THERMAL MANIKINS, THEIR ORIGINS AND ROLE

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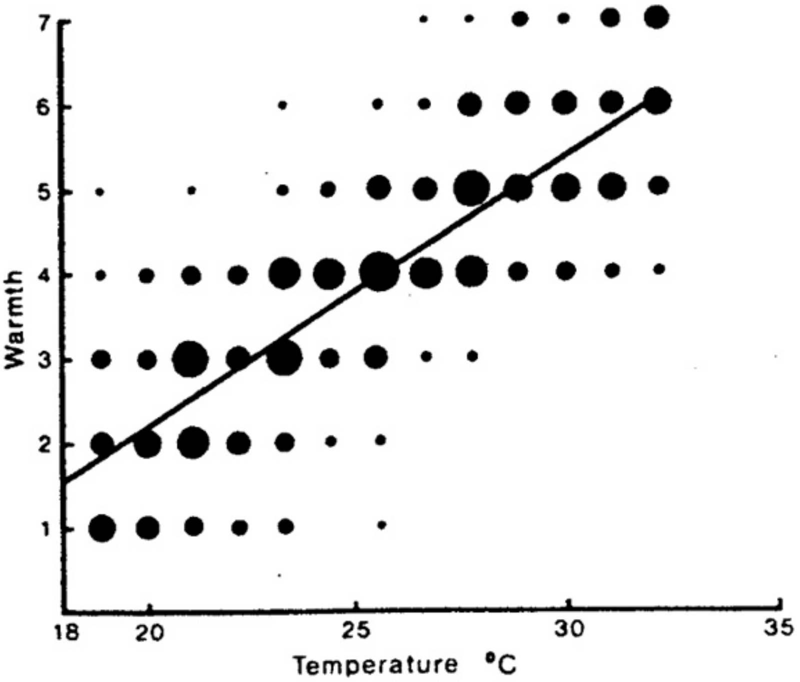
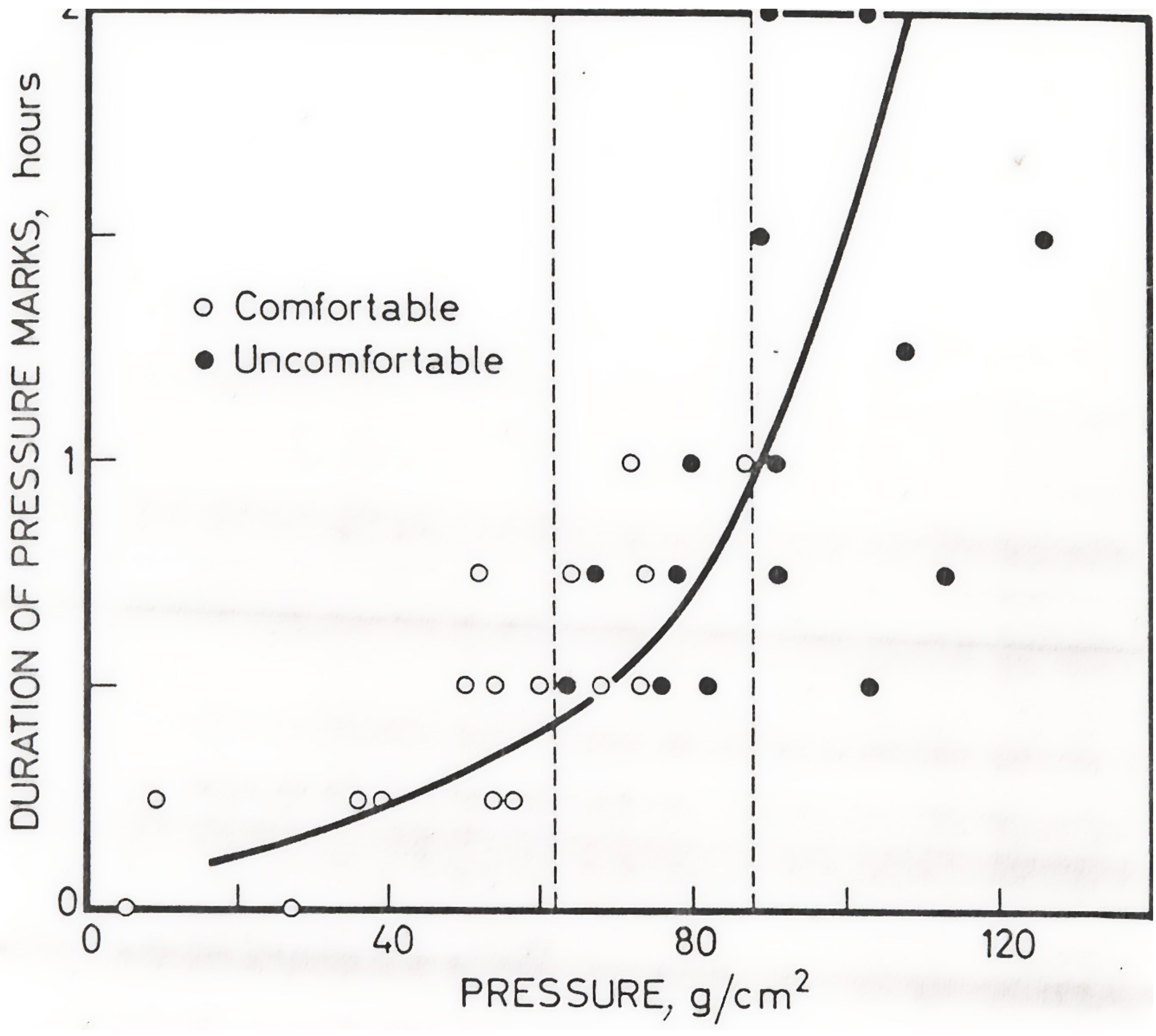
COMFORT:

