Industrial Archaeology of Watermills and Waterpower

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Project Technology Handbook

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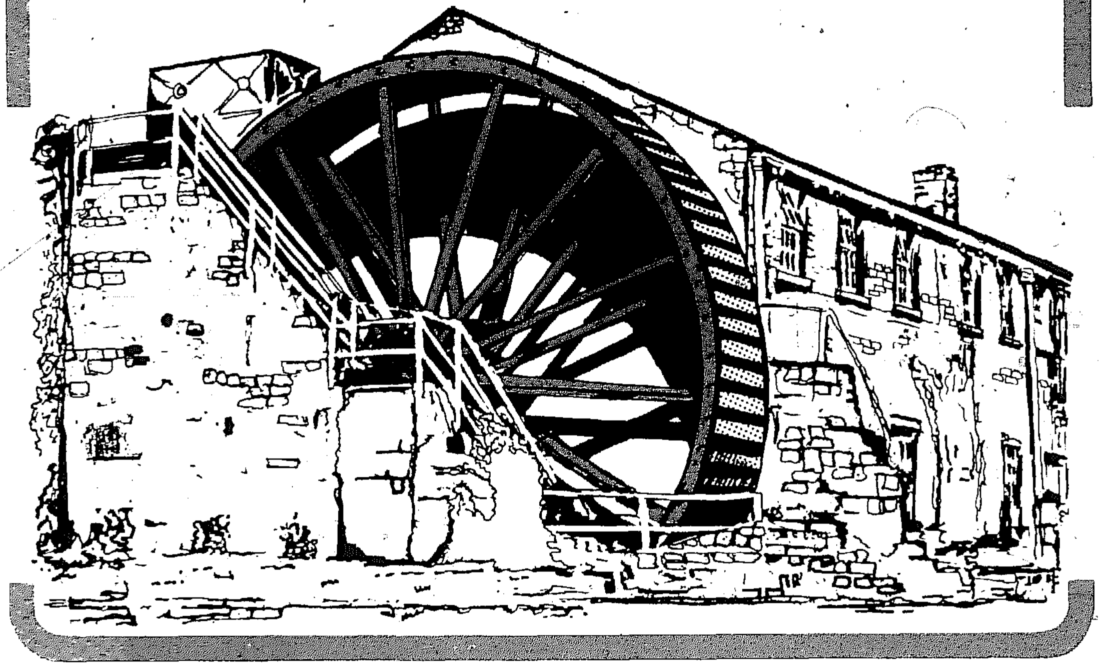
INDUSTRIAL ARCHAEOLOGY OF WATERMILLS & WATERPOWER



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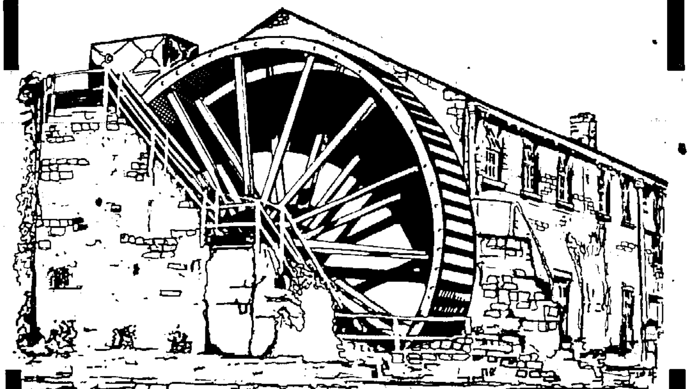

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Foreword

Technological activities are now firmly established in many schools. They have been introduced by diverse methods, but they are here to stay – and to develop further, given the help of publications such as this.

Sometimes teachers turn to Project Technology publications for general guidelines, at other times for more specific guidance. Some teachers aim to put over a body of knowledge, while others are concerned to develop in their students an attitude of mind and technological know-how invaluable in problem solving. Sometimes technological activities have originated in science departments, sometimes in school workshops, but usually they have developed to embrace or touch upon every department of the school. The whole range of teaching material produced by Project Technology is intended to help teachers achieve the balance natural in their schools.

These publications play a vital role in realizing the central aims of Project Technology to see that all students become aware of the technological forces of significance for society, to give as many students as possible opportunity to become involved in the technological design process, and to help them push forward the frontiers of their own technological resources in terms of both theoretical knowledge and practical skills.

Many people, particularly those responsible for the diversity of activities in the regional groups of Project Technology, have played important parts in developing and writing teaching material. In the case of *Industrial Archaeology of Watermills and Waterpower* (and its companion volume, *Industrial Archaeology for Schools*) we are indebted to Mr Geoffrey Starmer, formerly head of the Education Unit at Lanchester Polytechnic (Rugby), and now a Senior Adviser with Northamptonshire Education Department, for developing and writing up this material.

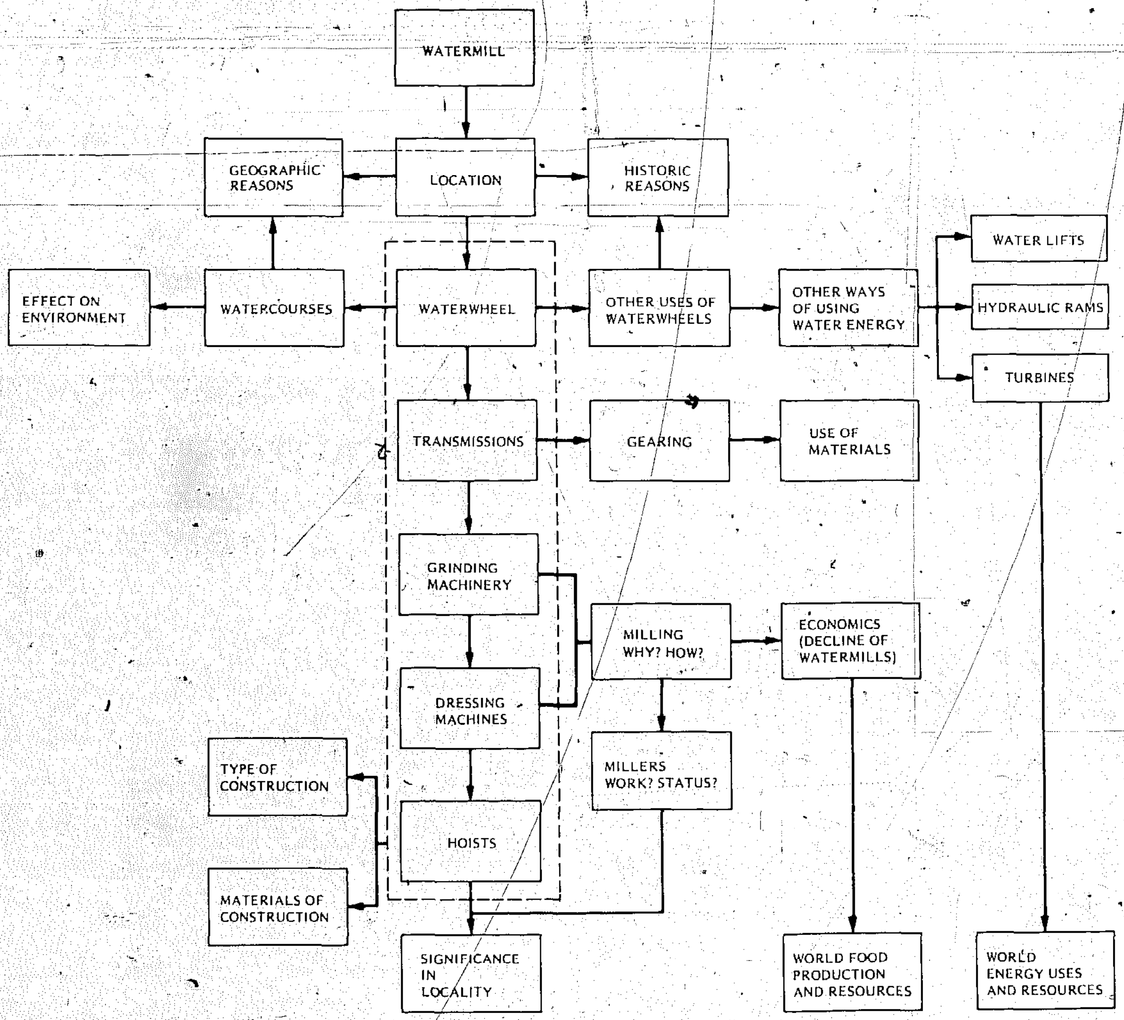
1975 *Schools Council Project Technology*

Introduction

Industrial Archaeology for Schools showed how a general approach to industrial archaeology can link science, technical, and arts subjects within the school in a way that helps to bring these subjects alive in the context of the community, past and present, around the school. A wide spectrum of past industrial activity was deliberately covered by this handbook in order to show teachers how they might make industrial archaeology a vital and meaningful study for their students.

This further handbook, *Industrial Archaeology of Watermills and Waterpower*, shows how a particular topic can be developed in depth. Although waterpower has been used for many industrial purposes, the most common evidence of waterpower application throughout the country is in connection with corn grinding. Therefore for many schools, the waterpowered corn-grinding mill is one of the most promising starting points for work in industrial archaeology.

It was stressed in *Industrial Archaeology for Schools* that most subjects in the school curriculum can be related to industrial archaeology. The diagram shows how a number of school subjects can be related in particular to the industrial archaeology of watermills.



Relationship of industrial archaeology of watermills to school subjects

1 Industrial archaeology of watermills

1.1 HISTORY OF WATERPOWER

One of the earliest known machines for utilizing waterpower is the noria or 'Persian wheel' shown in fig 1.1 used for irrigation purposes in the great river valleys of the Near East. There is evidence that these wheels were already known by the second century BC, and examples can still be found in Syria, some as large as 21 m diameter.

Various versions of the noria wheel existed, of which one form was a light wheel rotating on a horizontal axle and fitted with paddles which dipped into the stream where the current was relatively swift, so causing it to revolve. Small 'buckets' or pots attached to the rim were filled with water as the paddles dipped into the stream, and emptied near the top of the rotation of the wheel, as shown in fig 1.2.

The noria wheel was a self-contained device, not used to drive any other machine, but it may have influenced the arrangement of the horizontal-shaft Roman mill first described by Vitruvius (see Section 1.2, page 10). However, before this was introduced waterpower had been applied to corn grinding in the form of what was later known as the Greek mill (fig 1.17, page 10) or Norse Mill (in Northern Europe). Despite their inefficiency, these primitive horizontal waterwheels were applied for other purposes than milling; it is recorded that one was used to operate bellows in China in 31 AD. The horizontal wheel (known as the 'tirl' in northern areas) originally used flat wooden blades, the number varying between four and twelve. Paddles, curved in plan and carved from solid wood, were introduced later although flat blades continued in use.

However, until the fifteenth century the main developments in waterpower concerned the Vitruvian-type mill which by the fourth century was being used in increasing numbers.

The earliest vertical waterwheels were of the undershot type, but soon after their introduction the Romans realized the advantages of utilizing the weight of falling water as well as the velocity of a flowing stream for providing power. Where the levels of the ground were suitable water was carried over the top of the wheel, whose paddles were arranged to hold the falling water and so make use of its weight to drive the mill. Such overshot waterwheels were used in a remarkable installation (illustrated in fig 1.3) at Barbegal, 9.5 km from Arles, near the mouth of the Rhone in Southern France. Built in the early part of the fourth century in the time of Constantine, the power was obtained from eight pairs of overshot waterwheels (each 2.2 m diameter and 0.7 m wide), each driven by the tail-water from the wheel above and driving a pair of mill-stones of about 0.9 m diameter. With a total fall of 2 m it has been estimated that 28 tonnes of corn could be ground in a ten-hour working day – sufficient to feed a population of 80 000.

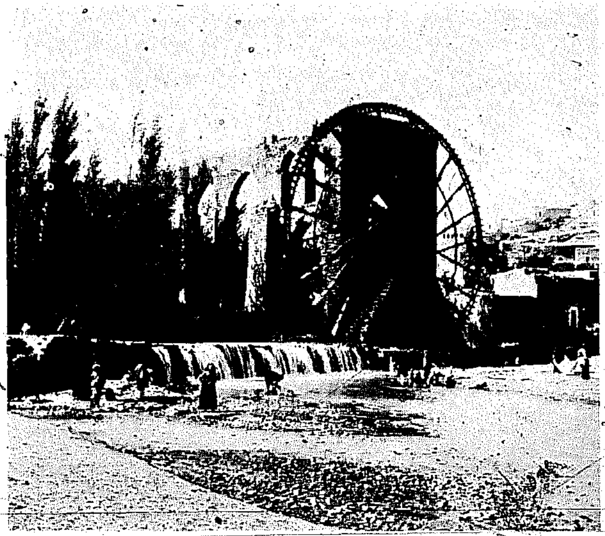


Fig 1.1 A current wheel at Hama, Syria, lifting water from the River Orontes by means of pots fixed around its circumference and discharging into the aqueduct just below the top of the wheel

Photo: Science Museum, London

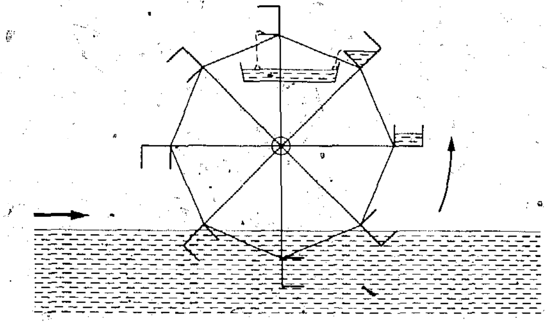


Fig 1.2 Principle of wheel of pots

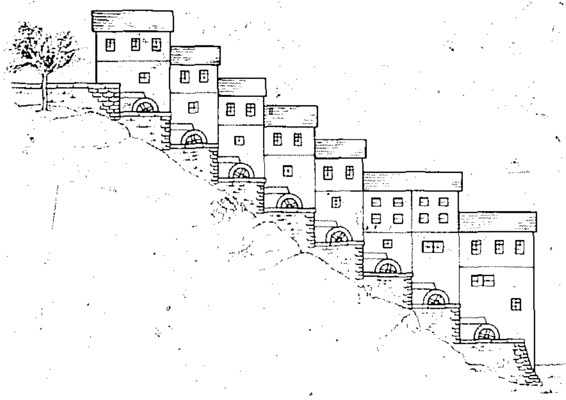


Fig 1.3 Diagram of Barbegal watermills

This was probably the largest waterpower installation in the whole world for fourteen to fifteen centuries.

In 536 AD, Vitiges, King of the Goths, besieged Rome and cut off the aquaducts which supplied the mills. This caused so much distress in the city that the Byzantine general Belisarius built floating mills which were moored in the Tiber, the wheels being driven round by the velocity of the current. Such floating mills were used on the River Tigris in the tenth century, on the River Seine in Paris in the twelfth, and on the River Thames in the sixteenth and seventeenth centuries. They were common on the Tiber and Danube in the nineteenth century, and some survive there today. Unlike most other waterwheels, the floating mills have the advantage of constant water level in relation to the wheel.

After the fall of Rome, the first developments in utilizing waterpower seem to have been the introduction of tide mills, from the eleventh century onwards, in this country. With these mills, a causeway was erected to retain water at high tide. The flood tide entered the enclosure through sluice gates which closed as the tide ebbed. As soon as the water level below the mill had dropped to the level of the tail-race, sluices were opened to allow the retained water to run away through the mill-race and so turn the waterwheel.

Soon afterwards, we find references to the use of waterpower other than for milling. In England, in a survey of the Templar's lands in 1185, there is mention of a 'molendium fulerez' or fulling mill at Newsham in Yorkshire, and another at Barton in the Cotswolds. Fulling is a process in the woollen trade. After weaving, the cloth is pounded in water to shrink it and to increase the density of the material by causing the fibres to bind together. During this process the cloth is cleaned by adding fuller's earth to remove the oil with which the wool was impregnated for spinning. Originally, fulling was done by hand with clubs or by trampling the cloths underfoot. This method was replaced by the waterwheel-driven fulling mill, fig 1.4, consisting of one or more hammers, actuated by trips operated by the waterwheel, which automatically beat the cloth in wooden troughs.

This operation demanded a minimum amount of supervision and physical effort from the workmen. The other processes involved in the production of woollen cloths (carding, spinning, and weaving) were carried on as cottage industries until the eighteenth century, but the advantages of the waterpowered fulling mill were sufficient to carry the woollen trade to those parts of the country where waterpower was available. This did not happen quickly, but whereas in the twelfth and thirteenth centuries the cloths being exported were 'of Stamford', 'of Lincoln', 'of Louth', 'of Beverley', and 'of York', by the fourteenth and fifteenth centuries the demand was for 'Kendals', 'Ludlows', 'Cotswolds', 'Strouduates', or 'Westerns'. Thus it seems that the advent of the water-driven fulling mill was one of the major factors influencing the movement of the woollen industry from urban to rural sites and from the south and east of England to the north and west.

Another industry which began to use waterpower was the iron industry. In the early iron smelting processes, the iron did not run out in the molten state for casting but was removed as a pasty lump ('bloom') of crude iron which was hammered to expel most of the slag. At first the hammering was by hand, but as the blooms became larger more powerful methods were required. There is a French record of a *moulin de fer* as early as 1249, and charters of 1311 refer to *molendina ferrea.* These could refer to water-driven tilt hammers which were probably adapted from the fulling mill. Fig 1.5 shows the operation of the tilt hammers.

In this country, the early centre of the iron industry was in the Weald, and the ironmasters in Kent, Sussex, and Surrey were eventually in difficulties due to the lack of suitable waterpower potential.

Considerable expense was involved in building and maintaining 'hammerponds' in order to conserve water. Even

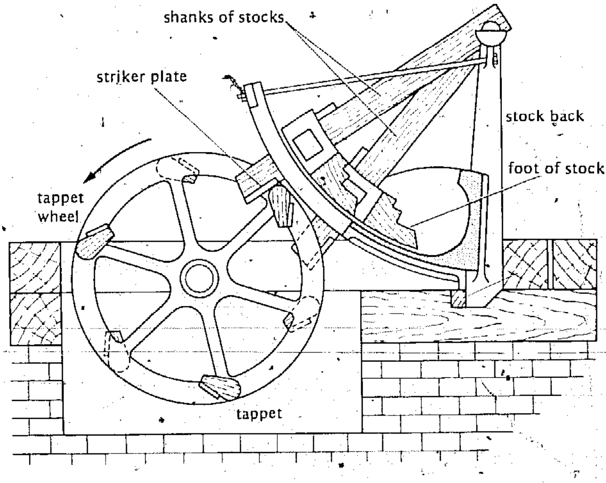


Fig 1.4 Fulling mill driven by waterwheel-driven trip hammers

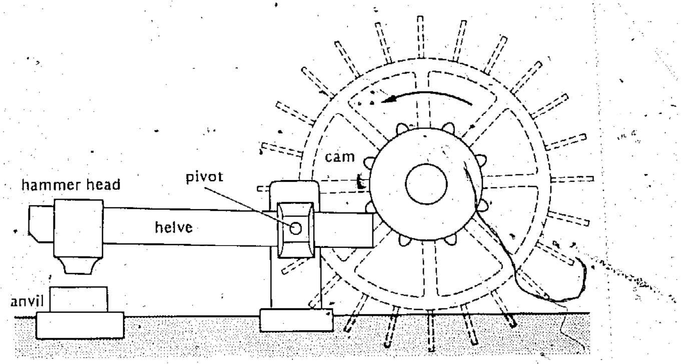


Fig 1.5 Tilt hammers for working iron

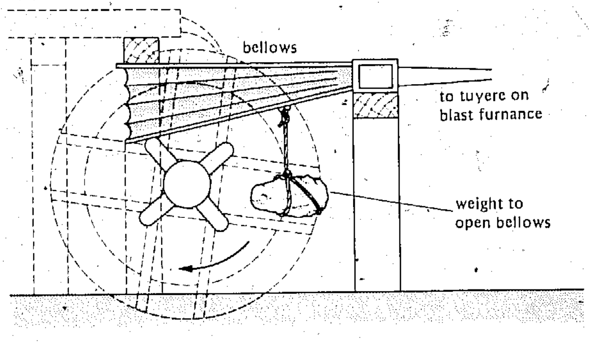


Fig 1.6 Water-driven bellows used in blast furnaces

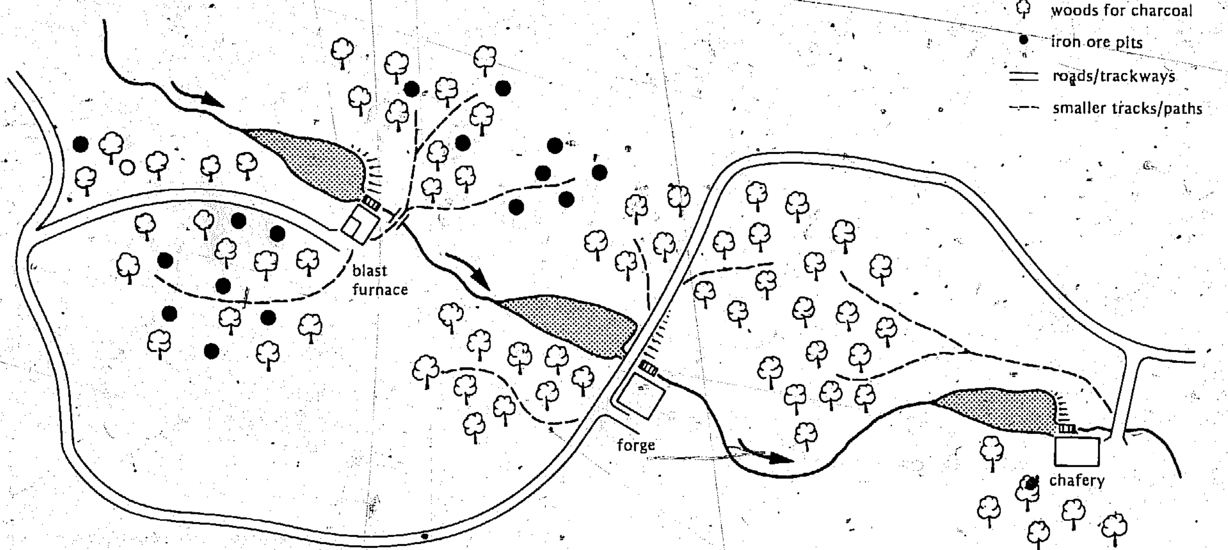
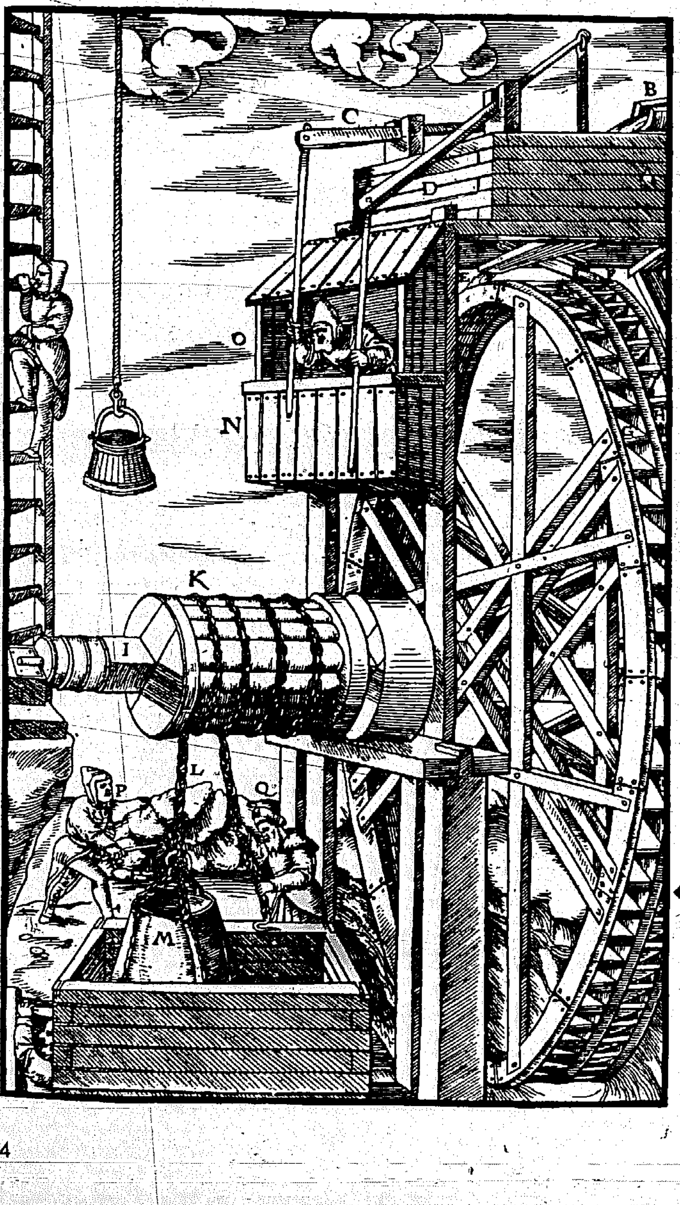
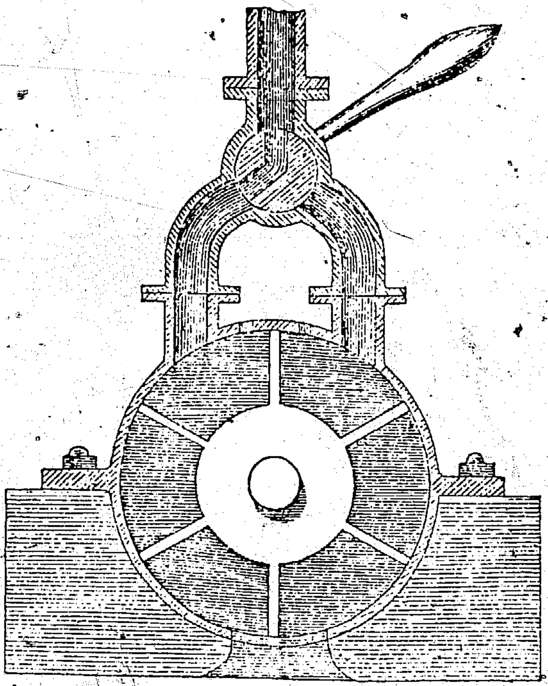


Fig 1.7 Three ponds for providing water power for the blast furnace forge, and chafery sites



By courtesy of Science Museum, London



▲ *Fig 1.9 A reversible waterwheel as used in the American gold mining areas. The direction was changed by turning the rotary valve on the inlet 120°*
From *On the power of water to turn mills*, by J Glynn, 1853

◀ *Fig 1.8 A sixteenth century example of a reversible waterwheel. The overshot wheel has two rows of buckets set facing opposite directions. The man at O, by means of rods and levers, is able to direct the water into either row of buckets. When he directs it through trough E on to the nearest row of buckets, the wheel will rotate anti-clockwise: if directed through F onto the furthest set of buckets, the wheel will turn clockwise. This was used to lift buckets of water and lower them again to the bottom of a mine*
From *De Re Metallica* by Georgius Agricola, 1556

so, the small streams feeding them sometimes failed completely in summer and it has been suggested that the very dry years of 1737 to 1750 contributed, along with the depletion of the natural forests, to the eventual demise of the Wealden iron industry. With the introduction of the blast furnace (an early reference to a blast furnace in England records one at Newbridge, Sussex, in 1496), waterwheels were used to supply the necessary blast and there was an increase in the demand for power because of the extra processes involved. See fig 1.6 on page 3.

The blast furnace produced molten iron which was cast into pigs. At that time the demand was still for wrought iron, so that the cast-iron pigs were taken to a forge where they were reheated in a charcoal-fired hearth or finery and stirred about whilst air was blown on it. The oxygen in the air combined with the carbon in the iron, thus gradually converting the cast iron to wrought iron. On removal from the finery, the iron was hammered into a roughly rectangular block, usually by means of a water-driven tilt hammer. To work the iron into its final shape, it was reheated once again in the chafery and hammered to the required form, also by tilt hammers. In many places the water supply was unable to provide the power required for the blast furnace, forge, and chafery when situated close together. To obtain the necessary power, the three activities were carried out some distance apart so that a suitably large pond could be available to serve a waterwheel for each operation. See fig 1.7.

By 1550, when Georgious Agricola completed his famous book on mining, *De Re Metallica* (first published in 1556, after his death), waterwheels were being used in central Europe for crushing ore, pumping, ventilating, and winding, in addition to blowing. Nearly all of the illustrations in Agricola's book show overshot waterwheels, and one, fig 1.8, depicts a waterwheel capable of reversing its direction of rotation. A later reversible waterwheel is shown in fig 1.9.

By the sixteenth century, the breastshot wheel had been introduced, and gave some of the advantages of the overshot wheel without the necessity to build elaborate earthworks and launders. The breastshot wheel required a definite head of water so that the number of waterpower sites which could work on a particular stretch of river became more limited. This gave rise to disputes between adjacent mill owners, and the number of law suits at this time increased enormously.

Up to this time the waterwheels were virtually all of wood, but during the sixteenth and seventeenth centuries wrought iron was introduced for parts subjected to heavy wear or loading, such as the gudgeons, inserted into the timber shafts, which rotated in the wheelshaft bearings.

As the demand for power increased it could not be satisfied by the seam engine, which was still in its infancy. (The first economic steam pumping engine was invented by Thomas Newcomen in 1712 for dewatering mines but was later adopted for other purposes.) The first textile mill was Thomas Lombe's silk throwing factory at Derby, which opened about 1721; 150m long and six storeys high, the considerable amount of machinery was driven by waterpower. Twenty years later, Lewis Paul and John Wyatt's roller method for the mechanical spinning of cotton was used in the Northampton Cotton Mill, which was driven by a waterwheel. Although this may have been the world's first power-driven cotton mill it was not successful, and it was Arkwright's mill at Cromford, completed in 1772, which laid the foundation for mechanizing the cotton industry. The invention, in 1785, of Cartwright's power loom increased production in the industry, which became even more dependent upon a reliable form of power.

It was at the start of this period of enormous increase in demand for power that John Smeaton made the first scientific study of waterwheels in 1752–3. He constructed a model which would run either as an undershot or overshot wheel, and measured the power output by the time necessary to raise a weight through a given height. The input, or rate of flow of water onto the wheel, was measured by the number of strokes of a pump of known dimensions to maintain a given head of water in the tank supplying water to the wheel. See fig 1.10.

Smeaton realized that a considerable amount of energy was lost when a jet of water struck the flat paddle of an undershot wheel, and that it was better to develop power by

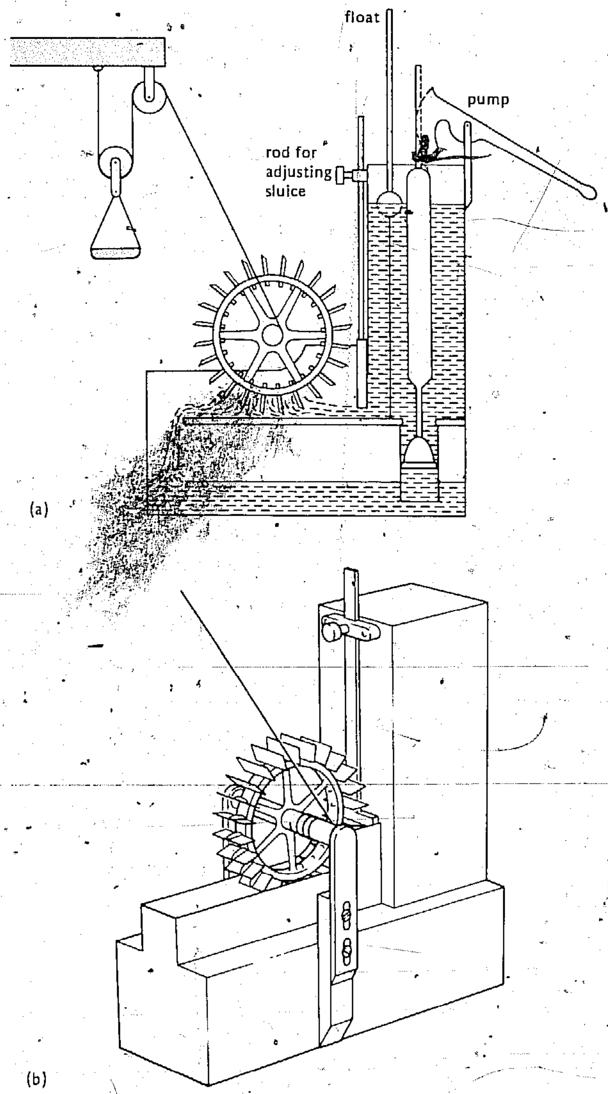


Fig 1.10 Smeaton's apparatus for (a) experiments with waterwheels, (b) means of altering position of wheel relative to sluice

filling the buckets of an overshot wheel. Assuming his relevant measurements were correct, he obtained 22 per cent efficiency with an undershot wheel and 63 per cent with an overshot wheel.

About this time, the efficiency of the breastshot wheel was considerably enhanced by introducing a close-fitting curved facing to the weir at the wheel. Waterwheels were built with larger diameters and widths than previously but were often not strong enough to produce the power expected. The weakest component was the shaft, and in 1769 John Smeaton fitted what is thought to be the first cast-iron shaft to a waterwheel driving a blowing engine at Carron Ironworks. There were difficulties in producing large castings so that many composite wheels were made using wood and iron, but by the turn of the century waterwheels were being produced with complete frames of iron, with wood used only for the paddles.

Already some industrial concerns were worried about the lack or uncertainty of waterpower at the sites on which they had been established. In 1777 James Watt erected one of his beam pumping engines at Soho to return tail-water to the waterwheel in times of drought. A model of the pumping engine is shown in fig 1.11.

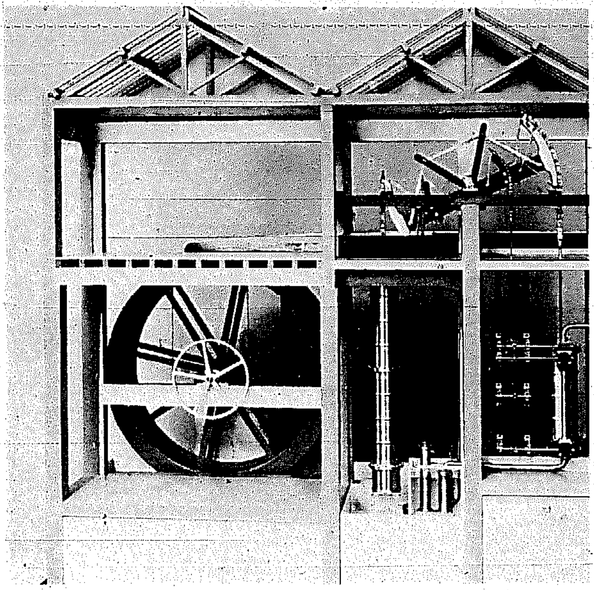


Fig 1.11 Model of 'Old Bess', erected at Matthew Boulton's manufactory at Soho, Birmingham, in 1777. Its duty was to pump water from the tail-race back into the head-race serving a waterwheel of 7 m diameter and 2 m wide, at times when the natural flow of the stream was inadequate. It has been estimated that the combined efficiency of the engine and waterwheel was about one-half of the mechanical efficiency of a rotative engine directly coupled to the shafting driving the machinery in the manufactory

Crown copyright. Science Museum, London

Joshua Rigley's rotary steam engine, fig 1.12, was also used to provide a head of water for an overshot wheel. With the chamber A almost filled with water, as shown in fig 1.12, a valve at D was opened to allow steam from the boiler B to enter the chamber A. The pressure inside A was then sufficient to open the 'clack', or self-operating valve, at F against atmospheric pressure, so discharging the water into the pentrough R feeding onto an overshot waterwheel, W.

When chamber A was almost full of steam, the steam valve was closed and another valve at D opened to inject cold water into A. The steam condensed and the atmospheric pressure on the water in the tail-race, H, caused the clack at G to open and allow water to rise up the vertical pipe and enter chamber A. When this was nearly full, the cycle of operations was repeated.

The steam inlet and injection water valves at D were worked alternately by two push rods (although only one is apparent in the diagram) operated by a cam plate, T, fixed to the waterwheel.

It was not until 1783 that Watt produced the first rotative engine, but over 300 of these were supplied by Boulton and Watt before the patent for the separate condenser (which gave their engines superior efficiencies compared with others) expired in 1800. It has been estimated that on average these engines gave about 11 kW. Despite their condenser patent, Boulton and Watt did not have a monopoly on the construction of rotative steam engines. Besides builders who 'pirated' the idea of the separate condenser, there were many engines built without it, ranging from rotary power adaptions of the inefficient Newcomen-type engine, to those built by the Manchester firm of Bateman and Sherratt which were identical to those of Boulton and Watt except for the separate condenser which was to be added as soon as the patent expired.

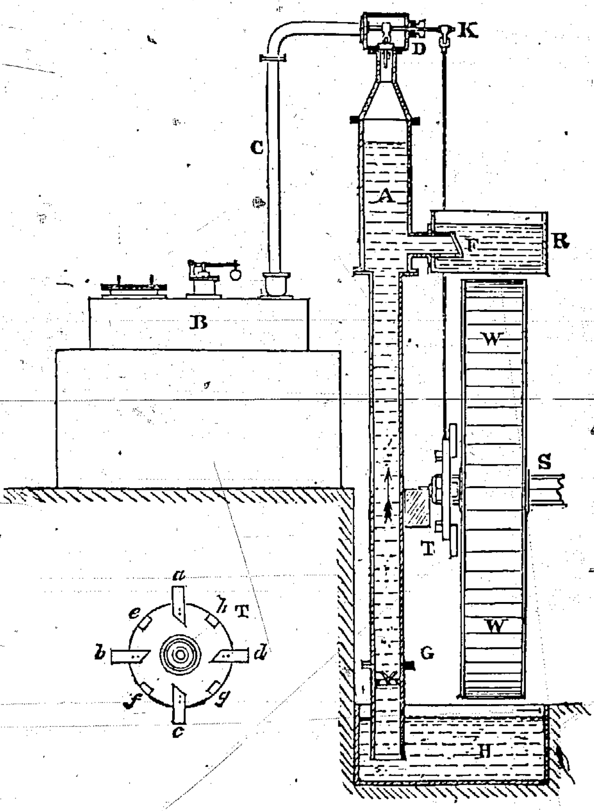


Fig 1.12 Arrangement of Joshua Rigley's rotary steam engine
(Reproduced from *Nicolson's Journal*, vol 1, 1797)

During this time it seems that waterwheels were still providing a large proportion of the country's power requirements and improvements were still being made in their design. A difficulty encountered with the overshot wheel was that its lowest buckets moved in the opposite direction to that of the flow of the tail-water. If the level of the tail-race rose so that the lower buckets of the wheel were submerged, the condition was described as 'back-watering' and the power output of the waterwheel was reduced. This was overcome by the introduction of the 'pitch-back' type, which was particularly useful when the water levels in the tail-race were liable to marked fluctuation.

Another trouble was encountered with the varying head of the water coming onto the wheel. For maximum efficiency, the largest available head needs to be used and to allow for this, John Rennie, in about 1783, invented a sliding hatch mechanism. This consisted of a fixed set of inclined slots in a curved plate following the shape of the outside of the wheel. The lowest slot was just below the water-level at minimum head, and the top slot was just below the water level at maximum head. The sliding hatch was a curved iron gate, operated by rack and pinion, to cover any of the slots. The maximum available head was utilized by lowering the hatch as the water level fell. This is shown in fig 1.13.

In 1824, the French engineer J V Poncelet greatly improved the efficiency of the primitive undershot wheel by channelling the water below an inclined sluice and, using sheet iron, was able to give the paddles a carefully calculated curve so that the water entered and left the wheel with very little shock. Large numbers of Poncelet wheels were installed during the nineteenth century. The principle of operation is shown in fig 1.14 on page 8.

The power from the waterwheel was normally transmitted through its shaft. However, since the wheels rotated comparatively slowly, the torque on the wheelshaft was high compared with the power transmitted. Even with an iron shaft, there was a limit to the power which could be developed if the shaft diameter was not to be uneconomically large, to prevent it failing under the shearing action of the high torques. Early in the nineteenth century, this difficulty was overcome by the introduction of rim drives in which a gear wheel was built up inside the rim of the waterwheel and transmitted power to a small pinion. This would run at very high speeds so that there was only a small torque on its shaft and the main shaft only had to be strong enough to support the weight of the waterwheel,

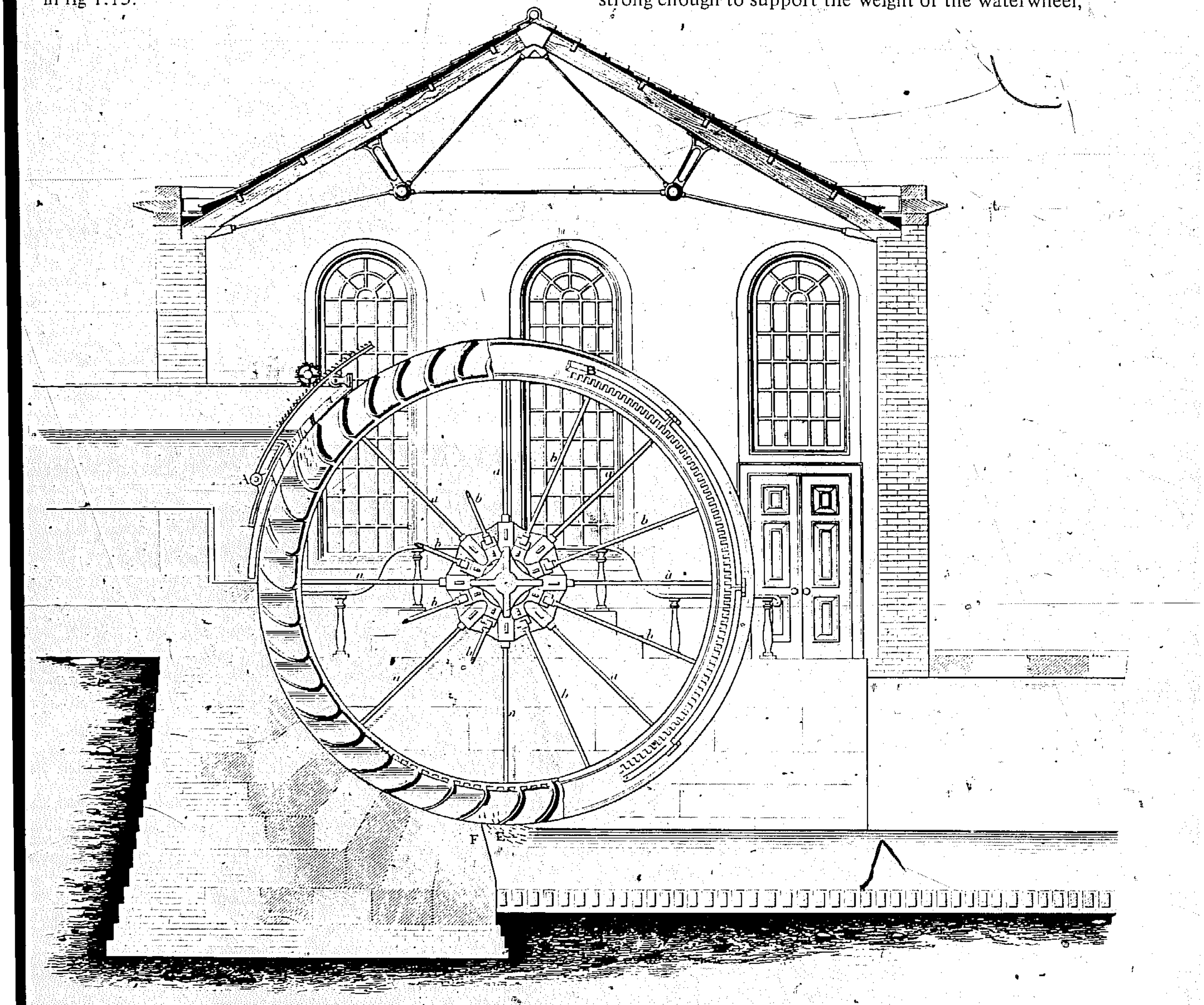


Fig 1.13 High breast wheel with Fairbairn's ventilated buckets and Rennie's hatch, operated by a pinion on a curved rack

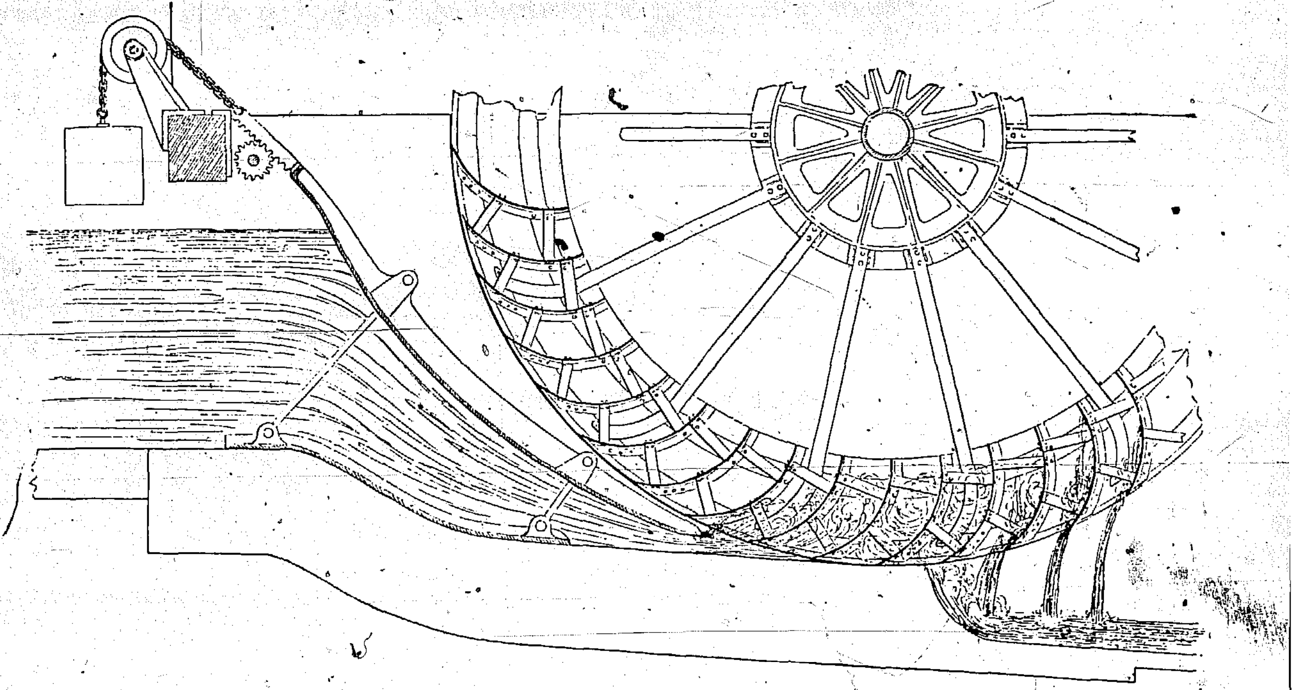


Fig 1.14 The Poncelet wheel – a great improvement on the primitive undershot wheel
From *On the power of water to turn mills*, J Glynn, 1853

which itself could now be of lighter design with spokes and bracing of wrought-iron rods in tension. (There was reputed to have been a waterwheel in Ireland with chains holding the rim and buckets to the shaft!) This opened the way to designers of even larger and more powerful waterwheels.

With the very large waterwheels, there were troubles due to air being trapped in the buckets as the water entered, so that the buckets did not get the required quantity, and also due to difficulties in emptying the buckets when the bottom of the wheel was running submerged. William Fairbairn introduced ventilated buckets, fig 1.13, which enabled the air to escape so that the water could enter more quickly and, at the bottom, for the air to re-enter, thus helping the water to discharge faster. He estimated that this modification gave a 25 per cent increase in power.

With these various improvements, some very powerful waterwheels were built during the first half of the nineteenth century. They needed good supplies of water, and the mill owners sought this either

1 by building their mills high up the valleys where the streams flowed swiftly and there was high rainfall, or
2 by constructing dams and mill-ponds to conserve the water from a relatively small flow so as to provide several hours of adequate supply, or
3 by participating in water supply schemes.

The earliest of these large-scale schemes in this country was Shaw's Waterworks for the supply of power and domestic water to Greenock which was completed in 1827. There were three reservoirs having areas of 150, 15, and 5 ha respectively, and a watercourse 9.7 km long bringing the water to the town (instead of the mills having to be built in remote places where water power was available). Several similar schemes were prompted in this country and also in America.

The following examples give an indication of the size and power of waterwheels at this time:

1 In 1827 a waterwheel 7 m diameter × 5 m wide gave 66 kW at Arkwright Mill at Bakewell. This was used by the DP Battery Company until 1955.
2 About 1830, a 21 m diameter wheel, 4 m wide, provided 142 kW at Shaw's Cotton Spinning Co, Greenock. This was one of the waterwheels supplied by Shaw's Waterworks, mentioned above.
3 About 1840, a 15 m diameter wheel, 3 m wide, gave 65 kW when pumping Wheal Friendship Mine near Tavistock, Devon.
4 In 1843, the British firm of Bryan Donkin built a wheel 23 m diameter and 0.6 m wide which was exported to Italy to drive a felted cloth mill.
5 In 1854 the Great Laxey Mining Co, on the Isle of Man, erected a 21 m diameter, 2 m wide pitch-back waterwheel weighing 100 tonnes giving 17.2 kW at 2½ rev/min and known as The Lady Isabella Wheel. This was used to pump water from a lead mine. The wheel was used until 1929, when the mines were abandoned, but is still standing as a tourist attraction (fig 1.15). The wheel axle is 5 m long and 0.5 m diameter, and has a crank of 3 m throw by which the power was transmitted to a series of horizontal oak connecting rods, carried on wheels running on an arched stone causeway to the top of the pump shaft 180 m away up the valley. See fig 1.16. The pump rod was 450 m long and lifted more than $1\ m^3$ per minute.

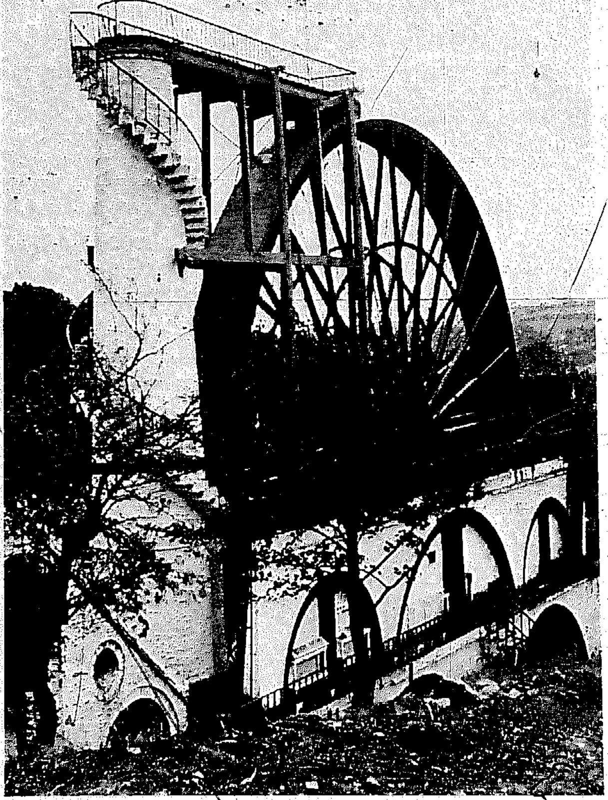


Fig 1.15 Pitch-back waterwheel at Laxey, Isle of Man. The water was supplied from a reservoir higher up the valley, the head of which is sufficient to raise the water up to the top of the circular tower and on to the launder serving the wheel. Note the stationary curved cover over the wheel near the tower, to prevent water being blown out of the buckets on the wheel. The crank, on the wheelshaft, is partly hidden by the tree in the foreground, but the connecting rod to the bell-crank lever and counterbalance weight is visible on the right of the masonry supporting the wheelshaft

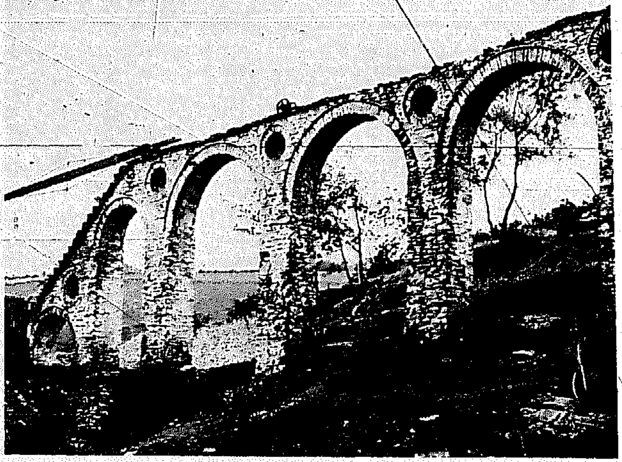


Fig 1.16 Some of the stone arches which used to support the series of connecting rods, the ends of each carried on wheels, which transmitted power to a bell-crank lever above the pump shaft, a quarter of a mile up the valley

6 In 1864 a 190 kW wheel, 17 m diameter, 4 m wide, was built at Rishworth Mills, near Halifax. This weighed 70 tonnes and is reputed to have been made up of 29 300 separate pieces. It was dismantled in 1949 and replaced by a turbine.

