EFFICIENCIES OF BIOLOGIC PROCESSES WITH SPECIAL REFERENCE TO MAN

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I. INTRODUCTION

A. Origin of Energy

Energy has its ultimate origin in the sun. Through photosynthesis, compounds of low potential energy (CO_2 and H_2O) are built to compounds of high potential energy (sugars). The 688,500 calories of synthetic energy required per mole of hexose sugars are supplied by solar radiation. The calories bound in the sugars represent potential free energy to any system that can reverse the photosynthetic process. Animal organisms can obtain this energy by burning glucose to CO_2 and H_2O.

The concept of efficiency arises in any output since no "machine" can deliver all the potential within it as free energy. Some 50% or less of the total energy of the system may be obtainable as free energy and the rest is lost as heat. In the body, the free energy is converted into a common currency, ATP, which is utilizable for all types of activities, i.e. mechanical, secretory, absorptive, osmotic, neural and others.

B. The Machine as an Energy Transformer

It is possible to solve problems of energy exchange by application of the physical laws of energy. Typical problems are involved in the use of machines. Machines may allow us to exert large forces by the application of much smaller forces, as for example, in levers. An example is to convert small motions into large ones, as in a bicycle. The same energetic laws involved apply to all living organisms as well as to non-living machines. The mechanical efficiency of these processes grossly stated is the work output divided by the energy input.

Work is an aspect of energy transformation. The study of energy exchanges in living or non-living systems is considered especially in thermodynamics. It was first exemplified in the study of a heat engine.

1. Efficiency of Different Machines

A heat engine is a device to obtain mechanical work from the heat energy of fuel. N.L. Sadi Carnot (1796-1832), a French physicist, laid the groundwork for the science of thermodynamics in his work on the improvement of steam engines. Carnot showed that the efficiency of an engine has a theoretical limit. A 100% efficient engine would convert all heat to work. An engine with the maximum possible efficiency is called a Carnot engine, but real engines do not realize this possibility.

In a simple steam engine, if the heat input is at 200°C (super-heated steam at a pressure of 11,650 torr) and if expansion of the steam pushes a piston, and the working substance, water, then condenses into water at 100°C, the maximum possible efficiency is,

$$\frac{473°K - 373°K}{473°K} = 21\%$$

or 79% of the input heat energy is not available for work. Frictional and other losses reduce the overall efficiency of a piston-type steam engine to 10-12%.

A very efficient engine, which is a supercharged, spark-ignited engine of the piston type, has a Carnot efficiency of

$$\frac{2143°K - 703°K}{2143°K} = 67\%$$

However, in practice, this is reduced to 42% (Miller, 1967, p. 330).

The overall efficiency of the usual small steam plant is at most 5%, of a high-grade locomotive, 10%, of large plants using condensors and multiple expansion engines or turbines, 20-25%, of automobile engines running optimally, 20-25%, and of diesel engines, 30-35% (Clathart, 1950).

Houssay (1955) tabulated some efficiencies ("net") as follows:

Steam engine	15%
Gasoline motor	18%
Horse	24%
Man (climbing stairs)	25%
Diesel motor	35%

The present review considers the efficiency of many processes in the living organism, with primary emphasis on man. For a comprehensive review of the energy cost in various human activities, the reader is referred to Passmore and Durnin (1955).

II. TERMINOLOGY

Efficiency, considered most simply as work/heat, is expressed in many ways (Houssay, 1955, pp. 508;814). Some common expressions follow.

Gross efficiency = 100 W/H where W is work done and H is total energy.

Net efficiency = 100 W/H-BMR where BMR is the resting metabolism. The net efficiency is conditioned by the type of work done (walking, running, carrying a load, treadmill).

Net mechanical efficiency is expressed by the same equation as the above. It considers the organism as a machine.

III. EFFICIENCY OF THE HUMAN BODY

As an "engine" fueled by chemical energy, the

$$\textit{gross efficiency} = \frac{\text{external work}}{\text{total internal energy conversion rate}}$$

and the *net efficiency* $= \dfrac{\text{external work}}{\text{internal energy conversion rate increase necessary to perform the work}}$

Exercising at a rate of 20 kcal/hr., there could be a metabolic rate increase from 80 kcal/hr. just prior to exercise to 180 kcal/hr. during exercise. The gross efficiency = 20/180 = 11% and the net efficiency = 20/(180-80) = 20%.

