

Models and Decision Aids for Prevention of Thermal Injuries in Extreme Environments

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Presenter(s)



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- Doctor of Philosophy (PhD) in Biomedical Informatics (Rutgers University)
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Disclosures



- Dr. Adam Potter and Dr. David Looney have no relevant financial or non-financial relationships to disclose relating to the content of this activity.
- The views expressed in this presentation are those of the authors and do not necessarily reflect the official policy or position of the Department of Defense, nor the U.S. Government.
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At the conclusion of this activity, participants will be able to:

- 1. Summarize key elements that affect thermal stress.
- 2. Identify potential use cases of decision aids.
- 3. Recognize different types of modeling methods.

U.S. Army Research Institute of Environmental Medicine (USARIEM)



Mission: Protect, sustain, and optimize the health and performance of Service Members through basic and applied research in environmental physiology and occupational medicine.

- Co-located with US Army Natick Soldier Systems Center (SSC)
- A subordinate lab of the US Army's Medical Research and Development Command (USMRDC)
- "World-Class" laboratory for environmental medicine, physiology, performance & nutrition research
- Integrated cellular, tissue, animal & human research programs





USARIEM Facilities



- Center for Military Biomechanics Research
- Doriot Climatic Facility
- High Altitude Laboratory (Pikes Peak CO)
- Hypobaric chambers & hypoxia rooms
- Manikins for heat transfer biophysics
- Thermal Chambers

[USARIEM, 2020]

- Water Immersion Laboratory
- Bone Health Laboratory
- Human Performance Laboratories
- Warfighter Cognitive Performance Lab



USARIEM Research



Biophysics & Biomedical Modeling

- Clothing Biophysics
- Biomedical Modeling
- Decision Aids, Algorithms and Mission Planning Models
- Real-Time Physiological Monitoring

Military Nutrition

- Performance and Recovery
 Nutrition
- Military Feeding & Combat Ration Support
 Dietary Supplements
- Physiological Resilience

U.S. Army Research Institute of Environmental Medicine

Thermal & Mountain Medicine

- Heat Stress
- Cold Stress
- Altitude and Hypoxia Stress
- Hydration
- Environmental Pathophysiology

Military Performance

- Physical Performance Optimization & Assessment
 Musculoskeletal Injury Reduction
 Military Biomechanics
 Return-to-Duty (RTD) Strategies
 Neurological Performance & Readiness
- Injury & Performance
 Epidemiology

Biophysics and Biomedical Modeling Division (BBMD)





Manikin Testing





Biomedical and Mathematical Modeling





Real-Time Health Status Monitoring





Goal: Practical Solutions





Clothing Biophysical Testing Process



Ideal testing process

Swatch Level

- » Sweating Guarded Hotplate (SGHP)
- » Material evaluations for prototype clothing



Individual Component

- » Thermal Hand, Foot, and Head Systems
- » More detailed data for extremities
- Full Ensemble
- » Four 20-zone Newton model manikins

Physiological Models

» Biophysical data – a main input parameter







[Potter et al., 2020b]

Quantifying Relationships



In order to model and predict heat rise or fall in humans, it is important to understand the interrelated elements involved in heat exchange. These individual relationships can be described mathematically.

Broadly, we can characterize heat storage (S) by calculating the sum of heat produced, heat gained, and heat lost. For humans, we simplify this into the heat balance equation:

$$S = M \pm W \pm R \pm C \pm K - E \qquad [W \cdot m^{-2}]$$

where M is metabolic heat production, W is work rate, R is radiation, C is convection, K is conduction, and E is evaporation.

