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THE ANIMAL AS A MACHINE AND PRIME MOVER.*

THE writer of these papers has been greatly interested in the study of the vital machine in its relations to the special work of the engineer and to the methods illustrated by it in transformation of potential energies into the mechanical form for useful purposes in the industries.

The value of this form of prime motor to the engineer is enormous, though rarely appreciated or realized. Until the introduction of the steam-engine into mills and factories through the inventions and enterprise of Watt and his partner, at the beginning of the century, horse-power and manual labor only were available for any work for which water-power could not be obtained, and hundreds of horses had even been employed, in earlier times, in draining of single mines. But, even at the present time, the horse is the prime motor for an enormous section of the industries; and all transportation on short routes or available lines, all agricultural work nearly, and work of whatever kind on the highway and in the by-ways must rely on this vital machine for its performance.

The theory of the machine and study of its methods of operation, of energy-conversion, and of economical application of power, is one of the most important subjects practically presented to either the engineer or the man of science, and this for two quite different reasons. In the first place, the vital machine has a higher efficiency than any steam-engine and involves methods of transformation, storage and application of energy which are as yet a mystery, and which, could they be discovered and simulated in engineering practice, might possibly prove

*Abstracted from The Animal as a Prime Motor; N. Y., J. Wiley & Sons, 1894. Journal of the Franklin Institute, Jan.–March, 1895.

more enormously valuable as improvements upon current methods than was the invention of the modern steam-engine and the displacement of the old machines of Worcester and Savery. It is also possible that nature's ways of producing light and electricity, as well as power, may be ultimately found immensely more economical than those of man. They certainly are quite different, and are inconceivably more efficient in themselves, as single transformations, than any processes yet discovered by science. In the second place, the laws of operation of the vital machine being fully revealed, it is possible that we may find ways of promoting the improvement of the machine in such a manner as to make the animal mechanism a more efficient and a better apparatus for the use of man, and even, perhaps, find ways of improving the instrument employed by the mind in its special operations, as well as the mechanism of the frame in which it is given a home and a vehicle.

The outcome of the investigations made up to the present time may be stated perhaps in the briefest and most intelligible way in the form of a series of theorems, thus:

(1.) *The Vital Machine is not a thermodynamic engine, a heat-motor.*

Many writers have taken for granted the now obviously incorrect hypothesis that, since the machine is evidently a source of heat, and its energy is derived from combustible materials, it must, therefore, be a heat-engine and its operations necessarily thermodynamic. This is easily disproved. In any thermodynamic machine, of whatever class, among the heat-motors, the proportion of heat converted into work, the 'efficiency' of the machine is measured by the range of temperature, from the highest to the lowest in the cycle operated in by the thermodynamic mechanism, divided by the maximum *absolute* temperature in the cycle. For the animal machine this would ordinarily be the widest range of temperature attainable in thermodynamic conversion divided by about 300° C. But the machine is, in this case, a mass of circulating fluids of fair conductivity, mainly, and can have no sensible range of temperature, so far as can be seen; and, in fact, it is known that differences of but one or two degrees, in different parts of the body, the only actual differences of temperature, are produced by a slight warming of the venous blood by chemical action, or by proximity to or distance from the epidermis. As a thermodynamic engine, even were it possible, therefore, the machine should have an exceedingly low efficiency. The fact is that its efficiency exceeds that of any heat-engine known to man, under the most favorable possible practical working conditions.

The vital engine is certainly not thermodynamic; its heat is a 'by-product.'

(2.) *The machine is probably not electrodynamic.*

Scoresby and Joule, and Sir William Thomson 'Lord Kelvin' and others among later writers, have suggested that the machine may be, as some have said, an electrodynamic machine, others an electro-magnetic engine. In support of this view it is pointed out that, in some cases, as in the gymnotus, the torpedo and some fifty other creatures, powerful electric batteries, accummulators, are found in the animal system; that all animals seem to have conductors, the nerves, and that electricity *leakage* is always to be detected in the living creature —currents passing in various directions through the body and leaking outward to the surface in all parts. The nerves terminate in 'plates' having close relation in form and structure to the more highly developed cells of the storage batteries of the eel and similar animal producers of electricity.

A great variety of facts and considerations based upon research in this field conspire to indicate, if not to fully prove, that the passage of the electric current along the nerve is the initial act in the motion and energy-production of the muscle. On the other hand, however, it may probably be stated, as conclusively ascertained, that there is no representative of the mechanism of our electro-dynamic machines, either of generator or motor, in the muscle, where, unquestionably, the applied energy is set free and utilized. There is no equivalent of magnet, of solenoid, of field or of armature. On the other hand, it is indicated by numerous and varied investigations and observations that the electric current has for its office, in the vital machine, the promotion of the chemical actions which accompany all motion and development of force and power. The familiar effects of currents having their origin outside the body afford illustrations of the fact and the method of action of these currents. The electric currents, so far as existing in the system, have light work to perform; and where, as in the gymnotus, they are given more formidable tasks, they require for their production and application very large special organs, and occupy an exorbitantly large proportion of the body.

