere (T_{Atmo}).

$$Q_{Atmo} = h_{Atmo} A_{Rad} (T_{Rad} - T_{Atmo}) \tag{4}$$

The atmospheric convective heat transfer coefficient is dependent on a number of fluid and composition factors. For the wind speeds of 0 m/s and 10 m/s in an atmosphere composed of 7 torr of carbon dioxide the coefficients of convective heat transfer are given in Table 2.

Table 2. Convective heat transfer coefficients. *The maximum and minimum atmospheric wind speeds[8].*

Wind Speed (m/s)	hAtmo (W/m^2 K)
0	0.276
10	2.038

For a steady-state model, these environmental fluxes must match internal metabolic heat production to maintain a comfortable environment. Material characteristics and suit architectures are two factors that can affect the amount of heat loss to the environment.

B. Modeling Spacesuit Architectures

For this analysis two spacesuit architectures were considered: Traditional GP and MCP. A generalized diagram for both spacesuit architecture is shown in Figure 3. The characteristics of each modeled layer can be altered to reflect a specific spacesuit material layup. The modeled layers include MCP or, when modeling the GP suit, a comfort layer, ventilation gas, and external cover garment. The cover garment is modeled with the same properties between the GP and MCP suits as this layer would be required for any architecture. The total material layup of either spacesuit is 5 mm as to keep with the thickness of the current spacesuit.

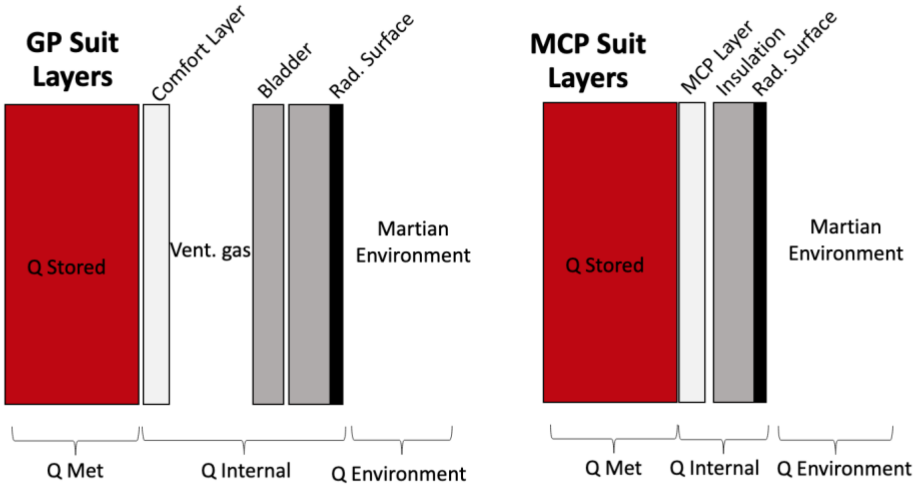


Figure 3. Heat flow within GP and MCP spacesuit layers. *Heat flow mechanisms within both GP and MCP spacesuits are dependent on the architectural design choices. The schematic on the left shows a generalized lay up of a GP spacesuit. The schematic on the right shows a generalized lay up of a GP spacesuit. Within each architecture the values of each layer can be modified to reflect a more specific design.*

Within $Q_{Internal}$ there are three main mechanisms of heat transfer which facilitate the movement of heat from the skin to the internal layer of the spacesuit: contact conduction, radiation, and convection.

Within GP suits, contact conduction is a source of high error due to the uncertainty in $h_{Contact}$. While surface characteristics can widely largely affect the value of $h_{Contact}$, in GP architectures a nominal value of 500 W/m2 K is assigned. $F_{Contact}$ is the faction of contact that the spacesuit makes with the skin of the astronaut [8,9]. In GP spacesuits, it has been found that the $F_{Contact}$ is on average 0.05 [8,9]. This value can differ greatly among regions of the body. In MCP models, ideal contact conductivity is assumed. This means the internal suit surface is equal to the skin's surface.

$$Q_{Contact} = h_{Contact} F_{Contact} A_{Skin} (T_{Int} - T_{Skin}) \tag{5}$$

In regions where skin is not making contact with the suit, radiative heat exchange occurs and is given by Eq 6[8,9]. Due to the ideal contact made between the MCP and the astronaut's skin, the view factor assumed to be 1, making internal radiative heat transfer negligible. The suit interior is assumed to have an IR emissivity (ϵ_{Int}) of 0.9 which is similar to dark paint or textiles[23]. Human skin has an emissivity of 0.99, but traditionally astronauts wear undergarments that alter the emissivity of the skin. As such, the emissivity of the skin is assumed to be 0.88, which is representative of polyester or nylon fabric[24].

