ADAPTATION OF 25-NODE HUMAN THERMAL MODEL FOR USE IN SIERRA NEVADA CORPORATION'S *DREAM CHASER*® SYSTEM-LEVEL THERMAL DESKTOP MODEL

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ABSTRACT

Sierra Nevada Corporation (SNC) is currently working with NASA's Commercial Crew Program to develop and configure the *Dream Chaser*® spacecraft for transportation services to low-Earth orbit destinations. Part of this effort is a system-level thermal model of the vehicle to predict its thermal response during the various phases of flight, and to help with the design of active and passive thermal control systems. Since the Dream Chaser is capable of piloted or autonomous flight, the thermal response is important to the overall thermal design, especially in the crew configuration.

NASA and its contractors have developed various human thermal models since the 1960's. Two models of note include the early 25-node human thermal model[1] and its successor, the 41-node METMAN model[2]. The model divides the human body into 6 or 10 compartments. Both models use 4 nodes to model the core, muscle, fat, and skin of each compartment. The final node is to model the blood flow. Heat losses due to convection, radiation, perspiration, and respiration are modeled. The major differences between these two models are that the 41-node model distinguishes between left and right arms and legs, and also has the ability to work with humans of various sizes. However, both of these models are executed in FORTRAN programs, and have not been adapted for public use in a system-level thermal model.

This paper describes how SNC and ATA Engineering, Inc. (ATA) converted the 25-node thermal model for use in the Thermal Desktop system-level thermal model, and added features from the METMAN model to model humans of different size and anthropomorphic constituency. The models consist of a combination of SINDA nodes and conduction, along with control logic to compute the metabolic heat loads based on environmental conditions and human activity. The models can be connected to a cabin air node or to a liquid cooled garment (LCG) loop node. The model also allows for the ability to compute human CO_2 and water vapor production for cabin air environment modeling.

INTRODUCTION

As part of the analysis that SNC is currently performing to support the Dream Chaser spacecraft, a human thermal model was needed to assess the integrated impact of the crew members in the cabin environment. The lack of a publically available human thermal model, implemented in Thermal Desktop, created the need to adapt a historical model. Conversion of a historical model allows for comparison to historical data to ensure better correlation than would be available with a newly developed model.

HISTORY OF HUMAN THERMAL MODELS

Since the 1960's, NASA has funded development of human thermal models, with some of the earliest work performed on analog computers[3]. Later versions of this research began to use FORTRAN programs for use on digital computers, and led to both the 25-node man model[1], and the 41-node METMAN model[2].

As described in the 25-node man model[1], these models have two separate systems: the control system and the controlled system. The controlled system represents the thermal characteristics of human body. Thermal stresses, such as changes in ambient temperature, act on the controlled system and cause thermal imbalances. The changes to this controlled system are acted upon by the control system to minimize the thermal imbalances. For these models, the controlled system is represented by 6 to 10 segments, with each segment having four concentric layers, plus a central blood compartment that exchanges heat with the layers of each segment. Each of the compartments is represented by a heat balance equation that accounts for conductive heat exchange with the adjacent compartments, metabolic heat production, convective heat exchange with the central block compartment, evaporative heat losses, and heat exchange with the ambient environment.

The control system is divided into three distinct parts. The first part consists of the sensors that recognize the thermal state of the controlled system. The second part evaluates the input from the sensors to determine the appropriate effector commands, such as increased blood flow, vascular dilation or constriction, sweating, or shivering. The third part of the system uses these commands to adjust the thermal conductors of the controlled model and apply heat loads, such as basal metabolic heating and heat generated due to work or shivering.

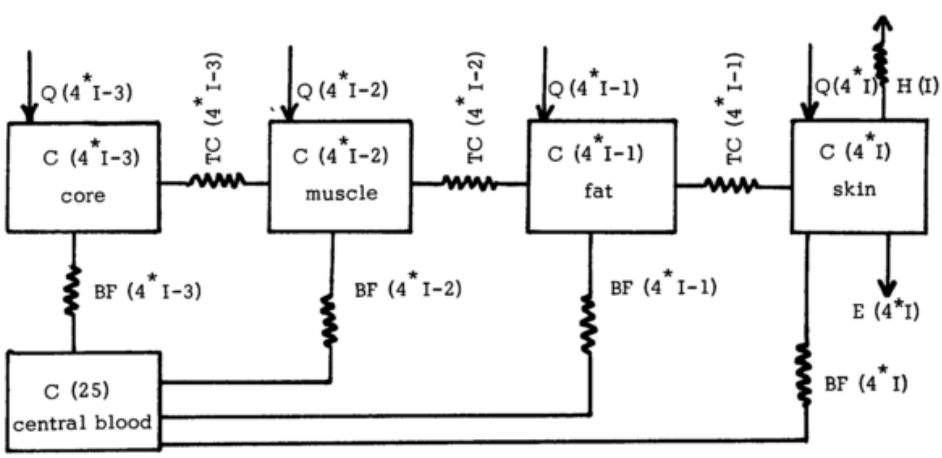
These models' output include the temperatures for each compartment and layer, metabolic rate, skin blood flow, estimated cardiac output, water loss/gain, and percentage of body that is wet with perspiration.

