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THE ENERGY COST OF CARRYING LOADS
IN PACK ANIMALS.

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A C K N O W L E D G E M E N T S

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Abbreviations used.

Carbon dioxide	CO ₂
Degrees of freedom	df
Endogenous urinary nitrogen	EUN
Figure	Fig
Gramme	g
Hour	hr
Joule	J
Kilogramme	kg
Kilojoule	kJ
Kilowatt	kW
Litre	l
Megajoule	MJ
Metabolisable energy	ME
Metre	m
Minute	min
Month	mth
Nitrogen	N
Oxygen	O ₂
Percent	%
Second	sec
Watt	W
Year	yr

A B S T R A C T

The energy cost of carrying loads, above that of walking unloaded, was measured in two Brahman cattle, two Water Buffaloes and an Exmoor pony. The animals walked on a treadmill and were fitted with a face mask connected to a gas analysis apparatus. The energy expenditure was calculated from their rate of oxygen consumption and carbon dioxide production.

The position of the load on the animal was found to have the most profound effect on the energy cost of carrying. For the Brahman cattle it was almost twice as economical to carry loads over the shoulders rather than over the back. Carrying loads over the shoulders of the Buffalo was more economical than carrying over the back, but not significantly so.

The influence of the walking speed was investigated and it was found that for the Brahman cattle and the Exmoor pony the energy cost of carrying loads tended to increase at higher walking speeds.

The Buffaloes were found to have a narrow range of effective walking speed around 1.0 m/sec.

The implications of the results to pack saddle design and the feed requirements of working animals are discussed.

GENERAL INTRODUCTION

There is no doubt that draught and pack animals will continue to play an important role in the agriculture and economy of many developing countries for some time to come. Indeed, following the rising concern in the world over the depletion of fossil fuel reserves, there has been a recent revival of interest in animals as a source of power for agriculture and general transport.

The importance of pack animals to the economy of many countries may be underestimated. Although not as efficient as the use of carts, they are of great value in mountainous or swampy areas where wheeled vehicles are impractical, or where roads are nonexistent or unsuitable for carts. Pack animals have the added advantage that they can manage with the barest minimum of harness, and may be used in areas where there are no craftsmen skilled in harness or cart making. Also, whereas each cart has to be handled by one man, a whole string of pack animals may be led over difficult terrain by one person.

Oil powered machines and vehicles are often too expensive or inappropriate to the needs of developing countries. Sophisticated agricultural machinery has often been introduced into countries where spare parts, fuel and maintenance services are scarce or unobtainable, and this has led to disappointment and economic hardship. Many countries where the land is traditionally tilled by human labour may now be contemplating the introduction of working animals into their agrarian structure instead of sophisticated machines. In order that they make most efficient use of these animals and to be able to predict their food requirements in advance, it is necessary to have at least a basic knowledge of their optimum requirements for work.

Whereas the energy expenditure for maintenance, growth, pregnancy and lactation have all been thoroughly investigated in most species

of large domestic animals, a detailed knowledge of the energy expenditure of working animals is sadly lacking.

This work is a contribution towards filling this gap of missing knowledge. It investigated the relationship between the rate of energy expenditure and the weight carried by pack animals, and how this relationship was effected by altering the position of the load and the walking speed.

Apart from being a unique physiological study, it has importance for calculating the energy requirements of pack animals, and as part of an overall attempt to quantify the nutritional requirements of draught animals.

The work involved designing and constructing suitable pack saddles for the experimental cattle, buffalo and pony, so that they could carry a range of weights while walking on a treadmill. Their rate of energy consumption was measured by employing the principle of indirect calorimetry, using a face mask and gas analysis.

With the ultimate aim of formulating a feeding system in mind, the main objective of the work was to derive a simple expression that related the the rate of energy consumption to the weight carried for each species. It soon became apparent that the most important factor affecting the rate of energy expenditure was not the species but the distribution of the load on the animal. Carrying weights over the shoulders was found to be more than twice as economical as carrying over the back. The Brahman cattle used during the experiment had the advantage that their hump is a useful anatomical structure over which a pack saddle can be worn. In contrast, the buffaloes would walk with their heads down low, and any load positioned over the shoulders tended to slip down the animals neck. There appears therefore to be a considerable difference in the efficiency of cattle and buffalo as pack animals, but this nearly reflects different distributions of the load.

I. Feeding of Working Animals.

There is little information available on the nutritional requirements for working animals, so rationing has, in the past, generally been by rule of thumb. Although this may be satisfactory in countries with a long tradition of stockmanship or in areas where grazing and feed is not in short supply, and does not need strict rationing, in many countries where working animals may be introduced, neither of these apply.

Now that knowledge is available regarding the work capacity of animals, it is possible to calculate the number of animals that will be needed for a particular amount of work. What is now required is a feeding system that can predict in advance the feed requirements of these animals.

The only attempt to date, at a feeding system for working bovines has been that suggested by the Ministère de la Coopération de la République Française. This system allocates feed according to the amount of work performed.

eg For a 300 kg bullock :

maintenance ration (M)	=	2.6 UF
total ration for light work	=	M + 1.4 UF
total ration for medium work	=	M + 2.6 UF
total ration for heavy work	=	M + 4.0 UF

where 1 UF = 1 forage unit equivalent to approximately 14 MJ ME

In general terms therefore, the requirements are :

for light work	$\frac{3}{2}$ M
for medium work	2 M
for heavy work	$\frac{5}{2}$ M

It is not stated how these values are obtained. The terminology in this system is vague and it is difficult to assess what constitutes light, medium or heavy work. It is also difficult to assess the number of light, medium or heavy days' work required in the course of the year and therefore the system is virtually useless for predicting the feed requirements in advance.

Feeding regimes recommended for working equines are equally vague. Miller and Robertson (1947) quote that working horses ought to be fed according to the amount of work they perform, but, they do not suggest any scale of feeding according to work.

Watson and Moore (1962) do attempt to quantify the amount of work that a horse may perform and allocate feed accordingly.

eg	Starch equivalent (lbs) per working hour per 1000 lb bodyweight
Light, slow work	$\frac{3}{4}$
Medium, slow work	1
Heavy, slow work	$1\frac{1}{4}$
Heavy, fast work	$1\frac{1}{2}$

Earlier work on the efficiency of working horses (Brody 1974) did reveal that they became less efficient at higher speeds of walking. This rationing system quoted by Watson and Moore takes this into account and allows extra feed for fast work.

The War Office Manual on Animal Management (1933) sets down guide lines for feeding working mules and oxen. It allocates feed according to the amount of work performed and also distinguishes between animals pulling loads and those carrying loads.

For example, the recommended feeding level for a 400 kg pack bullock, carrying a maximum load of 70 kg over a distance of 20 miles per day, at 2 - 2.5 mph, is as set out below.

Daily feed allowances for a 400 kg working bullock (Vet. Dept. of the War Office. 1933).

					Approximate daily intake of ME (MJ)	
	Draught animal	Pack animal	DM* (g/kg)	ME* (MJ/kg)	Draught animal	Pack animal
Barley	2.7 kg	1.8 kg	833	13.0	29.2	19.5
Green fodder	13.6 kg	9.1 kg	200	9.5	25.8	17.3
Bhusa (chopped straw)	6.4 kg	6.4 kg	860	6.5	35.8	35.8
					90.8	72.6

* estimated from : Nutrient allowances for cattle and sheep. 1978. Scottish Agricultural Colleges Publication 29.

The maintenance requirements of a 400 kg bullock are :

$$(0.091 \times 400) + 8.3 = 44.7 \text{ MJ/ME per day (M.A.F.F. Technical Bulletin 33. 1977)}$$

So this feed allowance is equivalent to twice maintenance allowance for draught work and 1.6 maintenance allowance for pack work.

According to the feeding scale of the Ministere de la Cooperation Republique Francaise (1980), this is sufficient only for light work in the case of a pack animal and medium work for a draught animal.

In all these feeding systems, the amount of work the animal may perform is only vaguely defined. In order to derive a more efficient feeding system for working animals, it is essential to quantify the amount of work performed, and then to investigate the energy requirements per unit of work.

II. Quantifying the Output of Working Animals.

The amount of work performed by animals hauling four wheeled carts over firm and level ground is a simple function of the force they work against and time. The force against which they act can be measured using strain gauges in the drawing shaft, and will depend on the weight of the load and the mechanical efficiency of the axles and wheel bearings. Since this latter value is fairly constant in any one design of cart, the work performed can be simplified to a function of load and time, or a function of load and distance covered, eg, kg metres or foot pounds.

For animals hauling two wheeled carts that are often out of balance, there is also a downward load on the shaft that must be overcome. Recent experiments in Madagascar have shown that locally manufactured two wheeled carts are totally out of balance because of the axle position. Even when empty, there was a downward force on the shaft of 75 kg, and when the driver sat on the special shelf at the front of the cart, the vertical load measured up to 125 kg (F.A.O. 1972) The work required to overcome the vertical load is a function of weight and time.

Animals pulling agricultural implements such as ploughs, are working against a force in a diagonal direction that can be resolved into vertical and horizontal vectors. The proportion of each will depend on the length of the shafts or harness trace.

Pack animals work against a vertical force and their work effort can be measured in terms of the weight carried and time.

This present study was concerned with investigating the energy cost of overcoming the vertical component of the work of draught animals as well as the energy requirements of pack animals.

III. The Energy Cost of Working Against a Horizontal Force.

In theory, there are three possible methods of measuring the energy cost of muscular work. Energy that is not converted to useful work is degraded to heat, therefore it is possible to use direct calorimetry methods involving heat production measurements on animals during work, but the practical and technical difficulties in applying these techniques to large domestic animals are enormous (Alexander and Goldspink, 1977). The most convenient and widely used method is indirect calorimetry, involving measurements of the exchange of respiratory gases and calculating the energy equivalent.

The third method is to measure the change in fuel content of the animal's tissues, but in the short term experiment, quite large errors will be incurred unless the changes in levels of certain intermediates of the metabolism are also measured. However, a similar technique was used by Emil Wolff (1888), (quoted by Kleiber, 1975), who measured the efficiency with which various feeds were used for sustaining the work of horses. He adapted the amount of work performed by the horses so that they maintained their body weight on different rations. He then calculated the amount of extra work that was required to keep the body weight stable when the dietary energy was increased by a set amount. He measured the work in metre tons, but his estimate of nutrient content of the feed was measured in grammes T.D.N. (Total Digestible Nutrients).

The increase in feed divided by the increase in work revealed the dietary requirement per unit of work. However, working with the T.D.N. system caused his results to vary according to the nature of the diet. For example, he found that :

- 2 g T.D.N. on a hay diet supported an extra 448 m tons work
- 1.5 g T.D.N. on an oat diet supported an extra 790 m tons work.

Wolff's most important conclusion therefore, was that the T.D.N. system of feed evaluation did not provide a proper comparison of the nutritive value of roughages and concentrates.

Max Klieber (1975) also quoted the work of Zuntz (1898) who conducted respiration trials with tracheotomised horses pulling loads while walking on a treadmill. He calculated the metabolic rate from the rate of oxygen consumption, using a value of 21 kJ per litre oxygen, which is the energetic equivalent for the oxidation of glucose.

He concluded that the horses expended approximately 35.6 J per kg metre of work, above that for standing at rest. Thus, the energetic efficiency of the work was approximately 28 %. (ie The energetic equivalent of 1 kg metre of work is about 10 Joules, therefore the efficiency of Zuntz's horses was $\frac{10}{35.6} \times 100 \% = 28 \%$). This value approximates to that derived by Brody (1974) and his group when they measured the work performance of horses pulling loads.

Brody used two techniques. He measured the work performance of horses pulling a load on a treadmill and estimated their energy expenditure from their rate of oxygen consumption. He also took his work into the field and measured the energy expended by a horse when pulling loads in an ergometer set in a trailer pulled by a car. The car also carried the gas analysis apparatus, and the walking speed of the horse was set by the speed of the car. In this manner, he hoped to investigate the effects of different ground conditions on the energy cost of pulling.

His results confirmed that the partial efficiency, ie. the energy expended, above standing at rest, per unit of work, was about 28 - 30 %. He also concluded that the gross efficiency, ie the total energy expended per unit of work, increased from 12.5 to 24 % as the rate of work increased from 0.5 horse power

to 2.0 horse power, and at a given horse power, the energetic efficiency was greater when pulling a large load at a slow speed compared with pulling a lighter load at faster speeds. This is not unexpected, since at increased rates of work, the energy required for maintenance and for walking is spread over a greater work output, and it is also known that as an animal walks faster, the more inefficient in energy consumption it becomes.

IV. The Energy Cost of Working Against a Vertical Force.

There is no information available relevant to the energy cost of carrying loads in domestic animals. The only data available concerning the energy cost of carrying, is in the field of human research, and there are obvious limitations in relating this information to four legged animals.

Most of the work in this field has been directed towards factory workers or active military personnel, to investigate means of reducing fatigue and increasing endurance.

In 1924 Bedale carried out a classic study on the efficiency of different methods of carrying loads. She, herself, acted as the subject, and measurements of energy expenditure were made, using a Douglas respiration bag and gas analysis techniques, while she walked 100 m, picked up a load, and returned with it at a speed of 1.26 m/sec. The loads were carried in 8 different positions. With the use of a yoke across the shoulders, the energy cost was minimal. If the load was carried under the arm, on the hip, the energy cost was maximal. Intermediate values were obtained when the load was carried in trays, hand bundles, on the head or over one shoulder. Some of her results are presented below.

Mode of carrying	Mean energy cost in excess of walking at the same speed (watts/kg)
Shoulder yoke	1.5
On head	4.1
In rucksack	4.2
On the hip	4.5

Bedale's results also show an increasing energy cost per kg carried as the overall weight carried increased, suggesting, that for some modes of carrying at least, the relationship between the weight carried and energy cost, is curvilinear. For example, carrying loads in a rucksack on the back, when the overall load was 22 kg, the rate of energy expenditure was 4.2 W/kg; when the overall load was 18 kg, then the rate of energy expenditure was only 3.5 W/kg.

Brezina and Kolmer (1912), quoted by Passmore and Durnin (1955), measured the energy expenditure of a young man walking while carrying loads in a knapsack high up on his back. The results agree well with those of Cathcart, Richardson and Campbell (also quoted by Passmore and Durnin 1955) who investigated the energy expended by soldiers wearing military equipment. They found that at slow speeds, the energy cost of carrying was not great, but as the speed increased, the energy cost rose rapidly. For example,

for a 68 kg soldier :

marching at 2mph with a 27 kg load,	the rate of energy consumption = 270 W
" " 3mph " " " " " " " "	= 370 W
" " 4mph " " " " " " " "	= 572 W

for a 70 kg soldier :

marching at 3mph, unloaded	the rate of energy consumption = 384 W
" " 3mph with a rifle (10kg) " " " " " "	= 453 W
" " 3mph + rifle & 12kg pack " " " " " "	= 558 W

From these results can be estimated the energy cost of carrying in excess of that required to walk unloaded, and it is found to be approximately 7.0 to 7.9 W/kg. This is even greater than the most uneconomical mode of carrying in Bedales experiment.

Comparing these figures to the energy cost of carrying in domestic animals has obvious limitations. A two legged animal has to spend a considerable proportion of its energy in maintaining its balance, and when carrying a load, the effort required will increase disproportionately according to the size of the load and how it is carried. Four legged animals do not have to spend such a large proportion of their energy output to maintain balance, and it may be expected therefore that their energy cost of carrying would be at least as economical as the most efficient means of carrying by a two legged animal.

M A T E R I A L S A N D M E T H O D S

I. The Theoretical Basis

When an animal is working at a steady rate, the energy it uses is derived, ultimately, from the oxidation of its food.

Quantitatively, the most important types of food molecules that are used for energy production are carbohydrates, fats and proteins, and the different compounds within each of these classes of foodstuff have almost the same empirical formulae and heats of combustion.

The amount of protein oxidised can be calculated from measurements of urinary nitrogen excretion, and the amounts of carbohydrate and fat oxidised can be calculated from the levels of oxygen consumption and the ratio of oxygen consumption to carbon dioxide production.

The data recommended by Brouwer (1965), Table 1, were used to derive a formula to predict the energy expenditure of an animal from its oxygen consumption, carbon dioxide production and urinary nitrogen output.

Table 1 Constants for protein, fat and carbohydrate when oxidised
in the animal body. (Brouwer 1965)

	O ₂ Consumed (litres)	CO ₂ Produced (litres)	Heat Production (kJ)
1g starch oxidised to CO ₂ and H ₂ O	0.83	0.83	17.6
1g fat oxidised to CO ₂ and H ₂ O	2.01	1.43	39.7
1g urinary N means 6.25g protein have been oxidised	5.98	4.83	115.0

If x g fat and y g carbohydrate are oxidised then:

$$\begin{aligned} \text{Total O}_2 \text{ consumed (E)} &= 2.01x + 0.83y \text{ litres} \dots\dots \text{i} \\ \text{Total CO}_2 \text{ produced (P)} &= 1.43x + 0.83y \text{ litres} \dots\dots \text{ii} \\ \text{Total heat produced (H)} &= 39.7x + 17.6y \text{ kJ} \dots\dots \text{iii} \end{aligned}$$

From equations i and ii can be derived expressions for x and y in terms of E and P . Substituting these expressions in equation iii then

$$H = 16.23E + 4.97P \dots\dots \text{iv} \\ \text{(Appendix 1)}$$

Using this equation to predict the heat produced from the oxidation of 6.25g protein:

$$\begin{aligned} H &= (16.23 \times 5.98) + (4.97 \times 4.83) \\ &= 121.06 \text{ kJ} \end{aligned}$$

This differs from its actual heat of combustion according to Brouwer's data by

$$121.06 - 115.0 = 6.06 \text{ kJ per g N in urine}$$

This factor is incorporated into the equation iv

$$\begin{aligned} H &= 16.23E + 4.97P - 6.06U \dots\dots \text{v} \\ \text{where U} &= \text{urinary nitrogen output (g)} \end{aligned}$$

However, if this is disregarded, the error is only minimal

eg Endogenous Urinary Nitrogen output (EUN) = $0.12 \times W^{0.73}$ g/day
(Nutrient Requirements of Farm Livestock. Agricultural Research Council 1965)

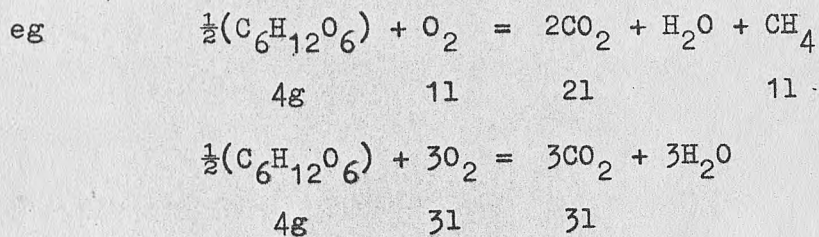
$$\begin{aligned} \text{For a 415 kg steer} \quad \text{EUN} &= 0.12 \times 81.5 \text{ g/day} \\ &= 9.78 \text{ g/day} \end{aligned}$$

$$\begin{aligned} \text{Therefore EUN error} &= 9.78 \times 6.06 \text{ kJ/day} \\ &= 59.3 \text{ kJ/day} \\ &= 0.0007 \text{ kJ/sec} \end{aligned}$$

From the experiment it was found that the total energy expended by 415 kg steer walking unloaded at 1.0 m/sec was approximately 1.2 kJ/sec

The error therefore is in the order of $\frac{0.0007}{1.2} \times 100 \% = 0.06 \%$

The relationship between respiratory exchange and heat production is further disturbed if the oxidation of fat or carbohydrate is incomplete. This occurs in ruminants when a proportion of the food is fermented to methane, but, in this case, for each litre of methane produced, the oxygen consumption is 2 litres less, and carbon dioxide production 1 litre less than if it had been completely oxidised to CO_2 and H_2O .



The apparent loss of energy therefore is

$$(16.23 \times 2) + (4.97 \times 1) = 37.43 \text{ kJ}$$

The increase in energy expenditure due to methane production is 39.5 kJ per litre methane. (Brouwer 1965).

