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FUNDAMENTAL ENERGY PROCESSES OF THE HUMAN BODY

by

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FUNDAMENTAL ENERGY PROCESSES OF THE HUMAN BODY

Within the hand that holds this sheet of paper there throb thousands of engines; each with its own fuel requirements; each yielding varying amounts of work, heat, and waste output. Each is a cell in your body.

Of course, these cells are not completely independent. They share in a society, but especially in an economy, of the whole organism. This economy does not trade dollars of differing currencies; rather, its commerce is in energy of differing forms.

A particularly important asset is thermal energy. It is the natural by-product of the various energy conversion processes, the biochemical reactions within the body. But, additionally, its average level of distribution throughout the body (i.e., the body's temperature) is significant in the maintenance of the proper rate of these same biochemical reactions.

The purpose of this module is to characterize and evaluate the energy management of the body, with special emphasis on relating the physical processes of thermal energy transport (i.e., heat flow) to the body's temperature regulation process.

EXPLORATION IN THINKING

Perhaps you may have wondered how it is that a huge green salad fills up your stomach but does not fatten you. On the other hand, a relatively small piece of candy is prohibited to those dieting. Try to identify what characteristic of foods discloses whether they are fattening or not.

Has it ever occurred to you that although it takes a great deal of work to put a load of groceries away up in a cupboard, it still takes work to bring them back down to the counter? Determine which is the common characteristic of machines (including the human body so considered) that requires they always be supplied with new energy in order to continue operating.

Only a spectacular athlete can run a four minute mile; but nearly anyone can pedal a bicycle the same distance in less time. Ponder for a while the possible reason that bicycle riding is less demanding than running. And while you are at it try to figure out why it was that man's quest to fly awaited the development of suitable ~~auxiliary~~ engines.

EXPLORATION IN DOING

1) External Energy Production by the Body.

Find a full shelf of substantial books which is located above the level of your head but not out of your reach from the floor. Then perform the following tasks while someone times your activity.

(a) Unload the entire shelf onto the floor in clusters which are light enough for you to handle and at a pace which is reasonably fast. Your partner should note the duration of this task. Make a note of how tired you feel when finished.

(b) Next have your partner load your arms with as many books from the floor as you can reasonably bear. Hold these for the entire length of the former work period, and note how tired you are when finished.

(c) After returning these books to the floor, set about reshelving the entire stack of books you lowered in part (a). Do this, if possible, in the same work period as in part (a). Note how tired you feel when finished.

2) Thermal Energy Production in the Body.

Make a list of sources of energy available for energy transformation in the body. You may wish to consult a biology text for information about metabolism. A simulation of thermal energy production in the model body is provided by a coil of nichrome wire buried within the metal ball. This coil is the locus for the transformation of electrical energy, from electric current flowing through it, into thermal energy of the ball. (In the body, the chemical reactions of the metabolic processes transform chemical energy into such thermal energy.)

Turn on the energy production by twisting the knob of the energy source. Set a fixed level of production and wait to observe changes in the ball.

Touch it from time to time. What does the thermistor thermometer tell you? What is the pattern as time passes? Change to a different level of energy production and repeat your observations. Does the thermal condition of the ball approach some equilibrium (i.e., steady) state after a long period of time?

3) Thermal Energy Transport from the Body.

Now, subject the ball to different thermal environments. You may wish to hang onto it with your hand (provided it's not too hot) for a time; turn on the fan for a time; put a "dress" on it once; and even spray some water on it. What is the effect of each on the equilibrium state? Can you identify and name the processes by which thermal energy is removed from the ball in each of these situations?

INVENTION

A. Prerequisities.

Before you begin this module, you should be able to:

1. Describe, using the appropriate units, the interrelatedness of the concepts of potential energy, kinetic energy, and mechanical power.
2. Calculate the magnitude of each in an example if given an object's mass, its relative height, time required for the work to be completed, and/or its velocity.
3. Distinguish between the terms "thermal energy" and "temperature" by providing a written explanation of what each term represents, by providing a basic example which illustrates your explanation, and by using the appropriate units in the discussion.
4. Utilize the concepts of conduction, convection, radiation, and evaporation to determine the quantity of heat transport in each process in a physical situation involving one or all of the processes.
5. Describe qualitatively, the variation of skin temperature of the human body at various locations (trunk, legs, head, etc.) compared to the internal (core) temperature as a function of environmental temperature.

B. Objectives.

After you have completed the content of this module, you will be able to:

1. Relate the metabolic rate of the body to the calculated work being performed and to the rate of heat transfer. Estimate the efficiency of the body in producing mechanical power in a given situation like running, cycling, or climbing stairs.
2. Describe qualitatively the function of each of the four thermal transport phenomena utilized by the body in regulation of its tem-

perature (conduction, convection, radiation, and evaporation) and outline the environmental conditions required for each of these transport phenomena to act at the body's surface in a maximum and in a minimum capacity relative to the others.

3. Calculate, for a human body in a given situation, the rate of energy produced in mechanical power, and lost through one or all of the four forms of heat transport at its surface, and write a total energy balance expression for the body.
4. Provide values, reasonable and appropriate for the human body, for quantities such as surface areas, skin temperatures, conductivities, etc.

C. References.

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D. Energy Conservation in a Living Organism.

Whether we are working, playing, sitting, or sleeping, our bodies are transforming the chemical energy stored in the food we eat into other varieties of chemical energy and into other forms of energy as well. Of special significance to our purposes here is the fact that ultimately much of the energy input from food sources ends up as thermal energy. For it is the difference between the rate of evolution of this thermal energy and the rate of its divestment from the body through heat flow which dictates whether or not the body's temperature remains constant.

Under normal operating conditions, the human body's temperature is well above the (ambient) temperature of its surroundings. Consequently, thermal energy is transported within and lost from the body through its surface by the standard heat flow processes. The body replenishes this lost thermal energy as a by-product of the processes whereby the food's chemical energy is transformed to other kinds of chemical energy and to external mechanical energy.

The human body can, indeed, be analyzed as a heat engine whose performance is evaluated by physical principles such as the conservation of energy. The engine operates on the chemical energy of the fuel (food) which is oxidized and reorganized into specialized energy chemicals (glucose, etc.) for use in the body. Ultimately, these are converted, at various sites throughout the body, into mechanical energy through work (to circulate blood, respirate air, etc.) and into thermal energy, some of which is exported as heat (thermal energy transferral to the environment due to the body/environment temperature difference).

How can one more precisely tabulate and relate to one another the energies involved in these transactions? One possibility is to apply the principle of the conservation of energy to the digestion process. Simply stated

(Food energy into the body) = (Internal energy added) + (Chemical energy in waste) (D.1)

The *difference* between the first and last terms here, the *internal energy increase* of the body, is the significant quantity for further energy analysis.