The net efficiency with the body operating optimally is about 25%. This exceeds the efficiency of a steam engine, equals that of an internal combustion engine, and is much less than that of a well-running electric motor. Usually, the mechanical efficiency of the body does not reach 25% (Ruch and Patton, 1965, p. 89).

Houssay (1955) stated that the gross efficiency of the "whole" organism is 17-20%, or less than one-fifth of the total energy that can be usefully recovered.

Growth is an aspect of whole body dynamics. Brody (1945) proposed a concept of "efficiency of growth." This is a relation between the total energy input of an organism and the energy retained in its cells and tissues. Thus,

$$\text{Gross efficiency} = \frac{\text{energy stored}}{\text{total energy input}} \times 100\%$$

$$\text{and net efficiency} = \frac{\text{energy stored}}{\text{total energy input minus energy needed for maintenance}} \times 100\%$$

No values are cited.

Mayer (1948) listed the "total efficiency" for growth of rats (at weaning) as 35%. This is in the same range as the values for chicken and cattle and it suggests that body size does not systematically affect the efficiency of food utilization.

Baldwin (1968) listed the theoretical efficiency of growth in young lambs as 78%. The concept of efficiency in synthesis and growth is very important in animal industry and is a continuing study.

IV. EFFICIENCIES OF ORGANS

A. The Heart

Efficiencies of specific organs have been considered for animals and man, discussions on the mammalian heart going back to 1914 (Evans and Matsouka, 1915).

There are many ways to calculate the efficiency of cardiac muscle, but as with an inanimate machine the "overall" efficiency is essentially the ratio of work accomplished to the total energy utilized.

Some of the early cardiac efficiency data were obtained in dogs (Gregg, 1950, pp. 153; 158). In unanesthetized dogs, efficiency approximates 31%; in anesthetized dogs, efficiency varies from 7 to 54%. The highest efficiencies are associated with large cardiac outputs together with high arterial pressure. If the demands on the muscle are great, oxygen usage disporportionately increases, the heart muscle dilates, and efficiency is reduced.

Pool and Sonneblick (1967) studied the chemical energetics of cardiac muscle in the cat during isometric contraction of the right ventricle papillary muscle. They use the term *mechanochemical coupling efficiency*, which is operationally equivalent to the coupling between the chemical and mechanical processes involved. The value found is 33%. It is uncertain whether this value is altered if the contractile state of the muscle is changed.

Bing et al. (1949) determined the oxygen consumption in normal human subjects to be 7.8 ml/min/100g for the left ventricle (LV) and they calculated the mechanical efficiency (work of LV/energy cost in LV) to be 21.2 to 24.5%.

Guyton (1981, p. 157) listed the efficiency of the human heart as 20-25%. Brachfeld (1978, p. 16) listed the human "overall" efficiency as 20-30%. He stated that 25% of the total energy is used to sustain ion transport plus other needs of internal cardiac maintenance and that if these allowances are subtracted, the "true mechanical efficiency" of cardiac contraction may exceed 50%.

Some workers claim that the mechanical efficiency of the heart is very low. Ruch and Patton (1965) listed the efficiency as usually less than 10%. In line with this, Katz (1977, p. 217) put the "overall" efficiency at 5 to 20%, varying with the nature and amount of work performed. He ascribed the lower values to the fact that the isovolumetric phase of the cardiac contraction absorbs energy.

Berne and Levy (1977) listed a value for "gross" cardiac efficiency as 14% and for "net" efficiency as 18%. They noted that the efficiency improves with exercise, because cardiac work and output then increase along with a lesser increase in myocardial oxygen consumption. These authors assumed an oxygen utilization of 9 ml/min/100g for both ventricles; thus a 300 g heart consumes 27 ml oxygen/min., equivalent to 130 calories. If both ventricles perform 8 kg.m. of work/min., equivalent to 18.7 calories, then the gross efficiency is $18.7/130 \times 100\% = 14\%$. The net efficiency is obtained by subtracting the oxygen consumption of the "nonbeating" heart (2 ml/min/100g) from the total oxygen consumption. The heart is said to derive about 60% of its energy from oxidation of fatty acids and up to 40% from carbohydrates.

Brobeck (1979) listed several values for cardiac efficiency. For contraction against pressure divided by total myocardial oxygen consumption minus resting oxygen consumption, values are 10-20% in experimental animals. By using a ratio of contractile element work (CEW) to chemical energy of activation (AE) and chemical energy of work (WE) minus resting energy (RE):

$$\text{Efficiency} = \frac{\text{CEW}}{[\,(\text{AE} + \text{WE}) \text{ minus RE}\,]} = 33\%,$$ for anerobic, iodoacetate-treated papillary muscle.