Perhaps the first use of a manikin in any thermal role was in about 1650 at Magdeburg University in Germany, where Otto von Guericke developed a manikin, rotating on some kind of spring. The manikin had an outstretched hand whose finger pointed to a set of numbers ranging from 1 to 7, labeled from “Maximum Frigor” to “Maximum Caldor”. Unfortunately, use of a 7-point scale for human thermal comfort by the American Society of Heating & Ventilation Engineers (ASHVE, the predecessor of ASHRAE), dating to the 1920’s, has been problematic; humans cannot reliably discriminate between hot, warm, slightly warm, comfortable, slightly cool, cool and cold. Also, comfort is not a “state variable”, but rather a state of mind. As shown by McIntyre, in the following Figure, the Standard Deviation of a Predicted Mean Vote (PMV) is one full scale unit; i.e., a “Comfort Vote” of 4, ± 2 Standard Deviations, has a 95% confidence interval ranging from 6, “warm”, to 2’ “cool”, or using Fanger’s rotation, where Comfort = a PMV of 0, the 95% confidence range is +2 to –2. Thus, those with access to tools to measure human heat transfer should avoid such psychological, mind based. “PMV” estimates of comfort, and instead rely on the much more reliable physics/biophysics of heat exchange to evaluate human comfort.



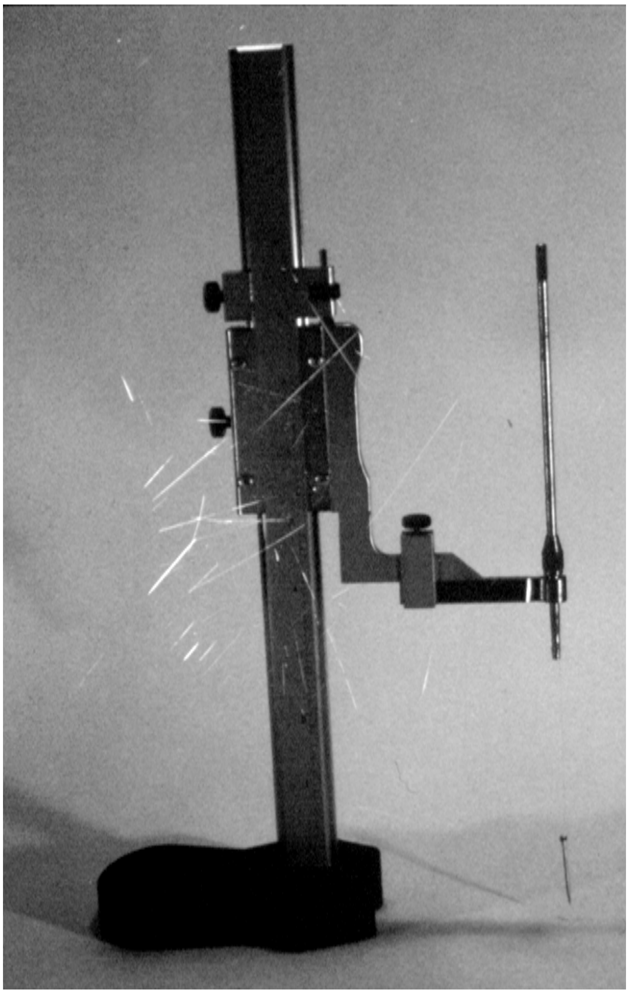
CLOTHING COMFORT:

Similarly, clothing comfort is not a state variable. Instead I have suggested it depends on the four factors I term “The Four Fs of Clothing: Fashion; Feel; Fit and Function”. **Fashion** is primarily created by advertising; if you question that, just look at your children’s clothing. **Feel**, i.e. the “hand” of fabrics, has been well delineated by Professor Kawabata. He characterized “fabric hand” using such parameters as roughness, smoothness, softness, crispness, bulk, et al., provided a series of booklets for sampling the range of many of these parameters by including swatches scaled from 1 to 10 of many of these parameters, and developed a series of instruments for some of them. **Fit**, including such factors as fabric drape and garment cut, is largely a function of pressure. An instrumented torso manikin was developed with pressure sensing switches indicating <1, 2 to 4 or > 5 psi pressures for use in developing military body armor; its application led to the adoption of the “Personal Armor System, Ground Troops” (PASGT) used by the U.S> Army in record time. In assisting clients, I built an instrumented female torso with pressure sensors for use in designing brassieres, and also developed a portable, infra-clothing, pressure sensor system that some graduate students have used for clothing design studies on jackets, shirt collars and the like. The Figure below summarizes some of the findings on Fit.