The next stage of this analysis involves the fate of that internal energy added from food digestion. This energy, largely in the form of the ready chemical energy of glucose but possibly also stored in fats, etc., plus some thermal energy from the digestion process, is transformed in the metabolic processes of cell respiration. This transformation is of chemical energy into thermal internal energy within the body. The *conservation of energy* requires that this internal energy, here called *metabolic energy*, equals

(metabolic energy) = (thermal energy retained) + (internal energy output) (D.2)

At this point an important distinction* must be made. The quantities in equations (1) and (2) above have an existence of their own (one can isolate and measure the quantities of food, glucose, waste products; stick in thermometers, etc.). In the next state of analysis, that of the *processes* of utilization of the outputted internal energy, appear two other "quantities," *heat* and *work*. These have definite (energy equivalent) values for any given utilization process (measured as energies before and then after transfer between two locations in that process). However, these have different values for one process as compared to another. These should be better called "processes" than "quantities" since their "existence" depends upon whether or not one or another process is performed and cannot be properly ascribed to the

---

* Caution: Not all authors agree on the importance of this distinction or are otherwise careless in their use of the term *heat*. It frequently is used interchangeably in reference to both *thermal energy* and the *heat transfer process*, a practice which is both inconsistent and which I find regrettable. Thus the phrase "heat energy" is a contradiction in terms. Read on.

system before or after that process occurs. They have existence only as a logical invention, not in reality. What one has in reality is a given amount of internal energy from the body being transferred to the outside. The total amount is fixed, but the processes of transfer may accomodate this energy in all possible combinations of heat and work, the only constraint being that whatever energy disappears from inside must appear outside. Thus in the general case, the sum of heat and work is fixed but not their individual values. These facts are summarized in the first law of thermodynamics.

$$\text{(Internal energy outputted)} = \begin{array}{c}\text{(heat transfer)}\\ + \\ \text{(external work done)}\end{array} \qquad \text{(D.3)}$$

The concept of efficiency of an activity (c.f. Equation E7.) characterizes what is the division of metabolized energy into heat and work processes.

These equations serve as the framework for posing many interesting problems in quantitative physiology of the bioenergetic system. These are amply described in some of the reference materials (e.g., Benedek and Villars). One especially useful fact to know is that one may readily measure the metabolic energy release by monitoring the oxygen consumption of a mammal. This serves as a convenient measuring tool in quantitative physiology.

Studies are often done over short time durations, measurements made quickly and repeatedly, in order to study how these energy transfers change during a course of time (i.e., from measurement to measurement). Thus, it is important to treat the quantities in an equation such as (3) as time rates of the respective energies. These are simply defined as, in each case

$$\text{(energy rate)} = \frac{\text{(energy exchanged)}}{\text{(time duration of measurement)}} \qquad \text{(D.4)}$$

This is done in order to conceptualize the instantaneous character of the energy exchange. Thereby one can compare the exchange during one time period with that energy exchanged during any other time period. It is helpful to remember that a time rate of energy exchange is called power.

Finally, we wish to connect the energy transfer processes with the regulation of body temperature. The body temperature is roughly proportional to the thermal energy content per unit mass of the body. The condition for no change in temperature is now clearly expressible in terms of the quantities of equation (2).

$$\text{(thermal energy retained)} = 0$$

whereby one has from the above and the division of equation (3) through by time

$$\text{Metabolic rate} = \text{Rate of heat exchange} + \text{Mechanical power} \qquad \text{(D.5)}$$

where the metabolic rate is the rate at which our bodies convert the chemical energy in glucose or fats into energy forms useful for body operation. The heat exchange rate (sometimes called heat flow) is the rate at which excess thermal energy is transferred to the body's environment. And, finally, the mechanical power represents the rate at which mechanical work is being done by the body.

EXERCISE D1

A bicycle rider produces about 150 watts of mechanical power for his bicycle when operating at a metabolic rate of 525 watts.

1. At what rate must the cyclist lose heat from his body if he is to maintain a constant body temperature of 37°C?
2. Suppose that this rider wants to pedal for eight hours today. To what value of total energy intake (i.e., caloric content of food) must he restrict himself if he wishes to lose at least some weight (i.e., metabolize some fat for energy needs)?

Solutions are given on the next page.

EXERCISE D1 SOLUTIONS AND/OR SUGGESTIONS

1. Metabolic Rate = = Rate of heat exchange with the environment + Mechanical Power

525 watts = Rate of heat exchange + 150 watts

Rate of heat exchange = 525 - 150 = 375 watts

2. Two steps of calculation are necessary. First, the food energy content must equal or fall short of the utilized (metabolized) energy if weight is to be lost.

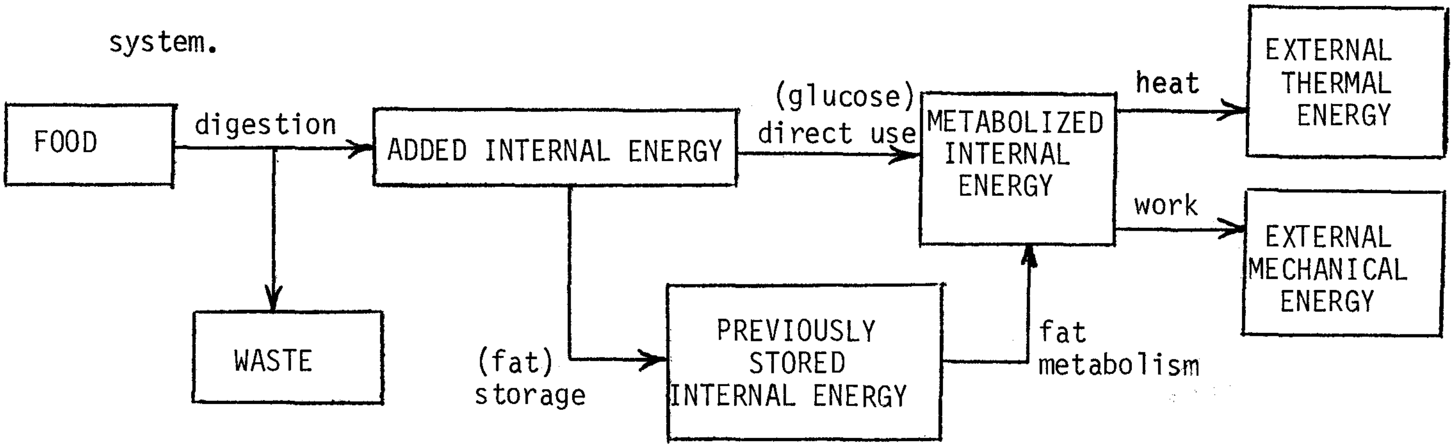
Food energy $\le$ total metabolic energy

Second, the total metabolic energy utilized must be computed from the metabolic rate (which is necessarily the sum of both heat rate and mechanical power). This is straightforward. Since 1 watt = 1 joule/sec one has

$$
\begin{aligned}
\text{total metabolic energy} &= (\text{metabolic rate}) \times (\text{elapsed time}) \\
&= (525 \text{ watts}) \times (8 \times 3600 \text{ sec}) \\
&= 1.5 \times 10^7 \text{ joules} = 15000 \text{ k joules} \\
&\cong 4000 \text{ kilocalories}
\end{aligned}
$$

(N.B.: 1 "food" calorie = 1 kilocalorie)

For future reference, here is an energy flow chart for the bioenergetic system.



Equation (5) expresses a relationship, among the three most important energy factors in the body system, which is fixed by energy conservation requirements. These energy and energy transfer processes have additional dependencies and interdependencies. For example, a certain excess of metastable energy is released whenever external work is done, but the amount of that excess is a different characteristic amount for each given work process (bike pedaling, wood chopping, etc.). Before we discuss the specific details of these interrelationships, let us look at the further dependencies of each individual component in that equation separately.

