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3D Modeling of Human Thermal Interaction in Complex Environments using the Wissler Human Thermal Model

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Models for human thermal evaluation in extreme environments have played a key role in life support, suit, and crewed vehicle development at NASA for many decades. These models, which include the 41-Node Metabolic Man and Wissler models, among others, have proved excellent tools in predicting survivability without performing costly testing in extreme environments. These models have been limited, however, to predictions in simple 1-D environments rather than the highly directional heat load environments experienced in space exploration. A three dimensional geometric interface to the NASA version of the Wissler human thermal model has been developed in Thermal Desktop to better support exploration suit design. This tool is employed in complex radiation environments to improve prediction of survivability in real environments. This paper describes the composition of this new tool and presents results of its predictions in a representative exploration environment.

Nomenclature

PLSS = Portable Life Support System
LCG = Liquid Cooled Garment
LCVG = Liquid Cooled and Ventilated Garment
MLI = Multi-Layer Insulation
CSSS = Constellation Space Suit System
EMU = Extra-vehicular Mobility Unit
CAD = Computer Aided Design
SINDA = C&R's Systems Improved Numerical Differencing Analyzer
TD = C&R's Thermal Desktop software

I. Introduction

Efforts to develop an engineering understanding of the thermoregulation of the human body have been driven over nearly a century by the practical need to understand the interaction between a human and the increasingly extreme environments that we are capable of exploring. Quantifying this interaction in first-principles based mathematical human thermal models has afforded tools for predicting human behavior in unencountered environments and under life-threatening conditions for the purpose of predicting survivability, identifying end of mission conditions, and evaluating off-design scenarios without the expense or risk to life that would be required of human testing. This capability informs NASA's continued development and maintenance of human thermal models for the purpose of space suit development, manned orbital vehicle design, and survivability studies for a full range of potential manned mission scenarios so that risk to human life is understood and minimized through design where possible, and procedure where required.

The 1927 experimental study of Bazett and McGlone,[1] which measured temperature gradients in the arm when exposed to a cold environment, is considered to be the first step toward a quantitative understanding of the human thermoregulatory system. Alan Burton in 1934 found this data to validate a first mathematical model of temperature distribution in the body based on the physical laws of heat transfer,[2] and subsequent experimental work by Burton and Bazett[3] formed the basis of a first transient conduction model for the body in 1936.

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Pennes'[4] 1948 work on the effect of blood flow on tissue temperature reflects a fundamental milestone in human thermal modeling. He proposed a relationship for the heat transfer rate from blood to local tissue and measured temperature profiles in the arm by drawing a fine thermocouple through the forearm. Most detailed models in present use employ the bioheat equation developed by Pennes.[5,6,7] Wissler applied the concepts developed by Pennes in his early steady-state[8] and transient[9] finite-difference whole-human thermal models. These models consisted of cylindrical elements representing body segments and considered countercurrent heat transfer between arterial and venous blood. Experimental work in 1966 by Stolwijk and Hardy[10,11] informed their development of two notable whole body models. The first,[12] developed in 1966, incorporated control functions for skin blood flow, sweating, and shivering. All following models have adopted the approach introduced in this work. The second,[13] produced for NASA in 1970 and referred to as the 25-node Stolwijk model, ran on an early digital computer and was used in the design and operation of the Portable Life Support System (PLSS) for Apollo missions. Another early progression of models developed by Kuznetz[14,15] and commonly referred to as the 41-node metabolic man found utility at NASA in the design of liquid cooled garments (LCG) for space suits, including the Extra-vehicular Mobility Unit (EMU). Taking advantage of improving technology, Wissler[16] later introduced a much improved fidelity 15 segment, 225-node whole-human model which was then modified by Nyberg[17] in 2001 to incorporate a detailed liquid cooling and ventilation garment (LCVG) and adopted by NASA JSC for analysis and design guidance to the Constellation Program. The latest well regarded whole-human thermal models have been developed by Wissler[18,5,6,7] and Fiala[19,20] and represent vast improvements in fidelity, the Wissler model having 3780 body nodes, improved statistical correlation to experimental data, and attention to finer thermoregulatory behaviors.