A correction factor of $(39.5 - 37.43) = 2.07 \text{ kJ}$ must be subtracted from the total energy cost for each litre methane produced, in equation v.

ie $H = 16.23E + 4.97P - 6.06U - 2.07M \dots \dots vi$

where M = litres methane produced

But, again, if this factor is disregarded, the error is minimal.

eg 415 kg steer consuming 60 MJ ME daily

Approximate methane production = 200 litres/day

Therefore methane error = 2.07 x 200 kJ/day

= 414 kJ/day

= 0.0048 kJ/sec

Total energy expended by 415 kg steer walking unloaded at 1.0 m/sec is approximately 1.2 kJ/sec.

$$\text{Error therefore} = \frac{0.0048}{1.2} \times 100 \%$$

$$= 0.4 \%$$

Urinary nitrogen excretion and methane production are therefore not measured and equation iv was used in all calculations.

II. The Animals Used

Table 2 The animals

	Sex	Age	Weight
i Swamp buffalo (<u>Bubalis bubalus</u>) (Fig 1)	Castrate	46 mth	630 kg
ii Swamp buffalo (Fig 2)	Bull	33 mth	510 kg
iii Brahman cattle (<u>Bos indicus</u>) (Fig 3)	Castrate	40 mth	415 kg
iv Brahman cattle (Fig 4)	Heifer	40 mth	410 kg
v Exmoor pony 12 hands	Gelding	18 yr	326 kg

All the animals were in good health and well fed. The cattle and buffalo were housed and fed ad libitum medium quality hay, replaced at 9.00 am and 4.00 pm daily. The pony was grazed in a paddock near the centre and received 1 kg rolled oats daily. The animals were all used to being handled and were of fairly quiet temperament.

The buffalo and cattle had been used in previous experiments at this centre to determine the energy cost of walking and so were not entirely unfamiliar with the apparatus. The Brahman heifer had recently calved and during the experiment was in full lactation.

III. Training

During the experiment each animal had to walk on a treadmill

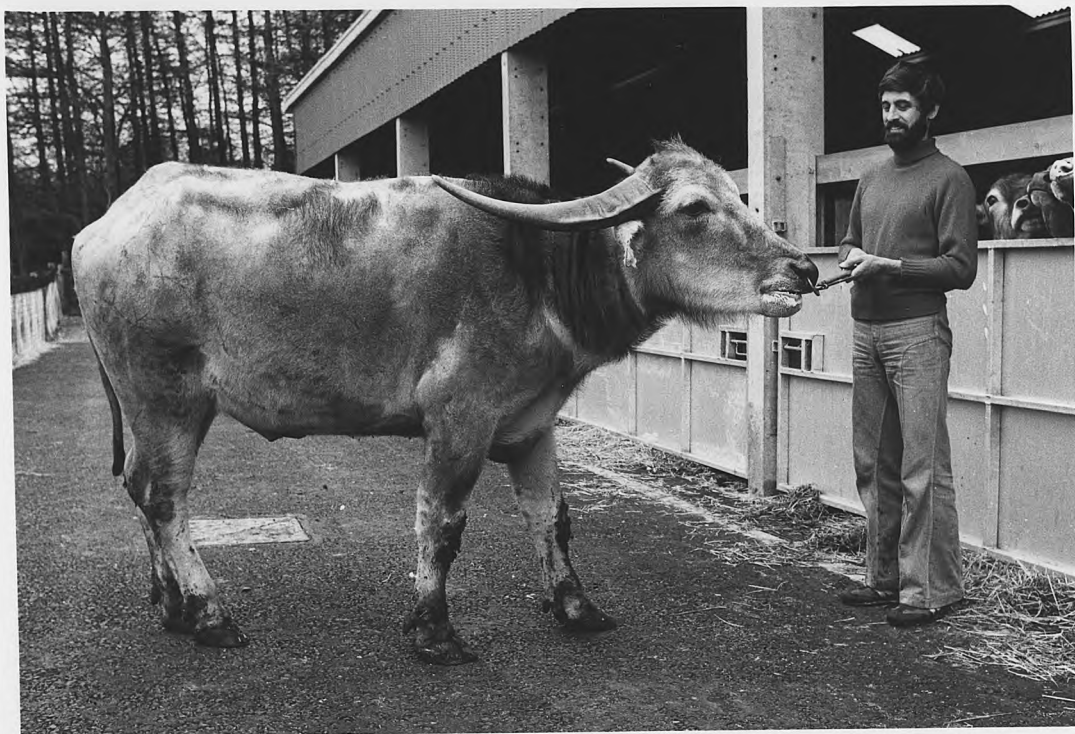


Figure 1. The Water Buffalo castrate.

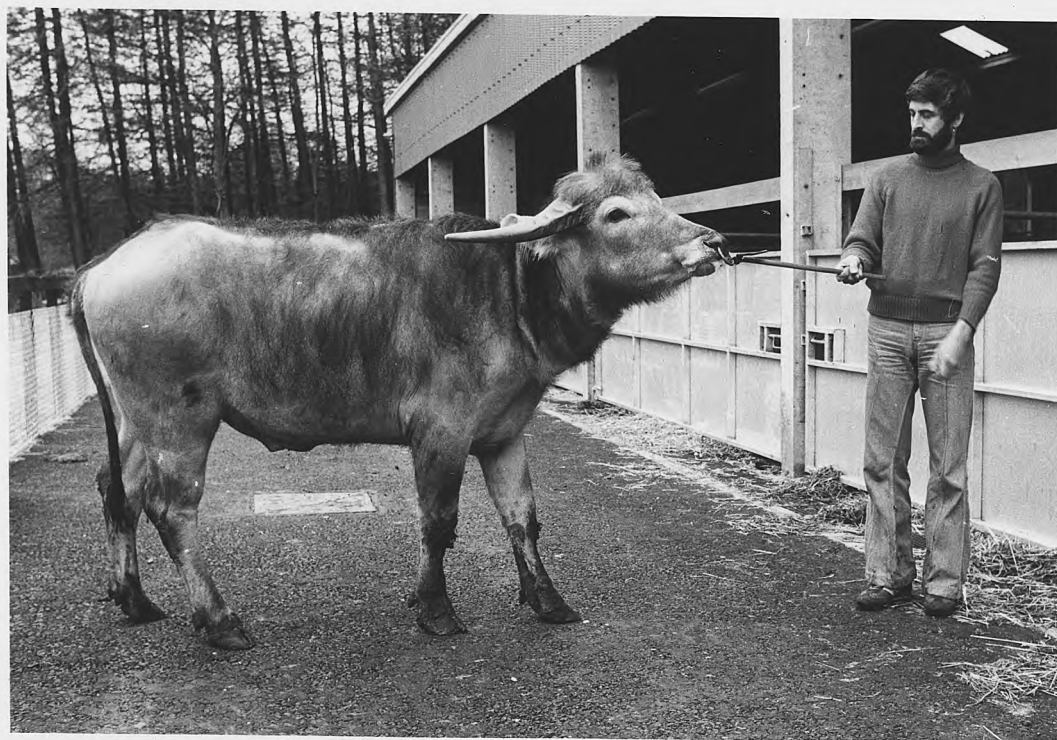


Figure 2. The Water Buffalo bull.



Figure 3. The Brahman steer.

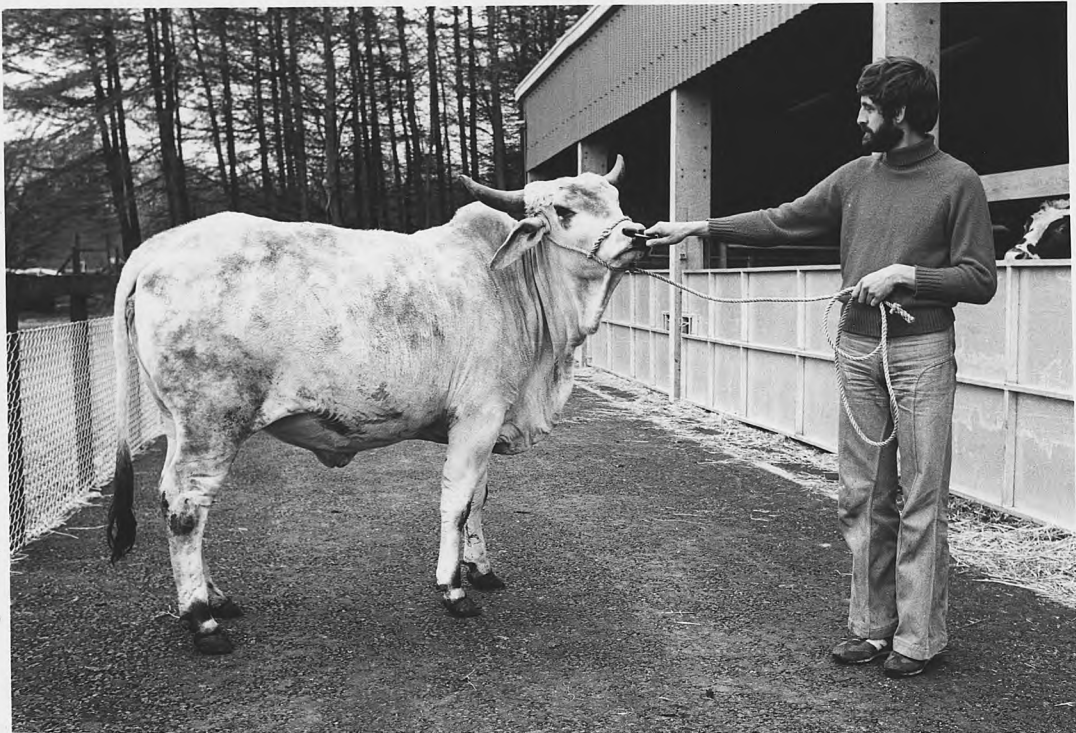


Figure 4. The Brahman heifer.

wearing a face mask, pack saddle and associated harness. It was found that nervous or excited animals expended much more energy and gave more erratic results than quiet and well trained animals. Great care was therefore taken to ensure that all the animals were thoroughly familiar with the apparatus and experimental routine.

Prior to the start of the experiment, each animal was saddled and led around the yard for half an hour every day. After 3 or 4 days when they no longer objected to being saddled, the animals were led on to the treadmill.

Once they had overcome their initial nervousness, they were saddled and the face mask put on and walked at a steady speed. Weights were loaded on to the saddle, 10 kg at a time, until the animal was carrying its maximum load.

A regular routine and gentle approach was used in the training of all the animals.

IV The Saddles

Three pack saddles were designed and constructed.

Saddle 1. Fig 5

Weighed 20 kg and was worn across the middle of the Brahman steer's back. It was secured with ^awebbing girth strap and surcingle.

Saddle 2. Figs 6 and 9

Weighed 22.5 kg and was worn by both buffalo across the middle of their backs. This, also, was secured by a webbing girth strap and surcingle.

Saddle 3. Fig 7

Weighed 20 kg and was worn by the Brahman steer and Brahman heifer. It was worn astride the animals hump over the shoulders,

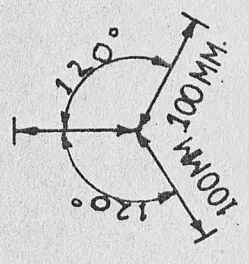
FIG. 5. BACK SADDLE FOR
BRAHMAN CATTLE.

MATERIALS:—

- MAIN FRAME — "DEXION 160"
- PADDING — FOAM RUBBER
- GIRTH STRAPS — JUTE WEBBING
- WOOD — 10 OR 25 MM. PLY

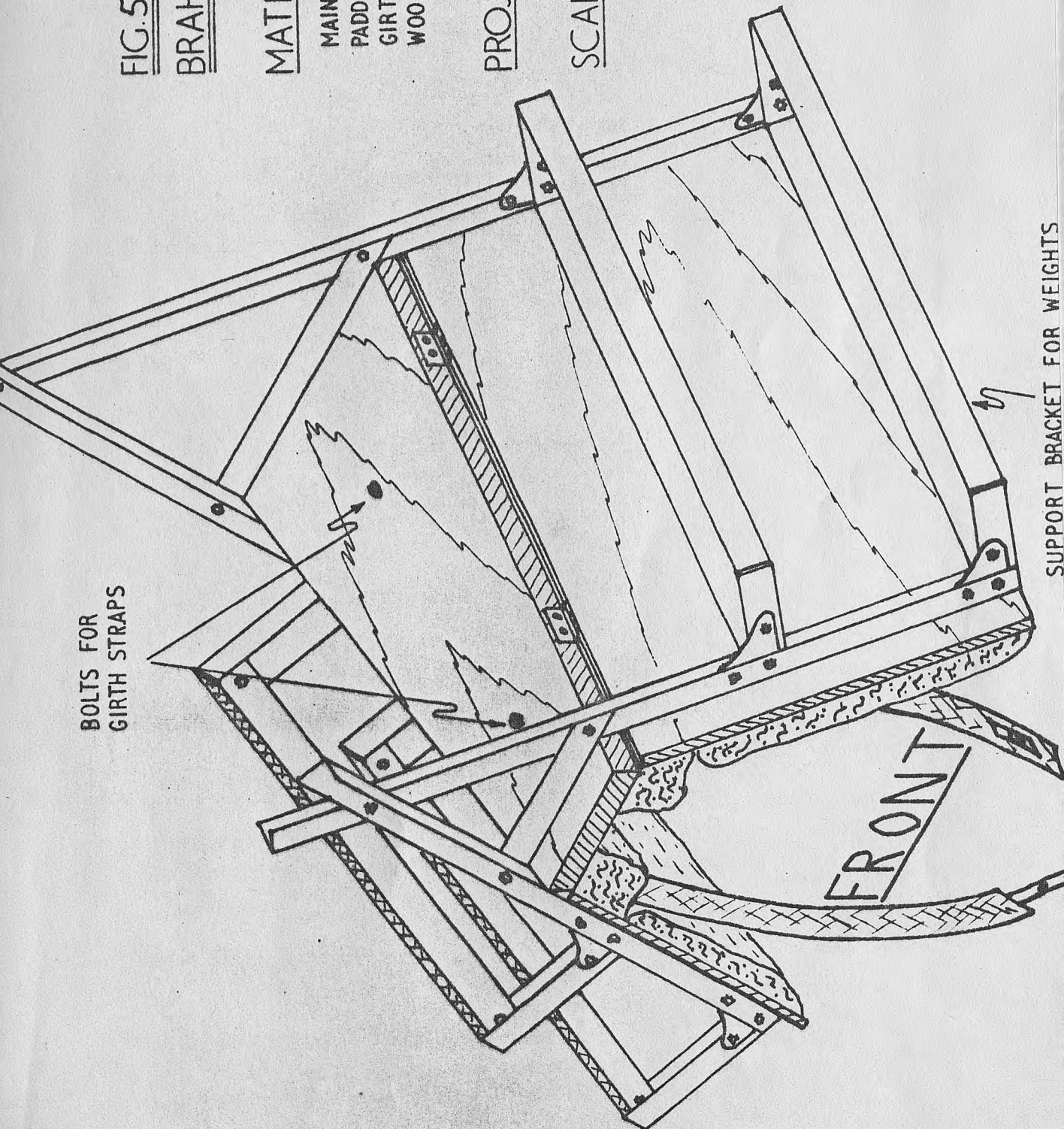
PROJECTION: ISOMETRIC

SCALE:



SCALE APPLICABLE
ALONG MAJOR AXES
ONLY.

SADDLE I



BOLTS FOR
GIRTH STRAPS

FRONT

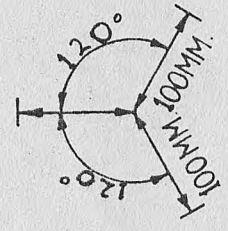
SUPPORT BRACKET FOR WEIGHTS

FIG. 6. BACK SADDLE FOR
BUFFALO.

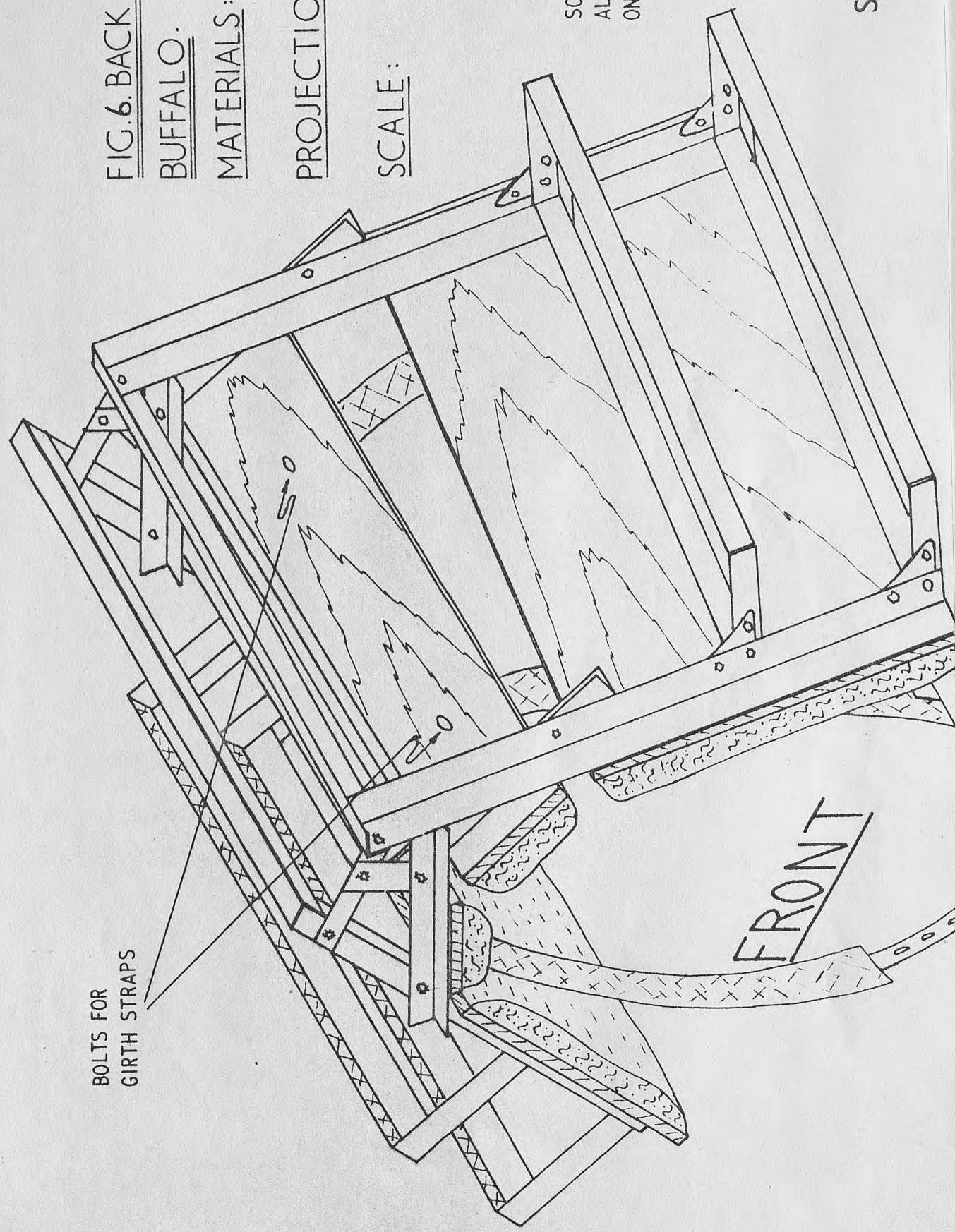
MATERIALS: AS FOR FIG 5.

PROJECTION: ISOMETRIC

SCALE:



SCALE APPLICABLE
ALONG MAJOR AXES
ONLY.



BOLTS FOR
GIRTH STRAPS

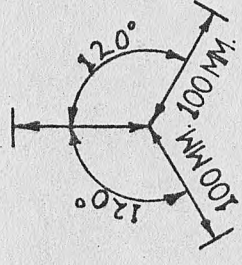
FRONT

FIG. 7. SHOULDER SADDLE FOR
BRAHMAN CATTLE / BACK SADDLE
FOR PONY.