Fibers, Fabrics & the like:

Evaluation of clothing fibers, fabrics, membranes and the like should not be done with manikins. Their five key parameters are too often masked by such factors as drape, fit, specific contact area and weight to glean appropriate information from manikin studies. These material properties are: 1) fabric insulation; 2) fabric moisture permeability; 3) wicking characteristics; 4) water uptake/holding characteristics; and 5) drying time. Instead, the classic “Cleveland guarded, heated flat plate”, in a climate controlled box chamber with high air motion over the plate (and not the newer version with air flow from one side, where one cannot be sure of the effective ambient temperature over the test section) should be used to measure the Clo value of materials. Also, material thickness should not be measured in accord with the ASTM Standard, which calls for measurement under a 7 gram per square centimeter pressure, but with a swinging pendulum technique, i.e., a common pin suspended on a fine thread attached to a °C Vernier caliper is set into motion and the Vernier gauge lowered slowly until the tip of the pin motion is just interfered with by the fine surface fibrils of the material. If the measured value is not 1.57 Clo/cm of material thickness, repeat the thickness and Clo measurement, since either one or the other measurement is wrong, or the material is unusually dense for clothing or has too little fiber bulk (e.g., micro-fiber batting) to block the normal heat transfer by radiation. As will be illustrated in the presentation, air is by far the dominant insulator in clothing, either contained in the fibers or between clothing layers.



MY FIVE LEVELS of ANALYSIS:

I highly recommend this approach, which evolved during my 50 years of R&D in this area and will be cited during the rest of my presentation; running from Level 1 to 5, these are:

1. **Physical analysis** of problem elements is carried out; e.g., fabrics, environment, load carried. No subjects are required, costs are minimal and the result is usually extremely helpful.

2. **Biophysical analysis** of the items (e.g., garments fabricated from new fabrics) is carried out. Prediction **modeling** to identify probable differences under various conditions, is a key element at this level. Again, no human subjects are involved although models, mock-ups, manikins, etc. may be, but these cost far less than human subject studies.

3. **Human physiological** (small scale with 6 to 8 Ss), "**validating**" studies under tightly controlled conditions (e.g., in climatic chambers, on treadmills, stopwatch paced, etc.) are carried out to confirm that the projected differences do indeed occur. These are unlikely to be successful unless Level 2 modeling was used to select an appropriate forcing function (work rate, rest/work/recovery cycles, exposure duration, environmental conditions).

4. **Controlled field trials**, modest in scale (~20 to 50 Ss), are conducted; the items are used by the intended users in the actual conditions of proposed use, but under conditions that Level 3 suggested would be neither excessive nor inadequate. Relatively expensive, but introduce “real world” variability; any surprises mean back to Level 3 for study.

5. User trials ("test marketing" in the civilian community, "user wear or operational trials" in the military; “field construction projects” in the working world) are the final step; these are usually large scale, time consuming and expensive, and may well prove fruitless, difficult or provide questionable information, unless levels 3 and 4 have preceded them.

This progression of test levels decreases in scientific information yield and reproducibility, and increases in cost and possible confounding from level one to level five. Many new approaches and/or ideas can be eliminated even at level one, with enormous savings of subsequent research effort. Still more may be eliminated at level two, but the real savings here comes in the selection of "adequate forcing functions" (i.e., optimal test conditions) for demonstrating supposed differences in user response to the test item. If the essential "background" studies of levels one and two are conscientiously carried out, there should be few surprises during level three testing. Real world factors, which might otherwise confound laboratory results, can usually be dissected out in level four studies. Finally, user acceptance or resistance can be rationally assessed, although the real merit of the item versus the claims made for it may not be detectible at level five. Of course, that is if one is looking for practical, meaningful differences rather than statistically significant ones, at least from level three on up.

THERMAL MANIKINS:

It all began with Sleeping Bags. In the late 1920s, a wealthy industrialist endowed a research program at Harvard Medical School to study the effects of “Fatigue” on workers. Most of the early studies were on work physiology, which fit well with the Medical School agenda. However, after baseline studies on work physiology were completed and the research focus shifted to problems in applied physiology, the “Harvard Fatigue Lab” was promptly shunted to the basement of Harvard Business School. By 1940 the Lab, directed by L.J. Henderson a respiratory physiologist, was well known for its studies of work at altitude and for studies by David Bruce Dill on work in the heat during the construction of the Boulder Dam in the Nevada desert. Along with collaborators from the Harvard Medical School and

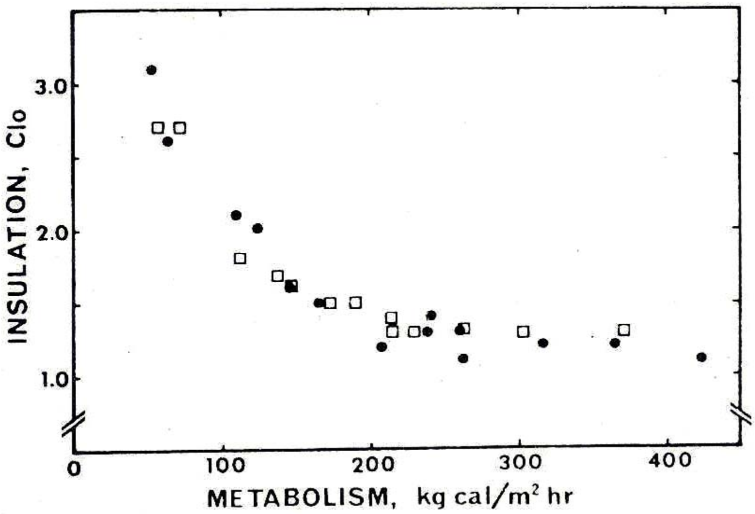
Massachusetts General Hospital, the Fatigue Lab staff provided the cadre for the laboratories that the United States set up to support its troops during 1942 after its entry into WW II on Dec. 7th, 1941. These, among others, included the U.S. Army Medical Armored Research Lab. (AMRL) at Fort Knox, Kentucky, which dealt with problems of armored vehicles during desert operations, and the U.S. Army Quartermaster Climatic Research Lab (CRL) at Lawrence, Massachusetts, with Harwood E. Belding (who became its Director in 1946, and others from the Fatigue Lab.) to study the problems of cold weather operations in Northern Europe and Alaska, where more soldiers were injured by cold than battle. CRL became the Environmental Research Division (EPRD) and moved to Natick, MA shortly before I went to work there in 1955. Parts of EPRD and AMRL were merged in the 1960s to form the U.S. Army Research Institute of Environmental Medicine ("USARIEM"). The field I developed during my 27 years in Natick, "Military Ergonomics", started with the pioneering work by Alan Burton of Canada, who had published (J. Nutrition 9:261, 1935) his two compartment (skin and core) body model, with a mean body temperature based on 1/3 skin and 2/3 core temperature, using an average specific heat for the body tissues of 0.83 kcal/kg.°C, and by Gagge, Burton and Bazett who introduced (Science 94:24, 1938) a clothing insulation unit, the Clo, equivalent to the 14% larger, "R value" used for thermal insulation in the construction and HVAC industries.