The 225-node NASA branch of the Wissler model, which is the subject model of this work, has been adapted specifically to address the needs of space flight. The model adds routines and logic for the active cooling of the astronaut, routines to address heat rejection by radiation in vacuum environments, logic for specific breathing mixtures, and specialized garment logic to incorporate the behavior of multi-layer insulation (MLI). This model has been distributed to and is presently used by several commercial crew and supporting space organizations, including Paragon Space Development, SpaceEx, and Boeing, and is the primary human thermal analysis tool for support of the development of the Constellation Space Suit System (CSSS).

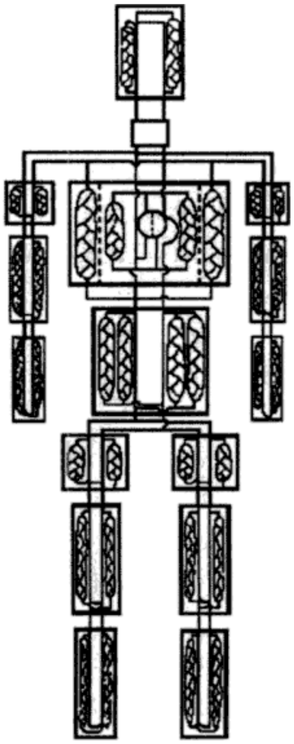

Figure 1. A Geometric Representation of the Wissler Human Thermal Model. *Shows body segments and blood flow in the 225-node Wissler model, the subject of this development.*

II. Description of the Model

Human thermal models have historically been standalone software tools. The Wissler model was designed as a monolithic tool, which is a common design paradigm of legacy Fortran software, that parses input, defines a geometry, computes environmental heat loads, computes a finite difference solution to the problem, and finally formats and writes the results to a file. The NASA branch of Wissler has recently been integrated into several analysis platforms including Excel, Python,[21] and Thermal Desktop[22] to facilitate engineering applications of the model. These integrations have allowed the communication of performance level predictions from the Wissler model such as core and skin temperature, energy storage, and LCVG heat rates for use in system level models and validation tools, but have not otherwise altered the all-in-one paradigm of the model.

This design means in particular that the model relies on internal environment calculations which are independent of the system model into which it is integrated and that it is unaware of the complex environments that are of interest at the system level. It also means that any environment calculations are limited to the fidelity and assumptions built into Wissler. The latter is fairly limiting, especially for radiation considerations, as the 225-node Wissler model computes a 1-D heat rate for each body segment assuming a cylindrical shape, with a rough nodalization, and ignoring any interaction between segments. One consequence of the 1-D Wissler computation is that common directionally significant situations, such as a suited crewmember in view of the sun, cannot be properly analyzed.

Further, a radiation analysis of the human form will identify view factors between arms, legs, head and trunk which are not considered in the Wissler model. Finally, the simplified cylindrical Wissler geometry prevents consideration of the real geometry of a suited crewmember and its thermal implications. The PLSS, for example, is an integral component of a spacesuit design, but its protruding off-center geometry cannot properly be accounted for in the 1-D Wissler configuration.

Paragon Space Development has therefore significantly modified the NASA Wissler model and developed an intimate interface, functionally described by Figure 2, to it for use in the Thermal Desktop (TD) analysis platform to overcome these issues in support of the new CSSS exploration suit design. Thermal desktop is a system level thermal analysis platform in a CAD environment that determines high fidelity geometry based radiation heat interactions using RadCAD, performs finite difference and finite element network heat rate solutions using SINDA, and 1-D lumped fluid flow solutions using FLUINT. The new interface allows Thermal Desktop to compute environment heat rates at the system level and impose these as boundary conditions directly upon each segment of the Wissler geometry. Wissler, in turn, communicates all interface boundary temperatures, coolant loop temperature, and other relevant information to the TD system level model. The new tool is composed of a modified NASA branch of the 225-node Wissler model, a Wissler interface, a TD/SINDA interface and geometry, and an external suit model developed for the CSSS program. The result is a fully integrated simulated-human-in-the-loop modeling environment that is far more capable than previous tools.

