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Developing a Daily Metabolic Rate Profile for Human Exploration Missions

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Loads imposed on the Environmental Control and Life Support System (ECLSS) of human spacecraft can be greatly affected by the activity level of the crew. Water vapor, sensible heat and carbon dioxide outputs are all affected by instantaneous and average metabolic rates. This is especially true when rigorous exercise is required during extended missions to maintain astronaut health and performance. Thus an appropriate metabolic rate profile based on mission duration as well as other factors is an important design driver for the ECLSS. These factors are discussed and updated based on NASA's latest exploration plans and data from ground testing involving human subjects. Some of the most significant updates from past metabolic rate profiles used by NASA are increased moisture from sweat, increased carbon dioxide due to longer exercise duration, and consideration of a wider range of crew body size and increased fitness levels.

Nomenclature

ARED	=	Advanced Resistive Exercise Device
CEVIS	=	Cycle Ergometer with Vibration Isolation and Stabilization
ECLSS	=	Environmental Control and Life Support System
EVA	=	ExtraVehicular Activity
HIDH	=	Human Integration Design Handbook
ISS	=	International Space Station
MPCV	=	Multi-purpose Crew Vehicle (aka Orion)
SODB	=	Shuttle Operations Data Book
T2	=	2nd generation Treadmill
VO_2max	=	Maximum rate of oxygen use

I. Introduction and History of Metabolic Profiles

In order to properly design the Environmental Control and Life Support System (ECLSS) of human spacecraft the metabolic loads of the crew must be known in addition to any heat and gas loads (and leaks) of the vehicle itself. For the humans, this means perspiration (liquid and vapor water), carbon dioxide exhaled, urine, feces and sensible heat. Loads on the air system in particular are greatly affected by the instantaneous and average metabolic rates, and thus activity level, of the crew.[1] For this reason, it is useful to have a realistic profile of these loads over the course of a typical day to design against. For future exploration missions, this starts with the exercise prescriptions expected. These activity levels, duration and planned frequency (i.e., days per week) can then be translated into metabolic rates of the crewmembers throughout a typical day. Human thermal modeling programs such as Metabolic Man[2] (aka MetMan or 41-node Man) and Wissler can then be run in transient mode to predict sensible and latent heat output

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versus time. Since crewmember size and fitness levels, as well as other assumptions, affect these results, several cases will be presented here. Exploration programs can then select which case(s) to design against based on mission plans and risk posture.

In the Space Shuttle program, the Shuttle Operations Data Book (SODB) gave maximum, minimum and average metabolic rates for sleep and awake periods, without mention of exercise.[3] Maximum (awake) was 686 kJ/hr (191 W, 650 BTU/hr), nominal 24-hour average was 472 kJ/hr (131 W, 447 BTU/hr) and minimum was 317 kJ/hr (88 W, 300 BTU/hr) during sleep.

When planning began for a crew exploration vehicle [later known as Multi-purpose Crew Vehicle (MPCV)] in the early 2000's, subject matter experts in human physiology and life support systems began working together to come up with a metabolic profile to use for ECLSS design. What they developed was eventually published in NASA's Human Integration Design Handbook (HIDH)[4] and Orion's Human Systems Integration Requirements[5]. The table for metabolic loads of an 82kg reference astronaut performing 30 minutes of daily exercise is reproduced in Table 1. The reference astronaut was based on the average size of the astronaut corps male population, projected to the year 2015.

Table 1: Daily Metabolic Load Profile Developed Originally for NASA's Crew Exploration Vehicle. *Adapted from ref. 4 with different units shown.*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	not listed	not listed	143	192	335	4.62	0.16	3.94	4.99
Exercise - Aerobic	0.25	not listed	not listed	173	653	826	12.84	3.35	3.94	4.99
Recovery	0.25	not listed	not listed	158	399	557	8.38	1.52	0.57	0.72
Recovery	0.25	not listed	not listed	136	164	299	4.03	0.04	0.57	0.72
Recovery	0.25	not listed	not listed	129	111	240	2.74	0.00	0.57	0.72
Recovery	0.25	not listed	not listed	126	82	209	2.04	0.00	0.57	0.72
Nominal	14.50	not listed	not listed	91	48	139	1.18	0.00	0.57	0.72
Sleep	8.00	not listed	not listed	62	26	88	0.63	0.00	0.36	0.46
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	**24.00**	not listed	not listed	**7351**	**4649**	**12000**	**1.85**	**0.08**	**0.82**	**1.04**

In 2017 subject matter experts began meeting again to discuss what human metabolic profile(s) might be appropriate for design of a deep space habitat or other long duration exploration vehicles for Mars missions. The first concern was to account for exercise periods longer than 30 minutes per day, which have become customary on the International Space Station (ISS) to maintain crewmember's health. Some discrepancies had also been found in the MetMan code and data assumptions used for earlier metabolic profile predictions, and the subject matter experts knew that the model's predictions were not always well correlated with test data. These discrepancies mainly delt with hard-coded values and input data that assumed a 70 kg (154 lb) person even though the HIDH size is 82 kg. The sections below describe the efforts of the group to improve the math models and recommend improved metabolic profiles suitable for exploration ECLSS design.