MATERIALS : AS FOR FIG. 5.

PROJECTION : ISOMETRIC

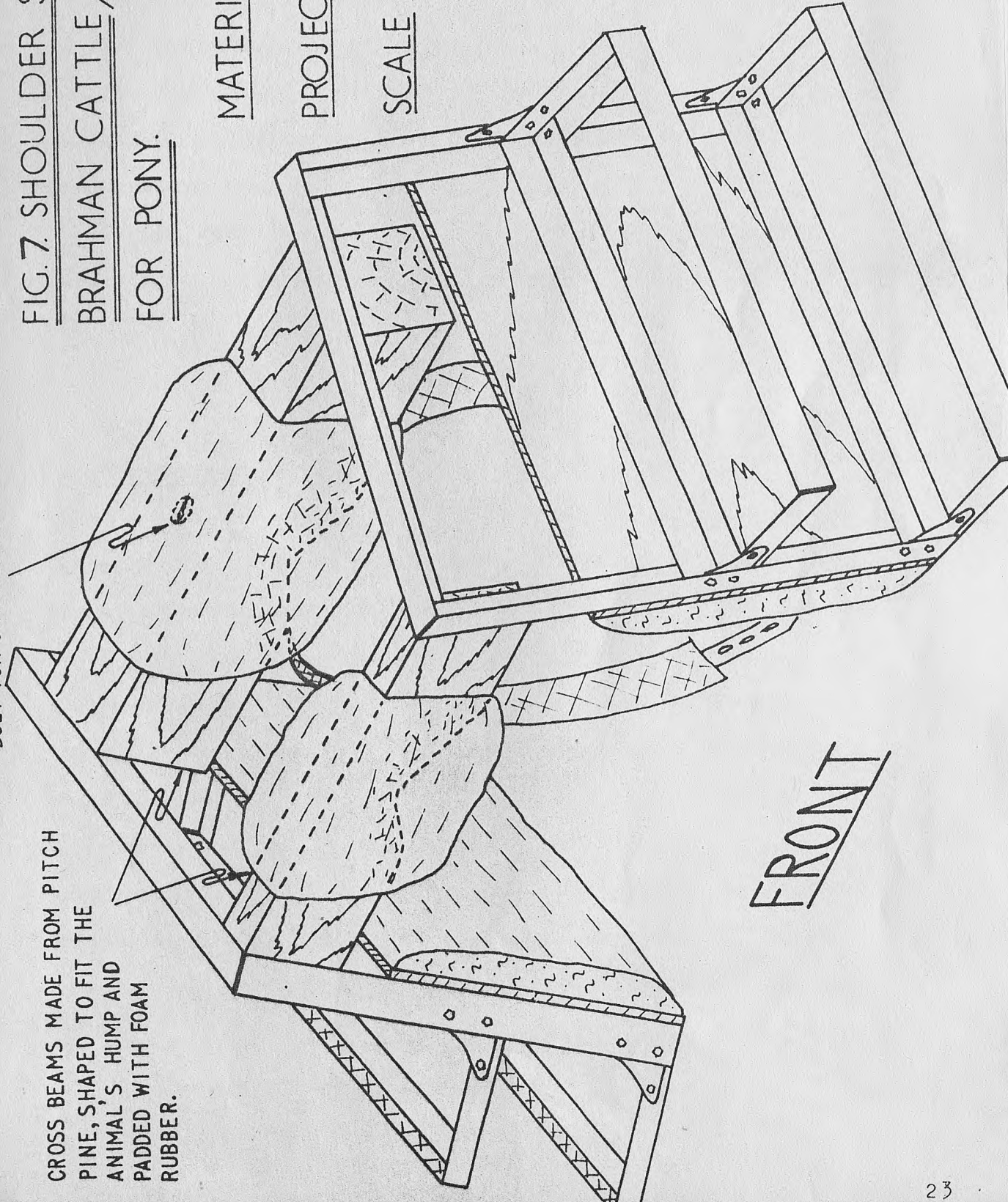
SCALE :



SCALE APPLICABLE
ALONG MAJOR AXES
ONLY.

BOLT FOR GIRTH STRAP

CROSS BEAMS MADE FROM PITCH
PINE, SHAPED TO FIT THE
ANIMAL'S HUMP AND
PADDED WITH FOAM
RUBBER.



FRONT

and was secured by a single girth strap. This saddle was also worn by the pony across his back.

Each saddle was constructed with a wooden top and sides held within a metal (Dexion) frame. Adjustment of the frame in saddles 1 and 2 enabled the width of the saddle to be adjusted in order to fit the animal as well as possible.

Every saddle was generously padded with foam rubber to make it fit more comfortably and to prevent saddle sores. The padding under the top platforms of saddles 1 and 2 lifted the saddles off the animals' spinal column so that its weight was transmitted through the padding on to the animals' ribs.

Dexion brackets along the sides of the saddles supported metal weights that were secured with string ties to the frame.

V. The Treadmills

Two separate treadmills were used. The larger one, used for the buffaloes, consisted of an endless belt of wooden slats, each 1.2 m x 150 mm x 25 mm, attached at either end to two endless chains. The links in the chain engaged with sprockets mounted on axils at the front and rear of the treadmills. The wooden slats were supported underneath by a bed of aluminium rollers. The area on which the animals walked measured 1.2 m wide x 3.6 m long.

The smaller treadmill was used for the cattle and the pony, and consisted of a plastic belt (Transilon 90 conveyor belt. Stephens Miralco Belts Ltd. Dukinfield, Cheshire) passing around 320 mm diameter rollers at the front and rear of the treadmill. The belt was supported on a bed of polished stainless steel. The total bed

area was 0.74 m x 3.0 m.

Both treadmills were driven by variable speed electric motors which were geared so that the speed of the belts could be set between 0 and 1.6 m/sec. The exact speed of each mill was measured using a stop watch and revolution counter.

VI The Gas Analysis Apparatus

The arrangement of the gas analysis equipment is illustrated in Fig 8. The exhaled air from the animal on the treadmill was drawn into the apparatus by a centrifugal pump via a face mask made from a plastic bucket padded around its open end with foam rubber. (Fig 9). The base of the face mask was coupled to a flexitrack ($1\frac{1}{2}$ " diameter) tube. This in turn was connected to the main pump via $1\frac{1}{2}$ " diameter plastic piping.

The airflow rate was regulated by a spigot top in front of the main pump. The flow rate was adjusted so that when the animals were working maximally, the carbon dioxide concentration or fall in oxygen concentration in the airstream did not exceed 1.0 %.

Usual flow rates were in the range 700 - 1000 l/min. This is 4 or 5 times the respiratory minute volume of the animals and so ensured that all exhaled air was drawn into the apparatus and not allowed to escape back around the sides of the face mask.

The airflow rate was measured using a Hasting mass flow transducer situated across a laminar ^{flow} element beyond the main pump. It measured the airflow rate to an accuracy of ± 5 l/min (ie ± 0.3 % full scale deflection) by the rate of heat extraction from a heated element.

After passing through the flowmeter, a small sample of air from

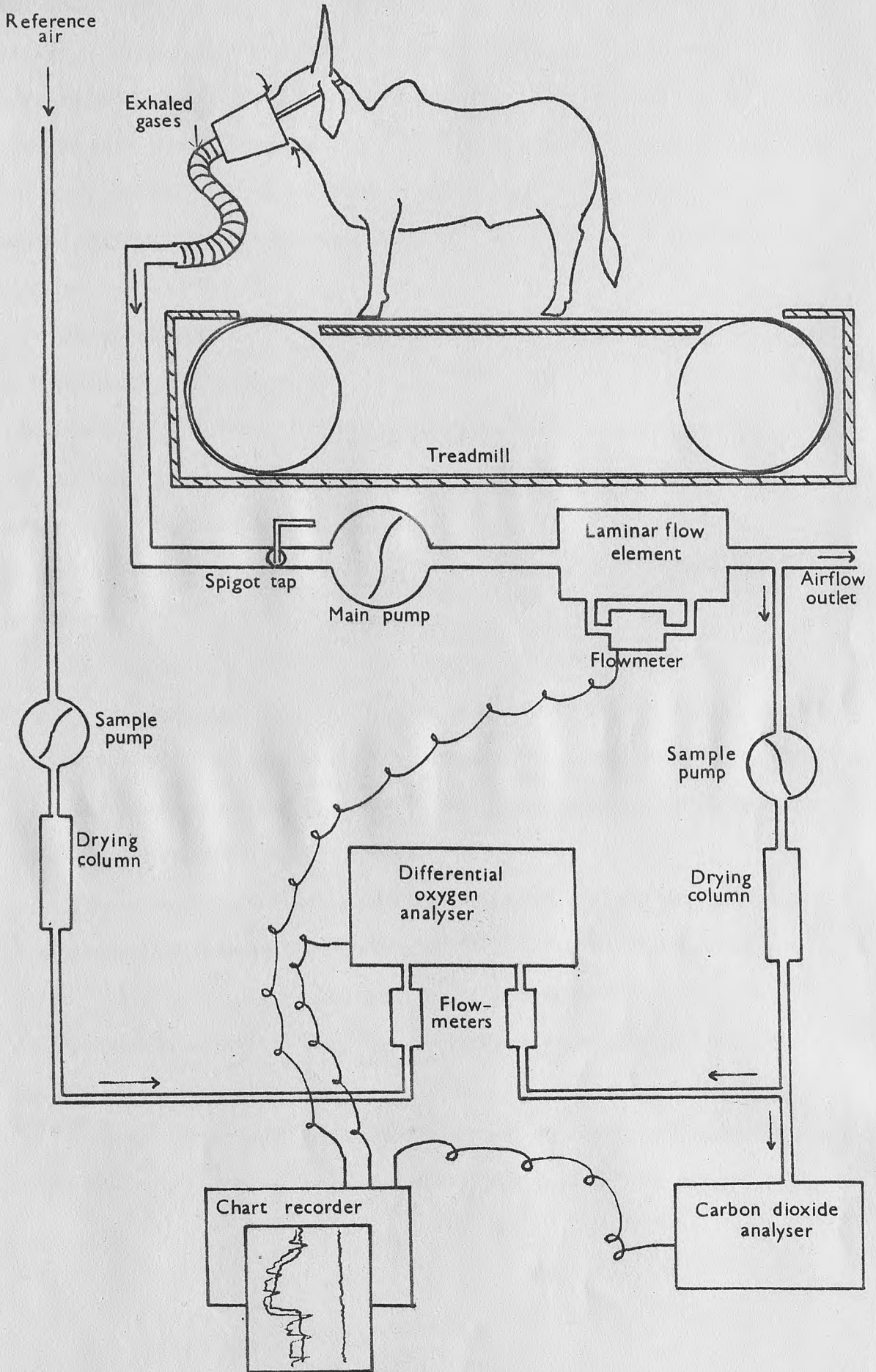


Figure 8. Arrangement of the gas analysis apparatus.

the face mask was extracted by a sample pump via narrow bore PVC tubing. This sampled air was dried in a column of magnesium perchlorate with silica gel indicator and then fed into a carbon dioxide analyser (Grubb Parsons IRGA 20 Infra Red gas spectrometer) at approximately 50 l/hr. This measured the percentage level of carbon dioxide in the sampled air, in the range 0 - 1.0 %, to an accuracy of ± 0.001 %.

A second portion of the sampled air was directed into a differential oxygen analyser (Taylor Servomex Model OA 184). Simultaneously, a sample of room air was fed via a second drying column and sample pump into the reference channel of the oxygen analyser. The flow rates, and hence pressures, of sampled and reference air were carefully equalised before they entered the analyser.

The oxygen analyser measured the percentage difference in oxygen concentration between sample and reference inputs by analysis of the paramagnetic properties of oxygen, to an accuracy of ± 0.001 %.

The drying columns were inspected regularly and the magnesium perchlorate replaced when required.

Measurements from the carbon dioxide and oxygen analysers were transferred to a chart recorder. A full scale deflection of the trace represented a 1 % carbon dioxide concentration or a 1 % difference in oxygen concentration between reference and sample channels.

The air flow rate was also monitored on the chart recorder in order to detect any unexpected variations during the experiment.

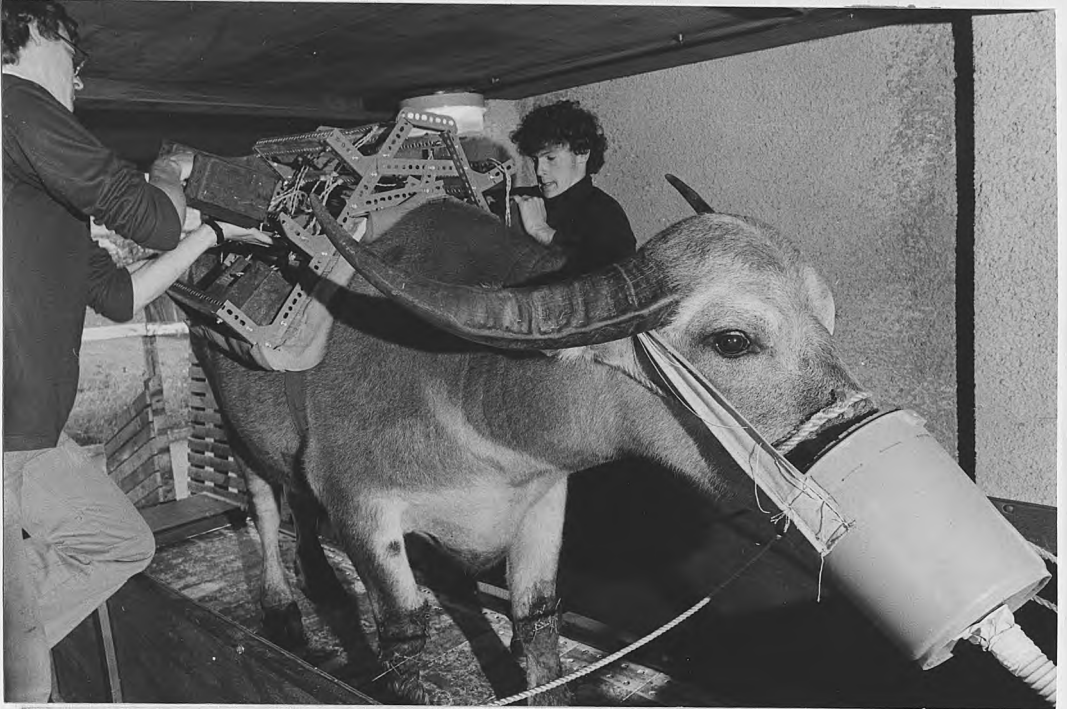


Figure 9. The Water Buffalo castrate on the large treadmill, wearing saddle 2 and the face mask.

VII. Calibration of the Apparatus

Before commencing each day's experiments, the main pump and the carbon dioxide analyser were switched on and allowed to warm up for two hours to reach a stable operating temperature. The oxygen analyser was left switched on permanently.

a Calibration of the carbon dioxide analyser. The carbon dioxide analyser was calibrated before each morning and afternoon's work. The scale was set to zero using a reference gas of 100 % nitrogen, and the span corrected using a calibration gas mixture (BOC) containing 0.83 % carbon dioxide in air. Simultaneously, the chart recorder trace base line and amplitude were corrected.

b Calibration of the oxygen analyser. The oxygen analyser was calibrated at least once a week or whenever it had been out of use for more than two days. 100 % nitrogen was fed through both reference and sample channels, and the readings adjusted to zero on both channels, as was the difference reading on the chart recorder. Dry fresh air was then passed through both channels and the corresponding span controls set to give meter readings of about 20.9 % on both channels, and a difference reading of zero on the chart recorder.

c Calibration of the flowmeter. The flowmeter was calibrated at the start and again towards the end of the experimental period.

A cylinder containing 100 % carbon dioxide was weighed to ± 5 g on a balance fitted with a hydrostatic tray. The gas analysis apparatus was prepared in the usual way and the airflow rate measured using the mass flowmeter. Carbon dioxide was then released from the cylinder for approximately ten minutes into the

face mask normally worn by the animals, at a rate sufficient to give a reading of 0.80 - 0.85 % on the carbon dioxide meter.

The amount of carbon dioxide released was found by reweighing the gas cylinder. This value was compared to the mass of carbon dioxide measured from the carbon dioxide concentration in the airflow, and the flowmeter reading.

The ratio $\frac{\text{measured mass CO}_2}{\text{weighed mass CO}_2}$ gave a correction factor used in

the calculations.

VIII. Calculation of Energy Expenditure from Trace Recording Measurements

The total energy expended by the animal was calculated from the formula $H = 16.23E + 4.97P$ kJ/sec

where E = oxygen consumption (l/sec)

P = carbon dioxide production (l/sec)

This formula has already been derived (Section I).

Fig 10 is an example of a typical trace obtained. The areas under the trace represent the rate of oxygen consumption and carbon dioxide production. This area was measured using a planimeter, and when divided by the time interval, gave the average concentration of gases over the experimental period. The peaks of carbon dioxide seen on the trace are most probably eructated gas of rumenal origin. Following each carbon dioxide peak is a small rise in the oxygen trace. This is due to dilution of the oxygen in the sampled air by the eructated gases, thus giving a greater difference in oxygen concentration between reference and sampled air.

Atmospheric carbon dioxide concentration was measured from the carbon dioxide trace base line (Fig 10) and this was subtracted from

the average concentration measured with the planimeter.

The average oxygen concentration was corrected for any drifting of the trace base line (Fig 10). Since measurements were of partial pressures, the average oxygen concentration was also corrected for atmospheric pressure.

The correction factor was $\frac{760}{\text{atmospheric pressure}}$

The atmospheric pressure was measured on a Fortin barometer at the start of each morning and afternoon's work.

The average concentration of carbon dioxide and oxygen, multiplied by the airflow rate (l/min) is the actual volume of gases produced or consumed.

The airflow rate was corrected for the temperature and relative humidity of the air passing through the flowmeter, and multiplied by the correction factor derived from the calibration trial. The airflow temperature and relative humidity were measured with a wet and dry bulb thermometer at the airflow outlet.

The results are presented in terms of the absolute energy cost of carrying loads. This is defined as : the total energy expended whilst carrying loads, minus, the energy expended in walking unloaded during that particular trial. Difference measurements, of this type, help to nullify the variations in metabolic rate caused by factors such as level of feeding, lactation, nervousness etc. The actual values of the resting metabolic rate and the energy cost of walking in these particular animals have already been measured in previous experiments. (Lawrence 1980).