The Wissler interface itself is a Fortran 2008 standard based object model that maps to three levels of data in the modified Wissler model. At the crewmember level it defines interface functions, LCVG data, whole-body characteristics such as body mass, metabolic rate, and activity, and environment data. At the segment level, layer data and named shortcuts to local core, skin, touch, and boundary layers of system level interest are defined. At the layer level, which describes each node of the Wissler model, temperature, heat rate, and similar layer specific data is defined and points to the appropriate Wissler value. The interface thereby abstracts Wissler data in an intuitive hierarchy of objects so that the interface is now independent of the underlying whole human model implementation. This abstracted design allows the interface to remain consistent should the underlying model be upgraded or further modified in future work.

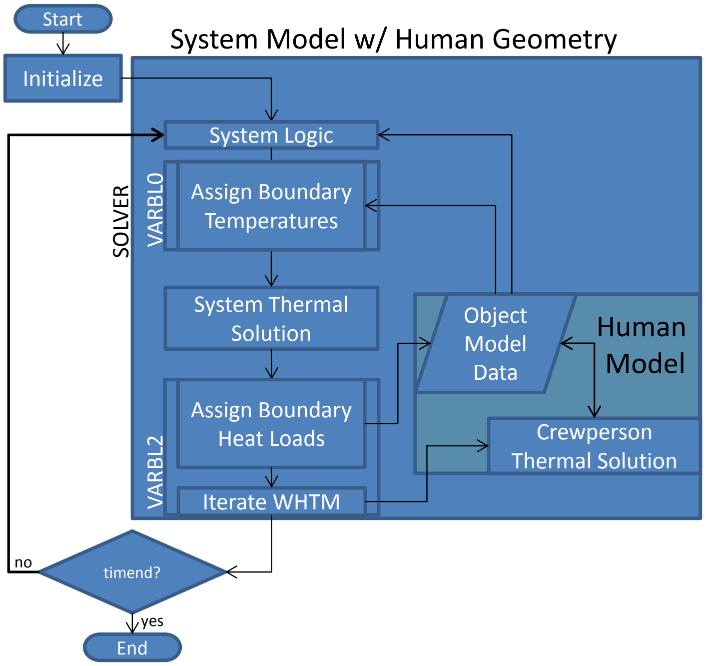

Figure 2. System level integration of the Wissler model with Thermal Desktop. *Crewmember information is mapped in an intuitive and implementation independent manner in the new interface to arrive at the greatest flexibility for model and system level integration*

The primary modification made to the Wissler model in implementing the new interface and behavior is the definition of a new environment case, ‘imposed’, and logic to implement imposed heat loads passed to Wissler. The new environment logic determines a heat flux from TD and implements this in the Wissler finite difference framework as a boundary temperature and heat transfer coefficient pair. Care was taken in making these changes to maintain backward compatibility with the previously defined interface and functionality, thus ‘vacuum’, ‘gas’, and ‘liquid’ environment cases remain intact so analysts using the NASA branch of the Wissler model may upgrade without breaking their current analysis tools.

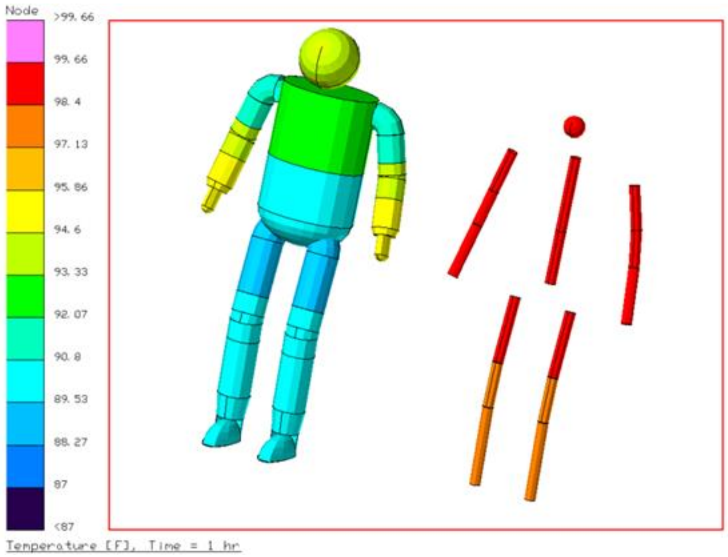

Figure 3. The Thermal Desktop Wissler geometry. *The left geometry defines the surface boundary separating Wissler human model and TD environment model. The right geometry is a mapping of Wissler core temperatures.*