A major focus for the Climatic Research Lab/Harvard Fatigue Lab team mobilized in Lawrence (where a large wool supply company had built a chamber capable of reaching – 40 ° to de-fat raw wool), was development of a sleeping bag to provide more cold protection than the Standard Government Issue, thin, single layer wool "blanket" bag and air mattress. The goal was to provide a bag which would "allow six hours of restful sleep at – 40 °C"; this goal has yet to be reached (physics rules - it requires ~ 12 Clo, which cannot be achieved because of the associated increase in surface area that accompanies increasing thickness of insulation around any cylindrical object, whether a human finger or body), so the "goal posts were moved" in stages to today's requirement of "2 hours of restful sleep"; **i.e., body heat debt should be ~ 80 kcal in about two hours**, a value that Belding suggested would wake a sleeping soldier, and my studies suggest would drive a working man to a re-warming shelter. The earliest studies in 1942 tested a variety of sleeping bags with at least 2 or 3 subjects trying to sleep at -18, -25, -32 and -40 °C, wearing 2 pair of heavy wool sox, 1 pair of arctic sox, 2 pairs of wool long underwear, a worsted wool shirt, 1 pair of heavy woolen mittens, plus a head toque muffler for the face. If a given subject found a bag acceptable, the test was repeated at the lower temperatures until it was not. One of the first 1942 reports (a Harvard Fatigue Lab study reported as CRL Rpt # 25) concluded that: 1) if a subject slept on his side, while the upper side might be ~ 35 °C initially, the lower side would start at least 3 °C colder, dropping to ~22 °C in 3 hours (from an initial reading of ~29 °C); 2) average human weight compression force at the hip was about 1 psi; 3) only the hardiest subjects could endure a hip temperature of 20.5 °C; and 4) a toe temperature of ~16 °C would be the end of any subject's tolerance. Even these first studies were useful; an air mattress, fitted inside with an insulating pad attached to its upper surface was tested in November 1942 and increased stay time. But analysis of subject variability for a repeat test on the same subject at the same air temperature gave a difference of ~ 9%; for the same man at 2 different temperatures it was ~ 17%; for 2 different men at the same temperature, ~ 15% and for 2 different subjects at 2 different temperatures it was ~ 14%.

J.R. Breckenridge, then an Army Technician 3rd class attached to CRL, who I selected to head my Biophysics Branch in the 1970's, told me of one of the earliest attempts to develop a heated manikin to use to reduce the variability of such human subject testing (and ? possibly eliminate the considerable subjective discomfort); "LUMPY" consisted of a set of water tight tin cans; four, roughly the size of a can of soup, served as hands and feet, larger ones simulated lower arms and legs, still larger ones upper arms and thighs, etc. The cans were linked by water tight tubing connections, and controlled temperature hot water was circulated between the cans. The temperature drop between inlet and outlet with time was used as a measure of bag insulation. However, as others have found in attempting to construct a circulating suit thermal calorimeter, it was very difficult to measure both the flow and inlet outlet ΔT with sufficient precision, to say nothing about the problems of mixing, so "Lumpy" was discarded.

By November of 1942(CRL Report # 43/Harvard Fatigue Lab. Rpt # 8), the science had advanced considerably. Human subject measurements now included 9 point mean skin temperature, measured every 15 minutes, rectal temperature measured hourly and body heat production (respiratory O_2 consumption) measured continuously; and body heat debt was calculated as 0.3xTs+0.7xTre. Pete Scholander was at the Harvard Fatigue Lab, along with Bruce Dill [and his future son-in law, Steve Horvath, who had just completed his Ph.D. studies at Harvard], Lucien Brouha [who I co-taught a class with at SUNY, Buffalo in 1961] and many other distinguished physiologists were active with the group. A "Cenco Fitch calorimeter" had been constructed, consisting of an upper metal vessel holding boiling water and a lower, well insulated, metal receiver with thermocouple temperature sensor, designed to exert a pressure of 1 psi (the pressure of a man's hip against the lower surface of his sleeping bag) allowed direct physical measurement of the sleeping bag material. The first model of an "Electrically Heated Dummy" with an internal fan blowing air across internal heating coils throughout the torso and down the extremities, using on-off thermostatic control to simulate human skin temperature, was introduced. The report concluded that: this dummy did not compress the sleeping bag adequately; at least two bag sizes had to be manufactured to fit the range of soldiers; and an auxiliary, highly insulated, foot bag was needed. An "ADEQUATE SLEEPING BAG" could now be defined in physical, biophysical and physiological terms; it "must keep lower hip skin temperature above 80 to 85 °F (~ 22.5 to 29.5 °C) for 3 hours and limit heat loss to ~ 40 to 45 kcal/ m^2.hr. A field trial with human subjects was run in December at Ladd Field, Alaska. By April, 1943 an improved "electrical dummy", with the electrical fan blowing air through tubes to the extremities was built. Run without head or arms, this dummy weighed 18 kg, surface area for heat loss was 1.5 m^2 and, with an internal temperature of ~ 40 °C, average skin temperature approximated human value. Using a watt-hour meter to measure internal heat supplied and "Clo value" to characterize heat loss, a 2% accuracy was achieved on repeated tests. The value measured for the dummy wearing wool knit underwear, with heavy wool sox + arctic sox was reported as 1.3 Clo.