II. Exercise for Exploration

Spaceflight missions require exercise countermeasures that are aimed at preventing loss of aerobic and musculoskeletal conditioning for any mission 8 days or longer. Aerobic and resistance exercise capabilities are current operational countermeasures on the ISS to maintain crew health and performance capabilities through mitigation of multi-system physiological adaptations to 0-g. Exercise prescriptions per crewmember for missions less than 30 days include a minimum of 30-60 minutes of alternating daily resistance and aerobic exercise. Missions longer than 30 days include up to 6 days a week of daily resistance and aerobic exercise. An exercise training stimulus needs to provide an overload stimulus (e.g. high intensity and high load capabilities). These maximal and sustained intensity efforts are critical training stimuli. Without dedicated exercise training (including time and vehicle system resources), performance decrements could lead to a loss of mission objectives and could put crewmembers' health and safety at risk.

ISS exercise hardware, including the advanced resistance exercise device (ARED), 2nd generation treadmill (T2), and cycle ergometer with vibration isolation and stabilization system (CEVIS), are designed to provide astronauts with the ability to exercise at higher resistance loading and higher aerobic-based exercise intensity. Many of the support improvements deployed to ISS will not be compatible with deep space vehicles in their present form. Mass and volume will be at a much greater premium than for current ISS missions or prior Space Shuttle missions. These vehicles, currently referred to as the Orion crew capsule, the lunar-orbiting ‘Gateway’ station, and a planned commercial lunar lander, constitute the ‘Artemis’ human lunar program. These vehicles will be smaller in size and will not be able to support the large resistive and aerobic exercise equipment currently deployed to ISS. These exploration programs are currently only allocating for a single exercise device to provide these high load and high aerobic based intensity exercise capabilities. This means the crew will need to perform back to back exercise sessions throughout the day in a confined space, which will stress the ECLSS compared to the larger volume and location of exercise devices available on ISS.

Exercise countermeasures will challenge the ECLSS beyond the normal energy expenditure of sleeping and other nominal non-exercise daily activities. Historically, the MetMan model has been used to calculate expected metabolic loads to inform ECLSS requirements. The primary limitation of the ECLSS as it relates to exercise is typically humidity control as opposed to maintenance of temperature or oxygen or carbon dioxide levels in the air. Exercising humans contribute significant moisture to the environment by increased sweating during exercise. Metabolic outputs for the crew based on the expected astronaut population size and fitness level need to be accommodated in order to allow for effective use of exercise hardware and maintenance of aerobic conditioning. While necessary to maintaining optimal crew performance, exercise requirements must be balanced against ECLSS capabilities. Allowing crew to exercise in-flight or on the lunar surface beyond what is necessary to maintain muscle, aerobic and mental fitness for duty, can have significant impacts within a closed-loop life support system. Unnecessary energy expenditure requires additional O_2, CO_2 and humidity removal, food and water consumption, and greater power usage to operate all these systems. So, although exercise is critical to mission success, the timing and dose of exercise countermeasures must be weighed against potential system impacts.

III. Human Metabolic Modeling

A. MetMan

The transient metabolic man computer program (MetMan), also known as 41-Node Man, is designed to simulate heat transfer from the human to the immediate environment. It includes the heat and mass transfer within the person and includes both shirt-sleeve environment and the use of a space suit for either intravehicular activity (IVA) or extravehicular activity (EVA). The 41 nodes consist of 10 body segments with 4 layers in each segment plus a central blood node for node 41. The focus of this paper will be in a cabin or shirt-sleeve environment, therefore the suited modes of operation will not be discussed.

The MetMan program is based on work by Stolwijk[6] under a NASA grant to develop a mathematical model of a human during the 1960’s for the Apollo Lunar program. This model was formulated as 25 nodes but was extended to 41-Nodes by NASA/JSC.

Historically the MetMan program has been used to determine if the crew would be in any risk due to its environment and metabolic activity. This was done for the Space Shuttle program to evaluate certain failure scenarios. Some of the outputs from MetMan are Oxygen (O_2) consumption, Carbon Dioxide (CO_2) production, sensible heat rejection and latent heat rejection. While O_2 use and CO_2 output are directly related to the metabolic rate, the sensible and latent heat rejection depend on the environment as well as the state of the crew.