The new TD/SINDA interface has two parts, a geometry that represents the segments and surface area of the internal Wissler geometry and an underlying logic framework written for the SINDA preprocessor. The geometry, shown in Figure 3, defines the surface boundary separating the Wissler human model and the TD environment model. Its segmented surface areas and nodalization matches the Wissler internal geometry to ensure the proper heat load is imposed onto the Wissler model. The temperatures of the surfaces are defined by Wissler.

This geometry is defined at the pressure garment layer of the Wissler CSSS space suit garment stack. This boundary choice is driven by limitations in the current external suit model. The Wissler model accounts for sweat absorption, evaporation, ventilation, cooling, and water vapor permeability in garments. While this capability may be built into the external suit model in the future using FLUINT tools, it was more expedient for the purpose of demonstrating this interface to define the boundary at an impermeable layer so that the additional work was not necessary.

The underlying SINDA logic performs the final translation from the SINDA data model to the Wissler interface. This logic initializes and invokes the Wissler interface, maps data between SINDA nodal locations or functions and the Wissler interface, and creates a framework for control of garment type, environment, metabolic rate, and other parametric crewmember level data.

Finally, the external suit model, shown in Figure 4, is an example of the potential of the new interface. This is a detailed geometric garment of arbitrary nodalization built over the Wissler interface geometry. Heat is conveyed between the differing nodalizations of the Wissler geometry and external suit geometry using a TD contactor. This geometry is complex and includes suit shape, helmet, PLSS, glove, and boot details that are important to a system level thermal understanding of the space suit design. The TD layer manager is used to define the entire stack of garment layers from the outer surface, including MLI, to the pressure garment layer. Additional control and components, such as heaters may be placed in gloves, boots or other locations readily by using TD surface or node heaters. The higher temperature apparent in the PLSS reflects just such a heat load representing PLSS avionics heat generation.

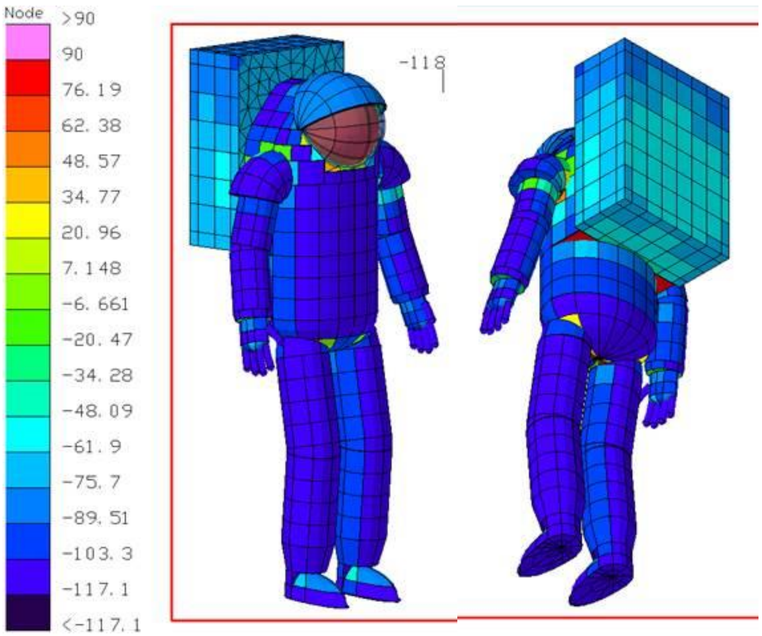

Figure 4. The Thermal Desktop External Suit geometry. *This suit geometry is built upon the Wissler geometry and affords analysis of detailed suit designs, including the effect of PLSS placement, solar view, and immediate surroundings.*