E. Mechanical Power.

The physical definition of power is that of the rate of energy transferred by means of a force.

$$\text{Power} = \frac{\text{Work}}{\text{Time}}$$

where work done is the amount of energy transferred by the force and this is divided by the time required for that energy to be transferred by the action of the force.

This work itself is related to both the strength of the force F (on the object) which transfers the energy in question, and the amount of movement d undergone (by the object) the recipient of that energy.

$$\text{work} = F \times d \ . \qquad \text{(E.6a)}$$

Two comments about work must be added which are especially important for the biological applications of energy:

(a) If either F or d is zero in value, no work is done (viz. no energy is transferred).

(b) The <u>direction</u> of the force F relative to the distance moved d is significant in determining the amount of energy transferred. <u>Only</u> that portion (i.e., component) of the distance d moved which can be thought of as lying <u>along</u> the direction of the force, call this (d_F), participates in a transfer of energy. Thus, equation (6) might better be written

$$\text{work} = F \times d_F \quad . \qquad \text{(E.6b)}$$

and

$$\text{power} = \frac{F \times d_F}{\text{time}} \quad . \qquad \text{(E.6c)}$$

To illustrate some consequences of point (a) above, consider the case where you are holding a case of beer out in front of yourself. Your arms exert a force upward (to balance the gravitational force on the beer, its weight). Application of equation (6) indicates that <u>no energy</u> is transferred from you to the case (i.e., no work is being done) since d is zero. Certainly this must be so from the standpoint of the case of beer, since it just sets there and might as well be on a table. However, after a while of profuse sweating you must be inclined to disagree. Indeed the left hand side of equation (D.5) is <u>not</u> zero in this case. Internal metabolic energy <u>is</u> being utilized but <u>not</u> to do external work. It is the <u>first</u> term on the right in that equation which accounts for this use of internal energy. That is what the sweating is all about; but the full story awaits the treatment of section (G).

To illustrate some consequences of point (b) above, consider the case where a billiard ball rolls across a (typically) level billiard table. A light tap sends the ball moving a very long distance before it eventually slows and stops. Alternatively, it is usually quite apparent if the table is inclined even only a small amount; for then the struck ball immediately either picks up or loses speed. In the first situation, the level table, the gravitational force on (i.e., weight of) the ball is exactly <u>perpendicular</u>

to the motion given to the ball and does not transfer any energy of motion to the ball; that is, it does no work since $d_F = 0$. In the second situation, the inclined table, this perpendicularity condition is no longer true and the motion has a vertical component (i.e., along the direction of the gravitational force). Thus, energy is transferred to the ball via the gravitational force. Your eye can judge in which of these two cases energy is transferred.

Clearly, then, both modes of internal energy utilization, internal dissipation and external work, are important in bioenergetics. Anyone who has ever carried a bucket of water across a level floor will testify to the significance of this first mode. So too will a runner on a level track. However, having run over hilly ground myself, I can vouch for the co-importance of both modes. It is harder on hills than on a level track.

A further question might arise as to why running up and down hills is any more difficult than on level ground. Going up the external work transfers your internal energy to the gravitational potential energy form; going down should do just the opposite. But this doesn't seem to be the case since we continue to get tired running downhill as well as uphill (even though less quickly in the former case than in the latter). The reason is that the transfer of our energy through external work is irreversible. It does one no good to get out of bed in the morning and (noticing that the breakfast cereal is gone) instead of eating, rather lower a shelf full of heavy cans to the floor. One derives no substitute for food nourishment this way even though the weight of these cans does work on you. In fact, studies have shown that when one uses muscles in a manner opposite to that in which they are normally used to do external work (for example, if a bicycle type device is motor driven and the pedaller is forced to restrain the motor while continuing to move the pedals in the forward direction), that the utilization of internal energy skyrockets, even though the external work is negative! You actually get more tired quickly than when you transfer energy to the bike. Too bad!

This brings up the final consideration of this section. What about this division of metabolized energy into dissipation and external work. Clearly the latter is desirable for doing jobs while the former is largely wasted energy "overhead." The quality of an activity which relates the energy utilized to the external work done is called its efficiency.

$$e = \frac{\text{mechanical power}}{\text{metabolic rate}} \tag{E.7}$$

Thus efficiency sets the division between heat and work in Equations (D3) and (D5). It is important to realize that this efficiency ratio is not a fixed number for a given body. It depends upon the task, upon the environmental conditions, and even upon whether the task was just begun or has been going on for some time. Some of these factors are now discussed.

Bicycle ergometers which sit at rest in the laboratory utilize a friction braking system against which force the leg muscles do work. By measuring the number of revolutions made by the rear wheel in a given time period, and noting the mechanical advantage of the pedal-sprocket system and the frictional force required to move the wheel, the power may be calculated using equation (6).

The mechanical power output of the body depends upon a number of items. These include metabolism, rate of cooling, length of time worked, etc. For example, Table (1) illustrates the decrease in mechanical power output available from the human body for work periods of various lengths.

Power (watts)	Horse Power	Time
1500	2	6 sec
750	1	1 min
260	.35	35 min
150	.2	5 hrs
75	.1	8 hrs

TABLE E.1
Maximum power outputs from the
human body for various time periods.

The efficiency of the body depends upon the mechanical task and the power level delivered. One of the most efficient schemes for the production of mechanical power by the body is the bicycle. Table (1) shows that a power level of about 150 watts is the maximum work rate which can be maintained for any extended length of time. Experiments for several activities showing power output, metabolic rate, and calculated efficiency are given in Table (2). Note that each activity listed is below the 100 watt level and thus, according to Table (1), could be maintained for a long period of time. For higher power levels and shorter periods of time, e.g. weight lifting, or running up a short flight of stairs, the efficiency would be larger.

	Power Output		Metabolic Rate	
Task	horse power	Watts	Watts	Efficiency e
cycling	.15	112	505	0.19
tramming*	.12	90	525	0.17
shoveling	.024	17.5	570	0.03

*Pushing a coal car in coal mine.

TABLE E.2
Human body efficiencies for
several long term activities.

EXERCISE E2.

1. The bike rider in the Exercise (D.1) on page 10 is producing 150 watts of mechanical power to maintain a constant velocity of 5 meters/sec. Find the total of the resisting forces doing work on the rider.
2. If the rider must ride up a long incline which is 100 meters long and 25 meters high and wishes to maintain his velocity, find the new mechanical power output required. Is this possible? (See Table E.1.) Assume that the rider has a weight of 700 Newtons.

Solutions are given on the next page.

EXERCISE E2 SOLUTIONS AND/OR SUGGESTIONS

1. $P = \frac{F \times d_F}{t}$

   $150 = F \times \frac{d_F}{t}$

   And since v is parallel to F, $d_F = d$ and

   $150 = F \times v = F \times (5)$

   $F_{resistance} = \frac{150}{5} = 30$ Newtons

2. Time to climb hill at same velocity $= \frac{100}{5} = 20$ sec

   Total power required $= 150 + \frac{\text{weight of body x vertical height}}{\text{time}}$

   $P_T = 150 + \frac{700 \times 25}{25} = 150 + 875 = 1025$ watts

   Interpolation of a log-log graph of Table E1 shows that this wattage production may just be possible for the 20 seconds required.

EXERCISE E3.