By September 1943 (Fatigue Lab Report # 122) the physiologic measurements had been upgraded to an 11-point mean weighted skin temperature, using weightings proportional to the surface area involved, rectal temperature measurement was standardized at a depth of 15 cm. and plotted every 15 minutes, and the calculation of mean body temperature was corrected to 1/3 Ts + 2/3 Tre. A wide variety of clothing materials were being measured on a new, "Cleveland" heated flat plate, guarded on all 4 sides, and across the bottom by heated sections set at the identical temperature as the central test section; this is still the recommended technique for measuring material insulation, but cannot simulate the effects of material weight or garment drape, size, cut, closures, etc. A new heated hand, and foot, for hand- and foot-wear Clo determinations had been constructed, and a new electrically heated dummy, made of 1.6 cm thick sheet copper, heated internally by resistance wire and electric light bulbs, with internal fan and on/off thermostatic control of temperature had been fabricated. A difference in measured insulation values of 5 % was now considered significant. Based on the success of using the manikins to supplement physiological determinations, e.g., the loss of clothing insulation worn by marching soldiers in the cold calculated from heat balance equations, as shown in the following Figure, Dr. Belding was ready to contract for a series of standard manikins.



A renowned artist Gutson Borglum, sculptor of the enormous, stone, Presidential faces on Mount Rushmore, was commissioned to sculpt the manikins in electrically conductive wax, using the mean anthropometric dimensions from a survey of almost 3000 aviation cadets at Wright Field. These wax figures were then electroplated to a ~3 mm thickness of copper, and then the wax melted out; this "cere perdu" process had been used since pre-historic time to make jewelry. The head, thumbs and forward part of the feet were made removable, and the shoulders were articulated to rotate 180 degrees, both for internal access and to facilitate donning clothing, hand and footwear. A small company, involved in making the earliest electrically heated blankets, provided panels of wires for six separate heating elements (head, torso, upper and lower arms, and upper and lower legs, with heating capacity proportional to the surface area to be heated) to be glued to cover the inner surfaces of the manikins; that company is now General Electric Corporation. Resistors were used to heat the hands and feet, whose temperatures could be adjusted apart from the thermostat used to control the overall skin temperature. Thermocouple temperature sensors, placed in 22 caliber bullet cartridge cases inserted into the skin at appropriate sites, were used to measure the average skin temperature of each section of the manikin, whose skin was blackened to more closely approximate the thermal emissivity of human skin. The first of these, named "Chauncy" by Dr. Belding, arrived early in 1946, and had connectors for power, thermostat control and skin temperature sensors in the area of what would have been the human navel. In a climatic chamber at an ambient air temperature of 10 °C, mean skin temperature averaged ~ 37.5 °C in a vertical position, with a measured surface air layer insulation of 0.64 Clo, and ~ 38.6 °C in a horizontal position, with a measured Ia of 0.73 as reported in CRL Report # 107, A Study of the Copper Man", 28 August 1946.

I believe ten manikins were eventually fabricated this way; one, whose fate is unknown, went to the U.S. Navy in Philadelphia (Dr, Ed Hendler); one went to the ASHVE Laboratory in Cincinnati, Ohio, was transferred (along with their climatic chambers) to Kansas State University when ASHRAE their successor Society closed that facility, and is still in use by Professor Elizabeth McCullough; one went to Prof. A. P. Gagge at the J.B. Pierce Foundation Institute in New Haven, Connecticut and was eventually thrown out with the trash after most of the information on the Clo values of clothing was known; Dr. Belding took Chauncy with him when he left the government to take a University position ("so his children could afford to go to college"); and three, one of which was a sectional manikin and another a seated version for aircraft cockpit studies, went to the U.S. Army Air Force at Wright Patterson Air Force Base. I acquired these three for USARIEM in the 1970s, when they needed major rewiring, and later arranged to purchase Chauncy for use at USARIEM. These four were united with the original three that had been at EPRD, two of which did not have articulated shoulders, had their wiring connected through the eye sockets, and thus could be used for sleeping bag studies or immersion in water to nose depth studies.

The following picture includes (Left to Right): James Bogart, who ran the USARIEM immersion pool; the water immersion manikin; Professor Harwood E. Belding; Chauncy; a, much younger, Professor Dr. Goldman; the original sweating man, wearing the original form fitting cotton skin I had tailored for him for sweating studies; and Mr. J. Robert Breckenridge who, was rated as an Army Technician 3rd Class with the original CRL team in the early 1940s, became a first rate Biophysicist, my mentor and my right hand as head of the Biophysics Branch of my Military Ergonomics Division at USARIEM, and is still a close friend.