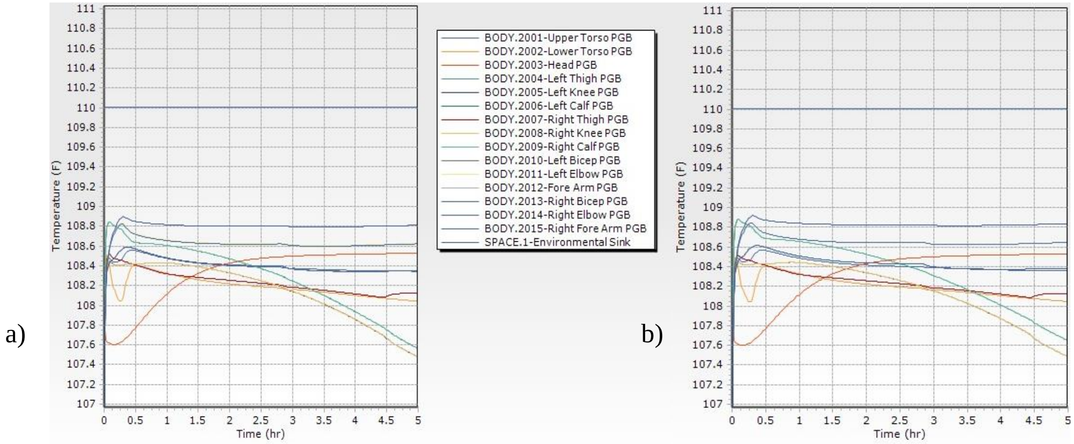

Figure 5. A High Temperature 1-D Validation case. *The graph on the left shows results from the new model with a dismembered geometry (no self-view). The graph on the right shows results from the previous model in an identical environment.*

III. Model Validation and Results

The interface geometry shown in Figure 3 was used in a set of simple, 1-D environments and compared to results of the previous baseline model in identical conditions to validate that the new model and interface behave correctly. Since the baseline 225-node Wissler model has been validated against experimental data, a comparable result between the two models given identical configurations would infer that both models are similarly validated to experiment. Details of the cases run are outlined in Table 1.

Table 1. Validation case characteristics.

Graph	Tspace	Garment	Met Rate	Environment
Fig. 5a	110 °F	TD+EXPO	1200 Btu/hr	'imposed'
Fig. 5b	110 °F	EXPO	1200 Btu/hr	'vacuum'
Fig. 6a	-110 °F	TD+EXPO	1200 Btu/hr	'imposed'
Fig. 6b	-110 °F	EXPO	1200 Btu/hr	'vacuum'
Fig. 7	110 °F	TD+EXPO	1200 Btu/hr	'imposed'
Fig. 8	-110 °F	TD+EXPO	1200 Btu/hr	'imposed'
Fig. 9	110 °F	External Suit	1200 Btu/hr	'imposed'
Fig. 10	-110 °F	External Suit	1200 Btu/hr	'imposed'

Thermal Desktop calculates a radiation view factor between all elements of the human interface geometry. This self-view is not in fact computed in the Wissler model, so introduces a heat rate discrepancy between the models. For the sake of a validation exercise, therefore, the interface geometry is dismembered with each limb and the head located in CAD space far from all other elements to force a negligible self-view. The outer suit surface temperatures of this dismembered geometry are seen in the left graph of Figure 5 and Figure 6. A comparable match of nodal temperature predictions to the baseline prediction results seen to the right of the same figures demonstrates matching behavior between new