As mentioned above, to develop crew interface requirements for MPCV (early name for Orion), a panel was put together to determine the nominal environment for the crew as well as the exercise requirement. Using these inputs, a nominal metabolic load table was created with MetMan that defined the sensible and latent heat on the cabin environment as well as CO_2 produced and O_2 consumed (Table 1). The metabolic load table was constructed based on 30 minutes of exercise followed by 1 hour of recovery reported in average rates over 15-minute increments. The exercise was assumed to be at 75% of the $VO_{2,max}$ value for the representative crewmember. This person was taken as the projected average size of the astronaut corps male subject in the year 2015, which was a weight of 82 kg (181 lbs). MetMan doesn’t differentiate between the male and female, but all of the original correlation work was performed using male test subjects. This table was later included in reference 4 and will be referred to as the HIDH metabolic loads and the HIDH reference size individual.

B. Sweat Test Data Correlation

MetMan sweat logic is based on work done by Bullard, Banerjee and MacIntyrl[7] which performed resistance hygrometry by measuring the amount of moisture from a small capsule placed over a subject’s thigh. This was performed for several test subjects and a correlation was developed that was extended over the entire body. Some studies have indicated that there is considerable variation in sweat rate in different body segments[8]. Analysis of the Stolwijk test data using the MetMan model has indicated that the model does a fairly good job at nominal environmental conditions but diverges substantially at high relative humidity.

In 2018, the Biomedical Research and Environmental Sciences Division at NASA/JSC in collaboration with the Crew and Thermal Systems Division performed a series of exercise tests for the purpose of studying reduced moisture loads on the the Orion ECLSS[9] during exercise. For 30 subjects, tests compared total sweat output from a thirty minute, continuous rowing sessions at ~75% of VO_2max with two other higher intensity but shorter duration interval sessions (four minute and thirty second interval sessions at ~120% and ~200% of continuous session workload respectively). The environmental conditions for these tests and subsequent analysis were at the center of the comfort envelope at 23.9°C (75°F) and 34% relative humidity. Because the interval sessions entail less total work and thus produced less total sweat, the study concluded that higher intensity interval exercise may be an alternative for reducing moisture load in a small habitable volume while preserving crew aerobic capacity.

Data from only the thirty minute continuous exercise sessions were used for MetMan correlation. Uncertainty in the MetMan program response to rapid transients of the interval exercise sessions could have added variability. Also, the continuous session is most similar to the aerobic exercise protocol for most space missions.

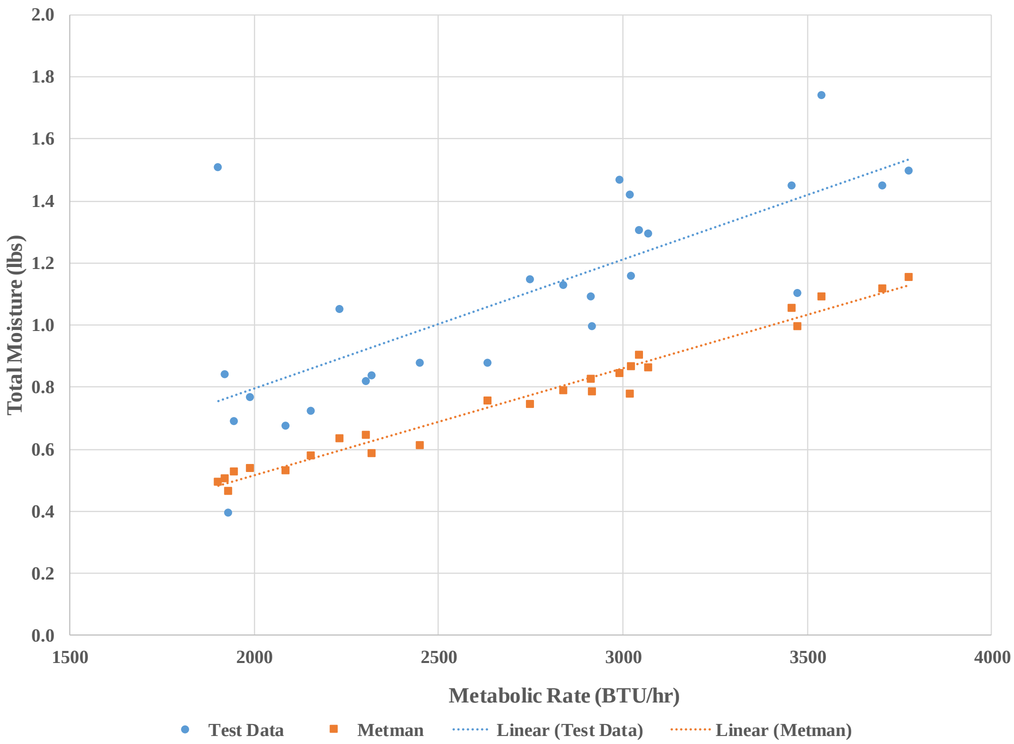

Figure 1. Metman Comparison with Test data. *This shows how the original Metman program total sweat production compared to the sweat test results (exercise plus recovery moisture; metabolic rate is average over the 30 minute exercise period)*