However, by 1840 the steam engine had become the generally accepted prime mover and was able to supply the enormous increase in demand for power. No longer was the availability of waterpower an influence upon the development or location of industrial activities, and soon steam engines were being built, each capable of providing thousands of kilowatts – an amount impossible with waterwheels in Britain, although in the USA, in 1822, on the Merrimack River near Lowell, high efficiency waterwheels developed a total of 7.5 mW.

In this country, the use of existing waterwheel installations declined throughout the nineteenth century, mainly for two reasons:

1 From the beginning of the century, the drainage of land was considerably improved. Although benefitting the land, this had an effect on the character of the rivers in that at times following rainfall there was flooding with rivers running very fast, and at other times their flow was as much reduced. This great variation made it impossible to work wheels economically at some sites.

2 There was an increasing diversion of water from higher districts to supply the domestic needs of the expanding towns and cities. Although mill owners stoutly defended their compensation-water rights, they were usually persuaded to give way due to the availability of alternative sources of power.

On the continent the situation was different, particularly in France where early in the nineteenth century successful attempts were made to use an improved device, the water turbine, to harness the water power resources there. The development of the turbine is dealt with later in Section 3.

1.2 HISTORY OF CORN MILLING

Modern wheats are derived from wild grasses which seem to have been first cultivated in the Middle East, at least 5000 years before the birth of Christ. Subsequent improvement of the strains by selection and experiment enabled wheat to become the main food crop in many countries throughout the world.

As soon as early man began to eat the grain or berry of the wild grasses, he must have realized the need for some preliminary crushing process. The first crushing would probably have been by pounding the grain between stones, and this operation developed to the use of pestles in stone mortars. This method was definitely used by the Egyptians, and on the evidence of one of the pictures that decorated the house walls in the town of Thebes, the crushed grain was emptied from the mortar into a sieve for sifting the bran from the flour.

Mills of the pestle and mortar type are based on the impact principle, but this was inefficient in its use of man's muscle power. By 4000 BC a true grinding action was produced by working a rubbing stone backwards and forwards across a base stone which eventually was given a saddle shape and resulted in the so-called *saddle quern.*

By the time of classical Greece, the *pushing mill* had been developed. In this, both stones were flat and grooved, with the grain being fed from a hollow in the upper surface of the top stone through a slot onto the grinding surfaces at the interface of the two stones. In some cases the top stone was fitted with a stick running across it as a handle by which to-and-fro circular motion was given to the top stone.

Another line of development seems to have started with grain rubbers in the form of a concave dish similar to a very shallow mortar, with a squat spherical rubbing stone like a bun-shaped pestle. With the addition of a handle eccentric to the axis of rotation in the top stone, this became the *rotary quern.* These were small, about 30–45 cm diameter at the most, and this type of mill seems to have reached southern England during the first century BC.

In the early combinations of mill-stones they tended to touch each other and contribute stone grit to the meal. The grit contained in the bread from such flour is reputed to have continued its grinding action on the teeth of those eating it, hence the pointed teeth found in the skeletons of early man. The arrangement of the stones gradually evolved so that a stage was reached in which the upper stone was carried on a protrusion or spindle from the centre of the lower stone so that the stones touched only lightly if at all. Stone-dust contamination was thus avoided.

Despite the small output of this type of mill, it was useful in a culture based mainly on domestic units. During the Roman period commercial milling establishments began to appear, using larger and more sophisticated versions of the rotary quern. There is evidence of donkey mills for cereals in Greece by 300 BC, and donkeys were used on the Roman mills. Those found among the ruins at Pompeii (dating from c 79 AD) are of a peculiar form of construction with the revolving stone shaped like a hollow hour-glass and rotating on a conical stone base. In general, the mill-stones were flat and continued so until the advent of roller grinding in the nineteenth century.

The earliest known reference to the use of a waterwheel for driving mill-stones is in the writings of Antipater of Thessalonica, about 85 BC, which translated reads:

> *Cease your work, ye maids, ye who laboured at the mill*
> *Sleep now, and let the birds sing to the ruddy morning*
> *For Ceres has commanded the water nymphs to perform your task*
> *These, obedient to her call, throw themselves on the wheel*
> *Force round the axle-tree and by these means the heavy mill.*

This mill appears to be of the type where the upper stone was driven from below by a vertical spindle carrying at its lower end a wooden rotor or impeller, as shown in fig 1.17. This primitive arrangement, which had no gearing, was known later as the *Greek mill.*

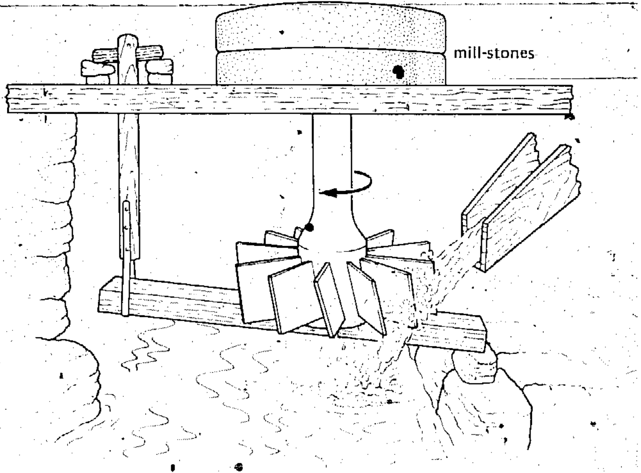


Fig 1.17 Primitive Greek mill

With the runner stone revolving at the same speed as the water-driven rotor, sufficient speed for grinding could only be obtained in small, fast-flowing streams. Therefore these mills were restricted to hilly regions where small quantities of fast-flowing water were found. They were inefficient and incapable of grinding much more than the needs of a single family. However, these primitive mills were soon widely adopted; the type has survived until the present day in Portugal and an example is preserved at Dounby in Orkney. See fig 1.18.

About 15 BC, Vitruvius wrote *De Architectura* in which he referred to engines for raising water which included the noria wheel (see page 2) and to the 'tympanum' and went on to describe a vertical waterwheel, ie rotating on a horizontal shaft, to which was fitted a toothed gear meshing with a larger toothed gear wheel mounted on the vertical spindle carrying the upper mill-stone. Rome did not make immediate use of this more efficient watermill and several reasons have been given for this:

1. Large numbers of slaves were employed in the city's mills. If these were made redundant by the new watermill, there would be the possibility of riots and other disorders.
2. The classical attitude of the time towards machinery was one of disinterest in practical applications. In conjunction with reason 1, there was no financial interest to encourage efforts to overcome the practical difficulties in applying gearing to such mills.

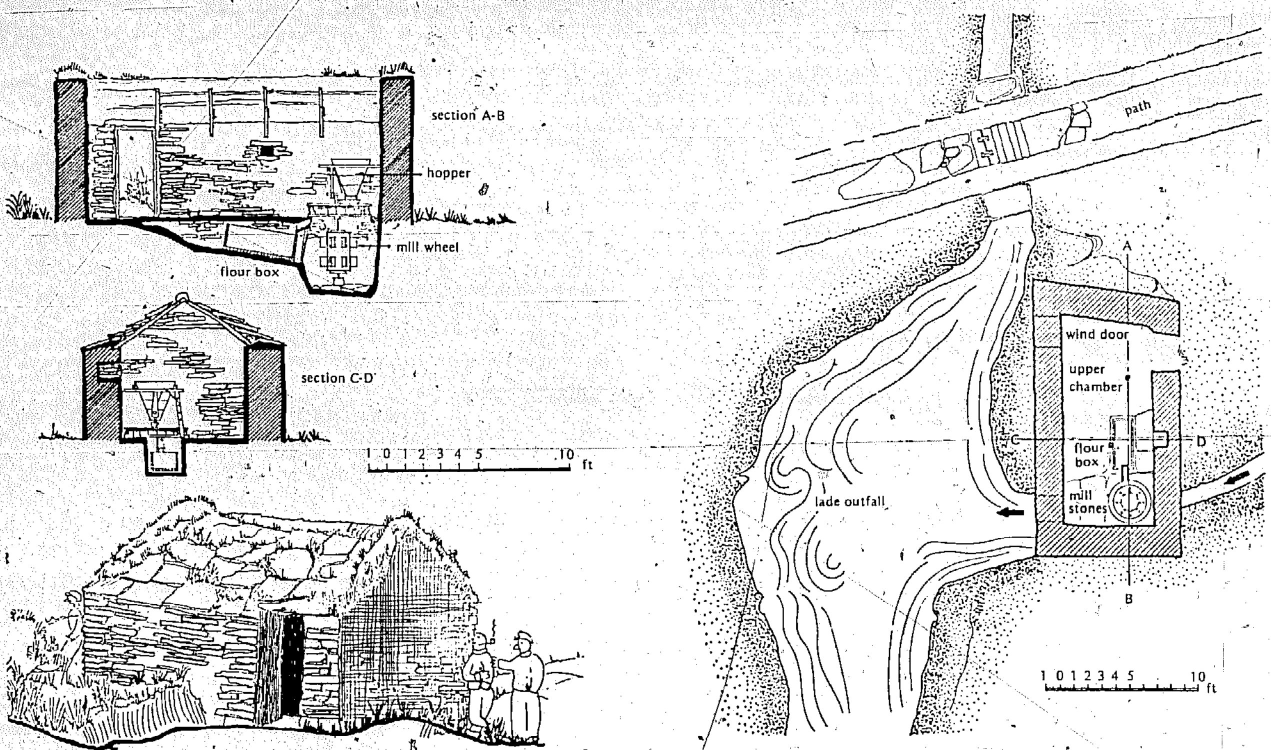


Fig 1.18 Click mill at Dounby, Orkney, preserved by the Department of the Environment. Although it represents the general arrangement of horizontal waterwheel mills, this example is unusual in that its runner has the blades arranged in two rows
Drawing from official guide published by HMSO

Fig 1.19 In the distance, Chesters Fort on Hadrians Wall, and in the foreground, the remains of the reputed Roman watermill

3 There could have been a fear, based on religious grounds, of harnessing any of the forces of nature. However, this last reason did not seem to deter the setting up of horizontal waterwheels.

In the distant provinces of the Roman Empire, the first of these reasons did not apply: there would have been some difficulty in supporting the large garrison on Hadrian's Wall with a relatively small local population to provide 'slave labour'. Thus there was an incentive to develop the latest labour-saving machinery before it was used in Rome itself, and the sites of two mills have been tentatively identified near Hadrian's Wall. See fig 1.19 on page 11.

With the adoption of Christianity by Emperor Constantine as the official religion of Rome, slavery was abolished, thus causing something of a labour shortage for the menial task of corn grinding. At the same time, the pagan worship of water spirits ceased and the power potential of the water supplies could be harnessed. By the end of the fourth century, an increasing number of references indicate the rising importance of the watermill, in Rome itself and elsewhere.

With improvements leading to overshot waterwheels it was possible to grind on a larger scale, and the outstanding example was the mill complex at Barbegal in Southern France where sixteen overshot waterwheels ground twenty-eight tonnes of corn every twenty-four hours (see page 2). By the sixth century, so important was waterpower to milling that when the Goths besieged Rome and cut the water supplies to the mills recourse was made to floating mills (see background of fig 1.21).

After the fall of Rome little is known relating to corn-milling, but references to watermills in Britain begin to appear in Saxon charters during the eighth century. In 1086, the Domesday Survey accounted for 5624 mills south of the River Trent. Some of these were probably worked by oxen but most were watermills. From the summary of the Domesday survey of mills in Warwickshire (see page 43) it will be seen that some of the dues included payments of eels. Many of the millers were also eel fishermen and primitive eel traps are shown in medieval prints. Eel traps are shown in the illustration of a watermill in the Luttrel Psalter, fig 1.20.

The Domesday Survey included the mills with the lands held by the different nobles from the king. By the Middle Ages the lord of the manor owned the mill, and by the ancient custom of 'sole rights' all the corn grown on the manor had to be ground at the lord's mill. The miller deducted a proportion of the flour or meal as a toll or payment for his work. Until the reign of Queen Elizabeth I, the miller was forbidden by law to deal in grain or meal although he was allowed to sell the corn taken as toll. Payment of money instead of toll started late in the thirteenth century at some mills in cities, but tolls continued elsewhere in Britain until the end of the eighteenth century.

The medieval custom of grinding corn only at the manorial mill was unpopular with the peasants who, whenever possible, resorted to using hand mills in their homes to grind their small amount of grain. However, the lord of the manor was usually anxious to enforce his rights so as to ensure the economic working of his mill. During the twelfth century, the windmill was introduced in manors having no suitable water supply for a watermill. Later mills did not have the privilege of claiming sole rights or freedom from tithes. In addition, the rivers were used far inland for transport and came under the jurisdiction of the Lord High Admiral who was empowered to order the destruction of mills and weirs when they impeded established trade routes on the river. From the eleventh century onwards, tide mills were erected at suitable sites offering shelter from the direct onslaught of stormy seas and gales (see page 3).

Each waterwheel usually drove only one pair of stones, and when a mill had more than one pair it would have a separate waterwheel for each, although all would probably be under the one roof, as in fig 1.21. This often leads to confusion when examining old documents which refer to a certain village as having two or three mills.

A new layout, widely adopted during the second half of the sixteenth century, had a main vertical shaft carrying a great spur wheel from which two or more pairs of stones could be driven (see page 24). This improved arrangement may have originated in windmill developments where a fresh set of sails could not be installed for every extra pair of stones in the mill.

The new layout of the mill made it easier to apply power to ancillary operations. In medieval times the sifting of flour from the bran was done by shaking in a hand sieve, and was regarded as part of the work of the baker rather

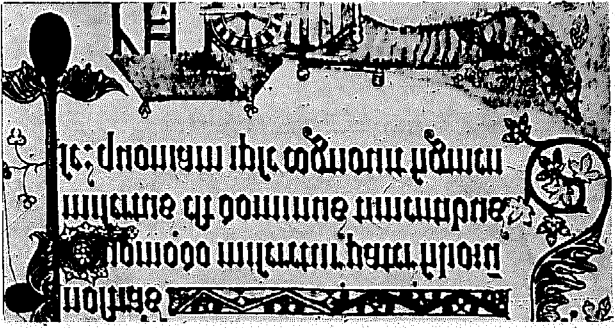


Fig 1.20 Part of the early fourteenth century Luttrell Psalter showing a medieval watermill with overshot wheel and eel traps.

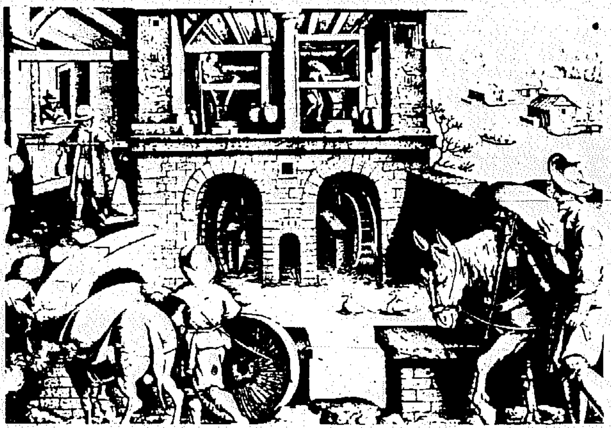


Fig 1.21 A sixteenth century watermill showing two pairs of millstones each powered by a separate waterwheel through peg and lantern gearing. Note the floating watermills at top right

From *Künstliche Abriss Allerhand Wasser-Wind-Ross and Handt Muhlen*, by Jan de Strada, 1617 than the miller. A mechanical sieve was invented in 1502 by an Austrian, Nicholas Boller, and the process of 'bolting' gradually spread to all parts of Europe. At first, the freshly ground meal from the stones fell into a long, inclined bolting bag of cloth which was shaken by a rod connected to the drive from the waterwheel. The finer particles were shaken through the cloth and fell onto the floor, or into a hopper, below which the bran made its way to the far end of the bag where it fell into a separate heap.

In this country, the bolter was developed to a form consisting of an inclined cylindrical frame rotating in a closed wooden casing. A tubular 'bolting cloth' was fitted over the frame. The meal was put in at the upper end of the revolving cylinder and weighed down the cloth so that it brushed against a number of wooden bars which shook the flour through the woven fabric. At first this was woollen cloth but, to give finer flour, wool was superseded first by calico and later by silk.

With the increase in demand for power for other purposes, from c 1750 improvements were made in the design of waterwheels. These were utilized in corn mills and during this period progress was made in applying power to other operations in the mill. Powered sack hoists came into use in watermills with the adoption of the vertical shaft arrangement of transmission. Although a hoist relieved the miller of the work of carrying the sacks to the top of the mill, he or his assistant still had to climb up to the garner floor to take the sack from the hoist and to manhandle the sack to the desired storage bin. During the later half of the eighteenth century, Oliver Evans equipped a mill with elevators (to lift the grain vertically) and augers rotating in wooden troughs (to move the grain horizontally). This machinery is illustrated in fig 1.22.

Evans' ideas found ready acceptance with the American millers, whose production was large-scale and labour comparatively scarce. In Europe his ideas were adopted more slowly.

Whilst mills in this country were grinding good locally-grown wheat, it was possible to grind in one pass through the mill-stones if they were set close together. This style of milling was termed 'low milling' and gave a fine, fairly white flour from good English wheats (which have a soft endosperm and tough bran coats). Using inferior wheats or setting the stones too close could result in the inclusion of bran and breaking up of the starch grains. Such flour made a dark loaf (due to the bran particles) which was heavy and sticky due to the action on the starch of enzymes

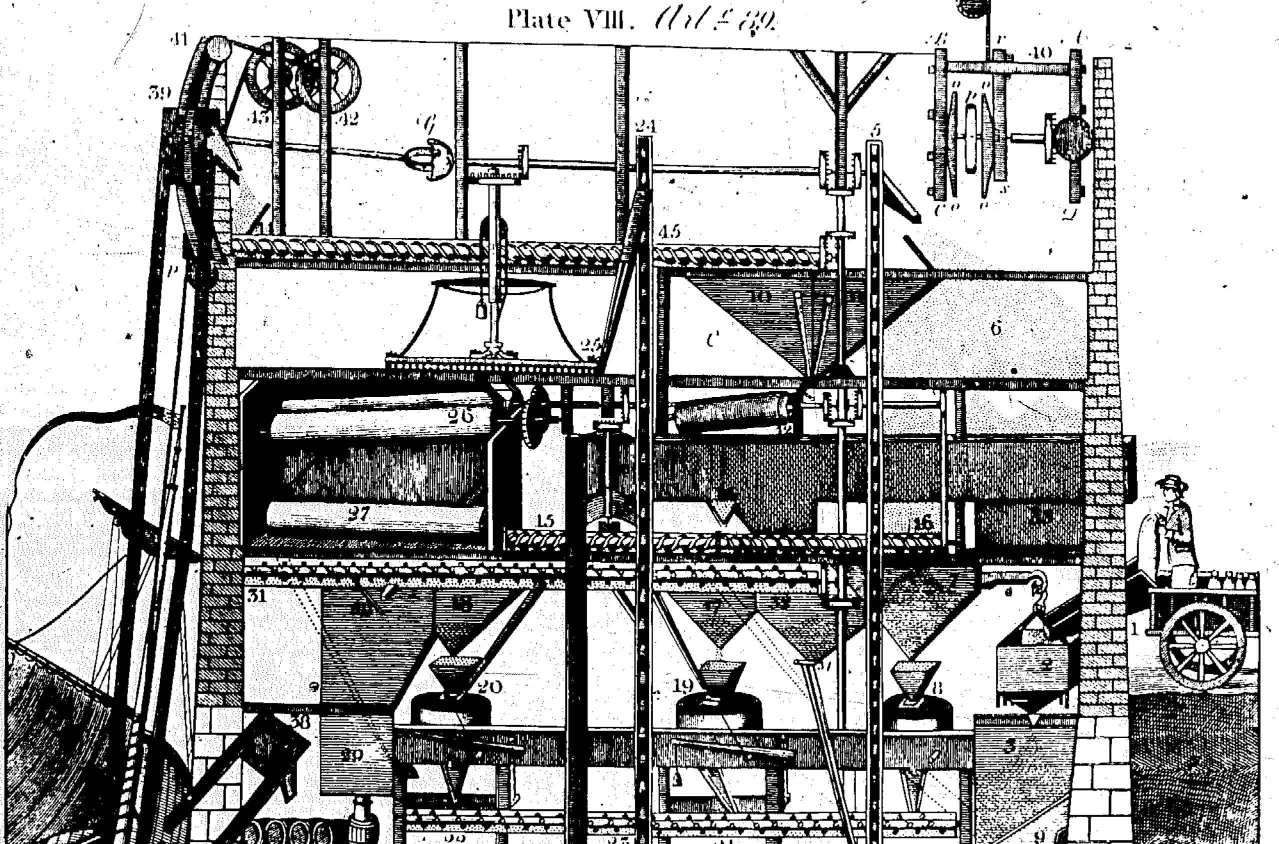


Fig 1.22 Late eighteenth century American mill showing elevators for moving stock (grain) vertically and screw conveyors (or augers) for moving grain horizontally
From *The Young Millwright's Guide* by Oliver Evans, c 1780. By courtesy of Science Museum, London

released from the embryo. The same effect was produced if low milling was used with the hard wheats of Hungary, North America etc, since their bran coats and endosperm are very brittle.

To avoid this the stones were set further apart, but this arrangement decreased the amount of usable flour obtained. From the sixteenth century French millers tried regrinding meal, and from this was developed the continental system of 'high milling' in which the meal passed through several pairs of stones set progressively closer together, grading being carried out after each pair of stones. The best flour produced was almost free of bran and of exceptional quality and whiteness. However, the poorer grades were far inferior to the wholemeal produced in British mills. High milling reached its peak in Hungary during the nineteenth century. The finest flour was highly regarded but the complexity of the processes used was very expensive in terms of time and labour. The system was only economic in countries where the social structure provided a market for widely differing qualities of flour, and was never used extensively in Britain.

Towards the end of the eighteenth century, we find the first examples of another rival to the waterwheel in powering corn mills. At Deptford, in 1781, 'The Steam Mill' was built to provide for the needs of the Fleet. However, the steam was used in a Newcomen type steam pump to lift water from the tail-race into tanks from which it flowed onto waterwheels working the mill. In 1785 John Rennie erected the Albion Mills, close to Blackfriars Bridge in London. This mill was powered by a Boulton and Watt steam engine, and started operation in 1786 with ten stones for grinding wheat.

Improvements in the actual grinding process involved setting, balancing and adjusting the stones, and the introduction of blast and exhaust whereby the stones could produce more and yet develop less frictional heat. None of these overcame the major disadvantages of grinding with stones, which were:

1 Some of the flour was lost with the coarse bran at each grinding.
2 The flour was darkened by minute particles of bran which were almost impossible to eliminate.
3 The crushed embryo and scutellum, although containing most of the vitamin B, also contains wheat oil which in time oxidizes with the result that stone-milled flour tended to go rancid if kept too long. This led to troubles in storage and long-distance transport.

It was realized that to avoid these difficulties some method of gradual reduction was necessary. The principle of the roller mill, fig 1.23, was illustrated by Ramelli in the sixteenth century and there are references to rollers being used for crushing corn in this country during the seventeenth and eighteenth centuries. During the early part of the nineteenth century there were several patents for roller mills, some anticipating corrugated surfaces and differential speeds. About 1840–50 the Ipswich firm of Turners made a form of roller mill for use in connection with mill-stones. A steam roller mill was used at the end of 1837 in Mainz and similar mills appeared in Austrian dominions, such as Budapest and Milan, at about the same time. These mills were mainly for the production of flour for export, and [illegible] was possible to grind only perfectly dry grain. They required excessive power and much labour: the Ludwig mill in Munich, when equipped with 36 roller mills employed 28 men to produce 420 m³ of flour per year, whereas later, when 13 pairs of stones were substituted for the roller mill, as few as nine men were able to produce 840 m³ of flour.

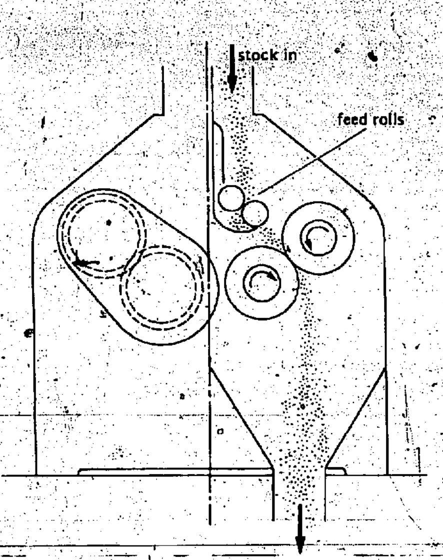


Fig 1.23 Roller-mill

During the 1840s, large mills were set up in Austria still utilizing mill-stones: at Fuime eighteen sets of French stones, 1.4–1.6 m in diameter, were driven by three overshot waterwheels with a total capacity of 70 kW. Another mill in Vienna had twenty-two sets of stones driven by three steam engines of a combined output of 150 kW.

After the repeal of the Corn Laws in 1847, foreign grain and flour were allowed into Britain duty free. Naturally the imports of flour rose rapidly (from 77 634 tonnes in 1840 to 192 752 tonnes in 1850, and 256 962 tonnes in 1860). Not only did the quantity increase but the quality of the flour also improved. The reason for the latter has been attributed to the assessment of the market by the Austrian-Hungarian millers, who held a leading position amongst the countries exporting their surplus flour to Great Britain. Those millers realized that since the home miller with the world's crops at command could always produce cheap blends, it was a waste of their time to compete on cheapness but profitable to fill the British market with high-class flour unobtainable from anywhere else. This induced them to improve the manufacturing methods in two ways:

1 by the use of purifiers to separate the middlings,
2 by the use of improved roller mills,

and resulted in the gradual reduction process of milling. This completely eliminated the wheat germ and bran, and it was not immediately realized that this meant a reduction in the vitamins present in the final white flour. Later, these deficiencies were recognized and various vitamins and minerals were added to the final product in an attempt to remedy this loss.

The first of the mills working on the new systems was in production about 1860 in Budapest. The first rolls were of cast iron, but in 1874 F Wegmann introduced porcelain for semolina grinding. The process made white flour of consistent quality available for mass consumption, and the demand caused further rises in imports to the dismay of British millers.

In 1877 a party of British millers visited the Continent to inspect several mills in Vienna and Budapest. Although on their return the prevailing idea was that the systems seen were too complex for the home mills, in 1878 the first complete roller system was installed in Barlow's Mill at Bilston. Previous to this there had been roller mills installed in 1872 at Muir's mill at Glasgow and at several other mills, but these were not complete roller systems.

At first many millers remained unconvinced of the utility of roller milling, but by the 1890s most of the medium and all of the larger mills had been converted to the new system. The waterwheel was often no longer able to provide sufficient power, although in some cases they were replaced by water turbines. In general, the power was supplied by steam engines and the mills tended to move to sites where communications were good for the delivery of grain and the distribution of flour. When J B Whitworth decided to erect his Victoria Mills at Wellingborough at the end of the nineteenth century, he chose a site bounded by the railway, by the present A45 road, and by the River Nene. The latter facilitated the transport of grain by canal boat, since the river connects with an arm of the Grand Union Canal at Northampton. Power for the mill was supplied by a large steam engine. A general view is shown in fig 1.24.

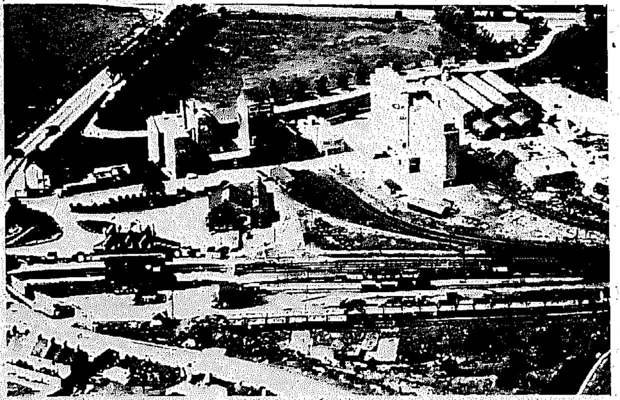


Fig 1.24 Aerial photograph of Whitworth's Victoria Mills, Little Irchester, near Wellingborough, showing their location between three forms of transport: the River Nene (behind the mills), the A45 road on the left and foreground; and the railway between Northampton and Peterborough

The small country mills, not equipped to meet the public demand for white flour and with their owners unable to afford the expensive new equipment, either closed or went over to gristing (grinding feed for animals). Since the Second World War, economies of large-scale production have resulted in closure of many of the medium-sized mills. The sequence of operations in a modern mill is shown in fig 1.25.

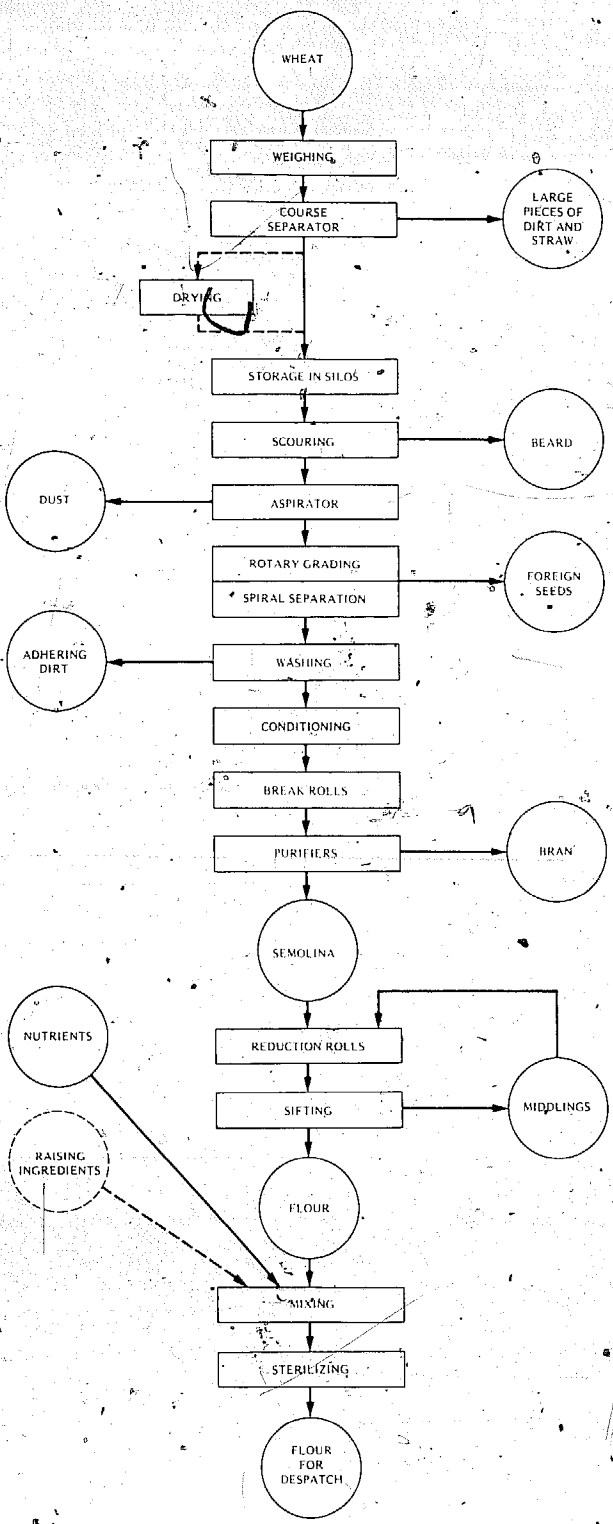


Fig 1.25 Flow chart for modern flour-milling

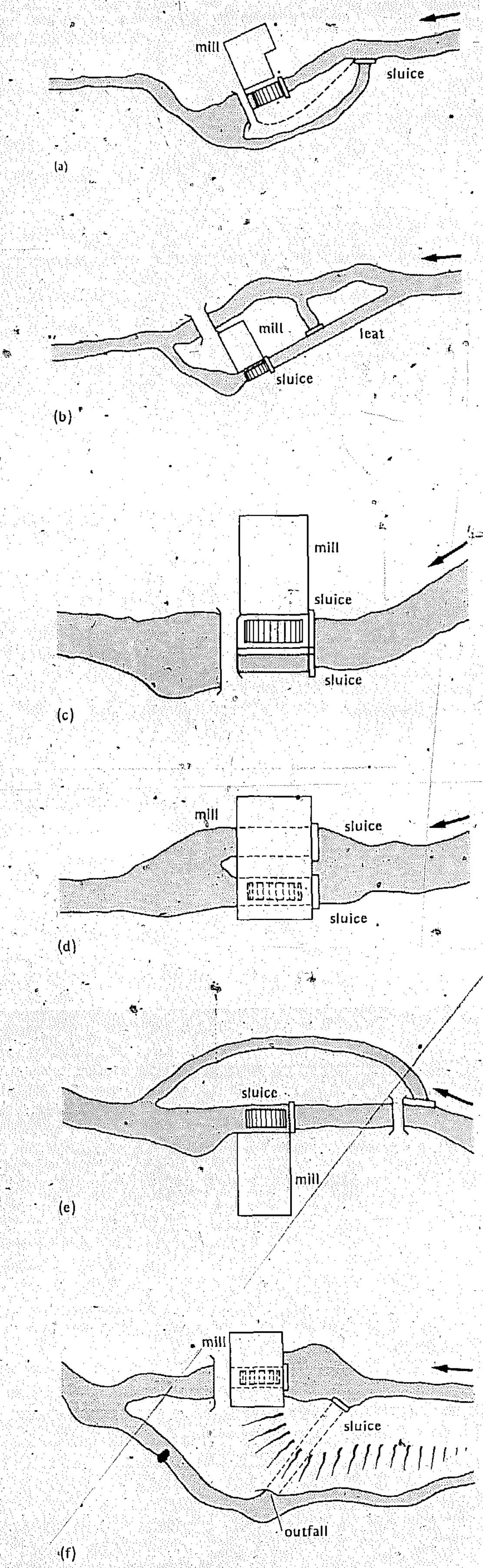


Fig 1.26 Various ways of bringing water to the mill

1.3 CORN MILL WATERCOURSES

The way in which water is brought to the waterwheel will depend on the mill's location and the local geography.

Sometimes the mill will be on the stream itself with an arrangement to by-pass the water when it is not required, as in fig 1.26a.

In other cases, to give the necessary head to drive the mill, an artificial channel (often called a 'leat') was made from the stream to feed the mill, as in fig 1.26b. In some areas, the leats are of considerable length and may lead onto wooden troughs (sometimes referred to as 'launders') or cast-iron penstocks delivering the water onto the wheels. On rivers used for navigation, it was also necessary to have the mill supplied by a separate watercourse.

In all cases provision was made for the escape of water not required to drive the waterwheel. This was necessary when, after prolonged rainfall, the water supply was in excess of that needed to drive the wheel at the desired speed, and also under normal conditions when the waterwheel was stopped by lowering the sluice to stop the water flowing onto it. See fig 1.27.

Sometimes the by-pass arrangement was a channel parallel to the wheel, as in fig 1.26c.

In some mills, the by-pass arrangement was made by another channel under the mill itself, as in fig 1.26d.

Often the by-pass channel was diverted well away from the mill itself but always there had to be access to the sluice for the by-pass and this normally required provision of an extra bridge. See fig 1.26e.

Some mills have by-pass sluices from which the water disappears into the ground and emerges some way distant along the tail-race or the natural course of the stream. See fig 1.26f.

Instead of having a sluice which had to be raised whenever excess water had to be diverted, some mill leats were provided with a fixed weir over which the water flowed when the level rose above normal at the mill. Such fixed weirs (referred to as 'low-shottes' in sixteenth century documents) were also provided when a number of mills were at work along a river and it was essential that the

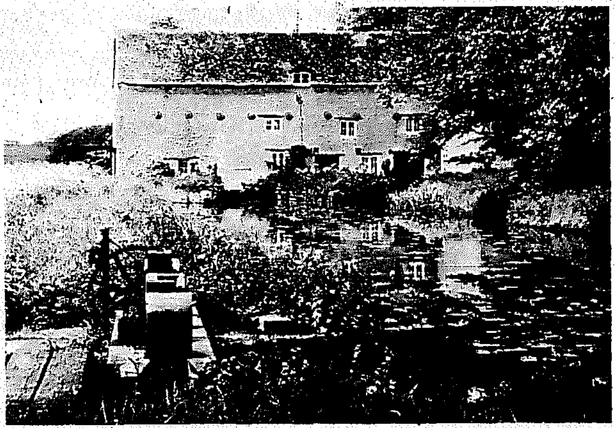


Fig 1.27 Wadenhoe Mill, near Oundle, Northamptonshire. The mill is situated on an artificial cut or leat and the main stream of the River Nene is navigable at this point. In the right foreground is the sluice for diverting water into the by-pass channel

water held back at one mill did not interfere with the run of water away from the tail of the next waterwheel upstream.

It was mentioned earlier, on page 12, that millers paid some of their dues in the form of a quantity of eels. Millers have often augmented their income by fishing for eels in the fast-flowing waters at their mills. In earlier times their eel traps were very primitive, as shown by medieval prints such as that in fig 1.20, page 12.

Later mills often trapped eels in the by-pass channel by immersing a 'cage' of iron bars open at the up-stream end so that the eels were carried into it (fig 1.28). Since the cage was closed at the downstream end, the eels could not escape against the fast flow of water and they were held until the cage was lifted out of the water for removal of the eels.

Where the flow of water was not sufficient to drive a mill, it could be used to fill a mill-pond, and only when this was full would the water be let out onto the waterwheel to work the mill. When the water in the pond fall below a certain level, the mill would have to stop work until the pond was replenished, as in fig 1.29a.

A variation on the use of mill-ponds is found in a special type of watermill known as a tidemill. Dams were erected across tidal creeks, the shallower portions of tidal estuaries or were made to enclose part of an estuary, leaving a channel for shipping. See fig 1.29b.

With the tidemill arrangement, the mill was part of the dam which had one or more inlets so that when the tide came in the water flowed into the pond, but when the tide turned the tendency of the water to flow out caused flap doors across the inlet to shut against the water, which was therefore held behind the dam. When the level of water downstream had dropped sufficiently, a sluice would be opened at the mill to allow the impounded water to flow out onto the waterwheel.

The tail-race from a millwheel may cause quite a wide, and sometimes deep, pool, and this feature is helpful in determining the location and in sorting out the water-courses for mills which have been demolished. When the mill is still standing, many of the features already described in connection with the water supply will usually be out of sight of the mill itself.

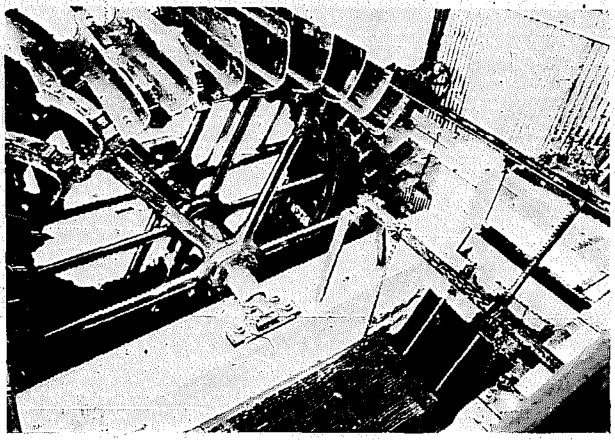


Fig 1.28 Poncelet-type undershot waterwheel, and eel trap in by-pass channel, at Billing Mill on the River Nene near Northampton. Note the shape of the floats or paddles and the three sets of iron arms each supporting a rim with 'starts' for supporting the floats

Photo: courtesy of Billing Aquadrome

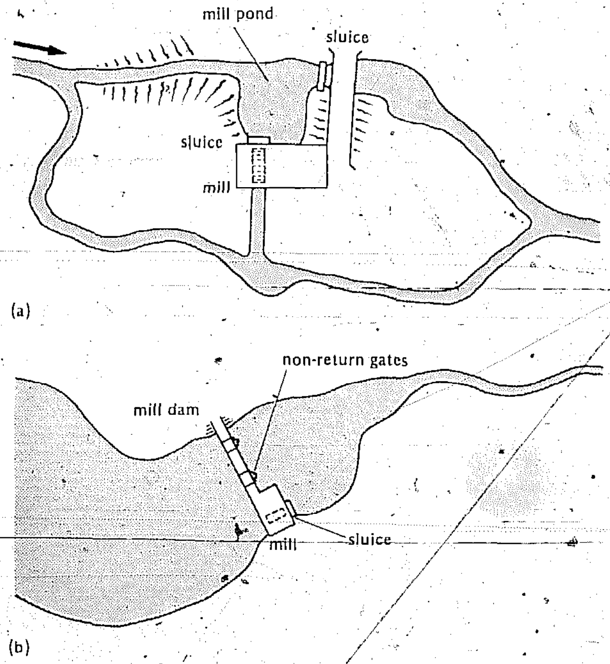


Fig 1.29 (a) Mill worked from mill-pond (b) Tidemill on creek or estuary

1.4 TYPES OF WATERWHEEL

The power was obtained from the water supply either by waterwheels or later, in some mills, by water turbines (these are considered in Section 3).

The waterwheels found in this country are usually of the vertical type, running on a horizontal shaft. There are a few mills in the north of Scotland which have horizontal waterwheels, and reference is made to this type in Section 1.2, page 10.)

The vertical waterwheel has been used in the following forms:

1 *Undershot*
The kinetic energy of the water flowing onto the blades is utilized to turn the wheel and give power, as in fig 1.30a. These wheels have relatively low efficiency.

2 *Poncelet*
This was an improved version of the primitive undershot wheel introduced early in the nineteenth century by the French engineer J V Poncelet. By channelling the water below an inclined sluice onto carefully calculated curved paddles so that the water entered and left the wheel with little shock, a great improvement in efficiency was obtained (fig 1.30b).

3 *Breastshot*
The water falls onto the blades or buckets so that the weight (or the potential energy) of the water does work in turning the wheel, instead of just the velocity (or kinetic energy) of the water as in the two previous cases. See figs 1.30c and 1.31.

Often the term 'breastshot wheel' is restricted to wheels where the water comes onto the wheel at about the level of the axle, and the terms low-breast or high-breast wheel are used when the water comes respectively below or above the level of the axle. Efficiencies ranged from 50–60 per cent.

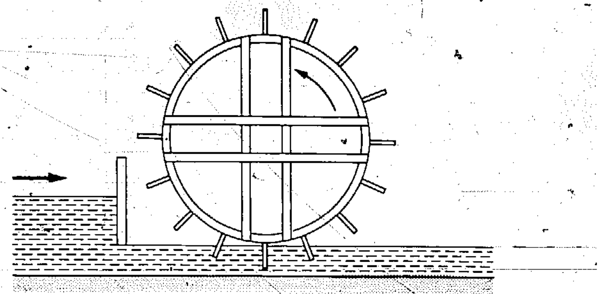
4 *Pitch-back*
This is an extreme example of the high-breast wheel with the water coming on to it almost at the top of the wheel. It was introduced to avoid the difficulties encountered with the tail-water on overshot wheels. The name of this fourth type derives from the motion of the wheel pitching back against the direction of the flow of water coming on to it. See figs 1.30d and 1.32.

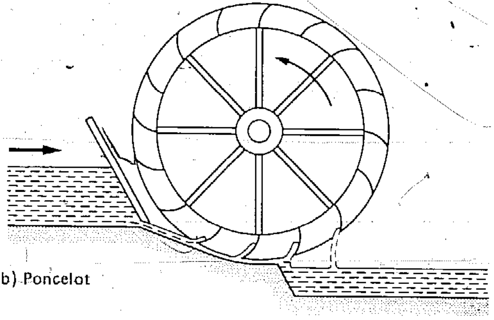
5 *Overshot*
The water comes on just past the top of the wheel, the periphery of which moves in the same direction as the water coming on to it. This smooth flow of the water is not obtained at the bottom where the tail water does not flow freely from the wheel pit but gives a certain amount of backwash in the opposite direction to the flow of the tail-race. This causes some loss of power but efficiencies of between 60 and 75 per cent have been quoted for this type of wheel. See figs 1.30e and 1.33.

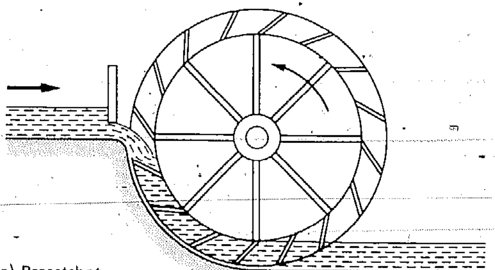
The main components of a waterwheel are:

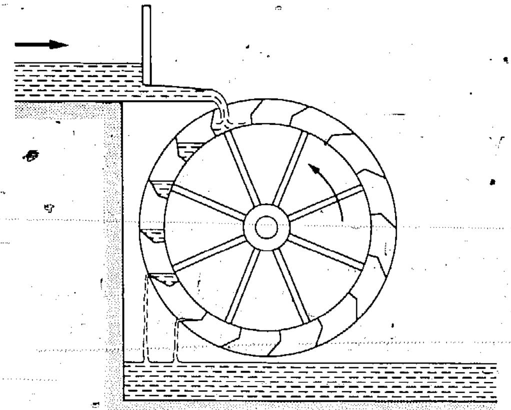
the wheelshaft or axle (sometimes termed axle tree),
the spokes or arms (connecting the rim to the shaft),
the rim (which carries the floats or buckets),
the floats or buckets.

There are numerous ways in which these components were shaped and connected to each other.


(a) Undershot


(b) Poncelot


(c) Breastshot


(d) Pitch-back

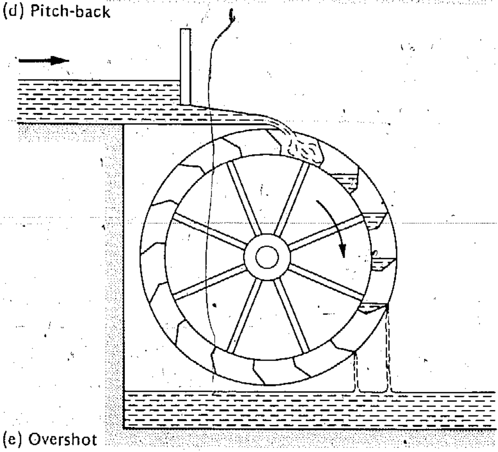

(e) Overshot

Fig 1.30 Types of waterwheel

Fig 1.31 The breastshot wheel which used to drive the corn mill at the end of Arkell's Donnington Brewery, near Stow-on-the-Wold, Gloucestershire

Fig 1.32 Pitch-back waterwheel at Millside, Witherslack, Westmorland. Note the cast-iron penstock for delivering water onto the wheel, the way the wooden boards forming the buckets are positioned and secured to the inside of the rims, and the boards forming the sole across the inside edges of the rims

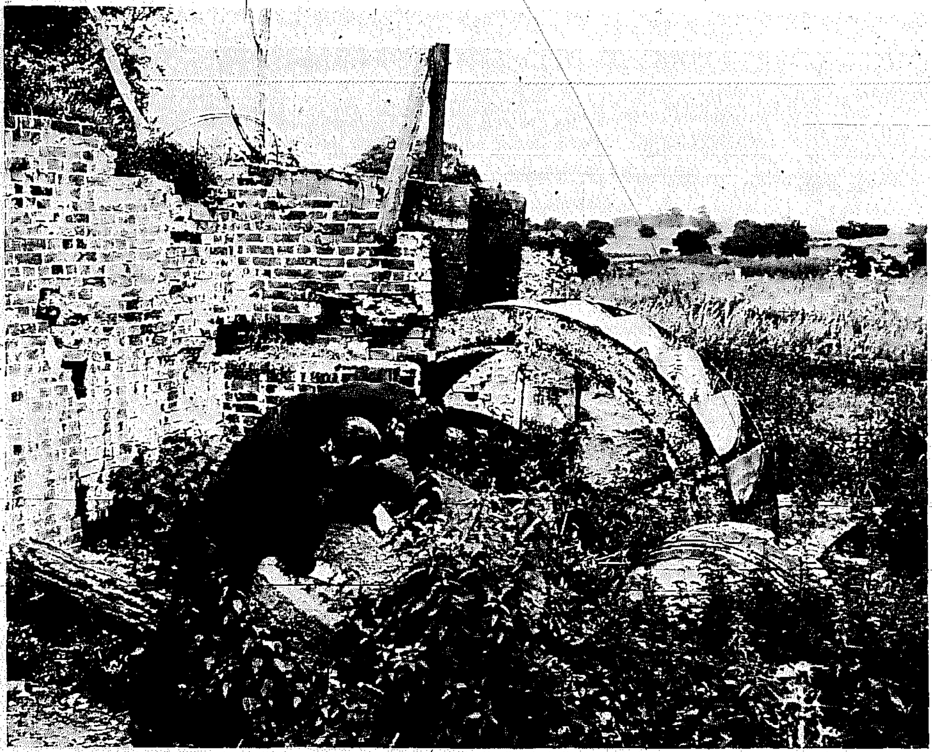


Fig 1.33 Overshot waterwheel in the ruined mill close to Churchover, near Rugby, Warwickshire. Note the remains of the wooden launder and 'shut' for bringing water onto the top of the wheel

The earliest wheels had the spokes passing through holes in the wooden axle trees, as in fig 1.34a. This form of construction is known as 'compass arm' but the holes considerably weaken the shaft.

Later wooden waterwheels were of clasp-arm construction, that is, on each side of the wheel pairs of parallel spokes were set at right angles to each other, with the axle passing through the space formed by their intersection. The spokes themselves did not touch the shaft but were located on the shaft by large wedges driven in along the shaft from each side of the wheel. This arrangement is shown in fig 1.34b.

To the ends of the spokes were fixed the felloes, the term for segments of the wooden rim. The joints between the ends of mating segments were strengthened by an iron strip bolted to the two felloes.

The wheelshafts were also of wood, and mounted in each end was a 'gudgeon' which rested in the bearings located either side of the wheel pit. Sometimes crosshead gudgeons were used with iron hoops on the outside of the ends of the axle.