(6)

$$Q_{Rad,Int} = \frac{\sigma(1 - F_{contact})A_{Skin}(T_{Skin}^4 - T_{Int}^4)}{\frac{1}{\epsilon_{Skin}} + \frac{1}{\epsilon_{Int}} - 1}$$

The convective heat transfer, given in Eq 7[8,9], is significant when gas is present in the system and increases with the presence of a ventilation system such as an LCVG.

$$Q_{Int,Conv} = \frac{A_{Skin}}{\frac{1}{\frac{A_{Suit}}{A_{Skin}} - f_{contact}} + \frac{1}{(1 - f_{contact})}\sqrt{\frac{L_{Skin}}{L_{Int}}}} h_{Conv}(T_{Skin} - T_{Int}) \tag{7}$$

The presence of air within the layers of the suit also provides an additional insulation layer or conduction, $Q_{Cond,Air}$. Air has a very low thermal conductivity making it an excellent insulator. This air layer is only applicable for GP architectures, since MCP does not use any amount of atmospheric pressure. Conduction from the air insulation layer is given in Eq. 8.

$$Q_{Cond,Air} = k_{air}A_{Cond,Air}(T_{Skin} - T_{Int}) \tag{8}$$

$$A_{Cond,Air} = \frac{A_{Int} - A_{Skin}}{\ln\left(\frac{A_{Int}}{A_{Skin}}\right)}$$

All suit architectures require heat from the suit's interior to pass through the material layers to reach the external radiative side. This mechanism is conduction through the material and is dependent on the net conductivity of the material layers (k_{suit}). Thermal conductivity of a material refers to the ability for heat to be transported within a material and is given in Eq. 9.

$$Q_{Cond,Suit} = k_{suit}A_{Cond,Suit}(T_{Int} - T_{Rad}) \tag{9}$$

$$A_{Cond,Suit} = \frac{A_{Rad} - A_{Int}}{\ln\left(\frac{A_{Rad}}{A_{Int}}\right)}$$

Previous research has found that suit conductivity is a key factor in providing thermal comfort in a range of environmental conditions using passive cooling[9]. Current spacesuits rely on multiple layers of insulation to decouple the astronaut from the highly variable thermal conditions of space, but in doing so prevent heat flow from the astronaut's skin to the environment. Traditional thermal and micrometeoroid garments (TMG) are designed to be ideal insulators which decouples the astronaut from the environment not allowing any heat to flow. Due to the prevention of heat flow, all heat produced by the astronaut has to be actively rejected to the environment. While effective for the thermal extremes in the vacuum of space, high insulation levels are not strictly desirable for the Martian environment where heat can be rejected passively[25]. Overall, the internal heat fluxes and conductive heat through the suit must match that of the metabolic rate of the astronaut in order to have a comfortable steady state. Any excess of heat must be accounted for with an active thermal system.

For polymeric fabric of 5 mm, the reasonable upper and lower bounds for thermal conductivity is 6 to 50 W/m^2K. Polymeric materials have relatively low thermal conductivity values in comparison to ceramics or metals, which makes them good insulators and ideal for cold environments like Mars. For modeling the summer and winter environments, thermal conductivity values of 25 W/m^2K and 15 W/m^2K were selected respectively. These thermal conductivity values were reflected to have adequate insulation for colder environments, where conduction for winter is lower. In addition, the values selected correspond to thermal material characteristics of the Ortho-fabric currently used in the exterior of the EMU spacesuit. The selection of these values provide some amount of insulation but still provides a pathway for conductive heat transfer from the interior of the suit to the exterior. A thermal conductivity value was used from initial simulation, which aligns with literature[23-24].