25-Node Man

The 25-node human thermal model[1] consists of 6 segments representing the head, trunk, arms, hands, legs, and feet. Each segment consists of 4 nodes, representing the core, muscle, fat, and skin. It also has 1 node to represent central blood loop. The internal heat transfer for a segment is shown in Figure 1. This model assumes a human with a mass of 74.4 kg, a surface area is 1.89 m^2, and a basal metabolic heat production rate of 74.45 Kcal/hr. The model also allows for the addition of heat due to work. The model was based on measurements collected from various sources.

The skin of the model is connected to the ambient air by convection and radiation. Convection is modeled with a film coefficient and radiation is linearized and also modeled with a film coefficient

The controller logic loop determines the heat load generated due to metabolic rates and shivering, the change in conduction from the blood loop to the other 24 nodes due to changes in blood flow rates, and heat and water loss/gain due to evaporation, condensation, and transpiration. The controller works to maintain the model at temperature set points for each of the segments. The temperature differences feed into 4 controllers: one for sweat production, one for blood vessel dilation, one for shivering, and one for blood vessel constriction. The signals from the controllers then affect the heat loads and conductors associated with blood flow and transpiration.



Head, I = 1 **Hands, I = 4**

Trunk, I = 2 **Legs, I = 5**

Arms, I = 3 **Feet, I = 6**

Figure 1. The schematic diagram of the four compartments of Segment I[1] shows heat transfer between segment nodes and to the central blood node.

41-Node METMAN

The 41-node METMAN model[2] was based on the work previously done [1,3]. The model consists of ten segments, representing the head, trunk, and right and left arms, hands, legs, and feet. The internal controller model is nearly identical to the 25-node model, but with variation to some of the control constants.

This model also does not assume a fixed body size, but allows for humans of various heights and weights. The height and weight information is used to determine surface area, internal conductor values, and metabolic rates. The internal capacitance is based on the mass of the body which is fat tissue and the mass of the body which is not fat. The model also allows for 4 different modes of operation: Shirt-sleeve, suited intra-vehicular activity (IVA), extravehicular activity (EVA), and helmet off. The last three modes allow for the use of a LCG loop and post-landing operations.

The model also has the additional complexity of modeling CO_2 in the vehicle, as well as modeling the LCG loop.

THERMAL DESKTOP IMPLEMENTATION

The Human Thermal Model (HTM) was created by first copying the FORTRAN code from the 25-node model[1], and running some of the test cases to determine if the model had been properly implemented. Unnecessary control parameters from the original model were removed to simplify the code. There were some variations in results, as some of the input parameters were missing, and had to be estimated.

The model was then converted to Thermal Desktop format. The capacitance of each layer was was modeled with a diffusion nodes, as shown in Figure 2. The thermal couplings were modeled with node-to-node conductors. The intra-layer conductors for each segment are shown in Figure 3, the blood loop conductors are shown in Figure 4, and the conductors to exterior sinks are shown in Figure 5. The external air sink was modeled with two arithmetic nodes: a head sink node coupled to skin layer of the head, and the body sink node coupled to the skin layers of the remaining segments. This split was to allow for modeling a suited crew member. Also, two surfaces representing the head and torso were modeled, as shown in Figure 6. These surfaces are used to visually locate the crew members in the system-level model. The nodes and conductors were given the nominal capacitance and conductance values from the FORTRAN code.

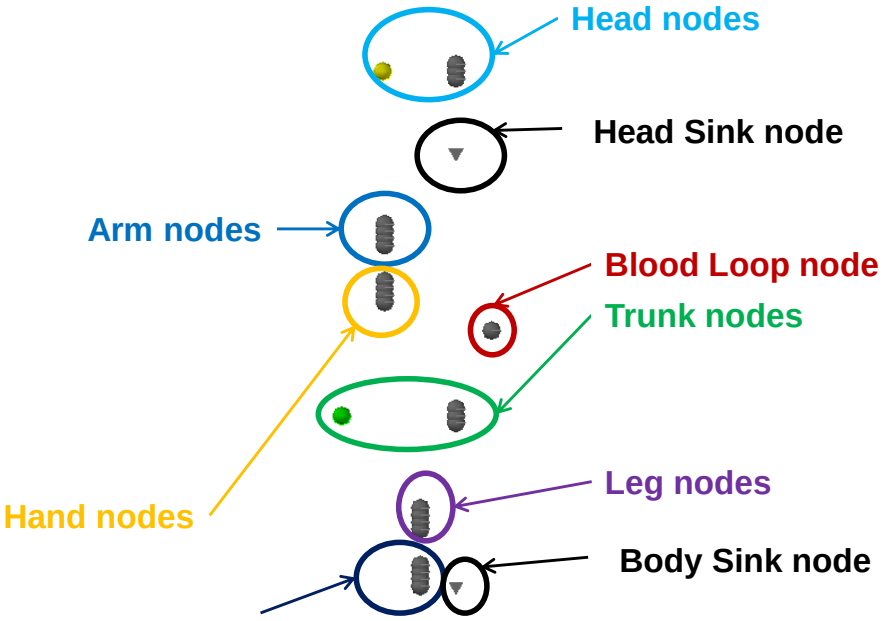


Figure 2. Visual representation of Human Thermal Model Nodes included in Thermal Desktop.