1. Calculate the efficiency of the bicycle rider of Exercise (D.1) when riding on level ground.
2. Repeat the above calculation for the cyclist climbing the hill as outlined in Exercise E.2. Assume that the metabolic rate of this cyclist increases by a factor of four as compared with the level rider.

Solutions are given on the next page.

EXERCISE E3 SOLUTIONS AND/OR SUGGESTIONS

1. $e = \frac{\text{Power}}{\text{Metabolic Rate}} = \frac{150}{525} = 29\%$.

2. $e = \frac{1025}{2100} = 49\%$.

F. Metabolic Rate.

Food is oxidized in the body at a temperature of about 37°C. This process of energy is called METABOLISM. The basal metabolic rate is the rate of thermal energy production in the body under normal, resting conditions. Sleeping organisms operate at levels below the basal rate and working systems operate at higher metabolic rates. Quantitative measurements of metabolism can be accomplished in two ways:

1. Enclose the individual in a chamber (whole body "direct" calorimetry) so as to measure the heat contributed by the subject to the walls of the chamber and the enclosed atmosphere;
2. Monitor the ratio of the volume of carbon dioxide expired to the volume of oxygen inspired. (Called "indirect calorimetery.)

The first method, whole body-direct calorimetry, has been used extensively in researching basal metabolic rates of humans and animals. The second method, indirect calorimetry, is useful in determining the active metabolic rate of humans and animals. During the recent (1974) Sklyab missions, body metabolic rates were monitored closely using this technique while the astronauts peddled an exercise bike.*

Basal metabolic rates (BMR) per square meter of skin surface for animals with various skin surface areas are shown in Table (3).

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*Skylab and the Life Sciences, National Aeronautics and Space Administration, manned spacecraft center, Feb. 1973 (page 23).

	Mass (kg)	Basal Metabolism Rates per area (BMR) (watts/m^2)
Hog	128	52
Man*	64	50.4
Dog	15	50.3
Guinea Pig	0.5	60.3
Mouse	0.018	57.2

TABLE F3.
Basic metabolic rates per square meter of surface area for various sized animals.

Investigations over a wide range of animals sizes (from mice to elephants) shows little relationship between the size of the animal and its BMR per area in watts/m^2. (See exercise 8 in section A, the Questions and Exercises in the Applications section for this module.)

The basic metabolic rate for humans varies according to age, sex, and amount of inactive body tissue. Since the core of human metabolic activity centers in the protoplasm of active tissue, a body with a high percentage of inactive fatty tissue will show a lower BMR per area. For this reason, athletes tend to have higher than average BMR's per area, and women, whose percentage of fatty tissue is larger than men's, have lower BMR's per area than men. Table (4) shows average metabolic rates per area for males and females in watts/m^2.

*A man's average surface area is 1.8 m^2.

	Males	Females
Age at last birthday	Metabolism	Watts/m^2 *
6	61.5	58.8
7	60.9	57.0
8	60.1	54.6
9	58.7	53.3
10	56.3	53.3
11	54.8	52.6
12	54.3	51.4
13	53.8	49.8
14	53.8	48.1
15	58.8	46.6
16	53.1	45.1
17	52.0	43.9
18	50.2	42.7
19	49.1	42.7
20 - 24	47.8	42.0
25 - 44	45.2	41.5
45 - 49	43.4	40.6
50 - 54	42.6	39.4
55 - 59	41.9	38.5
60 - 64	40.6	37.9
65 - 69	40.4	37.5

TABLE F4.
Average Basal metabolic rates per area
for males and females from ages 6 to 69.

*An average adult's surface area is about 1.8 m^2.

As exercise rate increases, the body requires more energy for operation and the metabolic rate increases. Muscular work is the main factor which increases the metabolic rate as illustrated in TABLE (5).

Activity	Average Adult* Metabolic Rate per area (watts/m^2)
Sleeping	40
Sitting at rest	43
Standing	50
Walking at 1.2 m/sec	108
Walking down stairs	237
Walking up stairs	616

TABLE F5.
Approximate metabolic rates for various activities.

Other factors which have slight effects on the measured metabolic rate of individuals include the environmental temperature, diet, body temperature, and altitude.

---

*An average adult's surface area is 1.8 m^2.

G. Rate of Heat Loss.

As you go about daily activities, the metabolic rate of your body varies considerably, yet your body is required to maintain a perfect inner body temperature of 37°C. You aid in the regulation of the consequent heat flow at your body's surface by changing the texture and/or color of the clothing you wear or by increasing the flow and/or temperature of the air in the room where you reside. Your body directs the heat flow regulation from inside by altering blood flow, sweating, shivering, etc. We now examine a number of the surface processes in the context of some real life examples.

Suppose that you are on your way to the college library early one summer morning by bicycle. The day is clear, cool, and the air is dry. As you perform mechanical work your metabolic rate increases. Since only a portion of the energy from metabolism is converted into mechanical work, the additional energy must be lost from the body in heat flow if the level of internal energy remaining within the body, hence the body temperature, is to remain constant. In this instance the primary mechanism for heat exchange is through convection.

CONVECTION

If air is forcibly circulated over the body surface or if there is a reasonable amount of natural air movement, the rate of heat flow increases. This heat process is called convection. Figure (1) depicts the heat loss from the skin as the air moves past the surface.

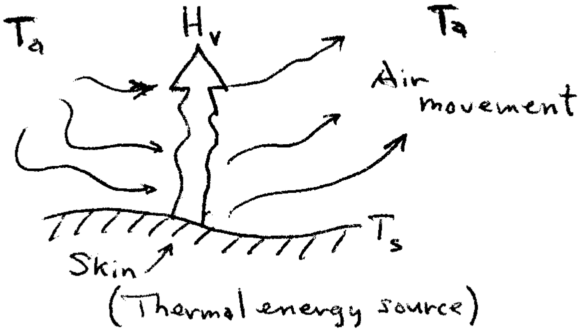


FIGURE G1.
Convection at the skin surface.

As the cool incoming air of ambient temperature T_a makes contact with the skin surface at temperature T_s the air gains thermal energy which, mixed into the larger body of air by the movement leaves the total air with a temperature essentially unchanged at T_a.

At the skin-air interface the flow of heat is proportional to the total temperature difference, $(T_s - T_a)$, so we may write the expression for the heat flow by convection for a body of area, A, as

$$H_v = K_v A \, (T_s - T_a) \qquad (G.8)$$

where K_v is the convection coefficient and depends upon the nature of the interface, the speed of the air movement, and the density and viscosity of air. The value of K_v is determined experimentally for various situations. Equation (8) was first developed as an empirical rule and is known as Newton's Law of Cooling. Figure (2) shows a typical empirical relationship between air velocity and the convection coefficient K_v.