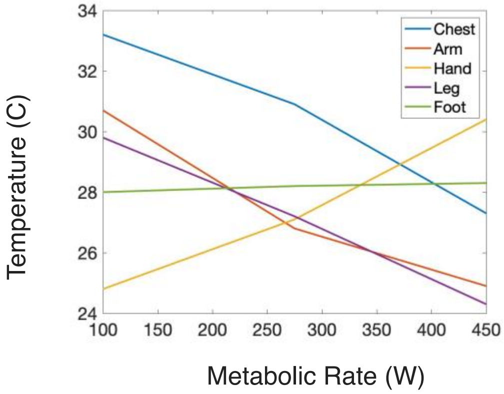
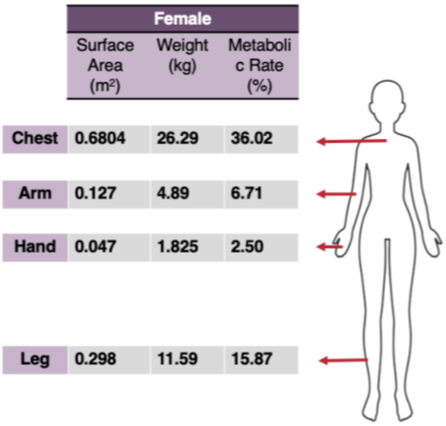


Figure 4. Region skin temperature of a female over a metabolic range[26].



	Female		
	Surface Area (m²)	Weight (kg)	Metabolic Rate (%)
Chest	0.6804	26.29	36.02
Arm	0.127	4.89	6.71
Hand	0.047	1.825	2.50
Leg	0.298	11.59	15.87

Figure 5. Physiological model parameters[28] .

C. Human Thermal System

Optimal skin temperature varies with metabolic heat load. Average skin temperature decreases as metabolic rate increases to facilitate increased conductive heat flow from the core to the skin[8,20]. Past human thermal models simplify the human body to a single cylinder of an assumed metabolic heat flux and associated skin temperature. While effective for initial review of proof of concept, that model does not consider the many distinct factors that affect the metabolism and skin temperature including sex, age, height, weight, region, and exercise. Thermoregulatory systems and nonuniformity in thermal receptors throughout the body segments create different perceived thermal comfort. In addition, because of the lower muscle mass and differences in tissue layers, women generally generate heat differently than men. Due to these differences, it is important to develop women specific models to account for this variation. As such, this work improves upon prior efforts to increase fidelity by adding body regions and sex specific characteristics.

For this work the body was segmented into five regions. The head was not considered for this study due to the complex interface associated with MCP helmets. Skin temperature were taken from the literature and were originally derived from experimental data with metabolic rates between 100-450 W[26]. Figure 4 shows region skin temperature for a 50th percentile female. In general, extremities trended hotter as metabolic rate increased while segments closer to the core trend colder. For spacesuit applications, since past designs have strived to avoid sweating to reduce moisture within the suit[27], metabolic rates above 450 W were not included as experimental data with higher intensity metabolic data was not found in the literature. Human characteristics such as segment surface area, weight, and metabolic rate can be customized through the Body Builder model given a sex and body mass index value. Figure 5. shows segment specific characteristics for the 50th percentile female[28].

In addition to thermal comfort from heat transfer to the environment, cold exposure is another thermal consideration. NASA specifies that no surface in contact with the astronaut can be below 4 C[29]. This becomes an important consideration for mechanical counterpressure which makes direct and full contact with the skin as well as lacks an additional insulation layer from the ventilation gas.

D. Steady-State Thermal Comfort

This modeling approach uses a steady state analysis which requires that all internal metabolic heat generated is passively rejected into the environment. This method has been used in the past for evaluating Martian spacesuit technology only using passive cooling[9]. While in dynamic settings, where internal control systems within the human body are able to store and regulate internal temperature, the difference between the passive threshold and human limits are used to indicate the level of active cooling that would be required. For this model, excess heat stored between the the internal heat flux and external environmental flux are used to develop requirements for active thermal regulation systems. Models were run with an assumed thermal conductivity value to solve for the amount of activity cooling (Q_{Active}) where:

$$Q_{Active} = Q_{Met} - Q_{Env}$$

A negative Q_{Active} value would indict the need for active heating systems where a positive Q_{Active} value would indicate the need for an active cooling system. This method introduces fundamental limitations, but it does provide an initial model for a first evaluation of novel spacesuit architectures.

IV. Results

Simulations were run at all planetary environment conditions for a traditional GP suit and MCP suit. The metrics for evaluation was the amount of active cooling needed for each configuration in Watts. This was determined by the difference between the internal heat flux, including metabolic rate and mechanisms of heat transfer within the spacesuit, and the environmental heat flux. These results are used as a use case example for the utility of a computation system in first principle analysis for system requirement development. A 50th percentile segmented female model was used as a proof of concept to explore the utility of the proposed approach. The Martian extreme hot and cold environmental conditions for the Summer and Winter seasons were simulated. A 400 W metabolic profile was used as it best represents the predicted average metabolic rate during a Martian EVA[30]. Final requirements for the capabilities of thermal systems for surface EVAs will likely exceed 400 W of metabolic heat as thermal systems must also consider contingency cases, such as emergency walk backs.