The ORIGIN of the SWEATING, and the “WALKING” MANIKIN:

When I first arrived at Natick, I found that most of the Copper manikins elsewhere, aside from the one at KSU in the Home Economics Department, had been put in storage, discarded, or were little used. Studies on the heated guarded flat plate apparatus, in heavy use to measure the insulation properties of new materials, had shown that clothing insulation was a linear function of the increasing circumference of the layers of clothing, and the air layers trapped between them, with practically negligible influence from any specific aspect of the materials or their fibers except their thickness, as shown in the following figures.

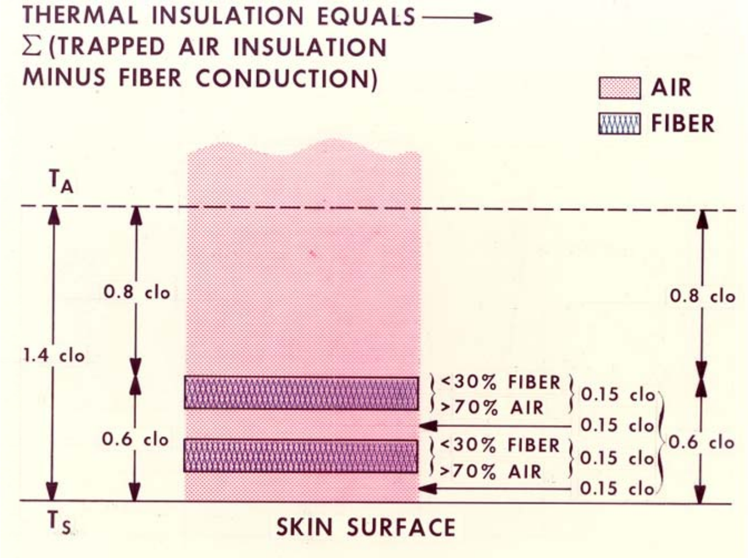
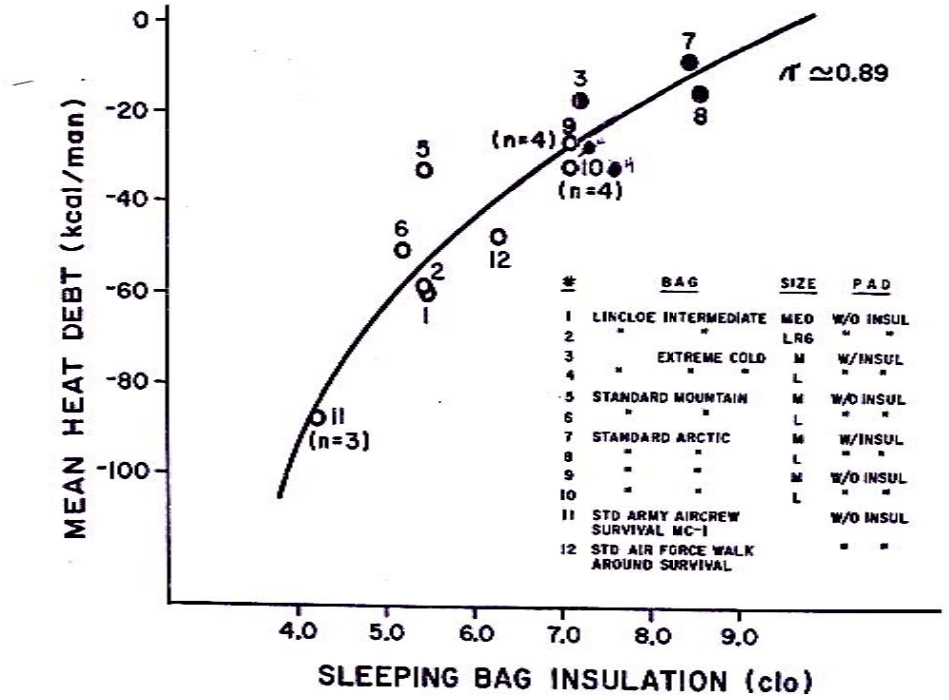


Figure 1. Diagram of the Thermal Insulation Around the Torso of an Individual Wearing a T-shirt, Shirt, and Winter Jacket

Layer (#)	Nature	Insulation* (clo)		
1	*Surface still air layer*	*0.8*		0.8
2	Jacket cover fabric		0.15	
3	*Trapped still air layer*	*0.15*		
4	Insulating batting		0.2 - 0.5	~ 0.9 - 1.2
5	*Trapped still air layer*	*0.15*		
6	Jacket lining		0.1	
7	*Trapped still air layer*	*0.15*		
8	Shirt		0.1	
9	*Trapped still air layer*	*0.2*		
10	Underwear		0.15	~ 0.6
11	*Trapped still air layer*	*0.15*		
	Torso surface total clo	1.6 *air* +	0.7 - 1.0 fabric	= 2.3 - 2.6 = total

Even at Natick, the R&D center for the U.S. Quartermaster Clothing & Equipment Development center, most of the manikin studies were at the Level 2 Measurement and Modeling of cold weather operations. The power of being able to select an adequate forcing function for subsequent human Level 3, validating studies is shown in the next Figure.