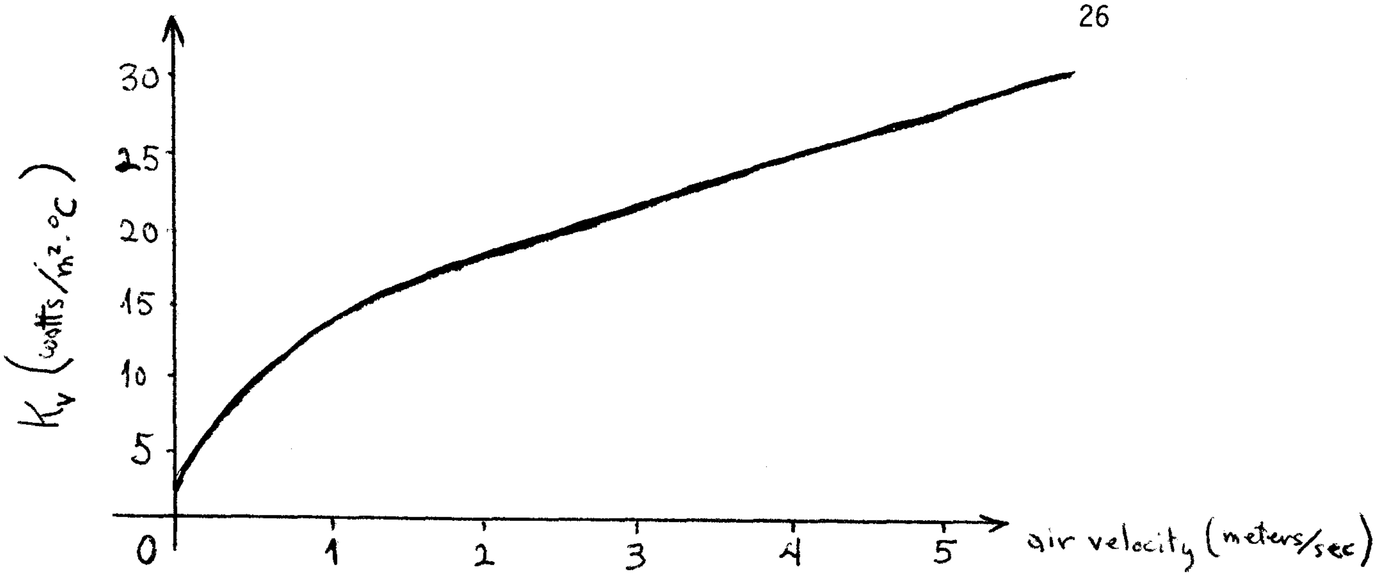


Figure G2. The convection coefficient, K_v, as a function of air velocity. (Ruch, T. C. and Patton, H. D., Physiology and Biophysics, W. B. Sanders Co., Philadelphia, 1965).

Under normal indoor conditions, approximately 30% of the total heat flow from the body is through convection. As the speed of the air past the body surface increases, as for a bike rider, a greater fraction of thermal energy is lost through this means.

In addition to this convective loss from the body's outer surface, a small amount is lost in warming inhaled air which is subsequently exhaled. Some animals, such as the dog, take greater advantage of this. They increase their breathing rate to enhance this cooling mechanism (panting) when other heat flow mechanisms are insufficient for controlling body temperature. This is reasonable since body hair discourages body surface convection (that's precisely what it's intended for) in such animals.

EXERCISE G4.

1. Assume that the bicycle rider of the EXERCISE D1 on page 10 is riding at a constant velocity of 5 meters/sec in humid, still air of temperature 28°C. Use Figure (G2) and calculate the rate of body thermal energy loss by convection. (You may take the body surface area to be 1.8m^2.)

2. What percentage of the total body thermal energy loss is through convection?
3. Repeat both (1) and (2) for the same rider at 7 meters/sec.

Solutions are given on the next page.

EXERCISE G4 SOLUTIONS AND/OR SUGGESTIONS

1. $H_v = K_v A\ (T_s - T_a) = (27\ \text{watts/m}^2\ °\text{K})\ (1.8\text{m}^2)\ (34°\text{C} - 28°\text{C}) = 292$ watts.

2. Metabolic Rate = 525 watts

   Power Produced = 150 watts

   Energy to be lost = 375 watts

   $\frac{292}{375} = 88\%$

3. $H_v = +(32)\ (1.8)\ (34 - 28) = 346$ watts

   $\frac{346}{375} = 92\%$

Once inside the library building, the rate of air flow decreases thus reducing the amount of heat which can be lost due to convection. As you explore the stacks for useful references or sit quietly and study, your body will take advantage of another major mechanism for heat called radiation.

RADIATION

The radiant energy emitted per unit area per unit time (i.e., radiant power per unit area) depends upon the nature of the surface and the temperature of the surface. In fact, the radiant heat in watts per square meter is proportional to the fourth power of the absolute temperature of the surface. This relation is often written as

$$h_r = e\sigma\ T^4\ , \tag{G.9a}$$

where h_r is in watts/m^2, σ is the Stefan-Boltzmann constant (= 5.67×10^{-8} watts/m^2 °K^4), e is the surface emissivity, and T_s is the absolute Kelvin temperature of the emitting surface. The emissivity, e, is a unitless coefficient which varies from 1 for a perfect (black body) radiator, to 0 for a (polished) perfect reflector. The emissivity is the same number which describes the fraction of incident radiant heat absorbed by the surface according to

$$h_a = eh_{ir} \tag{G.9b}$$

where h_{ir} and h_a are the incident and absorbed radiant heat per m^2 of surface, respectively.

The actual loss of energy by radiation depends upon the radiation absorbed by the skin as well as the radiation transmitted from the skin. If we consider a body in a room, the body radiates energy to the walls and the walls radiate energy to the body. Together this may be stated in terms of the net heat transfer per m^2 of the surface (assuming the walls' emissivity is unity)

$$h_R = (e\sigma\ T^4)_{body} - (e\sigma\ T^4)_{walls} \tag{G.10a}$$

where h_R will be the net rate at which energy is gained or lost by the body through radiation per unit of its surface. Human skin and ordinary clothing has a 98^+ percent absorbitive and emissive properties for infrared heat radiation. In the absence of polished surfaces, the emissivity of most interior rooms is also above 95 percent. Thus e for both the body and room walls is approximately equal to one, and equation (10a) becomes

$$h_R = (5.67 \times 10^{-8} \text{watt/m}^2{}^\circ\text{K}^4)\,(T^4_{\text{body}} - T^4_{\text{walls}})\,, \qquad \text{(G.10b)}$$

and the total rate of radiation loss H_R from a hot body to its cooler environment is equal to the product of the radiating surface area of the body times the radiant power per unit area,

$$H_R = Ah_R = 5.67 \times 10^{-8}\, A_{\text{body}}\,(T^4_{\text{body}} - T^4_{\text{walls}})\,, \qquad \text{(G.11)}$$

where A is the radiating area in square meters. Depending upon a number of environmental conditions, the radiation losses from the body account for about 44% of the total thermal energy lost by the body. (See Regulation module for a more detailed account.)

EXERCISE G5.

1. At what rate does a human body whose surface area is 1.75m^2 and skin temperature is 34°C lose thermal energy to the walls of a cool room whose interior wall temperature is 29°C?
2. Assume the human in (1) is sitting quietly at rest. Use the metabolic rate suggested in Table F3 and calculate the percentage of the total energy lost through radiation. (You may assume the mechanical power to be zero.)
3. Explain qualitatively the result of placing $T_{\text{body}} = T_{\text{walls}}$ in equation (11). What about in Equation (8)? What consequences do these results have for temperature regulation in this situation?

Solutions are given on the next page.

