MAY, 1937 BULLETIN 383

UNIVERSITY OF MISSOURI COLLEGE OF AGRICULTURE
AGRICULTURAL EXPERIMENT STATION
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Efficiency of Horses, Men, and Motors

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COLUMBIA, MISSOURI

SUMMARY

This bulletin presents a study of various factors concerning efficiency of horses, men and motors, i. e. speed; load; size of animal; path of reaching maximum efficiency; relation between all day efficiency and efficiency while working; energy costs as related to speed, load, and work; comparative abilities of horses and men and factors limiting work output and efficiency; and a feeding standard for horses is also suggested.

Optimum or best speed for maximum efficiency is a compromise between muscle viscosity which requires slow movement for most efficient work, and overhead maintenance cost which requires rapid movements for most efficient work. Data studied indicate the probability that every horse, and man has a characteristic efficiency curve.

Efficiency tends to rise with increasing load until an optimum load and maximum efficiency are reached. Efficiency becomes less as load is increased thereafter.

The size of animal does not seem to influence maximum efficiency since all animals studied had approximately a 24% efficiency level.

Efficiency begins at zero (when the horse is doing no work) and builds up to maximum efficiency of 24% in a manner similar to the way a growing animal builds up to maximum body weight.

The fewer the working hours per day the lower the all day efficiency. When working at the rate of 1 horse-power the efficiency of the horse is about 17% for a 12 hour day; 14% for an 8 hour day; 10% for a 4 hour day, and 7% for a 2 hour day.

Energy expenditure increases in direct proportions with speed of pulling given loads; with load pulled at given speeds, and with horse power. Increasing horse power output demands proportionately increased energy expenditures.

Horses and man have the same work energy to basal energy ratios, namely 20 for maximum oxygen consumption (not including oxygen debt.); 100 for maximum brief effort involving great oxygen debt; 8 for sustained hard work as encountered in daily life.

Temperature, humidity, kind of feed, training and physical conditions are definitely related to energy efficiency.

The energetic efficiency and economy of the horse and mechanical power depend upon many factors and vary accordingly.

A feeding standard is set up.

The use of horse, mule or mechanical power depends upon kind of work, availability of power and feed or fuel for its operation.

Efficiency of Horses, Men, and Motors*

S. Brody and E. A. Trowbridge

INTRODUCTION

One feature which horses, men, and motors have in common is that under proper conditions they can all do mechanical work. It is an intriguing question as to which of these three can turn out mechanical work most efficiently as well as most economically. We investigated this question and this bulletin reports the less technical aspects of the results of the investigation.[1]

Fig. 1 shows how we measured the work output and efficiency of the horse. The horse pulled a weight, W, on a treadmill apron, the speed of which was regulated by an electric motor. This way we measured the *work*[2] accomplished. We studied the effect of pulling different loads at different speeds (or of the effect of power developed, which is the product of speed and load) on the amount of energy expended and on the work efficiency.[3]

Since we know that the amount of energy expended is directly proportional to the amount of oxygen used,[4] we measured the energy expended by the horse by connecting the muzzle with an oxygen tank, O_2, as shown in Fig. 1, and recording carefully the amount of oxygen used.

Knowing the work accomplished, and the energy expended to accomplish it, we can compute the energetic efficiency by dividing the energy of the work accomplished by the energy expended for accomplishing it. Thus if the horse accomplished 642 Calories of work, and expended 3210 Calories, then the efficiency of work was $\frac{642}{3210} \times 100 = 20\%$.

1 The detailed results of this research are described in Missouri Research Bulletins 244 and 209 to which the reader is referred for further information.

2 *Work* is measured in foot-pounds. A foot-pound is the work done by exerting a force (measured by a special spring scale) of 1 pound through a distance of 1 foot. Thus if a force of 1 pound is required to raise a window 1 foot, then 1 foot-pound work is done in raising the window. A horse pulling on 150 pounds (as in Fig. 1) 2.5 miles (that is 13200 feet) accomplishes $150 \times 13200 = 1,980,000$ foot-pounds, or 642 Calories of work. By the way, 642 Calories or 1,980,000 foot-pounds is the usual amount of work done by an average horse in one hour; and if this amount of work is done in an hour, the work is said to be accomplished at the rate of *1 horse-power.* A *horse-power* is work done at the *rate* of 33,000 foot pounds, or 10.7 Calories, per minute; or 1,980,000 foot-pounds or 642 Calories per hour.

3 *Efficiency* is the percentage ratio of energy equivalent of work accomplished to energy expended in accomplishing the work; or mathematically expressed

$$\text{Mechanical efficiency of work} = \frac{\text{Mechanical work accomplished}}{\text{Total energy expended in accomplishing work}} \times 100.$$

4 For every liter (about a quart) of oxygen used up about 5 Cals. of energy are expended. Thus to spend 42 Calories of energy, or 1 horse-power-hour, the horse had to use up $\frac{642}{5} = 128.4$ liters of oxygen.

*Paper 116 in the Herman Frasch Foundation Series.

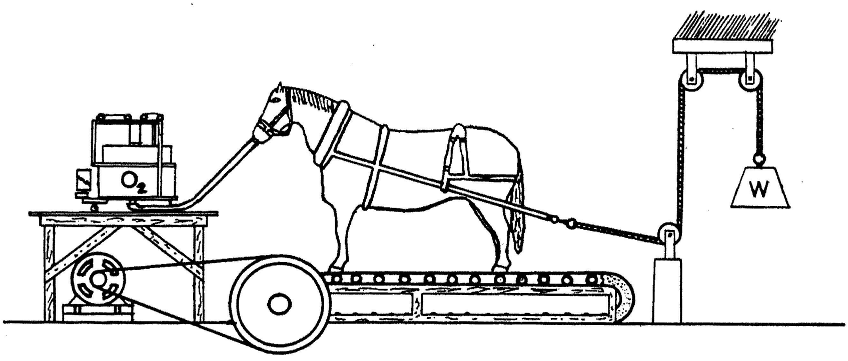

Fig. 1.—Method we used for measuring work performed (work=weight, W, in pounds times distance pulled in feet) and energy expended for performing the work (found by measuring "air" in the oxygen tank, O_2, used up while performing the work).

Efficiency of work is thus the percentage of total energy expended that is recovered in the form of useful work, and our problem was to determine the relative work efficiencies of horses, men, and motors, and the influence of various conditions on these efficiencies.

One particularly interesting unit which we used in this research is the *horse-power*.[5] Horse-power is the *speed,* or *rate,* of work. It is the rate at which an average horse is supposed to work, which fact explains the name 'horse-power.' Horse-power is work at the rate of 33,000 foot-pounds, or 10.7 Calories, per minute; or 1,980,000 foot-pounds, or 642 Calories, per hour.

While work is usually measured in foot-pounds or in horse-power-*hours,* and power, or *rate* of work, is usually measured in horse-power, all energy including work and power may be expressed in Calories. We shall frequently use this general energy unit, the Calorie.[6]

5 Instead of horse-power, kilowatts may be used. 1 Kilowatt is about 1 1/3 horse-power; or 1 horse-power is about 3/4 of a kilowatt. While horse-power and kilowatt are units of *power,* that is of speed or rate of work, horse-power-hours, and kilowatt hours, are units of *work.* A horse-power-hour is the amount of work accomplished in an hour working at the rate of 1 horse power (that is 33,000 foot-pounds per minute).