A. Spacesuit Architecture Evaluation

Tables 3 and 4 show the resulting excess heat, or the difference in metabolic and environmental heat fluxes, in a given environment and body segment for a 400 W metabolic load. A negative value indicates that the heat balance resulted in too much heat being removed from the astronaut and the need or an active heating system, while a positive value indicates there was heat buildup with in the spacesuit resulting the need for an active cooling system. Due to the highly compressive nature of an MCP suit, it can be modeled through ideal contact conductivity making convection and internal radiation heat fluxes negligible. The simplified internal heat transfer model as well as reduced surface area yields a range of excess heat buildup which is balanced between hot and cold conditions for both the Martian Summer and Martian Winter. For the MCP spacesuit, results from the model showed that there is a fairly equal amount of excess built up and rejected heat in both the Winter and Summer seasons, with slightly high heat building up in the extreme hot condition.

In contrast, the GP results skewed heavily towards in excess of rejected heat (negative excess heat) during the cold environment, with up to a -196 W difference between the internal heat flux and the environmental heat flux. During the winter season for all body segments the GP architecture exclusively had heat loss from the simulated steady state model. This significant increase in heat loss between the two architectures could be due to the larger radiative surface of the GP spacesuit in comparison to the MCP suit. This is further seen in the difference in excess heat between the chest, which has a large surface area, in comparison to the hand, which has a much smaller surface area. Additional, the GP suit uses convection via ventilation gas which past research has found to be a highly effective mechanism of moving heat from the skin to the interior of the spacesuit[18, 25].

B. Body Segmentation

For body segmentation, Tables 3 and 4 also show the difference excess heat buildup for region of the body. It can be seen that there are differences in body segments between spacesuit architecture as well as within each spacesuit architecture. Between spacesuit architectures, body segments in the GP suits trended colder with increased amounts of heat rejected from the system possibly resulting in perceived cold thermal discomfort. Within the spacesuit architecture for both GP and MCP, the larger regions of the body, such as the legs and chest, have an increased range of excess heat differentials in the Summer condition spanning both positive and negative values. For the Winter season the same remains true as the chest and legs have larger excess heat ranges compared to other body regions but for GP in the winter season excess heat range is exclusively negative, suggesting active heating systems would be needed primarily. While MCP, having both negative and positive excess heat, would suggest the need for both heating and cooling systems.

Table 3. Excess heat production of a 50th percentile female during Martian Summer at a metabolic rate of 400 W.

	Gas Pressure- Excess Heat (W)		Mechanical Counter Pressure- Excess Heat (W)	
Body Segment	Hot	Cold	Hot	Cold
Chest	9.06	-196.3	60.92	-123.3
Arm	24.96	-14.48	20.36	-21.28
Hand	13.25	-8.39	12.82	-9.0
Leg	-38.11	-149.2	36.01	-48.47

Table 4. Excess heat production of a 50th percentile female during Martian Winter at a metabolic rate of 400 W.

	Gas Pressure- Excess Heat (W)		Mechanical Counter Pressure- Excess Heat (W)	
Body Segment	Hot	Cold	Hot	Cold
Chest	0.37	-196.0	-21.63	-125.6
Arm	22.52	-15.24	-10.73	-21.78
Hand	12.47	-8.54	-10.73	-9.13
Leg	-39.53	-146.7	-11.09	-49.6

V. Discussion

The ultimate goal of this research is to develop models with increased fidelity in order to provide a method to rapidly compare spacesuit architectures with in the Martian environment. This allows for a thermal system trade space to be defined and the development of specific design requirements for a given operational exploration mission. In this way, the amount of passive cooling, which is uniquely effective for the Martian environment, can be understood so that an active system can be designed to supplement the passive heat rejection mechanisms. Historically, microgravity and Lunar EVAs have seen metabolic rates with an average of 264-287 W and maximum rates as high as 724 W[30]. The metabolic range in this study are on the lower end of what is expected for a Martian EVA, potentially corresponding to operational tasks such as sample collection, traversing in a rover, or stationary repairs. The upper metabolic limit, such as during an emergency walk back, is not captured and is a limitation of this work[31]. While only considering smaller metabolic heat loads, due to physical limitations it is likely that most surface operations will be within lower metabolic rates, and as such a system for the everyday is considered. It should be noted that the models developed in this research are not intended to be at an accuracy level which could be used to design final spacesuits, but to be used for comparing and analyzing trades across architectures for rapid design iterations. Dynamic and high fidelity modeling in future work may provide higher accuracy and bridge the gap for evaluating more realistic, non-steady state metabolic load profiles[8].