For values in pathology, Bing et. al. (1949) found the mechanical efficiency of the failing heart to be much less than the expected normal values (left ventricle) of 23%. In congestive failure the values are 12.9 to 14.6%. Katz (1977) reported a low efficiency in the dilated heart. Eckenhoff et al. (1948) calculated unusually high values of 32 to 35% in dogs, but they reported decreases in experimental hypotension. Importantly, they stressed that efficiency is not a valid measure to indicate cardiac capacity for work under changed conditions because there are metabolic changes not associated with external work (maintenance energy and that used in the isometric phase of ventricular systole).

B. Respiration

1. Normal Values

The muscles of breathing perform useful work against three main kinds of forces: (1) elastic forces of the chest and lung during volume changes, (2) resistance of the airways to the flow of gases and the nonelastic deformation of tissue, and (3) inertial forces involving the mass of gases and tissues.

Work is force x distance or, in respiration, pressure x volume of air moved. If one computes the work done and the oxygen consumed in doing the work, then:

$$\text{Efficiency of breathing} = \frac{\text{useful work accomplished}}{\text{total energy expended (as determined by oxygen consumption)}} \times 100\%$$

In computing the mechanical efficiency, the work done and the energy cost should be reduced to the same units, kg-meters. One liter of oxygen is equivalent to about 2100 kg-m. If oxygen cost is 100 ml 0_2 and the work done is 20kg-m, the efficiency is 10%.

The work done in moving the lungs only is calculated from the transpulmonary pressure applied x the volume of air moved at each instant. The greater work done in moving both the lungs and the thoracic cage can also be calculated (Comroe, 1962).

The oxygen consumed by a healthy subject to accomplish the work of breathing reflects only a small fraction of the total body metabolism. Brobeck (1979) stated that the oxygen cost of quiet breathing is less than 5% of the total resting oxygen consumption. Nunn (1969, p. 160) put the oxygen cost at less than 2%. Cotes (1968, p. 98) cited a quiet breathing cost of 1.5% of the total oxygen consumption. If one voluntarily hyperventilates, he can increase the cost to 30%. In obstructive lung disease, the oxygen cost of breathing can limit the ability to perform exercise. Nielsen (1936) stated that at least 9% of the total energy expenditure is used in respiratory work.

The mechanical efficiency of the respiratory muscles is low. Values depend partly on rate of breathing. Otis (1961) estimated the efficiency, at a breathing frequency of 5/minute, to be 3% and at 30/minute to be 8%. Comroe (1962) listed values of 5 to 10%. Milic-Emili and Petit (1960) listed a range of 19 to 25% which is much higher than those usually reported. Other representative values are 3% (Cain and Otis, 1949), 7.0 to 9.6% (Campbell et al., 1958), and 5 to 10% (Brobeck, 1979).

2. Efficiency in Disease

Cherniak (1959) compared efficiencies (mean 8.6%) in normal human subjects with those having emphysema (mean 1.8%). He studied the work done in moving the lung, chest wall, diaphragm and abdominal structures.

Comroe (1962) stated that the respiratory muscles do more work than normal and with a very high energy (oxygen) cost in certain cardiopulmonary disorders.

Cotes (1968, p. 98) found that the energy cost is high in pulmonary fibrosis, and particularly in the obese patient who has considerable resistance to thoracic movements.

Overall, the data are imprecise both in health and disease. The different methods used account for a range of efficiencies from a few percent up to 25%.

3. Efficiency of Respiration in Lower Vertebrates

Efficiencies, not exclusively mechanical, have been calculated for many biologic processes in the lower vertebrates. In fishes, ventilation occurs by the combined action of the mouth, which takes in water and forces it into the gill chambers, and the opening of the gills through which the water is actively aspirated. The effectiveness of the exchange is a ratio between the volume of water passed over the gills in a given time and the percent of oxygen extracted.

This ratio is the exchange efficiency (E.E.). The E.E. has been measured for many species of fishes and ranges from 30 to 80% (Scheer, 1963, p. 204).

C. Digestion

Literature concerning the efficiency of digestive processes is hardly available. Scheer (1963) considered this subject, but listed no numerical efficiency values. He noted that the most efficient digestive systems, in terms of the rate of digestion in relation to the mass of tissue involved, appear to be those of certain insects.