*The relationship and impact of these elements become more complicated as they are changed (e.g., protective clothing impacts the exchange of heat)



Quantifying Relationships



Historically, models have been developed using linear algebra to describe two dimensional relationships (typically the empirical approach); while differential equations have been developed to characterize the three dimensional relationships (typically the rational approach).

$$\rho c \cdot \frac{\partial T}{\partial t} = q_m + \lambda \cdot \nabla^2 T + \omega_{bl} \cdot \rho_{bl} c_{bl} \cdot (T_{bl} - T) -\lambda \cdot \frac{\partial T}{\partial n} = R + C + K + E$$

$$[W \cdot m^{-3}]$$
[core to skin]
$$[W \cdot m^{-2}]$$
[skin to environment]

where ρ is tissue mass (kg m⁻³), c is specific heat of the tissue (kJ kg^{-1°}C⁻¹), T is tissue temperature (°C), t is time (sec), q_m is metabolic heat production rate (W m⁻³), λ is tissue heat conductivity (W m⁻¹ °C⁻¹), ∇^2 is a Laplace transform for heat conduction based on the tissue temperature gradient, ω_{bl} is blood flow rate (m³s⁻¹m⁻³ tissue), ρ_{bl} is blood flow mass (kg m⁻³), c_{bl} is blood specific heat (kJ kg^{-1°}C⁻¹), and T_{bl} is blood temperature (°C), n is the tissue coordinate normal to the skin surface





Using the backdrop of the heat balance we can model out how much heat is lost, gained, and ultimate stored. This summed storage (positive or negative) can be translated into a rise or fall in core body temperature over time



Metabolic Heat Production



Metabolic Heat Production Body Surface Area



Formulae for calculating body surface area in modern U.S. Army Soldiers David P. Looney^a, Diana P. Sanford^{a,b}, Peng Li^c, William R. Santee^{a,b}, Elizabeth M. Doughty^{a,b}, Adam W Potter^{a,*}



Metabolic Heat Production

Movement Speed





Metabolic Heat Production Steep Uphill & Downhill Slopes





"Medically Ready Force...Ready Medical Force"

Metabolic Heat Production Equipment Load





Metabolic Heat Production

Difficult Terrain



TERRAIN FACTORS FOR PREDICTING WALKING Table 11. Recommended Values for η for use in eq 8. AND LOAD CARRIAGE ENERGY COSTS: REVIEW Terrain Comments η AND REFINEMENT Description Richmond PW¹, Potter AW², Santee WR² Rough Terrain Assume surface roughness affect is unknown JOURNAL OF SPORT AND HUMAN PERFORMANCE embedded in the η selected for the terrain. Slippery Terrain 1.7 Hard wet clay, ice N. $n = 0.0718V^3 + 1.3V^2 - 5.3701V$ Vegetation + 6.0705Based on Table 2 and Figure 5 for very Swamp 3.5 low cone index Paved Roads 1.0 See Table 3, there is variability and possibly a relationship to load and velocity Gravel Roads 1.2 "Dirt" Roads 1.2 $\eta = 1.5 + \frac{1.3}{V^2}$ Sand See Figure 1, for range of values, weaker sand will have higher values. Silts and Clays 2.5 For Cone Index ≤ 7 assume it is a $\eta = 1.0 + \frac{2.0}{(ConeIndex - 4.8)}$ swamp for ConeIndex ≥ 7

[Richmond, et al., 2015; 2019]

Metabolic Heat Production Complex Terrain



Metabolic Costs of Military Load Carriage over Complex Terrain

David P. Looney, PhD*†; William R. Santee, PhD*†; Anthony J. Karis, BS*; Laurie A. Blanchard, BS*; Maxwell N. Rome, BA*†; Alyssa J. Carter*; Adam W. Potter, MS*

MILITARY MEDICINE

[Looney, et al., 2018]





Metabolic Heat Production Cardiovascular Strain



Cardiorespiratory responses to heavy military load carriage over complex terrain $\stackrel{\star}{\times}$

David P. Looney^{a,*}, William R. Santee^{a,b}, Laurie A. Blanchard^a, Anthony J. Karis^a, Alyssa J. Carter^a, Adam W. Potter^a

Applied Ergonomics 73 (2018) 194-198



[Looney, et al., 2018]



Metabolic Heat Production Extreme Environments



Divers risk accelerated fatigue and core temperature rise during fully-immersed ²¹ exercise in warmer water temperature extremes

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TEMPERATURE https://doi.org/10.1080/23328940.2019.1599182



[Looney, et al., 2019]