When cast iron became available for use in machinery it was used for some parts of waterwheels, the rest still being made of wood. Nowadays such wheels are sometimes termed hybrid wheels, but apart from indicating that two different materials were used the term tells us little about the type of wheel or the way in which it was constructed. Foster Beck mill, shown in figs 1.35 and 1.36, is an example.

The use of iron made possible better fixing of the spokes or arms to the shaft, and more spokes could be used. Two types of cast-iron wheels are shown in fig 1.34c and d.

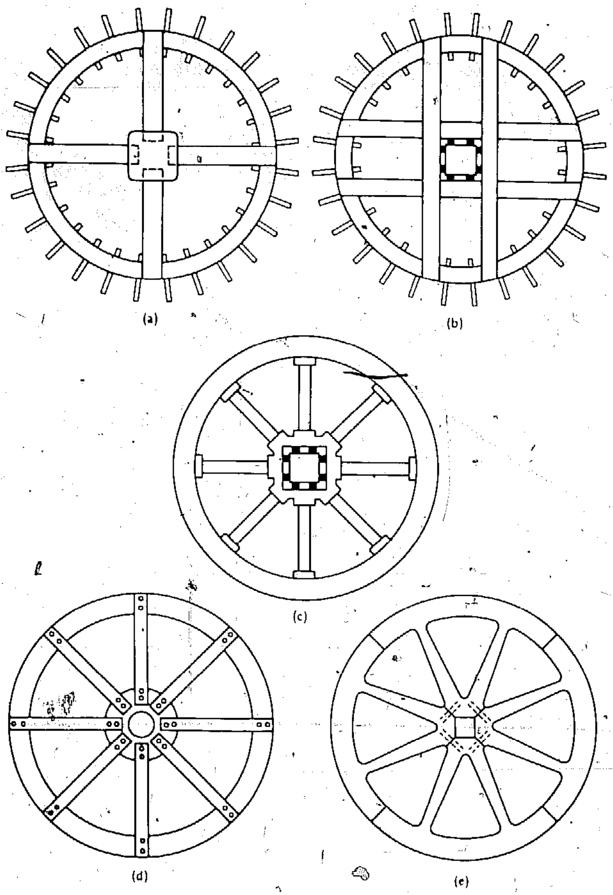


Fig 1.34 Various types of waterwheel construction

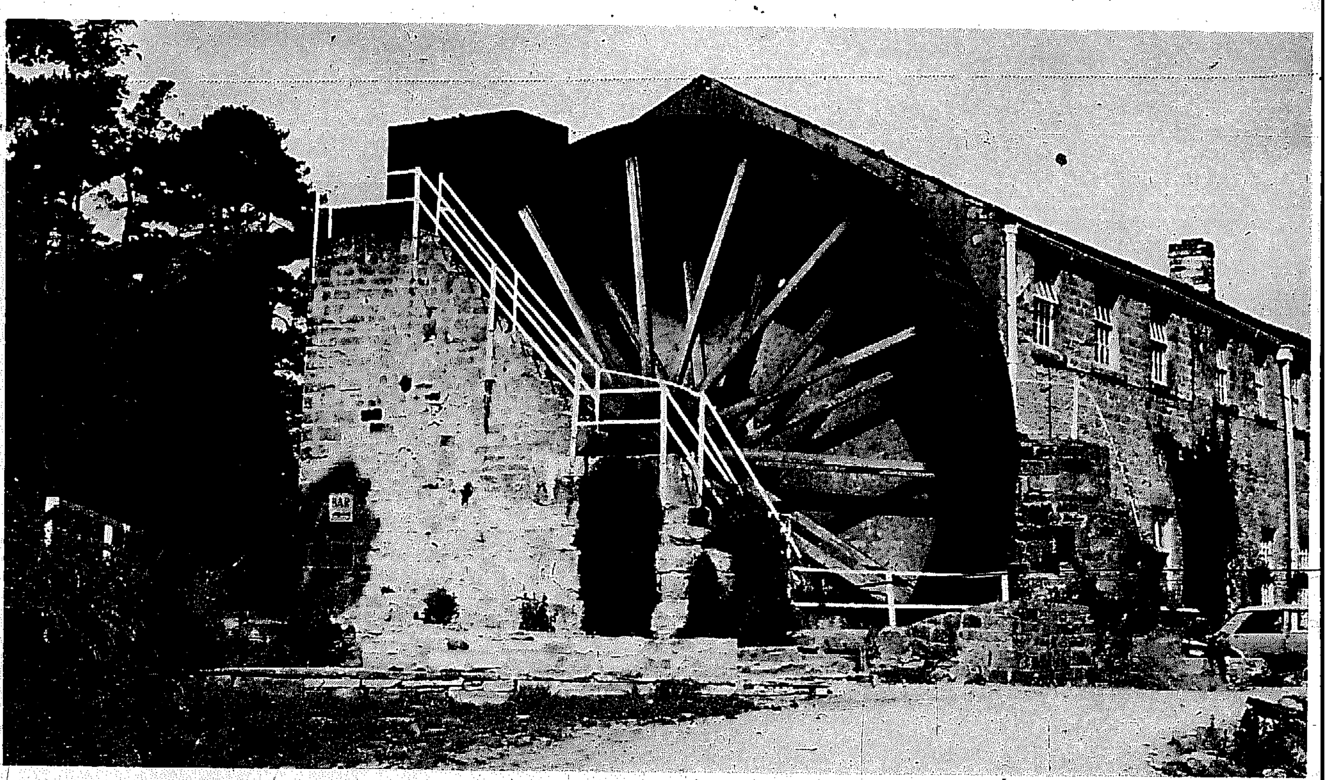


Fig 1.35 Foster Beck Mill, near Pately Bridge, north-west of Harrogate. This is a high breastshot wheel of 11 m diameter and 1.8 m width, formerly used to power a flax mill. The building is now a restaurant. The mill-pond is behind the bank, or dam, on the left of the picture, and the water was delivered through a large iron pipe into a 'starting box' at the wheel itself. The purpose of this box was to allow a sufficient quantity of water to build up to set such a large wheel in motion, but once it was turning a relatively small flow of water could keep the wheel operating

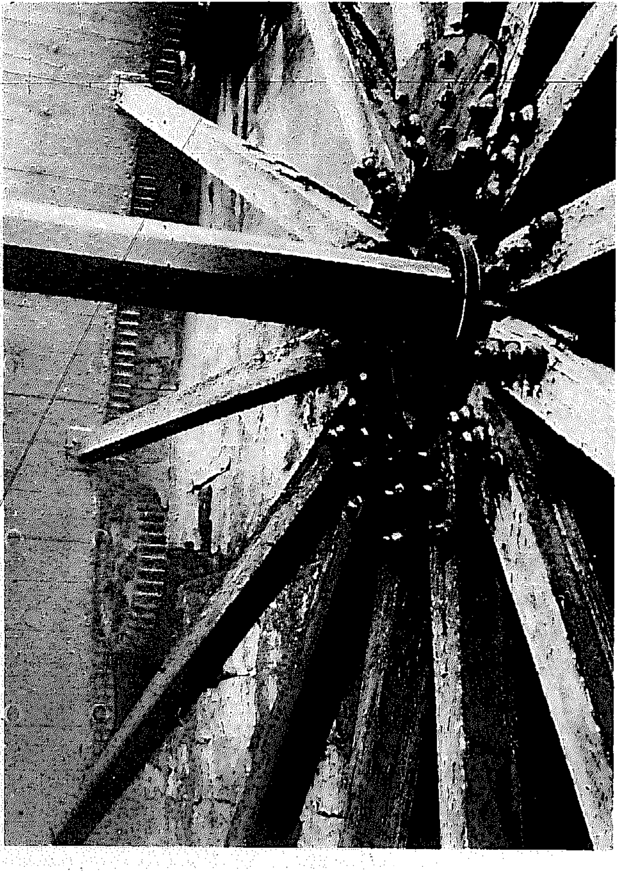


Fig 1.36 Detail of the construction of the wheel at Foster Beck Mill. The rim, wheelshaft, and flaunch (for securing the arms or spokes to the wheelshaft) are of iron, but the spokes and soleboards are of wood. Note the rim gearing at the inside of the wheel rim and the small pinion meshing with this

With mainly metal construction, the iron wheelshafts were often made circular with a straight-sided section at the position of the boss to which the spokes were secured. The spokes could have different cross sections – for example, flat rectangular, round, T-section, I-section. There were a number of ways in which the spokes could be fitted to the hub or the boss of the wheel, which was sometimes called a flaunch.

Some wheels were made by bolting together castings each of which consisted of a section of the rim cast integral with some spokes and a portion of the boss. An example of this kind of wheel is shown in fig 1.34e.

In the case of wide wheels, there may be three sets of spokes: two at the outsides and one in the centre, as shown in fig 1.37. This arrangement can be found in both wooden and iron wheels. With large diameter wheels, cross bracing was often used between the two sets of spokes.

There were two main forms of arrangement at the rim of the waterwheel depending on whether the wheel carried floats or buckets.

1 *Wheels with floats*
In the case of floats, these were carried on short wooden or metal posts (called 'starts') let into the rim of the wheel. On some wheels, the tips of the starts on each side of the wheel were connected by bracing rods, as in fig 1.38a.

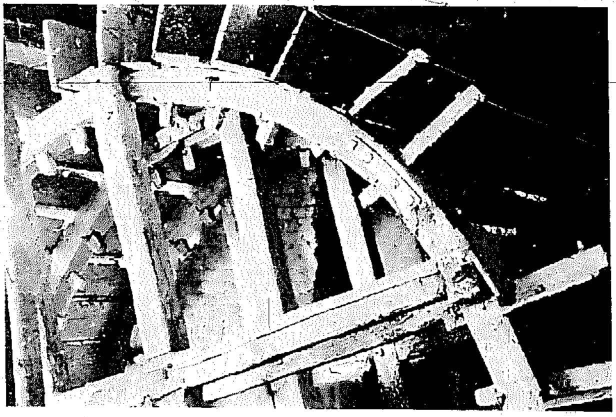


Fig 1.37 Old wooden wheel, at the now demolished Bosenham Mill, close to the Northamptonshire – Buckinghamshire border. Note the clasp-arm construction with three sets of arms (spokes), the attachment of the arms to the felloes forming the rim, and the starts (supporting the floats) mortised right through the felloes
Photo: Oliver Ranson

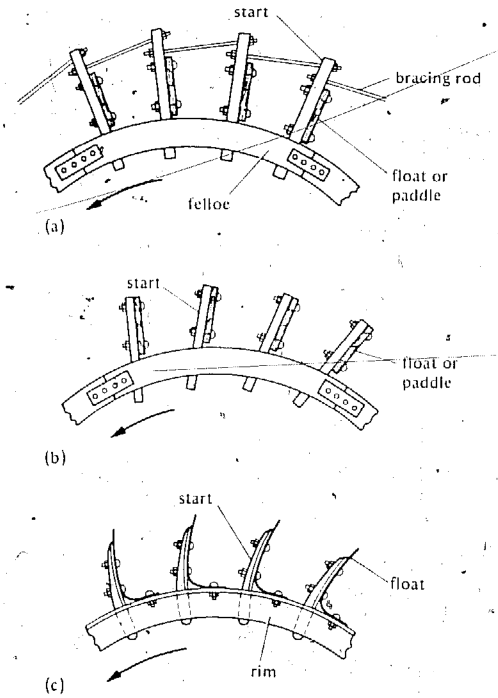


Fig 1.38 Detail of wheels with floats

The start, if straight, could be set either radially (as in fig 1.38a) or inclined slightly to the radius of the wheel fig 1.38b. In each case, the wooden floats (sometimes called 'paddles') were attached across them.

When curved floats were used, the starts might also be slightly curved. Metal floats with pronounced curvature would be attached to the starts and at their inner ends to the rim itself. L-shaped floats were also used in some cases, as in fig 1.38c.

2 *Wheels with buckets*
Wheels with buckets have them mounted between deep flat rims (sometimes referred to as 'shrouds'). When made of wood, the buckets will usually be a distorted L-shape and held in position by grooves, either cut into wooden rims, or formed by pairs of raised strips cast or bolted onto iron rims. Even if all of the timber has rotted away,

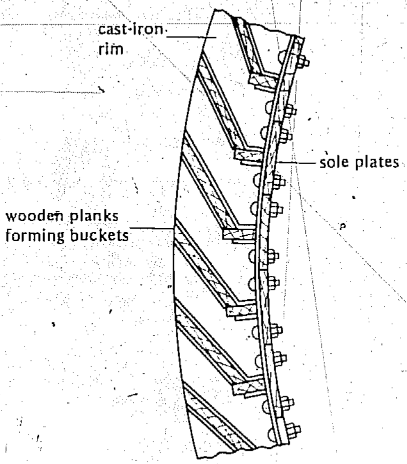


Fig 1.39 Detail of wheel with buckets

the grooves in an iron wheel may indicate the shape of bucket used. The other side to the bucket is formed by planks of wood fixed across the inside edges of the rims. This inner covering of the wheel is known as the 'sole'. See fig 1.39.

Metal buckets can have a variety of shapes but are mainly of U- or J-shape. If there is no gap between the buckets at their inside edge they are described as 'closed'.

Often a gap was left between the top of the inside of one bucket and the back of the following bucket so as to enable air to escape and thus allow the water to enter more quickly. These were known as 'ventilated buckets'. (See fig 1.13, page 7.)

On some waterwheels, gearing was fixed to the periphery of the wheel (see fig 1.36). This is part of the transmission arrangement and was discussed on page 7.

Iron wheels often have the name of the maker cast on them, sometimes on one of the spokes and occasionally on the rim.

Water turbines

As water turbines became commercially available during the nineteenth century, they were installed in some mills to replace the existing waterwheels. This involved considerable alteration to the mill-race and to the means of transmitting power to the machinery, since these turbines were installed below the water level and rotated about a vertical axis. See fig 1.40.

Because they are situated under water it is usually very difficult to see much of the turbines, although the presence of one is indicated by the grating across the race to prevent weeds and rubbish choking the turbine, and by the machinery in the mill being driven from a vertical shaft rising from the water. Later turbines also have handwheels and indicators to show whether the hatch (letting water onto the turbine's rotor) is open or closed, and also the position of the guide vanes. Handwheels and indicators are mounted on a cast-iron pillar in the centre of the floor above the turbine pit (fig 1.41).

The main types of turbines are described in Section 3 but a common type for English mills was the mixed-flow reaction type, similar to the Francis turbine, using adjustable guide blades.

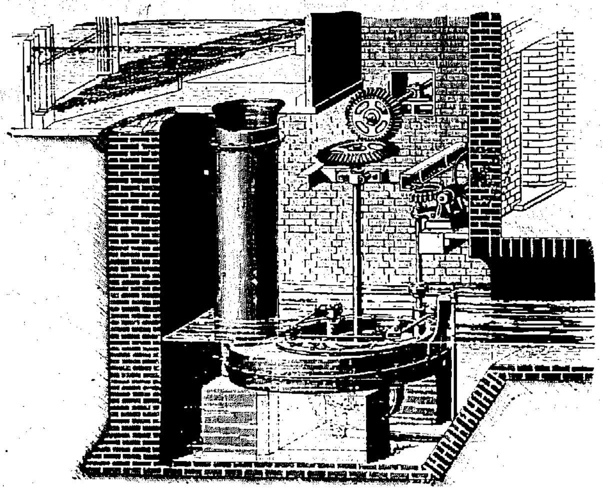


Fig 1.40 A turbine installation showing how most of the working parts of the turbine are below the surface of the water. This drawing shows a Thompson double vortex turbine
From P J Davies, *Practical Plumbing*, Vol 2, 1896

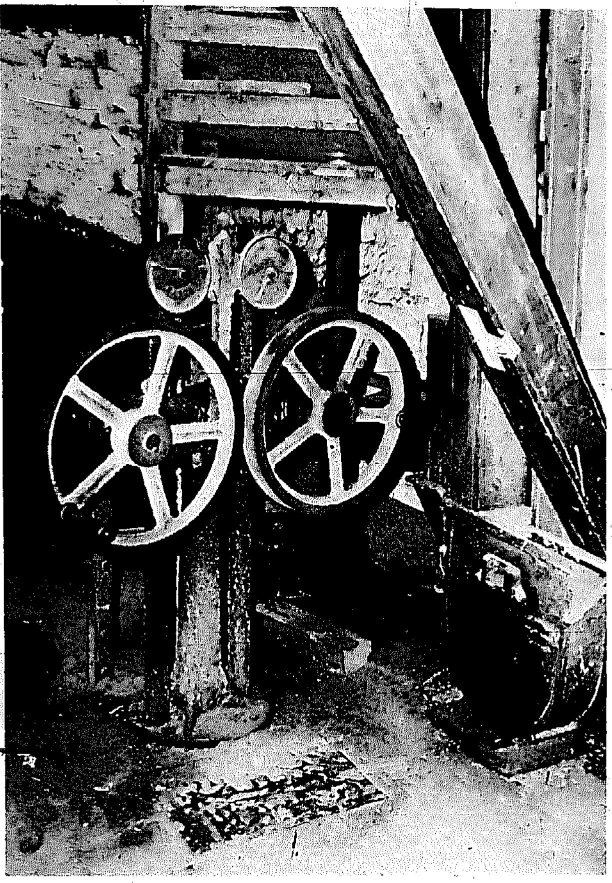


Fig 1.41 Controls for the water turbine at Towcester Mill. One handwheel controls the flow of water onto the turbine, the other adjusts the position of the guide vanes. Above the handwheels are the dials indicating the settings of the turbine. The vertical drive shaft from the turbine is seen emerging from the hole in the floor and passing behind the right-hand control wheel

1.5 THE ARRANGEMENT AND EQUIPMENT OF WATERMILLS FOR CORN MILLING

The wheat grain

In order to appreciate the working of the various grain preparation, grinding, and dressing machines it is necessary to consider the structure and composition of grain (fig 1.42).

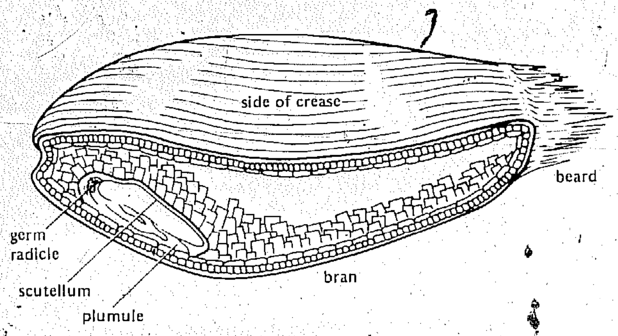


Fig 1.42 Structure of wheat grain

The functions of the grain are those of reproduction and the grain consists of three distinct parts:

1. The germ – the seed which develops ultimately into the plant.
2. The endosperm – a starchy substance constituting the main body of the grain and supplying food to the germ in the early period of its growth. It is this which yields flour when broken.
3. The bran – this consists of several separate coverings to enclose and protect both the germ and the endosperm. These coverings are composed of cellulose or woody fibre and of soluble albuminous matter.

   The outer layer of wheat bran is nearly all cellulose and therefore indigestible. The middle layer contains less cellulose but a significant amount of colouring matter. The inner layer contains only a small amount of cellulose but large quantities of protein.

In cornmilling, for the purpose of making the wheat palatable for human consumption the aim is to crush the kernel (the part containing the germ and endosperm) so giving flour. Various operations are necessary if this is to be achieved. When horizontal mill-stones were used, the stages were as follows:

1 *Preparation*
The grain arriving at the mill may contain various impurities which may be classified in three groups:

(a) admixtures which may poison or bring about a deterioration of the quality (colour or baking characteristics) of the flour, eg kernels of corn having some disease such as smut;

(b) impurities reducing the quality of the flour such as seeds of non-poisonous plants (eg rye, barley, oats), dust and dirt;

(c) impurities that may damage the mill machinery, eg stones and pieces of metal.

The grain must be freed of all of the above categories of foreign matter if a good quality flour is to be obtained. After the removal of the foreign matter from amongst the grain there may still be dirt adhering to the individual berries; this has to be removed, usually by a scouring process.

2 *Tempering or conditioning*
If the grain is very dry, the dried bran coat is very easily ground to dust during its passage through the stones and mixes with the flour. It is impossible to extract this dust from the flour, whereas if the bran coat is broken into particles larger than the flour they may subsequently be removed. Hence the need for tempering or conditioning. By damping the grain, the bran coat becomes more elastic and offers greater resistance to pulverization than the starchy mass of the kernel. The force required to break the kernel will then leave the bran coat in flakes rather than as dust.

3 *Grinding*
This is the stage at which the kernel (the endosperm and embryo) is reduced to flour, but at the same time the husk will be broken up. At the end of this stage the flour and broken husk are mixed together in a form known as *meal.*

4 *Separating*
If a white flour is required, this has to be separated or 'dressed' out of the meal, and may also be graded.

After watermills were no longer used for flour milling, many continued to be used for producing animal foods, in other words for provender milling. The second and fourth of the above stages were then often regarded as less important but at the same time, since it was realized that no one cereal can provide a satisfactory diet for livestock, attempts were made to provide balanced rations by thoroughly mixing a number of ground meals, leguminous seeds, oil cake, and sometimes minerals, molasses or cod liver oil.

Some of the ingredients of balanced rations were purchased from outside sources, but the mixing and grinding of the seeds, cereals, and oil cake were usually done in the provender mill itself and by machines different from those used for the production of flour. Cereals such as maize, barley, wheat, and rye were sometimes ground in a similar fashion to that used in flour milling but were also ground using metal disc and percussion grinders. Oats were crushed between rollers. Oil cake arrived in the form of slabs about 75 cm X 30 cm, and these were broken down into pieces of suitable size for the grinding plant by machines called cake breakers. Maize was damped, cooked, and flattened into flakes by rolls.

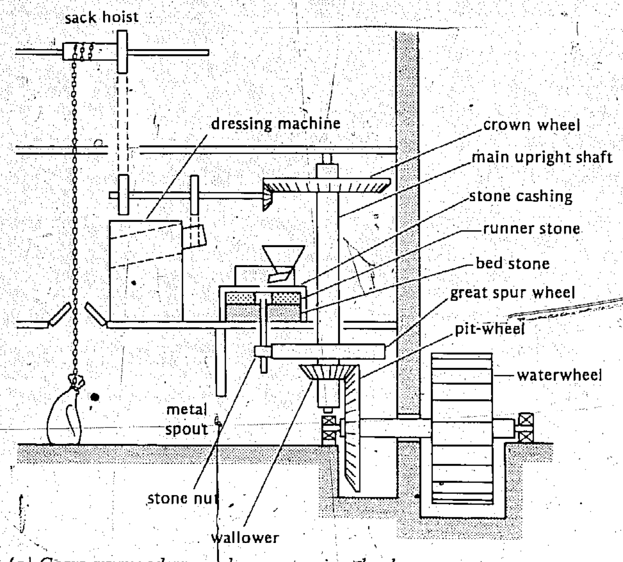
Arrangement of machinery inside watermills

Details of the arrangement of machinery will vary from one mill to another, but in general the layout will be one or other of the two forms shown in fig 1.43. The main difference between the two arrangements shown is in the way the power of the waterwheel is transmitted to drive the mill-stones.

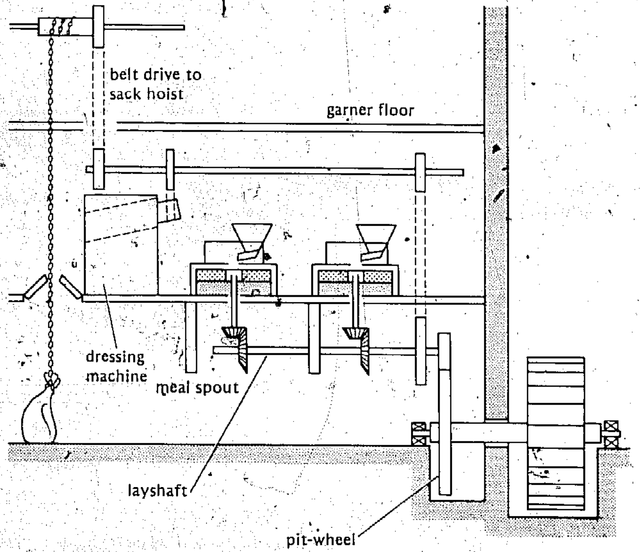
Transmissions

There were basically three ways of transmitting the power obtained at the waterwheel shaft to the mill-stones and other machinery:

1 by gears arranged around a great spur wheel
2 by bevel gears from a layshaft
3 by belts.



(a) Gears arranged around a great spur wheel



(b) Bevel gears from a layshaft

Fig 1.43 Two main forms of machinery arrangement

The earlier mills, driven by rapidly revolving undershot waterwheels, required only a comparatively small increase in speed from waterwheel to stones in addition to a change of motion from about the horizontal shaft at the wheel to about the vertical axis of the spindle driving the stone. Consequently it was possible to achieve this with only one pair of wheels, namely the face-wheel or pit-wheel on the waterwheel axis, and the lantern-wheel or trundle on the spindle for the mill-stone. (See fig 1.44.)

The rounds of wood later gave way to cogs let into wooden wheels, and thus it was possible to drive several pairs of stones using a vertical or upright shaft as the centre of the transmission system. This arrangement is shown in fig 1.45. On the end of the waterwheel shaft is the pit-wheel, so-called because of the hole let into the floor of the mill to accommodate it. Although in most mills this pit was stone or brick lined, some had narrow cast-iron boxes in which the pit-wheel rotated.

A few wooden pit-wheels are still to be seen but generally the wheels are made entirely of iron, although sometimes they have wooden teeth. When made of iron the wheels

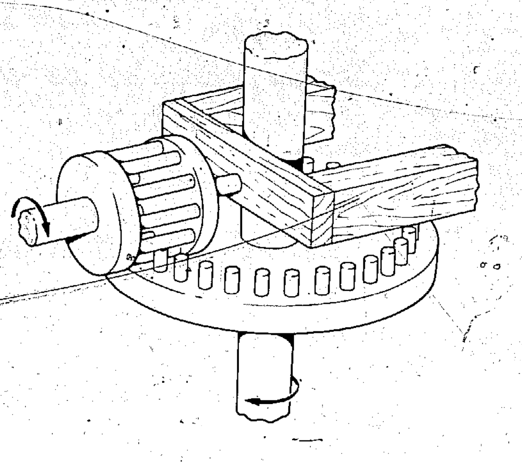


Fig 1.44 Lantern-wheel or trundle on mill-stone spindle

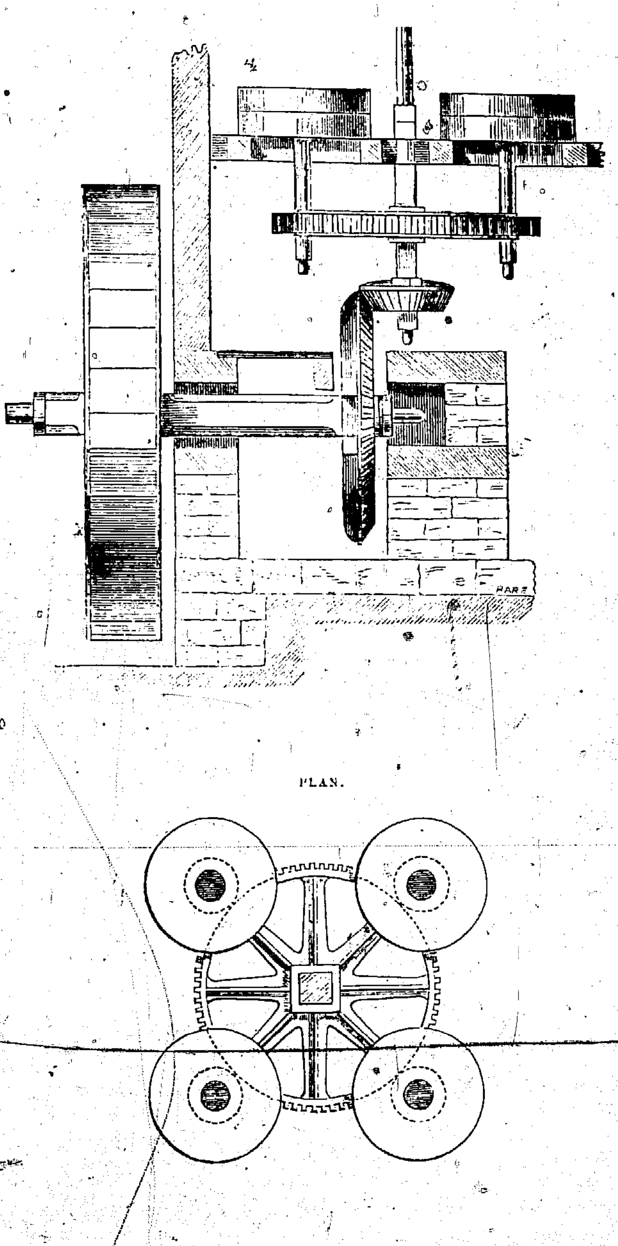


Fig 1.45 Arrangement of gearing when using a vertical main shaft
From J Glynn, *On the power of water to turn mills*, 1853

are normally in halves which are bolted together when in position on the wheelshaft. If this is of wood, then the centre of the pit-wheel will be in the form of a square box for wedging into position on the shaft as in the waterwheel shown in fig 1.34c, page 20.

The pit-wheel engages with a bevelled pinion fixed on the upright shaft. This pinion, called the 'wallower', is usually of iron and has far fewer teeth than the pit-wheel so that the upright shaft rotates faster than the waterwheel.

Older upright shafts are of wood but iron was later introduced for these, and octagonal, hexagonal, and round sections were used. The upright shaft is supported at the top by a journal bearing on the side of a beam. At the bottom, the whole weight of the shaft and the gear wheels on it is taken by a thrust bearing. This is usually required to be almost directly above the inside bearing for the waterwheel shaft. Traditionally, the thrust bearing was supported on a wooden beam (sometimes called a 'sprattle' although this was the name commonly given to the beam supporting the bearing at the top of the shaft in a windmill). This caused difficulty in gaining access to the wheelshaft bearing, and a more convenient arrangement was to foot the vertical shaft on an arch, sometimes of brick or stone but more often of cast iron. The gudgeon at the foot of the upright shaft runs in a toe-brass contained in a bridging box with four screws for lateral adjustment. See fig 1.46.

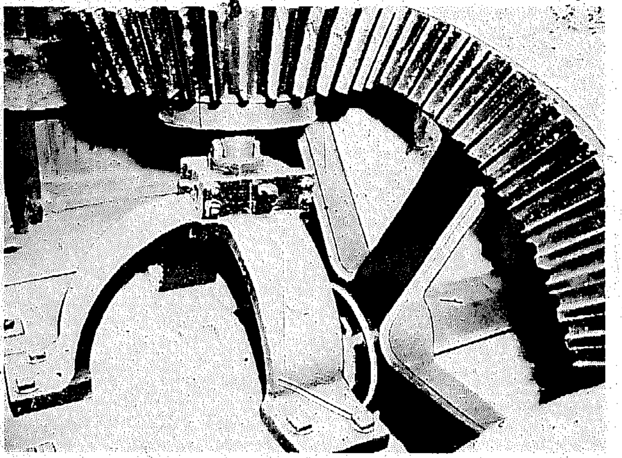


Fig 1.46 The foot of the upright shaft in Billing Mill. On the right is the horizontal shaft of the waterwheel, situated on the other side of the wall. On the wheelshaft is the iron pit-wheel, rotating in a well or pit in the floor. The pit-wheel meshes with an iron wallower near the bottom of the wooden upright shaft. Just below the wallower is an iron band around the upright shaft from which protrudes the gudgeon, running in a toe-brass contained in a bridging box: the square heads of two of the four adjusting screws can be seen. This bearing for the upright shaft is carried on a three-arm arch over the inside bearing for the waterwheel shaft

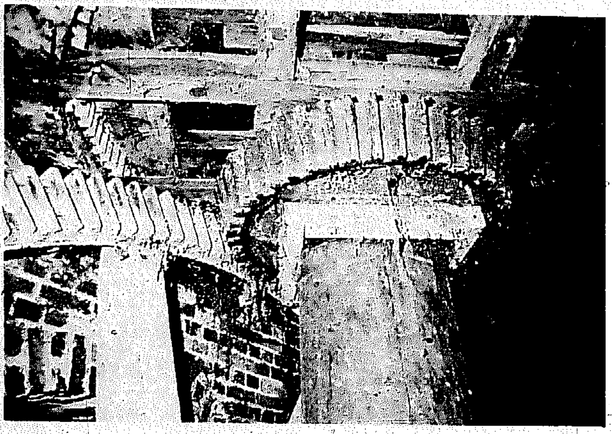


Fig 1.47 Top part of pit-wheel (on the left) meshing with the wallower at Dodford Mill, near Daventry, Northamptonshire. Above the wallower, and also on the upright shaft, is the wooden great spur wheel of clasp-arm construction. The inner portions of the wooden cogs are seen at the inside edge of the rim of the great spur wheel

Attached to the upright shaft is a spur wheel of large diameter, sometimes as great as 3 m. Some wooden spur wheels have their spokes passing through slots in the wooden upright shaft (compass arm construction) whilst others use the clasp arm method (fig 1.47). Whereas oak was often used for the arms and felloes of the wooden gear wheels, sometimes laminated with the grain crossing at right-angles, the wooden cogs were of apple, hornbeam, cherry wood, or sometimes beech.

Set around the great spur wheel are pinions known as 'stone nuts', one for each pair of mill-stones (fig 1.48). Some stone nuts are of wood but many are of iron, even when most of the other gearing is of wood. Iron teeth meshing with wooden cogs were considered to give smoother and quieter running. The stone nuts could be moved up or

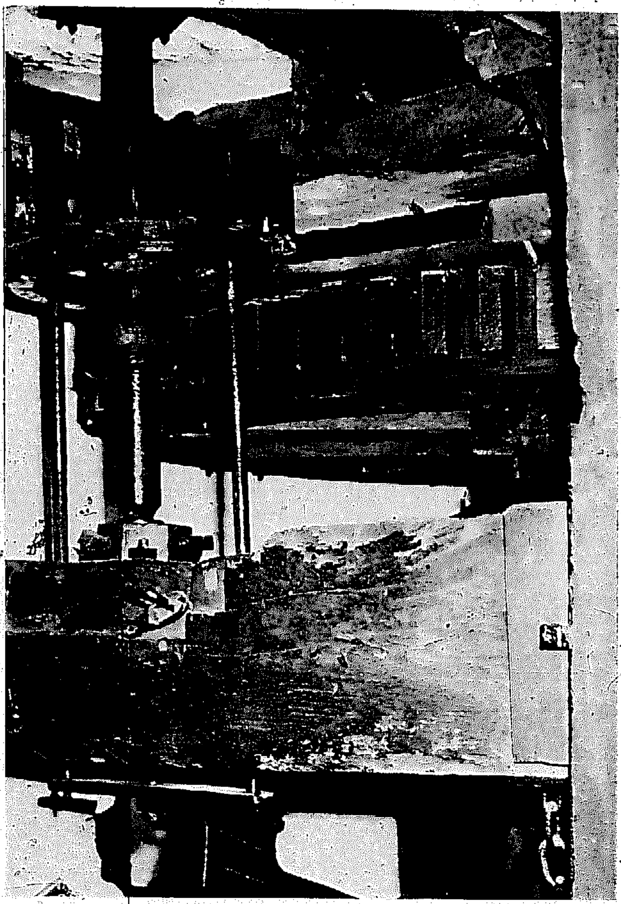


Fig 1.48 Iron stone nut and wooden great spur wheel at Billing Mill. The stone nut is held out of mesh by the jack ring supported by the two spindles passing through the wooden beam (or bridge tree) on either side of the bridging box carrying the footstep bearing for the stone spindle. When the jack ring is lowered by rotating the handle below the bridge tree, the stone nut descends to mate with the conical drive collar on the stone spindle and at the same time meshes with the cogs of the great spur wheel

down their shafts, termed 'stone spindles' so that any of the stone nuts could be disengaged and kept still whilst the others were at work.

The number of pairs of stones driven from a single great spur wheel seldom exceeded six, and many small mills would have only two pairs and some only one pair. It should be noted that when a large number of pairs of stones was arranged around the great spur wheel it was most unlikely that they would all be driven at the same time.

For space considerations, two waterwheels might be used; sometimes arranged one behind the other each with its own pit-wheel, wallower, and great spur wheel driving perhaps two pairs of stones. Only one waterwheel could work at a time, and when it was required to drive either or both of the other pairs of stones the other waterwheel would be brought into use. Alternatively, the wheels could be parallel, either side-by-side at the centre of the building or at opposite ends.

With the layshaft arrangement, any number of pairs of mill-stones could be placed in a straight line, or in two lines parallel to each other, each pair of stones requiring a set of bevelled wheels, as shown in fig 1.49.

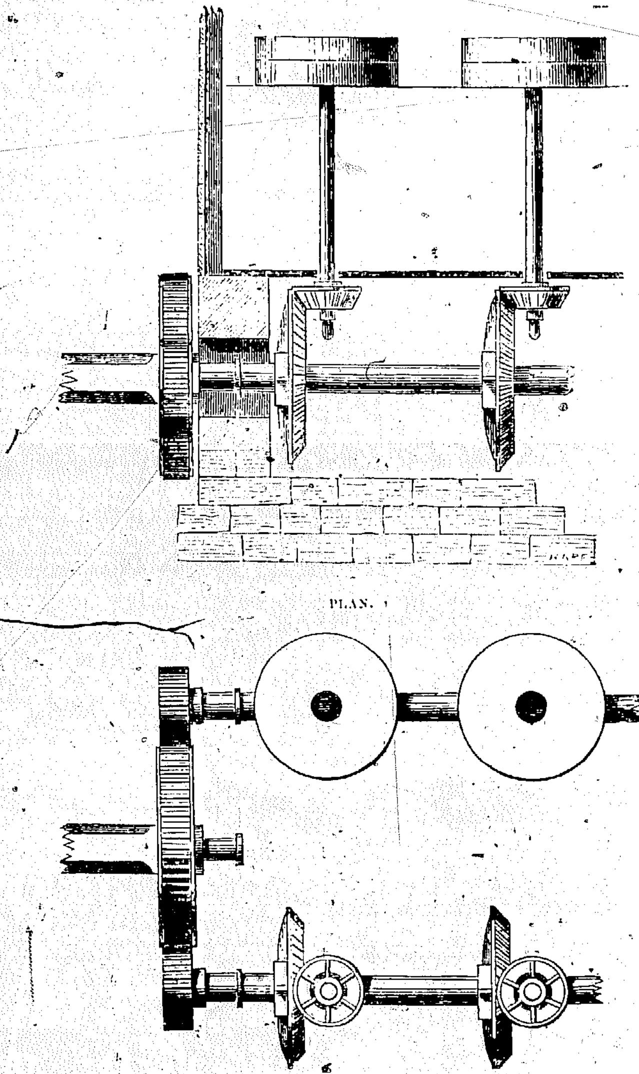


Fig 1.49 Arrangement of gearing when using a layshaft
From J Glynn, *On the power of water to turn mills*, 1853

With more slowly rotating breastshot and overshot wheels, it was possible to obtain the necessary increase in speed at the stones by introducing a further set of gears between the wheelshaft and the layshaft, as in fig 1.50.

Another method of obtaining the required speed increase was by the use of rim gearing on the waterwheel. (See fig 1.36, page 21.)

Although transmission by great spur wheel and by layshafts have been described separately, there are several instances of mills where the two arrangements were used in combination. An example is shown in fig 1.51.

With transmissions using gearing, various arrangements were employed to take the stone nuts out of mesh as required. Whatever the method, it was always used when the gearing was stationary, that is, the waterwheel was stopped before engaging or disengaging the stone nuts.

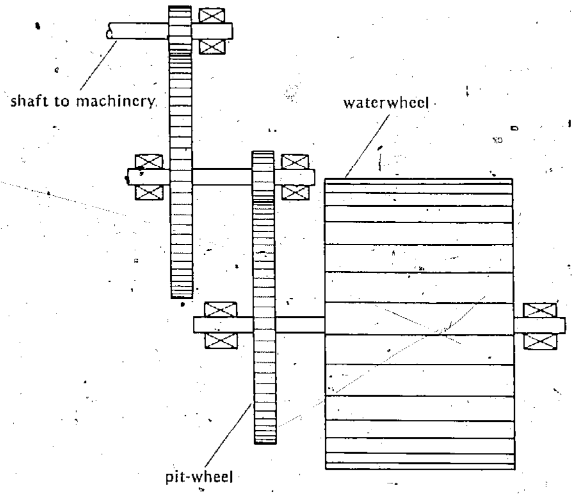


Fig 1.50 Additional gears increase speed

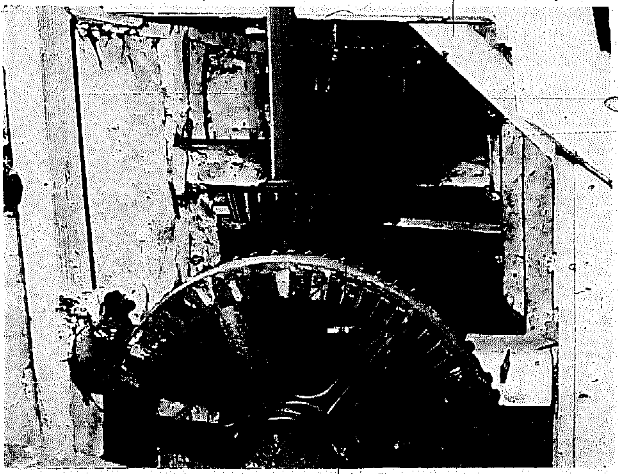


Fig 1.51 Titchmarsh Mill, on the River Nene near Thrapston, with a combination of upright main shaft and layshaft arrangements. In the foreground is a set of bevel gears to drive a pair of stones immediately above, whilst in the background is one of three stone nuts arranged around a great spur wheel. Out of sight behind this are a further two sets of bevel gears on a layshaft so that the mill has a total of six pairs of stones

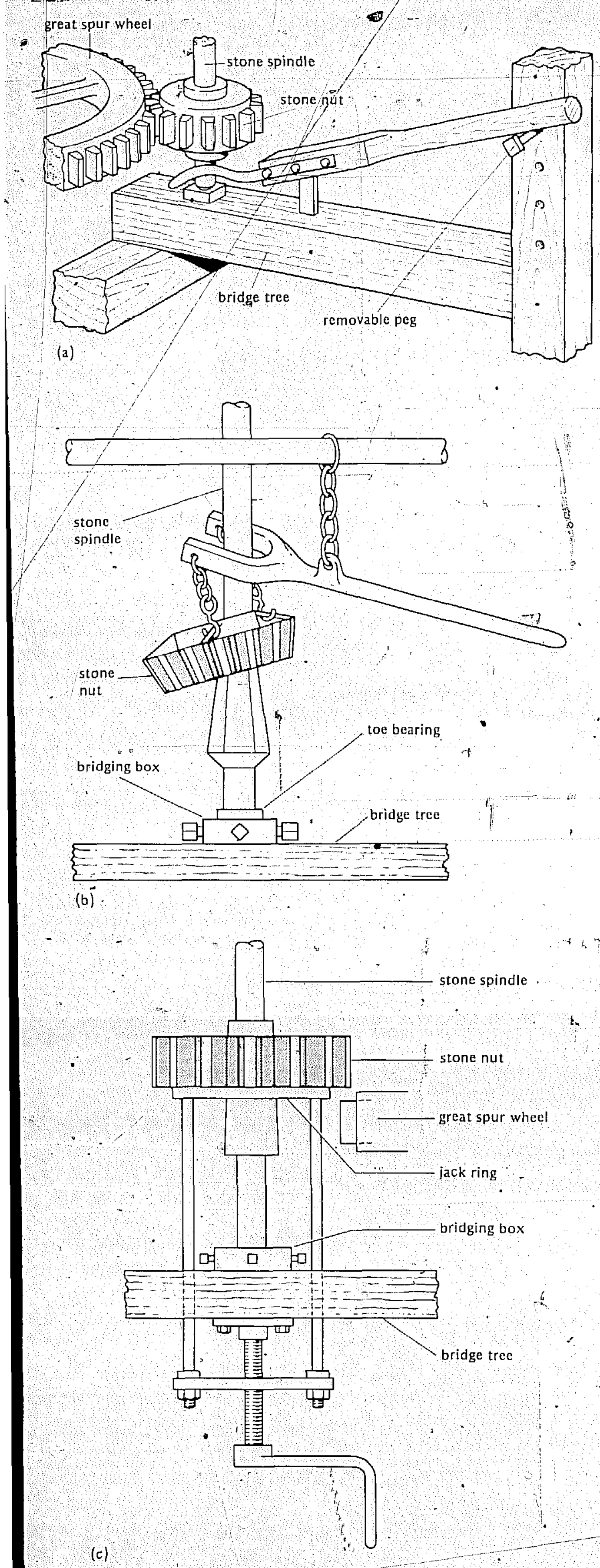


Fig 1.52 Disengaging the stone nut from the great spur wheel (a) Lever and fork, (b) Yoke and chain, (c) Jack ring and screw

Methods for disengaging the stone nut can be grouped into two categories: those where the stone nut is fixed on its shaft and those where it slides along the stone spindle. The use of slip cogs is an example of the first category. The stone nut is provided with a group of three or four slip cogs which are removed by taking out retaining pegs or pins. Thus with the nut in a certain position there are no cogs to engage with the spur wheel.

In the second category, a slot or keyway in the eye of the stone nut is able to engage with a long 'reed' or key held in a keyway in a tapered collar on the stone spindle.

One primitive method of disengaging the stone nut uses a lever on one end of which is a fork or yoke. This is placed under the stone nut and when the other end of the lever is depressed, the stone nut is lifted clear of the great spur wheel, and a peg in a convenient post of the hursting will hold down the lower end of the lever until it is decided to drop the stone nut back into engagement. This is shown in fig 1.52a.

A somewhat similar method used a yoked lever supported near the yoke by a chain attached to a beam above. The yoke extended over the stone nut and had two chains and hooks which could be placed under the arms of the nut. Pulling down on the other end of the lever would lift the nut out of engagement, as in fig 1.52b.

The most widely used arrangement employed a jack ring which could be raised by rotating a screwed rod located under the bridge tree supporting the foot bearing for the stone spindle. As the ring was raised it lifted the stone nut clear of the cogs on the great spur wheel (or the teeth of the bevel gear on the layshaft when that type of transmission was used). When the ring was lowered, the stone nut slipped down the tapered collar until its keyway engaged with the projecting key on the collar. See fig 1.52c.

Transmission of power from waterwheel to mill stones by belts, as in fig 1.53, was never popular despite the apparent advantage of a saving in the number of expensive gear wheels required.

The disadvantages lay in the troubles encountered in reversed bends in the belts, in disengaging individual stone spindles, in maintaining the correct tension in the belt,

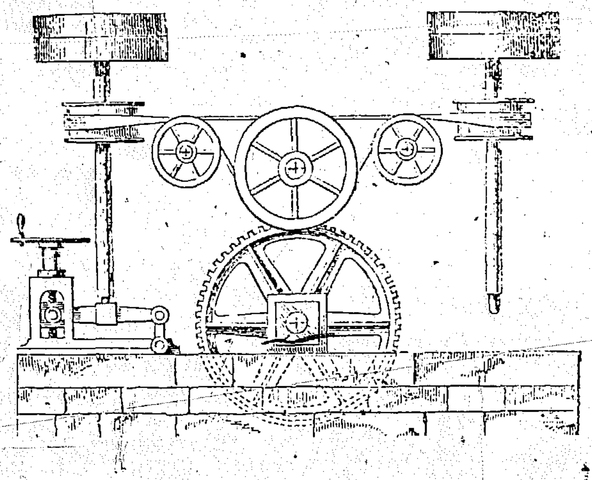


Fig 1.53 Arrangement of transmission to mill-stones using belts
From J Glynn, *On the power of water to turn mills*, 1853

and difficulties in preventing the stone spindle from being drawn to one side by the pull of the belt. However, belt drives were used in some water turbine installations, as in fig 1.54a.

When roller milling replaced horizontal stones, belt drives were the normal form of transmission but here the drive was between horizontal shafts. The bearings on the roller machines could be arranged to withstand the belt tension, and gravitational forces did not alter the position of the belt when on the fast or loose pulleys.

All the previously described transmissions drove the millstones from below (*underdrift*) and this was the customary arrangement in a watermill. However, there were some mills in which the stones were driven from above. (See figs 1.54b and 1.55.) They are then described as *overdrift* or *gripe* driven.

In the overdrift arrangement the stone nuts drive the stones by long shafts termed 'quants' or 'quills' which are held at their upper ends in 'glut boxes', that is bearings which could be opened. When a stone nut had to be disengaged, the outer section of the bearing was removed so that the quant could be tilted away to leave the stone nut clear of the cogs on the great spur wheel.

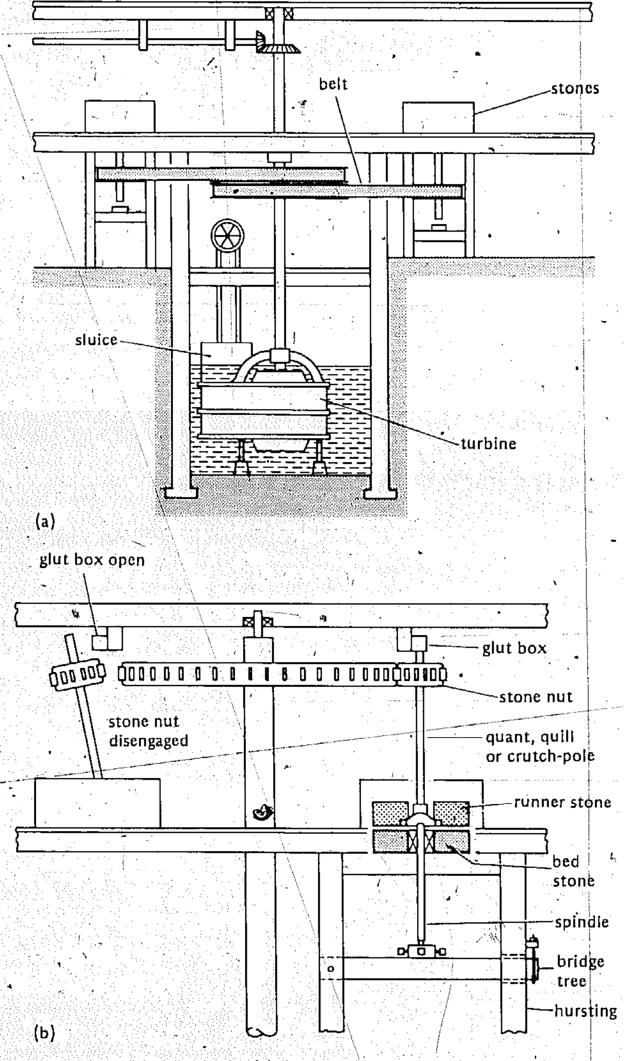


Fig 1.54 Transmission methods: (a) belt drive in turbine installation (underdrift), (b) overdrift or 'gripe' driven

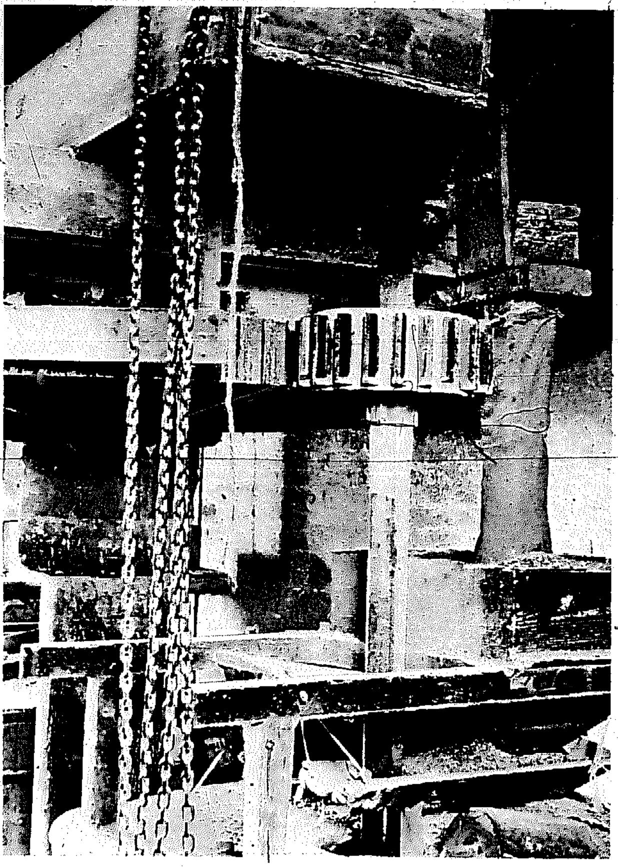


Fig 1.55 Overdrift stones at Ollerton Mill, north of Nottingham. The great spur wheel is in the upper half of the picture and the stone nut meshing with this is on a quant (sometimes called a quill or crutch-pole) supported at its upper end in a bearing known as a glut box mounted on a wooden beam. The lower end of the quant passes through the horse (the wooden four-legged frame supporting the hopper), the end of the shoe (carrying grain from the bottom of the hopper), and into the eye of the runner stone to connect with the drive arrangements.

