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Power and energy sources

THE sources of power available in classical antiquity were severely limited by comparison with those of the present day. Virtually all work was done by man-power or animal power, and the kind of constraint which this imposed may be seen from a simple illustration. One gallon of petrol may seem very expensive nowadays, but if used in an ordinary engine of average efficiency it will do the equivalent work of about 90 men, or of nine horses of the smallish size used in the ancient world, for one hour. Water power was used for pumping and industrial purposes, but probably not much before the first century B.C. The theoretical possibilities of steam power, hot air expansion and windmills were known, but apparently never exploited except on a very small scale, and not in useful or practical applications.

MAN-POWER

The most common mode of employing man-power was in the handling and porterage of small burdens of the order of 20–80lb (9–36kg). This is discussed in detail in Chapter 7, and all that needs to be done here is to note a very important limitation, which should be quite obvious, but is all too often forgotten. If a burden requires more than one man to handle it, its size and shape must be such as to allow the necessary number of men to stand close enough and get a grip on it. For example, in the fifth century B.C. the columns of Greek temples were built up from a number of sections, called 'column drums'; these might be anything up to 6ft 6in (2m) in diameter. The only possible place to grip such a lump of stone is around the lower edge, and it would be very difficult for more than 18 men to get into position to grip it at once. It follows, therefore, that if its total weight was more than about a ton (as it often was), they would be unable to lift it up off the ground, let alone move it, turn it round or position it on a column. They might just be able to roll it along level ground on its edge, but that would be all. When, therefore, people say 'of course they had thousands of slaves to do the building for them', two facts should be remembered. Though the Pharaohs in Egypt may have had vast resources of manpower, Greek and Roman building contractors rarely had more than a small labour force, and in any case, no matter how many they may have assembled for the more ambitious projects, they could never have man-handled the larger stones used in classical buildings. Either one of the lifting devices described in Chapter 4 must have been employed or else the very slow and extravagant method of building a ramp, and dragging the stones up the slope on rollers.

There were two important mechanical devices for harnessing man-power. One was the capstan or windlass, particularly useful on cranes or aboard ship. The power could be transmitted over a distance by ropes, its direction could be changed by pulleys, and the force could be multiplied by block-and-tackle arrangements. The windlass itself has a built-in mechanical advantage. It was also found to be ideal where traction was required, of low power but finely and accurately controlled. Two medical uses illustrate this. One was the so-called 'bench of Hippocrates'—a plinth with a windlass at each end to provide the extension needed for reducing fractures and dislocations of the arms and legs. The other was a device apparently used by some gynaecologists—a small capstan mounted below a 'midwifery stool', used for extracting a foetus from the uterus.*

It is generally agreed that the Greeks and Romans did not, apparently, discover or use the crank in place of the handspikes on a windlass. Hero of Alexandria speaks of something called a 'handholder' *(cheirolabe)* for turning axles. This might have been a crank, but there is no proof that it was. There was at least one situation in which the main advantage of the crank could have been exploited, and where its disadvantage would not have been noticed—the repeater catapult. Since it was not used on that weapon, it seems almost certain that it was not known to the designers.

How serious a drawback was the lack of this device? The answer seems to be—rather less than is sometimes suggested. The only real advantage of using a crank is speed. A single grip (firm, but loose enough to allow the handle to turn in the palms of the hands)

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*Hippocrates, *On Joints* chapter 72: Soranus, *Gynaeceia* XXI, 68.

can be maintained all the time, whereas with handspikes the grip has to be changed, usually four times per revolution. But in situations where speed is less important, the crank has a positive disadvantage. The force which can be applied to it varies according to its position in relation to the operator, reaching a minimum twice during each revolution when the handle crosses a line drawn through the operator's shoulders and the axis of the crank, and a maximum when it is roughly at right-angles to that line. This is why a car starting-handle used to be be so arranged that the points at which most force is needed to turn it occurred when the handle was at 'two o'clock' and 'eight o'clock'. This imposes a serious limitation on the crank. When it is under continuous loading (e.g. on a crane when the load is raised, or a well-head when the bucket is full), the reverse thrust applied to the crank handle by the load must never exceed the minimum applied by the operator at the two weakest points of the cycle. If it does, the handle will fly backwards, and once it has started swinging round the load may acquire momentum and make the handle impossible to stop. To avoid this danger, most modern cranked winches are fitted with a ratchet. Such a device, dating from the late fifth century B.C., was found near some naval installations at Sunium, and may have been used on a winch for hauling ships up slipways.