Scheer proposed the use of the following terms:

$$\text{Digestive efficiency} = \frac{\text{total organic intake minus organic loss}}{\text{total intake}}$$

$$\text{Growth efficiency} = \frac{\text{total organic matter assimilated}}{\text{total intake}}$$

$$\text{Net growth efficiency} = \frac{\text{total organic matter assimilated}}{\text{total intake minus maintenance energy}}$$

D. The Kidney

Some studies are available on the efficiency of the kidney (Lotspeick, 1959, p. 7). This involves an analysis of the ratio of the renal work done to the energy cost. Some of the work is reviewed by Eggleton et al. (1940).

The external work accomplished by the kidney is almost entirely represented by the osmotic work performed in forming urine from plasma. In the dog, Eggleton and co-workers found the total osmotic work done by the isolated kidney to be the equivalent of 300 cal/liter of urine formed. The value was calculated from concentrations of urea, chloride and creatinine in blood and urine as well as from the total electrolyte concentration in the urine.

The energy expended corresponding to oxygen consumption (dog) was calculated to be the equivalent of 5 kcal/liter of oxygen used. From these data, the "absolute" efficiency, i.e., the ratio of total osmotic work done to the energy expended, was computed. This is only a few percent.

These same investigators also calculated a "differential" efficiency, which takes into account increases in osmotic work as in diuresis, with efficiency values ranging from 0.8 to 4.6%. The values increase with increasing plasma urea, reaching a maximum of 4.6% at the highest urea concentration tested. An efficiency of 1% is usual when urine is secreted at "resting" activity.

If the blood flow remains constant, renal work changes can be accomplished without changes in oxygen consumption. The efficiency rises with increased osmotic work, although total renal efficiency is always relatively low.

Lassen et al. (1961) stated that concept of renal efficiency in a thermodynamic sense is not valid where the calculations for minimal renal work fail to consider the oxygen cost of sodium reabsorption. This cost is important because oxygen consumption in the kidney is dominated by the energy involved in active tubular sodium reabsorption. Also, the oxygen cost of the active outward renal transport of all electrolytes should not be disregarded. Lassen noted that if one calculates from literature data the ratio between active electrolyte transport and net oxygen consumption, a value of 16 to 25% termed the "stoichiometric efficiency" is obtained. It is unknown whether this efficiency value for the electrolyte transporting mechanism varies from one epithelial membrane to another.

Pitts (1974) emphasized the cost of renal electrolyte transfer. He stated that in man about 6% of the resting metabolism is devoted to reabsorption of sodium, chloride (and water) in the renal tubules. This activity constitutes a high proportion of the resting metabolism, but it is understandable in that the transport process is vital to survival.

Pitts listed no numerical value for the efficiency of the transport processes. This is not surprising since it has been emphasized by all workers that it is very difficult to partition the energy used for different kinds of renal activities. Lotspeick (1959) pointed out that it is confusing as to how the kidney uses 99% of its available energy. It may need great amounts of oxygen just to keep itself alive.

E. Voluntary Muscles

The literature is abundant in calculations and discussions of the mechanical efficiency of the human skeletal musculature under various conditions. Overall, the mechanical efficiency (M.E.) in percent is the ratio of external work done to the energy expended (in calories).

If the muscle is fixed (isometric contraction), all the energy expended is converted to heat and the work and M.E. are zero. In moderate isotonic exercise, about 75% of the chemical potential is transformed to heat and the M.E. is about 25%. This value indicates that the contraction of skeletal muscle is among the most efficient processes in organ function in the higher organisms and man. The efficiency will be seen to vary with many factors, e.g. speed, load, oxygen availability, type of activity, training, and others (Stuart et al., 1981).

At least three expressions of efficiencies are noted in the literature on muscle exercise:

1. Gross efficiency = $\dfrac{\text{work done}}{\text{energy expended}} \times 100\%$

This considers all the energy expended while performing a given amount of work. It includes energy that may be unrelated to the work output.

2. Delta efficiency = $\dfrac{\text{Delta work done}}{\text{Delta energy expended}} \times 100\%$

This measures the efficiency with which any increment of work is performed, not the overall efficiency of the total work done at a given rate. This figure expresses the changes at any point in the activity.

3. Instantaneous efficiency is a delta efficiency over an extremely small increment of work that can be calculated at a given work rate.

Stuart (1981) provided typical data which illustrates the usage of these efficiencies under different conditions. Stainsby et al. (1980) contended that none of the above three exercise efficiences truly indicates muscle efficiency.