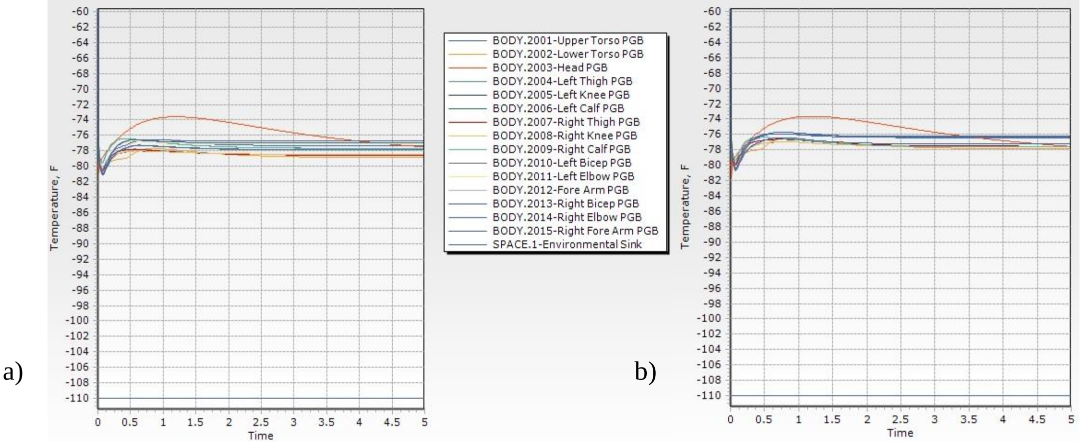

Figure 6. A Low Temperature 1-D Validation case. *The graph on the left shows results from the new model with a dismembered geometry (no self-view). The graph on the right shows results from the previous model in an identical environment.*

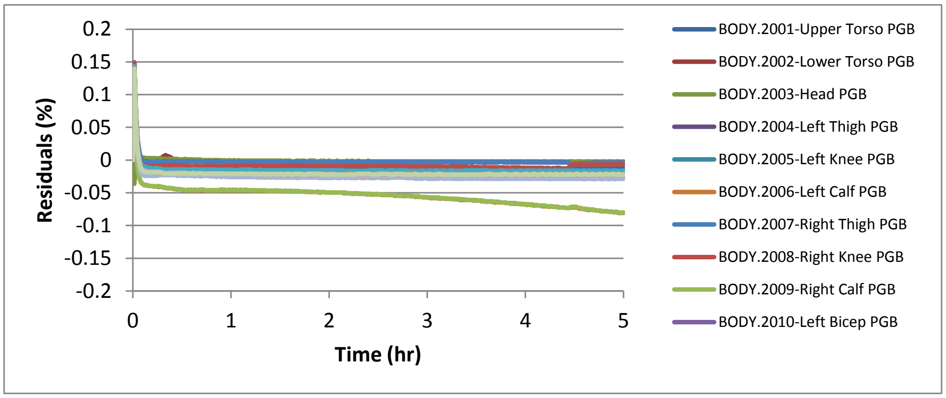

Figure 7. Residuals for the High Temperature 1-D Validation case.

and baseline models.

Small differences are evident between the new and baseline models primarily as a result of the Monte Carlo ray tracing methodology that RadCAD employs to determine radiation heat transfer. This stochastic method introduces slight variations in the area and radiation view factor to space which are illustrated through Table 2 with RadCAD results for the 110°F environment validation case. Differances here in composite surface emissivity, ε, which is 0.837 for most surfaces in Wissler, view factor to space, B_{ij}, which is assumed in Wissler to be 1, and self view, B_{ij} *self*, for complex surfaces such as boots (BODY.2006 and BODY.2009) result in a lower heat rate to space than is predicted by the overly idealized Wissler radiation heat transfer computation.

Table 2. RadCAD Results from the High Temperature 1-D Validation case

Thermal Desktop / RadCAD Geometry							Wissler	Area
Node ID	Sink ID	B_{ij}	B_{ij} self	B_{ij} inact	ε	Area (ft^2)	Surface Area (ft^2)	% diff
BODY.2001	SPACE.1	0.993437	0	0.007	0.8369	3.956	3.956	0.00%
BODY.2002	SPACE.1	0.999949		0	0.8367	3.213	3.213	0.00%
BODY.2003	SPACE.1	0.999962			0.8800	3.344	3.344	0.00%
BODY.2004	SPACE.1	0.999423	0	0	0.8374	3.190	3.190	0.01%
BODY.2005	SPACE.1	0.995986	0.001	0.004	0.8373	1.331	1.331	0.02%
BODY.2006	SPACE.1	0.972783	0.01	0.027	0.8371	2.862	2.862	-0.01%
BODY.2007	SPACE.1	0.999896	0	0	0.8366	3.190	3.190	0.01%
BODY.2008	SPACE.1	0.995894	0.001	0.004	0.8374	1.331	1.331	0.02%
BODY.2009	SPACE.1	0.972702	0.01	0.027	0.8371	2.862	2.862	-0.01%
BODY.2010	SPACE.1	0.985521	0.002	0.014	0.8363	1.201	1.201	0.00%
BODY.2011	SPACE.1	0.989739	0.002	0.01	0.8369	0.973	0.973	0.01%
BODY.2012	SPACE.1	0.988361	0.008	0.011	0.8369	1.281	1.281	0.01%
BODY.2013	SPACE.1	0.985994	0.003	0.014	0.8359	1.201	1.201	0.00%
BODY.2014	SPACE.1	0.984314	0.002	0.015	0.8371	0.973	0.973	0.01%
BODY.2015	SPACE.1	0.988222	0.008	0.012	0.8371	1.281	1.281	0.01%