The implications for ancient devices worked by handspikes are clear enough. For cranes or hoists of any kind the use of a crank would have lowered the handling capacity by some 20–30%, and it seems rather improbable that a slight increase of speed would justify that sacrifice. On the repeater catapult the slider was fitted with pawls and a ratchet, and would only fly forward a short distance if the tension on the draw-back cord were relaxed. It would therefore have been reasonably safe to use a crank on the capstan at the rear of the machine and thereby speed up the loading operation—a particularly important benefit, for that particular weapon.

The other mechanical device was the treadmill—a pair of vertical wheels with treads (like those of a step-ladder) between them. It has become very difficult nowadays to talk, or even to think about this apparatus unemotionally, and in purely engineering terms, but in fact, if well designed, it can be one of the most efficient devices for this purpose, and the most comfortable for the operator—in so far as any continuous, monotonous physical work can be comfortable. The basic action is not unlike that of pedalling a bicycle, and it is significant that recent attempts to reach the absolute limits of the human body's capabilities, in the development of man-powered flight, have mostly used that arrangement. The difference is that a cyclist pulls on the handlebars, and uses the abdominal muscles as well as the leg muscles; the treadmill operator uses the reaction from lifting his body weight, mainly with the leg muscles.

A very useful feature of the treadmill, especially when used on a crane, is that the torque, which determines the pull on the hoisting-cable, can be easily and accurately adjusted by the operator shifting his position on the wheel. The maximum torque is obtained when the operator treads the wheel at a point on a level with the axle (this can only be done from the outside). If he treads above that point (outside) or below it (inside) the torque is less, and if he stands directly above or below the axle it is zero. Thus the amount of torque required between the maximum and zero, can be obtained by moving forwards or backwards.

This may possibly afford an explanation of a rather mysterious length of wood with notches along one side, found near the Roman water pumps in the Rio Tinto mines. When these pumps (which themselves acted as treadmills) were being used in a series, it would be very important to keep the output of each of them constant, and consistently the same as that of the pumps above and below —otherwise the sumps would either empty or overflow. If this piece of wood was one of two beams supporting a movable handrail, the necessary adjustments for men of different weights working the same pumps at different times could be made by shifting the rail along one or two notches, forwards to reduce output or backwards to increase it.

A second valuable feature of the man-powered treadmill is its mobility. The crane shown on the monument of the Haterii (p. 84) could presumably have been dismantled, and its jib laid horizontally on one or more carts, while the treadmill itself could have been rolled along any reasonably level road (that was also one method used for transporting column-drums). There was, in fact, no other suitable power source available. Wind power is hopelessly unreliable, and a builder would be extremely lucky to have water power available on the site at all, let alone near enough to any particular building. A glance at the later history of cranes shows that the treadmill continued to serve this need right through the Middle Ages and Renaissance, and that the first alternative to be made effectively mobile was steam, as used on railway breakdown cranes. Indeed, the problem is still with us. Owing to difficulties of gearing and transmission the internal combustion engine is not very suitable for large cranes, and the cost of laying supply cables makes it uneconomical to use electricity for anything less than a large and lengthy building project.

The Greeks and Romans also used manpower for the propulsion of virtually all fighting ships. Merchant ships, except for quite small ones, were normally under sail. Warships used sails on long voyages, or while cruising on patrol, but in battle conditions, or during a battle alert, they usually left mast, yard and mainsail ashore, to cut down weight to the absolute minimum, and relied entirely on rowers.

ANIMAL POWER

From remote antiquity there has been a contrast between the working animals used in the Mediterranean area and those used in northern Europe. The predominance of the horse in northern Europe, closely related to climatic and ecological factors, could never have occurred in classical Greece, and did not affect Roman practice to any great extent except in so far as Roman armies came into contact with the peoples of France, Germany and central Europe. The situation in classical Greece is summed up both accurately and poetically by Aeschylus in a passage of his *Prometheus Bound.* The hero, describing his services to mankind, says (lines 462–6)

'And I was the first to link oxen beneath the yoke
With yoke-straps, to be man's slaves, and with their bodies' strength
Give him relief from the heaviest of his toil;
And to the chariot-pole I brought
Horses that love the guiding reins,
Delight and pride of massive wealth and luxury'.