51804

START WALKING

MASK ON, STANDING STILL

FACE MASK OFF

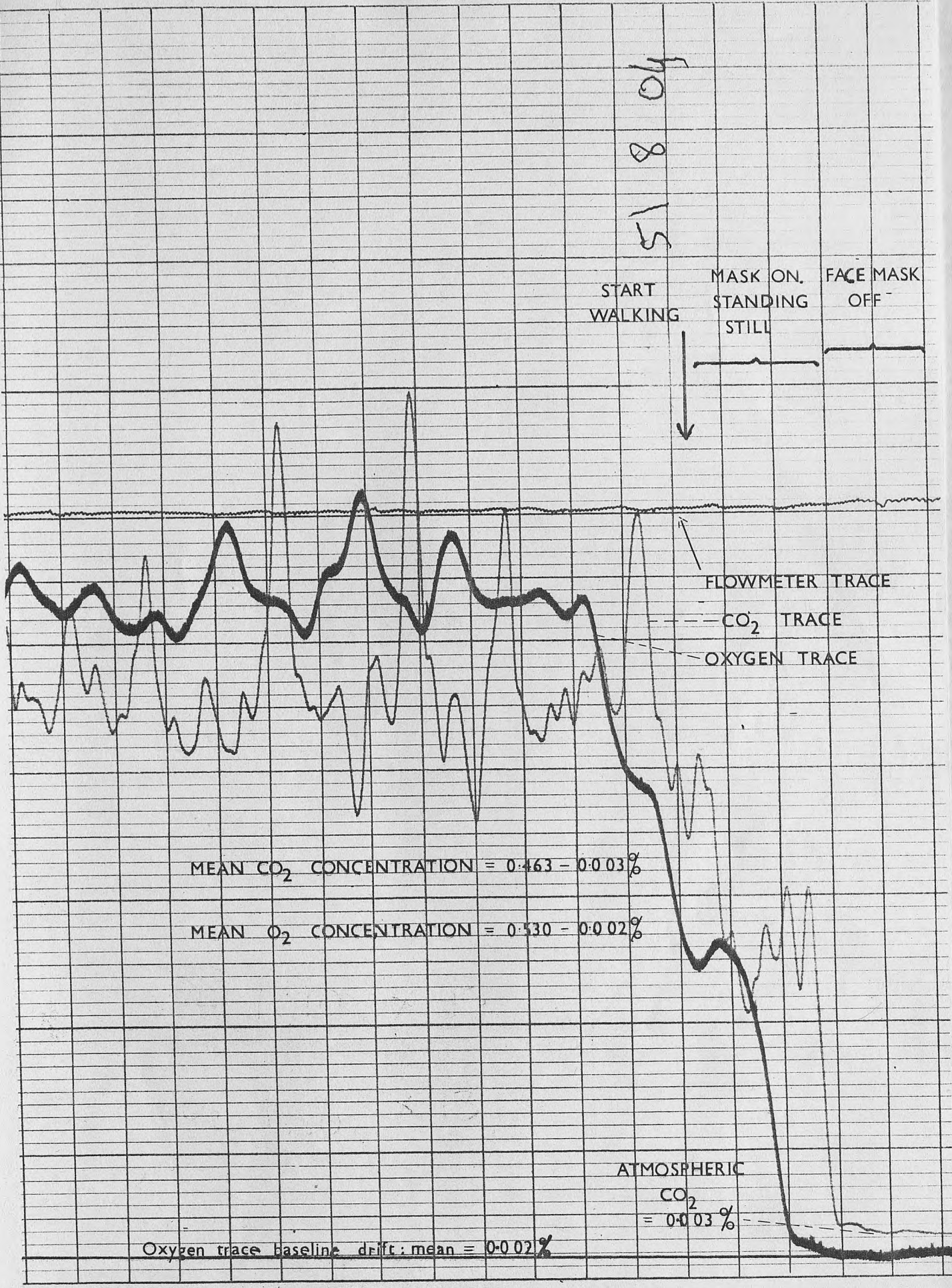


Figure 10. An example of the trace from the chart recorder.

In this case, the Brahman heifer carrying 40 kg

IX. Experimental Design and Procedure.

The work was conducted at the Centre for Tropical Veterinary Medicine, Roslin, Edinburgh during July and August 1980.

The estimates of energy expenditure were made between 11.00 am and 12.30 pm, and between 2.00 pm and 4.00 pm each day.

For each load at each speed, the animal walked for approximately 10 minutes while measurements of energy expenditure were made.

The loads, speed of walking and sequence of measurements were as shown in Table 3.

Table 3 The measurements taken.

Animal	Saddle number	Walking speed (m/sec)	Number of trials	Loads and sequence of loading (kg)							
Brahman steer	1	1.0	3	0	50	70	40	20	0		
	3	0.8	3	0	50	70	60	40	20	0	
	3	1.0	3	0	50	70	60	40	20	0	
Brahman heifer	3	1.2	3	0	50	70	60	40	20	0	
	3	0.8	3	0	50	70	60	40	20	0	
	3	1.0	3	0	50	70	60	40	20	0	
Buffalo bull	3	1.2	2	0	50	70	60	40	20	0	
	2	0.8	1	0	52.5	72.5	62.5	42.5	22.5	0	
	2	1.0	4	0	52.5	72.5	62.5	42.5	22.5	0	
Buffalo castrate	2	1.2	1	0	52.5	72.5	62.5	42.5	22.5	0	
	2	0.6	1	0	52.5	92.5	72.5	42.5	22.5	0	
	2	0.8	1	0	52.5	92.5	72.5	42.5	22.5	0	
	2	1.0	4	0	52.5	92.5	122.5	72.5	42.5	22.5	0
	2	1.2	1	0	52.5	92.5	72.5	42.5	22.5	0	
Pony	-	1.0	1	0	52.5	92.5	72.5	42.5	22.5	0	
	3	0.8	2	0	70	50	40	20	0		
	3	1.0	4	0	70	50	40	20	0		
	3	1.2	2	0	70	50	40	20	0		
Man(69kg)	-	1.3	1	0	10	20	30	40	0		
Man(85kg)	-	1.3	1	0	10	20	30	40	0		

For the purpose of comparison with the animals and with previous work on the energy cost of carrying in people, the rate of energy consumption of two men was measured whilst they carried loads of 10 - 40 kg on the treadmill.

Measurements were also made of the rate of energy consumption by the Buffalo castrate when carrying loads suspended over his shoulders on a foam rubber pad. This arrangement, however, proved unsatisfactory and only one trial was completed.

The final measurement of each trial with the animals walking unloaded was used as the base line for calculation of the absolute energy cost. The first measurement made whilst the animals settled down to the days work was a less accurate estimation of the energy cost of walking.

RESULTS

I. Introduction

Measurements of energy expenditure were made on all five animals while walking at speeds of 0.8, 1.0 and 1.2 m/sec and carrying loads of 0 - 70 kg. In addition, measurements were made on the larger of the two Water Buffalo at 0.6 m/sec and with loads up to 120 kg. When, from the results of the Brahman steer, it became apparent that the position of the load influenced the rate of energy consumption, then one set of measurements were taken with weights slung over the shoulders of the Buffalo castrate (Table 3) to see if this also reduced the energy cost.

The results are all in terms of the absolute energy cost of carrying (Method Section IV) and presented in units of watts (W) and watts per kg carried (W/kg) which are more convenient expressions of the rate of energy consumption than kJ/sec.

$$1 \text{ kJ/sec} = 1 \text{ kW} = 1000 \text{ W}$$

II. Results from the Individual Animals.

a Brahman steer

Position of the load. The position of the load on the animal was found to have a profound effect both on the rate of energy consumption (Fig 11) and the ability of the animal to carry loads.

When the load was placed in the middle of the animal's back using saddle 1 (Fig 5), any given load caused the animal to use about twice as much energy as when the load was placed over the shoulders in saddle 3 (Fig 7). Also, the steer resented carrying loads in excess of 40 kg using saddle 1 but appeared quite

- Carrying over the back in saddle 1.
- Carrying over the shoulders in saddle 3.

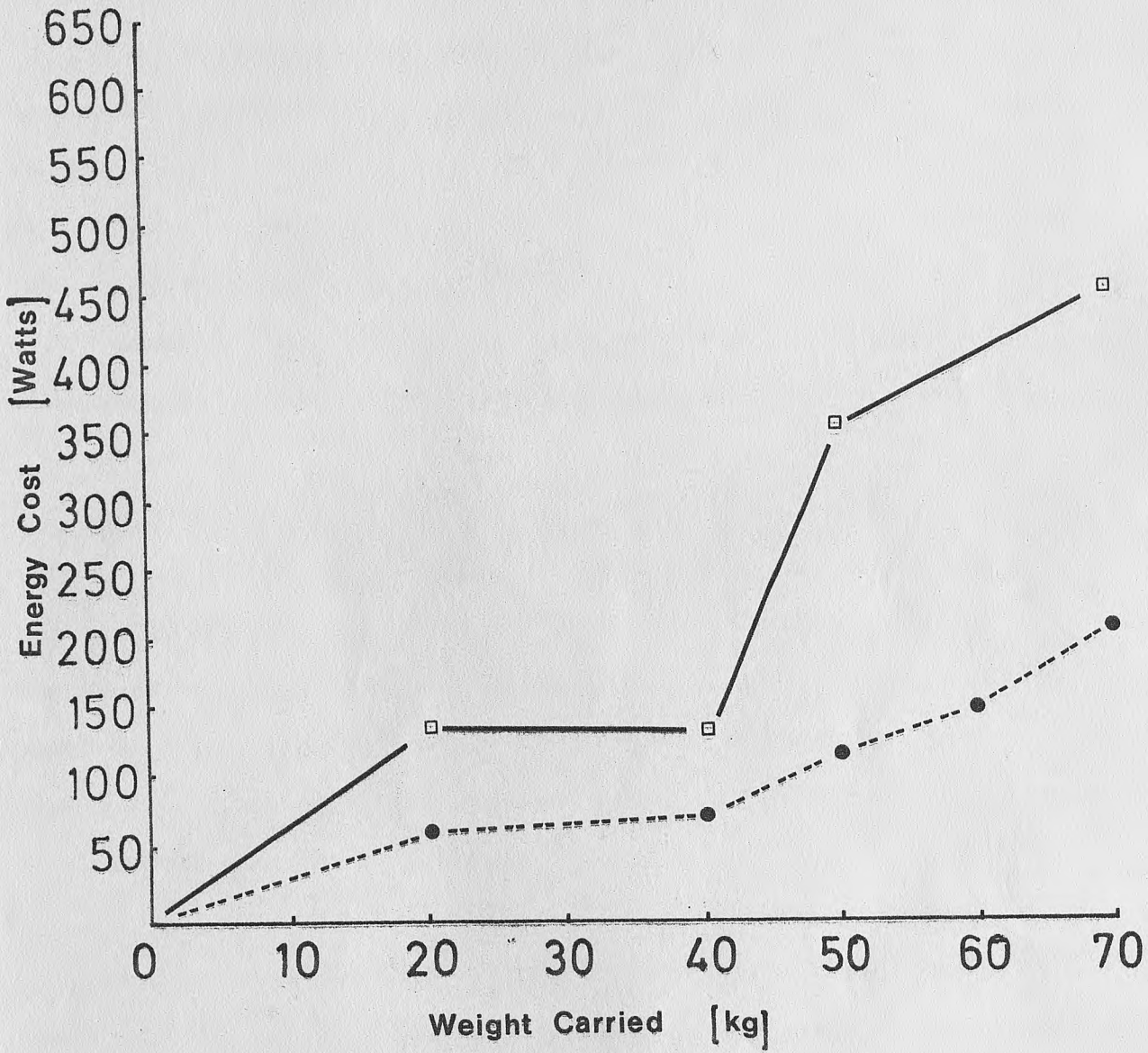


Figure 11. The Brahman steer. The absolute energy cost for carrying loads over the back or shoulders while walking at 1.0m/sec. Each point is the mean of 3 measurements.

comfortable when carrying loads of 70 kg with saddle 3. I felt that he would willingly have carried more using this saddle, but 70 kg is the maximum load recommended for an animal of his weight. (Veterinary Department of the War Office 1933. UFAW Handbook 1975).

An approximately linear relationship (Table 13) was obtained between the weight carried and the rate of energy consumption. Average values of 5.91 and 2.64 W/kg were obtained for carrying with saddles 1 and 3 respectively, both at a walking speed of 1.0 m/sec. This difference was highly significant at $P < 0.001$. ($t = 5.15$ & 11 df)

Because it had proved so much more efficient, all subsequent measurements on the two Brahman cattle were made using saddle 3 only.

Effect of walking speed on the energy cost of carrying. The rate of energy consumption tended to be higher at the higher walking speeds (Fig 12) but this difference only reached significance in one case (ie carrying 60 kg at 0.8 and 1.2 m/sec). However, the mean energy cost per kg carried taken over all the weights did show a significant difference between 0.8 and 1.2 m/sec at $P < 0.05$ ($t = 2.799$ & 14 df).

At each speed there was an approximately linear relationship between the rate of energy consumption and weight carried. (Table 13). Table 4 illustrates the mean rate of energy consumption at each speed.

Table 4 Rates of energy consumption per kg carried by the Brahman steer at various walking speeds.

Speed (m/sec)	Rate of energy consumption(W/kg)	Number of observations	Standard error
0.8	2.16	15	± 0.172
1.0	2.64	15	± 0.193
1.2	2.84	15	± 0.173
Average of all speeds	2.55	45	± 0.109

- - - - ■ Walking speed 0.8 m/sec.
- — — □ Walking speed 1.0 m/sec.
- △ - - - △ Walking speed 1.2 m/sec.

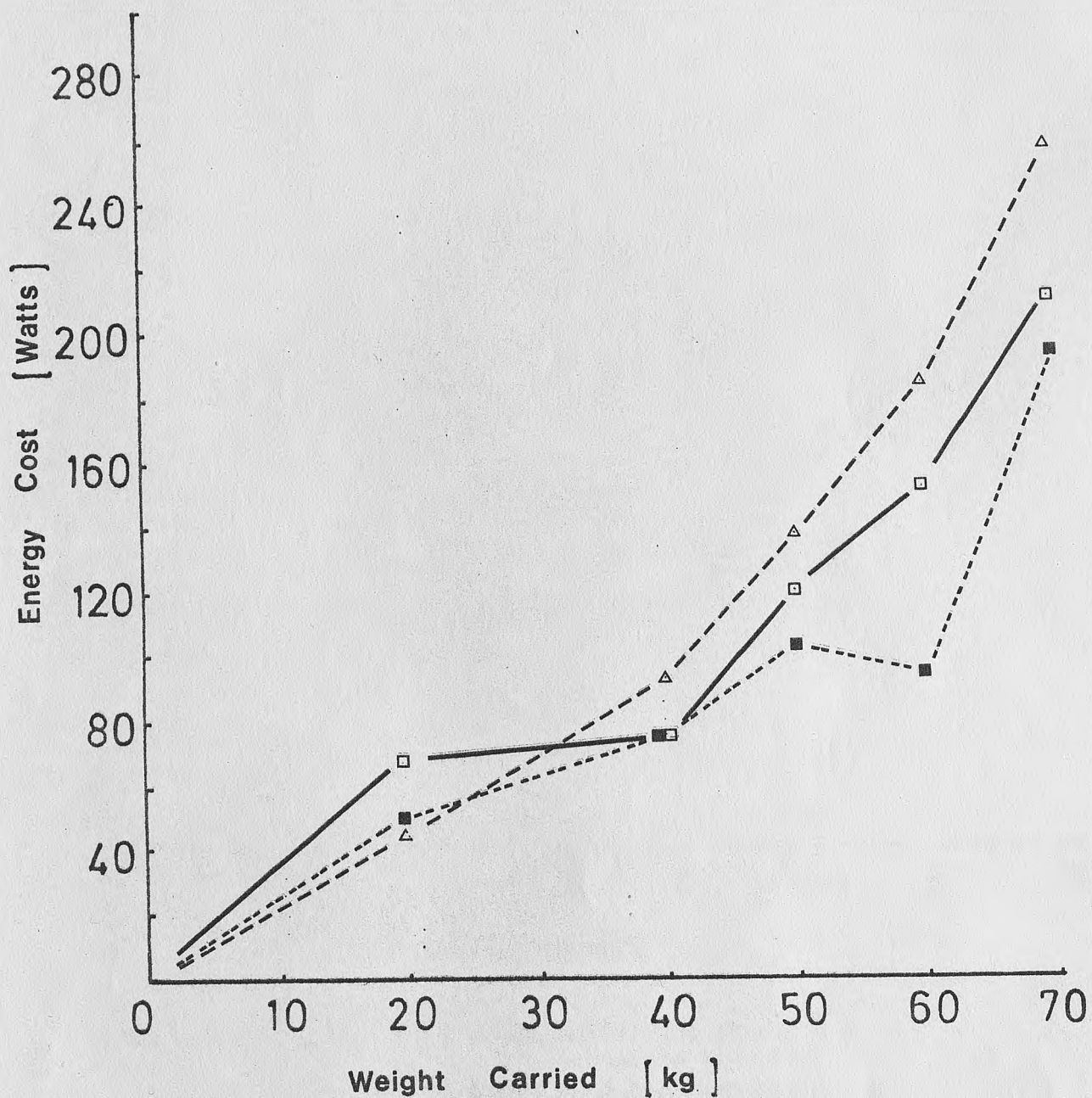


Figure 12. The Brahman steer. The absolute energy cost of carrying loads over the shoulders, using saddle 3, at different walking speeds. Each point is the mean of three measurements.

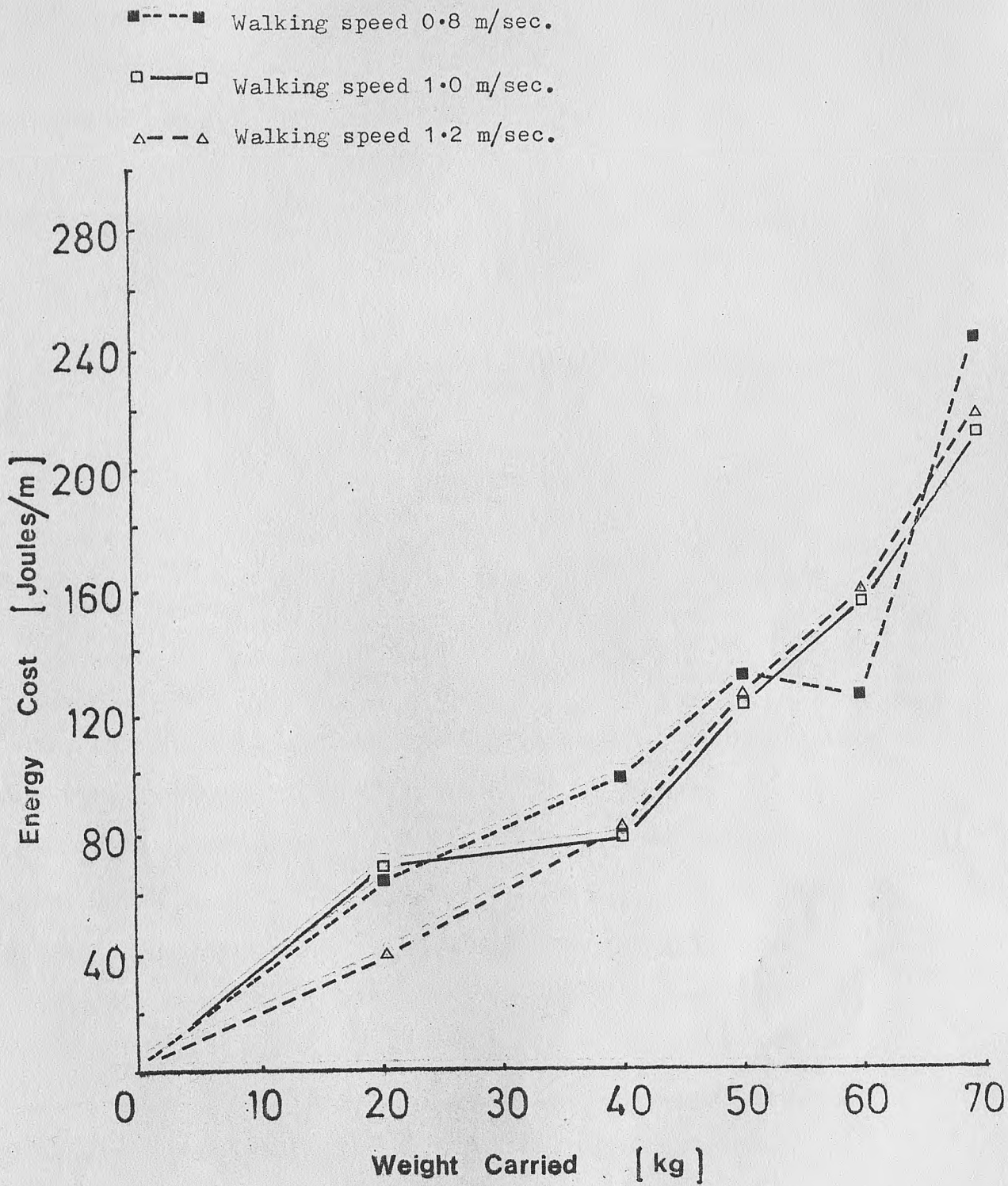


Figure 13. The Brahman steer. The absolute energy cost of carrying per metre travelled. Each point is the mean of 3 measurements.

When the energy expended per metre travelled was calculated the differences between the speeds was reduced to non significant levels (Table 5), but it became apparent that the energy cost per metre declined as the animal walked faster. (Fig. 13).

Table 5 Average energy consumed by the Brahman steer to carry 1 kg a distance of 1 metre.