6 A Calorie is the amount of heat required to raise the temperature of 1 Kilogram of water 1° Centigrade or 4 pounds of water 1° Fahrenheit. Another heat unit is the British Thermal Unit, usually written B.T.U. A B.T.U. is the amount of heat required to raise the temperature of 1 pound of water 1° F. 1 Cal. is equal to about 4 B.T.U.'s; 1 B.T.U. is equal to about 1/4 Cal. There is nothing mysterious about calories. A Calorie is a unit of energy or heat just as a pound is a unit of weight or a foot is a unit of length. Thus if a pound of kerosene or gasoline, or fuel oil is burned, about 5000 Cals. (or about 20,000 B.T.U.'s) of heat are given off. If a pound of fat, such as lard, or cotton seed oil, or olive oil, is burned about 4000 Cals. of heat are given off. If a pound of starch is burned, about 1900 Cals. of heat are given off. 1 pound bread has about 1000 Cals.; a pound of beef (lean round) about 700 Cals.; 1 pound crackers 1800 to 1900 Cals.; 1 pound cheese, about 2000 Cals.; 1 quart milk, 700 Cals.; 1 pound cabbage, 130 Cals.; 1 pound carrots, 200 Cals., etc. Any form of energy can, according to the law of conservation of energy, be converted to Cals. Thus 1 horse-power is equivalent to 642 Cals.; 1 Kilowatt-hour is equivalent to 860 Cals. **1 horse-power is equivalent to 10.7 Cals. per minute or 624 Cals. per hour.**

INFLUENCE OF SPEED ON EFFICIENCY

Muscles and their surrounding fluids resemble heavy oils in being viscous. The more rapid the movements of, or through, viscous fluids, the greater the energy cost for overcoming the internal resistance. From this point of view the slower the movements the more efficient the process.

But the slower the movements, the longer the time taken for performing the work, and therefore the greater the overhead maintenance expense. From this point of view the more rapid the movements the more efficient the process.

The optimum or best speed, that is for maximum efficiency, is necessarily a compromise between muscle viscosity which requires slow movement for most efficient work, and overhead maintenance cost which requires rapid movement for most efficient work.

Figs. 2a, 2b, and 2c illustrate this idea of optimum speed for animal and motor.

Fig. 2a shows how the energy cost and efficiency of climbing 78 steps varies with the time taken to climb them. The energy cost

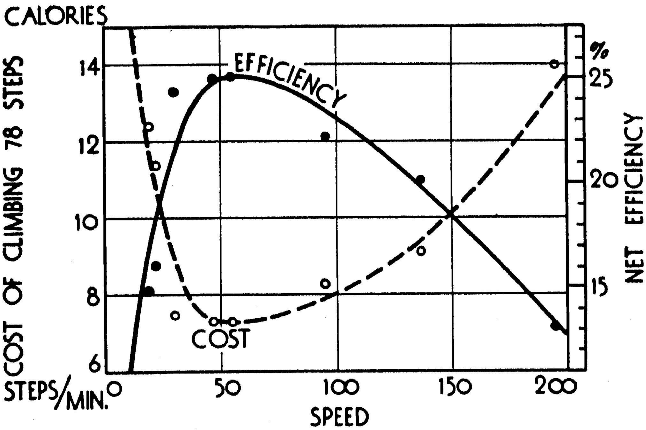

Fig. 2a.—Influence of speed of climbing stairs on energy cost (broken curve) and energetic efficiency (smooth curve). The cost is lowest, or efficiency highest, when the 78 steps were climbed in 100 seconds (Lupton's data).

goes down and the efficiency goes up until a speed of 78 steps per 100 second is reached; exceeding this speed, the cost goes up and the efficiency goes down.

Fig. 2b shows the way mileage per gallon gasoline of low-cost cars changes with speed. Traveling at the rate of 25 miles an hour under the given conditions resulted in the least cost of gasoline per mile, or in the most efficient transportation. Speeds below 20 or above 30 definitely decreased the efficiency.

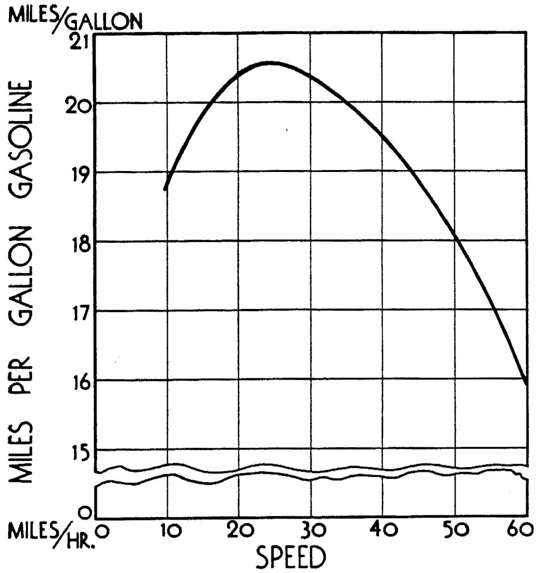

Fig. 2b.—Influence of speed of driving car on efficiency in terms of miles travelled per gallon gasoline. Note the resemblance between the efficiency curves of climbing steps and the efficiency curve of an automobile. In each case there is an optimum speed at which efficiency is maximum or cost minimum. (We prepared this composite curve from the individual data points for the Ford, Plymouth, and Chevrolet cars published in Consumers' Research Bulletin, Vol. II, No. 6, p. 4, March, 1936 by Consumers' Research, Inc., Washington, New Jersey. We used these data by special permission given to W. R. Graham Jr., July 13, 1936).

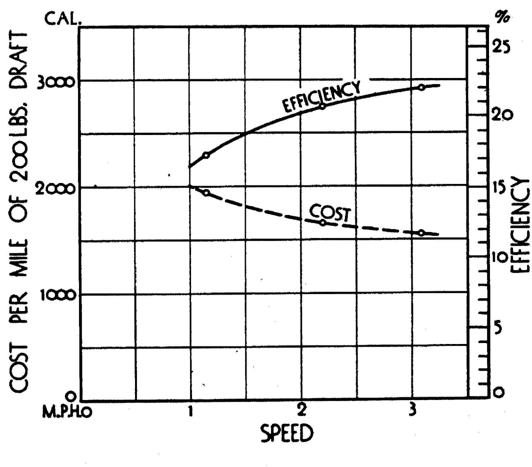

Fig. 2c.—Influence of 3 working speeds on efficiency and cost per mile of 300-pound draft exerted by our 1500-pound horse 19.

It is probable that every horse (also man and machine) has a characteristic efficiency curve analogous to the curves in Figs. 2a, 2b, and 2c.

INFLUENCE OF LOAD ON EFFICIENCY

When load is zero, no work is accomplished, and the efficiency is zero. When, on the other hand, the load is so great that the horse while trying to move it fails, no work is accomplished, and the efficiency is likewise zero. Somewhere between these two zero limits, there is an optimum load with a maximum efficiency. We have not worked out the complete curve of rising and declining efficiency with increasing load because our treadmill broke down when the loads were too heavy. But reasoning from Figs. 2a and 2b, the curve of efficiency of work in the horse rises and declines with increasing load in the same manner as with increasing speed. Fig. 2c shows the part of the curve that we have worked out.

Most of our experiments were carried out on a 4-year-old 1500 to 1600-pound Percheron gelding, and a 4-year-old 600-pound mare. Fig. 3 is a photograph of the two horses. They were both sturdy work animals. The Percheron worked on a farm, while the pony worked in a mine. The large Percheron was, however, in much better working condition than the pony.

