Efficiency of Energy Utilization in Farm Animals

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THE UTILIZATION of energy in farm animals means transfer of energy from feed to animal products or work. Some biochemists use the term utilization in a different way. They measure, for example, utilization of an organic compound by the carbon dioxide which is produced from the compound. If this production of carbon dioxide is paralleled by heat production, as it usually is, then this means waste and not utilization for farm animals.

Efficiency is the ratio of the energy in the desired product to the energy in feed. It may be total efficiency, namely, G/I with G = gain in energy of milk or body substance, or eggs or work, and I = energy in feed; or it may be partial efficiency, namely, $\Delta G/\Delta I$ with ΔG as a change in gain and ΔI the corresponding change in food energy taken in. ΔI may be expressed as heat of combustion of feed, or digestible or metabolizable energy of feed.

PARTIAL EFFICIENCY FOR MAINTENANCE

Armsby[1] measured the partial efficiency of the energy present in timothy hay for maintaining steers. He carried out difference trials, measuring the production of heat (by the heat loss) of steers at two levels of feeding below maintenance in a respiration calorimeter (Table I).

Changing the ration from 10.21 to 6.27 pounds of hay per day decreased the metabolizable energy by 3,776 kilocalories per day. The decrease in heat production amounted to 1,748 kilocalories per day. With the lower ration, the steer lost 2,296 kilocalories chemical energy of body substance more than he lost with the higher ration. Therefore, 4.04 pounds of hay saved 2,028 kilocalories of body substance which amounts to 502 kilocalories of body substance saved per pound of hay. The partial efficiency of the metabolizable energy in timothy hay was the following.

$$\frac{\Delta G}{\Delta I} = \frac{2{,}028}{3{,}776} = 0.54 = 54\%$$

PARTIAL EFFICIENCY FOR FAT PRODUCTION

Difference trials with steers on fattening rations were conducted by Kellner.[2] He measured the carbon and nitrogen balances of the steers at two different levels of food intake above maintenance in a respiration apparatus. Table II gives the results of one of the difference trials in which Kellner measured the utilization of starch for formation of body fat. The experiment is somewhat complicated because the steer gained weight from one trial to the next. This weight gain increased his maintenance requirement and decreased the amount of feed energy available for fat production. By estimating the maintenance requirement Kellner could calculate how much metabolizable energy of the ration was available for fat production.

The addition of starch to the diet increased the metabolizable energy available for fat production from 13.7 to 16.1 kilocalories. This difference in metabolizable energy of 2.4 megacalories produced an increase in fat production of 1.4 megacalories. Thus the

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TABLE I
Determination of Net Energy Value of Timothy Hay for Maintenance

	Dry Matter of Hay Eaten (pounds)	Metabolizable Energy (kilocalories)	Heat Produced (kilocalories)	Gain of Energy (kilocalories)
Period 4	10.21	9,544	9,812	−268
Period 3	6.17	5,768	8,064	−2,296
Difference	4.04	3,776	1,748	2,028
Difference per pound dry matter of hay	...	935	433	502

TABLE II
Kellner's Measurement of Net Energy in Starch*

	Metabolizable Energy in Feed (megacalories)	Body Weight (kg.)	Metabolizable Energy		Net Energy Body Fat (megacalories)
			Maintenance (megacalories)	Production (megacalories)	
Basic ration	26.8	600	13.1	13.7	7.5
Basic ration	29.9	650	13.8	16.1	8.9
Difference: starch	3.1	50	0.7	2.4	1.4

NOTE: Net availability of starch net/metabol. = 1.4/2.4 = 0.58 = 58%.
* Difference trial. Landw. Vers. Stat., 53, 1,900.