Asmussen (1965) discussed efficiency values occurring in different types of activities. He used the term "net" efficiency (N.E.), which equals external work rate/corresponding increase in metabolic rate above the resting metabolic rate. The N.E. decreases in very heavy (anerobic) work, which involves a large oxygen debt. Here the calorie output must be measured during recovery as well as during work.

The N.E. in riding a bicycle ergometer, climbing stairs or walking on an inclined treadmill varies from 19 to 25%. The maximum efficiency is realized when the muscles contract at moderate speed. In very slow contraction large amounts of maintenance heat are released, so the efficiency decreases. In very rapid contraction large amounts of energy are used to overcome viscous friction in the muscles

(Guyton, 1976, p. 140). Swimming is only 0.5 to 2.0% efficient. In fairly simple activities, e.g. walking, running, or bicycling, there is only a very slight increase in efficiency with training. The more complex the exercise, the greater is the efficiency with training (Astrand and Rodahl, 1970, p. 71).

The efficiency of a muscle *in vivo* is not the same as that of an experimentally isolated muscle. In life the efficiency is decreased by posture, conditions of movement, and stresses on the circulation and respiration. In isolated muscle the efficiency of the entire chain of reactions between the oxidation of glycogen and the performance of mechanical work is less than 20% (Wilkie, 1960).

Much experimentation is available on isolated muscles of lower vertebrates. As an example, Woledge (1968) listed the efficiency of tortoise muscle over the entire cycle of contraction and recovery as 35%. This is contrasted with 20% for frog muscle (Hill, 1939). The greater efficiency in the turtle muscle is controversially associated with slowness of movement in such animals and it is also ascribed to lower enzyme activity. It was emphasized by Kushmerick and Davies (1960, pp. 315;353), on working with the isolated frog sartorius muscle, that the mechanochemical efficiency is zero at maximal and zero velocities of contraction.

F. Nerve

Brobeck (1979, p. 50) discussed "efficiency" of ion exchange through membranes in resting frog sciatic nerve.

The following computations can be made. There is electrical work of 0.015 cal/g/hr and concentration work of 0.007 cal/g/hr as the energy necessary to pump Na^+ out of the fiber. To pump K^+ in, the energy needed is 0.019 cal/g/hr. The work necessary to pump both Na^+ and K^+ is 0.041 cal/g/hr. At an efficiency of 50% (see below) this operation accounts for 0.082 cal or 50% of the total energy consumption of 0.15 cal/g/hr (the resting release of heat).

Corresponding to the resting release of heat, there is an oxygen consumption of 30 to 40 mm^3/g wet weight/hr. (This is in contrast with mammalian nerve which consumes 200 to 300 mm^3/g/hr.) The efficiency of the process, using these figures, is 50%.

Caldwell (1968) studied the net active transport of Na^+ and K^+ across muscle and nerve membranes and concluded that this is achieved with an overall efficiency of 58%.

G. Metabolism - Cellular oxidation

Efficiencies have been calculated for the burning of foods in cells (Scheer, 1963; Astrand and Rodahl, 1970, pp. 16-17).

1. Carbohydrates

a. Anerobic breakdown of glycogen to lactic acid

These processes release about 55 kcal for each six-carbon unit (glucose) glycolyzed. It takes one molecule of ATP for the reaction. In breaking down one mole of glucose, 4 ATP molecules are formed. This leaves a net gain of 3 molecules of ATP. It conserves 3 x 7, or 21 kcal. (Generation of ATP from ADP and phosphate conserves energy, at least 7 kcal/mole of ATP.)

The efficiency of the energy conservation is: 21/55 x 100% = 38%

b. Complete aerobic oxidation of glucose

Oxidation of one mole of glucose to carbon dioxide and water yields 686 kcal. Since the free energy is 686 kcal and since 38 molecules of ATP are produced, each requiring at least 7 kcal/mole, the efficiency of energy conservation is (38 x 7/686) x 100% = 39%. Dietrich (1979) stated that if the cells metabolized pyruvate anerobically, the efficiency would be less than 10%.

c. Oxidation of a fatty acid

Palmitic acid may be selected as an example. Then, palmitic acid ($C_{16}H_{32}O_2$) + 130 phosphate + 130 ADP + 23 O_2 yields 16 CO_2 + 16 H_2O + 130 ATP. The free energy is 2340 kcal of which 130 moles of ATP capture a minimum of 7 x 130 = 910 kcal.