Speed (m/sec)	Energy consumption. Joules per kg carried per m walked.	Number of observations	Standard error
0.8	2.70	15	\pm 0.209
1.0	2.64	15	\pm 0.193
1.2	2.37	15	\pm 0.144
Average of all speeds	2.57	45	\pm 0.107

b Brahman heifer

Measurements were made using saddle 3 only. As for the steer, there was a tendency for the rate of energy expenditure to be higher at the faster speeds of walking (Fig 14). There was a highly significant linear relationship between the rate of energy consumption and the weight carried at each speed (Table 13).

The mean energy cost per kg carried showed a significant difference between the values at 0.8 and 1.2 m/sec, $P < 0.05$ ($t = 2.420$ & 14 df), (Table 6), although the only significant differences between the corresponding loads carried, are between 0.8 and 1.2 m/sec when carrying loads of 60 and 70 kg.

As for the Brahman steer the energy cost per metre travelled was not altered significantly by the walking speed, but the results do suggest that the slower the animal walked, the less economical it became (Table 7 & Fig 15).

- - - - ■ Walking speed 0.8 m/sec.
- - - - □ Walking speed 1.0 m/sec.
- △ - - - △ Walking speed 1.2 m/sec.

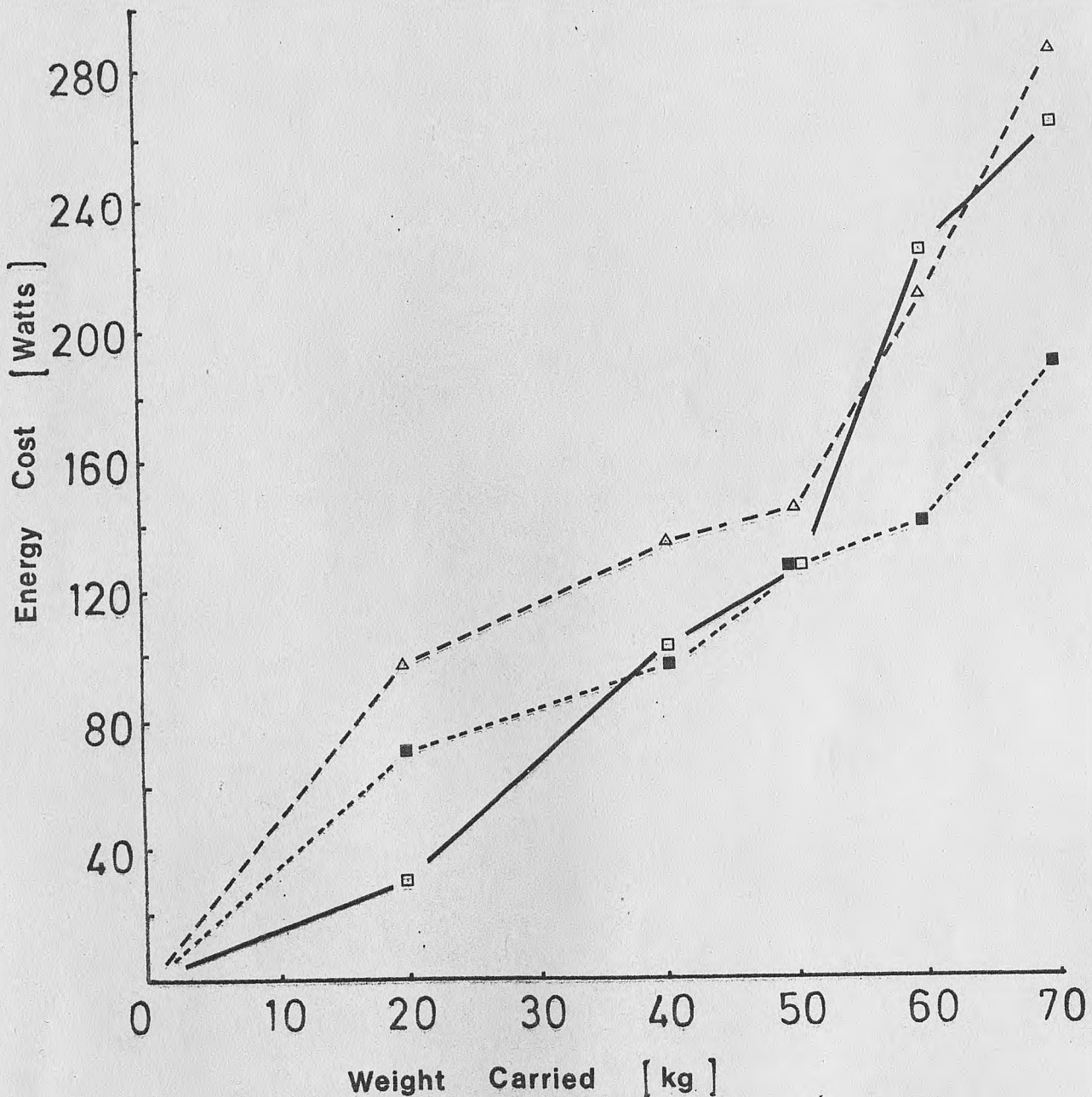


Figure 14. The Brahman heifer. The absolute energy cost of carrying loads over the shoulders, using saddle 3, at different walking speeds. Each point at 0.8 m/sec and 1.0 m/sec is the mean of 3 measurements. Each point at 1.2 m/sec is the mean of two measurements.

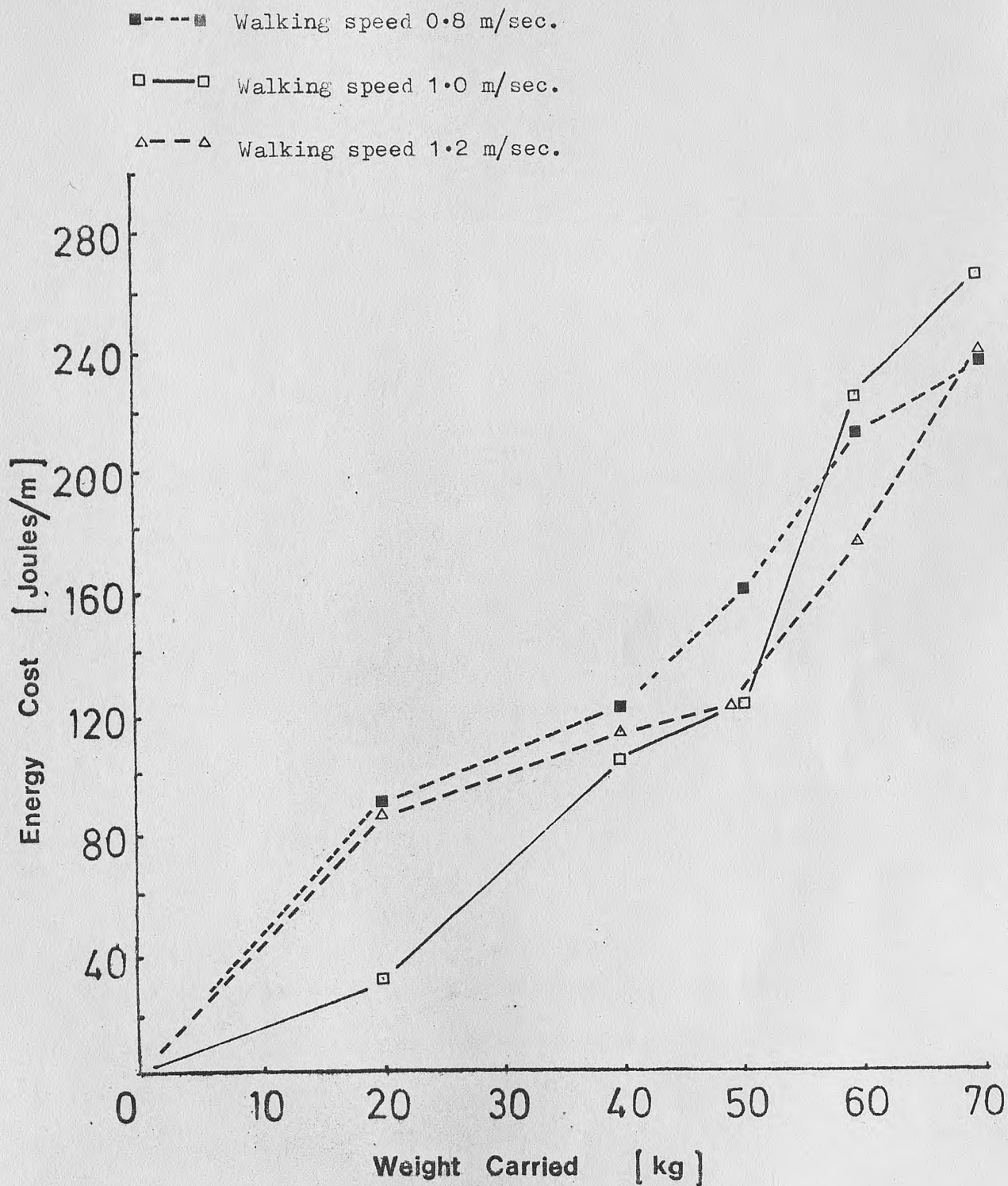


Figure 15. The Brahman heifer. The absolute energy cost of carrying per metre travelled. Each point is the mean of 3 measurements at 0.8 & 1.0 m/sec. At 1.2 m/sec each point is the mean of 2 measurements.

Table 6 Rates of energy consumption per kg carried by the Brahman heifer at various walking speeds.

Speed (m/sec)	Rate of energy consumption (W/kg)	Number of observations	Standard error
0.8	2.78	15	± 0.223
1.0	2.95	15	± 0.348
1.2	3.76	10	± 0.338
Average of all speeds	3.04	40	± 0.181

Table 7 Average energy consumed by the Brahman heifer to carry 1 kg 1 metre.

Speed (m/sec)	Energy consumption. Joules per kg carried per m walked.	Number of observations	Standard error
0.8	3.48	15	± 0.278
1.0	2.95	15	± 0.348
1.2	3.132	10	± 0.282
Average of all speeds	3.143	40	± 0.179

c Buffalo bull.

Most of the measurements with this animal were made at a walking speed of 1.0 m/sec, and the data obtained are included in Fig 16. At this speed there was a significant linear relationship between the rate of energy consumption and the weight carried (Table 13). The average rate of energy consumption per kg carried was 3.7 W/kg at this speed.

Effect of walking speed on the energy cost of carrying. It became evident during the experiment that the Buffalo have a very narrow range of effective walking speeds when loaded with a pack saddle. Attempts to measure the bull's metabolic rate at speeds

- - - - ■ Walking speed 0.8 m/sec.
- — — □ Walking speed 1.0 m/sec.
- △ - - - △ Walking speed 1.2 m/sec.

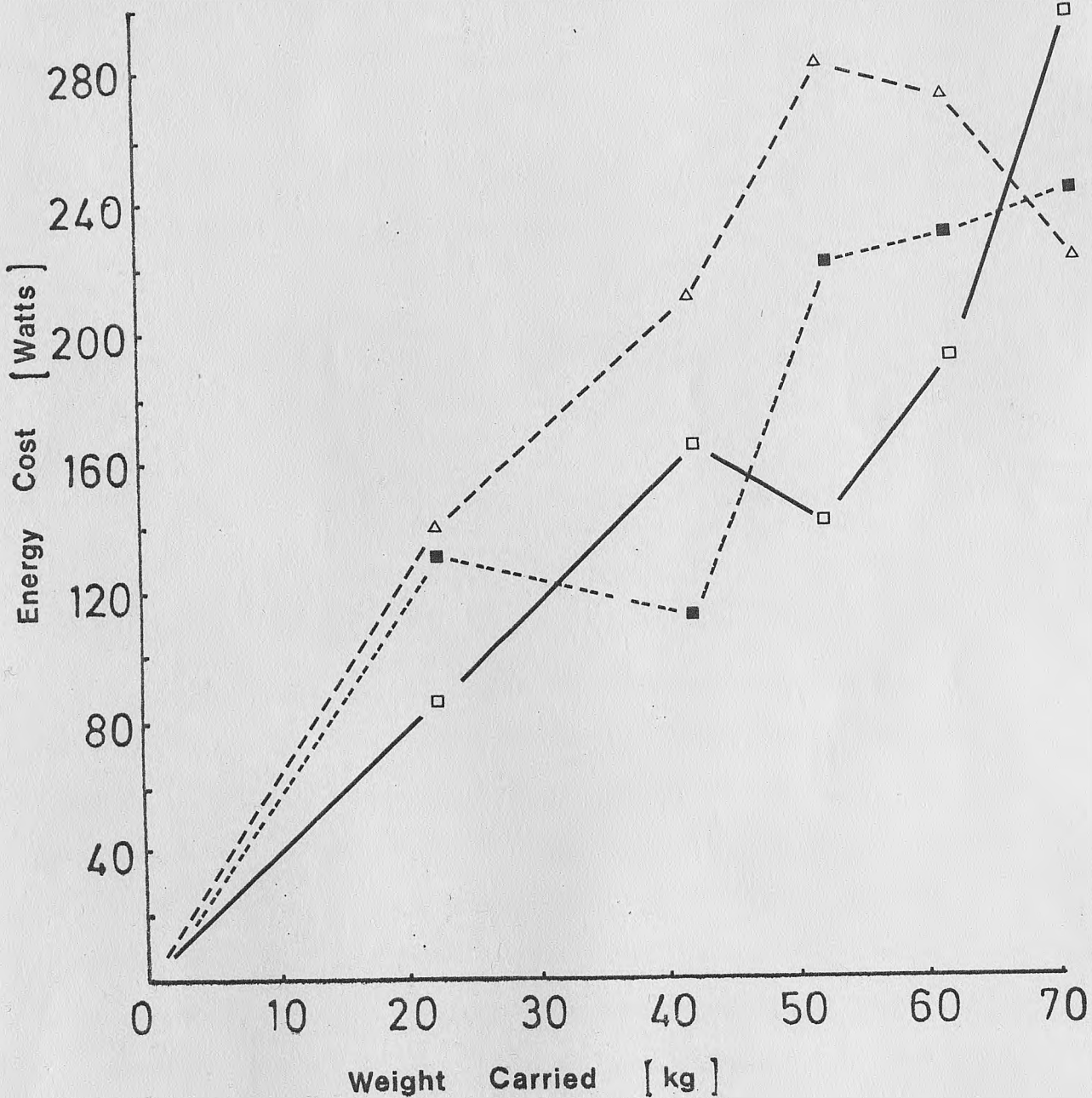


Figure 16. The Buffalo bull. The absolute energy cost of carrying loads over the back, using saddle 2, at different walking speeds. Each point at 1.0 m/sec is the mean of 4 measurements. At 0.8 m/sec & 1.2 m/sec these were the only measurements taken.

of 0.8 and 1.2 m/sec proved difficult due to the animal's reluctance to walk at any speed other than 1.0 m/sec. It was only possible to complete one full trial at 0.8 and 1.2 m/sec (Fig 16).

There is no significant correlation between weight carried and energy consumption at these walking speeds (Table 13) and there were no significant differences between the mean rates of energy consumption per kg carried at the different speeds, due to the low number of trials and large standard errors (Table 8).

Table 8 Rates of energy consumption per kg carried by the Buffalo bull at various walking speeds.

Speed (m/sec)	Rate of energy consumption (W/kg)	Number of observations	Standard error
0.8	4.18	5	± 0.639
1.0	3.71	20	± 0.308
1.2	5.10	5	± 0.636
Average of all speeds	4.02	30	± 0.263

d Buffalo castrate.

Position of the load. Unlike the Brahman steer, shifting the position of the load did not alter the rate of energy consumption significantly, despite the apparently appreciable differences (Fig 17). Mean values of 5.33 W/kg and 3.87 W/kg were obtained for carrying loads with saddle 2 and over the shoulders respectively, both at a walking speed of 1.0 m/sec, but the variability of the data and large standard errors precludes statistical significance (Table 9).

Problems were encountered when suspending the weights over the shoulders of the animal due to the characteristic posture of the Buffalo while walking (ie with its head down). The load would often slip forward on to his neck, and time was not available to design and construct a suitable saddle for him to wear over the shoulders.

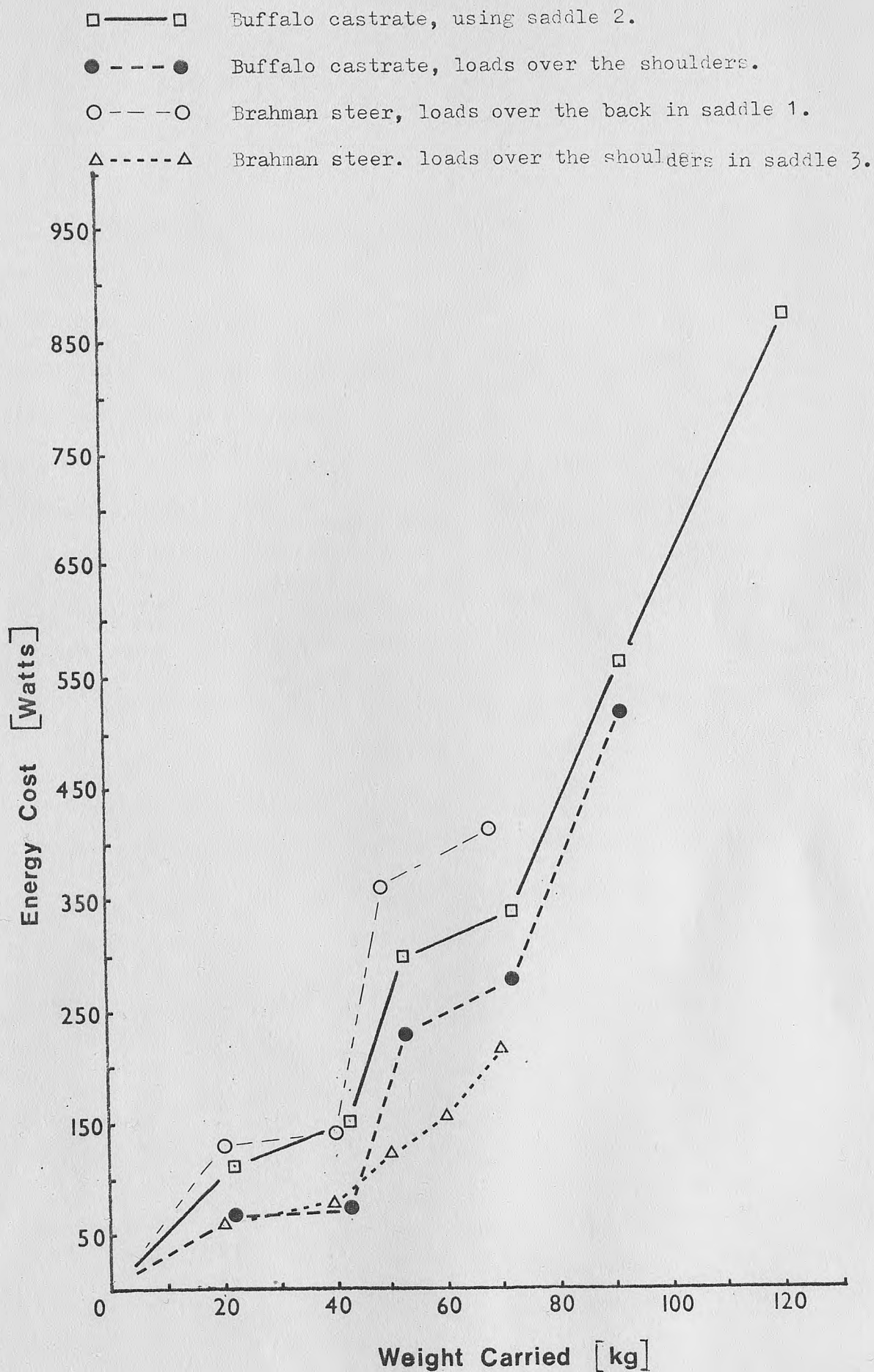


Figure 17. A comparison of the absolute energy cost of carrying loads over the back and over the shoulders for the Buffalo castrate and the Brahman steer.

Significant correlations were obtained between the weight carried and the rate of energy consumption when using either weights over the shoulder or saddle 2 at a walking speed of 1.0 m/sec (Table 13).