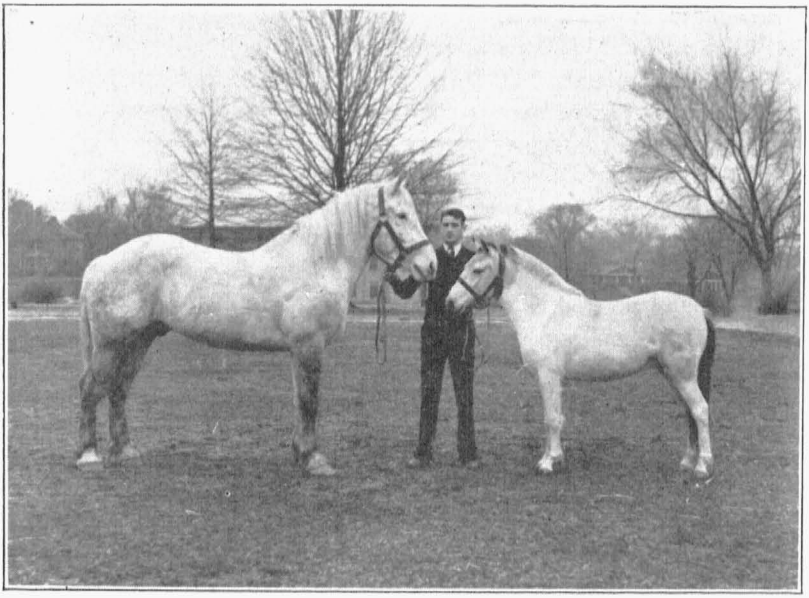

Fig. 3.—Photograph of Horses 19 and 2 which furnished the bulk of the data for the present research.

A careful comparison of the relative energetic efficiencies of large and small horses and of (150-pound) men, convinced us that maximum energetic efficiency is independent of size or even of species of animal. Small and large horses, and still smaller men, all reached approximately the same maximum efficiency level, of about 24%. That is to say, of 100 Calories expended, not over 25 may be recovered in useful work, and at least 75 wasted as heat, for overcoming friction of the muscles, etc., and regardless of size of animal. Size of animal is, of course, an important consideration, but not from the standpoint of energetic efficiency.

THE PATH BY WHICH MAXIMUM EFFICIENCY IS REACHED

The maximum gross energetic efficiency of work is about 24%. Does the maximum energetic efficiency of work correspond economically to the most profitable work? Under what conditions is this maximum reached? What are the intermediate efficiencies betwen the zero and the 24% maximum levels? In other words what is the *path* whereby this maximum level is reached? There are many ways of answering this question, but the simplest is to plot efficiency of work against horse-power of work.

We have already explained that horse-power is the *rate* of work; it is the product of weight pulled and distance pulled *per unit time*. Thus 1 horse-power is work at the rate of 33,000 foot-pounds *per minute*. Note that we get 33,000 foot-pounds when the animals pulls 1 pound for 33,000 feet, or pulls 33,000 pounds 1 foot. The product is in both these examples (as in many other combinations of factors), 33,000. Horse-power then combines three factors into one: load, distance, time; or speed and load. In order to save space, let us study the relation between efficiency and horse-power, rather than separate efficiency with each of the constituent factors which go to make up horse-power.[7]

Fig. 4 shows how efficiency rises with increasing horse-power for the 600-pound pony pulling load at 2.2 miles an hour, and for 1500-pound horse 19 pulling loads at 3 different speeds—1.2, 2.2, and 3.1 miles per hour.

First, note on the left axis of Fig. 4 that in all cases the top efficiency is about 24%.

Second, note in Fig. 4 that efficiency begins at zero, when the horse does no work, and it builds up to top efficiency in a manner similar to the way a growing animal builds up to top body weight. The shape of the curve makes it clear that no matter how hard the horse may work,

7 The reader who wishes to see how efficiency varies with each of the factors constituting horse-power is referred to Missouri Research Bulletin 244.

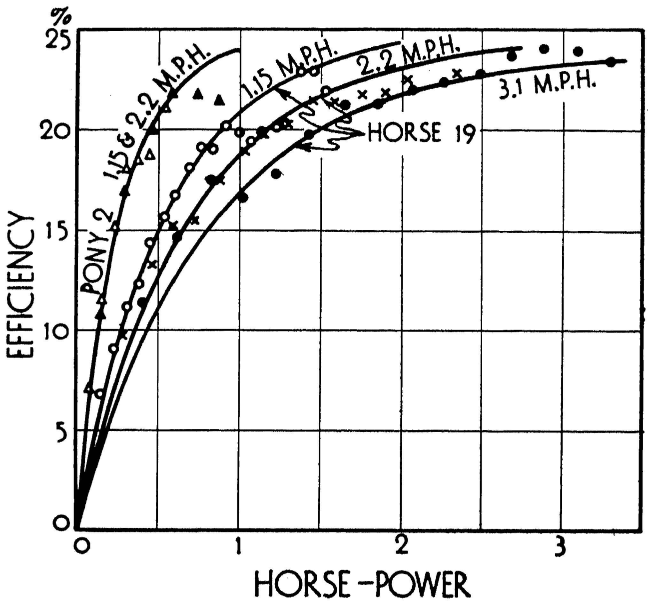

Fig. 4.—The way gross energetic efficiency increases with increasing rate of work (horse-power).

he can never exceed 25% efficiency; just as no matter how much an animal may eat, it can never exceed a certain body weight. However, while different animals reach different mature weights depending on hereditary make-up, no animal can exceed a 25% efficiency. *The energetic efficiency of muscular work is independent of body size.*

Third, note in Fig. 4 that within the speed limits investigated—that is, 1.1, 2.2, and 3.1 miles per hour—the slower the speed for a given horse-power (therefore the larger the load for the given H.P.) the greater the energetic efficiency of the work. Thus from this chart, at a working rate of 1 horse-power, the efficiencies for Horse 19 are 17% for 3.1 miles per hour; 19% at 2.2 m.p.h.; 21% at 1.15 m.p.h. The conclusion is that from the standpoint of energetic efficiency, work horses should not be hurried, and that they are more efficient *when working at a given horse-power* when pulling a heavy load at a slow speed than a light load at a high speed. One reason for this, as explained in connection with Fig. 2, is that the energy losses of overcoming the viscous resistance of the muscles increase more rapidly than the speed. However the total energy cost for accomplishing a given job is smaller at a higher speed because of the saving of maintenance expense resulting from the reduction in the time required to complete the job.

Fourth, note in Fig. 4 how the efficiency increases with increasing work rate. Let us take the 2.2 miles per hour speed. When Horse 19 works at ½ horse-power, his efficiency is 12½%; doubling the work rate to 1 horse-power does not double his efficiency to 12½x2, or 25%, but only to 18%; at 2 horse-power, his efficiency is not 12½x4 or 50%, but only 22%; at 3 horse-power his efficiency is not 12½x6 or 75%, but only 24%. In other words, the efficiency falls further and further behind the increase in work accomplished: the law of diminishing returns is definitely appliable to muscular work. The lesson is obvious. One should not increase the work rate beyond that at which the curve begins to flatten decidedly. While the maximum efficiency is reached at a high work-rate, yet for steady work day after day, work at the rate of about 1 horse-power is about right for the 1500-pound Horse 19, and this is the customary rate of work; for 600-pound pony about ¼ horse-power is approximately right.[8]

In other words, one must differentiate between *maximum energetic efficiency* and physiologically, or economically, *best rate of work* continued day after day for perhaps 10 hours a day. One of the important unsolved problems in horse husbandry is to determine the maximum rate of work that horses of different sizes can do day in and day out 6 to 10 hours a day, and still fully retain body weight and vigor to an advanced age. A safe tentative recommendation for the average horse in Missouri is a tractive draft equal to 10% of body weight pulled at about 2½ miles an hour. This will usually amount to work at the rate of about 1 horse-power.