TABLE III
Energy in Nutrients

	Heat of Combustion (Digestible Energy) (kilocalories)	Metabolizable Energy (kilocalories)	Net Energy (kilocalories)	Partial Efficiency of Metabolizable Energy (%)
Digested starch 1 kg.	4,180	3,760	2,360	63
Digested protein 1 kg.	5,780	4,700	2,230	48
Digested fat 1 kg.	8,820	8,820	5,680	64

partial efficiency of starch for fat production was the following.

$$\frac{\Delta G}{\Delta I} = \frac{1.4}{2.4} = 0.58 = 58\%$$

Kellner ran similar difference trials using protein (wheat gluten) and fat (peanut oil) as additions to the basic ration. A summary of the results is shown in Table III.

Kellner assumed that the net energy of a feed could be calculated as the sum of the net energy content in protein, fat and carbohydrate of the feed, but when he added hay to a basic ration its fattening effect was considerably less than that predicted from the net energy in the constituents. Kellner noticed that the discrepancy was greater the higher the crude fiber content in the roughage became. On the average, 1 gm. crude fiber depressed the fattening effect 1.36 kilocalories, the net energy in 0.58 gm. of starch.

PARTIAL EFFICIENCY FOR WORK

Horses and mules still do some farm work. As early as 1888 Emil Wolff[3] measured their efficiency by feeding horses combinations of

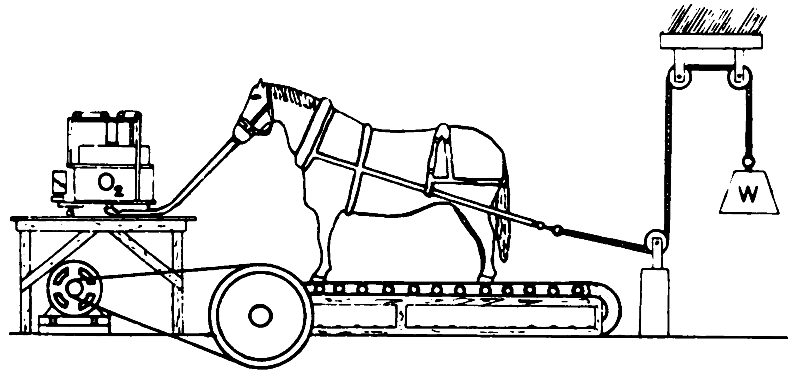


FIG. 1. Measuring efficiency of working horse. (From: BRODY, S. and CUNNINGHAM, R. *Missouri Research Bull.*, 38:238, 1936.[5])

hay and oats, adjusting their daily work so that on any given ration the horses maintained their body weight.

These were experiments of long duration. At the turn of the century (1898) Zuntz and Hagemann[4] investigated the work efficiency of tracheotomized horses walking on a treadmill against a measured pull. This arrangement, using a face mask instead of a tracheal cannula, is shown in Figure 1 (taken from a publication by Brody and Cunningham[5]). The picture is self explanatory.

One of the results of Zuntz and Hagemann[4] is shown in Table IV.

During rest, the horse consumed 1.68 liters oxygen per minute. This corresponded to a heat production of 8.3 kilocalories per minute. When the horse performed 5,313 meter-kilograms per minute, equivalent to 12.5 kilocalories of work per minute, the catabolic rate rose to 53.4 kilocalories per minute. Thus, 12.5 kilocalories of work was produced by an increase of catabolism of 45.1 kilocalories. The partial efficiency of body energy for work was

$$\frac{\Delta \text{ work}}{\Delta \text{ catabolism}}, \text{ was therefore } \frac{12.5}{45.1} = 0.28 = 28\%.$$

This is an efficiency of net energy for work because the body energy, such as fat, glycogen, protein and even glucose in the bloodstream, has already resulted from a transfer of food to body substance with the heat increment involved.