The gearing between the waterwheel shaft and the stone spindles has three functions:

1 To alter the direction of motion about a horizontal axis to motion about a vertical axis.

2 To provide for one or several pairs of stones to be driven from a single waterwheel.

3 To provide an increase in speed from that of the waterwheel to that required at the mill-stones.

This increase in speed was achieved by having different numbers of cogs or teeth on the various gear wheels. By counting the teeth on the different wheels it is possible to calculate the overall gear ratio and hence the speed increase. Before giving examples of these calculations there are several points to be considered when counting the teeth on a gear wheel in a mill:

1 With a large number of teeth on a wheel, it is easy to lose count if one has to change position to count round the other side of an obstacle such as a shaft, and also to forget from where one started counting.

A chalk mark can be made at the point where counting begins, and if a smaller mark is made on every tenth cog or tooth it is easier to keep a check on the number despite distractions.

2 Sometimes it will not be possible to count the whole way round a wheel because of its inaccessibility. In such cases the teeth in a definite section (a half or a quarter) of the wheel can be counted and then multiplied accordingly to estimate the teeth in the whole. With wheels cast in sections, the sections themselves provide a convenient proportion of the wheel for counting.

This procedure should only be resorted to if it is impossible to count the whole way round since there can be troubles regarding the next point.

3 The millwright often avoided simple gear ratios by inserting an extra, or 'hunting cog', in one of the meshing wheels. This ensured that the same teeth did not mesh together every revolution and avoided uneven wear if one tooth had some irregularity. Consequently when counting teeth, do not be surprised if, despite several recounts, an awkward number such as 37 or 49 results.

Consider a certain mill with the spur wheel arrangement shown in fig 1.43a on page 24. After counting teeth at the mill we find that:

the pit-wheel has 168 teeth
the wallower has 48 teeth
the great spur wheel has 120 teeth
the stone nuts each have 20 teeth.

If the waterwheel rotates once, the pit-wheel will rotate once. The pit-wheel meshes with the wallower, which has fewer teeth, so that when the pit-wheel rotates once, the wallower rotates 168/48 = 3.5 times.

The wallower is on the same shaft as the great spur wheel and will rotate with it. The spur wheel meshes with the stone nut which has fewer teeth, so that when the wallower rotates once, the stone nut rotates 120/20 = 6 times.

However, when the waterwheel rotates once the wallower rotates 3.5 times, and as the stone nut rotates 6 times as fast as the wallower it will rotate 6 X 3.5 = 21 times as fast as the waterwheel.

We will consider the speeds of mill-stones on page 35, but if, in the mill considered for this calculation, the stones worked at 210 revolutions per minute, the waterwheel would be rotating at 10 revolutions per minute.

Similar calculations can be made for mills with the layshaft arrangements shown in figs 1.43b and 1.49.

Besides driving the mill-stones, the waterwheel also powered auxiliary equipment such as cleaning machines (see page 35), dressing machines (see page 36) and for transporting stock (see page 38). For mills with the stones driven from a great spur wheel on a vertical shaft, it was usual to have this shaft extending to the top floor of the mill where it carried a large horizontal face gear termed the 'crown wheel', as shown in fig 1.56. Engaging with this was a pinion (or in some cases, several pinions) on a shaft from which belt drives were taken to the auxiliary machinery, as shown in fig 1.43a, page 24.

Often the auxiliary shaft was supported at its end near the crown wheel in a bearing mounted on a lever, as shown in fig 1.57. By pulling down on the other end of the lever, the bearing and shaft were raised so that the pinion was lifted out of mesh with the crown wheel. In general, the construction and materials used for the crown wheel followed the patterns described previously for other gear wheels in the mill.

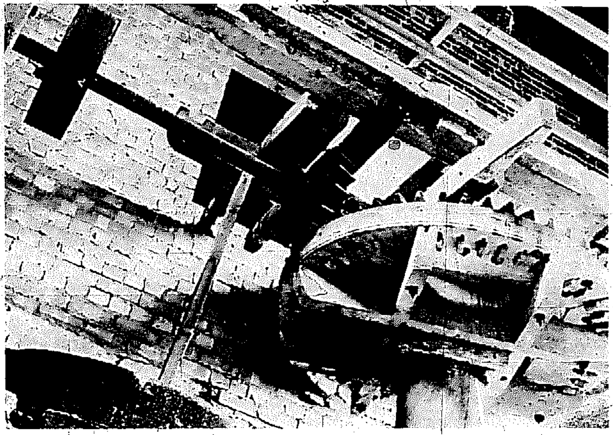


Fig 1.56 Crown wheel and auxiliary shaft at Billing Mill before restoration. The crown wheel is of clasp arm construction

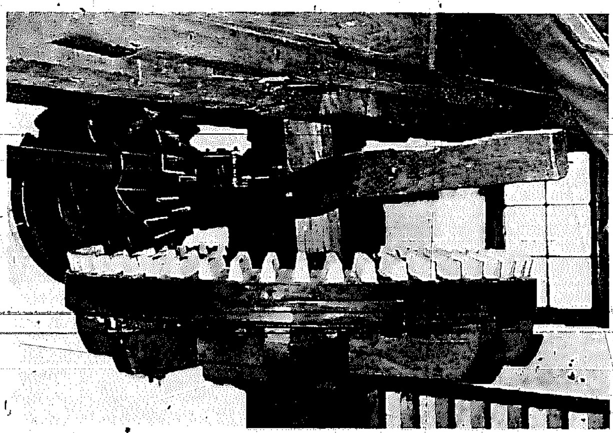


Fig 1.57 Crown wheel and pinion at Billing Mill after restoration. Note the distance between the teeth on the iron pinion, and also the profile of its teeth and that of the wooden cogs in the crown wheel. The end of the auxiliary shaft beyond the pinion is carried in a bearing supported at one end of a lever. When the right-hand end of this lever is depressed, the pinion is taken out of mesh with the crown wheel

In mills with the layshaft transmission, it was customary to have a pulley on the layshaft driving a belt to transmit power to a shaft on the floor above, from which the drives were taken to the other machines, as shown in fig 1.43b, page 24.

Grinding machinery

The main function of the water-driven corn mill is performed at the mill-stones. To do their work, the stones must be of a suitable material and have their working surfaces prepared to deal with the type of grain being ground. The stone spindle (or quant in an overdrift mill) had to be connected to drive the upper or 'runner' stone, and it was necessary to maintain the correct gap between the working surfaces of the two stones. In addition, provision had to be made to feed the grain to the stones and take away the meal produced.

Mill-stones have been made of a variety of substances, and in earlier times from local stone if any was available.

Later more suitable stones were adopted in areas remote from the quarries. These included:

1 *Quartz stones.* The best of these, having a roseate hue, are the French stones, found in the vicinity of La-Ferté-sous-Jouare and Epernon. Because of the peculiar formation of French Burr it was difficult to get a whole stone of uniform quality throughout, and it was usual to build the mill-stone of selected pieces cemented together with plaster of Paris and bound around the circumference with iron hoops. The stone was then smoothed off with cement on the back and the working face was dressed. These stones were particularly suitable for finer grinding, and in the later days of horizontal stone grinding nearly all flour was produced on such stones.

2 *Sandstones.* Derbyshire Peak Stone is one example of sandstone. The stone was hewn in one piece out of a solid block. These sandstones were much softer and less durable than mill-stones of French Burr but produced a meal of particularly soft and pleasant texture and were used mainly for grinding barley and oats.

3 *Stones of volcanic origin.* The best known of these were quarried in the Andernach and Koblenz areas of Germany and brought down the Rhine for shipment to this country, where they were known as 'Dutch blue stones'. These were preferable to the Peak stones but were themselves displaced by the French Burr stones during the nineteenth century.

4 *Artificial or composite stones.* These were made by reducing French Burr or emery to particles of 0.3 cm or less in diameter and embedding them in a strong cement. Mixtures of other particles have been used to give a finished stone of a particular hardness to suit the purpose for which it was intended. Besides this control of properties, composite stones had the advantages of being free from the soft spots that sometimes occur in natural stones, and of being self-sharpening owing to the multitude of cutting edges presented by the embedded particles.

These artificial stones were usually made by pouring the liquid composition onto a cast-iron backing plate, provided with undercut grooves to hold the solidified composition securely in place. This backing plate simplified the mounting of the stone on the driving spindle, and enabled it to be removed and replaced more easily than with natural stones. It also stiffened the stone so that it could be used until the composition was almost entirely worn away.

Two stones are arranged as in fig 1.58 for horizontal grinding: a stationary stone bedded into the floor (and known variously as a bed stone, nether stone, or sometimes as a 'ligger'), and an upper, revolving stone generally known as a runner stone.

The working surface of the runner stone is recessed at the centre (or 'eye') into a conical depression, or 'swallow', so that the grain which is introduced at the centre can enter without difficulty and distribute itself evenly.

At the end of this portion is the reducing zone where the grain is crushed and pushed to the actual grinding zone before emerging as meal at the skirt of the stone.

The 'dressing' of the stone is the operation of cutting on the grinding face a series of furrows, each about 1–2 cm deep. The purpose of the furrows is mainly:

1 to act as a distributor to propel the grist to its exit,
2 to ventilate the working space.

There are furrows on the upper and lower stone so that when one is laid upon the other, the furrows cross each other at an angle.

The actual grinding of the grain is done by the flat surface between the furrows known as the 'land', and this is generally picked or 'cracked' to give fine 'featherings' or 'stitching' to produce a better grinding effect. Too much 'land' causes overheating and, as a general rule, the more numerous the furrows, the cooler the grinding and the greater the capacity of the stones. Naturally, large stock caught between the edges of the furrows would be crushed. The furrows were usually cut with a near vertical back edge and a sloping bottom.

The pattern of the dressing was usually in the form shown in fig 1.59 and consisted of a number of master furrows running from the eye to the circumference, with tributary furrows placed at an angle, each master furrow with its tributaries comprising a 'harp'. The furrows do not run radially from the centre to the circumference, but start

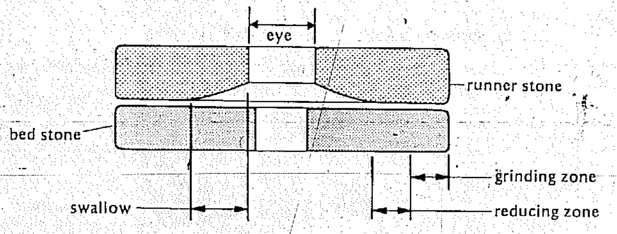


Fig 1.58 Horizontal grinding with lower (nether) stone and upper (runner) stone

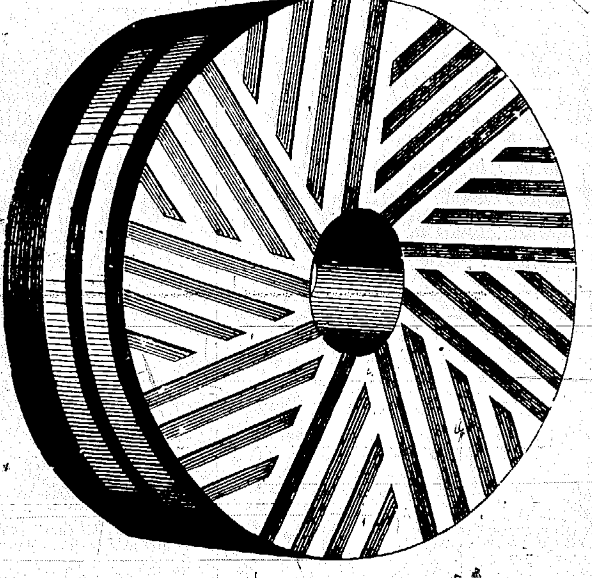


Fig 1.59 Pattern of dressing on a mill-stone suitable for ordinary low grinding, divided into nine quarters or harps with four furrows to each quarter. For a stone of 1.2 m diameter, the furrows would be 35 mm × 8 mm cross section

Diagram from catalogue, c 1890, of W Gardner, Gloucester tangentially from a circle rather smaller than the eye of the stone. The radius of this circle is the lead or 'draft' of the furrows and has an important influence on the distribution, grinding, and discharge of the stock.

Some stones have circular furrows, sometimes referred to as 'sickle' dressing, and again the start of the master furrows is tangential to a 'draft' circle.

Periodically, sometimes after only a week if the mill was working hard, the furrows were redressed either by the miller or by a specialist stone dresser. When this was necessary, the runner stone had to be lifted off the bed stone, swung away, and turned over so that the grinding faces of both stones were exposed. Since stones could weigh over one ton when new, there was a need for lifting tackle such as hoists, stone cranes, or callipers to remove and turn over the runner stone once it had been raised by driving large wooden wedges between the working surfaces of the stones.

The tools used for dressing the stones were the 'bill', a tempered steel cutting tool shaped like a double-ended wedge, and the 'pick', a pointed cutting tool.

These were mounted in wooden handles, called 'thrifts'. (See fig 1.60). A bill would need resharpening after about fifteen to twenty minutes work on the stones, so that often there was a circular grindstone arranged vertically and driven by a belt from one of the rotating shafts in the mill.

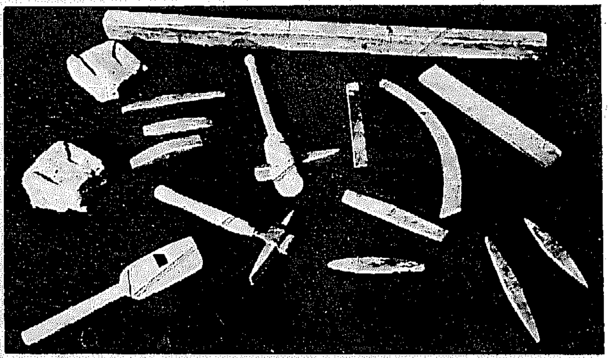


Fig 1.60 Equipment for dressing mill-stones. At the rear is the proving staff for checking the flatness of the stones, in front are the wooden handles ('thrifts') for the mill bills and picks. On the right, near the proving staff, are templates for dressing stones, including one for the curved furrows in sickle dressing. The two pieces of stone on the left are part of a French Burr mill-stone

In use, the two stones did not come into actual contact although the space between them was very small (about 0.03 cm according to one stone dresser) and carefully controlled to produce the best results. The process of adjusting the gap is called 'tentering' and the mechanism to do this is termed 'tentering gear'.

For both underdrift and overdrift stones, the weight of the runner stone is supported from below by the stone spindle, which is supported by a 'toe' or thrust bearing in an iron 'bridging box'. The latter has four hackle-screws which can be adjusted from outside to position the toe bearing accurately. The two main methods of tentering differ in the way the bridging box is supported. They are as follows:

1 The bridging box may be secured to a stout timber beam (the *bridge tree*) which is pivoted at one end, and has some means of adjusting the vertical position of the other end. This arrangement is shown in fig 1.61a.

  In many instances, the position of the movable end of the bridge tree was supported in a stirrup from which a screwed rod passed upwards through an eye or bracket fixed to an upright of the hursting. The stirrup was held by a nut on the screwed rod above the eye, and by turning this nut with a spanner a fine adjustment could be made to the vertical position of the stirrup, as in fig 1.61a.

2 In another method of tentering, the bridging box was mounted in a vertical slide in the bridge tree which remained stationary.

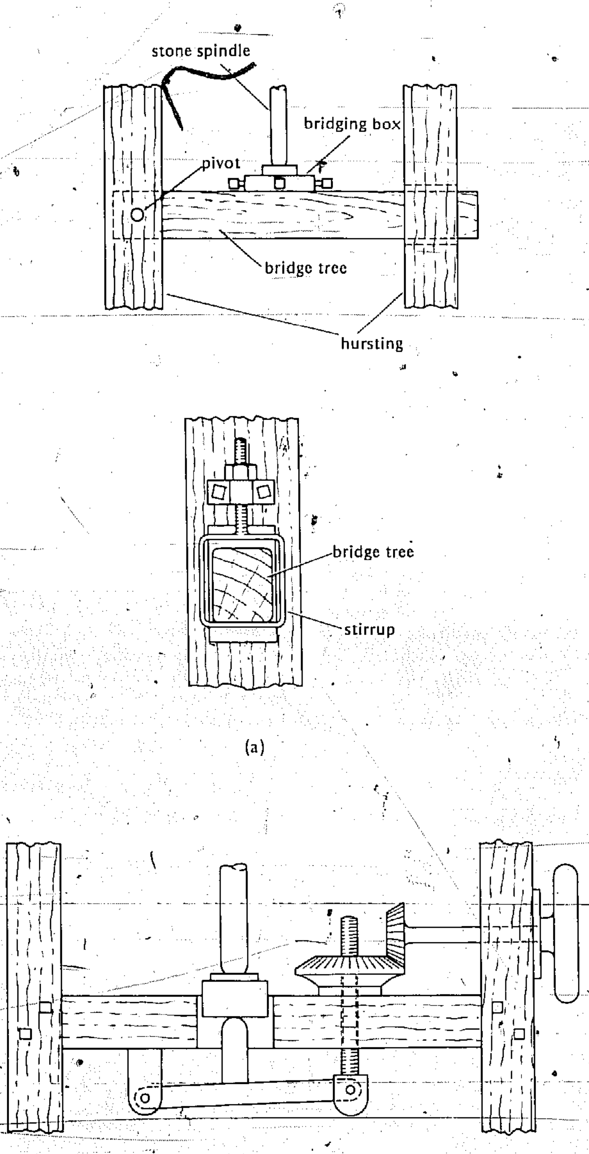


Fig 1.61 Methods of 'tentering' or adjusting the gap between the two stones. (a) Bridging box secured to bridge tree. Below is shown detail of stirrup held by adjustable nut. (b) Peg mounted centrally, on lever below bridge tree

The adjustment was obtained from a peg mounted centrally in a lever below the bridge tree, as shown in figs 1.61b and 1.62. This supported one end of the lever but the other end was carried by a screwed rod passing through a nut integral with a bevel gear which was rotated through a mating gear by turning a handwheel outside the hursting.

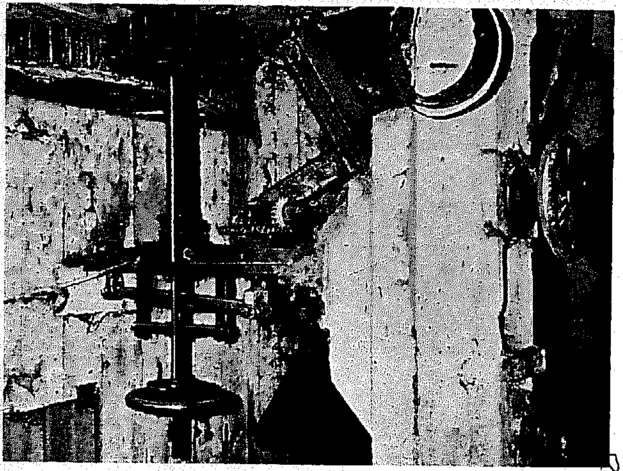


Fig 1.62 Tentering gear formerly at West Farndon Mill, north-east of Banbury. The iron bridge tree carried the jack ring gear with the operating handwheel below. The gap between the stones was adjusted by a small vertical movement of the footstep bearing carried on the bridge tree, by turning the handwheel on the vertical post at the right of the picture

In many mills, the supply of water to the wheel is more or less constant so that the mill-stones rotate at the same speed. Once the stones have been running for about half an hour, so that the gap between the stones can be set at the normal running temperature, no further tentering is required. However for some mills, such as those supplied from a pond, the water level will drop, and if no alteration is made to the setting of the sluice the speed of the waterwheel will decrease and consequently the driven millstones will run more slowly. The gap between the stones must then be adjusted if grinding is to be consistent.

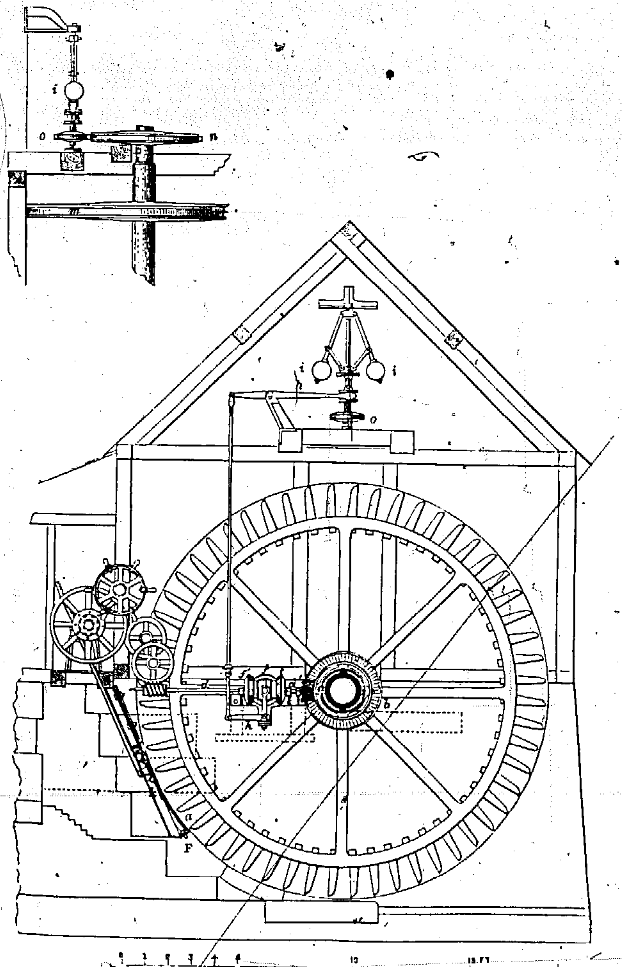
In some cases where the head of water might alter, automatic devices were installed and these worked by either

1 altering the flow of water onto the wheel so that its speed and that of the mill-stone remained more or less constant, or

2 altering the gap between the stones to compensate for the change in speed.

In both cases the devices generally utilized a centrifugal ball governor first applied to clocks in the seventeenth century, and patented for use in windmills in 1787, and then in some watermills. Two balls were suspended from rods attached to a collar fixed to a rotating vertical shaft driven from whatever was subjected to a change in speed. See fig 1.63. As the shaft rotated faster the balls would fly out. As they did so, links connecting them to a sliding collar lower on the vertical shaft would cause the collar to slide upwards. This movement was utilized, normally by a system of levers, to compensate for increase in speed. Governors for automatic tentering are shown in figs 1.64 and 1.65.

Near its upper end the stone spindle passed through the centre of the bed (ie the stationary) stone, where it was



WATER-WHEEL AT WALTHAM ABBEY.

Fig 1.63 Waterwheel driving governor which controls setting of sluice admitting water onto the wheel
From J Glynn, *On the power of water to turn mills*, 1853

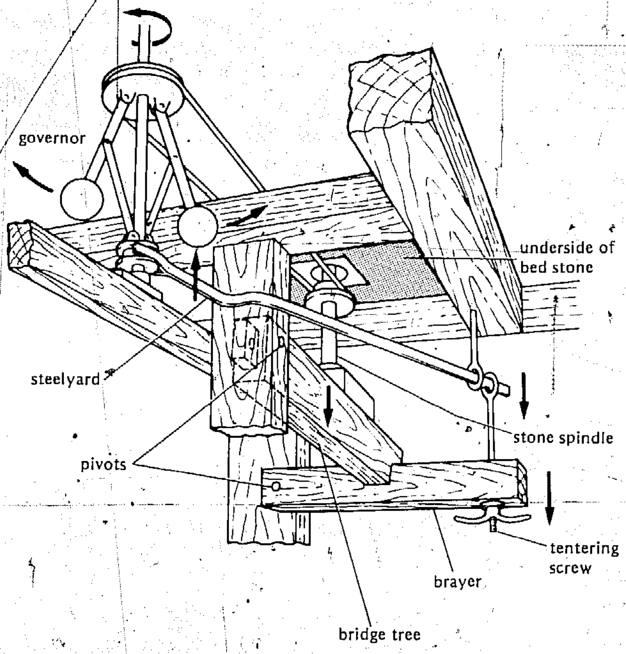


Fig 1.64 Typical arrangement of levers and governor for automatic tentering

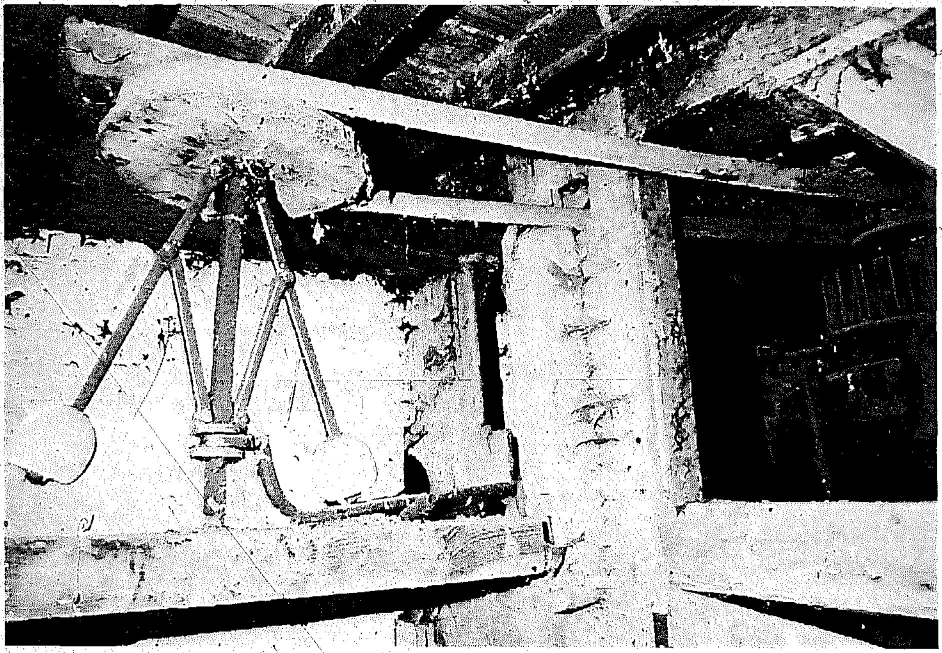


Fig 1.65 Governor for automatically tentering one of the pairs of stones at Dodford Mill, near Daventry. The governor is belt-driven from a pulley on the stone spindle. Movement of the collar, near the bottom of the governor's vertical spindle, is transmitted by the swan-neck-lever to the free end of the bridge tree inside the hursting

laterally located by a bearing consisting of brass bearing pads held tight against the journal of the stone spindle by wedge pieces in recesses formed in the square bearing block or 'neck box'. This was fixed into the centre of the bed stone. A cover plate was fastened across the top of the neck box to prevent the grain and dust getting into the bearing and instead direct it into the 'swallow' of the stones.

From just above where it emerged through the cover plate, the stone spindle was shaped to a square section usually tapering towards the end. On the upper portion of this square section was positioned the means of supporting and driving the runner stone. The most common methods used were:

1 a rynd or iron cross
2 a mace and bar (or rynd)
3 a mace and gimbals.

The rynd or iron cross was the earlier method, in which the rynd was set directly onto the tapered part of the stone spindle and the extremities of its arms let into recesses in the underside (ie the working face) of the runner stone. This was virtually a rigid mounting and gave difficulties in balancing.

The other two methods both used a mace head which was of cast iron and set onto the tapered portion of the stone spindle.

In method 2 above, illustrated in fig 1.66a, the bar (sometimes called a 'bridge rynd' or 'gimbal bar') again had its ends located in cavities, diametrically opposite across the eye of the stone. However, the bar was shaped so that its recessed centre could rest on top of the stone spindle which was given a spherical apex. The bar was embraced and driven by the protruding lugs of the mace head (or 'driver'). This was usually provided with recesses to drive the damsel, which was fitted in from above the stones (see page 34).

In the true gimbals method, shown in fig 1.66b, the mace head was provided with trunnions (instead of a slot or

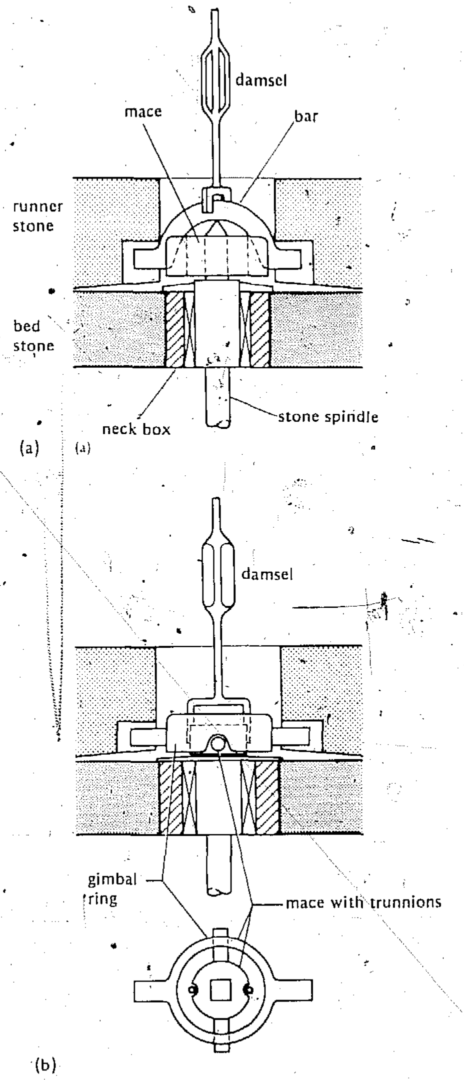


Fig 1.66 Methods of driving runner stone (a) Mace and bar (b) Mace with trunnions and gimbal ring

forked ends) and these were located in two recesses in the underside of the gimbal ring (sometimes this was of elliptical shape). At right angles to these recesses were trunnions which registered with the cavities either side of the eye of the stone.

When the runner stone was in motion it was essential that the stones never actually touched, since this would produce very rapid wear of the stones and also sparks which might set the mill on fire. Because of the way the runner stone was supported and driven, it was necessary to balance it exactly. This was sometimes done by cutting cavities in the back (or upper surface) of the stone and running in lead. Later, adjustable balance weights, patented by Henry Clarke in 1859, were used.

In use, the stones were enclosed in a wooden cover ('tun' or 'vat'), usually round but sometimes octagonal, on which stood a framework (known as the 'horse') supporting a wooden hopper. From the horse was pivoted a wooden spout (called the 'shoe') which fed the grain into the eye of the runner stone. The usual arrangement is shown in figs 1.67 and 1.68.

Grain was delivered into the hopper through spouts from the bins on the garner floor above. It was essential to keep grain between the stones when they were rotating, otherwise there was the chance of damage to the stones or even of sparks to set off a fire. To warn the miller that the hopper was running empty, a leather strap was often placed across it with one end fastened to the far side of the hopper and the other end hanging over the lip of the hopper above the eye of the stones with a small bell attached to it. When there was a reasonable amount of grain in the hopper, its weight was sufficient to hold down the strap so that the bell was held up. As the quantity of grain fell its weight was eventually unable to restrain the strap, which rose so that its free end slid down over the edge of the hopper. This allowed the bell to come into contact with an irregularly-shaped piece of iron (called a 'damsel') rotating with the runner stone. Thus the bell rang a warning to the miller that the stones would soon be running 'dry'.

From the hopper, the grain ran into the shoe. Pivoted at its rear end to the horse, the front of the shoe was pulled to one side by a cord attached to a springy piece of wood (or, in later years, of metal). This caused a hard block of wood (the 'rap') on the inside of the shoe to catch on the rotating damsel so that the shoe vibrated and helped the grain travel down into the eye of the stone.

The front of the shoe was held vertically by another cord fastened to it and running over part of the horse and/or a bobbin so as to clear the edge of the stone cover in passing through a hole in the floor. From below, the miller could alter the inclination of the shoe, and thus regulate the amount of grain passing to the stones, by adjusting the cord on a twist peg located near the meal spout. In some cases there was an additional control of the flow of grain by means of a sliding door or hatch in the front of the hopper.

From the shoe, the grain fell into the eye of the runner stone (which was sometimes lined with thin metal sheet) and passed into the swallow, and then ground on its passage through the stones. It emerged at their circumference as meal, and was trapped by the stone cover. A metal 'tag' or 'paddle' was sometimes attached to the

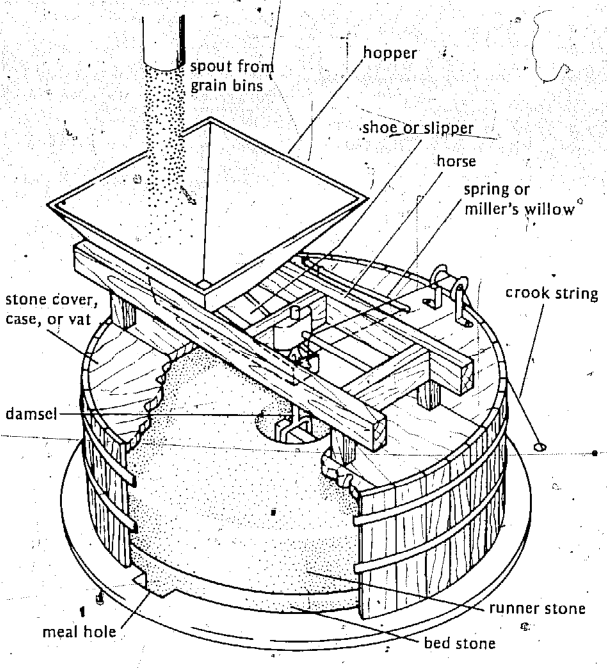


Fig 1.67 Feeding grain into the eye of the runner stone

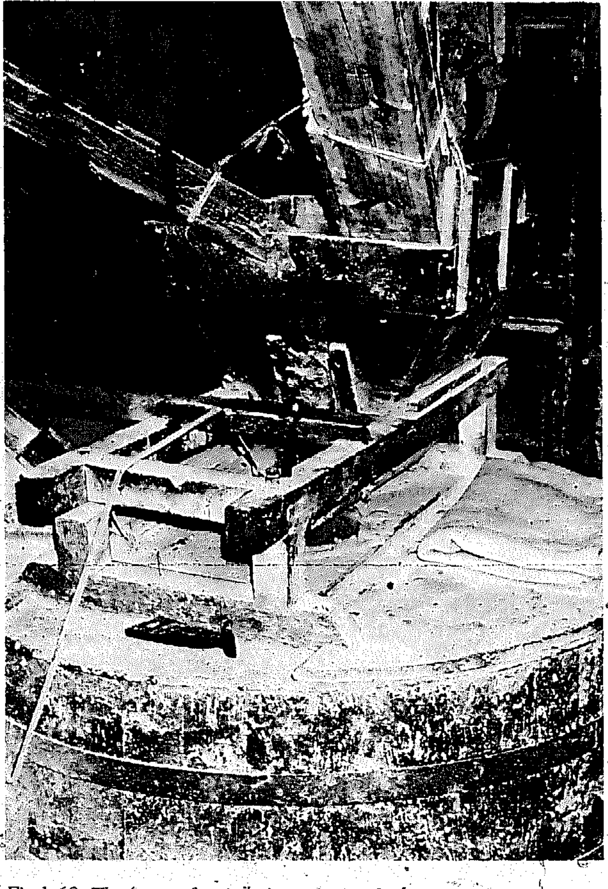


Fig 1.68 The 'stone furniture' on a pair of stones at work at Buckland Brewer, south of Bideford, Devon. Grain from the storage bins on the floor above descends through the wooden spouts into the hopper, carried on the wooden frame called a 'horse'. Beneath the hopper is the shoe, pivoted to the rear of the horse and suspended at the front by the crook string passing over parts of the horse. This stands on the wooden stone case, which completely encloses the mill-stones except for where the shoe delivers grain into the eye of the runner stone

runner stone. This helped to sweep the meal round the annular space between the edge of the stones and the inside of the stone cover to a hole in the floor, through which it fell via the meal spout into a bin or sack below.

The output of the stones depended upon their size and since the relative linear velocity between runner and bed stone could not be too great, the larger diameter stones were run more slowly. The relationship between size, capacity, and speed of rotation is shown in the following table.

	Diameter of stones (cm)			
	75	**90**	**105**	**120**
Speed of rotation of runner stones (revolutions per minute)	250	200	180	150
Quantity of corn ground into meal containing fine flour (bushels/hour)	2½	3¼	4	5
Quantity of corn ground into course meal for animal food (bushels/hour)	5	6½	8	10

Grain cleaning machinery

In addition to grinding, there might be ancillary processes which required machines for which the drive was taken from layshafts (see page 29). Grain cleaning was a preliminary to the grinding process described in the last section.

When delivered to the mill, the grain might contain various impurities, as described on page 23, and might also have undesirable matter adhering to the individual grains. The former were removed by various types of separating machine, and the adhering dirt, together with the husk, beard, and any smut, was removed by scouring.

The impurities generally differed from the sound grain by one or more of the following characteristics:

1 size
2 specific weight
3 shape
4 magnetic properties.

Different types of separating machinery were designed to utilize each of these differences, but often the separation of the grain from impurities differing from it in size and specific weight was carried out in a single machine.

Separating by size was a sifting process. The sieves were either of woven iron, steel, copper, or bronze wire, or of perforated sheets of metal. As the grain passed over the sieve, the separate grains fell through when the meshes were slightly larger than the grains, and the larger impurities fell off the end of the sieve. In other words, the 'throughs' supplied the grain and the 'overtails' consisted of the larger impurities. To remove the smaller impurities, the grain passed over a sieve with meshes smaller than the smallest grains, which all went to the 'overtails' whilst the small impurities formed the 'throughs'.

In order to make the product travel over the sieves, there were in general two forms of sifting machines:

1 those with vibratory motion
2 those with rotary motion.

In the first type, the sieves are set at a slight angle to the horizontal plane and given reciprocating motion by means of a crank. In the second type, often termed 'reel separators', the working surfaces revolved. The reels could be round or, for cheapness and ease of construction, hexagonal in shape.

Fig 1.69 shows a simple reel separator. The reel is inclined and the grain flows in to the upper end through a spout. As the reel rotates, the grain tends to lift up the sides and then falls back to the bottom and slowly travels towards the lower end of the reel. The first, or upper, part of the reel is cased with sieves of finer mesh than the grain so that the small impurities pass through to a collecting chamber below. The last part of the reel is cased with sieves with a mesh slightly larger than the grain which passes through to the hopper below whilst the larger impurities overtail through the open end of the cylinder.

Separation by specific weight was performed in machines providing an air draught. The simplest form, often called an aspirator, is shown in fig 1.70, and consisted of a chamber and a fan.

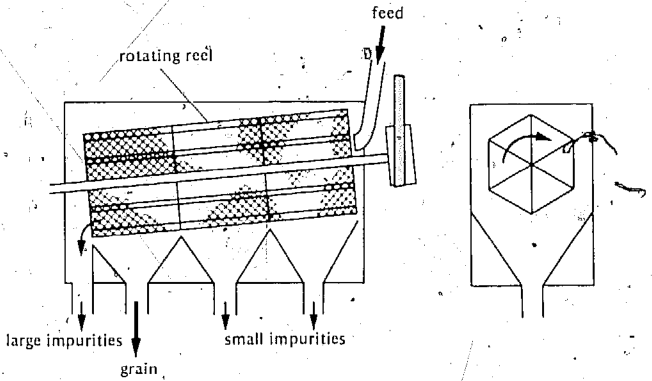


Fig 1.69 A simple reel separator

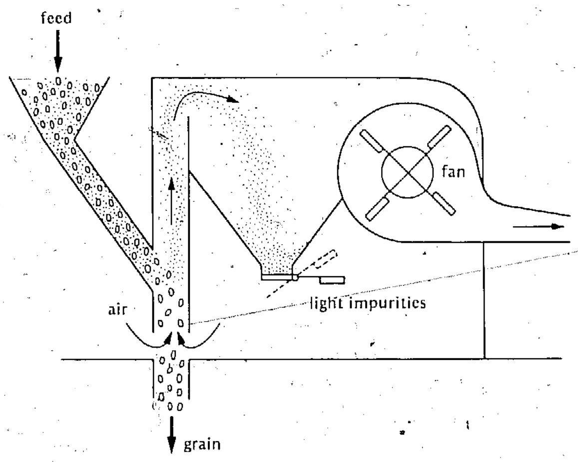


Fig 1.70 Aspirator for separation of grains by specific weight

The grain enters by an inclined spout and encounters a current of air aspirated by a fan which draws up those impurities lighter than the wheat. These are carried on to the chamber, where the lightest are ejected by the fan and the not-so-light fall into the hopper, from where they are eventually discharged. With only single aspiration the cleaning was only partially effective, so machines were made with multiple stages of aspiration.

Often oscillating sieves and an air draught were combined in cleaning machines, as shown in fig 1.71. The incoming grain encountered a draught of air which removed the dust and a good deal of the chaff. The top sieve had holes slightly larger than the wheat, which fell through, whilst the larger impurities continued down as 'overtails' into a discharge chute. The lower sieve had holes smaller than the grain so that the small impurities constituted the 'throughs' and the grain overtailed to discharge. Here it met a draught of air which removed the remaining chaff and any other light impurities which had been shaken loose as the stock passed down the sieves.

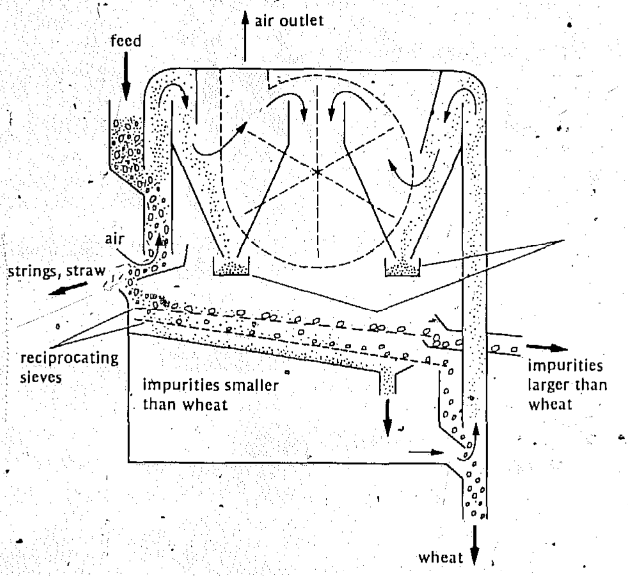


Fig 1.71 Combined cleaning machine

To rid the grain of 'foreign' matter such as rye, barley, oats, and cockle, machines were used which separated by shape. One of the earliest of these was the 'trieur', which was invented by the Frenchmen Vachon (father and son) in 1845 and was used well into the twentieth century.

The trieur consisted of an inclined cylinder of sheet iron, fig 1.72, with small cylindrical recesses on the inside surface. The cylinder was rotated but inside was positioned a stationary conveyor box. Grain entered the raised end of the cylinder and the round grains of the 'foreign' cereals fell into the recesses, in which they were carried up as the cylinder rotated until at a certain height they dropped out and into the conveyor box. The wheat grain travelled down the cylinder by gravity, helped by the rotation of the cylinder, and was discharged through a spout at the lower end. The foreign matter was propelled along the conveyor box by a rotating screw or worm to a separate discharge spout.

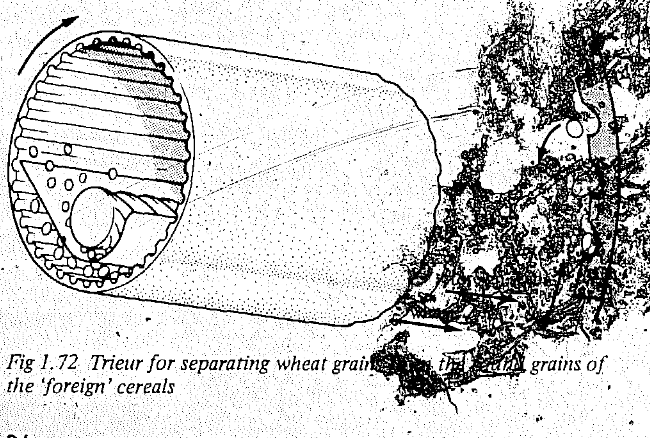


Fig 1.72 Trieur for separating wheat grain from the round grains of the 'foreign' cereals

Trieurs became less common after the introduction, during the 1920s, of the *disc separator* which had rotating vertical discs with recesses to trap the unwanted cereals.

Matter adhering to the individual wheat grains was removed by scouring. During the latter part of the nineteenth century this was done mainly in machines called 'smutters', a name they were given because they were first developed to deal with grain suffering from a disease which produced black 'smut' balls. Smutters consisted of a series of iron or steel beaters rotating at about 450 rev/min inside a cylinder of wire mesh or perforated sheet iron. The aim was to keep the grain rubbing on the cylinder and so burst the smut balls and rub dirt from the grain. The resulting dust was extracted by an aspirator. Smutters were made with the cylinders either vertical (in which case intermediate trays or tables were fitted) or horizontal.

Flour dressing and grading machines

After passing through the mill-stones, the grain was converted to meal – a mixture of flour with pieces of the broken bran-coat. To obtain flour, it was necessary to separate the branny particles from it by sifting. Some of the methods used were similar to those already described in the previous section for preparing grain. However, whereas the working surfaces in the grain preparation machines consisted of sieves of perforated metal plate or wire mesh, those for grading flour utilized cloth and, more usually, silk.

Bolters

The earliest bolters were simply a long cylindrical cloth sleeve held in an inclined position with its upper end arranged just below the mill-stones to receive the freshly ground meal. The sleeve was agitated by a wooden rod worked by the drive to the stones. The flour was shaken through the sleeve and collected, whilst the bran particles came out at the lower end of the sleeve.

By the nineteenth century, the bolter in most common use in England consisted of a wooden casing in which rotated an inclined, wooden, cylindrical frame or 'reel'. Over this was fitted a tubular bolting cloth. The meal was fed into the upper end of the cloth and as the reel rotated (at about fifty revolutions per minute) the meal inside was turned over and over so that the flour passed through the fine mesh of the sleeve. Under the weight of meal inside, the sleeve sagged to rub onto several longitudinal bars fixed about 1 cm away from the bottom of the reel, and this helped the flour to pass through. At first the sleeves were made from wool, then from calico, and finally from silk. However, by the time silk was introduced there had been developments in the rest of the machine, which was then usually termed a reel separator – see page 37.

Wire machines

An alternative to the bolter was the wire machine (often referred to simply as a 'dresser') in which the sifting surface was a stationary cylindrical frame, about 2 m long and 40 cm in diameter. It was lined with wire cloth and placed in an inclined position (between 20° and 45°) over a series of hoppers, the whole being enclosed in a wooden box-like structure, as shown in fig 1.73. The finest wire was at the upper end, the size of wire and meshes increasing towards the lower end where the bran was discharged. Inside this cylinder was a reel fitted with brushes and revolving at high speed (320 to 450 rev/min were normal but some ran in excess of 500 rev/min).

The meal was delivered into the top of the cylinder by a wooden spout and was driven through the appropriately sized mesh by the rapidly revolving brushes. Surviving examples of wire machines are shown in figs 1.74 and 1.75.

Reel separators
By the 1880s the old-style bolter and the wire dresser had been replaced in most of the larger and medium-sized mills by the silk reel or reel separator. The longitudinal bars of the rotating reel were shaped to propel the stock along the cylinder. See fig 1.76.

Centrifugals
Because, in the ordinary reel separators, at any instant only a third of the available sifting area was being used, they had to be made very large to deal with the outputs required. Centrifugal reel separators, fig 1.77, were evolved in an attempt to produce a more compact machine by moving the meal at a wide angle to the bolting surface and so to utilize most of the area of the sieve. Centrifugal flour dressers had the reel and silk rotating at between twenty and thirty rev/min, and inside this, rotating in the same direction but at about eight times the speed, were beaters.

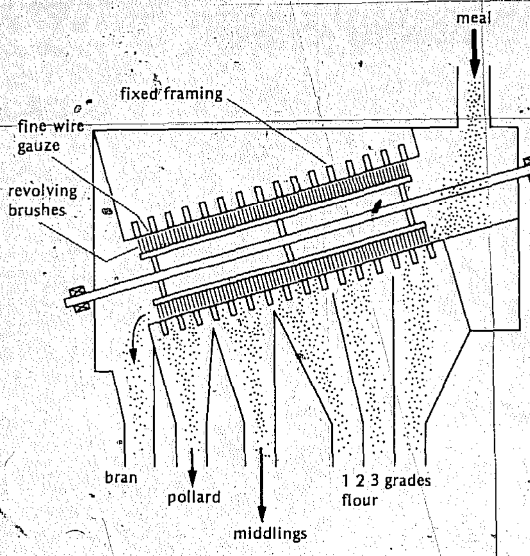


Fig 1.73 Wire machine

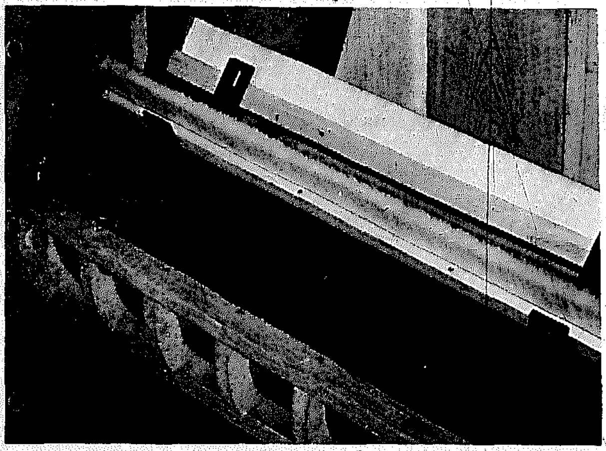


Fig 1.74 Dilapidated wire machine at Dodford Mill. The front cover of the machine has been removed so that the fixed wooden reel, for supporting the wire mesh, can be seen

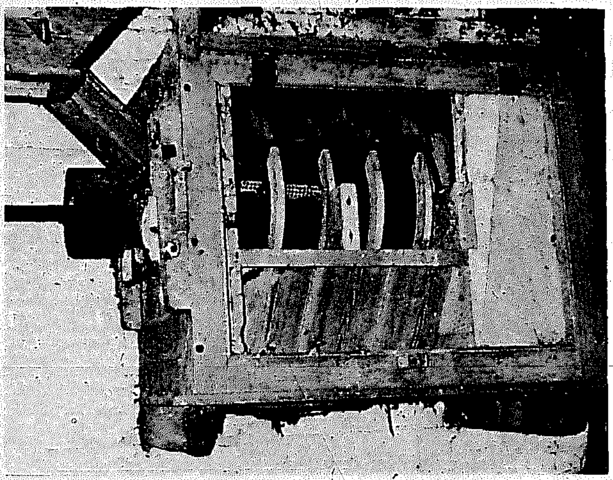


Fig 1.75 The wire machine at Sarehole Mill, Birmingham. The wooden reel and wire mesh has been partly removed to show the brushes which used to rotate when the machine was in use

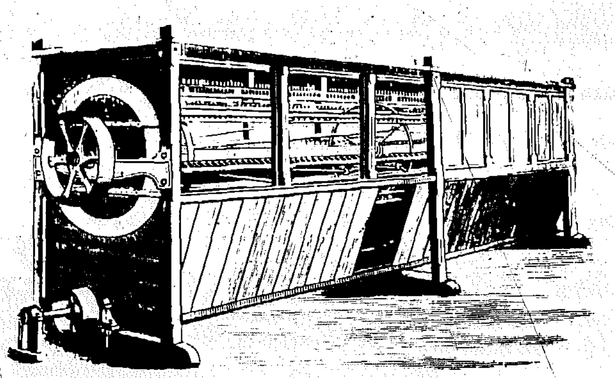


Fig 1.76 Flour-dressing reel. The stock was propelled along by the longitudinal bars
From catalogue, c 1890, of W Gardner, Gloucester

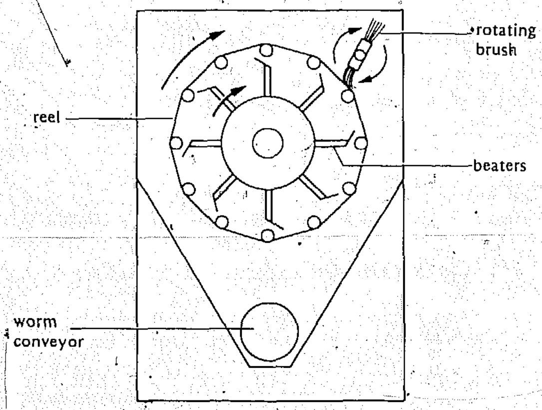


Fig 1.77 Centrifugal reel separator

The meal was lifted by the rotating reel, eventually to drop back onto the beaters which threw it onto the bolting surface and so increased the throughput.