RELATION BETWEEN ALL-DAY EFFICIENCY AND EFFICIENCY WHILE WORKING

The above discussion of a top efficiency of 24%, indicated by Fig. 4 was concerned with efficiency *while working*. However, unlike a tractor, a horse burns up fuel not only while working, but also when not working; and horses are not working at least ½ to ¾ of the 24-hour day. How does the all-day efficiency differ from the working efficiency?

Fig. 5 shows all-day efficiencies when the horse is working 12, 10, 8, 6, 4, and 2 hours out of the 24-hour day. When working at a rate of 1 horse-power, the efficiency is about 17% for a 12-hour day; 14% for an 8-hour day; 10% for a 4-hour day; 7% for a 2-hour day, etc. Naturally, the fewer the working hours per day, the lower the all-day efficiency.[9]

8 A horse working at the rate of 1 horse-power accomplished 1 horse-power-hour of work per hour; so that knowing the number of hours a horse works, we also know the horse-power-hours of work accomplished.

9 This matter is discussed in greater detail in Missuri Research Bulletin 244.

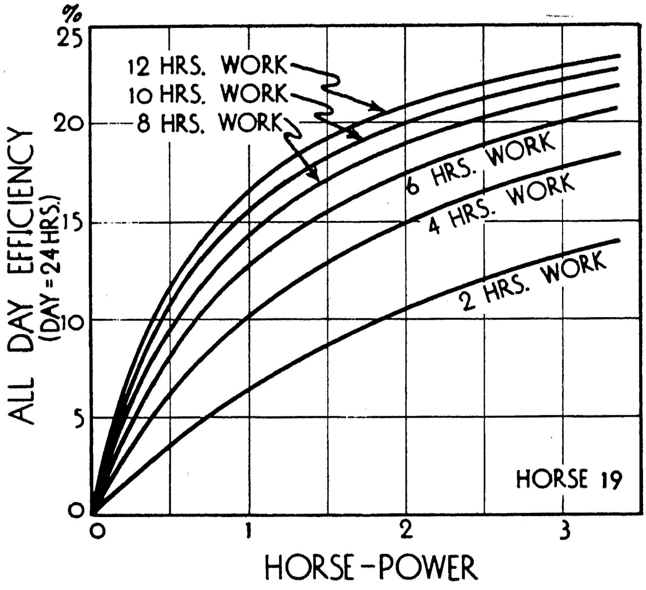

Fig. 5.—How all-day efficiency (including expense of maintaining animal at rest) varies with rate of work (horse-power) and number of hours worked per day.

THE WAY ENERGY COST (OR FEED COST) INCREASES WITH SPEED, LOAD, AND WORK RATE

Before presenting the data on the relation between energy expenditure and work performed, it may be useful to recall two facts. First, while energy expenditure was estimated in terms of Calories by the method of oxygen consumption illustrated in Fig. 1, it is easy to express the cost of work in pounds of feed from the fact that 1 pound total digestible nutrients (TDN) is equivalent to about 1800 calories, or to about 360 liters[11] oxygen. To represent the cost of work in terms of pound TDN, it is only necessary to divide the Calorie cost by 1800 or the liters oxygen consumed by 360. Second, the energy cost of performing a given job is easily estimated from the efficiency of the work and the energy equivalent of work performed[10]. Thus if the efficiency of a given job is 10%, then the energy expended in performing the job is 10 times the energy equivalent of the work accomplished.

10 The energy of the work accomplished is, as previously explained, easily computed from the load pulled and distance through which it was pulled. Thus a horse pulling on a 150-pound load (as measured by a spring scale) for 2.5 miles, performs 33,000 foot-pounds or 642 Calories.

11 1 liter is roughly the same as 1 quart.

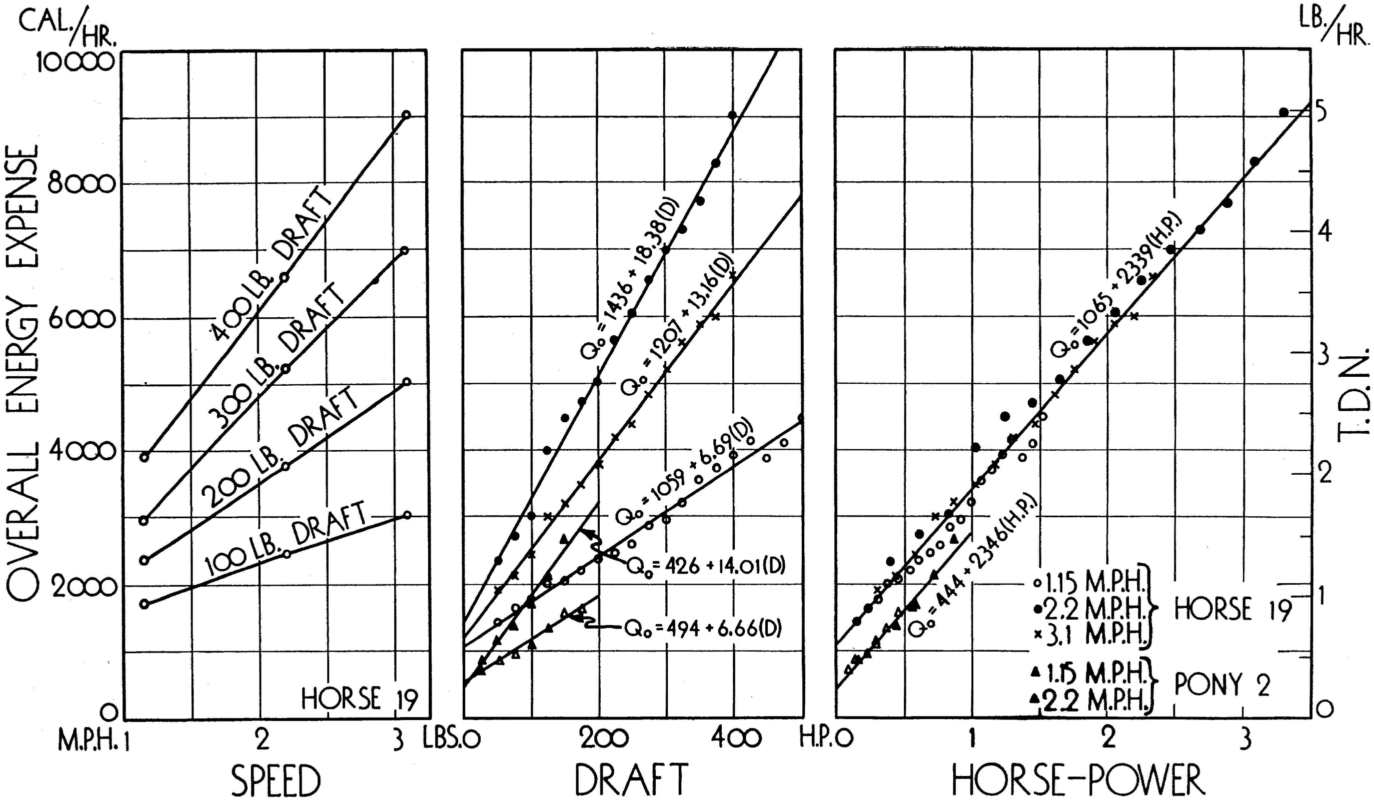

Fig. 6.—The chart shows the Calories (left axis) or pounds TDN (right axis), expended per hour when horses work at different rates (horse-power), also at different speeds pulling different loads.