Using the VO_2 data along with the height and weight of the test subjects, a series of MetMan input files were generated to determine how the model compared to the sweat plus respiration produced during the test. The VO_2 data were converted to metabolic rates for the 30 test subjects. The sweat data was obtained by taking the nude body weights prior to the test, at the end of exercise, and at the end of a 30 minute recovery period with a high accuracy scale. The clothing was weighed prior to exercise and at the end of exercise and a second set of clothes was weighed prior to recovery and at the end of recovery. Respiratory gases were collected with a metabolic measurements system. Using these weights, all of the sweat and respiration data were captured.

Examination of the total sweat and respiration moisture produced, as shown in Figure 1 for the 30 tests, and comparing it to the MetMan analyses showed that the model under-predicts the total moisture under these conditions. Using the total sweat plus respiration produced during the test as an indicator, the comparison between Metman and the test data yielded a sum of the error squared as 4.36. Even though there was more variability in the test subjects than the analyses, it was decided that the sweat equation should be modified in the model.

Since the model needed to be improved in order to become a better predictor of total sweat output during exercise, the task was to determine how to modify the program. Several parameters were examined to see how they would modify the end result and also to make certain there is justification to make the modification.

The sweat equation surfaced as the most compelling factor to be changed since there was some uncertainty in how well the original data fits the test subjects at the time the work was being done. The sweat equation as used in MetMan is presented below. This assumes that thermoreceptor structures are present in all tissues. The output from the thermoreceptors would result in an error signal on how much deviation exists between the actual temperature and the set point temperature of that compartment.

$$Sweat = CSW \bullet Error(1) + PSW \bullet Warm(1) \bullet Warms$$

Where:
CSW = 884 (Sweating from head core) (BTU/hr/°F)
PSW = 73.4 (Sweating from skin and head core) (BTU/hr/°F^2)
Warms = Integrated output from skin warm receptors (°F)
Warm (1) = Thermal signal from brain (°F)
Error = output from thermoreceptors in the compartment (°F)
Sweat = summation of sweat output signals from all compartments (BTU/hr)

The latent heat is then determined by:

$$Q_{latent} = Q_{Dif} + Skins \bullet Sweat \bullet 2^{(T - T_{set})/7.2}$$

Where:
Q_{Dif} = Heat transfer by diffusion (BTU/hr)
Skins = Fraction of sweating command applicable to skin
Sweat = Total efferent sweat command from Sweat equation above
T_{set} = Set point temperature of body segment (°F)
T = Temperature of body segment (°F)
Qlatent = Total latent heat from skin for each segment (BTU/hr)

The term that was modified to correlate the MetMan model with the sweat test data was the Sweat term. The total efferent sweat command was modified by a multiplication factor for the exercise period. This factor was triggered by the total metabolic rate being above 700 BTU/hr (205 Watts). The result of this correlation effort is shown in Figure 2. It shows the MetMan model now agrees better with test data. In the improved model, the Root Mean Square Deviation (RMSD) is 0.23 versus 0.38 for the previous model, which is a better predictor overall.

C. Metabolic Profile Updates

Initial work focused on the reference 82kg subject profile and differences from HIDH[10]. Preparation for currently planned exploration missions such as Orion and Gateway also required that the metabolic load table assumptions be reviewed and updated. In terms of environmental factors, the air and wall temperatures were changed from 21°C to 24°C (70°F to 75°F), respectively. The spacecraft pressure was changed from 70.3 kPa (10.2 psia) to 101.4 kPa (14.7 psia). The work efficiency of the exercise device was changed from 5% to 15% based on the sweat study with a rowing type device. Also the respiratory quotient (RQ) was originally assumed to be 0.92 for all metabolic rates. The RQ is defined as the molar ratio of CO_2 released to the O_2 consumed. The actual value of RQ depends on the proportion of carbohydrate, fat and protein metabolized[11] and is dependent on the individual diet as well as exercise level. The Biomedical Research and Environmental Sciences Division performed some measurements at different metabolic rates and the new RQ was determined to be 0.86 for nominal and sleep, 0.95 for aerobic exercise and 0.96 for resistive exercise.[12]