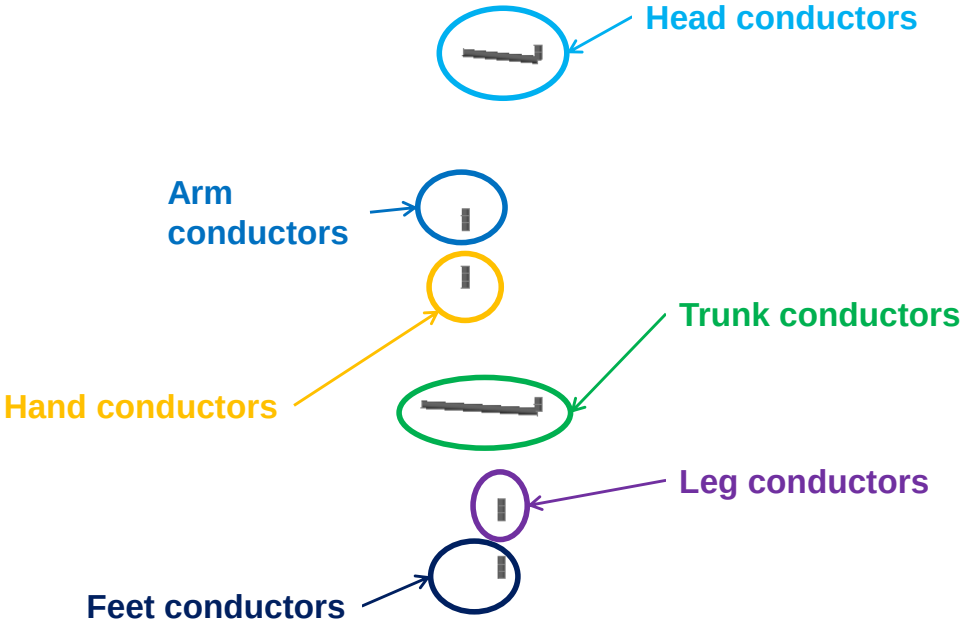


Figure 3. Visual representation of segment conductors included in Thermal Desktop model.

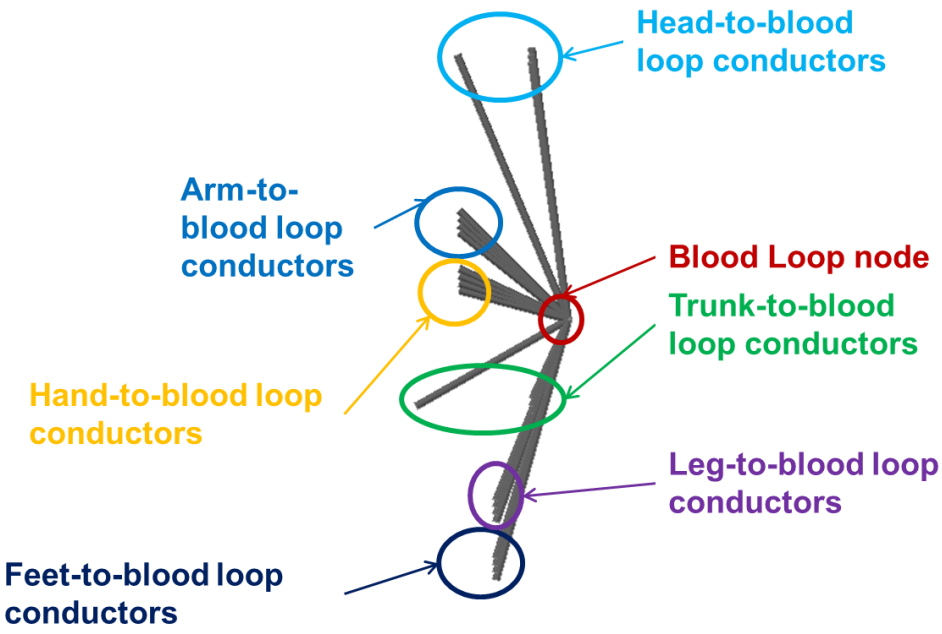


Figure 4. Visual representation of blood loop conductors included in Thermal Desktop model.

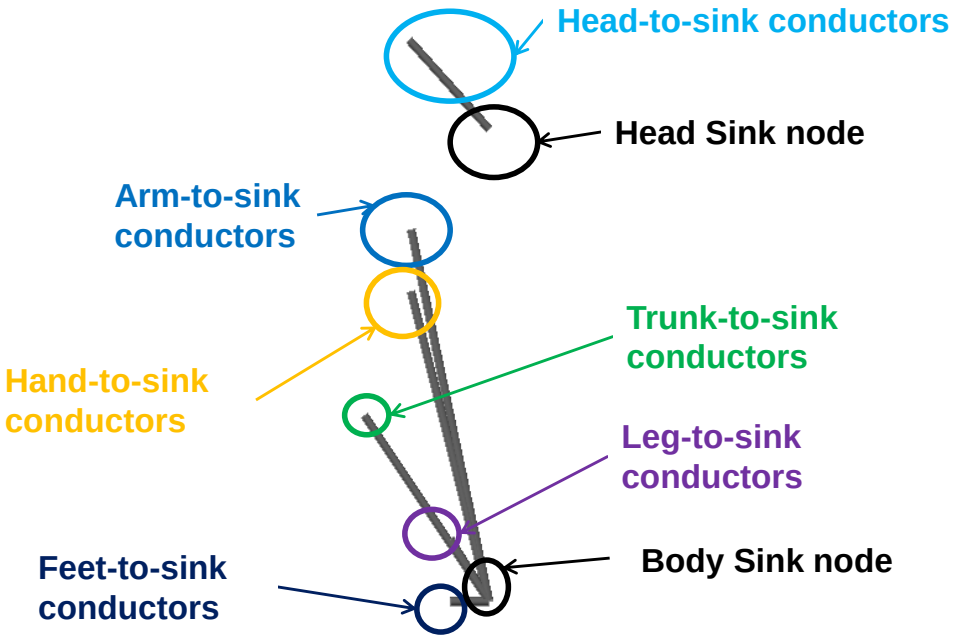


Figure 5. Visual representation of external conductors included in Thermal Desktop model.