The vital machine is probably not an electro-dynamic motor.

(3.) *The animal prime mover is very probably an example of an exceedingly highly organized and efficient chemico-dynamic motor.*

There are but three known forms of energy available in conversion of the stored potential energy of the foods into dynamic form. Two of these have been seen to be, the one certainly, the other probably, unutilized in the energy-conversion of the vital machine. The third, until some as yet undiscovered process and energy is found to be available, must be assumed to be the source of all dynamic phenomena in the animal system. The machine is probably a chemico-dynamic prime mover, in which the developments of energy in active form, their magnitude and their applications, are directed by the supreme authority of the system through a very perfect arrangement of electric apparatus, by means of which the necessary orders are telegraphed to the various points at which energy is to be liberated and applied, and by the currents traversing which apparatus the chemical reactions needed in transformation of the potential energy of the fats and glycose, and of the products of broken-down tissue, into active and useful form are inaugurated. Electricity, or some related energy, serves as the directing and stimulating power, and the resolution of fats and other substances into glycosic compounds and their oxidation, at the point at which power is to be developed, into carbon-dioxide and water, by chemical changes resulting in the transformation of potential into actual energies, supplies the working power of the system. The presence of electricity is always observable in the vital machine, and the chemist-physiologists have traced the processes of supply and transportation of potential energy and of the liberation of active energies down to the very last, though still mysterious, act of utilization.

These authorities are now apparently substantially unanimous in declaring it well settled that the action of muscle, for example, is due to what is termed an 'explosive' chemical action in the mass of the organ, the outcome of which is mechanical energy and the liberation of carbon-dioxide. The physicist-physiologists are equally united in testifying that the provocation of this explosive action, at will and in proper quantity, is effected by a nerve-impulse which is more nearly like the electric current than any other known form of physical energy; and the process of doing work by muscular action is likened to the firing of a charge of explosive in the mine by a current sent over a wire, in this case along a nerve, and the provocation, by its action, of instantaneous oxidation of carbon into carbon-dioxide with change of the physical state from the solid or liquid form into gas liberated in a small space under high compression, and thus in a condition to perform maximum work by its expansion.

(4.) *In this chemico-dynamic machine, the energy displayed in its dynamic operations, as in its muscular work, is generated and applied locally.*

It has been supposed by some writers that the power of the muscular system was derived by transmission from some central or remote source to the point of application, by the nervous system, there to be utilized in the act of muscular stress. It is now well ascertained that not only is there no provision for such transmission of energy, but that the liberation of energy occurs within the mass of the muscle itself, and within its tissue-cells. That the action is local is easily seen in the fact that the excised heart, an excised bit of intestinal muscle, the corpuscles of the blood itself, and the amœba-form protoplasm of which the flesh is composed, in its minutest elements, possess this attribute of energy-development. The heart beats, often for hours in some cases, after removal from the body; the excised muscular tissue exhibits its rythmic pulsations visibly after isolation; the white blood corpuscle, even, propels itself independently into the locality in which it is to join its energies and activities with those of the already built-up living substance; the elemental protoplasm everywhere exhibits these characteristics of what we call 'living' matter.

Thus complete elemental vital systems are found distributed, in many forms, in all parts of the machine, with their directing and initiative forces as well as their energy-transforming apparatus.

Further: It is now well settled and easily shown that the potential energy supplied is tendered to the working system in the form of glucosic matter, sugars, produced from fats and starches, and sent through the arterial pipe lines to the capillaries and thence into the very cells of the organs in which work is done. There they are resolved into carbon-dioxide and water; the location and to some extent the nature of the energy-transformation being thus fully revealed. It is a local transformation of chemical into mechanical energy, directly or indirectly, at the very point and in the very cell, apparently, where the work of that elementary portion of potential energy is performed. The question remaining to be solved is whether this transformation is direct or indirect, a single step or a series of energy-changes, not whether it is effected locally or generally or within some special organ appropriated to that duty. Each cell appears to be an elementary prime motor, an elemental vital machine; and the muscular mechanism is a combination of innumerable elements of similar composition and method of action, in each of which a similar process of energy-transformation is conducted.