Heat Stress

Schematic of the Heat Strain Decision Aid (HSDA)







Heat stress [Assessment 1] – Individual



Heat stress [Assessment 1] – Individual



2 Studies (Lab and Field); Chemical Protective Clothing, N = 28

Environment	Clothing	Observed T _c	Bias	MAE	RMSE
	L1	37.64 ± 0.55	-0.15 ± 0.26	0.23 ± 0.20	0.30 ± 0.13
T - L	L2	37.75 ± 0.64	-0.14 ± 0.34	0.29 ± 0.24	0.38 ± 0.20
Laboratory	L3	37.88 ± 0.70	0.03 ± 0.42	0.31 ± 0.28	0.42 ± 0.33
	Total	37.76 ± 0.64	-0.10 ± 0.36	0.28 ± 0.24	0.37 ± 0.24
	F1	37.69 ± 0.35	0.22 ± 0.30	0.29 ± 0.24	0.37 ± 0.21
Etal 4	F2	37.67 ± 0.36	0.21 ± 0.32	0.30 ± 0.24	0.39 ± 0.21
Fleid	F3	37.55 ± 0.35	0.36 ± 0.30	0.37 ± 0.28	0.47 ± 0.27
	F4	37.79 ± 0.43	0.13 ± 0.32	0.27 ± 0.23	0.35 ± 0.20
	Total	37.68 ± 0.38	0.23 ± 0.32	0.30 ± 0.25	0.40 ± 0.25
Collective Total	L1-L3 F1-F4	37.69 ± 0.45	0.16 ± 0.36	0.30 ± 0.25	0.39 ± 0.23
		Acceptable	bias: ± 0.27°C	[P	otter, et al., 20

Heat stress [Assessment 1] – Individual

2 Studies (Lab and Field); Chemical Protective Clothing, N = 28





Heat stress [Assessment 1] – Group Mean



1 Study (Lab); 3 Chemical Protective Clothing ensembles (Human subjects; N = 8)



Heat Strain Decision Aid (HSDA)



Summary Switch Chart Type Run Model	Activity	Areat Strain Decision Aid
Councilation Time (min.)	○ 5 mi Run ● 12 mi Ruck	Temperature over Time
121	Modify Course Length:	105
141.	Completion Time	100 192 F 101
161	Movement Speed	Temperature (
201-	Carried Load (including armor if worn)	98 97 0.00 0.30 1.00 1.30 2.00 2.30 3.30 4.00 4.30 5.00 Elapsed Time (shrmm)
221.	Uniform Shorts/T-shirt ACU ACU + armor	SELECTIONS SCALES
0 11 22 33 44 55 66 Load (bs)	77 88 Environment	Work intensity: ①
	Temp. 70 deg. F	Clothing: ①
	Full Sun O Partly Cloudy O Cloudy O Night	ACU
	Wind: 💿 Calm 🔿 Gentle 🔿 Breezy 🔿 Windy	Lighting conditions:
⊲	0	

- For use in materiel developer down-selection or assessment
- Customizable for specific end users



Cold Stress

Simplified Modeling of Cold Exposure Survival





Constructed using data from Santee [1996]

Modeling of Cold Response





Human Representation





[Potter, et al., 2020b]

"Medically Ready Force...Ready Medical Force"

Cold Weather Ensemble Decision Aid (CoWEDA)





CoWEDA Displays



Display can be changed 'simple' or 'advanced' input views



CoWEDA Results



Example Output, where (a) shows the area of outputs or plots can be generated



CoWEDA Validation Predicted skin temperatures





Note: error bars indicate weighted error of group mean data; solid line is linear regression plot



Extreme highs, lows, and in between...

- Immersion in water...
- Underwater...
- Disabled submarine...
- Enclosed spaces (vehicles, aircrafts, etc.)...
- Subterranean environments...
- High altitude...
- Space...