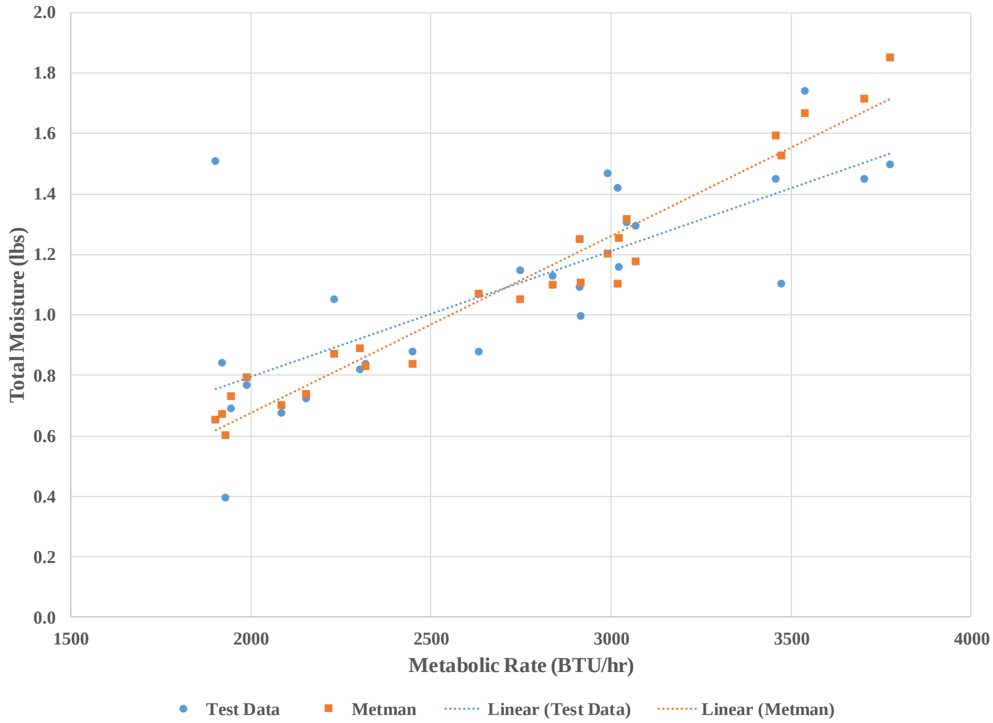

Figure 2. MetMan Correlation with Test Data. *Final correlation for the total sweat production from MetMan compared to the test data (exercise plus recovery moisture; metabolic rate is average over the 30 minute exercise period).*

The actual metabolic rates and length of exercise were also updated to match current practice as described in section II. The original HIDH metabolic rate during exercise was set at 3458 kJ/hr (961W, 3278 BTU/hr). This was not stated in Table 1 explicitly as the values in the table are the output results from MetMan. The HIDH metabolic rate was developed from the astronaut corps data for the MPCV program and was agreed to by the experts at the time. The new exploration mission profile has two types of exercise - aerobic and resistive. The aerobic exercise is set at 3487 kJ/hr (969 W, 3305 BTU/hr) and the resistive exercise is estimated to average 1251 kJ/hr (348 W, 1186 BTU/hr) for a medium fit person. These metabolic rates are normalized for the HIDH size individual of 82 kg and based on studies performed by the Biomedical Research and Environmental Sciences Division.

Finally the length of the exercise and type is determined by the length of the mission planned. For missions less than or equal to 30 days, the exercise is 30 minutes of aerobic exercise followed by 1 hour of recovery. Resistive exercise (done on alternate days) will not be as challenging a case for the ECLSS since average metabolic rates during the exercise period are lower, so the resistive only case is not considered for spacecraft design. For missions greater than 30 days, the exercise would be 30 minutes of aerobic plus 60 minutes of resistive on the same day, followed by one hour of recovery. The one hour recovery period (compared to a half hour modeled in HIDH) was selected to improve fidelity.

The fitness level of the individual will make a difference in the metabolic rate as computed from the VO_2 data. The fitness level is termed as low, medium or high. The low, medium and high fitness levels were defined as 35, 45 and 55 ml/kg/min VO_2max, respectively. In most cases, medium fitness level was selected, although the high fitness level is used in some cases to define the worst case conditions.

Tables 2 and 3 show the final metabolic load tables for the short (≤30 days) and long (>30 days) exercise protocol. Examination of the totals row shows that most of the extra energy for the long exercise duration goes into the latent heat output.