The slowness and ugliness of oxen (a generic word, meaning 'great knobbly beasties' is used in the Greek original) is contrasted with the speed and elegance of horses. The assertion in the last line, that horses were expensive to buy and maintain, is borne out by the fact that several words denoting social and economic status in classical Greece were connected with horses. The word *hippeus,* referring to a particular income-group, originally meant a man wealthy enough to own his own horse and (in wartime) to fight in the cavalry of the citizen army. In Athens the next lower property-classification was *zeugites,* meaning a man who owned a pair of oxen. The historian Herodotus, wishing to stress the great wealth of a particular family, calls them *tethrippotrophon*—able to maintain a four-horse racing chariot (for entry at the races during the great games at Olympia, Delphi and elsewhere). The 'conspicuous consumption' of such a family must have made a deep impression.

By contrast, a pair of oxen could be fed much more cheaply, on inferior fodder of a kind available in areas of Greece and Italy where the pasture was not adequate to support horses. They yielded a return on the owner's investment; they could pull a heavier load than two horses of comparable size. Their progress was slower, but then speed was not the most important consideration in ancient farming or transport. Farm animals had to be fed all the time, whether in use or not; a transport contractor would naturally want to complete each job as soon as possible to be ready for the next. But to use horses to speed up his operations would have been quite impractical. And finally—an important point for people living close to subsistence level—when their working life was over, oxen could serve as food. The meat would be tough as old boot, no doubt, and would need a long spell in the stewpot, but it would be better than nothing. The Greeks and Romans, for reasons not clearly defined but presumably religious, did not as a rule eat horsemeat.

The one advantage that the horse had over the ox was speed, and it was precisely in those situations where speed outweighed everything else that the horse was used—in warfare and in chariot-racing. The high mobility of the cavalry gave that arm its particular role in battle tactics, and on the race-course a chariot, made as light as possible, and drawn by a matched team of two or four horses, represented the ultimate in speed to the Greeks from the eighth century B.C. onwards, and to the Romans after them.

Oxen, then, propelled the heavy lorries of the ancient world, and highly-bred horses its Aston Martins and its Lamborghinis. Between these extremes of utility and luxury came the small travelling vehicle for passengers or light merchandise, drawn by donkeys or mules. These animals could move rather faster than oxen, but not as fast as horses. They cost a little more to feed (in proportion to their weight and pulling capacity) than oxen, but only about 60–70% of the cost of horses.

The use of animals in transport, and the problems connected with harness, are discussed in Chapter 7. Apart from transport, the use of animal power was rare. In mining operations it seems to have been almost negligible, for obvious practical reasons. Unless there was access via horizontal tunnels ('adits'), it would be very difficult indeed to get animals into or out of a mine, and ancient workings did not normally include entrance edits or any galleries or spaces in which animals could be kept, fed and housed underground. The haulage of ores and spoil seems to have been done exclusively by man-power, using buckets on ropes, and it was extracted via the nearest shaft, not taken along any great distance underground.

Until about the first century B.C. animals were not used in milling. The only type of mill which can be operated by a horse or donkey is a rotary mill, and that invention did hot come into the classical Greek world at all. The so-called Pompeian mill, with a fixed lower stone of conical shape, and a rotating upper stone shaped like an hour-glass was quite certainly designed to be turned by animal power, despite the fact that the space available in some of the buildings for the animals to walk round seems very limited indeed. The earlier 'pushing' type of mill, in which a grinding stone is pushed back and forth over a trough, must have depended on human effort. Such work was sometimes imposed on slaves as a punishment, but at all times it had to be done by someone, and as a punishment it was probably not much more severe than the 'spud-bashing' to which army offenders used to be subjected—a tedious, irksome job which nobody would do from choice. Some illustrations of rotary mills being turned by horses give a highly idealized picture of noble steeds striding around; in real life, the oldest and most broken-down horses and donkeys were put to this kind of work—the last stage on the road to the knacker's yard.