EXERCISE G5 SOLUTIONS AND/OR SUGGESTIONS

1. $H_R = 5.67 \times 10^{-8}$ watts/m^2°K^4 $(307^4 - 302^4)$ (°K^4)

   $= 32$ watts/m^2

   Total rate = (32 watts/m^2. 1.75m^2) = 56 watts

2. $\dfrac{56 \text{ watts}}{87.5 \text{ watts}} = 64\%$

3. The rate of energy radiated by the warm body is exactly matched by incoming radiation from the walls in the room. Thus, the heat exchange by the radiative mechanism is zero. The convective heat exchange is also zero (if the wall temperature is taken as the ambient temperature). Thus, some other mechanism must exist for temperature regulation. This is described in the following subsection.

Early in the afternoon as you ride your cycle home from the library. The conditions influencing heat transfer from your body have changed since morning. The air temperature has increased thus decreasing the rate by which heat transfer from the body occurs through convection. Therefore, another thermal energy transfer mechanism, evaporation, becomes important.

EVAPORATION

Under normal indoor conditions when the environmental temperature is lower than body temperature and the work is light, this heat transfer from the body by evaporation is small compared to heat transfer through convection and radiation.

Evaporation of moisture from the skin without secretion of sweat is called insensible perspiration. This release of moisture is caused by diffusion of water through the epidermis from the lower layers of the skin. Insensible evaporation from the skin of a resting male subject is about 20 grams/hour. Evaporation from the wet passages of the lungs and air passages varies with the rate of respiration and for a resting subject may account for a loss of body liquid of approximately 10 grams/hour. This rate of insensible respiratory evaporation increases proportionally with metabolic rate.

When the environmental temperature rises above 29°C - 31°C, heat transfer through convection and radiation are not adequate for a resting subject. Evaporation from the skin is increased by secretion of fluid from eccrine sweat glands distributed over the entire surface.

As water evaporates, its change of state requires 2424 Joules for each gram of water vaporized. This means that the amount of thermal energy lost from the body through evaporation is directly related to the amount of both insensible perspiration and sweat vaporized. Measurement of loss of body mass (Δm) during an exercise period will approximate the lost water and the thermal energy lost through evaporation will be,

$$E = 2424 \ (\Delta m) \text{ Joules} . \qquad (G.12)$$

The rate of thermal energy lost in watts is then approximated by

$$H_E = 2424 \frac{\Delta m}{\Delta t} , \qquad (G.13)$$

where $\frac{\Delta m}{\Delta t}$ is the rate of mass loss in gram per sec. Water lost by sweat dripping off the body produces no cooling effect.

Important: Notice that thermal energy loss by evaporation does not depend upon temperature difference between the body and its surroundings. Thus, properly speaking, this process is not heat which is energy transfer because of a temperature difference between two bodies. For this reason, it becomes the dominant mode of thermal energy divestment by the body as the environmental temperatures approach and exceed the body temperature.

Two obvious environmental factors which influence the thermal energy loss by evaporation are air temperature and relative humidity. Below an environmental temperature of about 30°C a unclothed human has only a slight evaporation loss of approximately 12 watts/m^2. As the air temperature increases this rate rises dramatically as shown in Table (5).

Air Temp °C	Skin Temp °C	Evaporative Rate watts/m^2
28	28	11
29	29	11.5
30	30	12.0
31	31	12.5
32	32	13
33	33	15
38	34	25
44	35	90

TABLE G.5
Evaporative heat loss from an unclothed, resting human body at various skin temperatures.

EXERCISE G6.

1. Assume that on a warm dry day the bicycle rider of the EXERCISE (D1) page 10 loses 300 grams of body mass through perspiration per hour. If the metabolic rate and the average rate of performing mechanical work are maintained as constants during this time (150 watts and 525 watts, respectively), at what rate is thermal energy lost through evaporation?
2. What percentage of the total thermal energy loss is through evaporation?

Solutions are given on the next page.

EXERCISE G6 SOLUTIONS AND/OR SUGGESTIONS

1. $H_E = 2424\ (\frac{300}{3600}) = 202$ watts
2. Since $P = 150$ watts and $M = 525$ watts,

   Thermal energy loss = 525-150 = 375 watts

   and $\frac{202}{375} = 54\%$.

In many parts of the United States an afternoon cycle ride is usually taken under more severe conditions than those just described. Suppose that coming home from the library, you find it to be warm and humid afternoon. Since the relative humidity is high, the evaporation rate from the surface of your skin is reduced thus slowing the total thermal energy loss rate. Your body may become overheated. You may want to use some alternative body cooling mechanisms.

Under these conditions you may find it difficult to pass by your neighborhood swimming pool without cooling off your body.

Once in the cool water (assumed to be lower than the average body skin temperature), your body loses heat to the water by another thermal transport process called <u>conduction</u>.

CONDUCTION

When the body is surrounded by air, thermal conduction of heat from the surface of the body is usually of minor consequence. If, however, the skin surface is placed in contact with another large dense material (the earth, metal, or emersed in a liquid such as water), this thermal transport mechanism can become a major contributor to the total body thermal energy loss.

In general, conduction of heat takes place when there exist a difference of temperature and a suitable medium between two objects. The ratio of the temperature difference to separation distance is called a thermal gradient and it is written as $\frac{\Delta T}{\Delta X}$. The thermal energy transferred from a point of high temperature to a point of low temperature will be proportional to this thermal gradient. The rate of heat flow, H_d, for thermal conductivity can be written as

$$H_d = K_d A \frac{T}{X} \qquad (G.14)$$

where A is the cross sectional surface area through which heat flow occurs and perpendicular to which a thermal gradient $\frac{\Delta T}{\Delta x}$ exists. K_d is a constant for a given connective material between the two objects and is called the thermal coefficient of conductivity for that material. For H_d in watts, K_d will have the units of watts/cm°C. Table (6) gives values for K_d measured for various materials. (For most materials including human skin, the value of K_d depends somewhat upon the temperature. However, this variation is usually so small that for our purpose it will be neglected.)

Materials-Metals	K_d(watts/cm°C)
Aluminum	2.1
Brass	1.1
Copper	3.9
Mercury	0.084
Silver	4.1
Steel	0.50
Various Solids	
Insulating Brick	1.5×10^{-3}
Construction Brick	6.3×10^{-3}
Concrete	8.4×10^{-3}
Cork	0.42×10^{-3}
Glass	8.4×10^{-3}
Wood	0.42×10^{-3}
Fluids	
Air	2.4×10^{-4}
Hydrogen	1.4×10^{-3}
Oxygen	2.3×10^{-4}
Water	5.9×10^{-3}
Body Materials	
Fat	2.1×10^{-3}
Muscle	4.2×10^{-3}
Bone	4.2×10^{-3}

TABLE G.6
Thermal coefficients of thermal conductivity for various materials.

In the usual case of heat transfer from the human body by conduction, the simple application of equation (14) is not adequate. Notice that in Figure (3) the skin interface is between the external material and the body's interior. Thus, the heat flow must go through <u>two</u> different materials in succession, and two expressions of equation (14) must be solved simultaneously. Let T_s be the skin temperature, T_b be the interior body temperature, and T_a be the temperature of the surrounding material. Further, let x_{in} be the (interior) skin thickness and x_{out} be the (exterior) thickness of the heated region which one presumes occurs in the vicinity of the skin surface. Note that although x_{in} is a definite measurable quantity, x_{out} is not and must be in any case estimated.