Effect of walking speeds on the energy cost of carrying. Like the Buffalo bull, the castrate had a limited range of effective walking speeds. Most measurements were made at 1.0 m/sec, this being the speed at which he felt most comfortable. Only one full trial was completed at speeds of 0.6, 0.8 and 1.2 m/sec (Fig 18). Only at 0.6 and 1.0 m/sec was there a significant linear relationship between the energy cost and the weight carried (Table 13).

The mean rate of energy consumption per kg carried taken over all the loads carried at each speed showed a significant difference between the energy cost at 1.2 m/sec and that at all other speeds, at $P < 0.01$ ($t = 5.260$ & 3df) (Table 9). There were no significant differences between the other values.

Table 9 Mean rates of energy consumption per kg carried by the Buffalo castrate at various walking speeds.

Speed (m/sec)	Rate of energy consumption (W/kg)	Number of observations	Standard error
0.6	4.64	4	± 0.162
0.8	3.83	5	± 0.887
1.0 (saddle)	5.33	24	± 0.313
1.0 (shoulders)	3.87	5	± 0.557
1.2	10.80	4	± 0.994
Average of all speeds	5.38	42	± 0.398

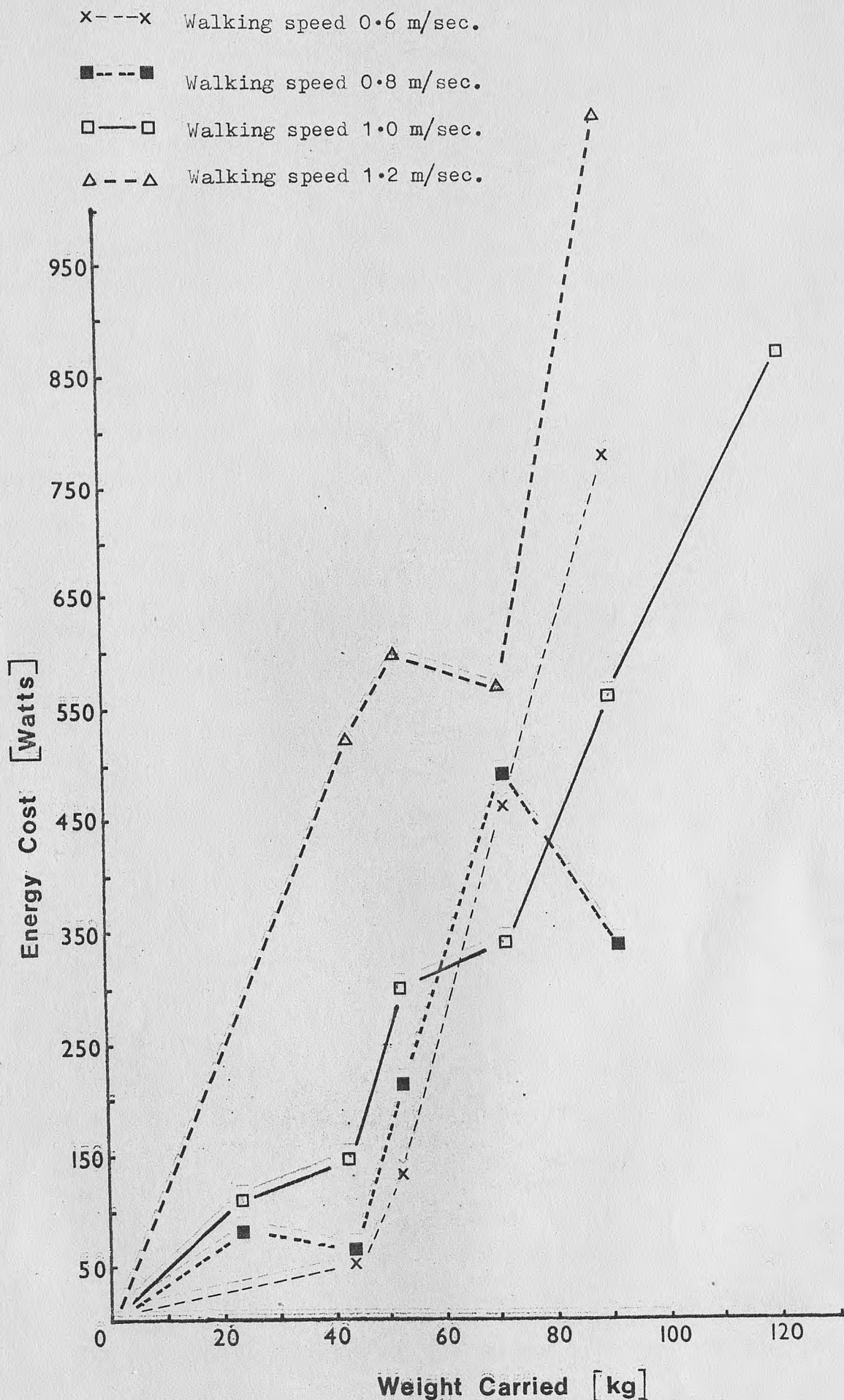


Figure 18. The Buffalo castrate. The absolute energy cost of carrying loads over the back using saddle 2. Each point at 1.0 m/sec is the mean of 4 measurements. At 0.6 0.8 & 1.2 m/sec, this was the only data obtained.

e Exmoor pony

The pony carried loads using saddle 3. It was worn over his back, but fitted as far forward over his withers as possible. The rear cross bar of the saddle rested over the pony's 14 - 16th ribs.

Measurements were made at walking speeds of 0.8, 1.0 and 1.2 m/sec (Fig 19). Approximately linear relationships were obtained between the rate of energy expenditure and the weight carried, and this correlation was significant at speeds of 0.8 and 1.2 m/sec (Table 13).

The differences between the mean energy cost per kg carried at the three speeds is only small and does not reach significance in any case (Table 10).

Table 10 Mean rates of energy consumption per kg carried by the pony at various walking speeds.

Speed (m/sec)	Rate of energy consumption (W/kg)	Number of observations	Standard error
0.8	3.23	7	± 0.671
1.0	3.38	16	± 0.449
1.2	3.66	7	± 0.149
Average of all speeds	3.41	30	± 0.281

f Men

For the purpose of comparison, the energy cost of carrying loads of 10, 20, 30 and 40 kg was measured in two men weighing 69 and 85 kg. The loads were carried in a rucksack on the back at a walking speed of 1.3 m/sec (Fig 20).

The correlation between the rate of energy consumption and weight carried was very highly significant in both cases (Table 13).

The mean energy cost per kg carried was 3.84 and 2.37 W/kg for

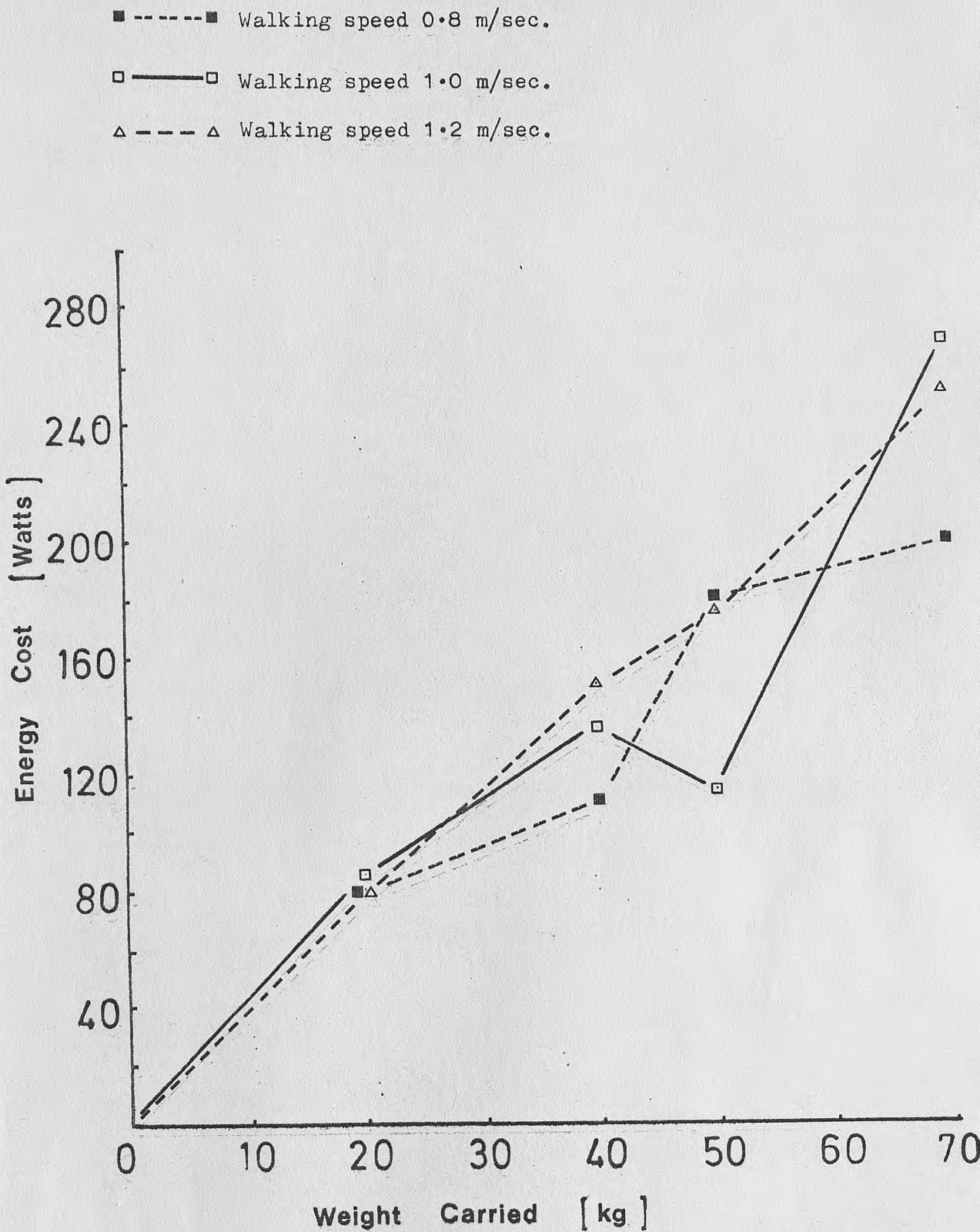


Figure 19. The Exmoor pony. The absolute energy cost of carrying loads over the back using saddle 3. Each point at 1.0 m/sec is the mean of 4 measurements. Each point at 0.8 m/sec & 1.2 m/sec is the mean of 2 measurements.

the 69 kg and 85 kg man respectively. Despite this large difference, the values are not significantly different due to the large standard errors (Table 11).

Table 11 Mean rates of energy consumption per kg carried by two men.

Speed (m/sec)	Body weight (kg)	Rate of energy consumption (W/kg)	Number of observations	Standard error
1.3	69	3.84	4	± 0.426
1.3	85	2.37	4	± 0.735
Average of both		3.10	8	± 0.482

The high standard errors are despite the very significant correlation between the rate of energy consumption and the weight carried, and are due to the fact that, as the overall load increased, the energy cost per kg carried also increased (Table 12).

Table 12 Rates of energy consumption per kg carried by the men according to the size of the load.

Body weight (kg)	Rate of energy consumption (W/kg) when load is			
	10 kg	20 kg	30 kg	40 kg
69	2.7	3.7	4.4	4.6
85	0.3	2.4	3.3	3.5

○---○ 69 kg Man.

□---□ 85 kg Man.

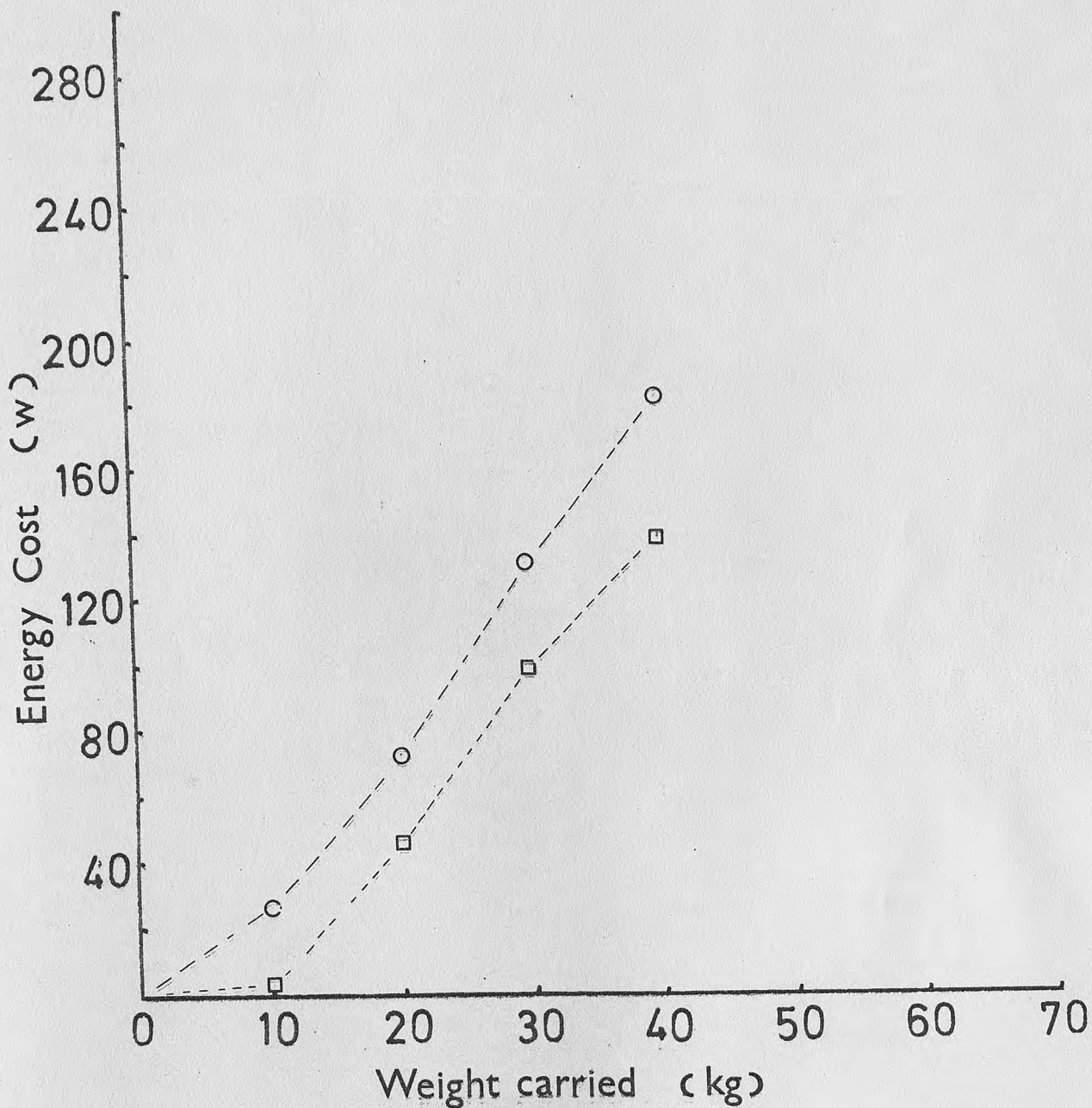


Figure 20. The absolute energy cost of carrying for two men, walking at 1.3 m/sec.

III. Comparison of the Results from the Different Animals.

Although the Brahman steer differs significantly ($P < 0.05$) from the heifer and the Buffalo castrate differs significantly ($P < 0.01$) from the Buffalo bull (Table 14), these differences can be partially explained by the fit of the saddle and the size of the load in relation to body weight (Discussion Section III and V). They are therefore not considered as important as the difference in the energy cost according to the position of the load on the animal.

Table 14 Comparison of the mean absolute ^{energy} cost per kg carried for all the animals.

Animal	Rate of energy consumption(W/kg)	Number of observations	Standard error
Brahman steer (saddle 1)	5.91	12	± 0.471
Brahman steer (saddle 3)	2.55	45	± 0.109
Brahman heifer	3.04	40	± 0.181
Buffalo bull	4.02	30	± 0.263
Buffalo castrate	5.38	42	± 0.398
Pony	3.41	30	± 0.281
Men	3.10	8	± 0.482

Table 15 compares the mean energy cost for the Brahman carrying loads over the shoulder with the mean energy cost for the Buffaloes carrying weights over their backs. The difference is very highly significant at $P < 0.001$ ($t = 6.93$ & 72 df). The difference between the energy cost for the Brahman steer to carry

loads over his back compared with over his shoulders is also very highly significant at $P < 0.001$ ($t = 6.48$ & 12 df).

The value obtained for the pony is significantly higher than that obtained for the Brahman carrying weights over the shoulders, at $P < 0.05$ ($t = 2.09$ & 30 df), and significantly less than the energy cost of carrying over the back for the Buffaloes, at $P < 0.01$ ($t = 3.48$ & 30 df).

The mean rate of energy consumption for the men is intermediate between that of the pony and the Brahman carrying weights over the shoulders and is not significantly different from either.

Table 15 Comparison of the mean energy cost per kg carried
between the species.

Animal	Rate of energy consumption(w/kg)	Number of observations	Standard error
Brahman (load over back)	5.91	12	± 0.471
Brahman (load over shoulders)	2.78	85	± 0.106
Buffaloes	4.75	72	± 0.264
Pony	3.41	30	± 0.281
Men	3.10	8	± 0.482

The scattergrams (Figs 21 & 22) illustrate the variance of the full data obtained for the Brahman and Buffalo.

Brahman heifer	Walking speed	Brahman steer
■	0.8	●
□	1.0	○
△	1.2	▲

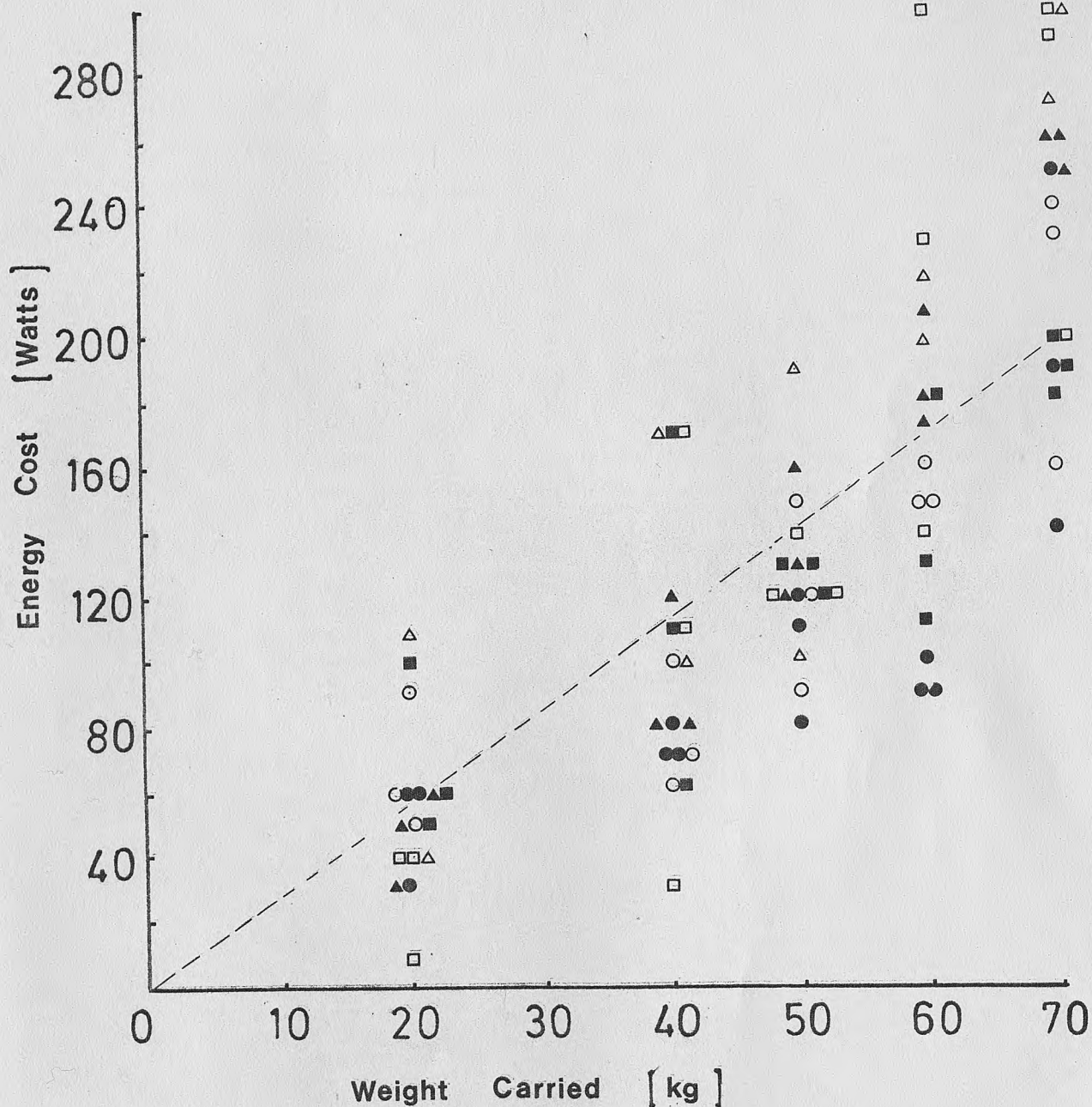


Figure 21. The full data obtained for the Brahman steer and heifer. The absolute energy cost of carrying loads over the shoulders using saddle 3.