Plansifters

Because of the power consumed by reels and centrifugals, and inequality of work on the bolting surfaces, machines were developed using flat sieves. There were two basic types:

1 machines with rectilinear reciprocating motion of the sieves
2 machines with gyrating progressive motion of the sieves.

The former were a useful alternative to the reel in small mills where space was a major concern. The second type provided great capacities to suit the needs of large mills working on the gradual reduction process, and are in use today in flour mills.

Transportation of stock

The incoming grain was usually stored in wooden bins at the top of the mill so that it could be fed by gravity to the hoppers and thence to the stones. Thus there was a need to lift the newly-delivered grain from the ground floor of the mill. A garner floor is shown in fig 1.78.

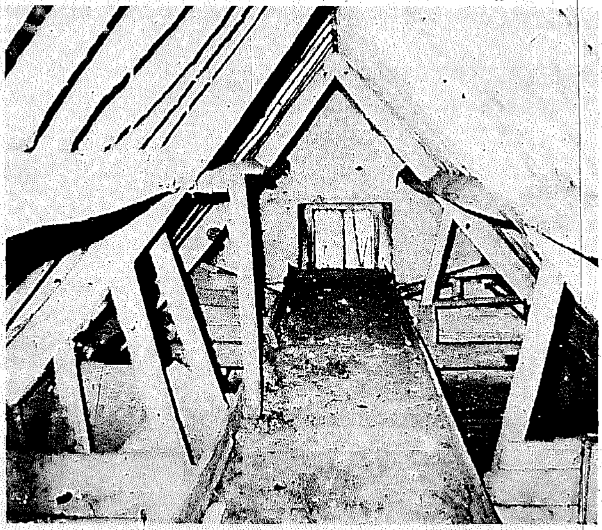


Fig 1.78 The garner floor at Long Buckby Bottom Mill, near Rugby, showing the storage bins on each side of the raised wooden walk-way

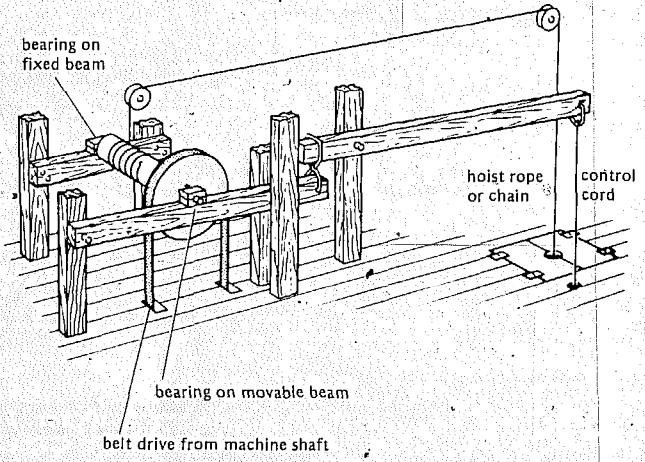


Fig 1.79 Sack hoist using the slack-and-tight belt principle

In some cases, the sacks of grain were man-handled into the bottom of the building to a position underneath the hinged trap doors which are a feature of most mills. There, a chain was looped around the neck of the sack and a hoist was used to wind up the chain until the sack reached the required floor.

There were several possible arrangements of sack hoist, the most usual being one where the chain was wound on a horizontal winding drum or barrel. Various ways of driving the drum can be found but a common method used the slack-and-tight belt principle illustrated in fig 1.79. Parts of a sack hoist are shown in fig 1.80.

In this the winding drum was supported by a fixed bearing at one end, but at the other, carrying the flanged wheel for the belt drives, the bearing could be moved vertically. When the hoist was not in use, the winding drum was inclined down towards this end and the belt from the lay-shaft below would be slack. By a system of levers, a steady pull on the control rope extending to the bottom of the mill could lift the movable bearing, so tightening the belt and setting the hoist in motion. When the control rope was released, this bearing dropped and the hoist quickly came to rest. If the control rope was not released in time, the sack might go all the way up to the hoist

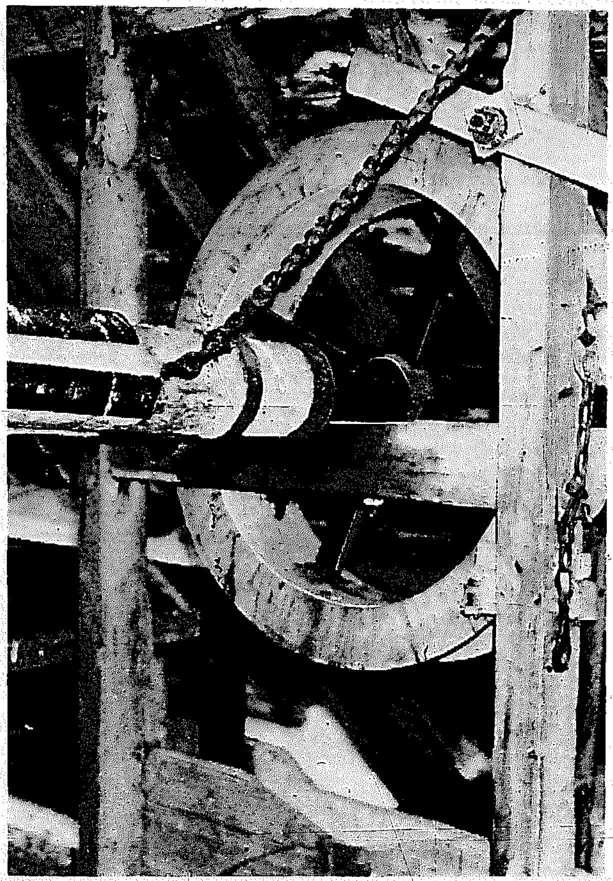


Fig 1.80 Part of the sack hoist at Dodford Mill, near Daventry. This shows the hoist barrel with its chain at the fullest extent (ie reaching to the bottom floor of the mill) and the pulley for taking the drive by a belt from the floor below. The beam carrying the bearing for the hoist barrel and pulley is pivoted to the vertical post at its left-hand end. At its other end, on the extreme right of the picture, is the chain connection to the long lever by which the pulley is lifted so as to tighten the belt and thus transmit power to the hoist barrel

barrel itself. Since this was often mounted high under the roof, the sack could cause serious damage to the roof as well as the hoist. In a few mills safety devices were provided to prevent the sacks travelling too far.

After tipping the grain from the sacks into the bins on the garner floor, the grain was fed, when required, down spouts to the hoppers feeding the stones. The control of the flow was achieved by wooden shutters, slid in or out as needed, and held by string when in the 'out' position. After grinding, the meal from the stones was collected below them in sacks which were lifted with the hoist to feed into the dressing machines.

To avoid the need to manhandle the incoming sacks off the wagon or cart and under the hoist inside the mill, some mills used an external hoist from a lucam, or small, covered projection from the side or roof of the mill. See fig 1.81. To assist in the dispatch of sacks of dressed flour, wooden slides were sometimes hinged to the sill of the door, often on the first floor, through which the sacks could be slid down onto the waiting vehicle. The movement of stock across the floors of the mill was usually by sack barrows.

As mills became bigger and there was a desire to make them more automatic, the handling of stock was considerably improved. In considering these developments, the transportation required within a mill can be considered under two categories:

1 from floor to floor, upwards or downwards

2 along one horizontal plane.

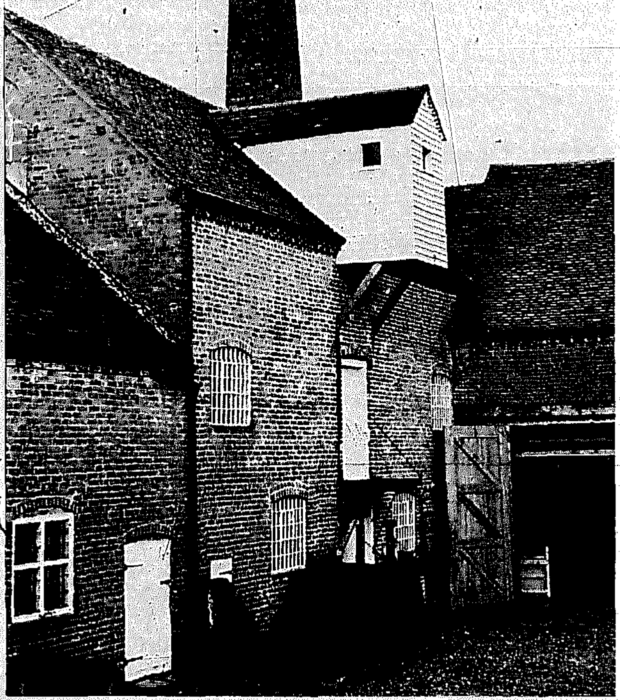


Fig 1.81 The white weather-boarded lucam, covering the external hoist, protruding from the roof at Sarehole Mill, Birmingham

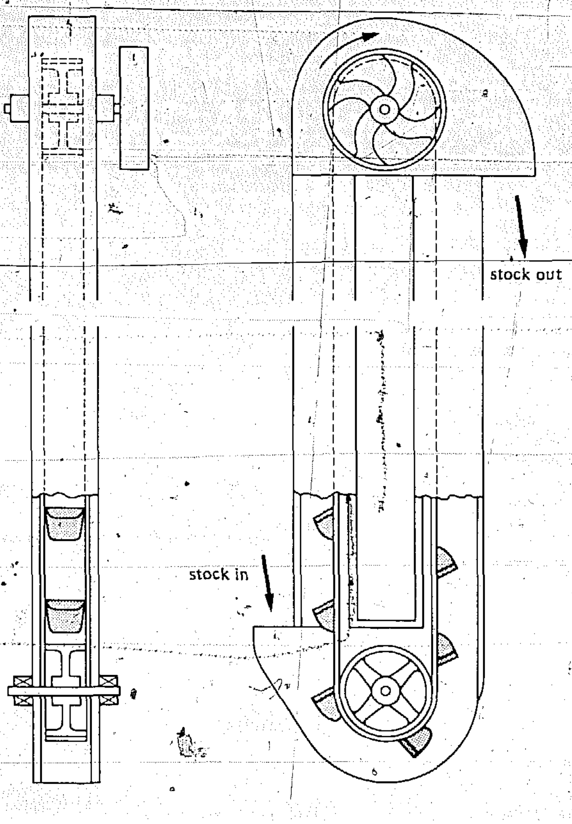


Fig 1.82 Vertical elevator for raising stock

Transmission downwards continued to be by spouts but transmission upwards was by elevators. These consisted of an endless belt with containers (boxes, cups, or buckets) attached to it and running over pulleys, one at the head and one at the foot (or boot) of the elevator. The belt was enclosed in a timber case to avoid scattering the stock being lifted. The arrangement is shown in fig 1.82.

Such elevators are nearly always vertical and only very rarely inclined, never more than 10° from the vertical, otherwise the sag of the belt on the upper side causes it to slide over the wood casing, so damaging the belt and causing friction which consumes extra power. The cups, usually made of galvanized sheet steel, were made in a variety of sizes and shapes with the intention of giving the most efficient transfer of stock. Some elevators had brushes fixed to the belt and these swept the dust from the walls of the casing.

For horizontal transport, the Archimedean screw, worm, or conveyor (sometimes called an 'auger') was used. It was usually contained either in a wooden box on the bottom of which was fastened a curved metal sheet, or in a cast-iron trough with a semi-circular bottom. In addition to screw conveyors, there were those utilizing flat scrapers running inside rectangular wooden troughs.

Machines for animal foods

As mentioned on page 23, many mills ended their days 'gristing' or making animal foods. Because some of the flour-milling equipment (such as the dressing machines) were no longer required, other machines had to be installed to meet the demand for balanced rations. These included:

1 oat crushing rolls
2 chaff cutters
3 bean kibblers
4 cake breakers
5 maize flaking rolls
6 decorticators (for removing from certain seeds the husks which have no food value).

For grinding, the old horizontal mill-stones were later replaced by machines such as vertical stone grinders, disc grinders, and hammer or percussion mills. A sectional view of a vertical stone mill is shown in fig 1.83.

Auxiliary power

Towards the end of their working days, many mills had the power from their waterwheels or turbines supplemented or supplanted by other forms of power – steam engines, oil engines, gas engines, and perhaps eventually electric motors. There were many ways in which the power was transmitted from the new source to the existing mill machinery.

In some, the drive from the new engine or motor was by belt to one of the horizontal shafts in the mill and, if this was only a supplementary to the waterwheel, the transmission would be by an arrangement of fast-and-loose pulleys. In cases where the auxiliary power was supplied by a portable source, a belt was taken up to a pulley on the outside of the mill, fig 1.84. This was usually on a shaft extending into the mill and carrying a pinion meshing with the crown wheel so that, through this and the vertical shaft, power could be transmitted to the stones.

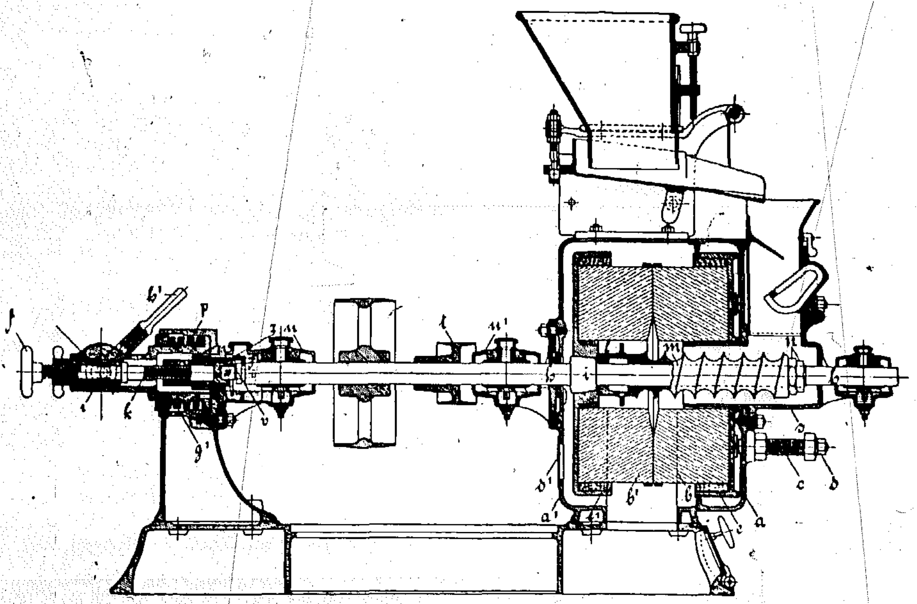


Fig 1.83 Vertical stone mill – the 'Selecta' – built by Seck Bros of Dresden, c 1917

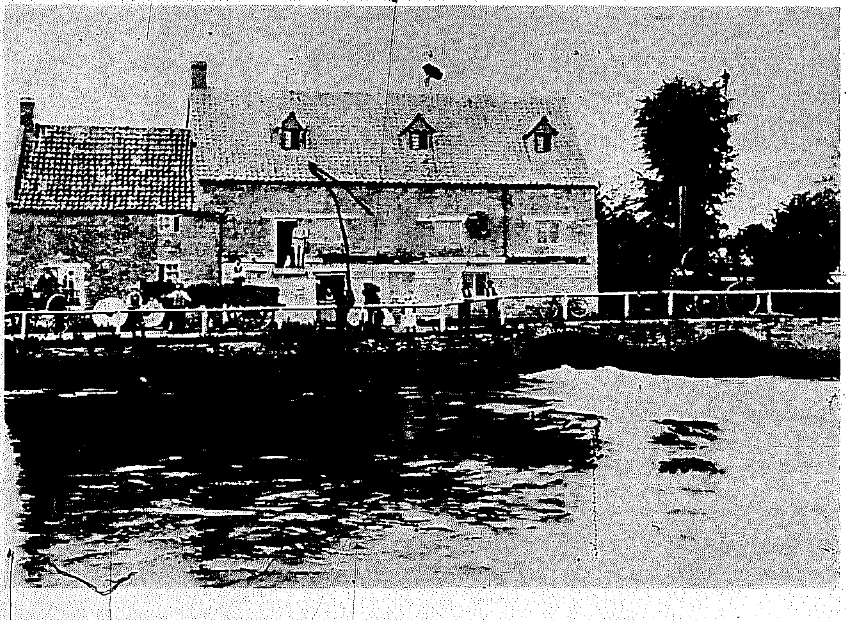


Fig 1.84 Titchmarsh Mill, on the River Nene, about 1914. With the river running in flood, the level of water in the tail-race prevented the waterwheel from working and a portable steam engine has been brought up to drive, by belt, the pulley protruding from the second storey

1.6 INDEX TO MILLING AND WATERPOWER TERMS

2 A school approach to watermills

2.1 LOCATION OF MILL SITES

Although some schools will be close to a well-known mill, in most cases it will be necessary for the teacher to seek out the nearest available watermill. For many parts of the country, publications listing watermills are now available as noted on page 95. For the areas covered by the *Industrial Archaeology of the British Isles* series, published by David and Charles, watermills are included in the gazetteer at the rear of each volume. However, being general gazetteers these include only some of the mills in the area considered.

The Domesday Survey of 1086 is supposed to have listed 5624 mills in the country south of the River Trent. For the counties for which they have been published, the appropriate volumes of the Victoria County History give information from the Domesday Survey and include references to the mills. Part of a summary of Warwickshire mills, compiled from the Domesday Survey section of Volume 1 of the *Victoria County History of Warwickshire*, is given in table 1.

Not all the mills listed in the Domesday Survey may have been waterpowered. Some are indicated in places with negligible flow of water, and it has been suggested that these used animal power. In earlier times a separate waterwheel seems to have been used for each pair of stones, so that when more than one mill is given for a particular place in the Survey it is possible that these were all under the same roof. See fig 1.21 on page 12.

Lists of local mills may also exist in manuscript form in local libraries and record offices. These institutions may be able to advise whether there is anyone who has been making a study of the mills in the locality. Some colleges of education have students working on environmental studies who have opted to look at the watermills in a given district, and their reports should be helpful to those wishing to identify the mills of interest in their locality.

If no lists of any sort are available, then the best starting point as far any likely physical remains are concerned are the Ordnance Survey maps. The latest editions, although showing buildings which were mills, often do not mark them as such because the buildings are no longer in use as a mill or are ruinous or abandoned. Nevertheless, such sites often contain items of equipment, perhaps even the derelict waterwheel, and so are still useful as a starting point for school activities. Since these mills were probably working at the time, the earlier editions of the Ordnance Survey maps will mark them as 'Mills' and these older maps are usually available for consultation in the local rooms of public libraries or the local records office (see fig 2.1).

At this stage we are concerned with the teacher locating a suitable mill to see if he or she can use it to achieve the particular educational objectives in mind. However, some of these objectives may be concerned with the use of maps, and when the students are introduced to the topic

Table 1

Domesday name	*Present name*	*No of mills*	*Dues*
Brailes	Brailes	1	10s
Bedeford	Bidford	4	43s 4d
Stanlei	Stoneleigh	2	35s 4d
Coleshelle	Coleshill	1	40d
Cotes	Coton (End) Suburb of Warwick	2	100s
Caldecote	Caldecote Juxta Weddington	1	2s
Taschebroc	Bishop's Tachbrook	2	12s 8d
Hantone	Hampton Lucy	1	6s 8d
Stradforde	Stratford on Avon	1	10s + 1000 eels
Alvestone	Alvestone	3	40s + 12 sticks (Stich of eels) 3 1000 (eels)
Spelesberie	Spilsbury	1	50d
Arue	Arrow	1	6s 8d
Edricestone	Atherstone upon Stour	1	10s + 10 sticks of eels
(G) Raneberge	Grandborough	1	16d
Sucham	Southam	2	4s
Sowa	Sowe	1	2s
Hunitone	Honington	4	54s 4d
Wasmertone	Wasperton	1	20s + 4 loads of salt and 1000 eels
Niwebold	Newbold (Comyn)	1	8s
Alne	Great Alne	1	5s
Whitelavesford	Wixford	1	10s + 20 sticks of eels
Salford	Abbot's Salford	1	10s + 20 sticks of eels

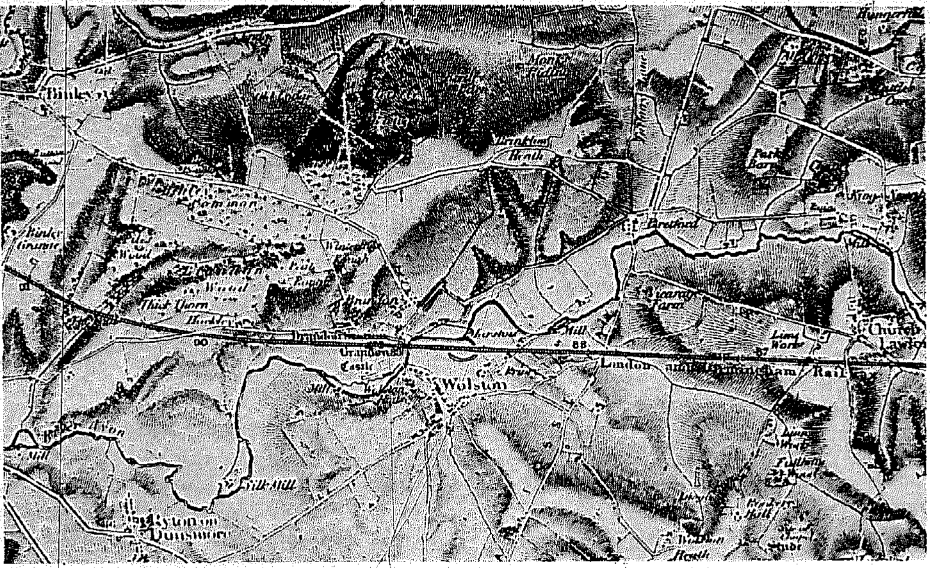


Fig 2.1 Part of the First Edition of the one-inch Ordnance Survey map of Warwickshire showing five watermills, including one silk mill, along this eight-mile (13 km) stretch of the River Avon

Fig 2.2 Girls from Quinton House School, Upton, near Northampton, observing a reminder of the time when this lane led to one of the Kingsthorpe corn mills. Although this was demolished over fifty years ago the watercourses remain, but the former tracks to the mill now constitute a through route linking newer parts of the town

they might be encouraged to peruse the maps to locate possible mills or mill sites to visit.

Another indication of a possible mill site is the presence of a Mill Street, Mill Road, or Mill Lane. Any of these could lead to a windmill site, or to a mill not concerned with corn grinding, but if the street leads towards a stream or river then there is more likelihood that it led to a watermill (fig 2.2).

Having located a mill suitable for school industrial archaeology, the teacher may need background information on:

1 identification of the various items of equipment in the mill and reasons for the layout and arrangement
2 the historical background to flour-milling
3 the history of the use of waterpower
4 the history of the particular mill and its significance in the locality.

The first three of these topics have been covered in the previous sections 1.5, 1.2, and 1.1 respectively, and we must now consider obtaining information for the fourth item.

2.2 HISTORY OF A PARTICULAR MILL

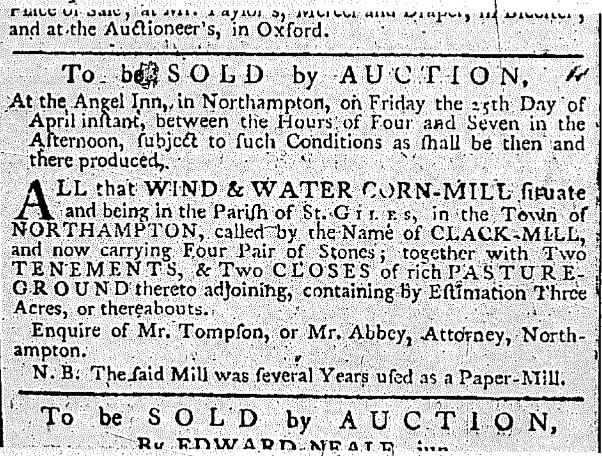
Industrial archaeology is concerned with the physical evidence of the watermill and its site. To make the most effective use of this evidence, it is necessary to complement it with information from other sources, particularly with regard to its history. The physical evidence will often contribute to this: datestones on the outside of the building, dates on beams and internal walls, different styles of parts of the buildings, the use of different materials and forms of construction for the machinery, and the remains of former watercourses. In searching for additional information the following notes may be helpful.

In the first instance, enquiry should be made at the local room of the public library in the district, or at the county record office, to see if a detailed history has already been compiled and/or published for the mill under consideration.

If there is no detailed information for the mill, then a brief summary of its history may appear in the lists of water-mills mentioned on page 98. However brief the historical information in these lists, one should get some pertinent dates as a start in using other sources of information such as local newspapers. (See fig 2.3). The dates of changes of ownership can indicate which issues of the newspaper to inspect for advertisements regarding the sale of the mill. These sometimes contain a surprising amount of detail of the machinery, and from this the method of working and the extent of application of the technological developments of that time.

Advertisements from the mills for their various products are also instructive in showing how they were working. Disputes were often reported in the local press, and from these one gets an idea of the social effects of the mill on the community and sometimes of the working hours, conditions, and output at the mill involved.

Failing even a brief description of the mill and its occupants in a published survey or list, the usual starting point is to see whether the parish had a mill at the time of the Domesday Survey in 1086 – see page 43. After this, one can start to compile a chronological list of the later millers by reference to local directories. It should be noted that the miller was often a farmer as well, and was sometimes to be found under the trade classification of farmer in the directory. Later directories give a classified list of millers for a whole county and indicate whether the mills were powered by wind, water, or steam. This is a help in giving an idea of when transition from one type of prime mover to another occurred. Unfortunately, directories were sometimes not up-to-date in their entries so the fact that a particular miller was given for a certain mill is not absolute evidence that he was there at the date of publication of the directory.



Place of Sale, at Mr. Taylor's, Mercer and Draper, in Bicester, and at the Auctioneer's, in Oxford.

To be SOLD by AUCTION,

At the Angel Inn, in Northampton, on Friday the 25th Day of April inſtant, between the Hours of Four and Seven in the Afternoon, ſubject to ſuch Conditions as ſhall be then and there produced,

ALL that WIND & WATER CORN-MILL ſituate and being in the Pariſh of St. GILES, in the Town of NORTHAMPTON, called by the Name of CLACK-MILL, and now carrying Four Pair of Stones; together with Two TENEMENTS, & Two CLOSES of rich PASTURE-GROUND thereto adjoining, containing by Eſtimation Three Acres, or thereabouts.

Enquire of Mr. Tompſon, or Mr. Abbey, Attorney, Northampton.

N. B. The ſaid Mill was ſeveral Years uſed as a Paper-Mill.

To be SOLD by AUCTION,

By EDWARD NEALE, jun.

Fig 2.3 An advertisement for the sale of a corn mill, listing the number of pairs of mill-stones

From Northampton Mercury, 12 April 1788

More reliable is the information given in manuscript material:

1 Parish registers of baptisms, marriages, and burials sometimes indicate the trades of those involved or of the witnesses, but the registers are tedious to examine and are not always readily accessible for inspection.

2 The Population Census Returns for the years 1841, 1851, and 1861 give the occupations of those involved, and can be of great assistance when investigating who was at the mill (or mills) in a specific parish. The Census Returns are held at the Public Record Office, London, but microfilm copies are often available for examination at County Record Offices.

3 Even earlier than the Census Returns are the Militia Lists drawn up in 1798 which, besides recording the names and occupations of all able-bodied men between the ages of fifteen and sixty years, also give the number of corn mills at work and their potential output. Unfortunately, this most useful document is not available for all parishes since many Militia Lists were lost or destroyed before the true value of these records was appreciated.

4 Insurance proposals, kept in ledgers by the local agent, have been deposited in some record offices and will contain proposals for watermills and/or their contents, together with information as to the owner and occupier. The ledgers also record endorsements to cover additions to the machinery in the mill and also for the installation of steam engines. Since the examination of these ledgers is very time consuming and may not reveal any information for a particular mill, it is advisable to ask the record office if anyone has already been through the ledgers to compile an index.

5 Millwrights' records are only occasionally found in record offices and, again, need time to research through to find references to a particular mill (often by reference to the miller and not the mill so it is useful first to have drawn up a list of millers for the mill being investigated). On the other hand the references will provide the best source of information on installation of new types of machinery and the extent to which the mill was using the latest techniques of the time.

Most library local rooms and record offices keep a card index catalogue, arranged in alphabetical order of villages and towns, of the individual documents relating to those places. By looking through the cards for the place where the mill is situated, you may come across information relating to it in the form of:

1 Legal documents – indentures, agreements, and deeds which will give details of change of ownership of the mill, its occupier (ie the miller), and sometimes the machinery and arrangement of the watercourses. Agreements as a result of disputes usually give an

indication of the effect on the locality of the way the mill was worked.

2 Sales notices and catalogues. For mills, these will usually provide detailed information on the equipment installed and an idea (usually on the optimistic side!) of the output of the mill and its trading business.

3 Account and/or day books of the mill. These are comparatively rare and only in a few cases deposited in record offices. For a particular mill, it is worthwhile enquiring of the people living close by as to where these books and other papers relating to the everyday running of the mill might be, as these documents really do bring to life the story of the mill when at work.

Besides inspecting the record office's catalogue under place names, it is essential to look for examples of these documents, under the catalogue for estates or family collections if the mill is known to have been part of such an estate.

In many places, it is still possible to find people who remember the local mill when it was at work. Sometimes the miller himself survives, but his sisters or brothers, sons or daughters can often fill in gaps in the later history of the mill or explain apparent contradictions arising from a study of the documentary evidence.

The development of the watercourses and of alterations to the arrangement of buildings on the site may be traced if sufficient old maps can be found. Apart from the obvious use of the earlier (and later) editions of the Ordnance Survey maps of various scales, reference to tithe maps and enclosure maps (if they exist) can be worthwhile, whilst for earlier periods estate maps, such as the example shown in fig 2.4, are the most likely source for showing watermills.

Lastly, to provide visual impact for the history of the mill, illustrations are required. Watermills have been fortunate in the amount of attention paid them by artists. Pictures in oils and water colour and pencil sketches were made in abundance during the earlier years of this century, and a surprising number survive, although they are widely dispersed. Despite the inaccuracies introduced by the artist's impression of the scenes (and also the difficulties caused by artists often attributing the wrong location to their pictures by caption or inscription on the back) it is worthwhile searching for these pictures. For many mills, pictures will be in the possession of the villagers, who may also be able to give verbal information. See fig 2.5.

Although watermills were not usually the major subject of engravings, they often appear in landscape scenes and,

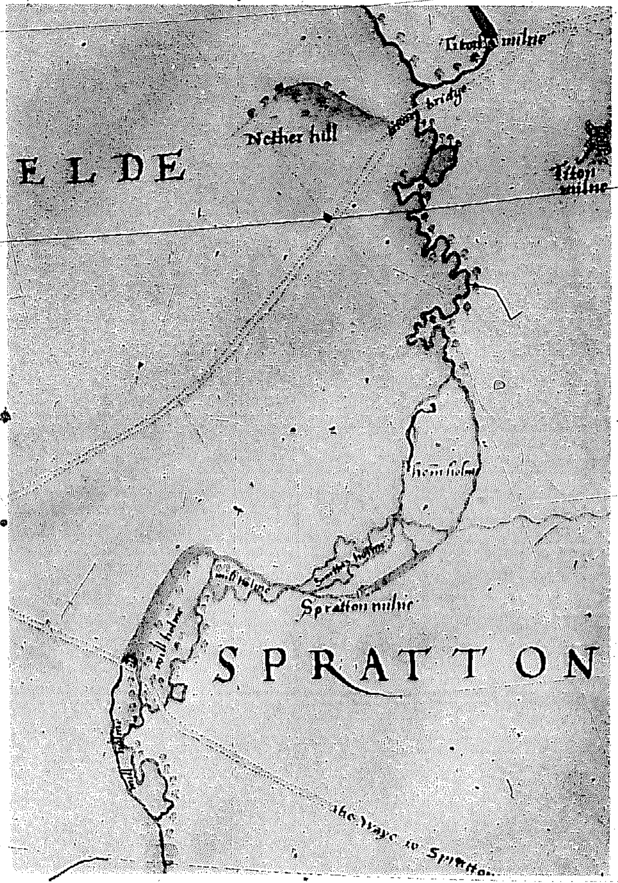


Fig 2.4 Part of a map of the Finch-Hatton estates in 1584 showing three watermills along a stretch, less than a mile long, of the Spratton Brook, a tributary of the River Nene, North Water

Courtesy of Northamptonshire Record Office

Fig 2.5 Reproduction of a painting of Bosenham Mill, near the Buckinghamshire-Northamptonshire border. This was one of a series of views around Grafton Regis made in the 1870s and now deposited in the Northamptonshire Record Office. The mill was demolished in the 1860s

Reproduced by permission of Northamptonshire Record Office

WATER AND STEAM FLOUR AND OATMEAL MILLS,
POTTERSPURY,
NEAR STONY STRATFORD.

W. W. SANDERS

Begs to inform the Nobility, Gentry, and Public generally, that he is now prepared to supply

PURE OATMEAL

at the lowest possible prices, either in large or small quantities, cut finely or coarsely, as it may be required, for PORRIDGE, CAKES, HUNTERS, SPORTING DOGS, &c., &c.

Orders addressed YARDLEY GOBION, near STONY STRATFORD, or to the MILLS, will be promptly executed.

Fig 2.6 An advertisement in Kelly's Directory for Northamptonshire, 1864, with an engraving of Potterspury Mill when worked by water and wind power

whilst allowing for misrepresentation by the engraver, may show whether the mill has been rebuilt since the time of the engraving.

Later, engravings were used in the advertisements for products of the mills, and such advertisements can sometimes be found in country directories, almanacs, or year books (see fig 2.6). Most record offices and libraries are building up their collections of old photographs and it is still possible to find photographs of watermills in the hands of private individuals, particularly relatives of those who worked at the mill. The same can be said of picture postcards, although many are to be found for sale in antique and second-hand book shops.

2.3 PLANNING WORK TO ACHIEVE OBJECTIVES

Having located a suitable watermill site, we have to consider how its educational potential can best be exploited in relation to our planned objectives. Examples of these were given in Handbook 10 *Industrial Archaeology for Schools* (page 24) and the following are suggestions as to how they may be achieved.

1 *Awareness of the many factors (eg social, economic as well as scientific) involved in technology*

(a) by investigating the siting of the mill with respect to other local features.

(b) by considering the arrangements for obtaining a water supply and the way in which this was used to give the most power.

(c) By discussing reasons for rebuilding the mill using the latest technological developments of the period.

(d) By investigating the materials used in the construction of the mill and whether or not these materials came from the locality (see fig 2.7).

(e) By comparing the style of building of the mill with other buildings in the area to see if this style evolved by local tradition or was adopted by its owner.

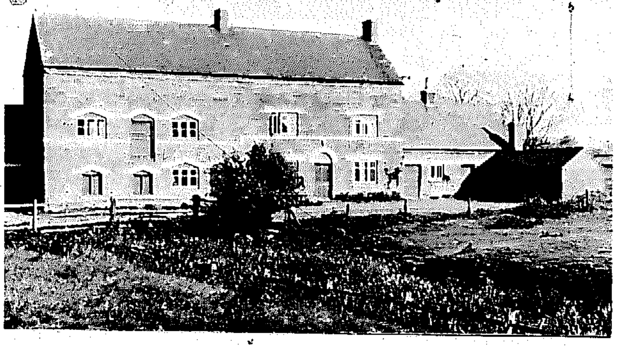


Fig 2.7 Holdenby, on a tributary of the North Water of the River Nene, and adjoining mill house. This is one of ironstone whereas most of the mills on the Nene West Water were of brick

2 *Appreciation of the social implications of technological developments*

(a) By investigating any modifications or extensions, particularly with regard to the mill house, to see if this related to the improved status of the miller in the community.

(b) By considering the change from flour-milling to gristing as flour production became concentrated in fewer but larger mills, and the possible decline in status of the miller.

(c) By discussing improvements in the efficiency of the use of available waterpower with the result that more milling could be done in the district.

(d) By recognizing the effect of the application of other sources of power to milling and of improvements in transport which could result in the community being better served by flour mills situated further away.

(e) By relating the increase in the number of mills in the district, or the rebuilding of one mill to give greater output, to population changes in the area.

3 *Recognition of the number of non-technical factors likely to be involved in a particular application of science*

(a) By considering the effects on the surroundings of attempts to obtain the maximum power from the available water supply, eg the effect of new watercourses; the possibility of flooding, and the effect on other mills upstream and downstream.

(b) By discussing why and when auxiliary sources of power were installed, eg improvements in transport which enabled coal to be delivered cheaply to the mill to raise steam for driving a steam engine.

(c) By identifying the period when flour dressing machines were installed and relating this to a general change in attitude of the 'consumers' towards white flour.

(d) By using the physical signs of the watercourses to identify changes in the flow of water, and by considering possible reasons such as the increased demand for domestic purposes.

4 *Awareness of the methods or techniques used in subjects other than the pupils' own specializations*

For non-science pupils:

(a) By making measurements of various physical quantities, eg water flows.

(b) By simple calculations for efficiency and considering ways of making the most effective use of the available energy.

(c) By simple surveying of site and measuring buildings.

(d) By referring to the basic science in using photography, especially of interiors and machinery.

(e) By helping to restore parts of the mill or its machinery.

For science/technology pupils:

(a) By making a documentary search for historical information.

(b) By using maps and studying topography regarding siting of the mill.

(c) By analysing weather records to deduce likely water supplies available to a mill.

(d) By interviewing people associated with the mill.

5 *Communication of specialist information in a way that can be understood by non-specialists*

(a) By presenting reports on the information recorded on site.

(b) By arranging displays, including working models.

(c) By presenting shows (e.g. colour slides, cine-film or tape-slide presentations) of the watermill, its work and history.

6 *Willingness to look beyond one's particular specialization before deciding on a course of action*

(a) By contrasting the types of plants and living creatures by the head-race, tail-race, and natural watercourses.

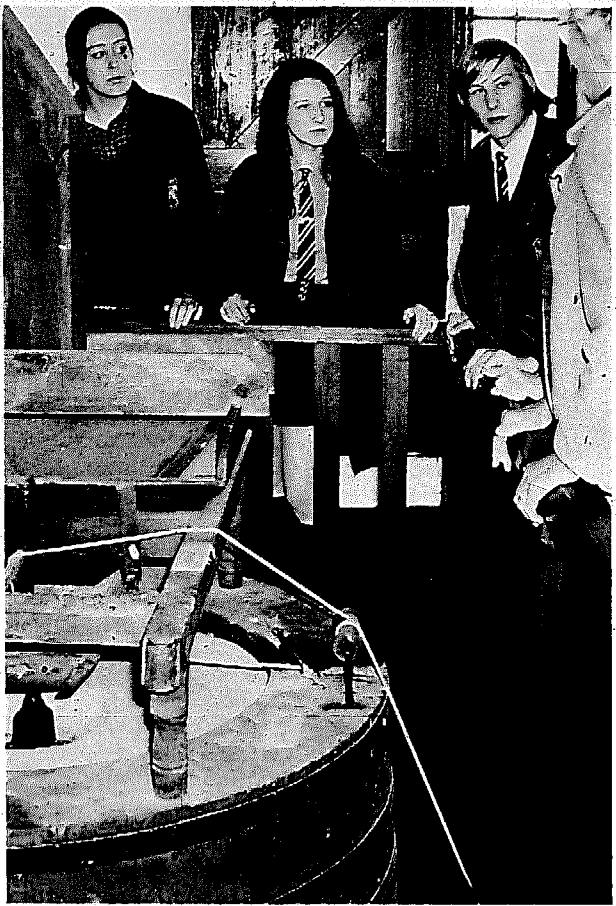


Fig 2.8 Pupils from Trinity Grammar School, Northampton, interviewing Mrs W Mahon who organized the Museum of Milling, in Billing Mill, near Northampton. In the left foreground, the circular stone cover on which stands the four-legged horse supporting the hopper and the back of the shoe. The front of the shoe is supported by the crook string passing over part of the horse, and a bobbin on the side of the cover through a hole in the floor below. Just to the left of the bobbin is a springy piece of metal to which is attached another cord so that it tends to pull the shoe over to the right against the action of the damsel – the black irregularly-shaped piece coming up from the eye of the runner stone and rotating with it

Fig 2.9 The artificial leat, made to serve Maidford Mill, on a tributary of the River Tove in Northamptonshire. The pentrough onto the overshot waterwheel is off the left of the picture. The natural course of the Maidford Brook is shown by the line of low hedges just in front of the field with sheep in the left background

(b) By considering what else is affected when water is used to provide power.

(c) By discussing the requirements for power in milling, eg was it essential that waterpower was used or could wind power affectively have met the demand?

(d) By considering other ways in which waterpower can be used.

7 *Development of a critical awareness of the technological contribution (both past and present) to the pupils' surroundings*

(a) By considering the effect of the watermill and its watercourses on the environment.

(b) By discussing the effect of the mill site on subsequent communications in the district.

(c) By considering the possible local *sources* of power if it was not possible to provide this from a central source (eg electricity generating station) and the effect these local power sources would have on the environment.

8 *Relationship of the historic, geographic, social, and technological aspects of past industrial activities*

(a) By considering the effect of ownership of surrounding land, geology, rainfall and water run-off on the siting of the mill.

(b) By observing the 'labour-saving' devices in the mill (eg sack hoists, automatic tentering gear), and by balancing the possible cost of these against financial savings in other directions.

9 *Awareness of the possible changes in the environment due to technological developments*

(a) By considering the effect of watercourses on the environment and of their later effects when the mill was no longer used.

(b) By identifying changes in the watercourses or the addition of auxiliary power sources due to interference with the water supply caused by new technological activities (eg building an embankment for a railway across the site of the mill-pond; River Authorities' desire to remove obstructions caused by waterwheels in order to execute flood relief or drainage schemes).

(c) By relating the decline in activity of some watermills to the decrease in the normal water supply due to alterations in the water run-off of land caused by changes in its agricultural use.

Some of these suggestions involve:

1 work on site

2 work in school subsequent to a site visit.

If the required objectives (or some of them) are to be achieved through work in school, then the planning must provide for a progression to this from the visit to the site. The next three sections (2.4 to 2.6) are concerned with the work on site and Sections 2.7 to 2.10 relate to the subsequent work in school.

2.4 INSTRUCTIONS FOR USE ON SITE

The previous section shows that work on site will fall into three main categories:

1 recording observations;

2 investigations, eg flow of water, power output;

3 constructional activities

How far one goes with each of these activities will depend on the age and ability ranges of the pupils involved. These factors will also affect the amount of detail given in the instructions for the work on site.

Recording observations

Recording can conveniently be divided into three parts:

1 the overall site and environment (including watercourses)

2 the buildings

3 the machinery.

1 *Recording the site*

Since it is unlikely that schools will undertake detailed surveys of a site from scratch, it is useful to start with an enlarged portion of a large-scale Ordnance Survey map. Elementary surveying techniques can then be used:

1 to confirm the location and present situation or state of the site;

2 to record features not marked on maps, eg underground watercourses, their entrances, and exits (see fig 1.26f, page 16).

Another method of recording the site is by aerial photography and there are a number of ways in which the camera may be taken to a suitable height. Although photographs taken from vertically above the site will provide easy comparison with maps and an aid to drawing site plans, oblique photographs often help with the interpretation of features. Thus it may be possible to take a photograph from a tree, or permission might be obtained to take a photograph from the tower of a nearby church.

Other ways of getting the camera high above the site involve the use of balloons, kites, and small, vertical take-off aircraft. These all involve hardware to be made or assembled, and the design and manufacture of this may enable some of the previously stated objectives to be achieved. Additionally, mathematics in the form of simple trigonometry must be used to ensure that the camera is above the 'target' by the time it has reached the desired height, taking into account the effect of the wind on the ascent of the device used to take the camera up.

The instructions as to what is be done on site should include:

1 an idea of the area or bounds of the site to be covered;

2 special features to be considered, eg underground water courses, disused trackways, gateways;

3 the limits beyond which pupils are not to go, eg onto land for which permission for access has not been obtained;

4 warnings of possible hazards such as trees unsafe to climb, electric overhead cables when 'flying' a camera above the site.

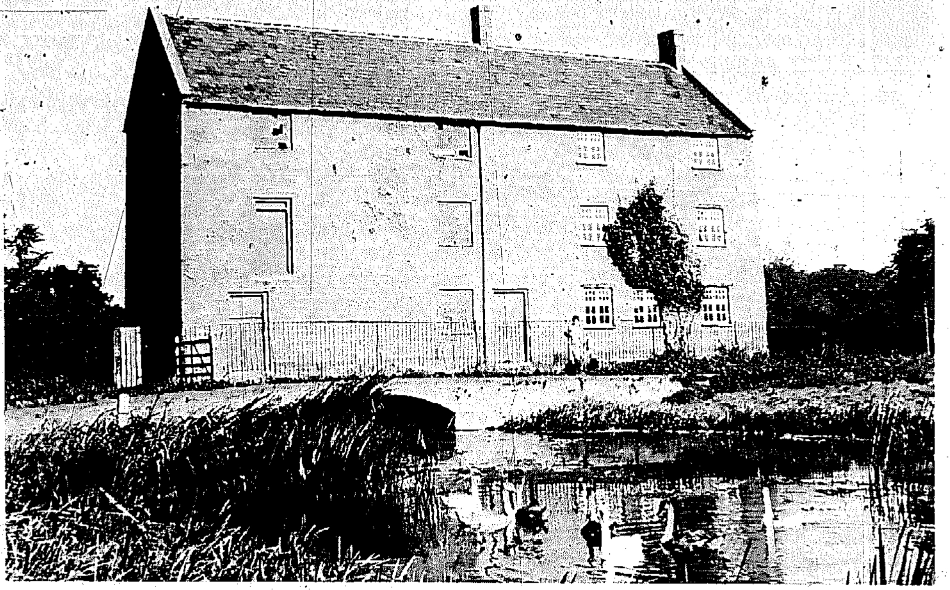


Fig 2.10 Upton Mill, on the River Nene west of Northampton, with the mill and millhouse under a continuous slate roof. The layout of windows and doors distinguishes the working part on the left from the domestic accommodation on the right

2 *Recording mill buildings*

In general, the procedures outlined on page 14 of *Industrial Archaeology for Schools* are applicable, but the following points are worthy of note:

1 It is useful to distinguish between the mill house and the mill proper, and to record communicating doors and/or passages between the two. The distinction is clear in fig 2.10.

2 Although sack hoists may be recorded along with the other machinery of the mill, external hoists were usually accomodated in a lucam, which is an extension to the mill structure (see page 39).

3 Many mills carry an initialled datestone. Apart from the usefulness of the date, the initials normally refer to the miller or owner at the time. Inside the mill, initials and dates on beams are often those of a millwright rather than the miller.

4 Often when mills were rebuilt, parts of the old mill were embodied in the new so attention should be paid to cases where different building materials are used, eg stone near ground level and brick above. Structural timbers were also re-used on occasions as evidenced by empty mortises. However, such a beam might have come from any building and not necessarily from the previous mill on the site, so care must be exercised in interpreting any dates or inscriptions on such timbers.

The basic information about the mill building is listed on the Survey Questionnaire (pages 82–4) and could form the basis of instructions to the pupils for recording the buildings.

3 *Recording the machinery*

The Survey Questionnaire provides a check-list of possible items to record, and all of these features have been described in Sections 1.3–1.5. To help locate these descriptions, an index to milling and waterpower terms is given on pages 41–2.

To complement the information on the questionnaire, a diagram of the layout of the machinery is useful. This may be of the form used in figs 1.43a and 1.43b, page 24, or instructions can be given to measure the position of the equipment inside the mill and so prepare measured drawings after the visit.

The maker(s) of the machinery may be shown by inscriptions sometimes on cast plates fixed to the outside of machines such as elevators, or the millwright's name may be cast on one of the spokes of the waterwheel. If these inscriptions are to be photographed it is useful to rub chalk (of the blackboard variety) over the raised portions so that they stand out from the background. Some elaborate inscriptions in cast metal lend themselves to reproduction on paper by techniques similar to those for church brass-rubbings. Thin aluminium foil can also be used to obtain an embossed reproduction of an inscription by rubbing (fig 2.11).

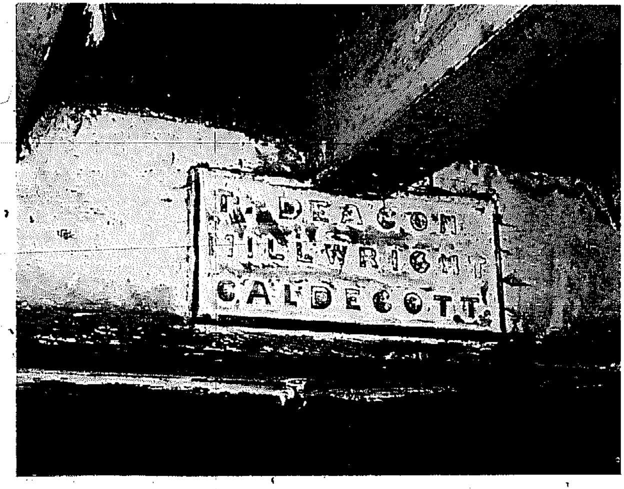


Fig 2.11 An example of a cast-iron plate in a mill which provides information on who repaired and renewed the equipment in the mill. In this case the flour dust was wiped off the raised portions so as to make them stand out from the rest of the plate

Investigations

Whilst recording will involve measurements of lengths, the investigations will require measurements of other physical quantities such as:

1 rate of flow of water supply

2 speeds of rotation of waterwheel and machinery

3 torque at wheelshaft

4 forces, including weights.