PARTIAL EFFICIENCY FOR MILK PRODUCTION AND GROWTH

In contrast to work and fat production, milk production and growth are not mainly energy transformations. This is especially

TABLE IV
Measurement of Partial Efficiency of Body Energy for Work in Horses

	Oxygen Consumption Per Minute (liters)	Catabolism Per Minute (kilocalories)
Rest	1.68	8.3
Work*	10.80	53.4
Increase by work	9.12	45.1

NOTE: Partial efficiency of body energy kilocalories of work/kilocalories of catabolism = 12.5/45.1 = 0.28 = 28%.

* 5,313 meter-kilograms/minute = 12.5 kilocalories/minute.

TABLE V
Energy Balance Per Day*

	Ingested (kilocalories)	Excreted (kilocalories)
Food†	35,150	10,110 (feces)
Digested	25,040	1,380 (urine)
		2,770 (methane 291 l.)
Metabolizable	20,890	6,060 (milk 8.5 kg.)
Catabolizable	14,830	16,170 (heat)
Gain in body substance	1,340	

* *Cow 1007.* Weight 460 kg., weight$^{3/4}$ = 99 kg.$^{3/4}$ February 19 to March 2, 1940.

† *Food: Dry matter.* 5,258 gm. Sudan hay, 519 gm. beet pulp, 521 gm. casein, 2,110 gm. glucose.

TABLE VI

Efficiency of Food Utilization vs. Protein—Ratio in Rations of Baby Chicks

Ration	Protein Ratio* (%)	Energy Intake Per Day Per Chick (kilocalories)	Total Efficiency	
			N (%)	Energy (%)
4.5 Casein 40.5 glucose 55 basal mix	36	123	35	20
20.0 Casein 19.0 glucose 55 basal mix	49	135	22	11
32.5 Casein 9.5 glucose 55 basal mix	64	126	16	9

$$* \text{ Protein ratio} = \frac{\text{Energy in protein}}{\text{Energy in total food}} 100.$$

true for the role of protein in these types of animal production. In the production of work or fat, protein can be regarded as a fuel. It can replace or can be replaced by fat or carbohydrate as sources of chemical energy. For the formation of casein or body protein, however, feed protein is a source of amino acids—building material instead of fuel.

Milk production or growth is not as closely correlated to feed intake as is fat production or work, at least within a normal range. Milk production is more dependent on other factors than food. Therefore, for milk production or growth, difference trials are not suitable for measuring efficiency.

Efficiency for comparison can still be measured, for example, by measuring the carbon and nitrogen balance and (for partial efficiency), estimating a given maintenance requirement without milk production or a catabolism without food.

The measurement of carbon and nitrogen balance in a lactating cow led to the results in terms of energy as shown in Table V. The Table illustrates the difference between the metabolizable and the catabolizable energy for lactation. This difference is especially obvious for the utilization of protein. A lack of clarity about this difference has led to confusing terms such as "corrected metabolizable energy."

One gm. of digestible protein may have 6 kilocalories metabolizable energy if it is converted to casein or body protein, but it has only 5 kilocalories catabolizable energy because in catabolism in the animal, about 20 per cent of the chemical energy of protein is lost as chemical energy of urine.

The mean partial efficiency for milk production can be calculated by subtracting the maintenance requirement from the metabolizable food energy or adding the basal metabolic rate to the energy in the daily milk, and then dividing by the metabolizable energy in the ration. This gives a ratio of total net energy (milk + maintenance) to total metabolizable food energy.

From the results given in Table V, total efficiency can be calculated.

Milk energy per day	6,060	kilocalories
Gain in body (this is a loss)	−1,340	kilocalories
Production effect of food	4,720	kilocalories
Metabolizable food energy	20,890	kilocalories
Total efficiency	$\frac{4,720}{20,890}$ 100 = 24%	

Estimate of mean partial efficiency:

Production effect of food	4,720	kilocalories
Basal metabolism estimated $70 \cdot W^{3/4}$	6,930	kilocalories
Production + maintenance effect of food	11,650	kilocalories
Mean partial efficiency of metabolizable energy	$\frac{11,650}{20,890}$ 100 = 56%	