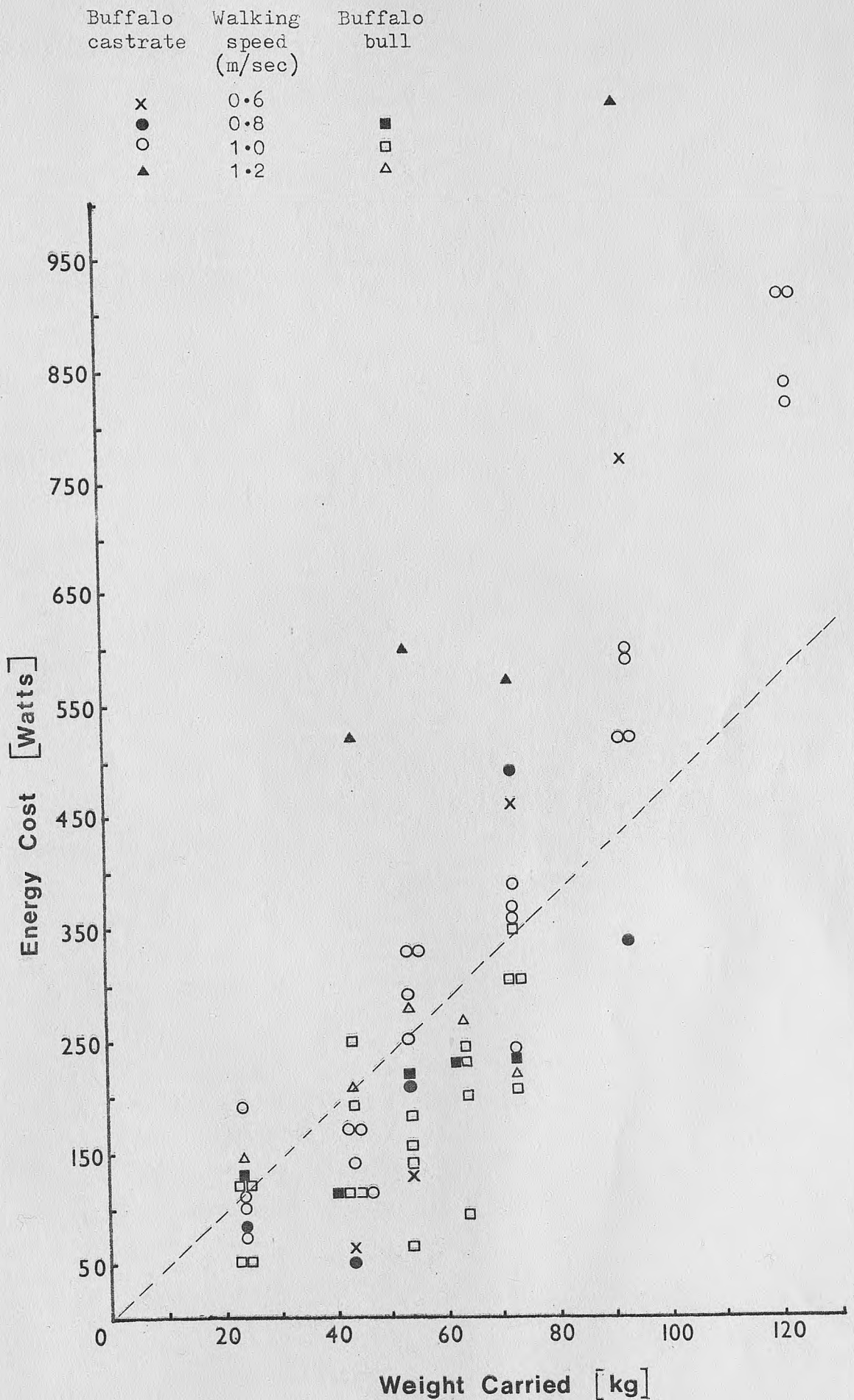


Figure 22. The full data obtained for the Buffalo castrate and Buffalo bull. The absolute energy cost of carrying loads over the back in saddle 2.

Table 13. Correlation between the load carried and the absolute energy cost of carrying for all the animals.

Animal	Walking speed (m/sec)	Saddle number	Correlation coefficient and degree of significance	Degrees of freedom (n - 2)
Brahman steer	1.0	1	0.911 ns	3
"	0.8	3	0.854 ns	3
"	1.0	3	0.938 *	3
"	1.2	3	0.973 **	3
Brahman heifer	0.8	3	0.966 **	3
"	1.0	3	0.977 **	3
"	1.2	3	0.960 **	3
Buffalo bull	0.8	2	0.843 ns	3
"	1.0	2	0.897 *	3
"	1.2	2	0.706 ns	3
Buffalo castrate	0.6	2	0.995 **	2
"	0.8	2	0.797 ns	3
"	1.0	2	0.977 ***	4
"	1.2	2	0.853 ns	2
"	1.0	-	0.955 *	3
Exmoor pony	0.8	3	0.958 *	2
"	1.0	3	0.887 ns	2
"	1.2	3	0.996 **	2
Man (69 kg)	1.3	-	0.999 ***	2
Man (85 kg)	1.3	-	0.999 ***	2

* = significant at $P < 0.05$
 ** = significant at $P < 0.01$
 *** = significant at $P < 0.001$
 ns = not significant

DISCUSSION

I. Introduction

The main points that emerge from the results are

i. The absolute energy cost of carrying for Brahman cattle is greatly influenced by the position of the load on the animal. The energy cost is approximately halved when the load is over the shoulders compared with over the back.

Altering the position of the load on the Buffalo did reduce the energy cost of carrying, but not significantly.

ii. The rate of energy consumption for the Brahman cattle increased as the speed of walking increased. The rate of energy consumption for the pony also increased as the walking speed increased, but not significantly.

iii. The Buffaloes both had a narrow range of effective walking speeds, being most comfortable at approximately 1.0 m/sec (ie 2.2 mph).

iv. The energy cost of carrying for the pony and for the men is intermediate between the value obtained for carrying loads over the shoulders for the Brahman cattle and the value for carrying loads over the back for both the Brahman and Buffaloes.

Mean values of 2.87 W/kg, 3.41 W/kg, 3.10 W/kg and 4.75 W/kg were obtained for the Brahman cattle, pony, men and Buffaloes respectively.

The findings have practical implications in the design of pack saddles as well as relevance to the dietary requirements of working animals.

The differences in energy expenditure according to the position of the load and speed of walking can be accounted for in the extra muscular work required to support the load and the energy

spent in mechanical work on the load. The size of the load in relation to body weight appears to be important to the energy cost of carrying in men.

11. Supporting the Load.

Fig 23 illustrates how saddle 3 transmitted its weight directly down the shoulders and forelimbs of the cattle. Its centre of gravity was estimated to be over the point of the animal's elbow, and most of the weight of the load was therefore supported by the appendicular skeleton and required a minimum amount of muscular effort to support.

In contrast, saddles 1 and 2 transmitted their weight down through the middle of the animal's back (Fig 24) and it is reasonable to assume that extra effort was required from the longissimus, serratus dorsalis, rectus abdominis and other muscles of the back, loins and abdomen to prevent bowing of the spine.

Saddle 3, on the pony, was fitted quite far forward over the withers, and although it did not transmit its weight directly down the forelimbs, its centre of gravity was further forward than was the case for saddles 1 and 2 (Fig 25). Supporting the load therefore required an intermediate amount of muscular effort.

Bedale (1924) also concluded from her work on the energy cost of carrying in women, that when the load transmitted its weight directly down the skeleton, the energy cost was at a minimum, and as the centre of gravity of the load moved away from the line of the skeleton, the energy cost increased.

Individual animals may vary in conformation and this can influence their ability to support loads. Pack mules and ponies

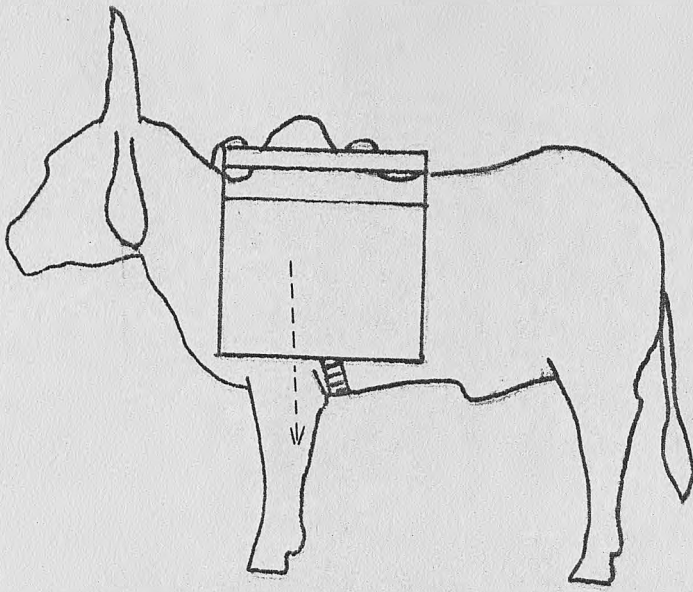


Figure 23. Showing the position of saddle 3 on the Brahman cattle, and the direction it transmitted its weight.

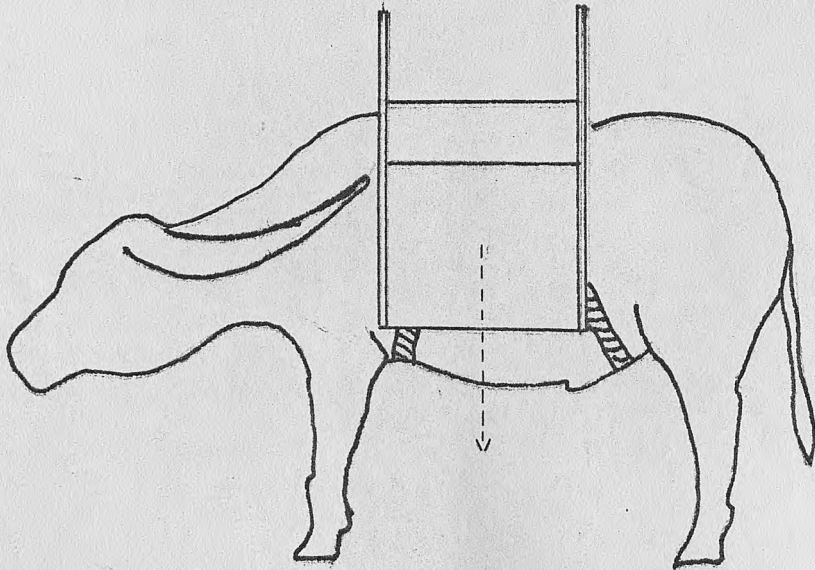


Figure 24. Showing the position of saddle 2 on the Water Buffaloes and the direction it transmitted its weight.

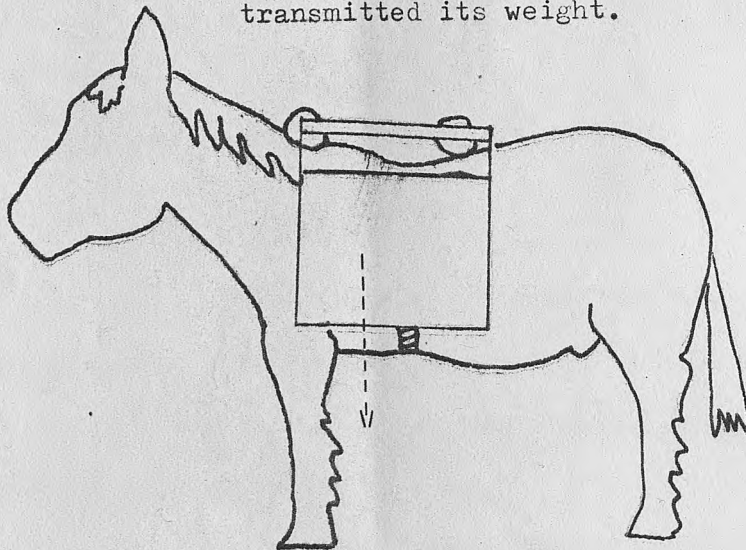


Figure 25. Showing the position of saddle 3 on the Exmoor pony, and the direction it transmitted its weight.

for military use have always been selected with roach backs, since it was well known that these animals were more suited to carrying heavy loads than were straight backed or dish backed animals. (Vet. Dept. War Office 1933). A convex spine would be mechanically stronger than a straight or concave spine and require less muscular effort to support a given weight.

In many countries, pack animals are loaded or ridden over the rump, because it is believed that in this position the animals can support a much greater weight (Cockrill 1974. Bulliet 1975). This is to be expected, since the appendicular skeleton is again supporting the load and it will require a minimum of muscular effort.

III. Mechanical Work on the Load.

In a physical sense, carrying a load at right angles to the force of gravity, involves no mechanical work, and should therefore require no energy inputs other than that required to accelerate the load when the animal starts to walk. For animals on a treadmill however, no effort is required to accelerate the load, and therefore if the load remains parallel to the ground, no extra energy need be expended to carry it, above that required to support it while standing still.

$$\begin{array}{rcl}
 \text{ie.} & \begin{array}{l} \text{The energy cost of} \\ \text{standing with the load} \end{array} & - \begin{array}{l} \text{The energy cost of} \\ \text{standing unloaded} \end{array} & = \\
 & \begin{array}{l} \text{The total energy} \\ \text{cost of carrying} \end{array} & - \begin{array}{l} \text{The energy cost of} \\ \text{walking unloaded.} \end{array} &
 \end{array}$$

If this were the case, then the speed of walking would not have altered the energy cost of carrying. As demonstrated in the results however, this was not the case and a certain amount of mechanical work must have been performed on the loads.

When the Brahman steer was using saddle 1, and the Buffaloes were using saddle 2, the rear end of the saddle was observed to rock sideways with each stride. As the left hind limb was extended forward, the saddle would drop towards the left. As the limbs crossed, the saddle would rise up, then drop again towards the right as the right hind limb was extended forward.

* A proportion of the load therefore had to be lifted through an arc, transversely across the animals back, a vertical distance of 10 - 15 cm, with each stride. When a load is lifted in this manner, against the force of gravity, it increases its potential energy and so requires greater effort from the muscles of the back and loins, therefore increasing the energy expenditure.

Due to the narrower span of the shoulders, no vertical oscillation of the load was observed when the Brahman cattle wore saddle 3. Instead, there was a forward and backward swaying action in time with the movement of the animals forearm. This action accelerated and decelerated the load in a horizontal plane with each stride. This required much less effort than the vertical oscillations seen with saddles 1 and 2.

Saddle 3 was originally designed to measurements taken from the Brahman steer, and it did not fit the heifer quite as well. Because it was looser fitting over the shoulders, more swaying of the load was noticed. The greater acceleration and deceleration of the load would have required a higher rate of energy expenditure, and may explain the apparent difference in the energy cost of carrying between the steer and heifer.

When the pony wore saddle 3 across his back, the rear cross beam rested no further back than his 16th rib. It was therefore not influenced by the movements of the lumbar spine and muscles, and no vertical movement of the load was observed. However, there was a forward and backward swaying action noticed, similar to that which occurred with saddle 3 on the Brahman cattle.

When weights were suspended over the shoulders of the large Buffalo, there was no discernable vertical movement of the load, just a similar forward and backward swaying action. Carrying weights in this manner did reduce the energy cost of carrying, but problems were encountered with the load sliding forward down the animal's neck and only one full trial was completed. Due to the low number of trials and the high standard error, the reduction in energy cost is not statistically significant. If time had been available to design and build a shoulder saddle for the Buffalo that did not slip forward, I feel certain that the reduction in energy cost could have been shown to be significant, and perhaps reduced to similar levels as the Brahman.

IV. The Influence of the Speed of Walking on the Energy Cost of Carrying.

A proportion of the energy expended for carrying must be devoted to the incidental movement of the load, which is in time with the animal's stride. When the Brahman cattle carried loads over the shoulders, this proportion of the energy was spent in causing the load to sway backwards and forwards at a frequency which is not its natural or resonant frequency of oscillation. Energy was therefore required to accelerate and decelerate the load at each stride.

Initially, to increase its walking speed, an animal will lengthen its stride, so although the rate of oscillation does not increase, slightly more energy will be required for greater acceleration and deceleration of the load. Hence, the rate of energy expenditure for carrying will increase at higher walking

speeds. This was demonstrated by the results from the Brahman cattle (Tables 4 & 6) and suggested by the results from the pony, although these results did not reach statistical significance (Table 10). A similar statement cannot be made for the Buffaloes, since at speeds other than 1.0 m/sec, they would indulge in a great deal of incidental movement and misbehaviour that confused the results.

The increase in energy expenditure at the higher speeds of walking was not proportional to the distance covered, and the energy cost per metre travelled decreased as the walking speed rose (Tables 5 & 7).

The limited selection of walking speeds tried during the experiment precludes the deduction of an accurate expression connecting the energy cost and the speed of walking. However, using the pooled data provided by the Brahman steer and heifer, an approximate expression can be calculated to illustrate the effect of different walking speeds on the overall efficiency of pack animals.

* The mean absolute energy cost of carrying at a speed of 0.8 m/sec for the Brahman cattle was 2.5 W/kg. At 1.0 m/sec, the mean energy cost was 2.8 W/kg and at 1.2 m/sec, it was 3.3 W/kg. The expression that best fits the data is $E = 2.8LV^{0.7}$ Watts

where E = the absolute energy cost of carrying

L = the load carried (kg)

V = the walking speed (m/sec)

The energy cost per metre travelled therefore is $2.8LV^{-0.3}$ J/m, and theoretically, the faster the animal walks, the more economical it becomes. However, the energy cost of walking, above that of standing, increases logarithmically with walking speed, and is equal to $1.5WV^{1.5}$ watts or $1.5WV^{0.5}$ Joules/m. (Lawrence 1980)

where W = the animal's bodyweight

The total energy cost (Q), above maintenance, of carrying a load

is therefore $Q = 2.8LV^{-0.3} + 1.5WV^{0.5}$ Joules/m

Since the carrying function decreases with increasing walking speed, and the walking function increases, there must be an optimum speed ($V_{opt.}$) at which the energy cost per metre travelled is a minimum.

Differentiating $\frac{dQ}{dV}$ it is found that $V_{opt.}$ depends only on the ratio of the load to the liveweight of the animal.

$$V_{opt.} = \left(\frac{1.12L}{W} \right)^{1.25} \text{ m/sec.}$$

$V_{opt.}$ is plotted against a range of loads as a percentage of bodyweight in Fig. 26. Between loads of 10 - 30 % bodyweight, the graph is almost a straight line, and the % bodyweight carried (P) and optimum speed ($V_{opt.}$) are connected by the equation :

$$V_{opt.} = 0.0092P - 0.027 \text{ m/sec.}$$

Values of the energy cost, above maintenance, of carrying a load are given in Fig. 27 for a 400 kg ox carrying a typical load of 70 kg (17.5 % of bodyweight). The percentage amount of energy wasted by an animal which does not walk at the optimum speed is given in Fig. 28.