Probability of Survival Decision Aid (PSDA)





Probability of Survival Decision Aid (PSDA)



Inputs

Outputs

Cold Thermore	gulation Mod	del - Researc	h Version :	1.0						J _ 4	1	• (*	f _x	Time												
File View H	elp									A A	B Ta head	C Tatorso Ri	D E Harsa Win	f To To b	G H Tsk Mtot	l Mext SV	J K	L	M WLP P	N O	POS	Q R Tm.arm Tm.les	S Tshead Ts	T U Jorso	V Ts hand	W X Ts lee
- Enviromental Para	ameters						Energy Usage	в		2 hrs	C	C	m/s	C	C W	W kg	W	1120	%			: C	C C	C	13.1010	C C
	Temp	erature	Hur	nidity	Wind	Speed	External Wor	dr (Matte)	0	3 0	29	29	0.4	0.1 35.79	33.13 84.97	250	0 3	13 0.1 13 0.05	0	1	1 1	32.94 35.0	1 34.61 8 34.2	34.17 31 18.35 10	.59 31.83	32.76 31.7E
	remp	erature	nur	niaity	wwinici -	speed	External wor	ik (vvalis)	U	5 0.3	25.1	14.11	0.4	0.89 50.79	18.74 1418.75	250	0.02 4	4.3 0.06	0	1	1 1	34 37.1	5 34.2 1 34.01	16.30 19	.44 17.46	18.74 16.64
Output Uniform	Celsius	•	Relative H	lum.(%) 🔻	Meters / S	ec 🔻	Activity (Wat	ts)	0	G 0.42	25.02	12.09	0.4	1 36.64	18.35 1430.75	250	0.05 4	.18 0.05	0	1	1 1	33.74 36.9	6 33.82	16.05 18	.09 16.92	18.38 16.14
Non-uniform	lotal	Final	lottal	Final	loital	Final				7 0.54	25	12.02	0.4	1 35.49	18.24 1442.27	250	0.05 4	.88 0.06 c0 0.06	0	1	1 1	33.58 36.7	9 33.66	15.94 17	1.99 16.72	18.27 15.98
0										9 0.8	25	12	0.4	1 36.37	18.16 1458.6	250	0.09 4	.39 0.06	0	1	1 1	33.4 36.5	7 33.3× 8 33.45	15.89 17	.93 16.55	18.21 15.85
Whole Body	29.00	29.00	40.00	40.00	0.10	0.10	Physical Attrib	outes		10 0.93	25	12	0.4	1 35.22	18.14 1453.3	250	0.11 4	.25 0.05	0	1	1 1	33.35 36.5	3 33.4	15.88 17	.91 16.51	18.19 15.83
Uned	20.00	20.00	40.00	40.00	0.10	0.10	Gender	@ M-I-	French	11 1.05	25	12	0.4	1 35.18	18.13 1466.56	250	0.13 4	.15 0.05	0	1	1 1	33.31 36.4	9 33.36	15.88 1	7.9 16.48	18.18 15.81
nedu	23.00	23.00	40.00	40.00	0.10	0.10		Male	Female	13 13	25	12	0.4	1 36.13	18.12 1408.39	250	0.14 4	.09 0.08	0	1	1 1	33.27 36.4	a 33.35 4 33.31	15.87 17	1.9 16.45	18.17 15.78
Torso	29.00	29.00	40.00	40.00	0.10	0.10	Ustable	User Defined	m 👻 174	14 1.42	25	12	0.4	1 35.12	18.11 1471.47	250	0.17	43 0.05	0	1	1 1	33.26 36.4	3 33.3	15.87 17	.89 16.44	18.17 15.78
						0.40	Height		1.74	15 1.55	25	12	0.4	1 36.1	18.11 1472.34	250	0.19 4	.97 0.06	0	1	1 1	33.24 36.4	2 33.29	15.87 17	.88 16.43	18.16 15.77
Arms	29.00	29.00	40.00	40.00	0.10	0.10	Weight	User Defined	ka 🔻 76.00	16 1.68	25	12	0.4	1 36.1	18.1 1472.98	250	0.2 4	95 0.06	0	1	1 1	33.23 36.4	1 33.28	15.86 17	188 16.42 188 16.42	18.16 15.77
Hands	29.00	29.00	40.00	40.00	0.10	0.10	weight			18 1.92	25	12	0.4	1 36.09	18.1 1473.78	250	0.23 4	.93 0.06	0	1	1 1	33.22 36	4 33.27	15.86 17	.88 16.42	18.16 15.7E
							F=t (%)	Check If Un	known 21.37	19 2.05	25	12	0.4	1 35.08	18.1 1474.05	250	0.25 4	.92 0.05	0	1	1 1	33.22 36.5	9 33.27	15.86 17	.88 16.41	18.16 15.7E
Legs	29.00	29.00	40.00	40.00	0.10	0.10	101 (10)			20 2.18	25	12	0.4	1 35.08	18.1 1474.27	250	0.26 4	.92 0.05	0	1	1 1	33.22 36.3	9 33.26	15.85 17	188 16.41	18.16 15.7E