1 *Flow measurements*

Generally, these measurements are made in an attempt to estimate the likely power to be obtained from the waterwheel. Therefore conditions should be arranged so as to be the same as when the wheel is or was at work. For example, by-pass sluices should be in the correct position. If the mill has been out of use for some time, it is likely that the watercourses will have been altered so that the flow in the mill-leat is unrepresentative of the flow when the mill was at work. Note that the opening or closing of sluices is often under the control of the local River Authority.

In a particular situation the suitability of the possible methods for measuring flow depends upon the size of the flow and whether or not it is possible to interfere temporarily with it.

(a) To measure the flow of a small stream, it may be dammed with a little clay or pieces of turf piled up across the stream, possibly backed up by larger stones, as shown in fig 2.12. Into this dam is inserted a short piece of pipe so as to deliver the whole flow into a convenient container such as a bucket.

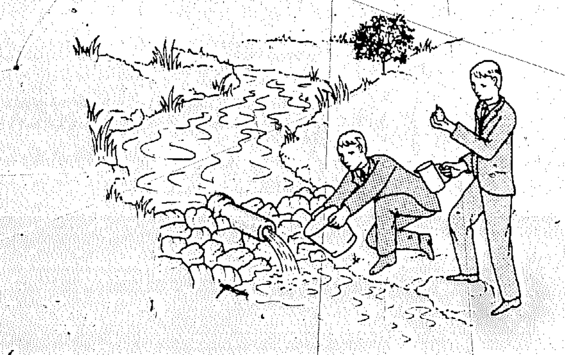


Fig 2.12. Measuring flow by damming and inserting a pipe

Two pupils are required to make the measurements, one keeping a record of the time and the other holding the container to catch the water. At a signal from the time-keeper, the second pupil positions the container under the delivery pipe for an exact interval of time (say 10, 15, or 30 seconds) and instantly takes it away at a signal from the time-keeper. The quantity of water caught in the container is then determined using any suitable measuring vessel.

For greater flows, two or more pipes may be inserted in the dam, and when all are running steadily (but not necessarily delivering the same flow as each other), the flow from each is measured separately and the sum of these should give the total flow.

This method can be used for flows of 0.6–1.0 m^3 per minute.

(b) Larger flows may be measured using a 'notch board'. The bed of the stream is built up a few inches, and onto this is bedded a board into which is cut a notch. The notch is chamfered off to a sharp (in practice, a very thin) edge, or formed of thin sheet metal supported by the edges of a slightly larger opening in the board itself. A peg is driven into the bed of the stream, about three feet upstream of the gauge-board, and with its top exactly level with the bottom of the notch. (This can be tested by observation just as the water rises to the bottom of the notch after the stream has been dammed.)

The notch can be rectangular in shape (see fig 2.13a) in which case its width should be about two-thirds that of the stream, or it can be in the form of a right-angled V as shown in fig 2.13b. When the water is flowing steadily through the notch, the depth of water flowing over it is determined by measuring from the top of the peg, set 1 m back, to the surface of the water, as shown in fig 2.13.

The flow can then be determined by reference to table 2.

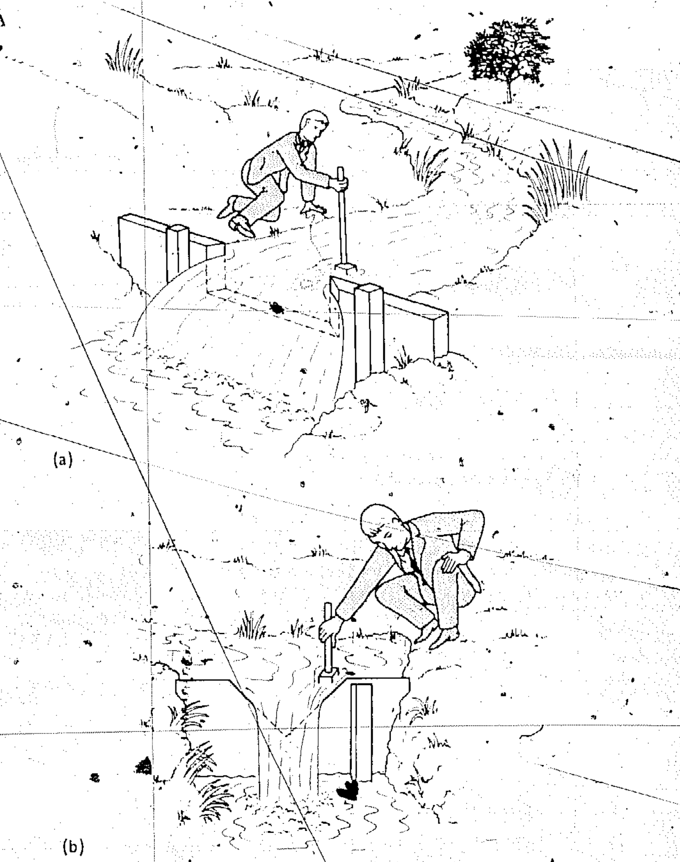


Fig 2.13 (a) Measuring flow using a rectangular notch; (b) measuring flow using a V-notch

(c) For larger streams and situations where it is not possible to dam the stream, even temporarily, it is more difficult to determine the rate of flow. It must be appreciated that the velocity of flow varies at different points of the cross-section of any channel. Frictional resistance from the sides causes the water to slow down towards the sides of the channel and air resistance causes a slight reduction of velocity at the free surface, even for a rectangular channel.

Table 2 Discharge of water over notches

Depth (mm above bottom of notch)	*Rectangular notch: approximate flow (litres/minute) for each 300 mm of width of notch*	*Right-angled V-notch: approx flow (litres/minute)*
12	50	–
20	90	–
25	145	–
32	205	–
38	264	–
45	336	–
50	410	48
57	490	65
63	572	85
70	664	107
76	754	134
83	850	164
90	950	198
95	1054	235
102	1164	276
115	1364	370
127	1672	482
140	1877	609
152	2136	759
165	2414	927
178	2695	1118
190	–	1327
204	–	1559
216	–	1818
230	–	2095
242	–	2395
254	–	2731
280	–	3463

Fig 2.14 shows the variation of velocity over the cross-section of a rectangular channel. The curves are lines of equal velocity. They have the greatest value at the centre, just below the water surface, and the values decrease towards the sides and bottom of the channel. The mean velocity on any vertical section occurs at approximately 0.6 of the depth, although this varies with the type of channel and the nature of the sides. The flow across the whole channel may be obtained by considering the section to be divided into vertical rectangles and finding the mean velocity for each of these. The flow through each rectangle will be its area multiplied by the mean velocity. The sum of the flows through each rectangle will be the total flow across the channel.

The flow through channels of irregular cross-section (fig 2.13b) may be determined by a similar method. On a straight uniform portion of the stream or river, the cross-section is considered as divided into vertical strips and the mean velocity of each strip is measured. The flow across each strip can thus be determined and the sum of these flows will give the total flow in the channel.

The mean flow can be measured using *rod floats.* These consist of wooden rods, weighted at the bottom so that they float in a vertical position. The rod will travel with a velocity equal to the mean velocity of the section traversed by the immersed length of the rod.

The rod should be almost as long as the depth of the water at the strip being investigated, so that several different lengths of rod will usually be required to cater for the different depths of water across the section of channel. Unfortunately, weeds on the bed of the river or stream will interfere with the use of float rods.

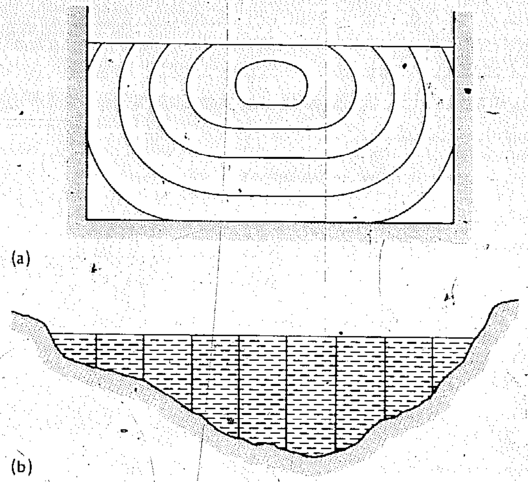


Fig 2.14 (a) Flow in a rectangular channel; (b) flow in a channel of irregular cross-section

When using devices which measure the velocity at a point, the mean velocity can be assumed to occur at 0.6 of the depth. The mean velocity may be determined more accurately by measuring the velocity at several depths and calculating the mean from these measurements. Suitable devices for this are:

(a) *pitot tube.* This consists of two vertical tubes, each having the lower end bent at right angles but facing in opposite directions (fig 2.15). These ends are tapered to a fine nozzle.

In use, the nozzles are positioned at the point at which the velocity is to be measured, with one of the horizontal tubes facing upstream and the other downstream. There will be a difference in the level of water in the two tubes and the velocity of flow can be calculated using the equation

velocity of flow
= constant x $\sqrt{}$(difference in level of water in tubes)

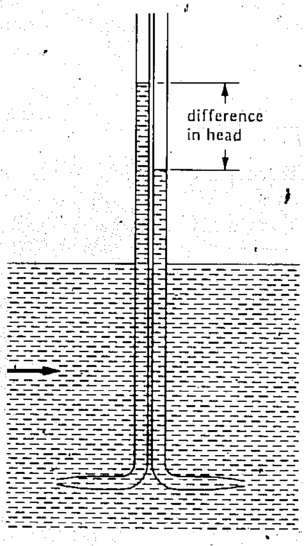


Fig 2.15 Simple pitot tube for measuring mean velocity

The constant will vary for different tubes and can be ascertained in the laboratory using a known rate of flow, before the instrument is taken out on site.

(b) *propeller-type meter.* The rate of revolution of a propeller immersed in a stream is related to the velocity of flow at the point and several methods have been devised to transmit the information from below the surface of the water to where it can be observed conveniently. In one method, fig 2.16, the propeller is connected to the shaft of a small electric generator (Most of the miniature electric motors sold for model-making will work in reverse as generators.) The whole unit is made waterproof and the output from the generator is taken by wires along a tube to a voltmeter on the bank. The reading of this will depend on the speed of rotation of the propeller, which in turn is dependent on the velocity of flow at the point.

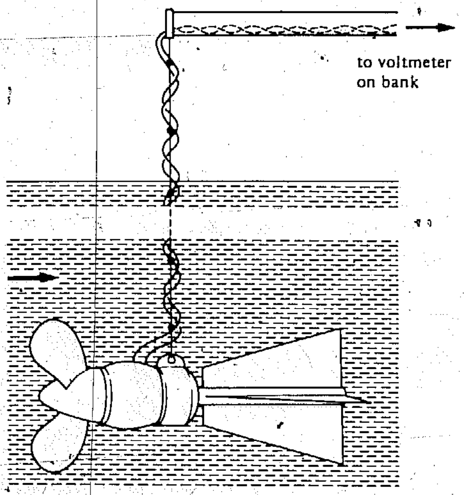


Fig 2.16 Propeller-type flow meter

2 *Speed measurement*

The speeds to be measured will be those of the machinery, usually of rotating parts.

Where the speeds are low, such as that of the waterwheel itself, the simplest method is to choose, or make, a distinguishing mark on the wheel itself, and count the number of times it passes a fixed reference point in a given time.

Where the speeds make it difficult to account for each revolution by eye, a mechanical revolution counter (of the bicycle mileage counter type) can be used. It is best mounted on a long rigid support which can be held against an adjacent part of the mill structure whilst it is being used. Some kind of 'trip' will have to be fixed to the rotating part so as to operate the revolution counter. For the speeds likely to be encountered in watermills, the trip can be made by clamping an angle piece to the rotating shaft with a Jubilee clip (whilst it is at rest!)

3 *Determination of torque*

Direct measurement of the torque at the shaft of an actual waterwheel is very difficult, and it is usually easier to estimate the torque (or turning effect of the wheel) from consideration of:

(a) the water carried in the buckets (in the case of high breastshot wheels and overshot wheels), and/or

(b) the impulse of the water on the paddles or buckets.

The calculations for determining torque, and hence power, are given under Section 2.7, but it is necessary to give instructions for the following information to be obtained during the visit to the mill:

(a) the number of buckets or paddles;

(b) the speed of rotation of the waterwheel

(c) the area of the orifice through which the water comes onto the wheel;

(d) the velocity of the water approaching the wheel from the orifice;

(e) the size and shape of the interior of each bucket, including its breadth, ie parallel to the axis of the wheel;

(f) the angle at which the bucket is positioned relative to the radius of the wheel;

(g) the size and profile of the paddles or vanes;

(h) the position of the profile relative to the radius of the wheel;

(i) the angle at which the water strikes the bucket, paddle or vane;

Note that some of the above items apply only to certain kinds of waterwheel.

4 *Force measurements*

The forces worth measuring are those concerned in operating the mill. For example, how much force did the miller have to exert to engage the sack hoist or to raise and lower the sluice? What forces are involved in tentering the stones?

For most purposes, the large, circular, dial-type spring balances are convenient, and their range can be extended by utilizing simple lever systems.

Constructional activities

Some of the suggested investigations will entail constructional activities on the site, for example, in gauging water flow by the use of notches. On the other hand, the group may be helping to restore parts of the mill machinery or be involved in erecting a new device to use the water.

With some groups, the teacher can make clear what it is hoped to achieve and then after discussion with the pupils, draw up a list of what has to be done. With other groups, the teacher will have to contribute much more as to how the work is to be done and will need to allocate tasks to individual members of the group.

2.5 INTRODUCTORY INFORMATION

The aim of the introductory information is to make clear to the students:

1 what they hope to do during the visit to the mill
2 how they are going to do it.

However, when introducing students to the work, there are two other aspects to be considered:

1 motivating or interesting the pupils
2 ensuring that they have sufficient knowledge or skills to do the work expected.

We must ask ourselves 'What are the available levels of knowledge and skills relative to the work to be undertaken?' We must ensure they have a mental framework in which to put the information and experience gained during the visit. For example:

- the purpose of milling (What does a grain of wheat consist of?)
- the separate stages of the milling process
- the visual appearance and purpose of the main items they are likely to see in the mill, eg
  - waterwheel and water supply
  - gearing transmitting power from waterwheel to milling machinery
  - grinding stones
  - grain cleaning machines
  - flour dressing machines
  - devices to move stock (grain, meal, or flour) within the mill.

The way in which this information is presented will depend on the resources available. Since we are concerned with physical objects then some visual material is desirable, for example: large diagrams/wall-charts, colour slides of mills and their interiors, cine-films, film loops, and models.

It is worth contacting the local museum's schools service to see if they are able to help in providing this type of material, particularly with regard to loaning models of waterwheels and gearing. Some of the items made by a previous group of pupils (for example, those given on page 68) may also be used to advantage in motivating and instructing a subsequent group.

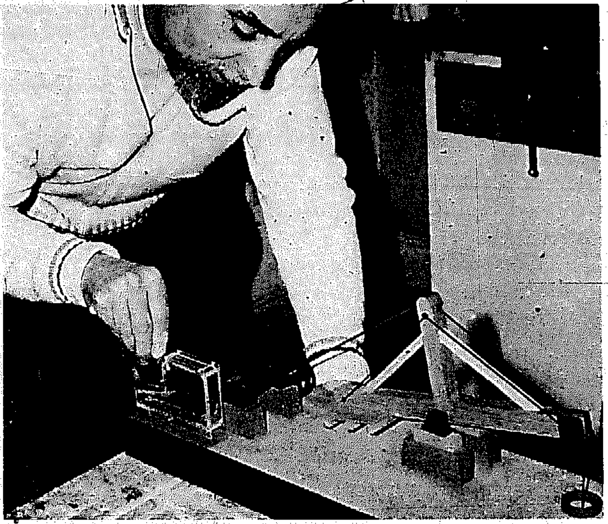


Fig 2.17 Mr P A Stevens, of Leicester Museums Schools Service, demonstrating a Pelton wheel driving a model well pump, which is available for loan to schools in the city and county of Leicester

Anecdotes of happenings at the mill, provided they are not too outrageous, are useful in gaining the interest of some youngsters. Tape-recording tales from older people who knew the mill might be used – this gives the teacher the opportunity to edit what has been said so as not to confuse the class with too much irrelevant detail. However, if the teacher is lucky, he or she may find a local character whose appearance and gestures will give life to the story.

With regard to skills, the most important in the initial stages are those of accurate observation and recording, but the degree of skill required will depend on the objectives to be achieved. The use of a questionnaire is helpful in guiding pupils' observations during the visit, but they will need some explanation of the terms used in the example of such a questionnaire given on page 82.

Other skills required are the ability to use maps, to measure buildings, and to record observations. If the visit to the mill is the first time this type of activity is undertaken, then it is worthwhile covering the basic procedures for measuring buildings and the layout of machinery by means of a practice survey of one of the rooms in the school. The pupils may also need to gain experience of other measuring techniques, for example, of water flow, and perhaps practice these at school or at the local technical college, before making the actual visit. In some cases, measuring equipment devised at school will need to be calibrated before it is used on site.

Bearing in mind some of the anticipated activities arising from the visit, it is worth indicating what else the pupils might do in addition to the visit. Do their relatives or friends have old pictures, postcards, or memories of the mill? Do they know of any people who were associated with the mill – not only the miller, but his wife or sisters or sons and daughters? Do they know who dressed the mill-stones? Do they know the millwright?

2.6 WORK ON SITE

The preceding sections have already indicated the activities likely to be undertaken on the visit to the mill, but to be able to engage in these a certain amount of equipment is required, namely:

1 Suitable clothing and footwear. Some parts of the mill will be dirty and dusty, and some places, inside and outside, will be very wet, particularly under foot.

2 Torches and hand-lamps. Many parts of the mill will be dark, especially around the gearing where it may be necessary to count the teeth or cogs on the various wheels in order to calculate speeds of the mill-stones.

3 Paper and boards. When recording measurements, the sketches need to be a reasonable size so that the information written on them is legible.

4 Pencils. These are better than ball-point pens when the paper gets damp.

5 Measuring tapes. The 2 m long steel flexible tapes are useful for measuring machinery but 20 m or longer tapes are needed if measuring the building is not to become too tedious.

6 Measuring sticks. Useful in inaccessible places where the far end of a measuring tape cannot be held in position. Simple measuring sticks can be made from broom-handles.

7 Line and plumb-bob. Useful for measuring elevations as well as checking on verticals.

8 Large protractor. For use in conjunction with line and plumb-bob to check angles of waterwheel vanes and bucket profiles.

9 Hand brush with stiff bristles and trowel. For cleaning away dirt etc in order to examine and/or photograph some parts

10 Piece of chalk. For highlighting cast inscriptions for photography or in order to decipher them.

11 Camera.

12 Photographic flash equipment and tripod. For time exposures inside the mill.

In addition to the above, extra items may be required to measure water flows (see pages 51–3), or to obtain aerial photographs.

On arrival at the site, a brief tour of the whole area and building should be made so that:

1 everyone has an overall idea of what is involved

2 each pupil knows where he or she will be going for the main part of the work

3 any possible hazards may be indicated.

The above assumes that the party will divide into smaller groups. Possible division of the work are:

1 obtaining overall arrangement of site, buildings, bridges, and trackways. (Note that the results of this group's work will provide a framework into which other groups' work will fit. Therefore the members of this first group should be chosen with this special responsibility in mind.)

2 measuring stream flows.

3 recording watercourses and overflow or by-pass sluices.

4 measuring and recording the exterior of mill and millhouse.

5 measuring and recording interior of mill. This can be further sub-divided into (a) ground floor, (b) first floor, (c) second floor, etc. It is then necessary to ensure that each stairway is the responsibility of one group, and to point out that the stairs will link the recordings of the different groups.

6 measuring and recording interior of millhouse.

7 obtaining overall arrangement of waterwheel and machinery, including drives from any auxiliary engines. (The same remarks apply here as were made for item 1.)

8 recording waterwheel and sluice (or shut).

9 recording transmission, eg counting teeth or cogs.

10 recording stones and 'stone furniture' and tentering arrangements.

11 recording items used for transporting stock; eg sack hoists, elevators.

12 recording other machines, eg grain cleaners, flour dressers.

Rarely will it be possible for a school to break down the work into all the divisions given above. For making measurements it is convenient to have three pupils in a group, one at each end of the measuring tape and one recording the measurements called out.

Whatever sub-divisions of the work are adopted, there must be some measurements and recordings which will link the work of the individual groups. For example, those measuring the interior of the mill should record the location of the mill-stones on the first floor, and this will link with the information recorded by those measuring the mill-stones and stone furniture.

At the end of the visit some teachers may consider it advisable to collect all the separate records made by the pupils so that all of these are at hand when the follow-up work is undertaken in school.

2.7 CLASSIFYING AND ORDERING INFORMATION

As a result of the work on site, it is hoped that the class will have numerous notes and information. Before the class can discuss it, the information must be classified and put in order. In the case of investigations, some calculations will be necessary to obtain information which can be discussed.

Presenting recordings and measurements

If the results of the 'ordering' are to be the basis for later discussion by the class, then all must be able to see this information. Some schools are in the fortunate position of being able to arrange for each member of the class to have his or her own copy. More often one copy will have to suffice for the whole class, and thus it is necessary for each group to present the results of its work in the form of large drawings or diagrams.

The groups concerned with recording the building and interior should make their elevation drawings to a common scale so that they can be combined on one panel to give a complete picture of the mill. An overlay of the whole exterior elevation can be hinged from one side so that it can be folded back to reveal the interior arrangement of the mill. Additional overlays, in different colours on transparent paper, can be used to show separately:

1 transmission and gearing
2 flow of materials (ie grain, meal, flour, and bran) through the mill
3 supposed position of machinery if the mill was incomplete.

Calculations

Some of the other information recorded will involve calculations before useful discussions can be held. Some of the procedures for calculations have already been given: For speeds of mill-stones and machinery from counting the teeth on gear wheels, see page 29; for determining water flows, see pages 51–3.

The calculation of the power of a waterwheel is more difficult, involving both torque (or turning moment) and speed of rotation. The calculation is further complicated since many types of waterwheels derive their torque from both the weight of the water in their buckets and the impulse of the water striking the buckets, paddles or vanes. The following are suggestions for very approximate approaches to estimating the power from waterwheels.

For undershot and low-breast wheels, with flat paddles

Referring to fig 2.18,

let N = speed of rotation of the waterwheel, in revolutions per second;
a = cross-sectional area of the stream of water striking the paddle, in square metres;
V = velocity of stream of the water striking the paddle, in metres per second;
ρ = density of water, in kilogrammes/cubic metre
v = linear velocity, in metres/second, of the paddle, at point X where the centre of the stream of water strikes it.

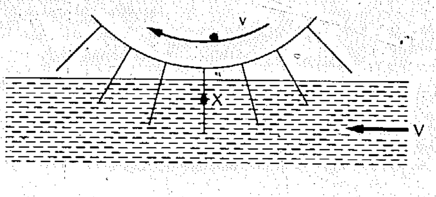


Fig 2.18

v can be calculated from the speed of rotation of the wheel since:

v = circumference of circle at point X
X speed of rotation of wheel
= 2 (radius to point X in metres X N)

If the waterwheel is not in workable condition, it is impossible to observe a value for the speed of rotation N, but an estimate of the probable wheel speed can be obtained from an old millwright's rule that for a low breast wheel the linear velocity of the paddle should be one-third to one-half that of the water.

force on one paddle

= rate of change in momentum of water
= rate of change (mass X velocity)
= mass of water striking paddle/second
X change in its velocity
= $\rho a V (V - v)$ newtons

work done on paddle per second
= $\rho a V (V - v) \times v$ newton metres/second (or watts)

Assuming that:

1 the water normally strikes onto only one paddle at a time, and
2 there are sufficient paddles to ensure that there is always a paddle positioned so as to be affected by the full impulsive force of the water,

then the work done per second on one paddle will be the work done per second, or power, of the waterwheel itself.

Since one horse power is equivalent to 745.7 watts,

$$\text{horse power of wheel} = \rho a V(V - v)v \times \frac{1}{745.7}$$

For undershot and low-breast wheels with curved vanes

When curved vanes were used, the intention was to enable the water to flow onto and off the vane as smoothly as possible to avoid loss of energy due to shock.

Let V = velocity of the stream of water striking the paddle (in metres/second)
v = linear velocity (in metres/second) of the vane,
V_W = component of velocity in the direction of motion of the vane of the water coming onto it
V_{W1} = component of velocity, in the direction of motion of the vane of the water leaving it,
V_r = resultant velocity of the water on the vane,
V = absolute velocity of the water leaving the vane.

Consider the water coming onto the vane (position 1 in fig 2.19)

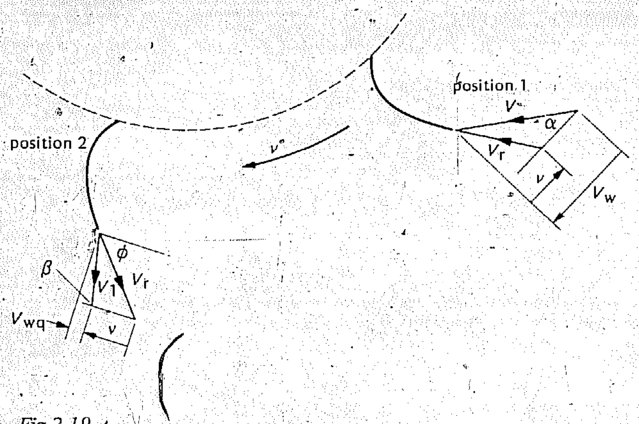


Fig 2.19

Component of velocity of water in direction of motion of vane,

$$V_W = V \cos \alpha$$

where α is the angle between the direction of the water stream and the direction of the linear velocity of the vane as the water strikes it.

Since the vane is moving away from the water, the resultant velocity of the water on the vane, V_r, is obtained from the triangle of velocities.

After running up the vane to point O, the water returns and, assuming no friction losses, runs off the edge of the vane with the same magnitude of velocity, V_r, but in the opposite direction.

Consider water coming off the vane (position 2 in fig 2.19).

The resultant velocity of the water has the same direction as the extreme edge of the vane, ie angle ϕ in fig 2.19. This resultant velocity is due to the absolute velocity of the water leaving the vane, V, and the velocity of the vane, v. From the triangle of velocities drawn by position 2, it is possible to determine the value of V and the angle β.

Component of velocity in direction of motion of the vane of water leaving it,

$$V_W = V \cos \beta$$

in the opposite direction to V_W.

Force causing rotation of wheel

= change in momentum of water in direction of motion of wheel

= mass of water flowing onto vane X change in velocity of water in direction of motion of wheel

$= \rho a V(V_W + V_W)$

Note that the change in velocities is the addition of their separate quantities since they are in opposite directions.

Work done per second on vane

$= \rho a V(V_W + V_W) v$

Making the same assumptions as for flat paddles (see page 56) this will be the power of the waterwheel. However, the true power would be somewhat less than this due to losses from friction and splashing, which could account for 30 per cent of the power of these types of wheels.

For breast wheels and overshot wheels

These have been described as 'weight and impulse wheels' implying that they derive their power from both the velocity and the weight of the water entering their buckets. The significance of the 'impulse' contribution will vary for different types of wheels. For example, any kinetic energy (ie energy due to its velocity) in the water coming on to a pitch-back waterwheel tends to cause the wheel to rotate in the opposite direction to that caused by the gravitational pull on the mass of water in the buckets. On the other hand, kinetic energy in the water supply onto an overshot wheel would help the rotation produced by the weight of the water in the buckets.

If it is decided that the energy due to the velocity of the water affects the power developed by the waterwheel, calculations for its contribution can be based on those given for undershot wheels with flat paddles.

Under ideal conditions of no friction, no leakage, and no splashing or spilling,

energy given to the wheel due to the weight of water = gravitational pull on mass of water, ie weight of water X height descended by water between entering and leaving wheel

Work done per minute = weight of water flowing onto wheel per minute X height descended by water between entering and leaving wheel

Measurements made on waterwheels in the mid-nineteenth century showed that the friction, leakage, and splashing caused losses of between 18 per cent and 26 per cent of the power.

From inspection of the shape of the buckets of overshot wheels (see page 22) it is apparent that the buckets cannot be full of water at the very top of the wheel, and for overshot, breast, and pitch-back wheels most of the water will run out of the buckets before they reach the lowest part of the wheel. Therefore the expression given above cannot be used directly. The ways in which this problem may be approached will be illustrated by reference to work undertaken by Mr John Harrison and sixth-form boys of Eston Grammar School, on the large waterwheel at Killhope Lead Crushing Mill, Weardale, County Durham (see figs 2.20 and 2.21.)

This overshot wheel is 10 m in diameter and is made of wrought iron and steel rivetted together. Castings are used only for the bearing blocks, hub plates, and ring gear segments. There are seventy-four buckets of roughly J-shape, ventilating into a space between the back of the buckets and the sole plate of the wheel.

Assuming that each bucket contains as much water as possible at any position, the distribution of water between the buckets on one half of the wheel would be as shown in fig 2.21. This is a little pessimistic for the buckets near the top, since the water flowing into them would tend to carry up inside the curved front of the bucket to a level above the height of the ventilating opening at the inside trailing edge of the bucket.

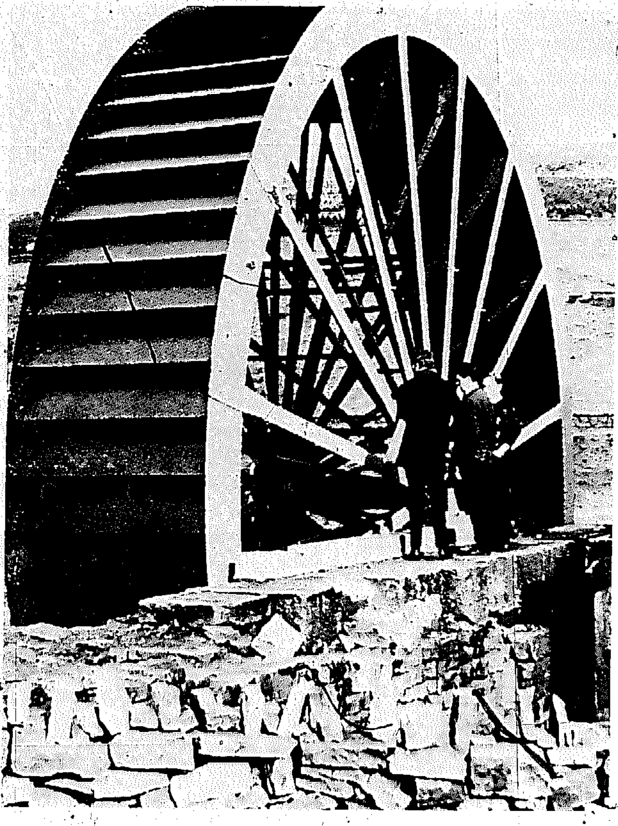


Fig 2.20 Mr John Harrison (centre) and sixth-form boys of Eston Grammar School inspecting the large metal waterwheel at Killhope lead crushing mill, Weardale, County Durham. The launder which brought water to the top of this overshot waterwheel has been demolished. The lines of rivet heads on the outside of the shrouds indicate the shape of the buckets attached to the inside

On the space diagram (fig 2.22) which shows the quantities as measured in Imperial units, the weight of water in each bucket was obtained by measuring the cross-sectional area of water in the bucket, and multiplying by the width of bucket (1.7 m) and by the density of water.

Using the energy approach outlined previously the average weight of water in each bucket for the whole descent from top to bottom is given by

$$\frac{\text{total weight of water in buckets}}{\text{number of buckets on this half of wheel}} = \frac{9915}{37} \text{ pounds}$$

$$= 268 \text{ pounds}$$

The work done by one bucket moving from top to bottom is given by

$$268 \times \text{diameter of wheel} = 268 \times 33\tfrac{2}{3} \text{ foot pounds}$$

$$= 9000 \text{ foot pounds}$$

Work done per minute = 9000 × number of buckets which descend each minute

To determine the number of buckets which descend per minute we need to know the speed of rotation of the wheel. If it is not working, the speed must be estimated. In the latter part of the nineteenth century, the general rule was that the linear velocity of the buckets should be between 3 and 6 feet/second, with wheels above 20 feet diameter being worked at the upper limit and smaller wheels approaching the lower value.

Using this rule, a wheel of 33 ft 8 in. diameter would rotate with a circumferential velocity of about 6 ft per second.

$$\text{Speed of rotation} = \frac{\text{circumferential velocity}}{\text{circumference}}$$

$$= \frac{6}{\pi \,.\, 33\tfrac{2}{3}} \text{ revolutions/second}$$

$$= \frac{6 \times 60}{\pi \,.\, 33\tfrac{2}{3}} \text{ revolutions/minute}$$

$$= 3.4 \text{ revolutions/minute}$$

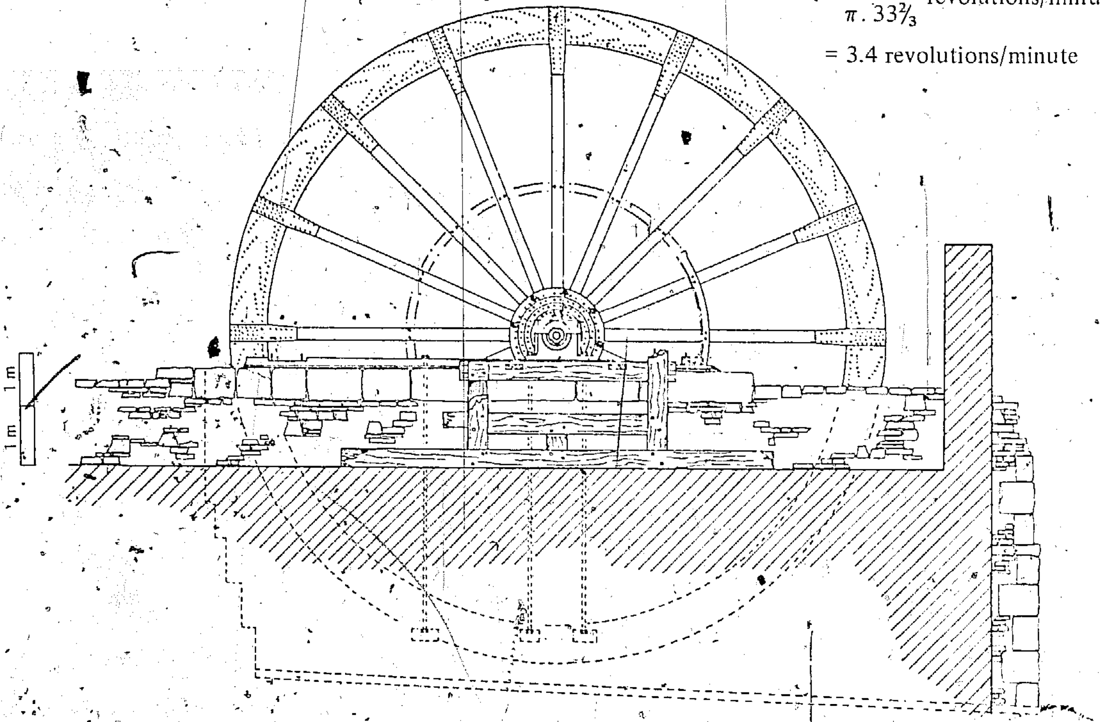


Fig 2.21 Drawing of the waterwheel at Killhope crushing mill, prepared by sixth-form boys of Eston Grammar School

At 3.4 revolutions/minute and with 74 buckets on the wheel,

$$\text{Number of buckets descending/minute} = 74 \times 3.4$$
$$= 252$$

$$\text{Work done per minute} = 9000 \times 252$$
$$= 2\,260\,000 \text{ foot pounds}$$

$$\text{Horse power} = \frac{2\,260\,000}{33000}$$
$$= 68.5 \text{ (or 51 kW in SI units)}$$

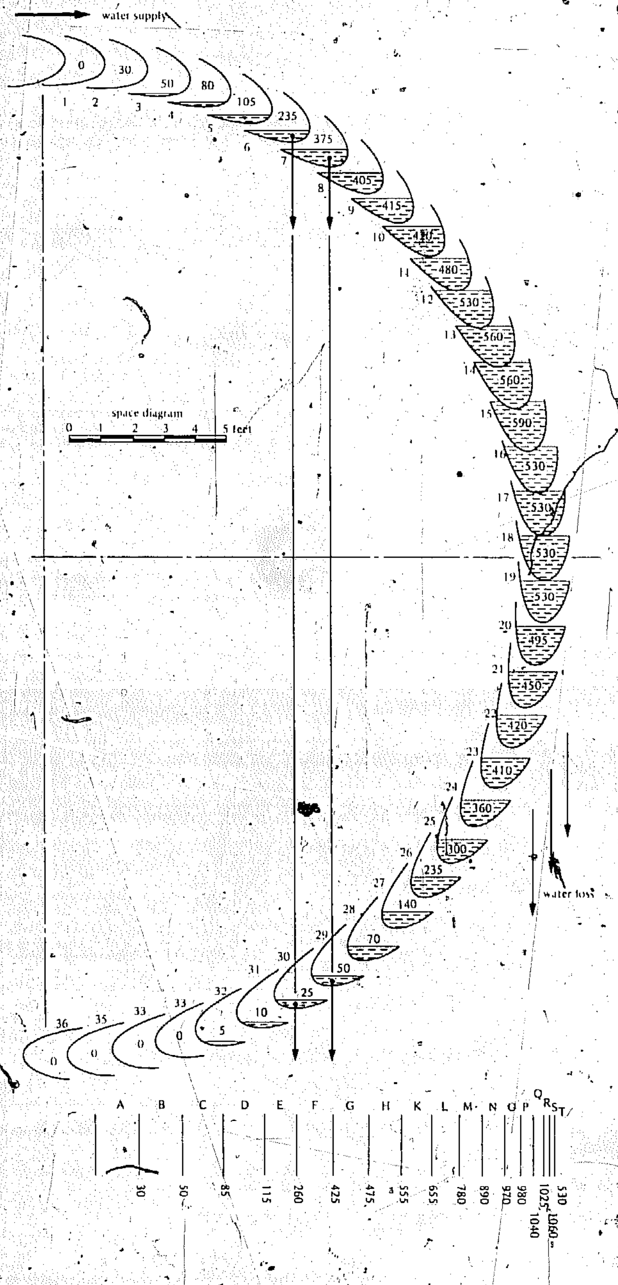


Fig 2.22 Space diagram of Killhope watermill, with conjectural amounts of water in buckets

The losses due to friction etc are yet to be taken into account, but these will be considered after describing the second method.

In the second method, the torque on the waterwheel is determined by evaluating the position and magnitude of the resultant downward force from the weight of water in the different buckets. The resultant can be calculated, but it can also be determined by graphical statics as follows:

1 The weight in each bucket is considered as a single force acting vertically downwards through the centre of gravity of the water.
2 It is assumed for fig 2.22 that for each bucket in the upper portion of the wheel, the line of action of the force due to the water in the bucket coincides with that of the bucket in the lower part of the wheel vertically below it. For example, there is a common line of action of the forces from buckets 6 and 30.
3 Each value in the row of figures at the bottom of fig 2.22 is the sum of the forces in the two buckets vertically above.
4 The letters between the figures enable the forces to be designated (Bow's notation). For example, force EF of magnitude 260 pounds is that due to the water in buckets 6 and 30.
5 The force diagram for this system of parallel coplanar forces is shown on the right of fig 2.23. Vector ab represents force AB to scale, bc represents BC and so

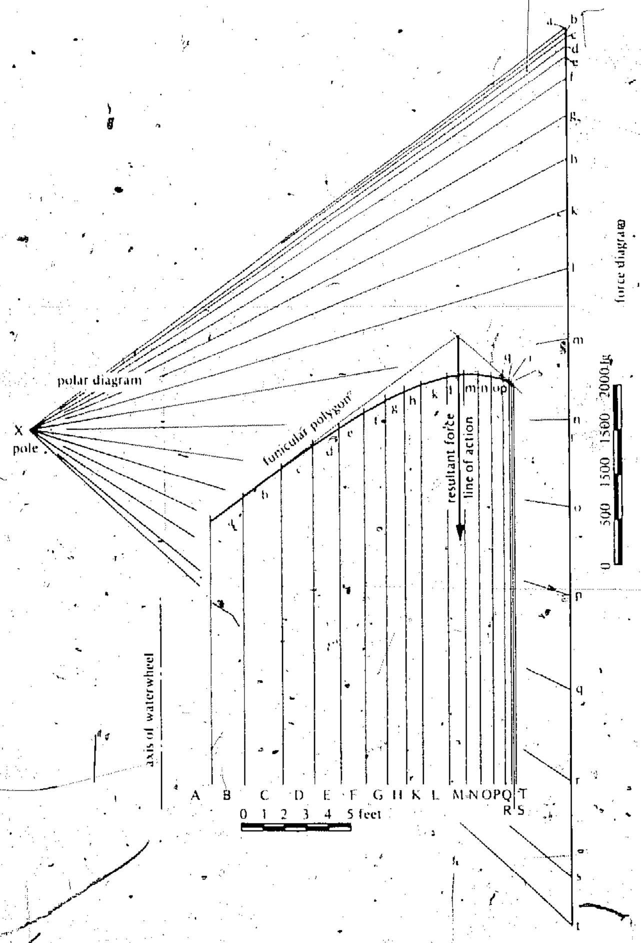


Fig 2.23 Force diagram, polar diagram, and funicular polygon for Killhope waterwheel

on, with **ef** representing force EF. If the system is in equilibrium, the force diagram 'closes', that is, the last vector (representing the equilibrant) ends at the starting point of the first. In this case, **ta** is the equilibrant and the resultant will have the same magnitude but act in the opposite direction.

6 The position of the equilibrant (and thus of the resultant) is found by means of a funicular polygon. First, a polar diagram is drawn by selecting any pole X (on the left of fig 2.23) and connecting this to each point on the force diagram, that is, draw lines xa, xb, xc, and so on.

7 The funicular polygon is drawn in the spaces between the lines of action of the various forces – see middle of fig 2.23. Starting at a point on AB, a line is drawn parallel to xb on the polar diagram across space B to cut the line of action of force BC. From this intersection, a line is drawn parallel to xc on the polar diagram, across space C to out the line of action CD, and so on until the line of action ST is reached.

8 From the starting point on AB a line is drawn parallel to xa on the polar diagram, and from the finishing point on ST a line is drawn parallel to xt. These two lines are extended to intersect at Z, thus completing the funicular polygon.

9 The resultant force acts vertically downwards through Z. In this case, the magnitude of the resultant is 9915 pounds (that is, the sum of all the downward forces from water in the buckets) and, from the funicular polygon on fig 2.23, acts at 13.4 ft from the centre of the waterwheel.

torque on waterwheel = force X perpendicular distance of its line of action from the centre of rotation

= 9915 X 13.4

= 133 000 foot pounds

work done by torque per minute = torque X angle (in radians) turned through per minute

= torque X 2π X revolutions per minute

Assuming the same speed of revolution of 3.4 revolutions per minute, as taken for the previous method, page 58,

work done by torque per minute = 133 000 X 2π X 3.4

$$\text{horse power} = \frac{133\,000 \times 2\pi \times 3.4}{33\,000}$$

= 85.5

(or 64 kW, in SI units)

Comparing with the value on page 59 there is almost 25 per cent difference between the power estimated from the two methods. However, consider the case when the total weight of water on the wheel remains the same but is distributed so that there is more water in the buckets near the top of the wheel and correspondingly less in those at the right-hand side of the wheel. The power estimated from the energy method will remain unchanged, but that deduced from the resultant force and consequent torque will decrease significantly.

Neither of the powers estimated from the two methods accounts for losses due to friction, splashing etc. Assuming these losses to be 22 per cent,

probable horse power (by energy method) = 68.5 X .78

= 53 (40 kW)

If the lower portion of the waterwheel was 'drowned' in the tail-race then there would be a further loss of power in working against this. In the nineteenth century a drowned wheel was considered to have an efficiency only three-quarters that of a wheel not drowned.

2.8 POSSIBILITIES FOR FURTHER WORK

Further work depends on the chosen objectives. The appropriate leads to these can be developed when the class or group discusses the results of their visit to the water-mill site. The possibilities for further work are grouped under three headings:

1. involvement with technology
2. involvement with non-technical subjects
3. communication of the information collected.

Involvement with technology

Recording

It may be that the first visit to the site was used in getting familiar with recording techniques, and that as a result of classifying and collating the information obtained, the teacher feels that more recording is required to achieve his or her objectives. Thus, some of the activities referred to earlier (pages 49–53) may be relevant. For example, after surveying the site from the ground, the pupils may be motivated towards trying to take aerial photographs so that they can be involved in design and construction work if this is relevant to the teacher's objectives.

Measurements

Disillusionment with the accuracy of results of the first session of trying to measure water flow or power may lead to more experimental work in school in order to develop more reliable techniques. In the estimation of power output of the waterwheel, the previous section showed the possible discrepancies due to lack of knowledge of the behaviour of the water as it comes onto the wheel. This could be investigated by building transparent models and observing the water flow into the buckets so that a more reasonable water distribution can be drawn for the actual waterwheel.

Investigations of the efficiency of ways of using waterpower

From the visit to the site, the pupils may be encouraged to question the efficiency of the waterwheel arrangement seen and to compare the effectiveness of different ways of obtaining rotary power from water by practical investigations.

Providing the hardware for these investigations may be a means of achieving objectives involving design. The following shows the variety of decisions the pupils will have to make in designing even a simple waterwheel using the supply from the classroom tap:

How is a constant flow onto the wheel to be provided?

How is the water to be brought onto the wheel? (See fig 2.24.)

What provision is to be made to reduce splashing and the effects of splashing? (See fig 2.25.)

How is water to be taken away after driving the wheel?

What type is the waterwheel?

What is the size of wheel?

What are the number and shape of the paddles, vanes, or buckets?

What materials should be chosen for working in water or damp conditions? (See fig 2.26.)

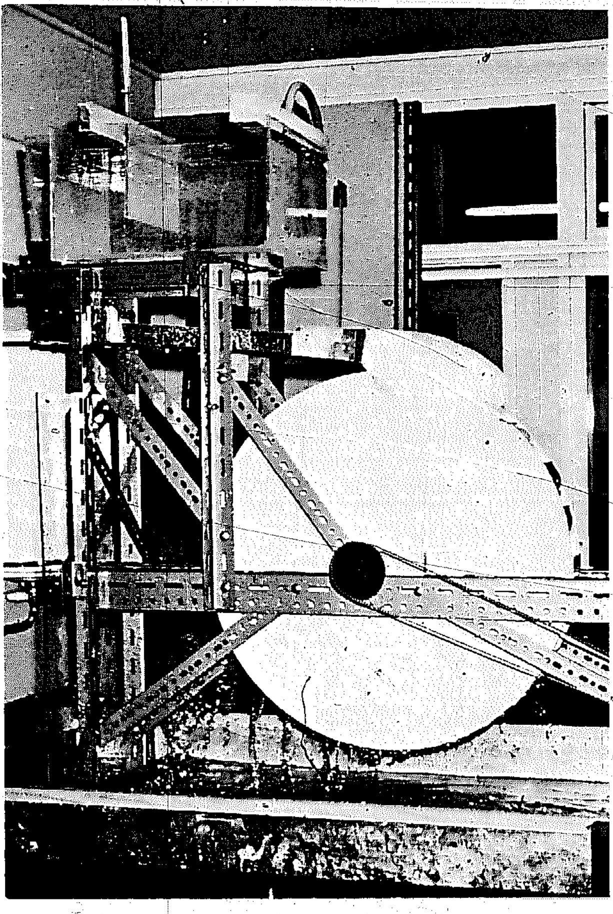


Fig 2.24 A large, experimental model waterwheel with metal buckets contained within large wooden discs which perform the function of shrouds and also of attaching the buckets to the wheel axle. The water is supplied from the laboratory tap into a header tank with means for measuring the flow from the left-hand end into the bent tin-plate pentrough delivering water onto the overshot waterwheel. Note that the water is still leaving the buckets even after they have risen by moving almost a quarter of a revolution from the bottom position. This indicates a poor design of bucket and/or incorrect choice of speed of rotation

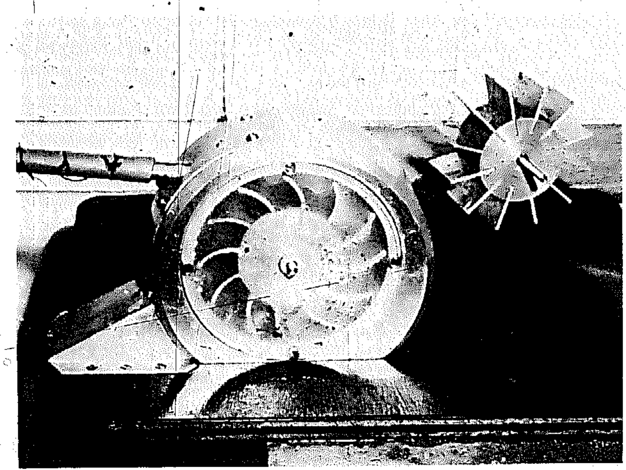


Fig 2.25 A small impulse waterwheel made by boys at Hinckley Upper School, Leicestershire. Made mainly of metal, this has a Perspex front to study the flow of water on the vanes and the design allows easy replacement of one rotor with others of different vane profiles and numbers of vanes such as the example in the right background. Note the cover over the discharge into the sink to minimize splashing

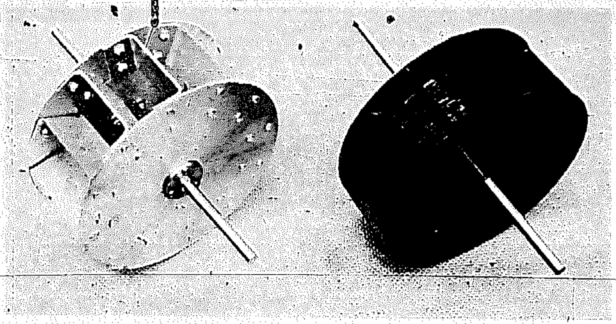


Fig 2.26 A contrast in materials and methods of construction of similar model undershot waterwheels. The example on the left is of light alloy sheet, cut and rivetted together: that on the right is of PVC sheet and chipboard waterproofed by coating with polyester resin after assembly

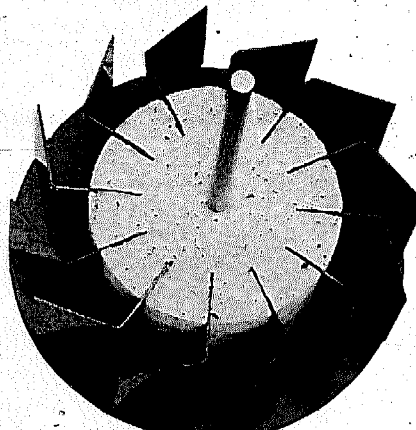


Fig 2.27 A partially-made model waterwheel with buckets, showing the chip board 'boss' slotted to take the buckets formed by heating PVC sheet and bending in a jig. The wheel will be finished by attaching another disc of PVC sheet to provide the second set of shrouds for the buckets

2.28 A pupil from the Dunsmore School for Girls, Rugby, observing the head of water flowing over a V-notch. Note that the sides of the notch are chamfered to present a sharp edge. The scale is fixed to the cross member but the screwed rod, carrying the pointer, is adjustable so that its lower end, pointed and bent through 180° to point upwards, just touches the surface of the water about 75 mm upstream of the notch

How is the wheel to be supported (bearings and their supports)?

How is the wheel to be attached to the shaft?

Will other devices (eg for power measurement) have to be attached to the shaft and if so, how will this be done?

To compare the efficiencies of different model waterwheels, we need to measure:

1 the input to the wheel, eg water flow and head (fig 2.28)

2 the output.

Some methods of flow measurement have already been described in relation to the flow of actual streams (see pages 51–3), and some of these can be adapted for use with smaller flows. Besides proprietary flowmeters employing rotors and floats, school-built devices can be quite effective.