The optimum speed, even when carrying a large load in proportion to bodyweight, is well below the normal walking speed of working cattle. However, the increase in energy expenditure due to walking faster than the optimum speed, may be more than offset by savings in time. The graphs do show, however, that an animal carrying a heavy load at a slow speed will approximate to the optimum walking speed better, and therefore be more economical, than one carrying a light load at higher speeds.

V. The Energy Cost of Carrying in Relation to Bodyweight.

The results from the two men showed an increasing absolute energy cost per kg as the overall weight they carried increased. This is consistent with the findings of Bedale (1924), who found that the absolute energy cost of carrying was 3.42 W/kg for a

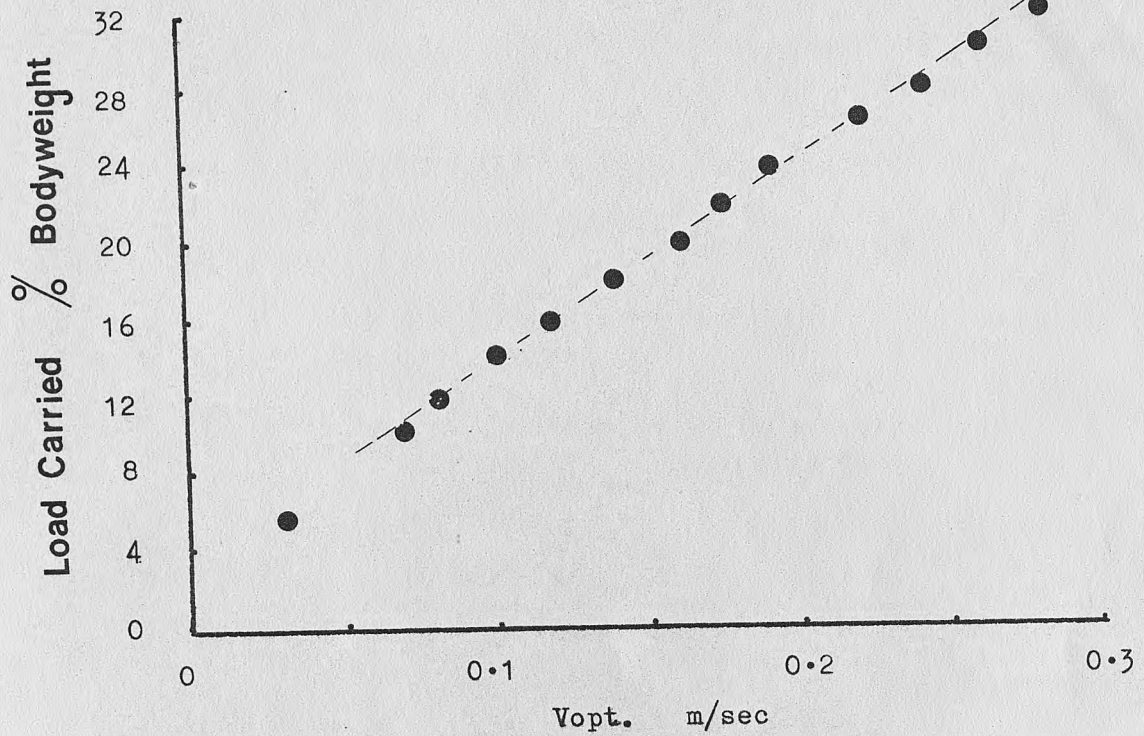


Figure 26. Graph of the load carried by a pack animal as a % of its bodyweight vs. the most economical walking speed (Vopt.)

Based on the equation
$$V_{opt.} = \left(\frac{1.12L}{W} \right)^{1.25}$$

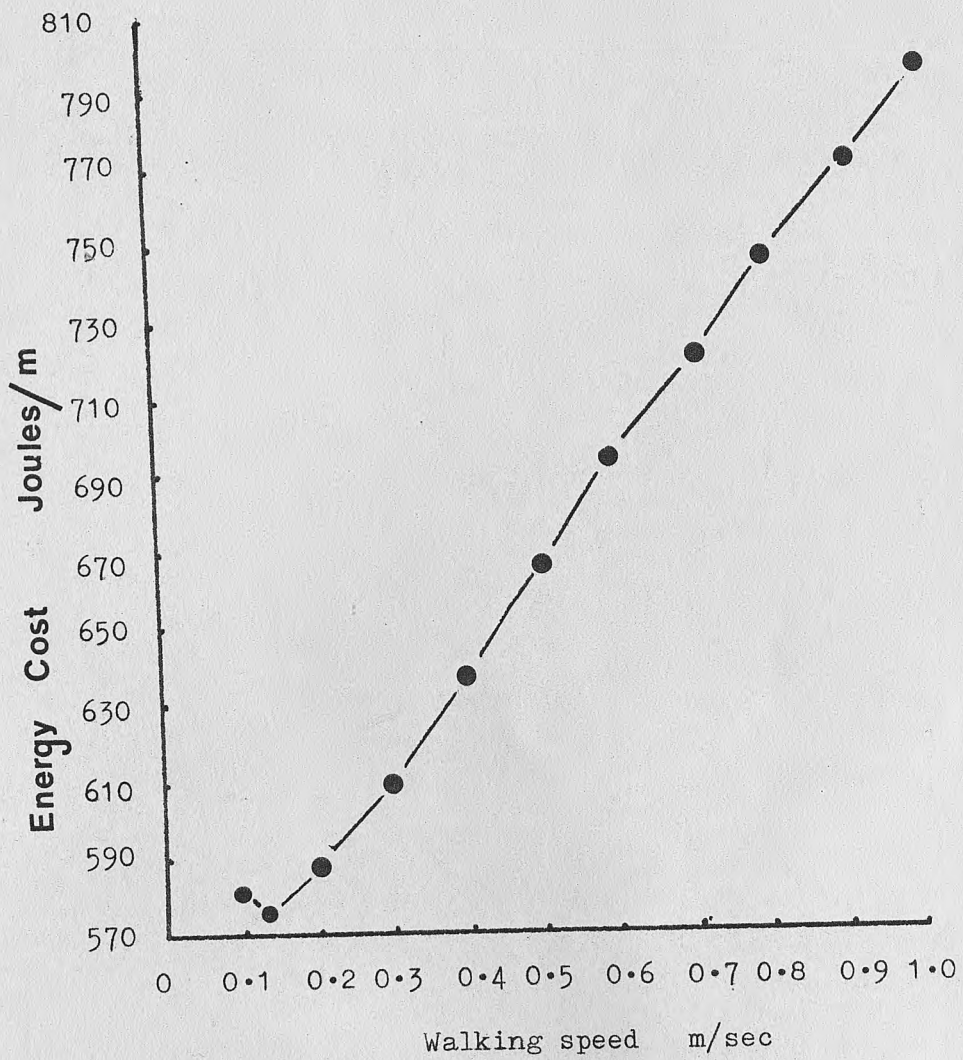


Figure 27. Graph of the energy cost, above maintenance, per metre travelled vs. the walking speed, for a 400 kg ox carrying a 70 kg load.

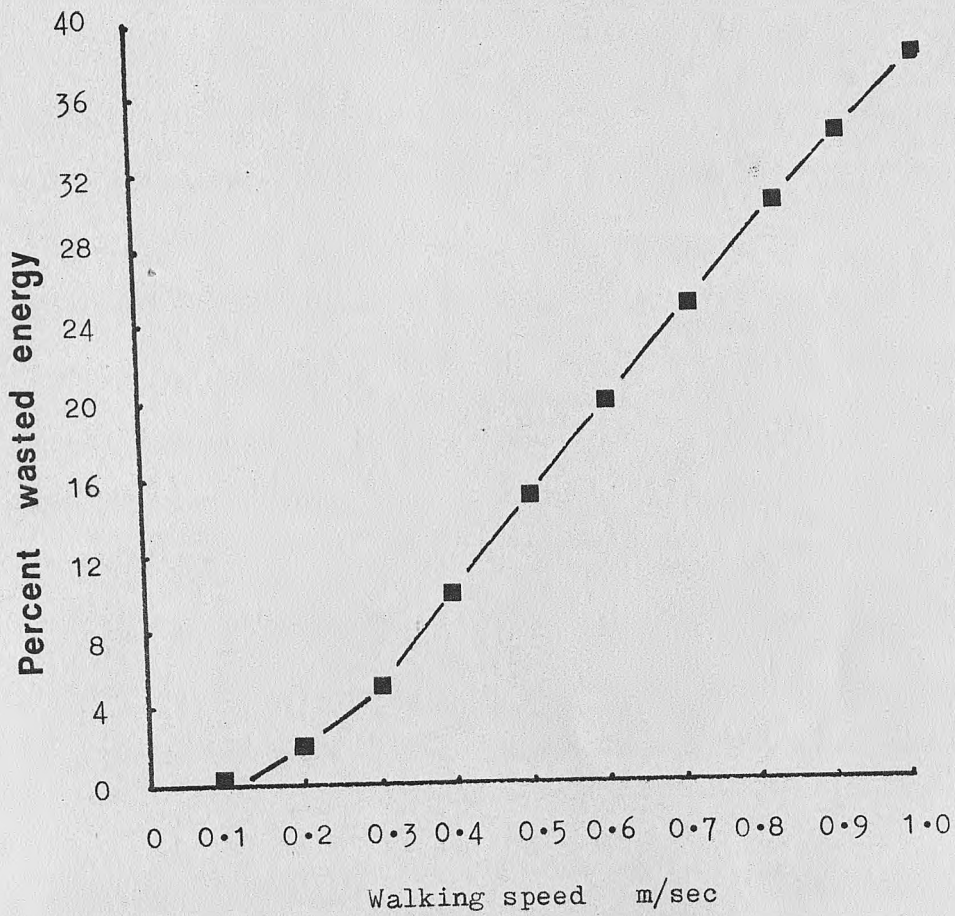


Figure 28. The percentage wastage of energy, above maintenance, incurred by using a pack animal at various speeds. Based on the data for a 400 kg ox carrying a load of 70 kg.

60 kg woman carrying 18 kg (ie 30 % of her bodyweight), and 4.2 W/kg when carrying 22 kg (ie 37 % of her bodyweight). The woman in this case carried loads in a rucksack on her back and walked at a speed of 1.26 m/sec.

The increase in energy cost per kg carried may be because the measurements for the men were made over a much greater range of weights, in proportion to their bodyweight, than was made for the animals. The men carried loads equivalent to 14, 29, 44 and 58 % of their bodyweight, compared with only 4 - 14 % of bodyweight for the Buffalo bull. The other animals carried only a slightly larger range of weights ie 4 - 20 % of bodyweight for the large Buffalo, 5 - 17 % for the Brahman cattle and 6 - 22 % for the pony.

It is also of note that the men expended a similar amount of energy to carry equivalent percentages of their bodyweight, and these figures agree with those of Bedale (1924) (Table 16).

Table 16. The absolute energy cost of carrying loads by the men according to the overall weight carried.

Load carried as % bodyweight	Energy cost (Watts)		
	69 kg man	85 kg man	60 kg woman (from Bedale, 1924)
14.5	27	11*	
29.0	74	69*	
30.0	76*	71*	62
37.0	99*	98*	92
43.5	123	123*	
58.0	183	180*	

* These values were predicted from the graph of energy cost against weight carried for the two men (Fig 20)

When carrying a load, a two legged animal would have to spend a greater proportion of its energy in maintaining balance than would a four legged one, and the amount of energy required will increase disproportionately as the weight carried gets bigger. The energy cost of carrying for four legged animals may not therefore be expected to increase in a similar manner to the men.

It is a known biological fact that small animals are capable of carrying a much greater load in proportion to their bodyweight than are larger animals, and so it would be impossible to investigate the energy cost of carrying for cattle and Buffalo over a similar range of weights as for the men. However, the absolute energy cost per kg carried for the Buffalo castrate did show a significant increase when carrying loads of 122.5 kg compared with the lesser weights (Table 17).

Table 17. The absolute energy cost of carrying for the Buffalo castrate according to the overall weight carried.

Weight carried (kg)	Energy cost (W/kg)	Standard error	Significance of the difference from the value at 122.5 kg
22.5	4.52	± 0.756	P < 0.05
42.5	2.69	± 0.432	P < 0.01
52.5	4.82	± 0.515	P < 0.05
72.5	5.10	± 0.470	P < 0.05
92.5	5.96	± 0.526	ns
122.5	7.43	± 0.401	-

Moreover, when the overall energy cost per kg is estimated for the Buffalo castrate, excluding the data at 122.5 kg, so that the range of weights carried becomes equivalent to that carried by the Buffalo bull (ie 5 - 14 % of bodyweight), then the previous difference between the two Buffaloes is considerably reduced (Table 18).

Table 18. Comparison of the mean rates of absolute energy consumption between the Buffalo castrate and Buffalo bull.

Animal	Rate of energy consumption (W/kg)			
	Full data	Standard error	Data excluding 122.5 kg	Standard error
Buffalo castrate	5.38	± 0.398	4.88	± 0.293
Buffalo bull	4.02	± 0.263	4.02	± 0.263

The true relationship between the energy cost and the weight carried, when measured over a wide range of weights in proportion to bodyweight, may therefore be curvilinear. Within the range of weights that large animals are capable of carrying, for all practical purposes, this curve can be substituted by a straight line.

VI. Pack Saddle Design.

The difference in the energy cost of carrying according to the position of the load, indicates that, in practice, the design of the saddle will greatly influence the animal's efficiency as a pack animal.

Carrying loads over the shoulders had a twofold advantage over carrying loads on the back i.e. the load required less effort to support (a corollary to this is that the maximum load is increased) and it did not require as much energy to be spent on the incidental movement of the load.

There are a whole variety of designs of pack harness in use around the world, ranging from simple rope nets and wicker panniers

to fairly sophisticated pack saddles used for artillery mules (FAO 1972. Vet. Dept. of the War Office 1933). * The different designs will vary in their efficiency according to how they distribute the weight over the animal.

It has been known intuitively for a long time that the shoulders are best for supporting weight and that the loins should not be used for weight bearing. The more sophisticated pack saddles already comply with these recommendations (Miller and Robertson 1947). For example, the Indian Sunka pack saddle for donkeys and mules is simply a bolster stuffed with cane, folded double and placed on the animals back so that the bend is well forward of the withers. Loads are then suspended across the Sunka over the animals shoulders (Vet. Dept. of the War Office 1933). In this manner, the animal can carry considerable loads fairly comfortably.

In practice it should be a fairly easy task to design and construct a pack saddle to fit astride the hump of a Zebu animal. For Buffalo, the optimum design of pack saddle is more difficult to achieve since they have no hump and any load situated over the shoulders will tend to slip forwards. The answer, in this case, may lie in an arrangement employing a breeching strap to hold the saddle in place.

VII. Feeding of Pack Animals.

The total energy measurements made during the experiment includes energy spent on the following items :

- a. Maintenance requirements
 - i. Basal metabolism
 - ii. The heat increment associated with maintenance
 - iii. The energy cost of standing, above that of lying down.

- b. The energy cost of walking, above that of standing still including :
- i. The muscular effort required to move the limbs
 - ii. The energy cost of overcoming internal and external resistance eg. air drag, muscle colloids, tendon elasticity.
 - iii. The work involved in accelerating the body mass (not when walking on a treadmill)
 - iv. The energy spent in extra metabolic work associated with walking eg. increased respiration rate and heart rate.
- c. The heat increment of feeding associated with the muscular effort of walking.
- d. The energy cost of carrying, above that of walking unloaded, including :
- i. The energy spent in muscular work to support the load.
 - ii. The energy spent on mechanical work on the load ie. accelerating the load and the incidental movement of the load.
 - iii. The energy spent on extra metabolic work associated with carrying.
- e. The heat increment of feeding associated with the muscular effort of carrying.

Metabolisable energy is not used 100 % efficiently for muscular work, and some energy is therefore lost as a heat increment.

The baseline for calculation of the absolute energy cost of carrying, includes items a. b. and c. The absolute energy cost therefore comprises item d. Whether or not item e. is included in the absolute cost is debatable.

If the heat increment associated with the effort of carrying is emitted at the same time as the work is performed, then it is incorporated into the absolute energy cost of carrying. The results obtained therefore would be a measure of metabolisable energy and could be related directly to the dietary requirements.

However there is no reason to assume that the heat increment is emitted only at the same time as the work is performed. In animals that are working regularly, as were the animals in this experiment, it may be that the heat increment is given off

gradually during the day, so it becomes incorporated into the baseline measurement for the calculation of the absolute energy cost. The results may therefore be a measure of Net Energy (N.E.)

In order to resolve this problem, it would be necessary to starve the experimental animals so that they begin to metabolise their own body tissues. They would then be given a set amount of work to perform and their rate of energy expenditure measured. The results, in this case, would not include any heat increment of feeding and would therefore be N.E. values. They could then be compared with the results obtained during the present experiment.

If the present results do prove to be N.E. measurements, then when calculating the dietary requirements of working animals, an allowance will have to be made to cover the heat increments associated with muscular work.

The actual value of the heat increment could be calculated by feeding the animals a measured amount of metabolisable energy per day, so that they maintain a stable bodyweight whilst performing a set amount of work. Since the energy requirements for maintenance, the heat increment associated with maintenance, and the energy cost of walking and carrying are all known, the heat increment associated with muscular work could be determined.

A great proportion of the maintenance energy requirements is used to provide muscular tone and energy for the muscular effort of feeding and standing. It may be expected therefore, that metabolisable energy is used at a similar level of efficiency for muscular work as it is for maintenance i.e. approximately 72 % efficient.

To determine the total dietary requirements of a pack animal, it will be necessary to know the maintenance requirements, the energy requirement for walking and the energy requirement for carrying. If the animal's body weight, the distance travelled,

and the time taken, are all known, then the energy requirement for maintenance and walking can be calculated. In practice, within the normal range of walking speeds for working animals, the logarithmic relationship between walking speed and the energy cost can be replaced by a linear relationship that is simpler to calculate.

To determine the energy requirement for carrying, it will be necessary to know the size of the load and the time for which it is carried. By pooling the data obtained for the energy cost of carrying at the different speeds, an average value is obtained that can be used in practice. This will help simplify any calculations, and since pack and draught animals work in a similar range of speeds, their energy consumption will average out accordingly.

The energy expended by draught animals in overcoming the vertical component of their work (Literature Review, Section II) should be equivalent to that of the most economical means of carrying loads. The yoke is usually worn over the shoulders and will therefore require a minimum of muscular effort to support. Also, no energy will be wasted on mechanical work since the yoke, shaft or traces will not oscillate in a similar manner to a pack load.

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APPENDIX 1

Derivation of the equation used to predict the Energy Expenditure

If x gm fat & y gm carbohydrate are oxidised, then :

$$\text{Total } O_2 \text{ consumed (E)} = 2.01x + 0.83y \text{ litres} \text{ -----i}$$

$$\text{Total } CO_2 \text{ produced (P)} = 1.43x + 0.83y \text{ litres} \text{ -----ii}$$

$$\text{Total energy released (H)} = 39.7x + 17.6y \text{ KJ} \text{ -----iii}$$

To eliminate x & y ;

$$\text{From equation i} \quad x = \frac{E - 0.83y}{2.01}$$

$$\text{From equation ii} \quad P = 1.43 \frac{E - 0.83y}{2.01} + 0.83y$$

$$y = \frac{P - 0.71E}{0.24} \text{ -----iv}$$

$$\text{From equation iii} \quad H = 39.7 \frac{E - 0.83y}{2.01} + 17.6 \frac{P - 0.71E}{0.24}$$

$$H = 19.75E - 16.4y + 73.3P - 52.0E$$

Substituting equation iv for y ;

$$H = 19.75E - 52E + 73.3P - 16.4 \frac{P - 0.71E}{0.24}$$

$$H = 16.23E + 4.97P$$