East	29.00	29.00	40.00	40.00	0.10	0.10	Vo2-Max	Check If Un	known 44.4	22 2.43	25	12	0.4	1 36.08	18.1 1474.44	250	0.28 4	91 0.06	0	1	1 1	33.21 36.3	9 33.26	15.86 17	.88 16.41	18.16 15.7E
reel							102 1104			23 2.54	25	12	0.4	1 35.07	18.1 1474.65	250	0.31	2.9 0.06	0.01	1	1 1	33.21 36.3	9 33.26	15.86 17	.88 16.41	18.16 15.7E
						_	Ace Verr	•)	20	24 2.67	25	12	0.4	1 36.07	18.1 1474.73	250	0.33	2.9 0.05	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
	Immersion	No Immersion	n (In Air)		•	·	Age (reals	•)		25 2.8	25	12	0.4	1 35.07	18.1 1474.79	250	0.34	2.9 0.05	0.01	1	1 1	33.21 36.3	8 33.26	15.85 17	.88 16.41 188 16.41	18.16 15.7E
										27 3.06	25	12	0.4	1 36.07	18.1 1474.87	250	0.37	2.9 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
Clothing Paramete	ers		Time P	arameters			Output Result	ts		28 3.17	25	12	0.4	1 35.07	18.1 1474.89	250	0.39	2.9 0.05	0.01	1	1 1	33.21 36.5	8 33.26	15.86 17	.88 16.41	18.16 15.7E
Olothed	🔘 Und	lothed		The Ma		00.00	Core Temp ((°C) = Wa	ater Loss (kg) =	29 3.3	25	12	0.4	1 35.07	18.1 1474.92	250	0.4	2.9 0.05	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	188 16.41	18.16 15.7E
Llear Defined	_		Run	Time Min	ules •	00.00	Skin Temp ("C) - W:	ater Lose (%) -	31 3.55	25	12	0.4	1 36.07	18.1 1474.95	250	0.42	2.9 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	88 16.41	18.16 15.7E
User Delined	•			- II		10.00	Skin remp ((0)- 11	1033 (16) -	32 3.68	25	12	0.4	1 35.07	18.1 1474.95	250	0.45 4	.89 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
		1	Step	lime Mir	nutes 🔻	10.00	Output Resu	ult Time (min) =		33 3.81	25	12	0.4	1 36.07	18.1 1474.97	250	0.47 4	.89 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
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T	0.72	0.39			A		Interval 2	<u>e e</u>	Automatic Mode	37 4.3	25	12	0.4	1 35.07	18.1 1474.99	250	0.53 4	.89 0.05	0.01	1	1 1	33.21 36.5	8 33.26	15.86 17	.88 16.41	18.16 15.7E
I OISO				Í	کھٹ)	- 1	Interval 3	i C	Manual Mode	38 4,43	25	12	0.4	1 35.07	18.1 1474.99	250	0.54 4	89 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	00 16.41	18.16 15.7E
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Hands							Interval 6		Run Database	42 4.93	25	12	0.4	1 36.07	18.1 1474.99	250	0.61 4	.89 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
Legs	1.07	0.38	/				Interval /		national Name	43 5.05	25	12	0.4	1 36.07	18.1 1474.99	250	0.62 4	89 0.06	0.01	1	1 1	33.21 36.3	s 33.26 8 33.26	15.86 17	38 16.41 38 16.41	18.16 15.7E
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Feet				USH	NIC		Interval 1	0 -	Compute Results	46 5.42	25	12	0.4	1 35.07	18.1 1474.99	250	0.67 4	.89 0.05	0.01	1	1 1	33.21 36.5	8 33.26	15.86 17	.88 16.41	18.16 15.7E
1			W	/arfighter Hea	lth & Perfor	mance				47 5.55	25	12	0.4	1 35.07	18.1 1474.99	250	0.68 4	.89 0.06	0.01	1	1 1	33.21 36.3	8 33.26	15.86 17	.88 16.41	18.16 15.7E
																			T	(n	et	al	20	()8	• 2()141