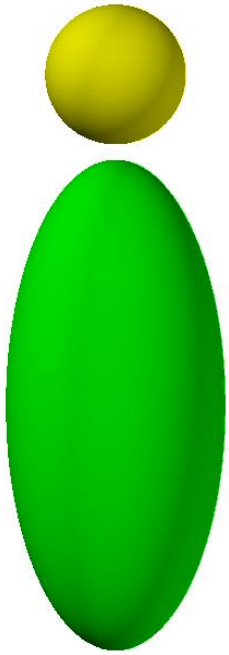


Figure 6. Surfaces used in Thermal Desktop model to visualize the Human Thermal Model.

With the conductor network created, the control system for the thermal model was adapted for use in Thermal Desktop subroutines. The routines were modified so that multiple crew members could be model in a simulation. The routines were also modified to accept any set of units required by the user, as the original model required units of kcal for energy, hours for time, °C for temperature, and meters for distance.

Features Added to 25-Node model

Once the model was adapted to work in Thermal Desktop, it was updated to allow for variable weight, height, and basal metabolic rate of crew members. The model now uses the METMAN model logic to compute: surface area based on weight and height, thermal capacitance, basal blood flow rates, and basal metabolic rate (if not specified by user). The capacitance of the model was modified from the METMAN equations to account for female crew members, as the ratio of lean body mass to total body mass is different between men and women of the same weight and height[4]. Instead of using the METMAN model equations to compute the conductors between the nodes of a segment, the conductors were modified by the ratio of the current $(\text{surface area})^2/\text{weight}$ divided by the baseline $(\text{surface area})^2/\text{weight}$. This was done to allow the model to have the same conductor values as the baseline for the same surface area and weight. The model also uses the ratio of the current model surface area to the baseline surface area to update the convective and radiative conductors and basal evaporative heat loss rates.

The model was also updated to allow for multiple crew members of different heights and weights in the integrated thermal model (ITM), and added ability to connect the model head and body air nodes to cabin air and LCG loop nodes during initialization.

Human Thermal Model Logic

The logic model for the HTM consists of 4 subroutines: an initialization routine, an update routine, a water vapor production routine, and a diagnostic print routine. These routines are stored in the GLOBAL SUBROUTINE logic block and are called from other logic blocks as described below.

The first subroutine initializes a human thermal model. It requires information about the HTM submodel name, the physical attributes of the simulated crew member, and its connections to the cabin or LCG loop. This routine is called once per HTM in the ITM from the GLOBAL TDPOSTBL logic block.

The second subroutine updates the state of the HTM at each time step (for transient) or iteration (for steady-state). The routine requires the relative humidity and the work done by the HTM. This routine performs the controller logic to update the model conductors, heat output, and water vapor output. This routine is called once for each HTM in the ITM from the GLOBAL Variables 1 logic block.

Once the model is updated, the third subroutine returns the water vapor production rate of the HTM. The output from this routine can be used to update the relative humidity in the cabin. It is called once per HTM from the GLOBAL Variables 1 logic block.

The final subroutine prints out diagnostic messages to a user-defined file. This routine is called once per model from the GLOBAL OUTPUT logic block.

FORTRAN Model Verification

Once the model was converted to Thermal Desktop format, it was compared against a test case from the original 25-node model[1]. The results are shown in Figure 7, with the results key shown in Table 1.

Table 1. Key to Column Values in Figure 7

Parameter	Definition
TIME	Time, in minutes
S	Rate of heat storage in Kcal/m^2/hr
M	Metabolic rate in Kcal/m^2/hr
EV	Total evaporative heat loss in Kcal/m^2/hr
TB	Mean weighted body temperature in °C
TS	Mean weighted skin temperature in °C
TH	Head core temperature in °C
TO	Central blood temperature in °C
TR	Trunk core temperature in °C
TM	Leg muscle temperature in °C
SBF	Total skin blood flow in liters/min
CO	Estimated cardiac output in liters/min
COND	Equivalent thermal conductance from core to skin, Kcal/m^2/hr/°C
PWET	Percentage of the skin surface as wetted area