With this introduction we are ready to inspect Fig. 6, which shows the overall energy expense in Calories per hour on the left axis, and the pound TDN (total digestible nutrients) per hour on the right axis plotted against: speeds of pulling given loads; loads pulled at given speeds; horse-power (which combines speed and load in one term). For the heaviest work (3.5 horse-power, or 400-pound pull at 3.1 miles per hour) the energy expended by Horse 19 is about 9000 calories per hour, equivalent to about 1800 liters of oxygen per hour, equivalent to about $\frac{9000}{1800}=5$ pounds TDN per hour. The interesting aspect of the curves in Fig. 6 is that they are straight; that is, the energy expenditure increases *directly* with speed of pulling given loads; with load pulled at given speeds; and with horse-power. Within the given limits, doubling horse-power doubles energy expenditure.[12]

COMPARISON OF WORK ABILITIES OF HORSES AND MEN

Efficiency being a *ratio*,[13] we had no difficulty in comparing energetic efficiencies of horses and men. We may similarly devise *ratios* for comparing work and energy outputs of horses and men[14].

The energy cost of maintenance of a horse or man when lying absolutely quiet with no food in the stomach, is called *basal metabolism*, or basal energy. We shall be able to compare the energy expenditures of horses and men, or in general of large and small animals, from the *ratios* of energy expended while working to energy expended under conditions of *basal metabolism;* or, if we prefer, we can compare the energy expenditure while working to energy expenditure while standing; or, in brief, compare the ratios $\frac{\text{work energy}}{\text{basal energy}}$ and $\frac{\text{work energy}}{\text{rest energy}}$ of horses and men.

We shall compare three types of ratios: (1) Ratio of maximum to minimum oxygen consumption of horses and men. (2) Ratio of peak-effort energy to basal and rest energy; (3) Ratio of sustained work energy, as in ordinary daily labor, to basal and rest energy.

(1) *Ratios of maximum to minimum oxygen consumption in horses and men.*—Fig. 7 shows such ratios for our horses plotted against speed, load or draft, and horse-power. The ratios of work energy to rest energy (or work oxygen to rest oxygen) go up to 15; while the

12 We must refer the reader to Research Bulletin 244 for additional charts and explanations on this matter.

13 Efficiency is the ratio of energy recovered in the performed work to total energy expended for performing the work.

14 It is necessary to resort to ratios for such comparisons because the size differences between men and horses make direct comparisons of *absolute* energy expenditures meaningless.

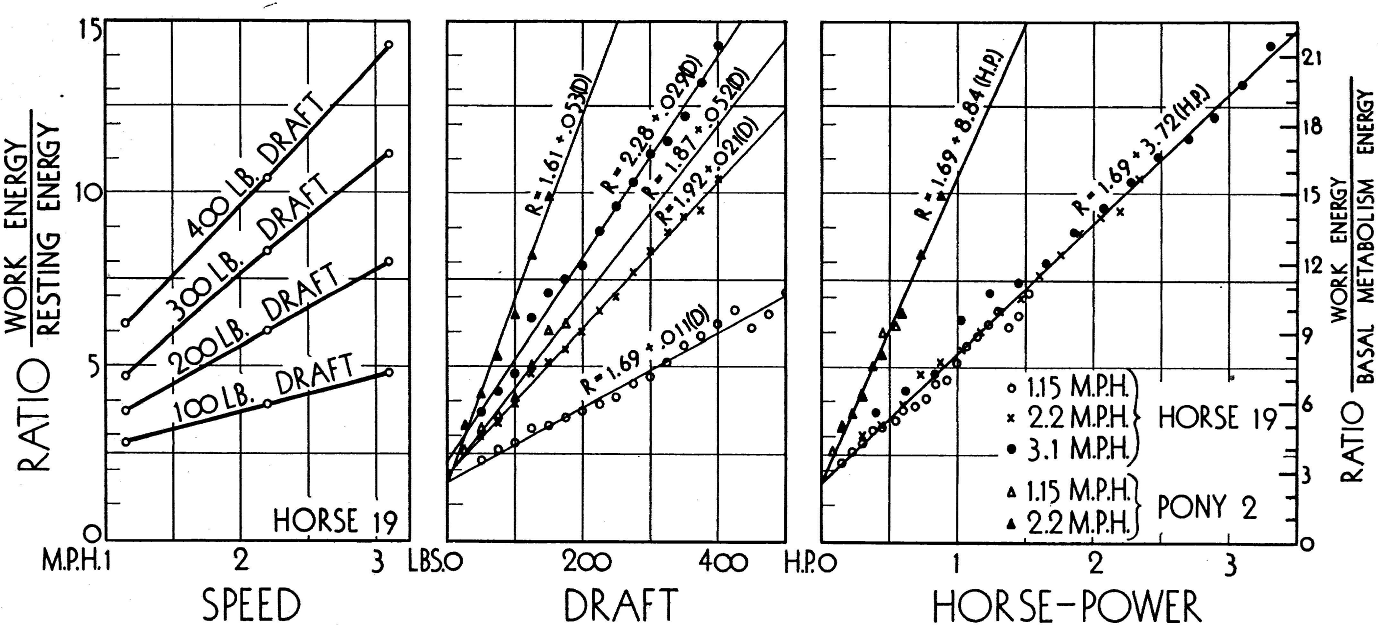

Fig. 7.—Ratio of work to rest (standing) energy on left side, and ratio of work to basal energy (right side) plotted against speed, load, and work rate (horse-power). Note that the ratio of maximum to basal energy is 21. These ratios do not include "oxygen debt." These ratios are consequently not peak-efforts of which animals are capable (including oxygen debt), but ratios of mamixum to minimum oxygen consumption.

ratios of work energy to basal energy (or work oxygen to basal oxygen) go up to 21.

In other words, a horse accomplishing work at a rate of 3.5 horse-power—which is 3.5 times the work ratio of the average hard-working horse—expends about 15 times as much energy, or consumes about 15 times as much oxygen, as when he stands; or about 21 times basal energy, as when he is lying down with no food in his stomach ("basal metabolism"). It must be understood that 3.5 horse-power is as high a rate of work output as a 1500-pound horse can maintain for several hours. Increasing rate of work beyond this limit would cause the horse to go into "oxygen debt:" the horse would get out of breath, and if compelled to go on for 3 to 4 hours might collapse and perhaps die from heart failure, as men sometimes do in severe athletic contests. This 21 ratio of work energy to basal energy means that the *maximum amount of oxygen that a work horse can utilize is 21 times* the minimum oxygen used.

How do men compare in this respect to horses? A careful study of the literature on this problem brought out the fact that the ratio of maximum oxygen consumption by men when running at top speed to minimum oxygen consumption varies in different men from 10 to 20, depending on physical development and training. We may therefore conclude that *our 4-year-old 1500-pound work horse, in excellent physical development and training, had approximately the same ratio of maximum to minimum oxygen consumption as a man of excellent development and training.* As in the case of energetic efficiency, work to rest oxygen consumption or energy expenditure is apparently independent of size or even species. This result means that in comparison to body weight, the lung-heart system concerned with pumping of the blood and supplying the muscles with oxygen is the same in superior work-horses as in athletic men. The work horse, 10 times the weight of man, has practically the same work to rest oxygen or energy ratio as an athletic man. Of course, race horses of extraordinary physical development and training probably have higher ratios than men or work horses. This is an attractive problem for study.