Finally, there is a bizarre invention described in a Latin work written in the latter half of the fourth century A.D., but almost certainly never constructed. The author's name is not known, and the work is usually referred to as *Anonymus De Rebus Bellicis*. Oxen are used to propel a ship (Fig. 1). They walk around in pairs, at opposite ends of a capstan-pole on a vertical axle. Through a gearing system (not described, but clearly a crown wheel and pinion, as used in water-mills) this axle drives a horizontal one athwart the ship, with a paddle wheel on each end—the description of the paddles has some verbal resemblances to Vitruvius' description of an undershot water wheel (X, 5, 1.) We are not told whether the paddle-wheel shaft was higher or lower than the platform on which the oxen walked, but since they were 'in the hold of the ship', it seems more likely to have been the former. The total number of oxen is not specified, except that there was more than one pair. Though there is no theoretical reason why this should not work, the whole idea does not sound very practical. The space needed for the oxen to move around would be considerable—a circle of 10ft (3m) diameter at the very least. If we assume three capstans, the ship would require a beam of about 13ft (4m) and a length overall of at least 43ft (13m), and at 'six oxpower' such a vessel would be rather under-engined. Communication between the 'bridge' and the 'engine-room' might also be a trifle difficult.

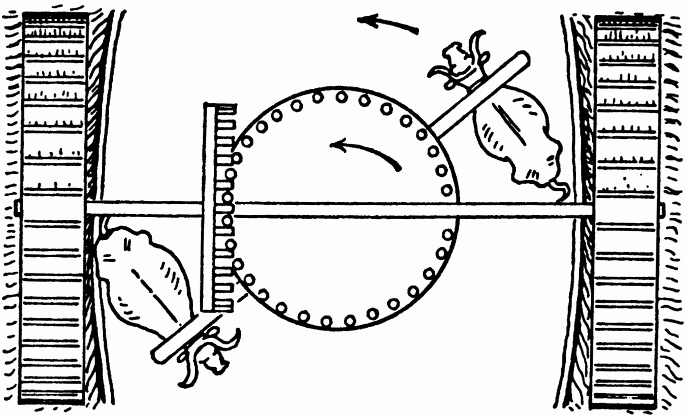

Fig. 1. Oxen used to propel a ship.

WATER POWER

Early Greek poetry contains striking passages in which the destructive force of rushing water is used as a piece of telling imagery, but the problems of harnessing such power and using it to drive machinery were apparently not explored until the early part of the first century B.C. According to the geographer Strabo (XII, 3, 40) a water-mill was built in the kingdom of Mithridates, at Kabeira in the Pontus (near the modern Niksar, N. central Turkey) in the first century B.C., some time before the earliest in Greece or Italy. There may be a simple explanation for this. The basic requirement for a water-wheel is a water supply which is steady all the year round, and, if it is to be anything more than a toy, the quantity of water needed is quite large. Mithridates' city was close to a substantial river, the Lycus (modern Kelkit) which, though the local rainfall is no greater than that of Greece or Italy, has a large catchment area. Relatively few of the rivers and streams of Greece and Italy (except in the north) maintain a substantial rate of flow during the dry season. However, the effect of this geographical fact on the history of the water-wheel should not be exaggerated. Once the basic idea has been put into practice, the conservation and management of limited or fluctuating water supplies follows soon afterwards.

Our knowledge of Greek and Roman attempts to harness water power rests on rather meagre evidence. Among the literary sources, Vitruvius (late first century B.C.) is much the most important, and he gives a clear description of an undershot wheel, which is discussed below. Two other allusions are important for the question of dating. A Greek epigram in the Palatine Anthology (IX, 418) speaks of the joyful release from drudgery which a water-mill has brought to the women servants who previously had to grind by hand. Its author was almost certainly Antipater of Thessalonika, who was closely associated with a Roman noble family, the Pisones. He lived and worked in Italy at the end of the first century B.C., and is probably referring to the installation of such a mill on a country estate. His poem would be contemporary with Vitruvius' work, but there is one interesting difference between the two. Antipater speaks of the Nymphs (which personify the water) as 'leaping down onto the topmost part of the wheel'. Though this has been disputed, there is really little doubt that he is talking about an overshot wheel—a more efficient type than Vitruvius' —and this raises a question of priority, which will be discussed later.