Table 14

TIME	S	M	EV	TB	TS	TH	TO	TR	TM	SBF	CO	COND	PWET
5	2.0	40.2	7.6	35.75	33.89	36.98	36.77	36.93	35.30	0.10	4.68	12.1	2.6
10	1.9	39.9	7.6	35.76	33.85	37.01	36.81	36.97	35.30	0.10	4.67	11.7	2.6
15	1.8	39.5	7.5	35.76	33.82	37.05	36.84	37.01	35.30	0.10	4.66	11.4	2.6
20	1.8	39.4	7.5	35.77	33.80	37.08	36.87	37.04	35.30	0.10	4.65	11.2	2.6
25	1.9	39.4	7.5	35.77	33.79	37.10	36.89	37.06	35.30	0.10	4.65	11.0	2.6
30	1.9	39.4	7.5	35.78	33.78	37.12	36.91	37.08	35.30	0.10	4.65	10.9	2.6
35	82.9	39.4	38.8	36.05	36.10	37.12	36.90	37.08	35.38	0.51	5.06	-56.0	34.9
40	55.2	39.4	63.6	36.24	36.48	37.22	37.01	37.15	35.57	0.78	5.33	-33.1	55.9
45	41.0	39.4	77.4	36.35	36.53	37.31	37.08	37.24	35.77	0.98	5.53	-6.0	67.7
50	31.9	39.4	86.2	36.45	36.57	37.38	37.13	37.30	35.94	1.16	5.71	10.3	73.8
55	26.4	39.4	91.5	36.52	36.59	37.42	37.16	37.34	36.08	1.26	5.82	19.8	77.6
60	23.2	39.4	94.6	36.59	36.61	37.44	37.18	37.36	36.21	1.32	5.88	25.4	79.8
65	21.2	39.4	96.5	36.65	36.63	37.46	37.20	37.38	36.31	1.37	5.92	29.1	81.0
70	19.3	39.4	98.2	36.70	36.66	37.48	37.22	37.40	36.40	1.41	5.97	32.8	82.0
75	17.8	39.4	99.6	36.75	36.68	37.49	37.23	37.42	36.48	1.45	6.00	35.7	82.8
80	16.6	39.4	100.7	36.80	36.69	37.51	37.24	37.43	36.56	1.48	6.04	38.3	83.5
85	15.4	39.4	101.7	36.84	36.71	37.52	37.26	37.45	36.63	1.51	6.07	40.7	84.1
90	14.2	39.4	102.8	36.88	36.73	37.53	37.27	37.46	36.69	1.55	6.10	43.1	84.7
95	13.3	39.4	103.6	36.92	36.74	37.54	37.28	37.47	36.74	1.57	6.13	44.8	85.2
100	12.2	39.4	104.6	36.95	36.75	37.56	37.29	37.48	36.80	1.61	6.16	47.0	85.7
105	11.5	39.4	105.4	36.98	36.76	37.57	37.30	37.49	36.83	1.63	6.18	48.5	86.2
110	10.6	39.4	106.2	37.01	36.77	37.57	37.31	37.50	36.87	1.66	6.21	50.2	86.7
115	10.0	39.4	106.7	37.04	36.78	37.58	37.32	37.51	36.91	1.67	6.23	51.4	87.0
120	9.3	39.4	107.3	37.07	36.79	37.59	37.33	37.52	36.94	1.69	6.25	52.7	87.3
125	8.7	39.4	107.8	37.09	36.79	37.60	37.33	37.53	36.97	1.71	6.26	53.8	87.6
130	8.2	39.4	108.3	37.11	36.80	37.61	37.34	37.53	37.00	1.73	6.28	54.8	87.9
135	7.5	39.4	109.0	37.13	36.81	37.61	37.34	37.54	37.02	1.75	6.30	56.1	88.3
140	7.1	39.4	109.4	37.15	36.81	37.62	37.35	37.55	37.05	1.76	6.31	57.0	88.6
145	6.6	39.4	109.8	37.17	36.82	37.62	37.35	37.55	37.07	1.77	6.33	57.8	88.8
150	6.2	39.4	110.2	37.18	36.82	37.63	37.36	37.56	37.09	1.79	6.34	58.6	89.0
155	-70.1	39.4	70.4	36.92	35.09	37.39	36.99	37.31	37.04	0.92	5.47	55.8	37.6
160	-37.1	39.4	39.0	36.79	34.89	37.23	36.94	37.16	36.93	0.55	5.11	35.9	20.3
165	-26.0	39.4	28.5	36.71	34.80	37.18	36.93	37.12	36.82	0.44	4.99	29.3	14.4
170	-21.0	39.4	24.0	36.64	34.71	37.16	36.93	37.12	36.71	0.38	4.93	25.9	11.9
175	-18.9	39.4	22.5	36.59	34.64	37.17	36.93	37.12	36.63	0.34	4.89	24.0	11.0
180	-17.1	39.4	21.3	36.55	34.56	37.17	36.94	37.12	36.55	0.31	4.86	22.4	10.5
185	-15.8	39.4	20.5	36.50	34.48	37.17	36.94	37.13	36.47	0.29	4.84	21.2	10.0
190	-14.6	39.4	19.6	36.46	34.43	37.17	36.94	37.13	36.41	0.27	4.83	20.2	9.6
195	-13.5	39.4	18.9	36.42	34.38	37.17	36.94	37.13	36.35	0.26	4.81	19.4	9.1
200	-12.5	39.4	18.2	36.39	34.34	37.17	36.94	37.13	36.30	0.25	4.80	18.7	8.8
205	-11.5	39.4	17.5	36.35	34.29	37.17	36.94	37.13	36.24	0.24	4.79	18.0	8.4
210	-10.7	39.4	16.9	36.33	34.27	37.17	36.94	37.13	36.20	0.23	4.79	17.5	8.0

(a)