Table 2. Metabolic Load Results for HIDH size with short exercise protocol. *This is at medium fitness level and a variable RQ.*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	968	132	133	272	405	6.72	1.19	3.99	5.22
Exercise - Aerobic	0.25	968	132	129	542	671	13.41	11.45	3.99	5.22
Recovery	0.25	139	0	94	278	372	6.87	1.53	0.59	0.69
Recovery	0.25	139	0	90	170	260	4.21	0.18	0.59	0.69
Recovery	0.25	139	0	88	127	215	3.15	0.03	0.59	0.69
Recovery	0.25	139	0	86	103	190	2.56	0.00	0.59	0.69
Recovery	0.25	139	0	86	88	174	2.17	0.00	0.59	0.69
Recovery	0.25	139	0	86	78	163	1.92	0.00	0.59	0.69
Recovery	0.25	139	0	85	71	156	1.75	0.00	0.59	0.69
Recovery	0.25	139	0	85	66	151	1.62	0.00	0.59	0.69
Recovery	0.25	139	0	85	62	147	1.54	0.00	0.59	0.69
Recovery	0.25	139	0	85	60	145	1.48	0.00	0.59	0.69
Recovery	0.25	139	0	85	58	143	1.43	0.00	0.59	0.69
Recovery	0.25	139	0	85	57	142	1.40	0.00	0.59	0.69
Nominal	12.50	139	0	85	54	139	1.33	0.00	0.59	0.69
Sleep	8.00	88	0	44	44	88	1.08	0.00	0.37	0.44
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	**24.00**	**12027**	**238**	**6283**	**5512**	**11795**	**2.27**	**0.22**	**0.84**	**1.01**

Table 3. Metabolic Load Results for HIDH size individual using long exercise protocol. *This is at medium fitness level and variable RQ.*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	968	132	134	283	417	6.99	1.34	3.99	5.22
Exercise - Aerobic	0.25	968	132	130	545	675	13.48	11.82	3.99	5.22
Exercise - Resistive	0.25	347	39	116	469	585	11.60	11.86	1.43	1.89
Exercise - Resistive	0.25	347	39	97	342	438	8.44	2.18	1.43	1.89
Exercise - Resistive	0.25	347	39	94	270	364	6.66	0.78	1.43	1.89
Exercise - Resistive	0.25	347	39	94	240	335	5.93	0.45	1.43	1.89
Recovery	0.25	139	0	77	101	178	2.50	0.00	0.59	0.69
Recovery	0.25	139	0	83	83	166	2.07	0.00	0.59	0.69
Recovery	0.25	139	0	84	72	156	1.79	0.00	0.59	0.69
Recovery	0.25	139	0	84	66	150	1.63	0.00	0.59	0.69
Recovery	0.25	139	0	84	62	146	1.53	0.00	0.59	0.69
Recovery	0.25	139	0	85	59	144	1.46	0.00	0.59	0.69
Recovery	0.25	139	0	85	57	142	1.41	0.00	0.59	0.69
Recovery	0.25	139	0	85	56	141	1.39	0.00	0.59	0.69
Recovery	0.25	139	0	85	55	140	1.37	0.00	0.59	0.69
Recovery	0.25	139	0	85	55	140	1.35	0.00	0.59	0.69
Recovery	0.25	139	0	85	54	139	1.35	0.00	0.59	0.69
Recovery	0.25	139	0	85	54	139	1.34	0.00	0.59	0.69
Nominal	11.5	139	0	85	54	139	1.33	0.00	0.59	0.69
Sleep	8	88	0	44	44	88	1.08	0.00	0.37	0.44
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	24.00	**12778**	**377**	**6308**	**6118**	**12425**	**2.52**	**0.43**	**0.90**	**1.08**

IV. Variations of the Reference Metabolic Profile

To study the effects of body size, it was desired to perform analyses on different size individuals. Analyses were conducted with the 5th percentile Japanese female and 95th percentile American male, by mass. While the MetMan program may not accurately predict the core temperature for persons that vary significantly from the standard size crewperson, the moisture output is in line with what was observed during testing. The height and mass were taken from NASA-STD-3000 but the metabolic rates were scaled to the different size individuals. The scaling algorithm used came from the MetMan program based on their body weight. This is known as the Kleiber relationship which is based on metabolic studies of various animals[13].

$$q_{met,2} = q_{met,1}\left(\frac{weight_2}{weight_1}\right)^{0.75}$$

Where:

$q_{met,1}$ = Metabolic rate of person 1

$q_{met,2}$ = Metabolic rate of person 2

$weight_1$= weight of person 1

$weight_2$= weight of person 2

Using this relationship, the metabolic rates were scaled for the different size individuals. The results of this scaling are shown in Table 4.

Table 4 Metabolic rates for different size individuals. *The first 2 are for medium fitness level. High fitness level is also shown for the 95th percentile to show overall worst case.*

Description	Metabolic Rates (KJ/hr)			
	Sleep	Nominal	Aerobic	Resistive
5th Percentile	218	345	2126	863
HIDH	317	500	3487	1251
95th Percentile	367	580	5197	1452

The resultant metabolic load results for these additional cases are shown in Tables 5-8 for both the short and long exercise protocols. The 95th percentile loads would place a much higher stress on the spacecraft ECLSS. This would make the design more robust, but may lead to a system that is larger than necessary. The 5th percentile case is one that would show how the system would respond to minimum metabolic loads.