EFFECT OF PROTEIN TO ENERGY RATIO ON EFFICIENCY FOR GROWTH OF CHICKS

That efficiency for growth, like that for milk production, depends on the protein to energy ratio of the ration, illustrated in Table VI. In this case the partial efficiency

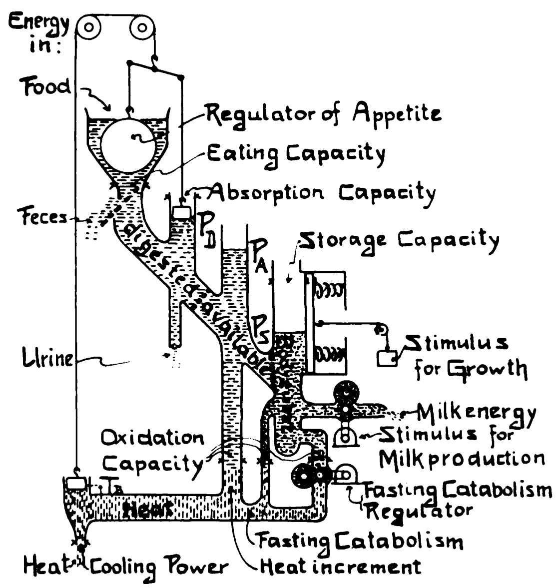


FIG. 2. Regulation of food intake.

decreases as the protein content of the ration increases. Again, what is measured is not partial efficiency because the trial is not a difference trial.

TOTAL EFFICIENCY AND FEED CAPACITY

The total efficiency is the ratio of gain over cost, or energy in product over food energy.

$$e_{tot} = \frac{G}{I}$$

G = energy in grain

I = energy in food

If the partial efficiency is independent of the plane of nutrition then the gain is proportional to that part of the food energy which is available for production. This relation may be formulated as follows:

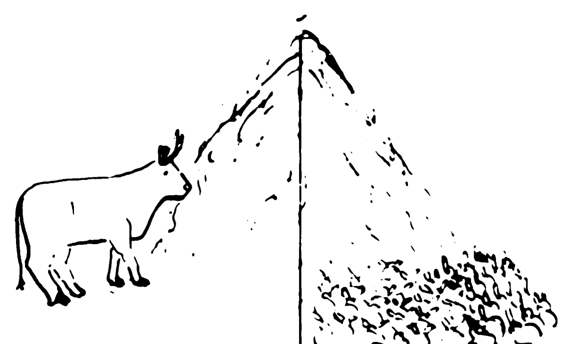
$$G = e_p(I - M)$$

where

e_p = partial efficiency
M = food energy required for maintenance G and I as defined above.

From that expression we can get the formulation of total efficiency as follows.

$$e_{tot} = \frac{G}{I} = \frac{e_p(I - M)}{I} = e_p - \frac{e_p \cdot M}{I}$$



Animals	1 steer	300 rabbits
Body weight total	1,300 lb.	1,300 lb.
Food consumption per day	16 2/3 lb.	66 2/3 lb.
1 ton of food lasts:	120 days	30 days
Heat loss per day	20,000 kcal.	80,000 kcal.
Gain in weight per day	2 lb.	8 lb.
Gain from 1 ton of food	240 lb.	240 lb.

FIG. 3. Food utilization versus body size.

TABLE VII
Utilization of Sun Energy for Animal Products

	Total Efficiency*		
	N/U (%)	U/S (%)	N/S (%)
Milk 1,200 lb. cow fed hay and beets 20 lb. milk per day 35 per cent partial efficiency	16	0.26	0.042
Pork quick fattening 40 to 220 lb. in twenty weeks potatoes, concentrates and silage	22	0.07	0.015
Eggs 50 eggs per 100 hens per day 10 Skandinavian feed units	4	0.05	0.002

* N = energy in animal product available for man; U = energy in animal feed; S = radiant energy from sun.