Probability of Survival Decision Aid (PSDA)



Prove Hep Normental Parameters From File Name 2014.1.10 - 8.54.11 Age 20 Fitness 7 Sex Male Female Height Medium 5 510° t/ in * From Sile Sex Male Female Height Medium 176.5 b Fat (%) Medium 23.3 Total Speed Numer sion State and Clothing Ensembles mmersion State and Clothing Ensembles mmersion State and Clothing Ensembles mersion Floatation Device Iothing Lond Ensembles Summer clothing (Parka & swester & heavy weight pants) Calculate Probability of Survival Probability of Survival Intersonal Floatation Device Iothing (Parka & swester & heavy weight pants) Calculate	obability of Survival Decision Aid 1.2 Beta			
Water Temperature 10.0 Weight 40.0 (%) Wind Speed 0.2 knots mmersion State and Clothing Ensembles mmersion Air/Boat Personal Floatation Device Heading (Ing-sleeve shirt & med-weight pant Summer Clothing (Ing-sleeve shirt & med-weight pant Winter clothing (Parka & sweeter & heavy weight pants) Fall / Spring clothing (Parka & sweeter &	e View Help Inviromental Parameters From File Air Temperature 10.0	Physical Name Age	Attributes 2014.1.10 - 8.54.11 20 - Fitness 7 -	Probability of Survival
mmersion State and Clothing Ensembles mmersion Air/Boat eat Loss Coeff. Laminar Turbulent Personal Floatation Device lothing Land Ensembles -Nude / swimsuit Summer clothing (Parka & sweater & heavy weight pants) Fall / Spring clothing (Parka & sweater & heavy weight pants) (Calculate	Vater Temperature 10.0 Vater Temperature 10.0 Vind Speed 0.2 knots •	Sex Height Weight Fat (%)	 Male Female Medium ▼ 176.5 Medium ▼ 23.3 	(%) (%)
Calculate	Immersion State and Clothing Ensemi Immersion Air/Boat • Heat Loss Coeff. © Laminar © Turbul Personal Floatation Device	oles ent	ResultsCold Functional Time (hr)23.1Cold Survival Time (hr)26.6Dehyd. Survival Time (hr)240.0	obability of Surviv
Survival Time (hours)	 □ Land Ensembles □ Nude / swimsuit □ Summer clothing, (T-shirt, light pants) □ Fall / Spring clothing (long-sleeve shirt & med- Winter clothing (Parka & sweater & heavy weig 	weight pant ht pants)	Calculate	Δ ²⁰⁻ 0.18.4 20.4 22.4 24.4 26.4 28.4 30.4 Survival Time (hours)

Other Species...





Canine Thermal Model



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A canine thermal model for simulating temperature responses of military working dogs

Check for updates

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ARTICLE INFO

Keywords: Fur Heat strain ABSTRACT

Military working dogs (MWDs) are often required to operate in dangerous or extreme environments, to include hot and humid climate conditions. These scenarios can put MWD at significant risk of heat injury. To address this

Canine Thermal Model









- Heat loss or gain can be effectively modeled when key parameters are known (or estimated).
- Metabolic heat production (e.g., heat produced from work) and clothing properties (insulation / vapor permeability) can significantly influence heat gain or loss.
- Scientifically-based decision aids can be used for risk mitigation, mission planning, and optimization.

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