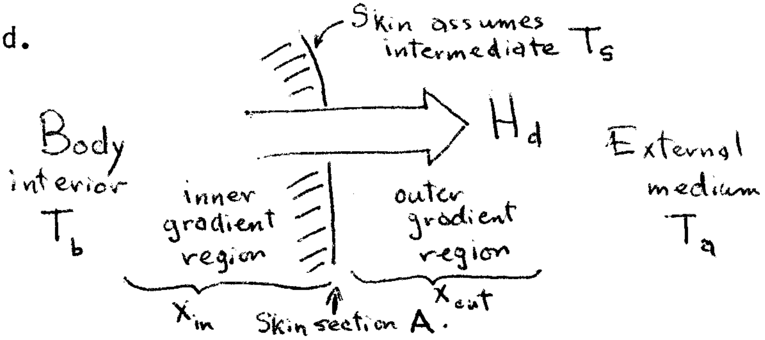


FIGURE G.3
Analysis of conduction at skin surface.

Using equation (14) <u>first</u> for the body-skin conduction and <u>then</u> for the skin-environment conduction, we have that for the definite section of skin of area A,

$$H_s = \frac{K_s A}{x_{in}} (T_b - T_s),$$ where K_s is the coefficient of thermal conductivity of the skin and $T_b - T_s = \Delta T_{in}$ (G.15)

and

$$H_M = \frac{K_M A}{x_{out}} (T_s - T_a),$$ where K_M is the coefficient of thermal conductivity for the surrounding material and $(T_s - T_a) = \Delta T_{out}$. (G.16)

Now, these equations must be solved simultaneously. In order to do this, we must make certain assumptions, since there are too many unknowns to otherwise solve them. If one considers only a definite section of skin, then the same heat flow must occur, successively, through both. Thus $H_s = H_M = H_d$. The other is but an arbitrary simplification: $X_{in} = X_{out} = \Delta X$. Eliminating the common T_s from these equations we obtain

$$H_d = \frac{K_s K_M A}{K_s + K_M} \left(\frac{\Delta T}{\Delta X}\right). \qquad (G.17)$$

Notice that the rate of heat flow across the skin interface in proportional to the total temperature drop from the interior body temperature to the temperature of the surrounding material, $T_b - T_a = \Delta T$.

It is now possible to see why thermal loss by conduction is so small when the body is surrounded by air. The coefficient of thermal conductivity of still air is approximately 2.4×10^{-4} watts/cm°C. This small conductivity restricts the rate of heat flow through the external layer X_{out}. One of the functions of warm clothing is to provide air traps to prevent air circulation near the skin's surface which would reduce $X_{out} \to 0$. Body hair does the same thing. "Goose pimples" are the body's way of erecting hair to maintain a larger value of X_{out}.

EXERCISE G.7

1. Resting with a BMR per area of 45 watts/m^2, an unclothed male subject is placed in an environmental chamber whose temperature is 31°C. Assume a core temperature of 37°C just 2 centimeters below the skin surface and an air temperature of 31°C just 2 centimeters above the skin surface and find the rate of heat flow as conduction per square meter of body area.
2. If the subject has a surface area of 1.8 m^2, what total energy does he lose due to conduction in 1 hour?
3. Since the subject is doing no mechanical work, approximate the percentage of thermal energy loss due to conduction.

Solutions are given on the next page.

EXERCISE G7 SOLUTIONS AND/OR SUGGESTIONS

1. $\frac{H_d}{A} = \frac{K_s K_a}{K_s + K_a} \; (\frac{T_b - T_a}{x} = \frac{(4.2 \times 10^{-3})(2.4 \times 10^{-4})}{(4.2 \times 10^{-3} + 2.4 \times 10^{-4})} \; \frac{(37°C - 31°C)}{(2)}$

   $\frac{H_d}{A} = 6.8 \times 10^{-4}$ watts/cm^2 = 6.8 watts/m^2

2. $E = (H_c)\ (A)\ (t)$ = 6.8 watts/m^2. 1.8 m^2. 3600 sec

   E = 44,064 Joules

3. BMR = 45 watts/m^2

   $\frac{H_d}{A}$ = 6.8 watts/m^2

   $\frac{4.5}{45}$ = 15%

When the skin makes direct contact with a massive cold or warm object, the $X_{out} \rightarrow 0$ and this second temperature gradient becomes "infinite." This means that the heat conduction is limited only by the inner layer and can be significant. We have all noticed that standing on a room temperature concrete or tile floor "feels" much cooler than a rug which laying over the floor has the same temperature. The latter maintains a low conductivity outer layer of thickness $X_{out} \doteq 0$. Our "sense" of cold is triggered in the former case because the skin surface is brought all the way down to T_a, that of the concrete floor.

EXERCISE G.8

1. The resting male of EXERCISE G.7 is emersed in a cool water pool. Assume that when the subject is initially placed in the 31°C water that the core body temperature of 37°C is detected at an average skin depth of 2 centimeters below the skin surface and that the water temperature of 31°C is found 2 centimeters above the surface. Calculate the rate of heat cnductance per square meter of body area.

EXERCISE (continued)

2. Compare the calculated rate of conductance found above to the similar body in air.
3. Since the subject is doing no mechanical work, approximate the percentage of thermal energy loss due to conduction.

Solutions are given on the next page.

EXERCISE G.8 SOLUTIONS AND/OR SUGGESTIONS

1. $$\frac{H_d}{A} = \frac{K_s K_w}{K_s + K_w}\left(\frac{T_b - T_w}{x}\right) = \frac{4.2 \times 10^{-3}\ 5.9 \times 10^{-3}}{4 \times 10^{-3} + 5.9 \times 10^{-3}}\left(\frac{37 - 31}{2}\right)$$

$$\frac{H_d}{A} = 7.5 \times 10^{-3} \text{ watts/cm}^2 = 75 \text{ watts/m}^2$$

2. Rate in Air = 6.8×10 watts/m^2

Rate in Water = 75 watts/m^2

$$\frac{75}{6.8} = 11 \text{ times larger in water}$$

3. BMR = 45 watts/m^2

$$\frac{H_d}{A} = 75 \text{ watts/m}^2$$

$$\frac{75}{45} = 166\%$$

What is the significance of a thermal energy loss rate greater than 100%?

APPLICATIONS

A. Illustrative Problem Solving

The problems in this section can be solved by selection of one or more of the following equations. The problems are gradated in order of difficulty. The first require only simple substitutions, and the latter demand considerable reasoning skills.