The residuals, or percent deviation from the baseline prediction, as seen in Figure 9 and Figure 10 are quite small though, 0.1% at the most in a hot environment and 1.7% at the most in a cold environment. For the cold environment this maximum residual describes an actual temperature difference of little more than 1°F. The greater residuals in the cold environment prediction are a function of the larger

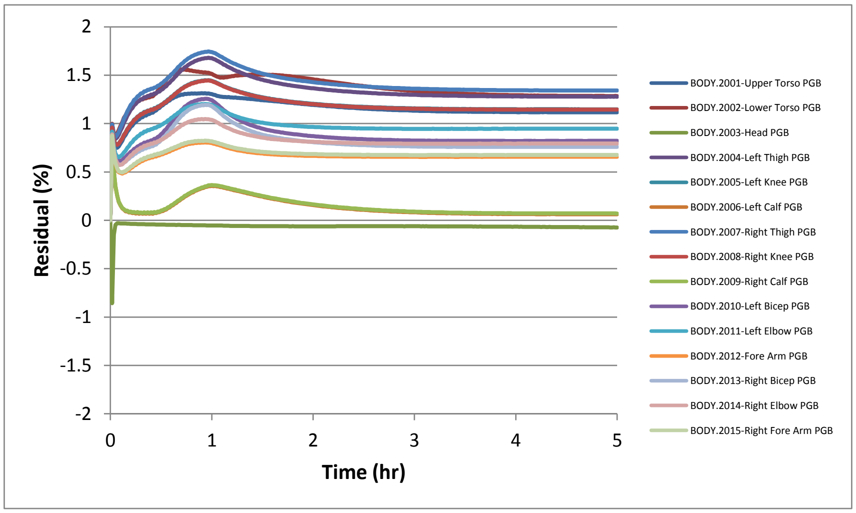

Figure 8. Residuals for the Low Temperature 1-D Validation case.

driving temperature difference between the crewmember being modeled and the environment sink temperature. In all cases the difference is well within experimental confidence for human based studies and readily explained by the heat transfer computation methodology used by the models.

The self-view heat rate calculation in the TD crewmember geometry produces a more realistic prediction of the environment heat load, so is considered a significant improvement and a benefit of the new geometry based interface. The detailed external suit geometry, because of the vastly differing shape, should be expected to produce a more realistic heat rate, and though environment conditions are similar its predictions should be expected to differ from those of the baseline model to a greater extent than those of the validation results discussed above.

The external suit geometry core and skin temperature predictions are compared to baseline predictions in Figure 9 and Figure 10 for high and low environment temperature, respectively. In both cases the difference in core and skin temperature in the new model is close to that of the baseline.