MEAN HEAT DEBT AFTER 3 HOURS at -34°C (-30°F) as
a FUNCTION of SLEEPING BAG INSULATION
(n=10, except as noted)



The close agreement (r = .89) between measured heat debt and sleeping bag insulation across a range of ~ 4 to 9 Clo sleeping bags with a three hour exposure, could not have been found without using the Level 2 analysis to choose the conditions for the human subject test.

The MOISTURE PERMEABILITY INDEX (Im):

During the “Cold War” of the early 1960’s, reports that large warehouses had been built near many of the airports led to discovery that large amounts of Chemical Warfare (CW) munitions were being stored in them. The question of the ability of U.S. troops to operate in the CW protective ensemble developed during WW II, but worn on very few occasions then, and not since then, was raised. This ensemble, worn with a gas mask, consisted of a set of CCl_3 impregnated long underwear worn under a buttoned up, CCl_3 impregnated, combat uniform, with impregnated, long cotton gauntlets and long, impregnated cotton sox, with a rubberized over-boot worn over the standard combat boots. A joint team from the Surgeon General’s Armored Medical Lab at Ft. Knox, KY and the Quartermaster Lab at Natick was tasked to run a small-scale field study (Level 4, in my system). The subjects, a 44 –man Platoon, set out on a morning march, with full combat loads, on a comfortably warm April morning in Virginia; in about one hour > 50% had suffered heat exhaustion, and I had a new career direction.

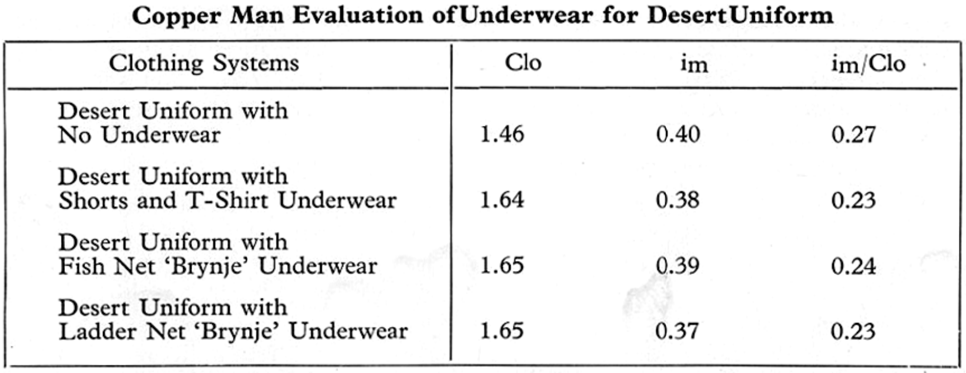
Fortunately, Dr. Alan Woodcock had been studying the evaporative transfer from a forearm sized, wetted cylinder, and had developed a permeability index ranging from 0 when the sweating cylinder was covered by a totally moisture vapor impermeable cover, to 1 if the evaporative cooling from the wet surface of the cylinder was equal to the maximum evaporative cooling (E_{max}) available in the ambient environment. For the case of an uncovered wet cylinder, E_{max} equaled the difference between the vapor pressure of water (≈ sweat) at the cylinder surface temperature, and the vapor pressure of the ambient air, provided that there was a high air motion to prevent any meaningful still air layer build up around the cylinder surface. He used the slope of the wet-bulb temperature lines on a standard "Molier Diagram", i.e., the psychrometric chart, which is 2 °C per mmHg vapor pressure difference, to convert the vapor pressure difference to an equivalent temperature difference, and then calculated the available evaporative cooling power as the appropriate measured Im fraction of that. When I stated that I could get a copper man to "sweat" Dr. Woodcock was sure I couldn't do that, and when I explained that I would then use his, "only theoretical", approach to calculate the actual evaporative cooling a man could get wearing any clothing system for which I had generated an Im on such a manikin he thought I had lost my mind.

I had an expert tailor from the Quartermaster group make a form fitting cotton skin top, bottom, full head cover and mittens, of good quality cotton with a high water holding capacity. After wrapping the manikin carefully in Saran© wrap, I dressed the manikin in this skin, put on the test clothing ensemble, ran a new "dry Clo value for the manikin + dry skin + test clothing to use as a baseline for calculating the additional heat loss when the manikin skin was wet. This was necessary because, no matter how carefully I wrapped, inevitably there were air pockets trapped under the arms and in the groin area.[1] After this "Dry skin Clo" determination for the ensemble being tested, the clothing was opened as far as possible (i.e., pants dropped, shirt open, cuffs unbuttoned, etc.) and a hand pressurized garden sprayer, filled with water at near skin temperature (i.e., ~ 35 °C) was used to repeatedly mist as much of the cotton skin and sock area until saturation was achieved, when the manikin was promptly redressed, with all apertures closed as normally worn. When all manikin skin temperature sites returned to the 35 °C level used for sweating runs, steady state Im values were recorded **until** a fall in the power demand by any section of the manikin (usually the head or hand) was observed, and the clothing opened and skin sprayed again until fully rewetted. If these two measured Im values agreed to the second decimal, that Im was accepted and the test ended; if not the rewet, retest procedure was repeated until they did. The amount of water supplied initially was always well in excess of 1 Liter, the sustainable maximum human hourly sweat rate, and generally > 2 Liters, in keeping with the maximum sweat rate of ~ 2.5 L/hr observed in some of my most severe heat stress studies. **I question the validity of Im values determined on any manikin with maximal sweat rates on the order of 1 L/hr or less**.