This process is not thermodynamic, is probably not electro-dynamic, is presumably chemico-dynamic, by which is meant that the energy of chemical action is probably directly transmuted into mechanical energy, not, as in thermodynamic machines, first into heat and then into work. A thermodynamic link in the chain would mean the loss of a large fraction of the whole supply; but it still remains to be ascertained how direct chemico-dynamic conversion of energy can give the remarkable efficiency observed in the vital machine.

(5) *The Nerve-Impulse, the physical energy relied upon for communicating the voluntary and the automatic stimuli which determine the time and intensity of the action of the muscular motor-system, is probably a form of electric energy or some closely related physical action.*

This is a system of telegraphy from nerve-ganglia, spine and brain which does not, as had been formerly supposed by some writers, transmit energy, but simply indicates where and when locally available stored energy is to be liberated and applied to definite purposes by appropriate muscles. It demands energy only in the manner and in the degree in which the electric current firing a mine expends energy in the initiation of the chemical action resulting in the tremendous effects observed. The work is done by the more or less complete transformation of the potential energy available in chemical combinations into mechanical energy, once the electric spark fires the charge.

The passage of the electric current through the fresh muscle produces the same effects as the nerve-impulse, and these effects may be reproduced again and again, until the muscle loses its store of glycose or until its structure changes. At every effort, the flexed muscle consumes glycose and liberates carbon-dioxide, precisely as in its natural operation under the stimulus of the nerve-impulse. This parallelism of action and effect may be taken as, perhaps, good circumstantial evidence. In every animal system, and in every mass of muscle within it, electricity-leakage, or other movements of electricity, may always be detected by the familiar methods of the electrician, and this everywhere distributed energy unquestionably originates in the system itself, and has place and purpose in its economy. In special cases, as in the gymnotus, Nature has magnified its work and given it larger place in the working of the machine than ordinarily, and thus has given us an opportunity to observe, on this magnified scale of working, both the form of the special constructions for the production of this form of energy, and the method of its transmission and application. We find the electric system of the gymnotus to be simply a development of the nerves and terminal plates found in all animals. That they have a common office, though very different in relative magnitude and importance in the two cases, is undoubted. That the origin, however, of this form of energy, simply as required for telegraphy, is chemical is very certain, also, since it must find its source in the common store of potential energy supplied the whole system. That this chemical process may be somewhat different from that producing chemico-dynamic effects is not improbable; especially as the presence of combustible fats of peculiar composition seem always an essential to nerve action. But all chemical action is accompanied by electric phenomena, and Nature here seems to make the fact subservient to her plans. But she adopts singular methods, and possibly a peculiar form of this energy; and the minute quantity detected by investigators, and the slow rate of progress along the nerve fibers, are elements of as yet unrevealed mystery. The familiar exhausting effect of continued nervous expenditure may be either due to large energy expenditure or to restricted supply of the special form of potential from which it is derived.

(6.) *The nature, source and methods of development and transformation of brain and nerve power do not appear to have been yet discovered, or even surmised.*

The fact that such energy is subject to exhaustion and renewal by precisely the same processes, so far as can be observed, certainly under the same conditions as produce fatigue or favor recuperation of muscular power would seem to justify the inference that the potential energy of the food and the processes of nutrition and of development of active physical energies in the brain, spine and nerves are so modified in these glands as to give a special product in the form of vital energy, and perhaps of brain-power, and of those initiative forces of the whole nervous system which inaugurate and direct, automatically or intelligently, the currents of nerve-impulse and set in operation and sustain the whole complicated life-system. But how the mind seizes upon these forces and compels these energies to work its will, or how the spine, and automatic mechanism, generally, is set in communication with the mind on the one side, and the organism of the machine on the other, remains a mystery challenging every resource of talent and the highest genius in the investigator. So far as a judgment or even a surmise is permitted, it may probably be assumed that, like all other energies of the vital machine, those of brain and spine and nervous system have a definite, quantivalent relation with the familiar physical energies, and fall within the province of modern scientific research. They demand, beyond a doubt, their proportion of the potential energy supplied in the daily ration.

(7.) *Observed phenomena and statistical data upon which these deductions are founded may be summarized as follows:*

Taking the human vital engine, in illustration, the amount of potential energy supplied the average individual may be taken at 2,500 or 3,000 calories when doing no external muscular work, 4,000 calories when performing a full day's work as a laborer.* This corresponds to 10,000 to 16,000 British thermal units, to from 8,000,000 to 12,500,000, nearly, British dynamic units, foot-pounds per individual per day, of which supply a part is wasted by defective digestion and assimilation and a portion by various defects of the machine itself. Taking the energy-supply of the vital machine as 8,000,000 foot-pounds for the man of sedentary habits and performing brain-work and 10,000,000 for a steady and hard-working laboring man, who does much muscular labor and little thinking, we have the basis of estimates which, though probably not very precise, may yet answer present purposes in giving general conclusions.