One simple device (fig 2.29) uses the difference in pressure across an orifice. The orifice can be made by brazing a drilled disc between two pieces of brass tube.

Note that the downstream attachment for the transparent plastics tubing is very close to the orifice plate.

The device may be calibrated by discharging the flow through it into a measuring container (fig 2.30). A plastic bucket marked to indicate a definite volume is suitable. The time is observed for the container to fill to the mark and at the same time the difference in head between the water in the tubes is noted. This is repeated for different flows so as to obtain a calibration table, or the information may be presented as a graph.

Note that in comparing waterwheels, it is often only necessary to ensure that the flow is the same onto each wheel tested, but if we wish to investigate how the performance of the wheel varies with different flows then a calibrated flow measuring device is essential.

In many schools there will be fluctuating flow from any ~~tap as~~ others are turned on or off. This will cause variations in the speed and power of the waterwheels under test, and a constant head arrangement is useful (fig 2.30).

The following methods have been used successfully for measuring the power output of model waterwheels:

1 *Lifting weights by winding cord onto a shaft.* A light cord is secured to the waterwheel shaft, and as it winds round the rotating shaft a weight is lifted by its lower

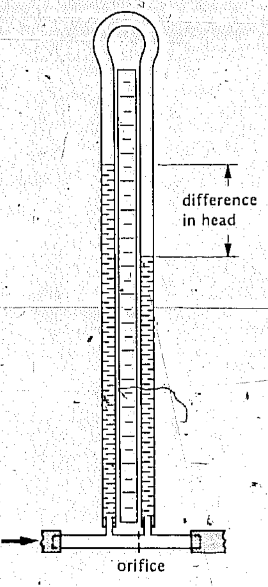


Fig 2.29 Flowmeter using difference in pressure across orifice

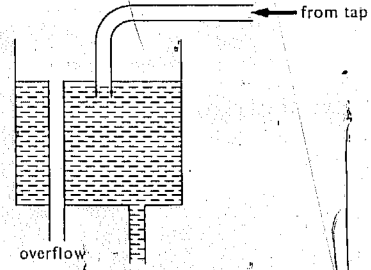


Fig 2.30 Constant head arrangement

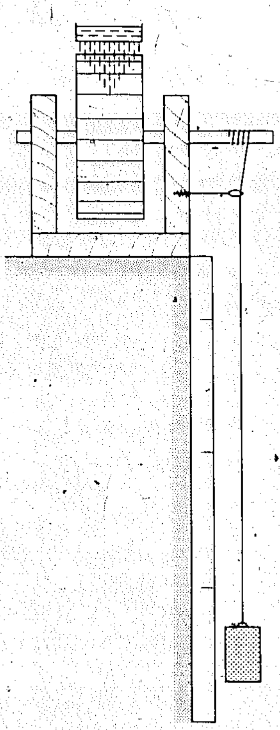


Fig 2.31 Lifting weights by winding cord onto shaft

end (fig 2.31). The weight has to be adjusted so that it eventually ascends at constant velocity. This can be checked by noting the time it takes to cover two successive and identical distances.

Because the wheel and weight have to accelerate from rest, they will move some distance from the starting point before their movement is uniform.

work done = force X distance moved

power = work done in unit time

= force X distance moved in unit time

If the mass on the end of the cord is 0.25 kilogrammes and the time it takes to travel 1 metre is 20 seconds, then the force on the end of the cord is 0.25 X 9.81 newtons.

power = 0.25 X 9.81 X $^1/_{20}$ newton metres/second

= 0.12 watts

Since 1 horse power is equivalent to 745.7 watts,

horse power = 0.00016

2 *Using a band brake with dead load and spring balance.* For small waterwheels, the weight of even a small spring balance can be significant compared with the torque on the brake wheel. To eliminate the effect of the weight of the balance, it can be attached to the end of the brake band through a lever, as shown in fig 2.32.

The brake enables the torque from the waterwheel to be determined, but to evaluate power the speed of revolution is also required. This is most conveniently measured by a stroboscope, and the type used for Nuffield physics courses is suitable.

Torque at wheelshaft
= radius of brake wheel X (force due to dead load – force shown by spring balance)

power = torque X angular displacement in radians in unit time

For example,

if radius of brake wheel = 25 millimetres
mass of dead load = 0.15 kilogrammes
spring balance reading = 0.25 newtons
speed of rotation = 200 revolutions/minute

Then force due to dead load

= 0.15 X 9.81 = 1.475 newtons

torque

$$= \frac{25}{1000} \times (1.475 - 0.25)$$

= 0.03 newton metres

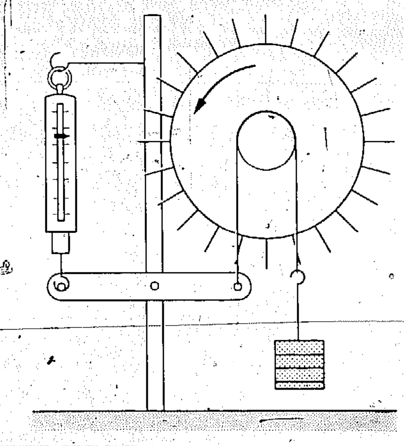
power

$$= 0.03 \times \frac{200}{60} \times 2\pi \text{ newton metres/second}$$

= 0.64 watts

Since one horse power is equivalent to 745.7 watts,

$$\text{horse power} = \frac{0.64}{745.7} = 0.00085$$



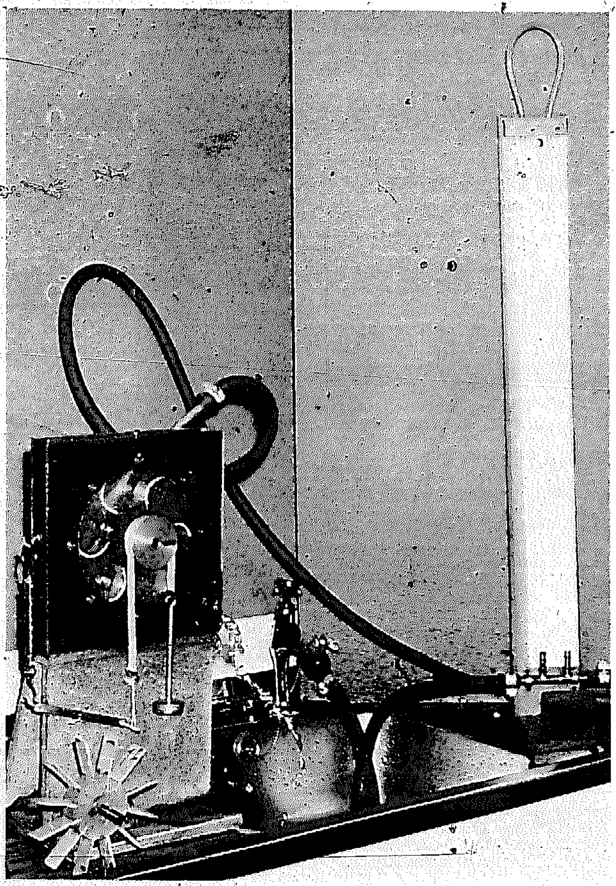


Fig 2.32 An impulse-type wheel fitted with a brake pulley on the wheelshaft. The torque is determined by dead-weight and spring balance. The pulley is marked with a line on its outer face for determining the speed of revolution with a stroboscope. The water supply to the nozzle at the wheel is from the laboratory tap through a flow measuring device (on the right) using the pressure difference across an orifice

3 *Using a band brake with dead load and electrical resistance strain gauges.* Because the tension in the brake band on the side away from the dead load changes by only a small amount, a more sensitive force-measuring device than a spring balance is useful.

One method of providing this sensitivity is to connect the brake band to the free end of a springy cantilever (see figs 2.33 and 2.34). A piece of hack-saw blade is suitable for this. The end of the cantilever will deflect proportionately to the force applied by the band-brake. Near to the fixed end, identical electrical-resistance strain gauges are fixed to top and bottom of the cantilever, and are affected by the compressive strain (on one side) and tensile strain (on the other) of the cantilever as it is deflected by the pull from the brake band.

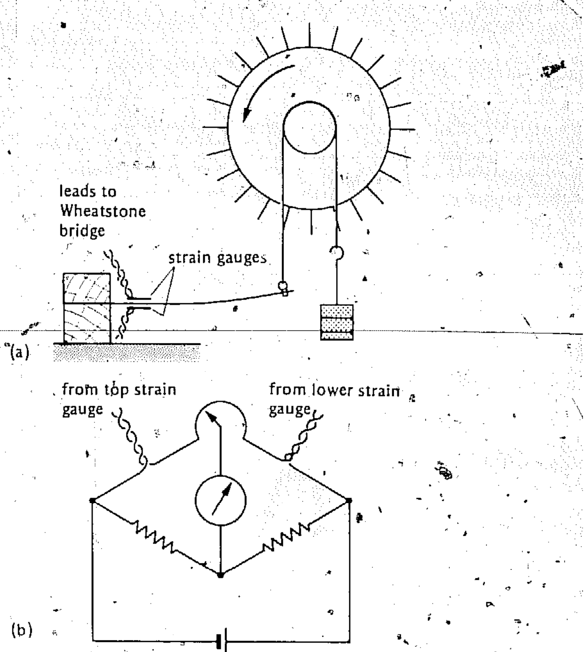


Fig 2.33 Force measuring device using strain gauges and Wheatstone bridge

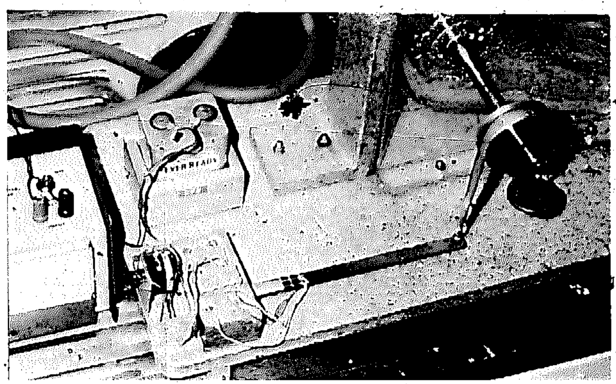


Fig 2.34 A Wheatstone bridge circuit for determining the change in resistance of electrical resistance strain gauges fixed to a flexible cantilever and so measuring the tension in the band brake over the pulley on the waterwheel shaft

The strain gauges form part of a Wheatstone bridge circuit (fig 2.33). The other arms of the bridge are formed of resistors of a similar resistance to that of the strain gauges. To adjust for initial balance, it is useful to have a potentiometer across the apex of the strain gauge connections.

In its simplest form, the arrangement can be calibrated by applying small known forces to the cantilever at the point where the band brake is normally attached, and observing the deflection on the galvanometer.

Again, the stroboscope is useful in determining the speed of rotation and the power is calculated as for method 2 above, using the force indicated by the strain gauges and bridge circuit instead of the spring balance.

4 *Driving electrical generators.* Provided their speed of rotation is high enough, small electric generators (which can be miniature model-making motors, as mentioned previously) can be connected directly to the waterwheel shaft. If the waterwheel speed is too low to produce anything at the generator, intermediate gearing must be introduced to give a suitable speed at the generator. There will be losses in the gearing but simple mechanical tests on the gearing alone should establish its efficiency.

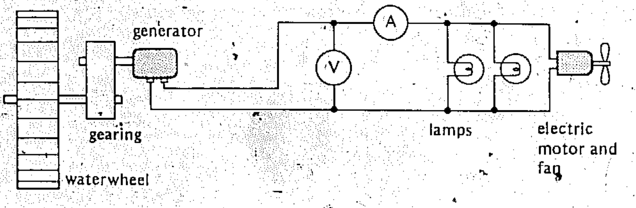


Fig 2.35

The output from the generator is used to supply an electrical load, for example illuminating small electric lamps or driving a smaller miniature electric motor. (This, too, will need to have a load, such as a small propeller on the end of the shaft working against air resistance.) The current to, and voltage across, these electrical 'loads' are then measured. See figs 2.35 and 2.36.

Electrical power = current X voltage

For example, if the ammeter indicates 0.02 A and the voltmeter indicates 4 V,

power = 0.02 X 4 = 0.08 W

Since 1 horse power is the equivalent of 746 W,

$$\text{horse power} = \frac{0.08}{746} = 0.0001$$

Turbines as well as waterwheels were, and are, used to develop power from water, and the investigations can extend to many of the types given on pages 85–96.

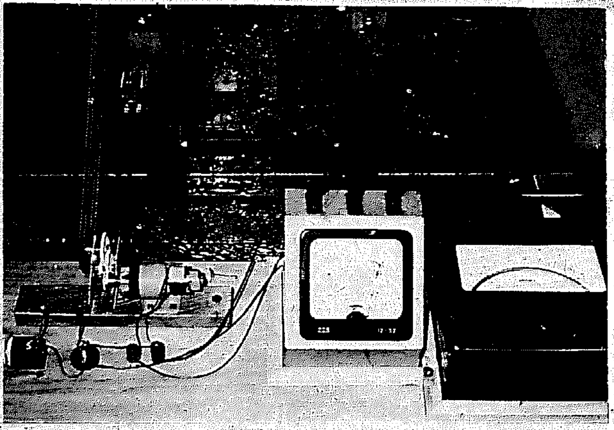
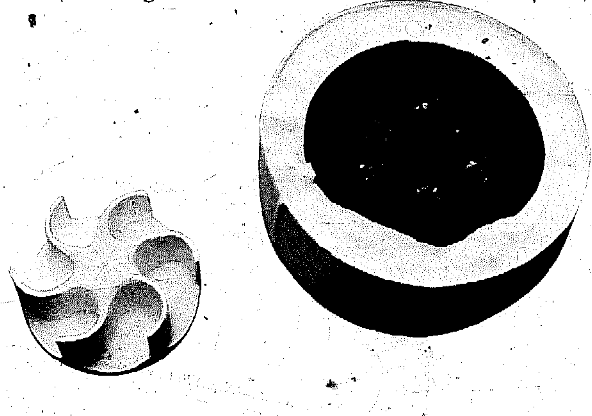


Fig 2.36 Measuring the power output from the large waterwheel shown in fig 2.24. Because of the slow speed of rotation of the waterwheel, a small gearbox has been constructed using proprietary plastics gears to give sufficient speed to work a Meccano electric motor as a generator. The output of this is used to illuminate a bulb and drive a miniature motor and balsa wood 'fan' in the left foreground. The instruments on the right are for measuring the current through the bulb and motor, and the voltage across these, so as to calculate the power

At first sight, most of these may seem too complicated in shape to make in schools, but with the current availability of plastics many of these awkward shapes can now be obtained.

For example, a rotor or impeller curving in three dimensions can be made by casting, in plaster of Paris, a cylinder of the overall dimensions of the part. Onto this is drawn the intended shape of the rotor and the surplus material is carved away with a knife. The plaster of Paris pattern is then used to make a vinyl rubber mould into which is layered up glass-reinforced plastic (glass fibre) to give the final rotor. The casings can be made by using GRP or by vacuum forming onto plaster, wood, metal, or composite patterns. (See fig 2.37.)

Rigid plastic water piping, for example Marley drain-pipes and fittings, can be used to reproduce turbines as shown in fig 2.38.



2.37 Pattern and mould for making a small turbine rotor, constructed by John Jeffreys of Pocklington School, Yorkshire, during a Schools Technology course in the Education Unit, Lanchester Polytechnic. The pattern on the left was made from a cylinder of plaster of Paris cast in an empty tobacco tin. The required shape was drawn in pencil and the unwanted portions carved away with a knife. The pattern was used to produce the vinyl rubber mould on the right. The surrounding ring of plaster of Paris, cast inside a cardboard former, gives rigidity to the mould when glass-reinforced plastic is laid up in it to produce the final rotor

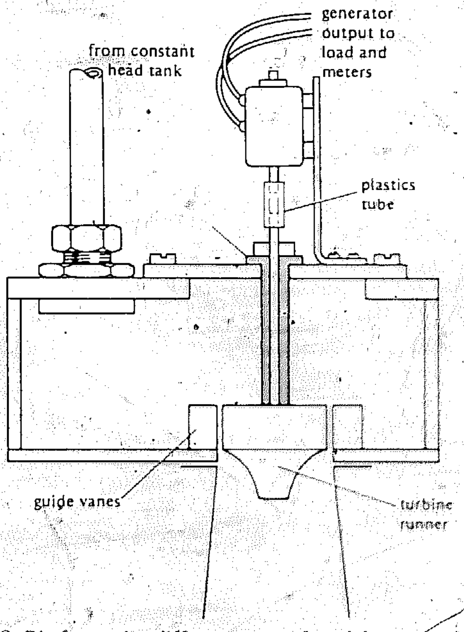


Fig 2.38 Rig for testing different types of model water turbines

This arrangement allows the fixed guide vanes and the rotors to be easily removed for alterations in the light of the results of each tests.

Practical investigations of transmissions
Apart from investigating the power source itself, pupils can consider how the rotary power obtained may be utilized for different purposes. Waterwheels being used to operate, oscillating fulling stocks and tilt hammers are shown on page 3. Other examples of different types of motion obtained from the rotation of a waterwheel are given on pages 72–6.

Attempts to make working models of these will bring the pupils into contact with problems encountered in transmissions or in converting one type of motion to another. The solutions can be related to present-day applications and the relevance of the work can be emphasized by presenting the pupils with the task of designing and producing (for being driven by waterwheels or turbines supplied from school taps) projects such as dish washers or agitators (for photography), reciprocating graters (for food preparation), and 'cocktail' shakers.

The later used of electricity as a means of transmission of power from water (see page 92 *et seq*) can also be investigated by using a waterwheel or turbine to drive a generator which supplies current to lamps at intervals along transmission lines so that the differing voltage drops along the lines can be demonstrated.

Other uses of water energy
Rotary power is not the only way in which water energy can be utilized, and some of the designs described on pages 77–80 provide scope for technological project work in schools.

Making actual use of an available water supply
Some schools may be fortunately situated with regard to a water supply, which may be conveniently harnessed to provide power for some project. This was the case at Aberdeen Grammar School where several boys decided to build a heat pump. This needed a continuing source of heat to evaporate its working fluid and also mechanical energy to drive the compressor in the heat pump. Both the source of heat and the mechanical energy were obtained from the Denburn, a stream flowing along a channel through the school grounds (fig 2.39).

Restoration of watermills and their artifacts
It is unlikely that a school will have either the opportunity or the inclination to undertake full-scale restoration of a mill. However, some schools have been able to make a worthwhile contribution to restoration/preservation schemes when the materials (which can prove to be very expensive in the quantities required for, say, a waterwheel) are provided.

One aspect which is within the capabilities of many schools, and which provides scope for overcoming design problems, is the restoration or reconstruction of the stone furniture, that is, the hoppers, horse, and shoe together with the control cords to ensure an even flow of grain to the stones.

The arrangement and development of the latter to ensure that the grain flows as required will provide plenty of scope for the analysis of problems and ingenuity in solving these.

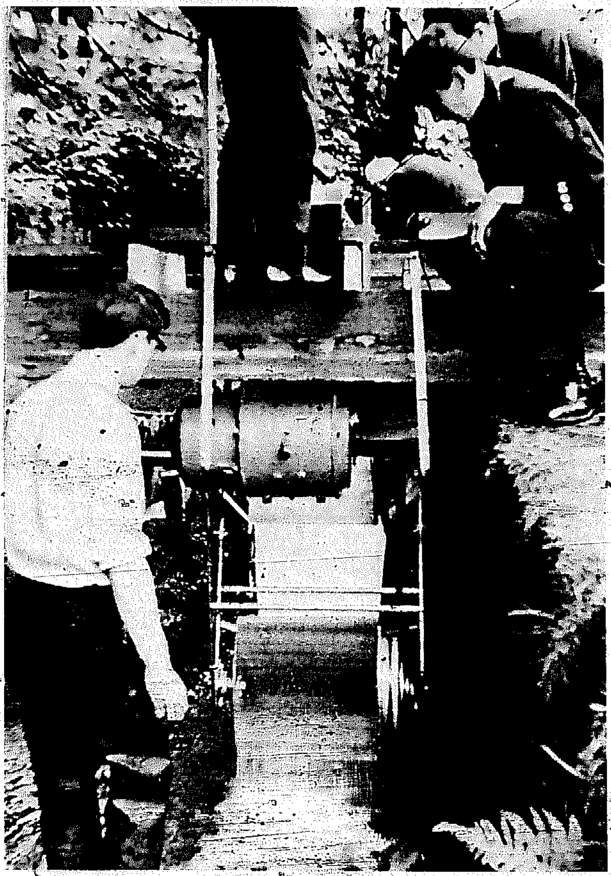


Fig 2.39 Banki turbine and electrical generator installed by boys from Aberdeen Grammar School to harness the energy from the Denburn

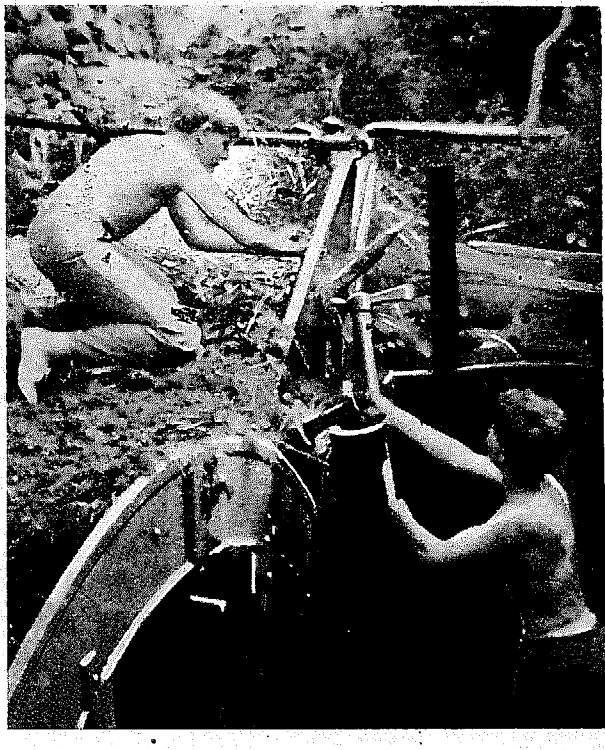


Fig 2.40 Boys from Grenville College, Bideford, clearing debris from the launder serving one of the waterwheels at the Finch Brothers 'Foundry', Sticklepath, Okehampton. These works have now been restored and the waterwheels work again under the auspices of a charitable trust
Photo by courtesy of B D Hughes

Involvement with non-technical aspects

Historical background

The antiquated appearance of the machinery in the mill may be used to interest the technically-minded pupil in asking about the history of the mill. Some 'key' dates may be known as a result of the visit to the mill – datestones on the building, and dates on millwrights' plates or on the machinery. Other important dates may be known through the pupils' acquaintance with people who knew or worked at the mill. This information can be used to start an investigation of the historical sources given on pages 45–7.

Distribution and location of other watermills in the district

Without even referring to published lists of mills in the locality (page 98) it is comparatively easy to obtain this information in sufficient detail for school discussion by examining copies of old maps in the local library or record office. If it is not feasible to take the whole class to these places, it is usually possible to obtain electrostatic copies at quite low cost to use in the school itself.

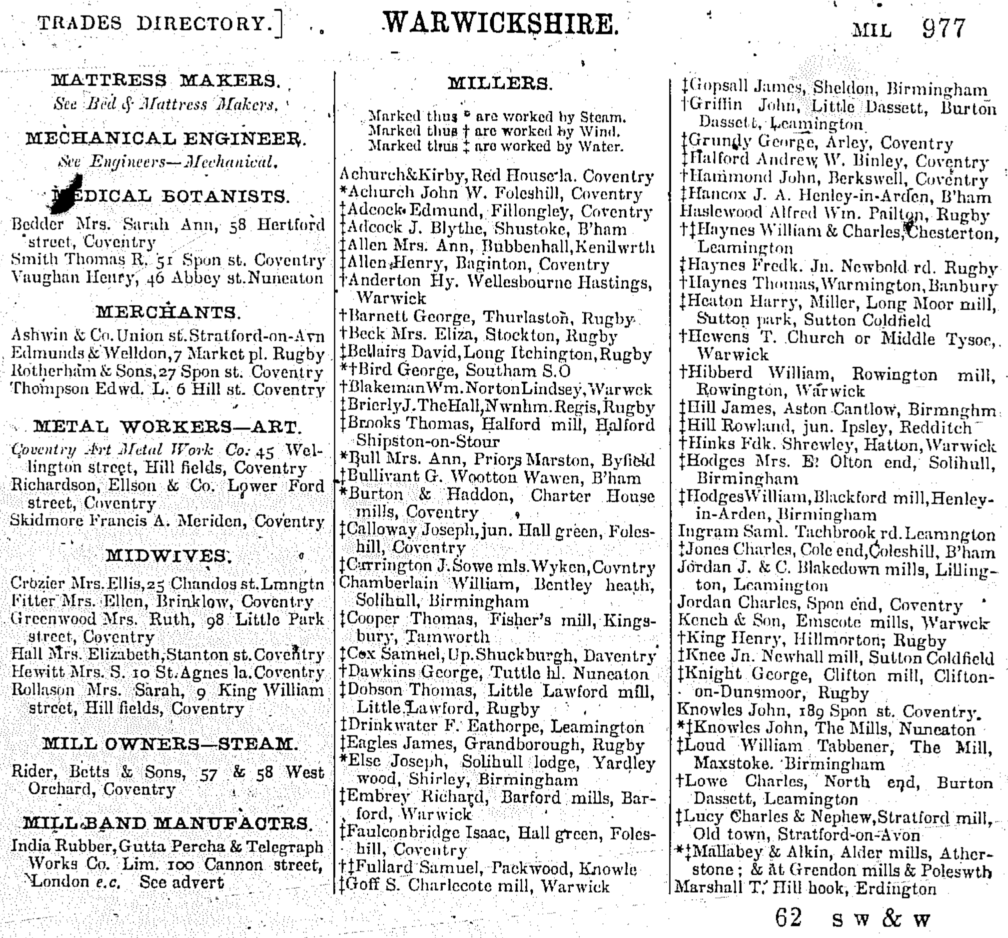
If it is thought that time can be allowed to look at only a few maps, the Ordnance Survey maps around the turn of the century should give a representative picture of the distribution of both water and wind mills. The first edition of the one-inch Ordnance Survey maps of Newton Abbott have recently been republished by David and Charles.

To obtain some idea of which mills were in use at the same time, directories such as Kelly's are useful (see fig 2.41). By the late 1800s, it was usual for the whole of a county's millers to be given together under the heading of their trade. Again, photocopies of the page or two containing these from the directories for several different years will enable the analysis to be done in school.

Environmental aspects

The watermill was built to make use of certain aspects of the environment and the following may be considered by the class:

1 the natural path or route of the river or stream
2 the contours of the land to produce a fall in the river or stream, or to allow the water to be impounded or diverted
3 the water table and rainfall governing the supply and quantity of water at the mill
4 the geology of the area, affecting both the water run-off and the availability of building materials
5 the interplay between several of the above aspects in determining the accessibility of the mill for the transport of grain and flour.



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‡Allen Mrs. Ann, Bubbenhall, Kenilwrth
‡Allen Henry, Baginton, Coventry
†Anderton Hy. Wellesbourne Hastings, Warwick
†Barnett George, Thurlaston, Rugby
†Beck Mrs. Eliza, Stockton, Rugby
‡Bellairs David, Long Itchington, Rugby
*†Bird George, Southam S.O
†Blakeman Wm. Norton Lindsey, Warwck
‡Brierly J. The Hall, Nwnhm. Regis, Rugby
‡Brooks Thomas, Halford mill, Halford Shipston-on-Stour
*Bull Mrs. Ann, Priors Marston, Byfield
‡Bullivant G. Wootton Wawen, B'ham
*Burton & Haddon, Charter House mills, Coventry
‡Calloway Joseph, jun. Hall green, Foleshill, Coventry
‡Carrington J. Sowe mls. Wyken, Covntry
Chamberlain William, Bentley heath, Solihull, Birmingham
‡Cooper Thomas, Fisher's mill, Kingsbury, Tamworth
‡Cox Samuel, Up. Shuckburgh, Daventry
†Dawkins George, Tuttle hl. Nuneaton
‡Dobson Thomas, Little Lawford mill, Little Lawford, Rugby
‡Drinkwater F. Eathorpe, Leamington
‡Eagles James, Grandborough, Rugby
*Else Joseph, Solihull lodge, Yardley wood, Shirley, Birmingham
‡Embrey Richard, Barford mills, Barford, Warwick
‡Faulconbridge Isaac, Hall green, Foleshill, Coventry
†‡Fullard Samuel, Packwood, Knowle
‡Goff S. Charlecote mill, Warwick
‡Gopsall James, Sheldon, Birmingham
†Griffin John, Little Dassett, Burton Dassett, Leamington
‡Grundy George, Arley, Coventry
‡Halford Andrew W. Binley, Coventry
†Hammond John, Berkswell, Coventry
‡Hancox J. A. Henley-in-Arden, B'ham
Haslewood Alfred Wm. Pailton, Rugby
†‡Haynes William & Charles, Chesterton, Leamington
‡Haynes Fredk. Jn. Newbold rd. Rugby
†Haynes Thomas, Warmington, Banbury
‡Heaton Harry, Miller, Long Moor mill, Sutton park, Sutton Coldfield
†Hewens T. Church or Middle Tysoe, Warwick
†Hibberd William, Rowington mill, Rowington, Warwick
‡Hill James, Aston Cantlow, Birmnghm
‡Hill Rowland, jun. Ipsley, Redditch
†Hinks Fdk. Shrewley, Hatton, Warwick
‡Hodges Mrs. E. Olton end, Solihull, Birmingham
‡Hodges William, Blackford mill, Henley-in-Arden, Birmingham
Ingram Saml. Tachbrook rd. Leamngton
‡Jones Charles, Cole end, Coleshill, B'ham
Jordan J. & C. Blakedown mills, Lillington, Leamington
Jordan Charles, Spon end, Coventry
Kench & Son, Emscote mills, Warwck
†King Henry, Hillmorton, Rugby
‡Knee Jn. Newhall mill, Sutton Coldfield
‡Knight George, Clifton mill, Clifton-on-Dunsmoor, Rugby
Knowles John, 189 Spon st. Coventry.
*‡Knowles John, The Mills, Nuneaton
‡Loud William Tabbener, The Mill, Maxstoke. Birmingham
†Lowe Charles, North end, Burton Dassett, Leamington
‡Lucy Charles & Nephew, Stratford mill, Old town, Stratford-on-Avon
*‡Mallabey & Alkin, Alder mills, Atherstone; & at Grendon mills & Poleswth
Marshall T. Hill hook, Erdington

62 s w & w

Fig 2.41 Extract from Kelly's Directory for Warwickshire, 1884, showing some of the entries under 'millers'. Note the distinction between those using steam, wind or water with George Bird of Southam using both steam and wind power

Once at work, the mill in turn began to affect the environment, and it is worthwhile discussing its influence on:

1 the vegetation, both due to alterations in watercourses, water flows, greater likelihood of flooding, increase in moisture content of the ground, and also due to human activities;
2 wild-life, due to changes in vegetation and to uses of the land;
3 communications, since people might come to trade with the mill from all directions which would create trackways providing routes for those who did not need to call at the mill.

Comparative studies might be made of soils (for moisture content at various depths), vegetation, and wild-life, both at the mill site and along the natural course of the stream or river serving it.

Social aspects
The style of the mill, and particularly of the mill house, as observed on the visit to the site, can lead to speculation about the position of the miller in the local community. Discussion of this could also provoke the following questions:

1 To whom did the mill actually belong?
2 What was the relationship between the owner and the miller?
3 Did the miller engage in other business activities – for example as a baker or as a farmer or grazier?
4 Did the miller hold any official positions in the parish?
5 How was capital raised for rebuilding the mill, new plant, or auxiliary engines?
6 How highly was the miller regarded by the local community?
7 Did all millers throughout the life of the mill enjoy this level of regard, or did it fluctuate? If so, why?
8 What is known of the miller's family? What sort of people did they marry?
9 What was the status of other people working at the mill?
10 Who else was affected by business at the mill?
11 What happened to the miller and his family as the business declined and closed?
12 How was the local community affected by the closure of its mill?

Communicating information
Although in schools the achievement of educational objectives must take precedence over the formal completion of an industrial archaeological study by depositing records or publication, nevertheless the activities of bringing records to a standard where they are acceptable for depositing in record offices etc, or putting on a display to show others the information obtained, can sometimes help to achieve certain of our objectives.

Records
If records are to be prepared to a standard worthy of placing in official repositories, it is as well to check that this has not already been done by someone else for the mill under consideration.

There are two main categories of record:

1 Records of surveys. In the case of watermills (and windmills), record cards have been prepared by the Wind and Watermill Section of the Society for the Protection of Ancient Buildings and an example of a completed card is shown in fig 2.42.

Before being deposited in the local record office, museum, or library, it is hoped that these cards will be sent to Dr R A Buchanan, Centre for the Study of the History of Technology, Bath University of Technology, Northgate House, Bath. The cards will then be copied for the National Record of Industrial Monuments and for the people maintaining the Indexes of Watermills and for Windmills for the SPAB. The card will then be returned to you from Bath for depositing locally.

2 Full recordings, with measured drawings and photographs, including those of details. It is worth checking with the depository you have in mind, as to the form and size which is most convenient for them.

Displays
The object of any display is to enable the 'displayers' to communicate with the viewers of that display. Unlike the preparation of records for depositing which must be to a certain standard, the display can be pitched at a level compatible with the abilities of the pupils staging it.

The display can be either set up so that the 'viewers' come to it, probably moving from one exhibit to the next, or in a form that it can be taken to the viewers, for example an audio-tape and colour slide show.

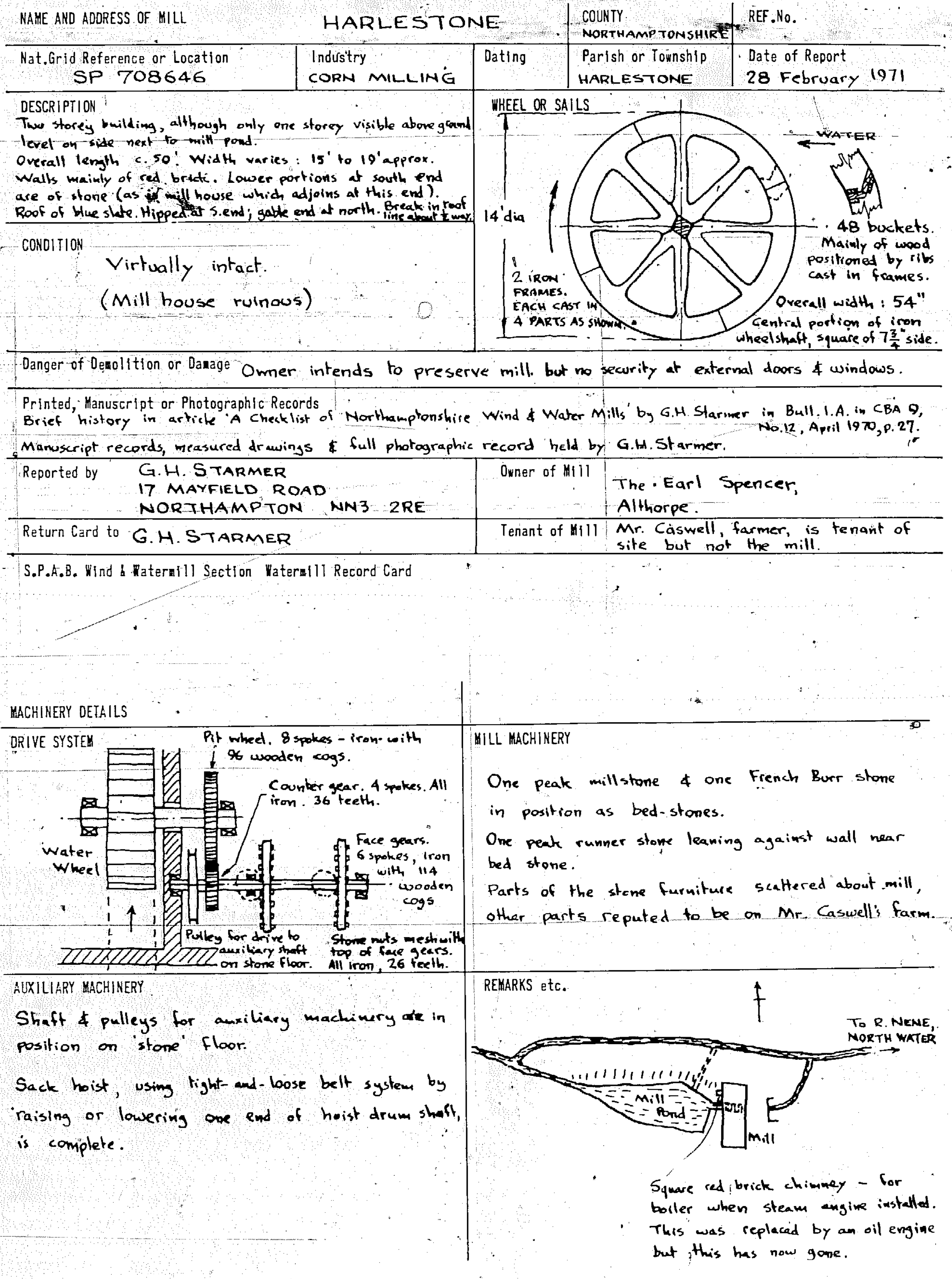
Both forms of display provide plenty of scope for cooperation between departments, including art and music which have so far not been mentioned specifically in this handbook.

In the first type of display, the information may be conveyed by:

charts, diagrams, and mounted photographs with captions,
smaller artifacts from the mill,
models,
working models (fig 2.43),
tape-recordings,
looped cine-film

The procedures involved in most of these display techniques are well known but possible methods for making static models of mill buildings are:

1 From expanded polystyrene sheet using hot wire cutters (in a well-ventilated work area) to cut out the sides and roof with appropriate openings for doors and windows and also to represent the joints between the stone or brick work and roofing tiles or slates. (See figs 2.44 and 2.45.) Walls can be glued, using pins to hold them until the glue sets, but it is often useful to have the roof and even some of the internal floors removable so that the interior arrangements can be inspected.
2 From scrap-wood, cut to shape for walls, window openings etc, assembled and then covered with a plaster (similar to Polyfilla), which when almost dry is marked to represent the joints between the stone or other building materials used in the actual mill.



NAME AND ADDRESS OF MILL HARLESTONE
COUNTY NORTHAMPTONSHIRE
REF.No.

Nat.Grid Reference or Location SP 708646	Industry CORN MILLING	Dating	Parish or Township HARLESTONE	Date of Report 28 February 1971

DESCRIPTION
Two storey building, although only one storey visible above ground level on side next to mill pond.
Overall length c. 50'. Width varies: 15' to 19' approx.
Walls mainly of red brick. Lower portions at south end are of stone (as mill house which adjoins at this end).
Roof of blue slate. Hipped at S.end; gable end at north. Break in roof line about ½ way.

CONDITION
Virtually intact.
(Mill house ruinous)

WHEEL OR SAILS
14' dia
WATER
2 IRON FRAMES. EACH CAST IN 4 PARTS AS SHOWN.
48 buckets. Mainly of wood positioned by ribs cast in frames.
Overall width: 54"
Central portion of iron wheelshaft, square of 7¾" side.

Danger of Demolition or Damage Owner intends to preserve mill but no security at external doors & windows.

Printed, Manuscript or Photographic Records
Brief history in article 'A Checklist of Northamptonshire Wind & Water Mills' by G.H. Starmer in Bull. I.A. in CBA 9, No.12, April 1970, p.27.
Manuscript records, measured drawings & full photographic record held by G.H. Starmer.

Reported by G.H. STARMER
17 MAYFIELD ROAD
NORTHAMPTON NN3 2RE

Owner of Mill The Earl Spencer, Althorpe.

Return Card to G.H. STARMER

Tenant of Mill Mr. Caswell, farmer, is tenant of site but not the mill.

S.P.A.B. Wind & Watermill Section Watermill Record Card

MACHINERY DETAILS

DRIVE SYSTEM
Pit wheel. 8 spokes - iron - with 96 wooden cogs.
Counter gear. 4 spokes. All iron. 36 teeth.
Water Wheel
Face gears. 6 spokes, iron with 114 wooden cogs
Pulley for drive to auxiliary shaft on stone floor.
Stone nuts mesh with top of face gears. All iron, 26 teeth.

MILL MACHINERY
One peak millstone & one French Burr stone in position as bed-stones.
One peak runner stone leaning against wall near bed stone.
Parts of the stone furniture scattered about mill, other parts reputed to be on Mr. Caswell's farm.

AUXILIARY MACHINERY
Shaft & pulleys for auxiliary machinery are in position on 'stone' floor.

Sack hoist, using tight-and-loose belt system by raising or lowering one end of hoist drum shaft, is complete.

REMARKS etc.
To R. NENE, NORTH WATER
Mill Pond
Mill
Square red brick chimney - for boiler when steam engine installed. This was replaced by an oil engine but this has now gone.

Fig 2.42 Front and rear of record card prepared by the Society for the Protection of Ancient Buildings (Wind and Watermill Section)

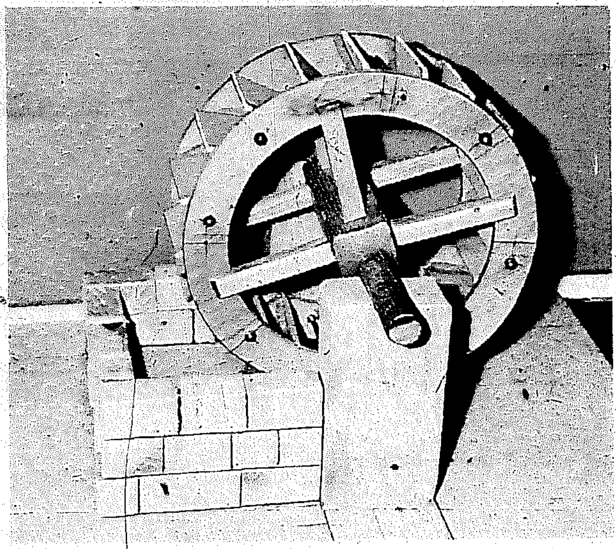


Fig 2.43 *Model undershot waterwheel under construction by Hayle County Secondary School, Cornwall. Note the compass arm construction, that is, spokes mortised into the wheelshaft, and the wooden blocks which will be rendered with plaster to simulate stone*

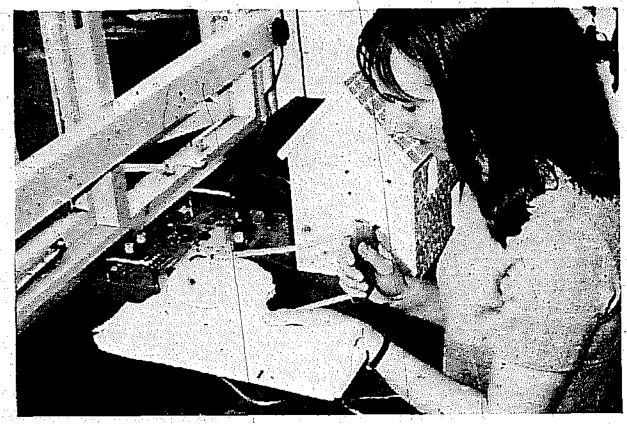


Fig 2.44 *Expanded polystyrene being shaped with a hot wire cutter to construct a model mill for display*

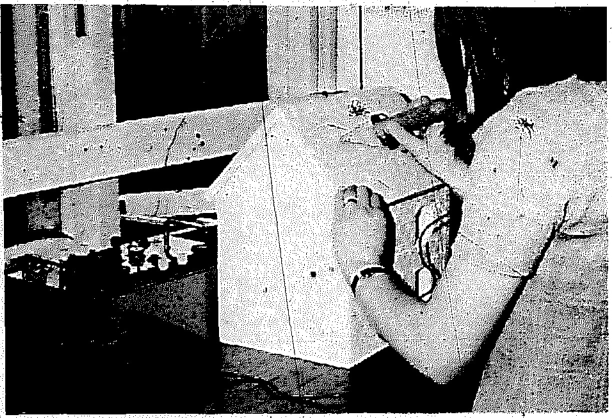


Fig 2.45 *A hot wire loop in use for marking the outlines of slates on the mill, the walls of which have already been marked to represent random coursed stone*

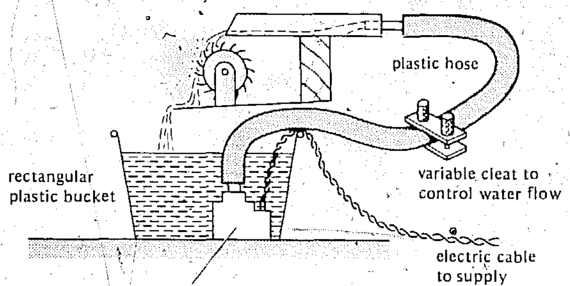


Fig 2.46 *Use of submersible electric pump for working model waterwheel*

3 For working models of waterwheels a self-contained, recirculating water system is useful, and can be made from a submersible electric pump of the type used to drive garden fountains (fig 2.46).

The second type of display or 'show' can take various forms including:

- presenting the information about the mill in the form of a play, with the minimum of visual material
- accompanying such a play with taped sound effects
- presentation as a play with tape recorded sound effects and 'props' representing the mill and its machinery
- slide show with commentary given by one person
- slide show with scripted dialogue
- slide show with tape recorded sound effects and sound 'story'
- cine-film.

With all of these forms, the pupils should be involved in preparing the script or the order of presentation and in doing this will learn the importance of an orderly sequence when communicating information.

Fig 2.47 *This cast iron nameplate of the old mill at Flore, near Weedon, Northamptonshire, invites reproduction for a school display. A wooden replica could be used to make vacuum-formed copies from plastics sheet or, with permission of the owner, an impression can be taken in thin aluminium foil using similar techniques to those for copying church brasses*

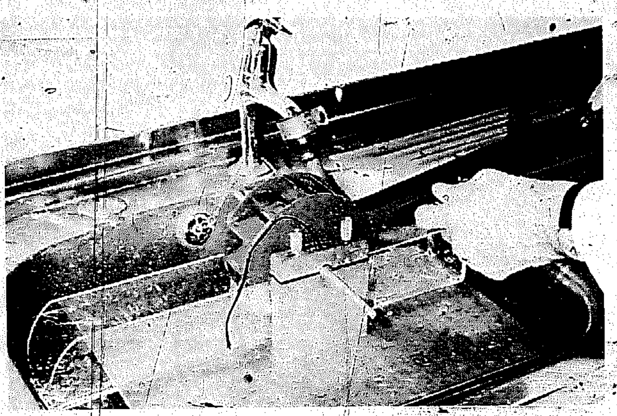


Fig 2.48 A demonstration model made by S Longstaff in the Education Unit, Lanchester Polytechnic. The waterwheel is that shown under construction in fig 2.27. The water is being directed onto the wheel at the level of its axle, thus representing a breastshot wheel. The long wheelshaft is intended for use with different devices secured to the wide baseboard

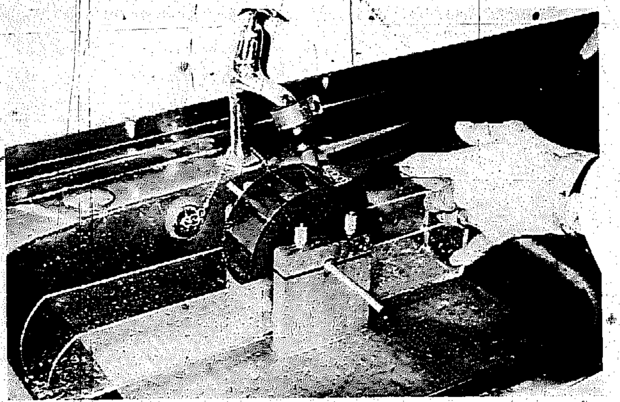


Fig 2.49 The same demonstration model with water being delivered to near the top of the wheel, so representing a pitch-back waterwheel. With the same flow of water as in the arrangement of fig 2.47, the increased speed of the wheel immediately shows the effect of raising the height through which the water falls in turning the wheel

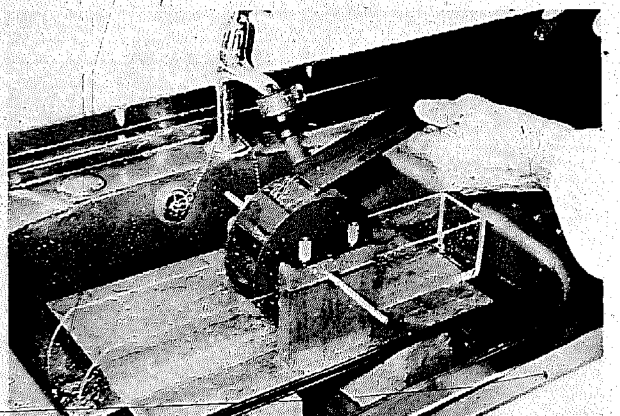


Fig 2.50 The same waterwheel and board after the whole has been turned through 180° relative to the delivery flow. The Perspex 'tail-race' has been turned through 180° relative to the baseboard and wheel. Delivering the water to the top of the wheel now gives an overshot wheel and the transparent tail-race makes it easy to see the water leaving the wheel, 'backing-up' against its direction of rotation

2.9 CLASS DISCUSSION OF FINDINGS

Having decided the areas of further work most likely to achieve our objectives, the results of the work at the mill site can then be discussed with the pupils, with a view to arousing an interest in this further work. The following are examples of discussion points and the possible further work to which these may lead. The page numbers in brackets refer to the section in this handbook where more information is given.

Discussion points	**Further work**
Watercourses	
Why are they in the positions recorded?	Environmental aspects (page 67).
Have we an overall record of the watercourses?	Aerial photography (page 61).
Have the watercourses been altered (by intent or accident) since the mill ceased work?	Effect of later technological developments on environment (page 67);
What effect have the watercourses had on the ecology around the mill site?	Environmental aspects (page 67).
Should more people be aware of what has happened at the mill site?	Communicating information (page 68).
Are the measurements obtained for water flow reasonable?	Improved measuring techniques (page 61).
Are these measurements typical of the flow when the mill was at work?	Consideration of rain-fall records and ground water run-off (page 57).
What is (or was) the effect of the mill dam and the operation of overflow sluices or provision of 'low-shots'?	Effect on river as a navigation – communications in environmental aspects (page 67). Also effect on mills upstream and downstream, and distribution of mills in locality (page 67).
Waterwheels or turbines	
Why was the observed type of waterwheel used at this mill?	Environmental aspects (page 67). Also investigations of efficiency of different ways of obtaining rotary power from water (page 61).
What was the likely power output from the wheel?	Need for more measurements and calculations (page 56).
Was this an effective use of the available water energy?	Investigations on models of different types of waterwheel and turbines (page 61). Other devices using water energy (page 77). Using the available water supply (page 66).

2.10 RELATING PARTICULAR ASPECTS TO THE GENERAL PICTURE

Whatever the particular topics chosen for further work, it is often necessary to relate this work to the overall picture of the activities, such as:

1 general development of water-driven corn mills
2 flour milling and food
3 other uses of waterwheels and turbines
4 other ways of using water energy
5 waterpower and other sources of energy.

General development of water-driven corn mills

The local watermill needs to be discussed in relation to the neighbourhood and also with regard to general developments in the use of watermills. See Sections 1.1 and 1.2.

Flour-milling and food

The development of techniques of flour-milling is given in Section 1.2. The Home Economics Department might cooperate in showing how flour (in bread, biscuits, cakes etc) contributes to our diet, and its relative importance compared with other foods.