TIME	S	M	EV	TB	TS	TH	TO	TR	TM	SBF	CO	COND	PWET
0	4.2	39.4	7.9	35.78	33.97	36.96	36.71	36.89	35.30	0.20	4.75	11.7	2.8
5	2.4	39.4	8.3	35.78	34.17	36.95	36.72	36.90	35.35	0.20	4.76	13.3	3.0
10	1.8	39.4	9.0	35.79	34.16	36.95	36.72	36.91	35.37	0.21	4.76	13.4	3.4
15	1.4	39.4	9.5	35.79	34.15	36.95	36.72	36.91	35.38	0.21	4.76	13.5	3.7
20	1.3	39.4	9.6	35.80	34.15	36.95	36.72	36.91	35.39	0.21	4.77	13.6	3.8
25	1.1	39.4	9.8	35.80	34.15	36.95	36.72	36.91	35.39	0.21	4.77	13.7	3.9
30	1.0	39.4	9.8	35.80	34.15	36.95	36.72	36.91	35.39	0.21	4.77	13.7	3.9
35	70.8	39.4	50.8	36.05	36.09	36.99	36.79	36.94	35.47	0.66	5.21	-47.0	46.4
40	46.0	39.4	73.8	36.20	36.34	37.10	36.88	37.03	35.64	0.98	5.53	-15.3	66.1
45	34.9	39.4	84.3	36.31	36.43	37.18	36.94	37.11	35.81	1.22	5.77	5.5	73.5
50	28.0	39.4	91.0	36.39	36.46	37.23	36.98	37.16	35.96	1.37	5.92	18.7	78.2
55	24.3	39.4	94.5	36.46	36.49	37.27	37.01	37.19	36.08	1.46	6.01	25.8	80.6
60	21.9	39.4	96.7	36.52	36.52	37.29	37.03	37.21	36.19	1.53	6.08	31.0	81.9
65	20.0	39.4	98.4	36.58	36.55	37.31	37.05	37.23	36.28	1.59	6.14	35.4	82.9
70	18.3	39.4	100.0	36.63	36.57	37.33	37.06	37.25	36.36	1.64	6.19	39.3	83.8
75	16.8	39.4	101.3	36.67	36.59	37.34	37.08	37.27	36.43	1.69	6.24	42.9	84.6
80	15.4	39.4	102.6	36.72	36.61	37.36	37.09	37.28	36.50	1.74	6.29	46.0	85.3
85	14.2	39.4	103.7	36.75	36.62	37.37	37.11	37.30	36.56	1.78	6.33	48.7	85.9
90	13.1	39.4	104.6	36.79	36.64	37.38	37.12	37.31	36.61	1.81	6.37	51.2	86.5
95	12.2	39.4	105.5	36.82	36.65	37.39	37.13	37.32	36.65	1.85	6.40	53.4	87.0
100	11.3	39.4	106.3	36.86	36.66	37.40	37.14	37.33	36.70	1.88	6.43	55.4	87.5
105	10.5	39.4	107.0	36.88	36.67	37.41	37.15	37.34	36.73	1.90	6.46	57.1	87.9
110	9.8	39.4	107.7	36.91	36.68	37.42	37.15	37.35	36.77	1.93	6.48	58.8	88.3
115	9.1	39.4	108.3	36.94	36.69	37.43	37.16	37.36	36.80	1.95	6.51	60.3	88.7
120	8.5	39.4	108.9	36.96	36.69	37.44	37.17	37.36	36.83	1.98	6.53	61.6	89.0
125	7.9	39.4	109.4	36.98	36.70	37.44	37.17	37.37	36.86	2.00	6.55	62.9	89.3
130	7.4	39.4	109.9	37.00	36.71	37.45	37.18	37.38	36.88	2.01	6.57	64.0	89.6
135	6.9	39.4	110.3	37.02	36.71	37.45	37.19	37.38	36.90	2.03	6.59	65.1	89.9
140	6.5	39.4	110.7	37.04	36.72	37.46	37.19	37.39	36.92	2.05	6.60	66.0	90.1
145	6.1	39.4	111.1	37.06	36.72	37.46	37.20	37.39	36.94	2.06	6.62	66.9	90.4
150	5.7	39.4	111.4	37.07	36.73	37.47	37.20	37.40	36.96	2.08	6.63	67.8	90.6
155	-63.8	39.4	68.8	36.80	35.00	37.21	36.81	37.13	36.91	0.90	5.45	55.2	37.4
160	-35.0	39.4	41.2	36.68	34.83	37.07	36.78	37.00	36.80	0.57	5.12	36.5	21.8
165	-25.3	39.4	32.1	36.60	34.74	37.03	36.78	36.97	36.70	0.46	5.01	30.2	16.7
170	-20.9	39.4	28.2	36.54	34.66	37.02	36.77	36.97	36.60	0.41	4.97	27.1	14.5
175	-18.1	39.4	25.8	36.48	34.60	37.01	36.77	36.96	36.52	0.39	4.94	25.1	13.2
180	-16.1	39.4	24.2	36.44	34.55	37.01	36.77	36.96	36.45	0.37	4.93	23.6	12.3
185	-14.5	39.4	22.9	36.40	34.51	37.00	36.77	36.96	36.38	0.36	4.91	22.5	11.5
190	-13.2	39.4	21.8	36.36	34.48	37.00	36.76	36.95	36.32	0.35	4.90	21.7	10.9
195	-12.1	39.4	20.9	36.33	34.45	37.00	36.76	36.95	36.26	0.34	4.89	20.9	10.4
200	-11.2	39.4	20.1	36.30	34.43	36.99	36.76	36.95	36.21	0.33	4.88	20.3	10.0
205	-10.3	39.4	19.4	36.27	34.41	36.99	36.76	36.95	36.16	0.32	4.87	19.8	9.6
210	-9.6	39.4	18.8	36.24	34.39	36.99	36.76	36.94	36.12	0.31	4.87	19.4	9.2