A. Material Layup Selection

Optimizing the thermal conductivity for a specific thermal control configuration could increase the upper metabolic limits in high thermal extreme environments. This can be done as the total heat injection or rejection for the overall system or by isolating and defining thermal properties of individual layers of each architecture. For this investigation thermal connectivity was generalized and assigned to the entire system, as to keep with softgood designs used by historical spacesuit system. This generalization did not optimize the amount of passive cooling that can be achieved by material properties alone. It also did not consider differences in body segmentation such as increased surface area or higher percentage of metabolic output. As material investigations increases in complexity and more specific requirements are defined, individual material layers can be called out and provided more specialized thermal function.

GP spacesuit, especially in the Winter season, resulted in having a negative excess of heat. While this model does not have a temporal aspect, it can be assumed that exposure to persistently cold environment could eventually lead to a decrease in core temperature resulting in physical and cognitive performance degradation. Therefore, decreased total thermal conductivity of the GP spacesuit layer would be needed if this material's properties were to be optimized. Ideally this would decrease the difference between the hot and cold excess heat values. The MCP architecture had a narrow and balanced excess heat range for both Summer and Winter seasons. This may suggest that the material selected for that architecture was closer to the ideal thermal conductivity value, but individual body segments maybe examined individually or as a full system to customize the material properties in a localized region. In addition, future work may explore variable thermal characteristics of materials or the advantages of a coverage architecture to increase or decrease the amount of insulation dynamically.

B. Development of Subsystem Requirements

From the results, MCP has a smaller range of excess heat production from the environment. From this we can infer that for a specified metabolic heat the active heating and cooling systems need to provide less active thermal regulation in comparison to GP suits. But unlike GP suits, the results from the MCP simulation suggest that a heating and a cooling system would need to be provided in the life support system since both positive and negative excess heat was reported for the external environmental extremes. It should be noted that while the difference between internal and environmental heat fluxes were quite large for GP suits they typically trended negative which from an active thermal system requirement means that only heating systems would be needed if the specified thermal conductivity was maintained. This has the potential to be advantageous since current cooling systems such as the LCVG are quite heavy and require significant amounts of consumables[2]. Current spacesuits such as the EMU only have heating mechanisms in the gloves so it isn't well known how a full body heating system might be implemented or the mass power requirements associated with it[33]. While the total heat required by the active system could be significantly smaller than other spacesuit architecture, since two separate systems are required for a MCP suit, ultimately the total thermal system could end up having higher mass, volume, and power requirements. The added complexity and consumables needed for a dual heating and cooling system needs to be considered when selecting materials.

As mentioned in the section above, some of the excess heat in the GP architecture can be accounted for in material selection. GP suits have a significantly larger radiative surface and will reject heat into the environment through radiative mechanisms more readily than an MCP designs. The total body radiative MCP suit surface area, assuming a 5 mm suit thickness, of a 50th percentile female, for example, is 1.8 m^2, which is significantly less than the average radiative surface of a current GP spacesuit, 3.5 m^2 [32]. From a use case, this number maybe slightly skewed since it does not account for other elements of the spacesuit including the life support system and helmet assembly. None the less, the difference in surface area must be considered for future thermal subsystems if a GP architecture is ultimately selected as the ideal pressure system for a Martian spacesuit. Increased layers of insulation will have implications on mobility and tactility of spacesuit, with the highest impact to surface operation. The hand would have significant decrements in functionality with the increase in material thickness.

It should also be noted that as mentioned earlier 400 W is expected to be around the average or in the lower limits of output for a Martian EVA. Therefore, having a baseline of negative excess heat maybe advantageous as metabolic loads increase allowing for thermal comfort to be achieved even at the upper limits of the metabolic rates. Ultimately, excess heat can be defined from the models. From that, informed decisions on technology complexity, material selection, and allowable metabolic rates can be determined.