(2) *Ratios of peak-effort energy to basal energy in horses and men; "oxygen debt"*: One feature that distinguishes animals from motors is the fact that animals can go into "oxygen debt"[15]—which debt is repaid later at leisure during rest and recovery from the effort. Athletes have been known to incur an oxygen debt of 8 liters during 15 seconds of sprinting at top speed. Such intense efforts can

15 See Missouri Res. Bul. 244 for a detailed discussion of oxygen debt.

last for only a few seconds, but the value of this ability to go into debt in emergencies is obvious and herein is one superiority of horse to tractor on the farm. Incidentally, ability to go into oxygen debt varies with physical condition, and great athletes have exceptionally high abilities in this direction. Likewise, no doubt, although this has never been investigated, superior race horses can go into greater "oxygen debt" than inferior ones, or than work horses. How does peak-effort energy to basal energy in man differ from that in the work horse?

Readers of this bulletin are no doubt familiar with "horse-pulling contests" in which horses exert a peak effort for a few seconds. A careful study of these contests showed that a 1500-pound horse can develop from 7 to 15 horse-power for 4 to 11 seconds. Assuming that the efficiency of the pull is 20%, then the horses expended energy at the rate of 35 to 75 horse-powers, or[16] 375 to 803 calories a minute. Since the basal metabolism energy of a 1500-pound horse is about 7 calories a minute, the ratio of peak energy expenditure to basal metabolism energy in the horse is about $\frac{375}{7}$ to $\frac{803}{7}$=53 to 115. In brief, *a work horse in good condition is capable of spending about 100 times as much energy for a few seconds as he does when he is absolutely quiet, under condtions of "basal metabolism"*.

In man, Fenn[17] found that a medical student developed 13 horse-power for a few seconds or performed work at the rate of 139 Calories per minute. If this man's basal metabolism was 1.2 Calories per minute, then the ratio of peak energy expenditure to basal energy in this man was $\frac{1.2}{139} = 116$.

This comparison leads to the conclusion that *both, men and work-horses, can exert a peak-effort which is about 100 times the basal energy expenditure.*

(3) *Ratios of sustained work energy as in ordinary daily labor to basal energy*: In such types of "hard" work as agriculture, mining, building trades, lumbering industry, men at work spend 3 to 8 times as much energy as during basal metabolism (estimate by Dill). How does the horse compare to man in this respect?

The answer to this question is clearly given in Fig. 7. As previously indicated, a 1500-pound farm horse at a consistent pace works at the rate of about 1 horse-power. From Fig. 7 it is seen that the work to basal-metabolism ratio for a 1500-pound horse working at a rate of 1 horse-power is of the order of 8, the same as in human at hard labor.

16 Since 1 horse-power is equivalent to 10.7 Calories per minute.
17 See Am. J. Physiol. Vols. 90, 92, and 93.

This discussion may be summarized by saying that *horse and man have the same work energy to basal energy ratios, namely: 20 for maximum oxygen consumption (not including oxygen debt); 100 for maximum brief effort involving great oxygen debt; 8 for sustained hard work as encountered in daily life.*

FACTORS WHICH MAY LIMIT WORK OUTPUT AND EFFICIENCY

What are the conditions which set a limit to peak effort and efficiency?

The explanation of the fact that gross energetic efficiency of muscular work can not exceed 25% is rather involved, and it seems best to refer the reader to Missouri Research Bulletin 244 for details. For the present it is sufficient to say that there is a "necessary" 60% energy loss in the process of converting glycogen ("body starch") to muscular work. Of the remaining 40% of energy which can theoretically be utilized, about half is wasted for overcoming: "internal friction", that is, resistance of the body colloids to change; friction between feet and ground; pull of gravity; wind resistance; energy expenditure for many useless motions associated with work. These wastes are often useful. Thus contradictory as it may seem, viscosity of muscles, while involving energetic waste in overcoming it, is yet useful because if it were not for the protecting properties of viscosity, the animal would "tear his tendons, break his bones, 'pull' his muscles, strain his joints". It is possible that very rapid runners have low muscle viscosity, and such often do strain themselves in various ways. Incidentally, the "warming up" process is valuable before a race because the viscosity of the muscle (like that of the winter oil in a car) is reduced, thereby permitting more efficient running. The usefulness of the pull of gravity is obvious in the case of horses pulling heavy loads, yet it takes energy to overcome this gravity pull. This discussion gives a rough idea how the 100 per cent energy is distributed and why the gross energetic efficiency of muscular work can not exceed 25%.

Several factors limiting work output and efficiency are relatively clear-cut and can be discussed in some detail. Some of these are: (1) Temperature and humidity; (2) Nature of diet; (3) Condition of heart and lungs; (d) Training; (e) Fatigue.

1. *Temperature and Humidity*: It is hardly necessary to say that horses, men, and machines produce extra heat during work and that water evaporation aided by air circulation is the means for cooling. The hotter and the more humid the environment and the less the air circulation, the more difficult it is to throw off the extra heat and to

lower the work efficiency.[18] Moreover, after the body's ability to dissipate heat is exceeded, the hotter it gets, the more heat the body produces. If the work is hard enough, the body may get so hot as to collapse. The influence of temperature and humidity on muscular work was investigated in detail by Dill and co-workers.[19]

When the temperature is high but dry, as happens in arid regions, the collapse in horses and men is usually due to *heat cramps,* caused by excessive loss of water *and of salt* through the sweat. This difficulty may be cured—or still better avoided—by taking generous amounts of water containing 1% common salt. *The salt is as important as the water.*

When, however, the temperature is hot and humid, as may happen in most of the United States, the collapse is usually due not to heat cramps, that is, loss of water and salt, but to *heat stroke* that is overheating of the body. The body's mechanism for throwing off extra heat is unable to meet the demands on it; the heart fails to meet demands for heat dissipation and for oxygen. The result is that the body temperature may rise to 110° F or 112° F. As the body cannot stand 112° F, death often follows, especially in the aged.

2. *Nature of Diet*: Everyone knows that some fuels are utilized in the automobile more efficiently than others. The same is true with the body. Carbohydrate (sugar) to the heart and muscles *during hard work* is what high grade gasoline is to the automobile engine. Carbohydrate is the body's preferred fuel for strenuous muscular exercise for at least four reasons:

(a) It requires 6% less oxygen to liberate a given amount of work energy from carbohydrate than from fat. This may be an important consideration in strenuous exertion as in racing, when oxygen want often sets a limit to maximal work that can be accomplished.

(b) Contrary to popular notions, high carbohydrate diets are less "heating" than high protein or high fat diets. A pound of protein gives off about 15% more of waste heat (which can not be used for work) than a pound of carbohydrate. Since inability to rid the body of excess heat during work most often—especially in hot humid weather—sets the upper limit to the work that can be accomplished, it is evident that high protein foods should be avoided on days of hard physical labor, especially if the weather is hot and humid.

There is another reason why high protein is objectionable on days of strenuous muscular exercise. Little, or no extra protein, is needed for muscular exercise above rest. Most of the protein consumed by an

18 The heat production by the body is increased by 13% for each increase in *body* temperature by 1°C. Since increase in heat production comes from using up extra feed, therefore the higher the body temperature the higher the maintenance cost of the animal and the lower its efficiency.

19 See, Physiol. Rev., *16,* 263, 1936.

adult animal, especially during work, is broken down to sugar and urea. The urea and related nitrogenous end products are excreted through the kidneys. But the excretory activities of the kidneys are greatly *reduced* by hard muscular work, so that these end products of protein metabolism are added on to the other waste products in the body, thus *aggravating the situation.*

(c) Carbohydrate is preferable to fat on days of unusual muscular exercise because under certain body and strenuous work conditions, fat sometimes does not completely burn, leaving *acetone bodies* which are poisonous to the body.