The efficiency is: (910/2340) x 100 = 39%

The efficiency of fatty acid burning is high. It might exceed the value stated because *in vivo* a reversible ATP/ADP + phosphate reaction may involve a change in energy level more than 7 kcal/mole. Thus, cellular respiration is much more efficient than physical work whose efficiency at most is 20 to 25%.

V. MISCELLANEOUS BIOENERGETIC PROCESSES

A. Feed Energy

There is a large body of literature, beyond the scope of this necessarily limited review, dealing with the efficiencies of synthesis of animal products from absorbed nutrients, in domestic animals. Milk production, tissue synthesis and the whole spectrum of feed energy are examples. The reader is referred to Krebs and Kornberg (1957), Blaxter (1967), Baldwin (1968) and Milligan (1971).

B. Efficiency of the Human Voice

Very little biologic function seems to have escaped bioenergetic analysis. The larynx as a generator of sound has been analyzed thusly. The efficiency of the voice is considered as a ratio of radiated acoustic power to subglottic pressure. The reader is referred to Van den Berg (1956).

C. Bioluminescence

Certain organisms produce radiation in the wave-lengths of visible light (Scheer, 1963). This occurs in some bacteria, fungi and in "representatives" of most animal phyla. The brightness is often relatively high, from 0.3 to 45 mL (the brightness of the blue sky being about one lambert, in comparison).

The *luminous efficiency*, or ratio of visible radiation to total radiation, is 20 to 90%. However, the *overall efficiency*, or ratio of energy output as radiation, to total energy output, is not very high. The luminous efficiency of luminous bacteria is 45%, but the overall efficiency is only 0.8%. In Scheer's account, he does not evaluate efficiency in the usual sense of (radiation) output to energy input (chemical potential).

D. Efficiency of Radiation on Biologic Tissue

Another aspect, not in our province, but of primary importance in radiotherapy, is the efficiency of radiation in the treatment of malignant disease. The reader is referred to Meredith and Massey (1972). Efficiency here is considered uniquely in that great emphasis is placed upon the source of the radiation from particular "generators."

E. Efficiency of Biosynthesis in Primitive Life Forms

Autotrophic bacteria are among the lowest forms of life. They are unusual in that they derive their energy from the oxidation of inorganic substances, e.g.

thiosulfates, hydrogen sulfide. These bacteria synthesize carbohydrates from substances which are of lower energy content. The efficiency of the autotrophs in synthesizing carbohydrates has been calculated. An example follows.

The Nitromonas bacteria, which derive their energy from $NH_4 + 3/2\ O_2 = NO_2 + H_2O + 2\ H^+$ assimilate 1 g of carbon for each 35 g of nitrogen oxidized, the carbon appearing as carbohydrate. The burning of each gram - ion of ammonium delivers 66.5 calories. Thus, oxidation of 35 of nitrogen produces 66.5/14 x 35 = 166 calories.

The amount of energy required for synthesis of carbohydrate from CO_2 demands an increase of free energy of 118 calories for each gram-molecule of CO_2 used, or 118/12 = 9.85 kg. cal per gram of carbon.

$$\text{Efficiency} = \frac{\text{amount of energy needed for synthesis}}{\text{amount of energy made available}}$$

= 9.85/166 = 0.059 = 5.9%. The remaining 94% of the energy made available by the oxidation of ammonia appears as heat.

A comparison of efficiency has been made with *Chilomonas paramecium* which grows on media containing acetate and ammonia. The efficiency of biosynthesis is 17%, much greater than that of the autotrophic bacteria (Davson, 1951, pp. 116-117).

VI. HUMAN PSYCHOLOGIC EFFICIENCY

Many writers have dealt with the efficiency of human performance in given tests and tasks and the variation of efficiency with diverse forms of stress, e.g. sleep deprivation, ambient temperature, memory load, and others. Reviews are available [see Poulton, 1970; Colquhoun, 1972].

VII. EPILOGUE

In the more abstract and difficult to quantify realm, people who are successful may perhaps be at most 10% more efficient than their more mundane competitors. This is exemplified and measurable by one yardstick in sports where as an example the best batting records are not much higher than the average. Superior performers in academic achievement are not necessarily endowed with vastly greater intelligence or efficiency than their colleagues. Somewhat related to this point of view is the statement by Muller (1980) that the external accomplishments of an individual are not well related to efficiency. A good scientist should take risks even if they only at rare times bring forth a superb discovery.

Perhaps the greatest application of the concept of efficiency in the future will be in how to reduce the inefficiency with which we use the unrenewable energy of the environment to satisfy our needs (Gofman, 1979).

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