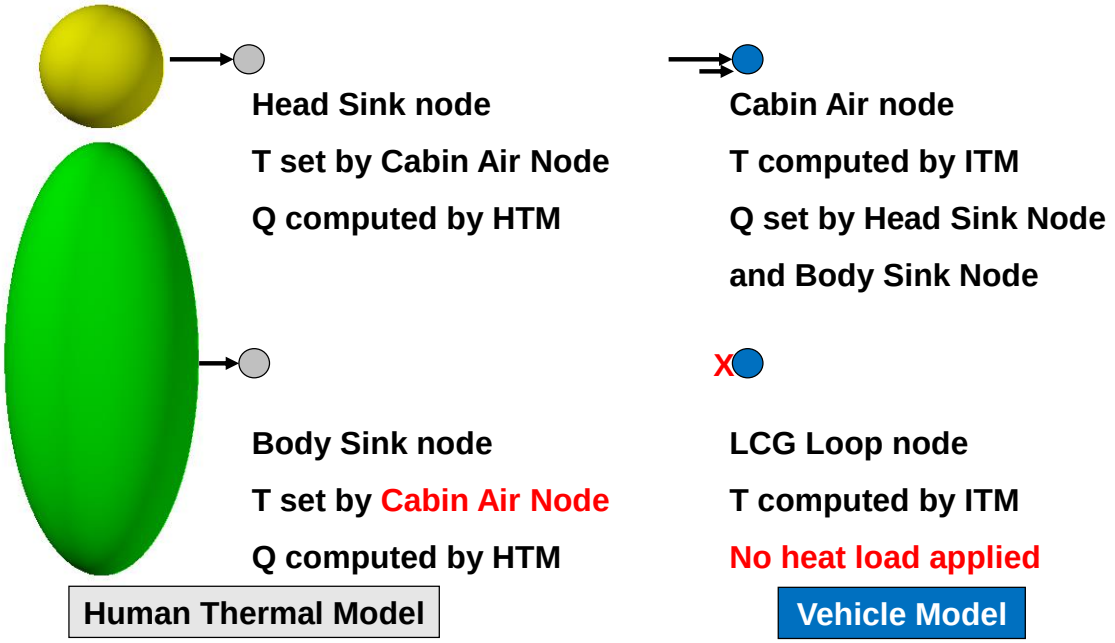
(b)

Figure 7. Results for original FORTRAN model (a) and current Thermal Desktop model (b) compare favorable to each other.

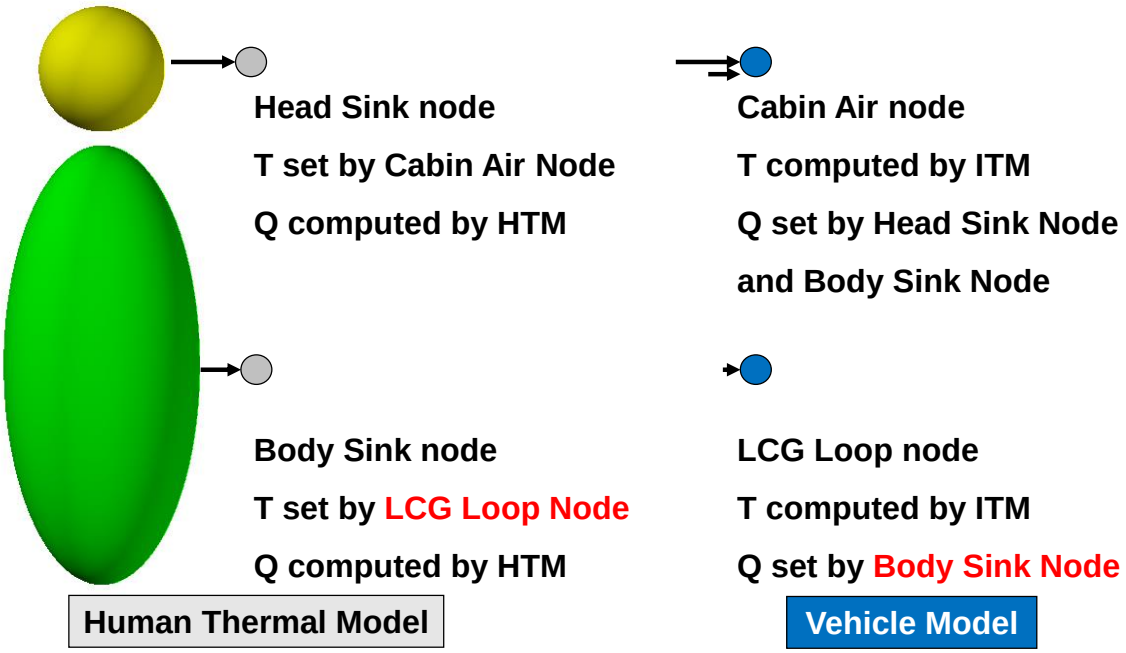
Connection to Environment

The human thermal model is not directly tied to the integrated thermal model. Instead, the air nodes for the head and body of the HTM are set based on the current temperature of a cabin air node or a LCG Loop node, and the heat gain or loss to the node is then applied to the cabin air node or LCG Loop node, depending on if the HTM is unsuited or suited and connected to the LCG loop, as shown in Figure 8. The mode of operation is set by the LCG_switch variable.