C. Translating to Thermal Comfort

Thermal comfort criteria can be divided into objective and subjective measures, where objective measures include body thermal storage, average skin temperature, and core body temperature, and subjective measures use predictive values from experimental survey data. This model uses skin temperature to create a steady state model and differences in internal and environmental heat to determine active cooling systems and infer thermal comfort of the modelled crew member. The integration or adaptation of subjective thermal comfort models such as the Berkeley comfort model could provide a more accurate depiction of perceived thermal comfort using validated experimental models[34-36]. While often subjected to uncertainties, such as misleading results for off nominal environments or underrepresented groups[37-38], subjective measures for assessing comfort provide a method to validate results against validated human experimental data without the use of invasive devices to monitor skin and core temperature. These and future models should subsequently be validated using a thermal vacuum chamber or thermal mannikin[39].

VI. Conclusion

The analysis described in this paper provides an initial case study for modeling human thermal regulation in alternative spacesuit architectures for the Martian environment. We present a case study example model to determine a set of baseline material requirements and understand the use of this type of computational modeling to advance the state of the art of novel spacesuit architectures for Martian surface operations. The primary goal was to present a computational model with increased fidelity and perform a first principle analysis of different spacesuit architectures in the Martian environment to determine the heating and cooling requirements for an active thermal system. From an initial case study we found that MCP requires both active heating and cooling systems for a 400 W metabolic rate, while GP suit only require heating systems, possibly simplifying the full thermal regulation system. This work is ongoing with plans to address additional considerations to ultimately increase the TRL of MCP in order to facilitate future astronaut planetary exploration.

From this baseline methodology, future work will improve model fidelity by sex and body region, evaluating material properties, and explore additional spacesuit architectures. While fidelity in sex and segmentation were increased from past models additional improvements can be made to incorporate heat redistribution throughout the body via a blood pool and thermoregulatory control systems. The addition of a blood pool and heat storage metric can provide metrics on time dependent processes such as cognitive and physical degradation. Additionally, increased human model fidelity can allow for a more in-depth analysis of body composition on thermal comfort for the generalization of thermal systems for a larger fleet size[30]. As space becomes more accessible, inclusive design parameters become a critical aspect to system development.

This paper addresses one possible materials solution for passive cooling, but future systems do not necessarily need to be constrained to a uniform thermal garment. Future development may explore variable thermal conductivity for regions that have been identified as chronically cold or chronically hot. Furthermore, alternative spacesuit architecture such as the segmented or layered hybrid concept[40-41] may provide additional cooling mechanisms such as ventilation gas in conjunction to MCP. Exploring novel material layups which optimize passive cooling as well as considering other planetary material requirements such as abrasion resistance, dust repulsion, and increased surface contact, needs to be a focus in future spacesuit development. In conjunction with material selection, active thermal technologies will also need to be considered for future systems. Heat rejection mechanisms used for EVAs today as well as thermal cooling technologies planned for lunar EVAs require nontrivial amounts of water making them heavy and cumbersome[2]. With the increased gravity level on Mars, this weight will become even more significant. Identifying and evaluating technologies with low power and mass consumption to fulfill the requirements for an active cooling system will be critical in developing low mass spacesuits for Martian exploration.

The results from this work provide results that could be considered counter intuitive in comparison to current spacesuit thermal modeling. This is primarily due to the fundamental differences in how current spacesuit are designed verses the proposed future systems. With current systems, insulation values are considered ideal preventing heat flow to the environment. Because of this all heat generated by the astronaut needs to be actively rejected. For the proposed design solution, insulation is not ideal which allows heat flow to the environment. Because of this fundamental change, astronauts have the potential to be over cooled which would require the addition of heat to the suit's internal. Within the methods, the fundamental guiding principles have been outlined providing a logical verification of the model. But, due to the unique environment and mechanisms of heat transfer, there is currently no data that can be used to validate our model. This is a major limitation. Experimental future work is need in order to full validate that our model reflects reality.

In general, the results of this first-order analysis suggest that a significant amount of passive cooling can be achieved for both GP and MCP spacesuits in the Martian surface environment. The initial results show that a simplified computational model can be an effective method to provide initial requirements for thermal system which can be highly customizable to exploration environment, spacesuit architecture, and crew member. The development of novel, low mass, and low power technologies will be needed to fill the gap in thermal regulation. Ultimately, this research aims to create an informed thermal design for future exploration spacesuits.

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