$$\text{Metabolic Rate} = \text{Rate of Heat Exchange} + \text{Mechanical Power} \qquad (D.5)$$

$$\text{Work} = F \times d \qquad (E.6b)$$

$$\text{Power} = \frac{\text{weight of body} \times \text{vertical height raised}}{\text{time}} \qquad (E.6c)$$

$$e = \frac{\text{mechanical power}}{\text{metabolic rate}} \qquad (E.7)$$

$$H_v = K_v A\,(T_s - T_a) \qquad (G.8)$$

$$H_R = (5.67 \times 10^{-8})\, A_{body}\, (T^4_{body} - T^4_{walls}) \qquad (G.11)$$

$$H_E = (2424)\,\frac{\Delta m}{\Delta t} \qquad (G.13)$$

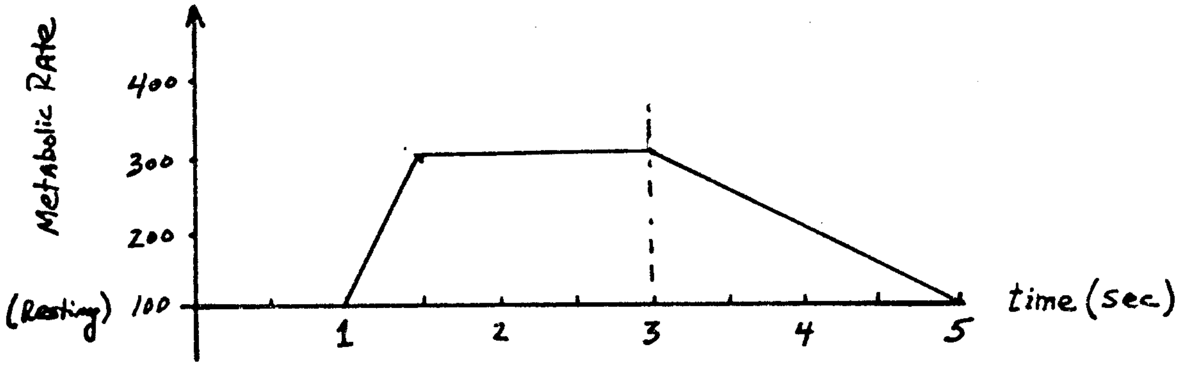
$$H_d = K_d\, A(\frac{\Delta T}{\Delta X}) \qquad (G.14)$$

1. A female subject, age 25, mass = 58 kilograms, skin surface area = 1.5 meter^2 is operating a treadmill in a laboratory. Her metabolic rate is indirectly measured at 400 watts and her power output is 100 watts. If her body remains at a constant temperature find the total rate of thermal energy loss through all available mechanisms taken together.
2. A weightlifter moves a 100 kilogram mass through a total distance of 2 meters. What mechanical work does he perform?
3. If the weightlifter does the lifting in 1.2 seconds, what mechanical power does he produce?
4. What is the activity efficiency of the female subject of question #1? How does this value compare with that given for long term cycling (in

the Invention Section)? What conclusion can you make about the duration of this activity?

5. A long distance runner is running at a constant speed of 4 meters/sec. His skin temperature is constant at 35°C, and his metabolic rate is approximated at 250 watts/m^2. Approximate the rate per m^2 of thermal energy loss through convection if the air temperature is 31°C.
6. If the laboratory walls are maintained at a temperature of 30°C and the skin temperature of the female subject in problem 1 is monitored at 34°C, find the rate of heat transfer from her body due to radiation.
7. The female subject in question #1 maintained the constant work load for a period of 4.5 minutes. Assuming that the parameters measured remain approximately the same, calculate the rate of thermal energy loss through evaporation if 25 grams of water were lost through perspiration during the exercise period.
8. Make a sketch of Table F.3 on log-log graph paper showing mass vs. metabolism in watts. Interpret the results of the graph. Can you find a rule that relates Mass (kg) and metabolic rate (watts) or not?
9. Suppose a friend who is 10 kilograms overweight wishes to lose mass through physical activity. If the metabolism of excess fat yields 9.3 kilocalories/gram (1 calorie = 4 joules), estimate the length of the exercise period required if he worked at a rate of 200 watts. Which activity might you recommend for quickest weight reduction?
10. Make a log-log plot of the data of Table El. Is there a simple rule (i.e., equation) relating the variables? Use this graph to determine whether the friend in problem (8) above can really lose the 10 kg at one time. If not, then calculate how many sessions it would require at the indicated activity level. If yes, then calculate the <u>maximal</u> weight loss until he must quit.

11. The graph below represents the monitored metabolic rate of an athlete during a five minute exercise period. During the first minute the subject was resting, waiting to begin. During the second and third minutes he produced mechanical power at the rate of 400 watts. During the third through the fifth minute he recovered to a normal metabolic rate.



a. What total mechanical work in joules did the athlete perform?

b. What average metabolic rate was maintained for the four minute work/recovery period?

c. What average thermal energy loss did the athlete require during the four minute work/recovery period to maintain a constant body temperature?

d. What was the maximum rate of thermal energy loss from the body? At what time during the 5 minute period did this maximum occur?

ANSWERS

1. $M = R_{\text{total heat exchange}} + P$

   $400 = R_{\text{total heat exchange}} + 100$

   $R_{\text{total heat exchange}} = 300$ watts

2. $W = F \times d$

   $= 100\ (913)$ newtons $\times$ 2 meters

   $= 1960$ Joules

3. $$\text{Power} = \frac{\text{weight x vertical height}}{\text{time}}$$

   $$= \frac{1960 \text{ Joules}}{1.25} = 1630 \text{ watts}$$

4. $$e = \frac{\text{mechanical power}}{\text{metabolic rate}}$$

   $$e = \frac{100}{400} = 25\%$$

   Cycling has efficiency of about 20% and is cited as being most efficient of almost any activity. Since the subject is on a treadmill (running?) one assumes that the abnormally high efficiency comes from this being above her normal long-term power level, hence maintainable for shorter durations only.

5. $$\frac{H_v}{A} = K_v\ (T_s - T_a)$$

   $$= 28\ (35 - 31)$$

   $$\frac{H_v}{A} = 112 \text{ watts/m}^2$$

6. $H_R = 5.67 \times 10^{-8}\ A_{body}(T^4_{body} - T^4_{walls})$

   $H_R = 5.67 \times 10^{-8}\ (1.5)\ (307^4 - 303^4)$

   $H_R = 38.6$ watts

7. $$H_E = 2424 \frac{\Delta m}{\Delta t}$$

$$= 2424 \frac{(25)}{(4.5)(60)}$$

$$H_E = 22.4 \text{ watts}$$

B. Applications for the Laboratory

The object of this exercise is to evaluate the relative importance of the various thermal energy loss mechanisms for the (simulated) body maintained at various steady temperatures above its surroundings.

1. Set the input electrical energy to the ball at some reasonable level. Wait until a steady state of temperature is achieved. Evaluate the electrical power input by measurement of both input current I and the energy per charge (i.e., voltage V) of that input current. The power input is simply the product $P = IV$. Note the value of the steady temperature. Repeat this for several different input energy levels, in each case being certain that a reasonably steady state has been reached after each charge input change. The value of P must just equal the heat exchange rate if the temperature of the body (i.e., ball) is constant (c.f. Equation D.5). For <u>each</u> of the different constant temperatures achieved, evaluate the following:

   a. Radiated power H_R; assumed T_{walls} is just the ambient temperature measured for the laboratory.

   b. Convected power H_V; assuming that only convection and radiation are available to this body as heat loss mechanisms.

   c. The convection coefficient K_V; this is expected to be nearly the same for each case of a different operating temperature.

2. Put the ball in a stream of air from a fan and again evaluate K_V by doing steps (a) through (c) for a new data set. Using the graph of K_V vs. velocity from the Invention Section, obtain an estimate of the air velocity in this situation.

3. Compare the percentages of thermal energy, lost by convective and radiative means in each of the two "simulation" body experiments above with values typical of the human body as indicated in the example problems given in the various exercises of the Invention Section. How good a simulator is the body used here?

4. Do only a "thought" experiment in which you design an experiment, or set of experiments, to measure the coefficient of thermal conductivity of a wrapping of cloth which you might place around the ball used in exercises (1) and (2) above.