It should be noted that these cases are extrapolations of the HIDH reference individual. The exercise metabolic rate of the 95th percentile individual has not actually been observed; however, there have not been many test subjects of that size. These high metabolic rates are physically possible, but unlikely. This area needs further study. Also, since the percentile data reported here is based on decades old astronaut data, updating these values to reflect the current astronaut population is another goal for future work.

Table 5. Metabolic Load Results for 5th percentile metabolic load table using short exercise protocol. *Medium fitness level.*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	590	78	103	171	274	4.24	0.45	2.44	3.18
Exercise - Aerobic	0.25	590	78	95	364	459	9.00	3.36	2.44	3.18
Recovery	0.25	96	0	70	141	211	3.48	0.22	0.41	0.48
Recovery	0.25	96	0	70	84	154	2.07	0.00	0.41	0.48
Recovery	0.25	96	0	69	63	133	1.57	0.00	0.41	0.48
Recovery	0.25	96	0	68	52	121	1.29	0.00	0.41	0.48
Recovery	0.25	96	0	68	45	113	1.11	0.00	0.41	0.48
Recovery	0.25	96	0	67	40	108	1.00	0.00	0.41	0.48
Recovery	0.25	96	0	67	37	104	0.92	0.00	0.41	0.48
Recovery	0.25	96	0	67	35	102	0.86	0.00	0.41	0.48
Recovery	0.25	96	0	67	33	100	0.83	0.00	0.41	0.48
Recovery	0.25	96	0	66	32	99	0.80	0.00	0.41	0.48
Recovery	0.25	96	0	66	32	98	0.78	0.00	0.41	0.48
Recovery	0.25	96	0	66	31	97	0.77	0.00	0.41	0.48
Nominal	12.50	96	0	66	30	96	0.74	0.00	0.41	0.48
Sleep	8.00	61	0	35	26	61	0.63	0.00	0.26	0.30
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	**24.00**	**8158**	**141**	**4894**	**3128**	**8021**	**1.29**	**0.06**	**0.57**	**0.69**

Table 6. Metabolic Load Results for 5th percentile metabolic load table with long exercise protocol. *Medium fitness level*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	590	78	103	171	274	4.24	0.45	2.44	3.18
Exercise - Aerobic	0.25	590	78	95	364	459	9.00	3.36	2.44	3.18
Exercise - Resistive	0.25	240	26	83	279	361	6.89	2.12	0.99	1.30
Exercise - Resistive	0.25	240	26	80	176	256	4.34	0.24	0.99	1.30
Exercise - Resistive	0.25	240	26	81	147	228	3.63	0.06	0.99	1.30
Exercise - Resistive	0.25	240	26	82	137	219	3.38	0.04	0.99	1.30
Recovery	0.25	96	0	64	60	124	1.49	0.00	0.41	0.48
Recovery	0.25	96	0	66	48	115	1.20	0.00	0.41	0.48
Recovery	0.25	96	0	67	41	108	1.02	0.00	0.41	0.48
Recovery	0.25	96	0	67	37	104	0.92	0.00	0.41	0.48
Recovery	0.25	96	0	66	35	101	0.86	0.00	0.41	0.48
Recovery	0.25	96	0	66	33	99	0.82	0.00	0.41	0.48
Recovery	0.25	96	0	66	32	98	0.79	0.00	0.41	0.48
Recovery	0.25	96	0	66	31	97	0.77	0.00	0.41	0.48
Recovery	0.25	96	0	66	31	97	0.76	0.00	0.41	0.48
Recovery	0.25	96	0	66	30	96	0.75	0.00	0.41	0.48
Recovery	0.25	96	0	66	30	96	0.75	0.00	0.41	0.48
Recovery	0.25	96	0	66	30	96	0.74	0.00	0.41	0.48
Nominal	11.5	0	0	66	30	96	0.74	0.00	0.41	0.48
Sleep	8	61	0	35	26	61	0.63	0.00	0.26	0.30
Daily units	**hr**	**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	**24.00**	**5916**	**234**	**4931**	**3516**	**8447**	**1.45**	**0.09**	**0.61**	**0.74**