[1] While running a manikin study this month (September 2006) with Mr. Joseph Giblo at the U.S. Navy Clothing Test Facility in Natick, he showed data that he had collected on a water proof manikin that did not need such wraps to avoid internal water damage when its cotton skin was thoroughly wet; the difference between values of clothing ensemble measurements

calculated based on the Clo values, whether the dry cotton skin was used as the baseline or not, was negligible. Thus, with such manikins there is no need for the extra measurement.

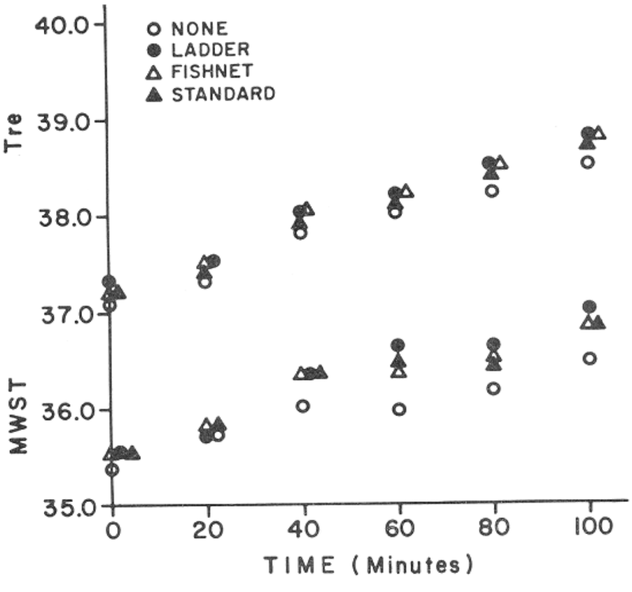
The discriminating power of the manikins NOW was extended from cold weather effects of clothing, to the effects in hot weather, or during physical work when sweat production was required to get the necessary evaporative cooling. An example comes from a study evaluating proposed differences between wearing no underwear, conventional T-Shirt and boxer shorts, conventional Brynje underwear (diamond shaped openings) or "Turmsk Brynje (ladder shaped columns), under the standard U.S. Army fatigue Uniform in desert conditions.



Copper Man Evaluation ofUnderwear for DesertUniform

Clothing Systems	Clo	im	im/Clo
Desert Uniform with No Underwear	1.46	0.40	0.27
Desert Uniform with Shorts and T-Shirt Underwear	1.64	0.38	0.23
Desert Uniform with Fish Net 'Brynje' Underwear	1.65	0.39	0.24
Desert Uniform with Ladder Net 'Brynje' Underwear	1.65	0.37	0.23

A Level 3, small-scale carefully controlled chamber study was designed using this data. Eight heat acclimatized subjects (the preferred number for Level 3 tests, since one subject's responses could actually be opposite to that of the other seven without eliminating the possibility of reaching a 5% level of statistically significant difference among the test variables) volunteered as subjects for the five-day study. Day one was a re-acclimatization and familiarization day, and also helped avoid the usual Day 1 anxiety and confusion. The next four days involved a Latin Square designed wear of the four test ensembles (each by 2 men each day) in a 49 °C Climatic chamber at 20 % RH (Wet Bulb = 29 °C), starting with a 40' treadmill walk at 4.8 km/hr, followed by a 20' rest, and concluding with a final 40' walk. These test conditions were chosen based on predicted heat storage under these test conditions, and my experience which strongly recommends the use of alternating periods of rest and work. The results are shown in the following figure.



ISSUES:

Use of Rc & Re versus Clo & Im:

Currently, there has been an increasing tendency to express insulation using Rc, rather than Clo, values. While this blurs the fact that the Clo value is a combined value incorporating both convective and radiant heat transfer (and accordingly, operative temperature, rather than air temperature should be used as the gradient against skin temperature), as long as one is aware of the difference this works. However, the wonderful ease of calculating the heat loss from a standard (1.8 m^2) man as 10/clo kcal/hr/°C difference between skin and air temperature is lost. However, using Re -- which is calculated based on Rc – practically guarantees that it will be difficult to determine whether the source of a heat stress problem is too high an insulation value of the clothing worn, or too low an evaporative cooling potential, whereas the simple "Clothing Permeability Index" (Im/Clo), not only identifies the source of any heat stress problem from the clothing but also specifies the precise percentage of the evaporative cooling power available in a given ambient environment as a function of the vapor pressure difference between sweat at skin temperature (42 mmHg for skin without much cover at 35 °C; 44 mmHg for skin at 36 °C, when heavier clothing is worn; or even ~ 48 mmHg or higher for men approaching heat exhaustion collapse), and the ambient vapor pressure; i.e., an Im/Clo of 0.3 indicates that only 33% of the maximum evaporative cooling power of the ambient environment [Emax = 2.2[2] x (Pskin – Pa)] can be obtained by the wearer. Try calculating that using Rc & Re? Are we trying to help or confuse with such "scientific" sophistry?

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[2] After several years of calculating heat loss using the 2 °C per mmHg conversion, which Woodcock had derived from the slope of the wet bulb temperature lines on a psychrometric chart (Molier Diagram), my friend Pharo Gagge pointed out that we should be using the Lewis Number value of 2.2 °C/mmHg vapor pressure difference, because the psychrometric wet bulb line reflected a 10% radiant regain by the wet bulb surface from the ambient air temperature.

(figure contrasts increased for web publication; 3 Dec 2007; G.Havenith)