Closely related to this is an allusion in Lucretius' poem *On the Nature of the Universe,* where the poet is speaking about the movement of the heavenly bodies (V, 509–33, particularly 515–6). It is a difficult and obscure passage, but the gist is that one explanation of the apparent diurnal rotation of the heavens is that a current of air circulates around the universe, causing the 'sphere' to rotate 'as we see rivers turning wheels and buckets *(rotas atque haustra)*'. Since Lucretius uses this as an illustration, he clearly assumes that water-wheels are familiar to his readers, and as he was writing some 40 years earlier than Vitruvius and Antipater, this suggests that the use of water power to work pumps (bucket-wheels or bucket-chains, see Chapter 3) came earlier than its use for milling.

Other literary allusions add little or nothing to this. The archaeological evidence is equally scarce, but very informative. Two important wheel sites have been excavated—one in the Agora at Athens, to the south of where the restored Stoa of Attalus now stands, dating from mid or late fifth century A.D. The other is at Barbegal, near Arles in southern France (just north of the Camargue). A very big installation was built there by the Romans in the late third or early fourth century, and was probably in use for the greater part of 100 years. It contained eight pairs of wheels, each driving millstones in a mill-chamber beside the wheel-pit, and its output would have been adequate not only for the 10,000 inhabitants of Arles, but for some area around. The presence of a Roman garrison might account for this. The remains are not very extensive, but the main essentials can be reconstructed from them. Evidence of an undershot wheel (in the form of chalk incrustation, the wood having all disappeared) has been found at Venafrum in central Italy, and a speculative reconstruction can be seen in the technology section of the Naples Museum.

There are three basic types of water-wheel—the vertical-shaft, the undershot and the overshot. The vertical-shaft wheel has a number of blades inclined at an angle of about 30° to the vertical, fixed to a hub near the bottom of the shaft. The water is directed onto the blades through a wooden trough which slopes down at a steep angle, so that the water strikes them at high speed. This requires a situation where there is a drop of some 10–12 ft (3m) immediately beside the water source. Sometimes a pit can be dug for this purpose, but adequate arrangements have to be made for the spent water to drain away from it. Since the shaft is vertical, it can be made to turn millstones directly, without any need for gears.

In the absence of any conclusive evidence, some historians of the subject have used the following argument: This is the 'most primitive' form of water-wheel, so, since the Romans developed the more sophisticated undershot and overshot wheels (for which we have good evidence), we must assume that they started with the vertical-shaft type. The parallel between this supposed sequence and that attested for Renaissance Europe is also invoked in support. This *a priori* argument is attractive, but it does rest on two doubtful assumptions (a) that milling was the first operation for which water power was used—and the passage from Lucretius quoted above makes this very doubtful—and (b) that gearing of some sort had not been previously invented for other purposes, such as coupling animals to a water-pump. Archaeological evidence (or rather, the lack of it) does not help to decide the question. No certainly identifiable Greek or Roman remains of this type of wheel have been found, but the entire structure, including all the water-guidance system, would have been made of perishable material. By contrast, the overshot wheel required a stone-built wheel-pit, which has good chances of survival, and can be identified as such.

The second basic type of wheel is the undershot, sometimes called 'Vitruvian' from that author's description (X, 5). It is highly significant, and consistent with the evidence from Lucretius, that he first introduces the water-wheel as a power source for working a bucket-chain, and then says, 'It is also used for corn milling, the design being the same except that there is a gear-wheel on one end of the axle . . .' He makes no mention of the vertical-shaft wheel. The structure he describes is very simple (Fig. 2). It consists of a spoked wheel of unspecified diameter, with vanes or paddles around its circumference (Vitruvius calls them *pinnae,* a word used elsewhere to mean the wing-feathers of a bird), which are driven round by the current in the river. There is nothing in his words to suggest that a mill-leat was channelled off for the purpose.

The third and most efficient type of wheel is the overshot (Fig. 3). Using the same kind of argument as with the vertical-shaft wheel, it is usually held that this was developed from the undershot wheel, the intermediate stage in this process being the so-called 'breast-shot' wheel, which is a simple modification of the undershot, the water being supplied through a trough level with the