(d) There is some reason for believing that fat cannot be used for muscular exercise but must first be converted to carbohydrate, and that there is a 10% waste in making this conversion from fat to carbohydrate.

While the above may be subject to modification, it is none the less safe to say that carbohydrate diets are best for days of strenuous exercise because carbohydrate is the preferred muscle fuel of the body, and less heating than protein or fat.

By carbohydrate diet we do not mean pure carbohydrate, such as sugar or starch, but an ordinary ration rather low in protein and fat and high in carbohydrates with the usual amount of vitamins and minerals. The idea is that for hard muscular work it may be for the best to replace as far as possible protein-high and fat-high by carbohydrate-high constituents in the usual ration.

Two famous scientific investigators[20] of Olympic contests recommended "eating a quarter of a pound of some simple candy such as peppermint creams a half to three-quarter of an hour before any prolonged contest". They believe that sugar is the fuel most immediately available for muscular work and that a relatively high carbohydrate and low fat diet would be helpful to the "wind" and for avoiding "overtraining". A famous experiment[21] has shown that persons who could carry on a given piece of hard work for 4 hours on a high-carbohydrate diet, could continue it only for 1½ hours on a high-fat diet. We may also cite an observation[22] that collapse in Marathon races is often caused by serious depletion of the blood sugar. A book has recently appeared[23] indicating that many types of fatigue are due to lowering of sugar in the blood, and that a light meal at 10 in the morning and 4 in the evening increases efficiency of factory workers.

We do not wish to give the impression that starchy or sugary foods are superior to other foods, because they are not; what we mean

20 Henderson and Haggard. Am. J. Phys. 72, 264, 1925.
21 Carried out by Christiansen (see Arbeitsphysiol. Volumes 4, 5, and 7).
22 By Levine (J. Am. Med. Assn. LXXXII, 1778, 1924).
23 By Haggard and Greenberg entitled "Diet and Physical Efficiency," New Haven, 1935.

is that for *hard muscular work,* especially if prolonged, a high carbohydrate diet is preferable, physiologically and also economically, to a high-fat or high-protein diet.

In view of the tremenduous importance of diet on efficiency, economy, endurance, and speed, it is strange that so little systematic investigation has been given to the influence of nature of diet on efficiency and endurance in work and sports (in work and race horses). We can not even give a clear-cut scientific reason for preferring oats to other grains as feed for horses. What particular constituent of the oat grain makes it superior—if it is really superior—to other grains? Some attribute vaguely and mysteriously the superior qualities of oats to its "laxative" properties; others to its "cooling" properties; still others to its superior bone-forming qualities (Dr. W. R. Graham, Jr. informed us that chickens raised by his father on oats had finer yet stronger bones than those raised on other grains).

3. *Condition of heart and lungs*: The function of the heart and lungs (including all blood vessels) is to maintain a proper "atmosphere" in the interior of the body. These two furnish oxygen to and remove carbon dioxide from every cell of the body. If the proper interior atmosphere cannot be maintained either on account of weak lungs, or more often weak heart, the animal often collapses and dies. The peak effort of an animal (as highest racing speed) is thus set by the heart-lung, or cardio-respiratory, system, or most usually by the heart alone, on account of its inability to pump fresh, oxygen-rich blood, rapidly enough to meet the oxygen needs of hard working muscles.

The tremenduous amount of work that the heart does can be realized from the estimate by Hill for an athlete whose heart pumped the almost unbelievable amount of 17 gallons of blood per minute against a (blood) pressure of at least 100 millimeters.* The heart obtains the nutrients and oxygen for this work through the coronary arteries. Ultimately, therefore, peak-effort is limited by the ability of the coronary vessels to carry enough oxygen and nutrients to the heart tissues to enable it to perform the work at the required rate. Great athletes are no doubt endowed with superior coronary circulation. Unfortunately, the coronary blood vessels thicken and harden rapidly with increasing age, which explains the fact that athletes can not hold championships much after age 30 years, or that older horses and men can not stand strain of hard work especially in hot and humid weather when the heat-regulating mechanism places the heart under heavy strain. Tests for "physical fitness" are therefore largely heart tests.

*Equivalent to work at the rate of 631 foot-pounds per minute or 0.02 horse-power.

4. *Training*: Training raises the limits of efficiency by increasing skill and decreasing lost motion, and avoiding the use of unnecessary muscles, which involves energy expenditure. It also teaches the individual to adjust his efforts to his powers and thus avoid premature fatigue or exhaustion. Training raises work output by improving the muscular, respiratory and, most important, circulatory (heart) systems. It is believed that training stimulates formation of new capillaries, or opening up of hitherto unused capillaries, of the vital coronary circulation. Training increases the number of red blood cells, and thus improves the oxygen-carrying capacity of the blood.

5. *Fatigue*: Fatigue as a limiting factor in efficiency and output of muscular work is due largely to "oxygen debt" or accumulation of lactic acid in the body[24] and depletion of blood sugar, as previously explained. Many other causes of fatigue were suggested, but need not be discussed because they are not well understood. Of course oxygen want, or lactic acid accumulation, or even sugar depletion, is not likely to be the cause of fatigue in light work, such as light factory work. Here other factors, such as boredom, cause "fatigue"—but with such types of fatigue we are not here concerned.

COMPARISON OF ENERGETIC EFFICIENCY AND ECONOMY OF HORSE AND TRACTOR

Many factors other than energetic efficiency or monetary cost of work enter into the choice of horse or tractor. Such factors are: income for young stock; utilization of pastures and feed which might otherwise be wasted; superior adaptability of horse; initial investment; "keeping the money on the farm". There is plenty of wisdom in Will Rogers' statement that: "The horse raises what the farmer eats. And eats what the farmer raises. But you can't plow in the ground and get gasoline. You don't have to pay some finance company 10 or 15 per cent to own a horse." Regardless of energetic efficiency and apparent monetary economy there is a place for the horse on the farm. However, it is instructive to compare horse and tractor with regard to efficiency. (Table 1).

The maximum energetic efficiency of the horse while working is 24%. But the maximum efficiency of steam engines is only 15% and of gasoline engines 18%. Only the Diesel engines, usually too expensive for tractor service on an average farm, can boast a 35% energetic efficiency. These efficiencies are "at the belt"; that is, when the tractor is stationary. The efficiencies at the "draw bar," when the tractor pulls itself as well as the load, is much lower. A careful study of 12 horse-power electric-ignition farm tractors gave an energetic efficiency at the draw bar of only 13%, as compared to 24% for the horse while working.

24 When the oxygen supply to the cells is inadequate lactic acid accumulates. This lactic acid is removed during the rest when the oxygen supply becomes adequate.

TABLE 1.—ENERGY AND MONETARY EXPENSES FOR A TYPICAL 1500-POUND WORK HORSE AND A TYPICAL IGNITION TYPE FARM TRACTOR. IT IS ASSUMED THAT THE HORSE PULLS 150 POUND DRAFT AT 2.5 M.P.H., OR WORKS AT THE RATE OF 1 HORSE-POWER. THE TRACTOR WORKS AT 12 H.P. WITH A GROSS EFFICIENCY OF 13.4%.