Table 7. Metabolic Load Results for 95th percentile metabolic load table with short exercise protocol. *(High fitness level).*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	1442	201	153	364	517	9.00	2.66	5.95	7.78
Exercise - Aerobic	0.25	1442	201	180	736	916	18.24	39.92	5.95	7.78
Recovery	0.25	161	0	132	428	560	10.62	9.33	0.68	0.81
Recovery	0.25	161	0	107	254	361	6.28	0.71	0.68	0.81
Recovery	0.25	161	0	99	194	292	4.79	0.25	0.68	0.81
Recovery	0.25	161	0	96	157	252	3.88	0.07	0.68	0.81
Recovery	0.25	161	0	94	132	226	3.26	0.02	0.68	0.81
Recovery	0.25	161	0	93	114	208	2.83	0.00	0.68	0.81
Recovery	0.25	161	0	93	102	195	2.52	0.00	0.68	0.81
Recovery	0.25	161	0	92	93	185	2.30	0.00	0.68	0.81
Recovery	0.25	161	0	92	86	179	2.14	0.00	0.68	0.81
Recovery	0.25	161	0	92	82	174	2.02	0.00	0.68	0.81
Recovery	0.25	161	0	92	78	170	1.93	0.00	0.68	0.81
Recovery	0.25	161	0	92	75	168	1.87	0.00	0.68	0.81
Nominal	12.50	161	0	92	69	161	1.70	0.00	0.68	0.81
Sleep	8.00	102	0	65	37	102	0.92	0.00	0.43	0.51
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	**24.00**	**14530**	**363**	**7382**	**6793**	**14175**	**2.80**	**0.79**	**1.02**	**1.23**

Table 8. Metabolic Load Results for 95th percentile metabolic load table with long exercise protocol. *High fitness level.*

Crewmember Activity	Duration (hr)	Metabolic rate (W)	Power to exercise device (W)	Sensible (dry) heat (W)	Latent (wet) heat (W)	Total Heat output (W)	Water vapor output (g/min)	Liquid sweat rate (g/min)	O2 Usage (g/min)	CO2 Output (g/min)
Exercise - Aerobic	0.25	1442	201	153	364	517	9.00	2.66	5.95	7.78
Exercise - Aerobic	0.25	1442	201	180	736	916	18.24	39.92	5.95	7.78
Exercise - Resistive	0.25	403	45	180	656	835	16.27	43.29	1.66	2.19
Exercise - Resistive	0.25	403	45	117	457	574	11.29	6.37	1.66	2.19
Exercise - Resistive	0.25	403	45	101	367	468	9.05	2.21	1.66	2.19
Exercise - Resistive	0.25	403	45	99	319	418	7.87	1.22	1.66	2.19
Recovery	0.25	161	0	83	135	217	3.32	0.03	0.68	0.81
Recovery	0.25	161	0	90	113	203	2.79	0.00	0.68	0.81
Recovery	0.25	161	0	91	98	189	2.43	0.00	0.68	0.81
Recovery	0.25	161	0	91	89	180	2.21	0.00	0.68	0.81
Recovery	0.25	161	0	91	83	174	2.05	0.00	0.68	0.81
Recovery	0.25	161	0	92	79	170	1.95	0.00	0.68	0.81
Recovery	0.25	161	0	92	76	168	1.87	0.00	0.68	0.81
Recovery	0.25	161	0	92	74	166	1.82	0.00	0.68	0.81
Recovery	0.25	161	0	92	72	164	1.78	0.00	0.68	0.81
Recovery	0.25	161	0	92	71	163	1.76	0.00	0.68	0.81
Recovery	0.25	161	0	92	70	163	1.74	0.00	0.68	0.81
Recovery	0.25	161	0	92	70	162	1.73	0.00	0.68	0.81
Nominal	11.5	161	0	92	69	161	1.70	0.00	0.68	0.81
Sleep	8	102	0	65	37	102	0.92	0.00	0.43	0.51
Daily units		**kJ**	**kJ**	**kJ**	**kJ**	**kJ**	**kg**	**kg**	**kg**	**kg**
Daily Totals	24.00	**15402**	**526**	**7420**	**7463**	**14883**	**3.07**	**1.44**	**1.08**	**1.31**

V. Conclusion

Thermal and life support system analysis of human spacecraft needs to accurately reflect crewmember activity levels, which are highest during exercise. Thus, NASA typically uses human thermal modeling tools such as MetMan and metabolic profiles created to represent a realistic worst case of crew outputs such as carbon dioxide and sweat. These help human missions develop technology, design spacecraft systems and plan mission consumables. This paper described recent efforts to improve both analysis assumptions and math model correlations in order to recommend updated daily metabolic rate profiles for Gateway and future human exploration missions.

While improvements were made to the MetMan model to improve its correlation to measured ground test data, further progress can and should be made toward accurately modeling human thermal response to different environmental and exercise parameters, with a goal of validating those models for use in NASA exploration missions. Other human thermal modeling tools besides MetMan are being investigated as well as methods to stochastically characterize crew size and fitness level. These future improvements will help ensure robust spacecraft for deep space exploration.

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