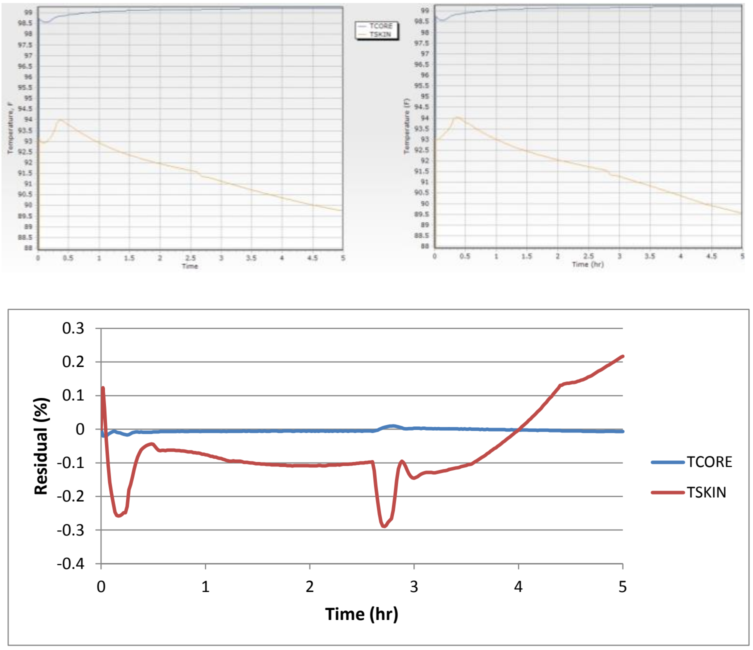

Figure 9. External Suit Geometry Core and Skin temperatures comparison and residuals at a high environment temperature. *Core and Skin temperatures of the external suit model (left) are compared to the baseline model (right). Results are similar as seen in residuals (bottom).*

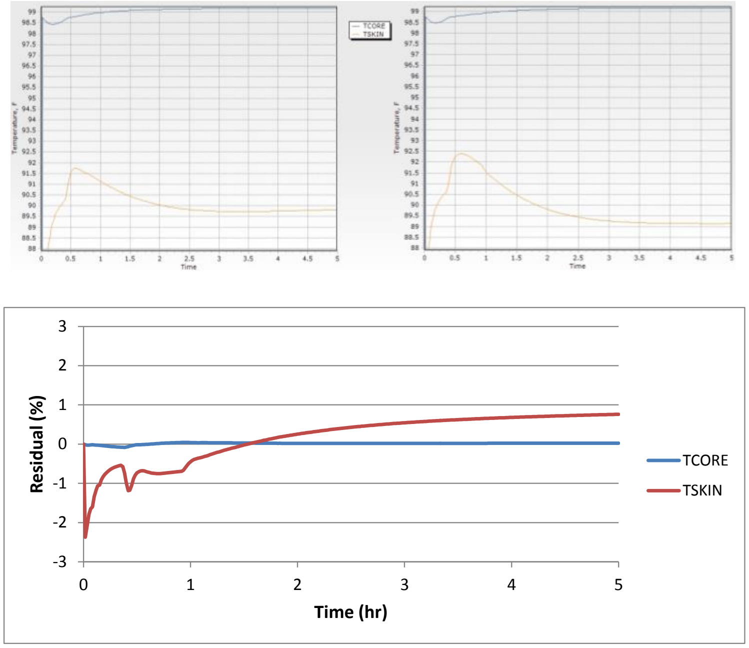

Figure 10. External Suit Geometry Core and Skin temperatures comparison and residuals at a low environment temperature. *Core and Skin temperatures of the external suit model (left) are compared to the baseline model (right). Results are similar as seen in residuals (bottom).*

IV. Conclusion

A geometric interface to the NASA version of the 225-node Wissler model has been developed and validated for the TD thermal analysis platform. The resulting tool makes possible an intimate integration of the human thermal model at the system level. This development takes advantage of the strengths of TD in geometry definition, radiation analysis, and thermal system analysis, to permit definition of complex environments and realistic suit geometries for higher fidelity system level analysis with a simulated-human-in-the-loop.

Note should be made regarding the flexibility of the newly developed Wissler interface. A primary reason the community continues to use the 225-node Wissler and 41-node metabolic man models is that these have been closely integrated with logic that is key to the space program, such as LCVG and MLI garments. By abstracting the core human model and the environment model, as has been done in this work, there is a potential path introduced toward the adoption of the latest Wissler model, the Fiala model, or future developments without the thus far limiting cost of reimplementing space industry trappings each time. What's more, this geometric interface can in future work be adapted to CFD and multiphysics platforms to analyze pressurized cabin scenarios, immersion scenarios, and perform high quality comfort studies.

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