*Pavy on Foods; Mott's Manual; Thurston's Animal as a Prime Mover; Year Book of the New York State Reformatory, 1894; Reports of the Conn. Agricultural Station.

Of this eight or ten millions of foot-pounds of energy supplied the machine in potential form, in the foods, not less than fifteen per cent. must be reckoned for deficiency of digestion and transformation into available form in the chyme and chyle, the solutions from which the system draws it for its various special purposes. This seems the minimum usual loss, and an excess is commonly observed, which is furnished by larger food-supply than the assumed figures as here given. A good 'digestion coefficient' is 85 per cent.*

Of the 8,000,000 foot-pounds of energy furnished in the food of the brain-worker, or 10,000,000 supplied the day laborer, something like 7,000,000 in the one case, and 8,500,000 in the other, pass into the reservoirs of potential energy of the vital machine, and circulate in the blood through all its organs; giving up to each that peculiar form of nutriment needed for its work or for its own maintenance. The muscles draw upon it for energy to be converted into the work of external labor or of internal operations essential to life; the various glands elaborate from it those special compositions required for their purposes; the brain and nervous system absorb from it the material for consumption in the operations directed by the mind or automatically conducted by the vital powers of the animal system. Of the 8,500,000 foot-pounds of energy thus furnished the mechanism of the laboring man, in the best cases of application, under most favorable conditions, about 2,000,000 are applied to the performance of

*Flint's Muscular Power; Woods's Digestibility of Feeding Stuffs, Awater's Studies of Dietaries, Report of Conn. Ag. Experimental Station, 1893.

the day's work; which is equivalent to saying that the efficiency of this vital machine, considered simply as prime mover, is $23\frac{1}{2}$ per cent. If efficiency of conversion of potential into dynamic energy of muscular work, internal as well as external, is considered, it is very possible that this figure may be doubled, and the efficiency to be taken in comparison with that of heat-engines may be somewhere between forty and fifty per cent. If the internal work of thought and of brain and nerve power is considered useful work, and the total compared with the energy supply, the efficiency will be a still higher figure, perhaps fifty or even sixty per cent.*

But the highest total efficiency of the best steam-engine yet constructed is but about twenty per cent., with its thermodynamic range of about 200° F. (111° C.) degrees, Fahr., and that of the best gas-engine is but about the same, with a range of ten times that extent. If the vital machine be a thermodynamic engine, therefore, its known efficiency, with no recognized temperature, range of heat 'let down,' is not less than twenty-five per cent. higher than, and may be twice as high as, the best heat-engines constructed by man. This is recognized by engineer and thermodynamist alike, as a *reductio ad absurdum*, and the vital engine is certainly not a heat-engine.

The facts regarding the distribution of potential energy to the various organs of the body; the development by each organ of its special form of product in new compositions or in a special energy; the localization of energy-transformations in the cells of the muscle, or other energy-producer; the accompanying liberation of carbon-dioxide from consumption of glycosic material; the utilization of a telegraphic, or rather a semaphoric, system communication between the mind or the interior automaton of the spine and cerebellum and the point of useful application of energy all: these are familiar to all physiologists.* Beyond these known phenomena lie the mysteries which the engineers, if possible more than the physiologists themselves, most desire to see completely solved. When they are thoroughly investigated and the operations of the vital machine become fully known, in all their details of energy-transformation, it may be possible to secure new prime movers of similarly high efficiency and thus to double the life of the race by prolonging the period marking the endurance of our supplies of potential energy in the coal-fields of the world. Should it prove that only by preliminary manufacture of fuel, in the form of sugars, can this result be attained, it may seem unlikely that, even when these operations are no longer mysteries, commercial applications of nature's methods can be expected to prove successful; yet when it is considered that the sugars are simply carbon and water, it will not be denied by either engineer, chemist or physiologist that a possibility still remains of effecting so enormously important an advance in the prime motors. If, further, nature's economies in light-production can be paralleled, the engineer may ultimately furnish heat, light and power, the three great products of his special labors of most value to the race, with insignificant wastes and approximately perfect efficiency and maximum cheapness. Given perfect efficiency of power-production and the main problem is solved.

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* Weisbach's Mechanics of Engineering; Rankine's Prime Movers; Thurston's Animal as a Prime Motor; Reynolds' Memoir of Joule.

* Foster's Physiology; Encyclopædia Britannica, Art. Physiology; Chauveau's Le Travail Musculaire.

HARSHBERGER ON THE ORIGIN OF OUR VERNAL FLORA.

BY way of a review of a paper by Mr. Henry L. Clarke, in the *American Natural-*