Hours work in 24	12	10	8	6	4	2	0
Hours rest in 24	12	14	16	18	20	22	24
I. Horse							
1. Work Accomplished:							
H. P.-hours	12	10	8.0	6.0	4.0	2.0	0.0
K. W.-hours	8.9	7.5	6.0	4.5	3.0	1.5	0.0
Calories	7700	6420	5140	3850	2570	1280	0.0
2. Energy Expended:							
Calories	46600	41300	35900	30600	25200	19900	14600
Lbs. TDN	25.7	22.8	19.8	16.9	13.9	11.0	8.0
Factor correcting expended energy for activity during rest=5100	1.04	1.05	1.07	1.09	1.12	1.17	1.25
3. All day energetic efficiency, %	16.5	15.5	14.3	12.6	10.2	6.4	0.0
4. Calories per H.P.-hour	3890	4130	4490	5_00	6300	9940	∞
5. Calories per K.W.-hour	5210	5540	6010	6840	8450	13300	∞
6. TDN per H.P.-hour, lbs.	2.14	2.28	2.48	2.82	3.48	5.50	∞
7. TDN per K.W.-hour, lbs.	2.87	3.06	3.32	3.78	4.66	7.37	∞
8. Cost of TDN per H.P.-hour ($1.00 per 100 lbs. TDN)	2.14c	2.28c	2.48c	2.82c	3.48c	5.50c	∞
II. Tractor							
1. Work Accomplished:							
H.P.-hours	144	120	96	72	48	24	0.0
K.W.-hours	107	90	72	54	36	18	0.0
Calories	92600	77100	61600	46300	30800	15400	0.0
2. Energy Expended:							
Calories	690000	575000	460000	345000	230000	115000	0.0
Gallons fuel	20.0	16.7	13.4	10.0	6.7	3.3	0.0
3. All-day Efficiency	13.4	13.4	13.4	13.4	13.4	13.4	0.0
4. Calories per H.P.-hour	4800	4800	4800	4800	4800	4800	∞
5. Calories per K.W.-hour	6420	6420	6420	6420	6420	6420	∞
6. Fuel per H.P.-hour, gallons	.139	.139	.139	.139	.139	.139	∞
7. Fuel per K.W.-hour, gallons	.186	.186	.186	.186	.186	.186	∞
8. Cost of fuel plus oil per H.P.-hour (fuel at 10c per gal., 20% for oil)	1.7c	1.7c	1.7c	1.7c	1.7c	1.7c	
III. Horse vs. Tractor							
1. Ratio: TDN cost per H.P.-hr. for horse to fuel and oil cost per H.P.-hr. tractor	1.26	1.34	1.46	1.66	2.05	3.24	
2. Cost per 100 lbs. TDN for above ratio to equal one. (horse feed cost = tractor fuel cost)	79c	74c	68c	58c	49c	31c	

However, the horse burns fuel not only while working but also while resting, while the tractor burns fuel only while working. The energetic efficiency of the horse must therefore be expressed in two ways: efficiency while working, and all-day efficiency including energy, or feed, cost of rest.

Fig. 5 shows how all-day energetic efficiency is affected by hours worked per day. Fig. 5 shows that working at one horse-power for 8 hours a day, our 1500-pound horse performed the work with an all-day energetic efficiency of only 14 per cent—which is about the same efficiency as shown by the tractor while working.

FEEDING STANDARD

The work horse uses his feed for two purposes: first, maintenance; second, work.[25] The amount of feed needed for maintenance depends on the size of the animal; the amount of feed used for work depends on the amount of energy expended for the work. The relations between size, work, feed requirements and profits on horse work are discussed in great detail in Missouri Research Bulletin 244. At this time we merely present Table 2 giving the relation between size of horse, number hours worked per day (assuming that horse exerted a tractive draft 10% of his body weight at 2.2 miles per hour) and TDN[26] requirements.

TABLE 2.—POUNDS DIGESTIBLE NUTRIENTS REQUIRED BY HORSES OF DIFFERENT LIVE WEIGHTS WORKING DIFFERFNT NUMBER HOURS PER DAY

Hours Worked per Day	600	700	800	900	1000	1100	1200
0	5.7	6.3	7.0	7.6	8.2	8.8	9.4
1	6.1	6.8	7.6	8.3	8.9	9.6	10.3
2	6.6	7.3	8.2	8.9	9.7	10.4	11.2
3	7.0	7.9	8.8	9.6	10.4	11.3	12.1
4	7.5	8.4	9.4	10.3	11.2	12.1	13.0
5	7.9	8.9	10.0	10.9	11.9	12.9	13.8
6	8.4	9.4	10.6	11.6	12.7	13.7	14.7
7	8.8	9.9	11.2	12.3	13.4	14.5	15.6
8	9.3	10.5	11.9	13.0	14.1	15.3	16.5
9	9.7	11.0	12.3	13.6	14.9	16.2	17.4
10	10.2	11.5	12.9	14.3	15.6	17.0	18.3
11	10.6	12.0	13.5	15.0	16.4	17.8	19.2
12	11.1	12.5	14.1	15.6	17.1	18.6	20.1

Hours Worked per Day	1300	1400	1500	1600	1700	1800
0	9.9	10.5	11.0	11.6	12.1	12.6
1	10.9	11.5	12.1	12.8	13.4	13.9
2	11.8	12.6	13.2	14.0	14.6	15.3
3	12.8	13.6	14.3	15.2	15.9	16.6
4	13.8	14.7	15.5	16.4	17.1	18.0
5	14.7	15.7	16.6	17.5	18.4	19.3
6	15.7	16.7	17.7	18.7	19.7	20.6
7	16.6	17.8	18.8	19.9	20.9	22.0
8	17.6	18.8	19.9	21.1	22.2	23.3
9	18.6	19.9	21.0	22.3	23.5	24.7
10	19.6	20.9	22.1	23.5	24.7	26.0
11	20.5	21.9	23.3	24.7	26.0	27.4
12	21.5	23.0	24.4	25.9	27.3	28.7

25 We might also mention feed used for reproduction.
26 Total digestible nutrients.

Thus from Table 2 the 1500-pound horse not working at all requires 11 pounds TDN; working 1 hour a day requires 12.1 pounds TDN; working 2 hours a day, requires 13.2 pounds TDN and so on. These values are of course estimates based on a limited amount of data, and they will no doubt be changed with further accumulation of data.[27]

A LOOK INTO THE FUTURE

During work, the maximum efficiency of work is the same for horses and men and nearly twice as great as for the 12-horse-power electric-ignition farm tractor. However, the all-day efficiency (including cost during rest) is nearly the same in horse and tractor because the horse uses fuel when resting while the tractor does not. (Table 1).

The ordinary and maximum work output energy bear the same relation to the basal energy in horses as in men. Horses have a tremenduous reserve or overload capacity (due to their ability to go into "oxygen debt") as compared to tractors, and this constitutes one of the superiorities of the horse over the tractor.

At current kerosene, oil, and feed price, the feed cost of performing a given amount of work by a horse is greater than by a tractor. However, other considerations such as initial investment and financing, utilization of pasture and other feeds, keeping money at home, etc., give the horse important advantages. The horse is especially desirable in times of depression when ready cash is scarce and feed at low cost plentiful. The desirability of the horse would be still greater if we tried to realize all his potentialities as engineers try to realize the full potentialities of the engine. There is real need for investigating the physiology of work, including the hereditary, nutritional, training as well as economic aspects; and not only work powers, but also sports, amusement, and educational value of the horse, as automobile manufacturers try to realize such potentialities for the automobile.

The economic importance of the horse may increase with the passage of time, with the depletion and eventual exhaustion of the petroleum resources, which are being depleted at a greater rate than the people generally realize. Attempts are being made, and rightly, to blend gasoline with alcohol. But alcohol as a fuel may not be able to compete with the original feed from which the alcohol was made. The feeds can, perhaps, be more efficiently converted to work by a horse than by an engine after the conversion of the feed into alcohol.

27 The reader is referred to Missouri Research Bulletin 244 for the detailed explanations, charts, tables and graphs by the aid of which Table 1 was computed.