If it is LCG_switch is 0, the HTM is in the unsuited mode. Both the head and body sink node temperatures are set to the current cabin air temperature, and the heat loads due to convection and radiation from the HTM are applied to the cabin node. If the LCG_switch is not 0, If the HTM is in the suited mode. The convective and radiative conductors are modified to reflect the suited configuration. The head sink node temperature is set to the cabin node temperature, and the body sink node set temperature to the current LCG loop node temperature. The convective heat loads for both the head and body are applied to the cabin air node, since the air in the suit is forced into the cabin. The radiative heat load for the head also applied to the cabin air node. In the suited mode, there are no losses from the body due to radiation, but there are due to conductive losses to the LCG loop. So the “radiative” conductors are modified to represent the conductive heat transfer, and the resulting heat load is applied to the LCG loop node.



(a)



(b)

Figure 8. Coupling methods for an unsuited (a) or suited (b) crew member allow heat transfer to be applied to the appropriate nodes of the ITM.

ITM APPLICATION

The human thermal model is self-contained and will run with the basic boundary conditions stated above. However, integration into an ITM requires that it be imported and set up to interface with existing nodes in the ITM. The FORTRAN subroutine and function calls keep the model modular and allow for easy integration. The geometric math model (GMM) portion of the model is for visual representation only, so no radiation groups or convection conductors are required to be set up. Once imported, the only setup requirement is to change the air and LCG boundary nodes in the initialization call to the proper ITM nodes.

Human Thermal Model Import

There are three primary, required, steps for the import of the human thermal model to an integrated thermal model. First, the model must be imported as a block and exploded. Any relocation of the human thermal model is most easily completed while still in block form. Second, the logic blocks and symbols must be imported. Lastly, the initialization logic block must be updated to use the correct boundary nodes.

Setup Subroutine Call and Output Logic

Further customization can be done depending on the specific needs of the model. This includes multiple crew members, tailoring to personal attributes such as gender, stature and metabolic rate and any model automation such as wrapping the subroutine calls in control logic.

For multiple crew members, the model must be imported again for each additional crew member. The default submodel name for the human thermal model is “HM25”. This must be changed before importing additional copies of the model. The procedure to add a crew member is: import the model as a block, relocate as needed, explode the block, and then rename the submodel. Each crew member must have a unique submodel name, such as “PILOT”, “COPILOT”, “CREW_1”, “CREW_2”, etc. In the GLOBAL TDPOSTBL logic block, a call to the initialization subroutine must be made for each crew member. This is where the submodel, crew number, and personal attributes are specified. The calculation update and output routines must also be called for each crew member in the appropriate logic block. If the number of crew members is variable, control logic can be used to call the correct number of crew for a given run. This would also correspond to a selective build statement in the case set manager.

Air Node Mass Requirements

When only looking at the effect of the environment on a crew member, the air node can be a boundary with a fixed temperature. However, if information about the crew member’s effect on the cabin environment is required, the heat load into the air can also be modeled. In this case, a diffusion node is required instead of an arithmetic node.

The human thermal model uses the temperature of the air node in calculations of physiological effects such as metabolic heat generation, shivering and sweating. The heat dissipation of the crew member is then calculated and applied to the air node. With this closed loop feedback, an arithmetic node can cause instability in the calculation that requires small time steps and leads to a slow integrated model. This issue is exacerbated by multiple crew members. To dampen the effect of the feedback, the air node needs to have mass to slow down the thermal response.

Integrated Model Data

For effects of the environment on the crew, the output file, as described above, will provide the necessary data. However, additional integrated model data interpretation is required to understand the crew member effects on the Environmental Control and Life Support System (ECLSS) system. The available data is dependent on the fidelity of the environmental model within the ITM.

At the minimum, the heat output of the crew members is available. With a diffusion air model, transient air temperature will be available. Furthermore, an available output of the human thermal model is humidity production. If a full ECLSS system in modeled, with humidity rejection capability, the relative humidity and condensation potential can also be calculated.

MODEL LIMITATIONS AND FUTURE UPDATES

The current model revision does not differentiate the heat transfer coefficient between suited and unsuited crew members. In reality, there will be a different capability to cool the crew by LCG than by air convection. The model has preliminary tags to allow for different coefficients; however they are unknown at this time. Future updates will include different values. Currently, the switch between LCG and air cooling changes the interface node for the body, and applies the LCG convective load to the LCG loop node.

CONCLUSIONS

Starting with an existing FORTRAN model and modifying it for use in Thermal Desktop has saved time and provided a valuable solution for integrated thermal modeling. The integration of a human thermal model with a vehicle level model allows a design time to verify that human comfort and survivability requirements are met. Along with a full ECLSS model, vehicle design requirements can also be verified with higher fidelity than rule of thumb type solutions that tend to drive up cost and mass.

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NOMENCLATURE, ACRONYMS, ABBREVIATIONS

ECLSS Environmental Control and Life Support System

HTM Human Thermal Model

ITM Integrated Thermal Model

LCG Liquid-Cooled Garment

SNC Sierra Nevada Corporation

ISS International Space Station

IVA Intra-vehicular Activity

EVA Extra-vehicular Activity

GMM Geometric Math Model

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