TABLE VIII
Area Yielding Food Energy for One Man Per Year*

	Efficiency (%)	Area Required	
		Square Meter	Acres
Algae (Warburg)	50	1	0.002
Potatoes	0.10	600	0.15
Grain	0.05	1,200	0.30
Prunes	0.04	1,500	0.37
Milk	0.04	1,500	0.37
Pork	0.015	4,000	1.0
Eggs	0.002	30,000	7.4

*Requirement: 10^9 calories per man year.
Flux density of sun's radiation in California: 1.6 × 10^9 calories per square meter per year.

The net energy for maintenance is $e_p \cdot M$, which is the amount of body energy saved by the maintenance food. This is the energy lost without food or the basal heat production. Thus, the equation is the following.

$$e_{tot} = e_p - \frac{B}{I}$$

The total efficiency of food utilization is greater the smaller the ratio, basalmet abolism/food intake, or the greater is the reciprocal, food intake/basal metabolism, which in an animal fed as much as it will eat may be called relative food capacity.

Food intake according to Adolph[6] is one of the best regulated animal functions.

Figure 2 shows an early, perhaps premature, attempt to present the interaction of various conditions affecting food intake.[7] The scheme is an attempt to integrate two major theories on regulation of food intake, the chemostatic[8] and the thermostatic[9] control of food intake.

FOOD UTILIZATION AND BODY SIZE

The total efficiency of animals can be expressed as the difference between the partial efficiency and the ratio of basal metabolic rate to rate of food intake (the reciprocal of relative food intake).

The partial efficiency is independent of the size of body as is the relative food capacity. Chicks and steers take in on the average from four to five times as much food energy as they lose from their body when they fast.[10]

We can therefore conclude that body size as such does not affect the efficiency of food utilization. Rabbits can be as efficient food utilizers as steers. Biologists know that the heat production per unit of body weight of small animals is greater than that of large animals. It appears, therefore, that small animals should waste more food energy per unit of time and therefore large animals should be more efficient.

The first part of the argument is correct but the conclusion is wrong as illustrated in Figure 3.

One ton of hay is fed to a steer weighing 1,300 pounds, and another ton of the same hay to 300 rabbits whose combined weight is also 1,300 pounds. The steer eats $16^2/_3$ pounds of hay per day, the rabbits $66^2/_3$ pounds of hay. Therefore, the ton of hay lasts 120 days for the steer and only thirty days for the rabbits. As expected from the law of body size and metabolic rate, the 300 rabbits produce daily four times as much heat as the steer. But the rabbits gain nearly four times as much body substance per day as did the steer. Therefore, the gain per ton of hay is the same for the steer (in 120 days) as for the rabbits in thirty days. The only difference is duration.

UTILIZATION OF SUN ENERGY FOR ANIMAL PRODUCTS

Table VII gives an estimate of the utilization of sun energy for milk, pork or egg production. The table is based on the estimated total efficiency of conversion of food energy to energy of the animal product. The next estimate is the energetic efficiency of plant production involved. In each case, the product of the two efficiencies is the total efficiency of conversion of sun energy to the energy of the animal product.

Table VIII gives an estimate of the area required to supply the food energy for one man for one year when he is satisfied with algae or depends on eggs alone for food.

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DISCUSSION

DR. HERVEY (*Sheffield, England*): I remember some work that was done in England during the war, when there was great enthusiasm for producing food, and people used to keep rabbits as part of their drive to win the war. One person kept some rabbits, and wore a Douglas bag during the time he was tending these rabbits. He compared the energy consumed in the extra work of looking after the rabbits with the energy which could be derived from eating them at the end of the process. He found that he used up about twice as much energy tending them as he received from them at the end of the period.

Does Dr. Kleiber know whether the steer is any better from that point of view than the three hundred rabbits?

DR. KLEIBER: Was this person a farmer?

DR. HERVEY: He was not.

DR. KLEIBER: He would have even a worse time with a steer.