Other uses of waterwheels and turbines

Waterwheels were used for many purposes other than corn grinding, even from quite early times as indicated in Section 1.1. References can be found to the eventual use of waterwheels and later turbines for nearly every industrial activity. Some examples of these are given in the following list:

Raw materials and basic processes

(a) For winding from underground mines (see fig 1.8, page 4).
(b) For pumping water from underground mines (see fig 2.51a).
(c) Driving fans to ventilate mines (fig 2.51b).
(d) Powering hammers in iron forges. (See fig 1.5, page 3).
(e) Working bellows for providing the blast in iron smelting furnaces. (See fig 1.6, page 3).
(f) Operating stamps for crushing ore (fig 2.52).
(g) Cutting and polishing marble (this was recorded in 379 AD on the River Ruwer, a tributary of the River Mosel in Germany).

Farming and forestry

(a) Driving barn machinery including threshing machines, turnip choppers, chaff cutters, butter churns.
(b) Driving saw-mills (figs 2.53 and 2.57).

Manufacturing

(a) Driving metal-working machinery, such as cylinder-boring machines (figs 2.54 and 2.55).
(b) Working the scouring runners and barrelling equipment in needle-making (fig 2.56).
(c) Powering paper mills (figs 2.57 and 2.58).
(d) Driving edge rollers in gunpowder mills.
(e) Working bark mills for grinding oak bark for use in tanning hides.
(f) Powering machinery for textile manufacture.

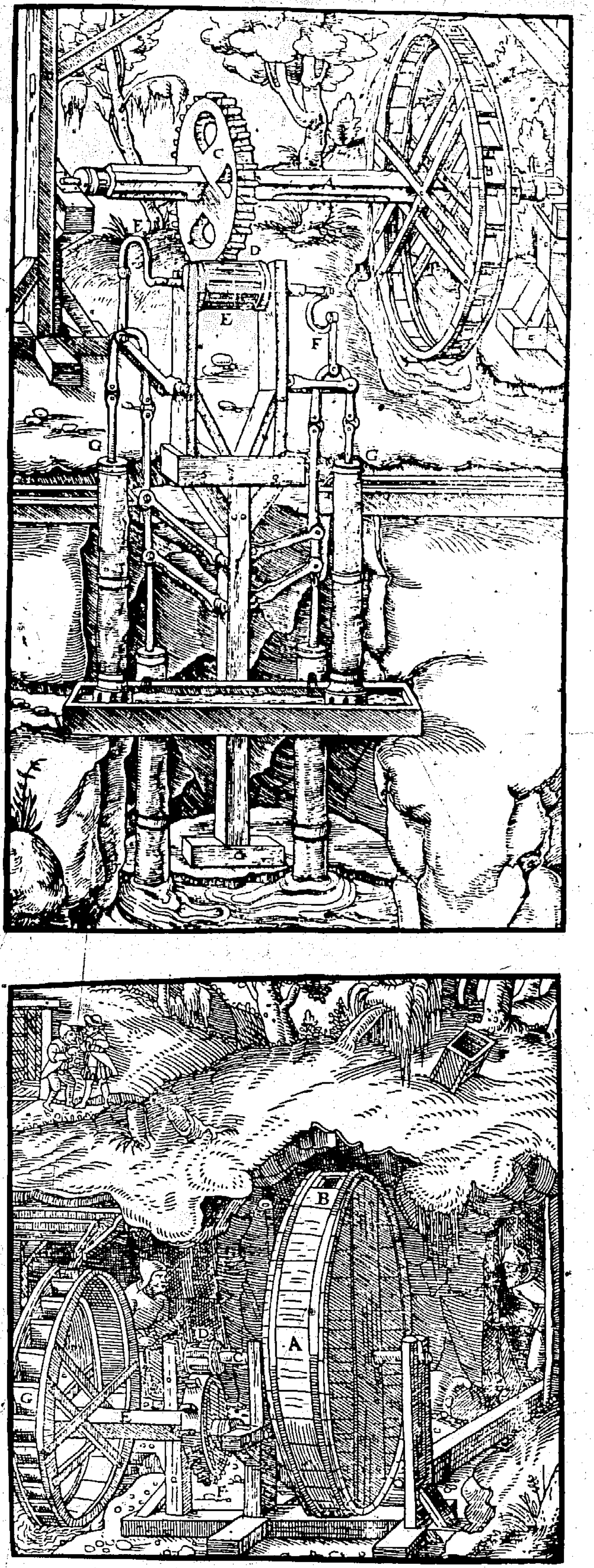


Fig 2.51 (a) Draining a mine in the sixteenth century, with an overshot waterwheel driving pumps to lift the water in two stages.
(b) Sixteenth century mine ventilation using a fan driven by a waterwheel
From *De Re Metallica* by Georgius Agricola, 1556

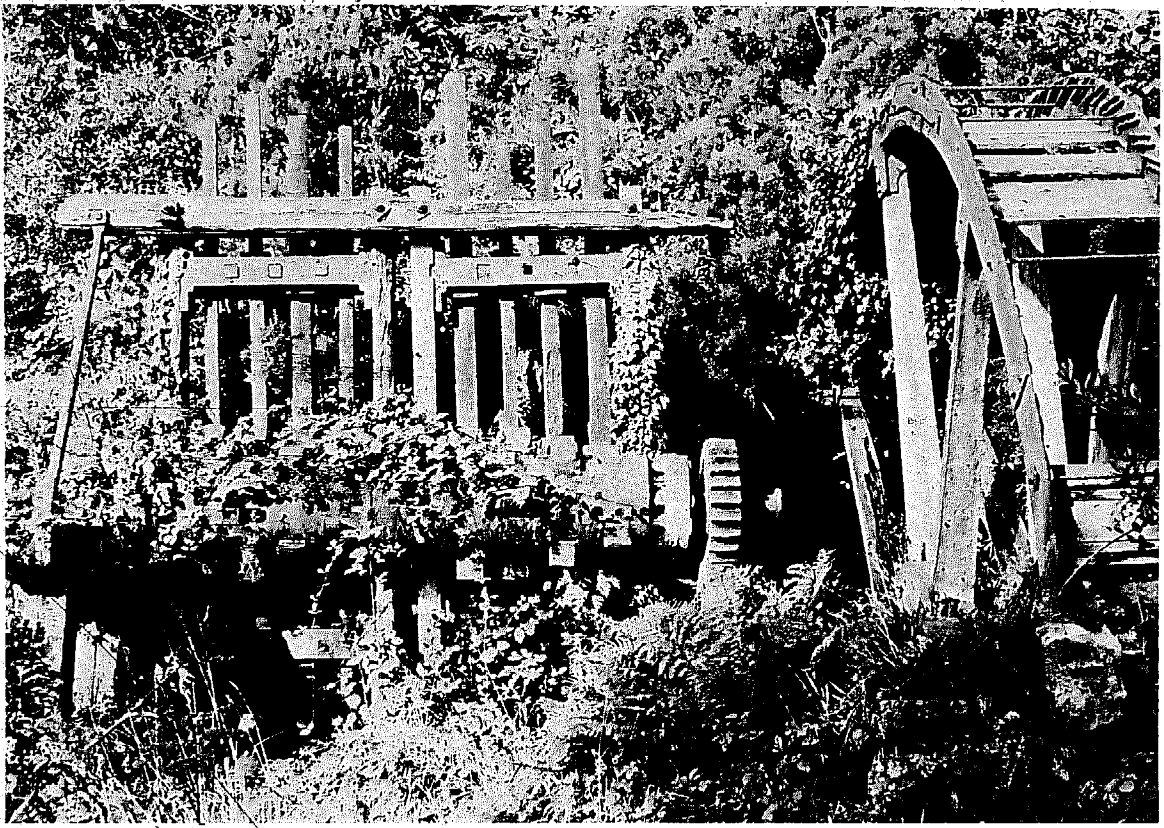


Fig 2.52 Overgrown tin-stamps near St Ives, Cornwall. The waterwheel has wooden spokes and cast-iron shrouds. On the inside of these, the cast guides for the wooden buckets indicate that this was a high breast or pitch-back wheel, even though most of the buckets have rotted away. A spur gear on the wheelshaft meshed with a slightly smaller gear on a cast-iron shaft. This is fitted with protruding cams which engage with the tappets on each of the eight vertical stems, so lifting and dropping the heads onto the ore placed at the bottom of the stamps

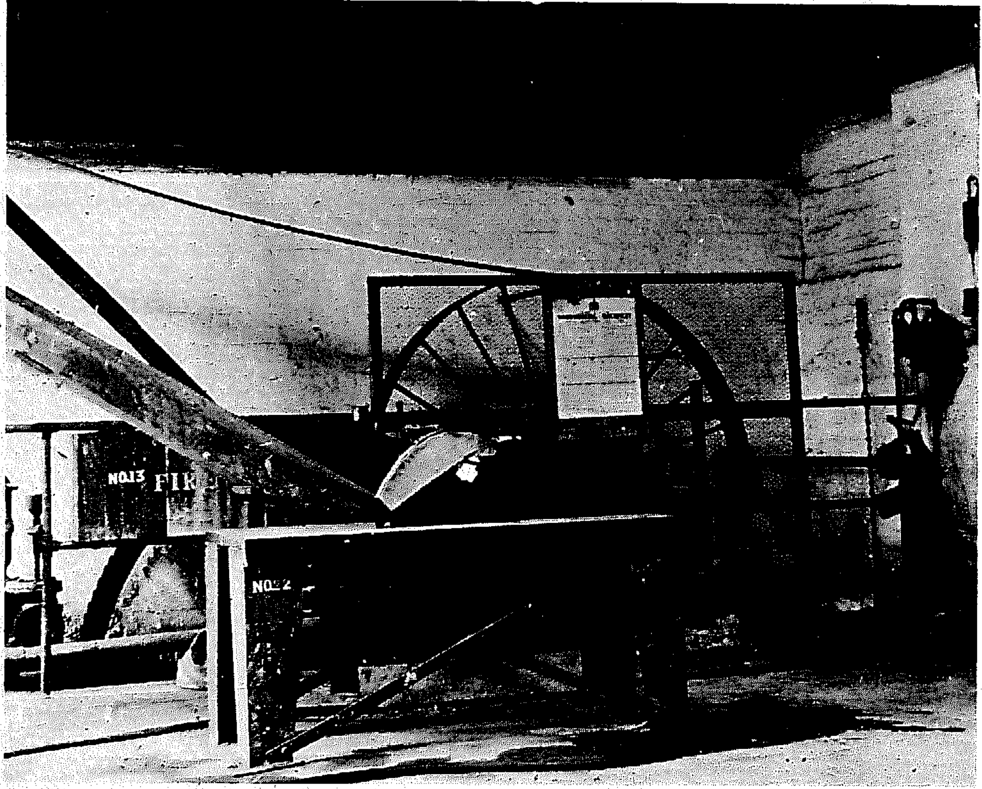


Fig 2.53 A circular saw driven by a waterwheel in the maintenance department of the Cooperative Wholesale Society's fellmongering department, on the River Nene east of Northampton. Since the waterwheel rotates comparitively slowly, it is necessary to obtain a great increase in speed at the saw if this is to function properly. On the waterwheel shaft is a large gear which meshes with a much smaller pinion on the shaft carrying the large belt wheel. The belt drives a smaller pulley on the counter-shaft just off the top left of the picture. The final drive is from a large pulley on the counter shaft to a smaller one on the shaft carrying the circular saw. Thus there are three stages of increasing speed

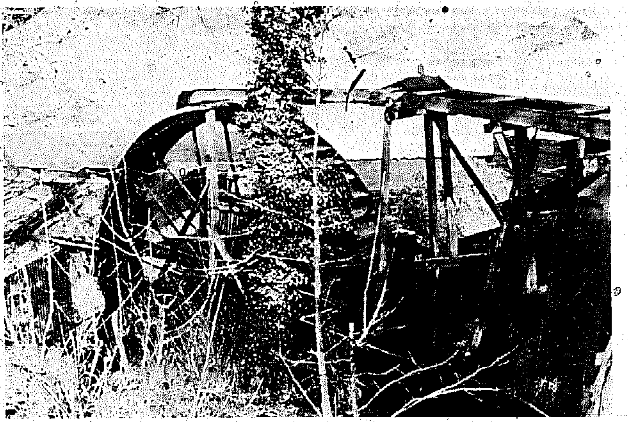


Fig 2.54 An overshot waterwheel, one of several used for driving machinery and blowers for the cupola at Sara's Foundry just off the by-pass to the west of Redruth in Cornwall. Note the high wooden launder bringing the water to the top of the wheel

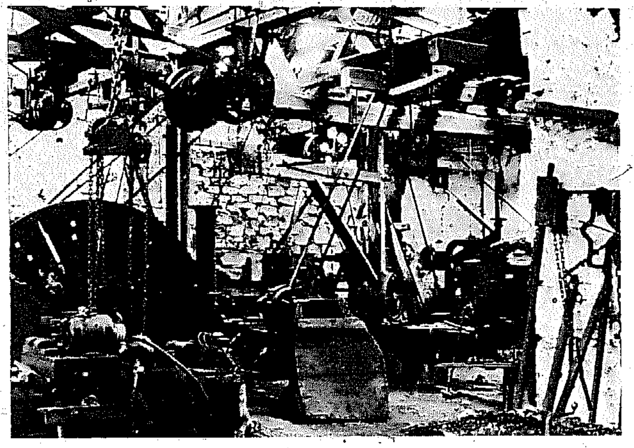


Fig 2.55 Inside the machine shop of Sara's Foundry, showing the overhead line-shafting driven by the waterwheel and the belt drives down to the individual machines

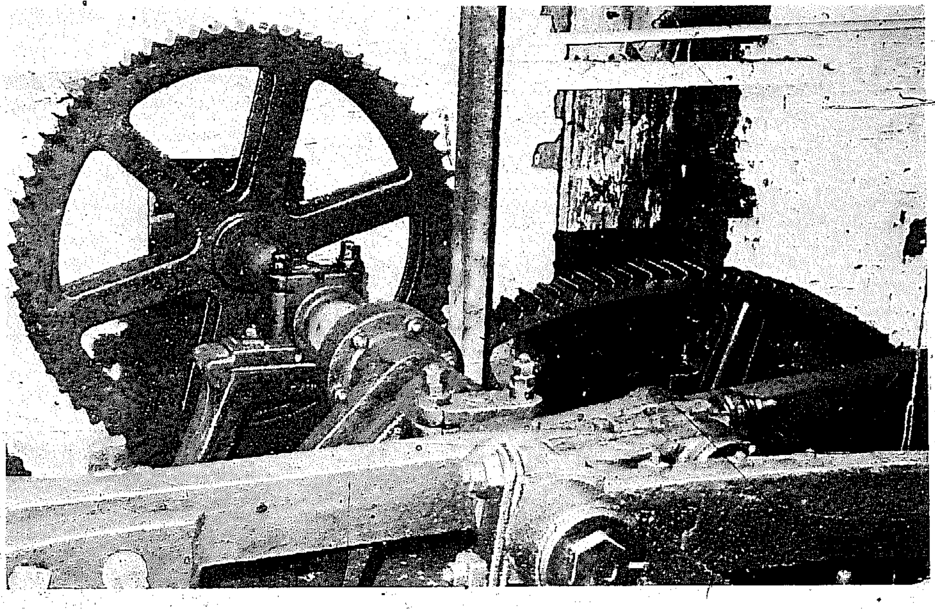


Fig 2.56 The crankshaft at the Forge Mill, Redditch. The drive from the waterwheel is through a large gear wheel in the right background. The connecting rods from the cranks drive rocking frames (on both the left and the right of the crankshaft) operating further connecting rods to give reciprocating horizontal motion to the runners. Under these were placed the bundles of needles together with fine abrasive, all wrapped in heavy grade of sacking, in order to scour the needles

Fig 2.57 Close-up of the first stage of gearing for the sawmill in fig 2.53, showing double helical gearing, which is unusual for a watermill but is probably a relic of the former use of this mill for paper making

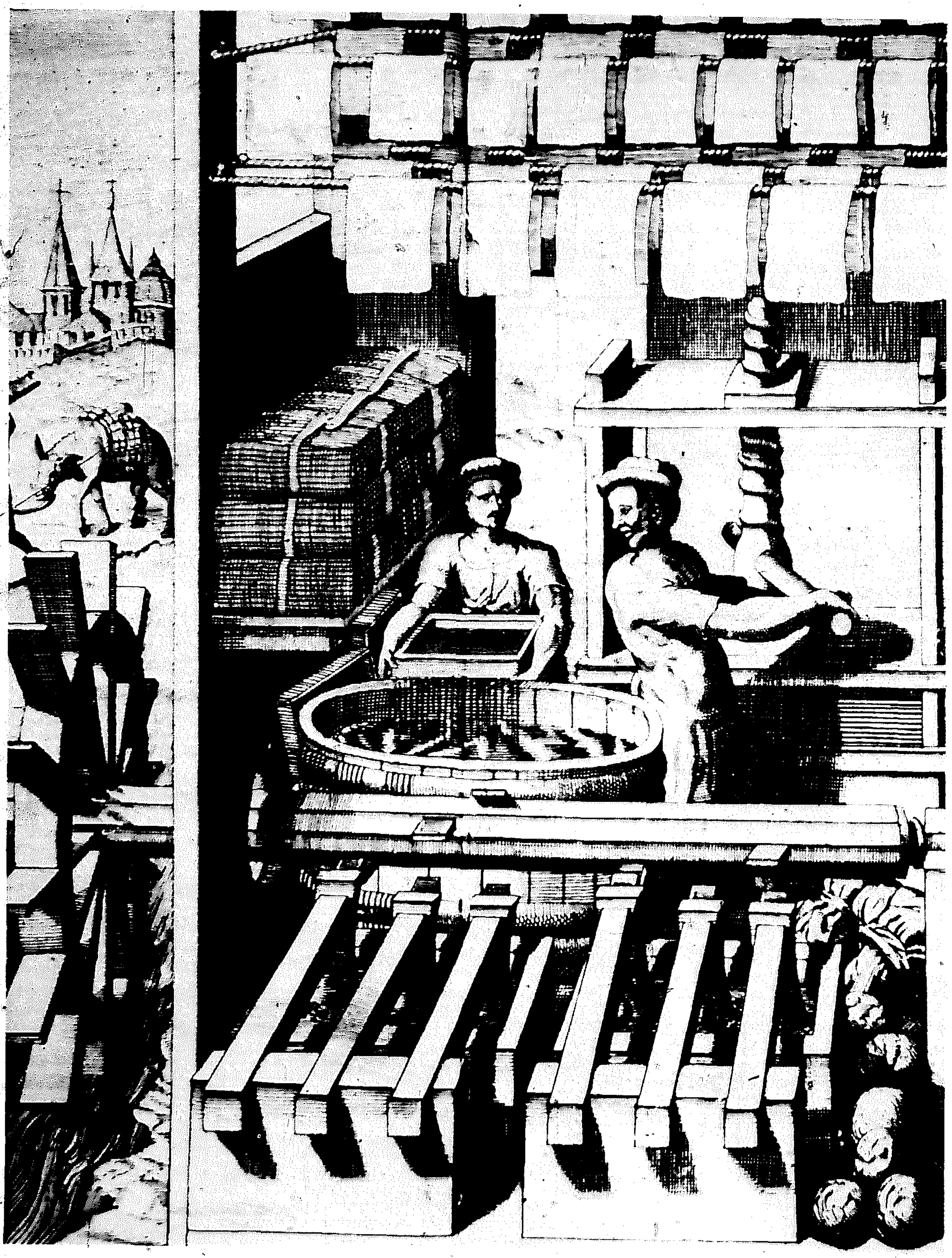


Fig 2.58 A sixteenth century paper mill in which rotted rags and similar cellulose material were placed in the water filled troughs (called 'mortars') and macerated into pulp by a number of iron-tipped wooden stamps actuated by trips on a shaft driven by an undershot water-wheel. After beating, the stuff was placed with water in a vat kept lukewarm and agitated by a pole. The vatman is seen removing a wire mesh bottomed mould after its immersion in the vat. A series of shakes removed the water and caused the fibres of pulp to intertwine. The matted layer formed a sheet of paper which was taken from the mould and laid with other sheets alternately with sheets of woollen felt. This pile was put under a screw press to squeeze out most of the water. The sheets were finally hung on horse-hair covered lines to dry out

From *Kunstliche Abriss, aller handt Wasserkunsten*, by Octavius de Strada, c 1662

(g) Operating fulling stocks in the manufacture of woollen cloths. (See fig 2.59.)

(h) Powering machinery in breweries.

Transport

(a) Pumping water into canals (fig 2.60).

(b) Winding boats up inclined planes.

Trade and commerce

Many warehouses and dockside cranes used hydraulic motors (see page 80) but not waterwheels or turbines supplied from a natural source of water.

Other services

(a) Driving pumps for water supply (fig 2.63).

(b) Hydro-electric schemes, both for private estates and for public supply. The latter is now the main way in which waterpower is utilized (figs 2.61 and 2.62).

Other ways of using water energy

Other uses of waterpower can be categorized into those utilizing:

(a) a natural water supply

(b) water which has had energy given to it from another source.

(a) Using a natural water supply

The flop-jack. This was used in the West Country to lift small quantities of water and operates through the balance of a lever being upset by water flowing into a receptacle on one end of it. (See fig 2.64.) As the lever tilts, the water flows out of the container so that the lever returns

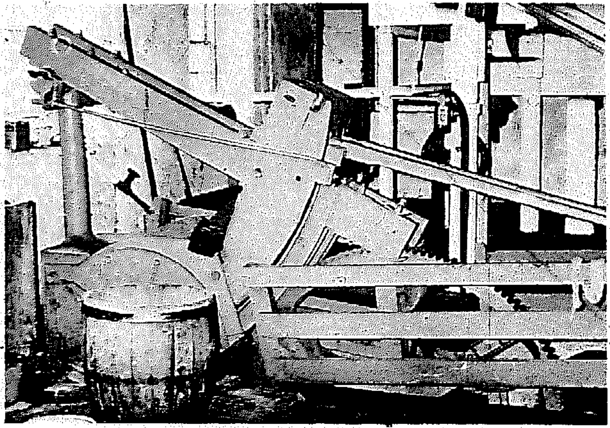


Fig 2.59 Fulling stocks at Otterburn Tweed Mills, Northumberland, driven by a water turbine. Both stocks are supported in the upper position for cloth to be put in the 'box' immediately behind the wooden cask. In use, the two stocks would be lifted and allowed to fall alternately: the tappets for the left-hand stock are on the near side of the toothed tappet wheel and two are visible at approximately the two o'clock and ten o'clock positions. The other stock is operated by tappets on the far side of the toothed wheel, and one can be seen at the twelve o'clock position. Note the steel striker plates, with upturned ends, where the stock comes into contact with the tappets

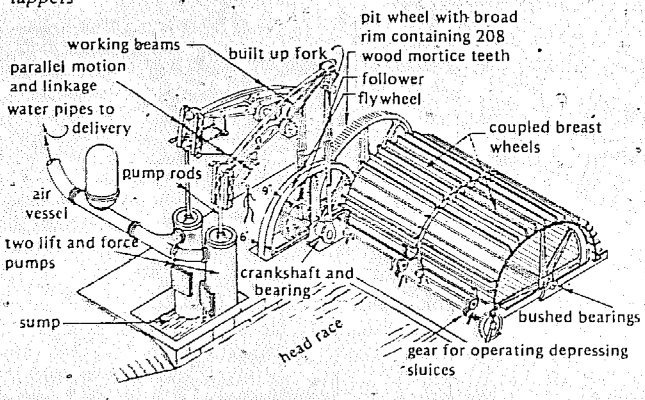


Fig 2.60 Waterwheel driving pumps at Claverton Pumping Station on the Kennet and Avon Canal

Drawing by courtesy of Dr C T G Boucher

Fig 2.61 A small overshot waterwheel driving reciprocating pumps at Nantellan, near Grampound, Cornwall

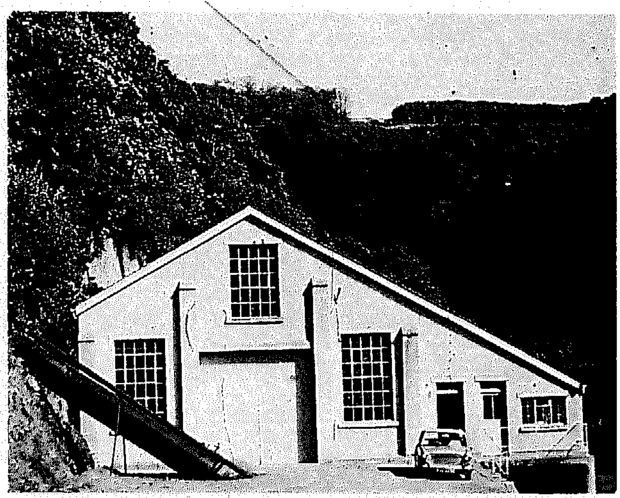


Fig 2.62 Morwellham generating station of the Central Electricity Generating Board. This is on the Devon side of the River Tamar and obtains approximately 20 000 m^3 of water per hour from the disused Tavistock canal via the pipe which crosses in front of the bottom left of the building

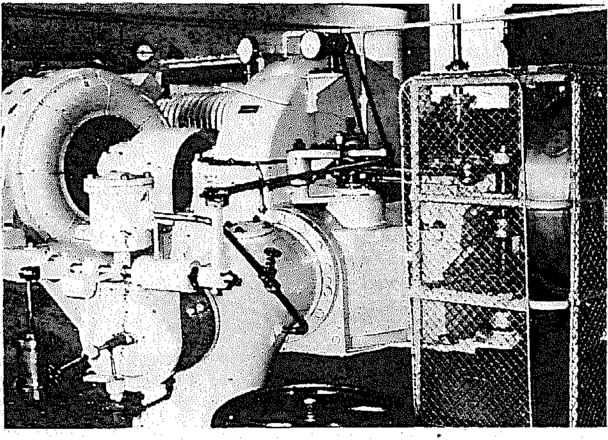


Fig 2.63 Inside Morwellham generating station showing one of the two generating sets. The impulse turbine was constructed by Gilbert Gilkes and Gordon to work with 76 m head of water at 428 rev/min giving 350 kVA from the Crompton Parkinson alternator (left background). The Turgo turbine is within the circular casing in the upper centre of the picture. The water comes onto the wheel through the curved pipe in the left foreground. Speed control is by the governor (on extreme right of picture, within the wire 'cage') and the linkages to the arrangement (left) on the curved inlet pipe adjusting the position of the spear within the nozzle

to its initial position until the receptacle again contains enough water to upset it. Attached to the other end of the lever is a connection to the plunger of a reciprocating pump which is thus worked by the oscillations of the lever. A working model of a flop-jack is shown in fig 2.65.

The hydraulic ram pump. This is another device for lifting water, and is first recorded as the invention of Mr Whitehurst of Derby in 1772, but the Frenchman J M Montgolfier is also attributed with its invention in 1779. It came into general use during the second quarter of the nineteenth century. (The principle of operation is illustrated by fig 2.66.)

On opening the spill valve, the head of water in the feed tank forces the water along the drive pipe into the body of the pump and out through the spill valve (also referred to as a beat valve, pulse valve, or waste valve). After a short interval of time the velocity of the water flow reaches a value sufficient to close this valve. The flow immediately stops and the momentum of the water is converted to an impulsive force which acts on the inside of the pump (ie similar to 'water-hammer', which occurs in a pipe when a stop cock is turned off suddenly).

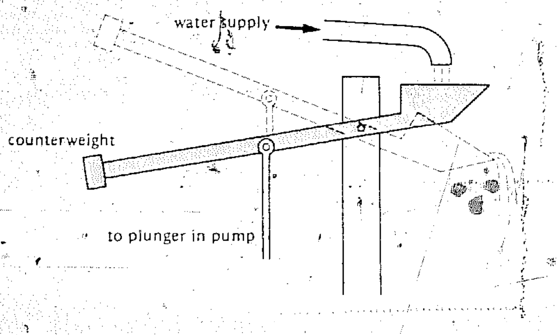


Fig 2.64 Flop-jack

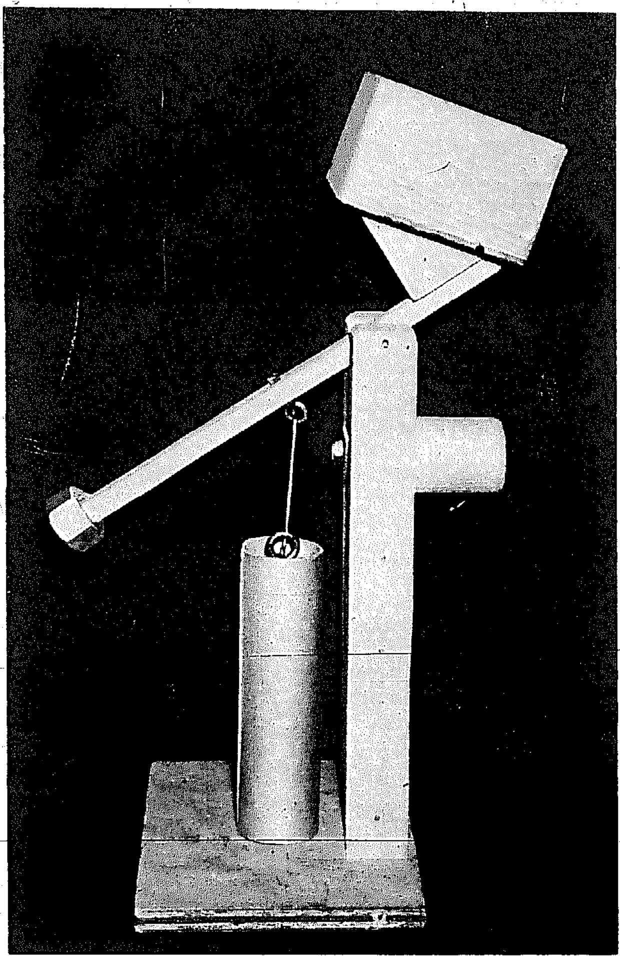


Fig 2.65 Working model of a flop-jack made by pupils of Hayle County Secondary School, Cornwall. With the receptacle on the rocking arm empty, the weight on the other end of the arm depresses that end. As water runs into the receptacle, the latter descends, lifting the weight and the pump piston on the other side of the fulcrum. A stop has been provided on the right of the vertical support to prevent the arm rotating past the point where the weight has sufficient moment to return the arm to the initial position

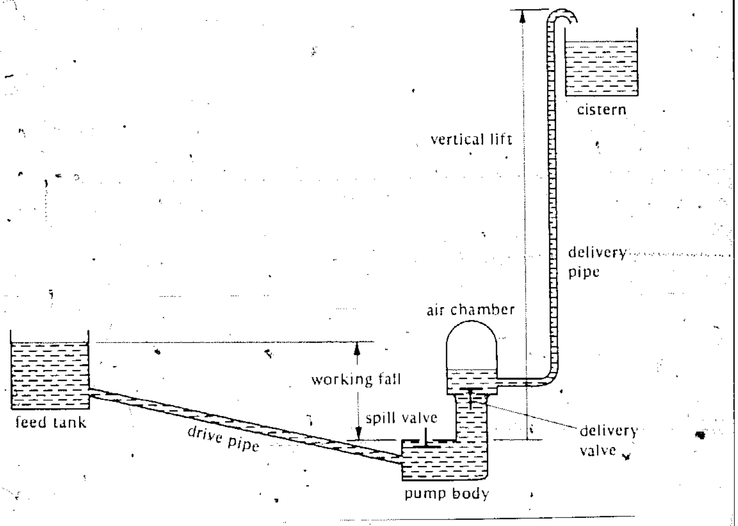


Fig 2.66 Hydraulic ram pump

This force opens the delivery valve and pushes some of the water into the air chamber. The reflected shock wave, subsequent to the sudden closure of the spill valve, causes a slight recoil of the water in the drive pipe, so momentarily decreasing the pressure in the body of the pump. (A demonstration model is shown in figs 2.67 and 2.68.)

This causes the delivery valve to close and at the same time causes the spill valve to open since the atmospheric pressure above it is in excess of the reduced pressure in the body of the pump. The water begins to flow through this valve again and the whole cycle of operations is repeated. Since the only outlet from the air chamber is the delivery pipe, each cycle causes a small amount of water to be forced up to the storage tank, with the air in the chamber serving as a cushion to stabilize the flow.

In practice, the air chambers of hydraulic ram pumps are fitted with a snift valve which admits air into the body of the pump each time the internal pressure falls below that of the atmosphere, ie at each pulse. The purpose of this is to ensure that the air chamber always has a sufficient amount of air to give adequate cushioning to the heavy hydraulic blow caused by the sudden closing of the spill valve. Without the snift valve, the air in the chamber would gradually decrease as the water entering under pressure on each stroke absorbs a small quantity. Since a school-built hydraulic ram pump will usually only be worked for short periods, the snift valve is not essential.

Many hydraulic ram pumps are still in use (see fig 2.69), mainly raising water from a stream to a farm to provide a general water supply, including drinking water for animals, but only rarely for domestic drinking water; to the latter filters have to be fitted.

Since the hydraulic ram is one of the simplest of water machines, it is a very suitable subject for a working model. Successful operation will depend on:

(a) The working fall: a feed tank and drive pipe must be provided and *not* a direct connection from a pressure source, such as a tap, to the ram body.
(b) The length of the drive pipe.
(c) The bore of the drive pipe.
(d) The aperture at the spill valve.
(e) The length of travel of the spill valve (it is advisable to make this adjustable).

Water pressure engines. These were generally similar to reciprocating steam engines, having distributing valves (for regulating the supply and discharge of the water) which were operated by the engine itself, which, once set in motion, continued until it was stopped by cutting off the supply of water.

Water lifts. The simplest kind of water lift consisted of a strong vertical frame, supporting large pulleys at the top. Over these passed chains, their ends on one side being attached to a cage to contain whatever was to be lifted. (See fig 2.73).

The cage moved between vertical guides and strong catches were provided to hold the cage at the higher or lower platforms as required. The other ends of the

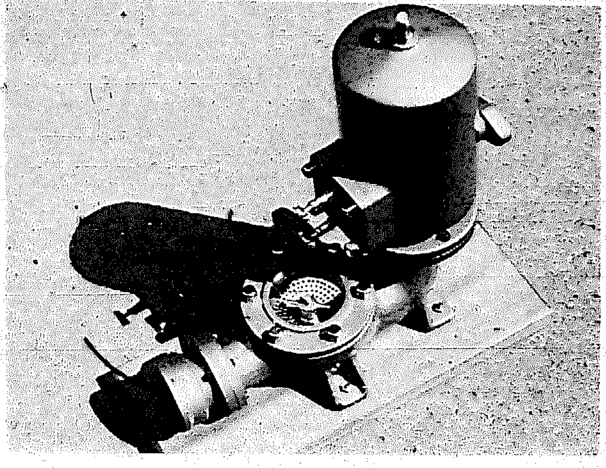


Fig 2.67 A demonstration model of hydraulic ram made by Blakes of Accrington. Water supply is from the left, the perforated cup is at the spill valve and the water lifted is taken from the flanged outlet on the right of the air vessel
Photo by courtesy of John Blake Ltd

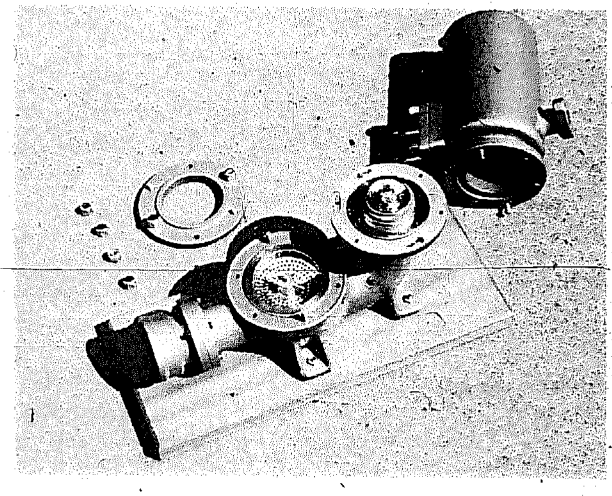


Fig 2.68 The same model, partially dismantled to show the other valve
Photo by courtesy of John Blake Ltd

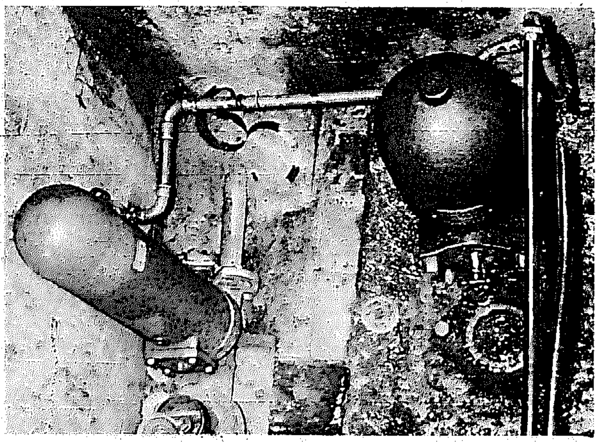


Fig 2.69 Blakes Hydram (right) at work on a farm at Duncote, near the A5, Towcester, Northamptonshire. A disused hydraulic ram by another maker is on the left

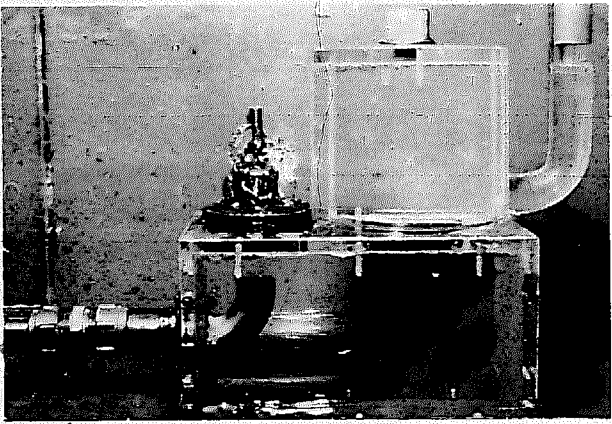


Fig 2.70 A demonstration model hydraulic ram made by T G Jones and S Longstaff of the Education Unit, Lanchester Polytechnic. This was made of Perspex to enable the water flows to be observed. The water is supplied from the left and water is seen passing through the spill valve immediately above the upturned inlet pipe

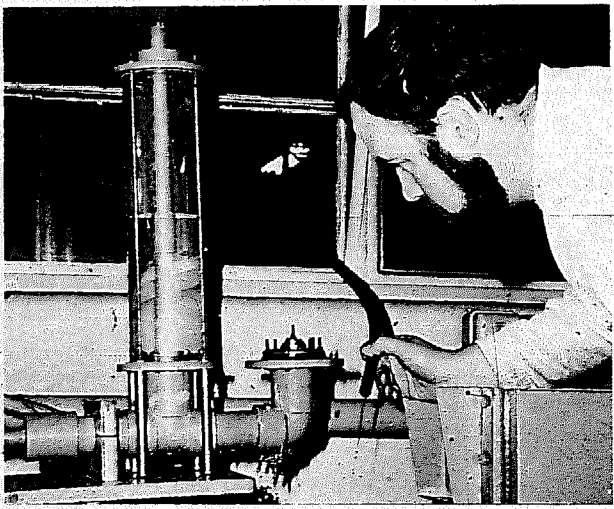


Fig 2.71 Alan Windhaber of Portsmouth Technical High School, with a hydraulic ram made whilst he was working in the Education Unit, Lanchester Polytechnic. This utilizes standard plastics water pipe fittings for the main body of the pump. When supplied with a head of 0.3 m through a 1.2 m long supply pipe, this ram can easily lift water to 2.4 m above

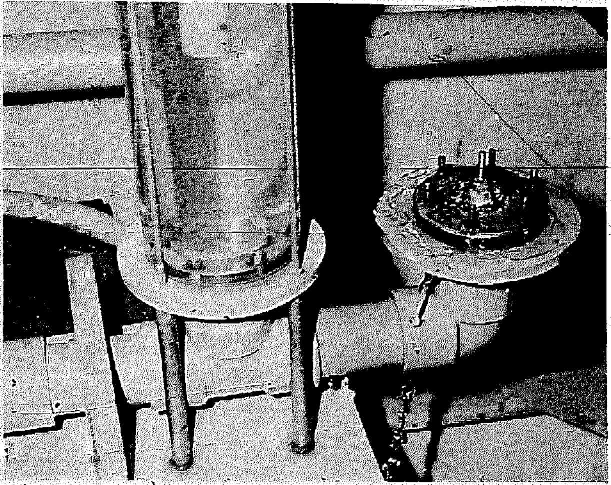


Fig 2.72 Close-up of the valves on the plastics-pipe hydraulic ram

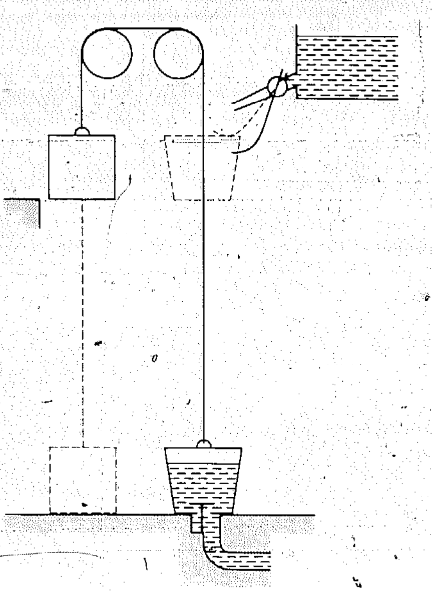


Fig 2.73 Water lift

chains were attached to a water 'bucket', having a valve in the bottom opening upwards, for discharging the water. Sometimes this valve was made self-acting by having its spindle projecting down below the bottom of the bucket so that at the bottom of the descent the spindle struck the floor and opened the valve. A reservoir and spout were provided to fill the bucket when at the upper level. The valve on the spout was in some cases also made self-acting, by causing it to be opened by a weighted lever being lifted by the edge of the bucket as it reached the top of its ascent, held up until the bucket was full, and then dropping to close the valve as the bucket began its descent.

The weight of the unloaded cage was slightly in excess of that of the empty bucket, and the weight of the full bucket was slightly in excess of that of the loaded cage.

Where loads had to be moved both up and down, two cages were used, each fitted with a container for water and connected by wire ropes or chains passing over pulleys at the top. Sufficient water was run into the container of the cage at the upper level to enable the earth's gravitational pull on this combined mass to pull up the lower cage also, with its container empty of water. When the descending cage reached the bottom the water was discharged, whilst at the same time water was run into the other cage now at the top, so that the cages were again able to change places between the two levels.

This is the principle of operation of water lifts used for carrying passengers up and down cliffs at coastal resorts – for example, between Lynton and Lynmouth – and also for inland locations such as Bridgnorth. (See figs 2.74 and 2.75.)

(b) Using artificial water supplies

The smoothness and steadiness of motion of waterpowered machinery, together with requirements for considerable amounts of power for short durations and at long intervals, sometimes led to the equipment being used with the flow and head of water produced artificially, for example by

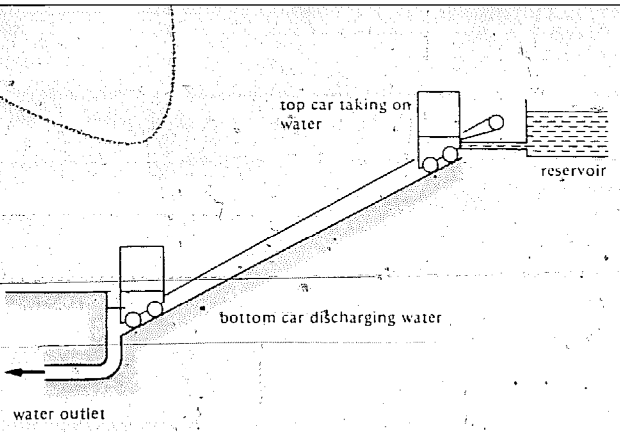


Fig 2.74 Water-operated cliff railway

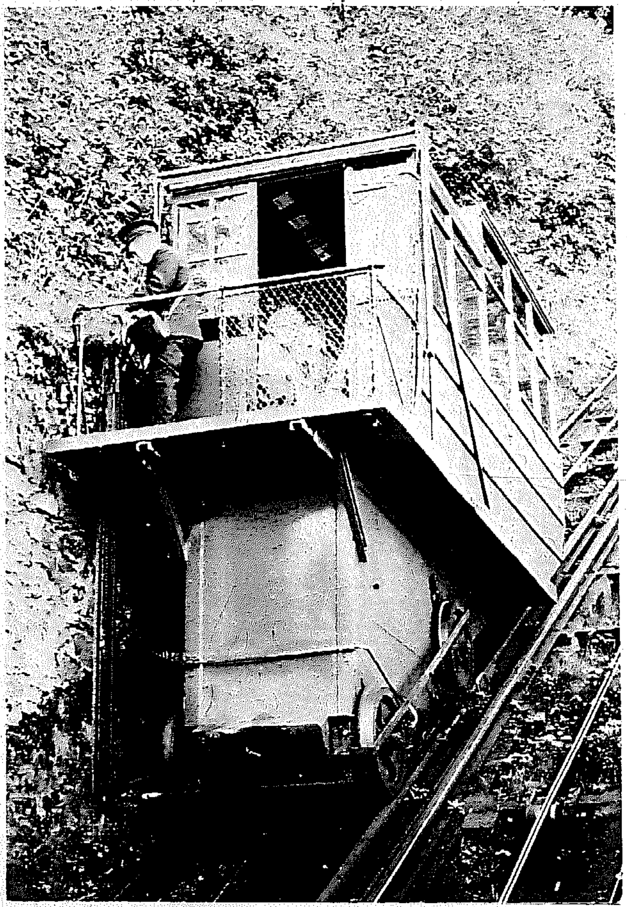


Fig 2.75 Car descending on the water-operated lift from Lynton to Lynmouth

pumps worked by hand in a hydraulic press, or by pumps worked by steam engines as in some hydraulic hoists and cranes.

Water lifts, such as those used for raising barrows of iron ore, limestone, and coke for feeding into the top of old types of blast furnace, were served by storage tanks into which the water was raised by a pump worked by a steam engine. During the intervals when the lift was standing idle, the steam engine was still storing energy by pumping water into the tank. Thus the energy required by the lift working for a total of a few hours each day was distributed, so far as the expenditure of energy of the steam engine was concerned, over the whole twenty-four hours. This could be achieved by a far smaller engine than that required to lift the load directly.

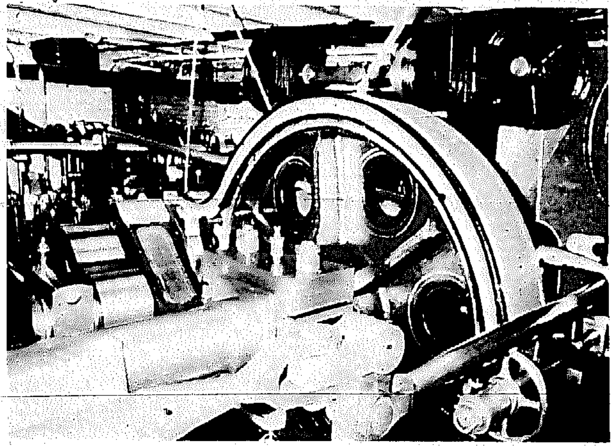


Fig 2.76 One of the large hydraulic motors used to lift the bascules of Tower Bridge, London. These have been in use since the bridge was opened in 1874

Some companies were established to supply hydraulic power which they produced in steam pumping stations and distributed in hydraulic mains to the users.

Nowadays, so-called hydraulic transmissions on vehicles and machines use oil as the working fluid. A great many types of hydraulic motors are produced but on the unit 1 twin spindle milling machine of the System 24 machines produced by the Molins Machine Company Ltd of High Wycombe, small Pelton wheel turbines are used (fig 2.77). These provide compact power for the machine spindles and have an additional advantage that the flow of hydraulic oil is used for heat transfer: the oil from the turbine returns to a heat exchanger in the hydraulic power pack before being circulated back to the turbine under pressure.

Waterpower and other sources of energy

In earlier times, waterpower was used because it was one of the easiest sources to harness to provided mechanical energy. Subsequently, we find many other energy sources being utilized, for example wind, to provide mechanical power; burning of fossil fuels, to give heat (eg on domestic fires, for cooking, for smelting and treatment of metals and other processing of materials, and to give power, either in producing steam to power steam engines or turbines, or later to burn in internal combustion engines; and nuclear fuels.

With the appreciation of the advantages of electrical transmission, power generation could be concentrated away from the user and conveniently transmitted to where it was needed. This enabled waterpower resources in remote places to be utilized. The contribution of hydro-electric generation to the total production of electrical energy is shown by table 3 compiled from Basic Statistics of Energy in Statistical Bulletins of Organization for Economic Cooperation and Development.

The figures in table 3 show that although the consumption of electrical energy increased by 190 per cent, the proportion produced by hydro-electric generation decreased from 39 per cent to 27.5 per cent.

In this country, hydro-electric generation contributes a very small proportion of the total energy consumed, as shown in fig 2.78 which also shows the contribution of

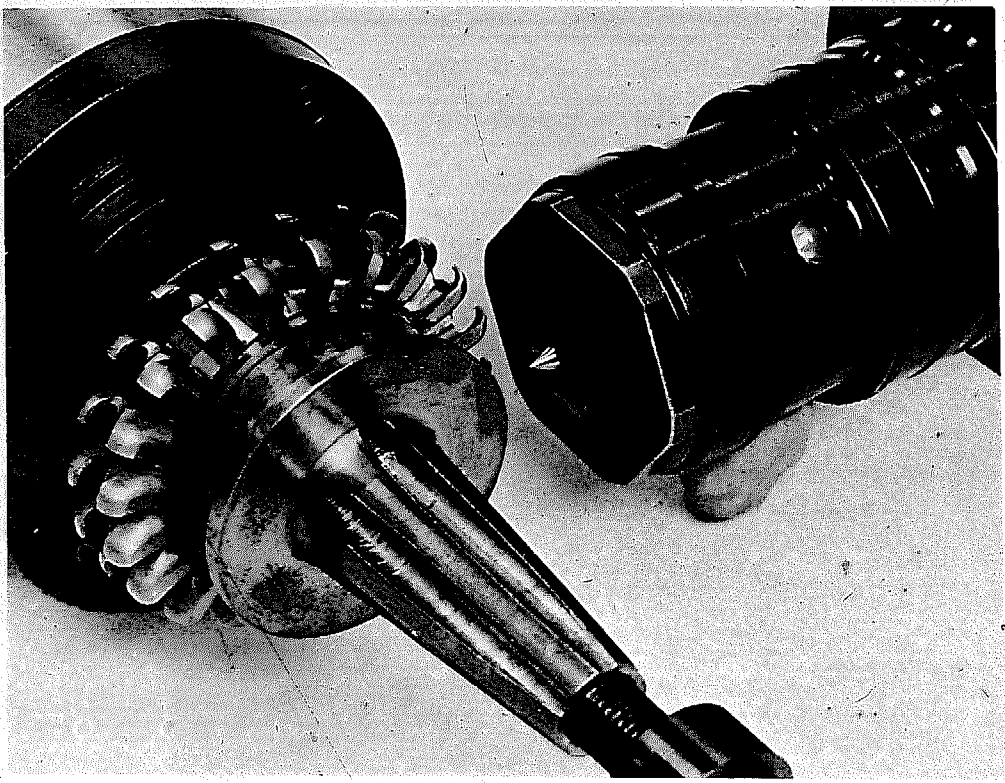


Fig 2.77 Pelton wheel turbine used on a twin spindle milling machine in the Molins System 24. The turbine uses oil and gives a maximum output of 11 kW at 24 000 rev/min. The oil flow through the spear valve (shown on right) is 0.16 m³ at 140 kg/cm²
Photo by courtesy of Molins Machine Company Ltd

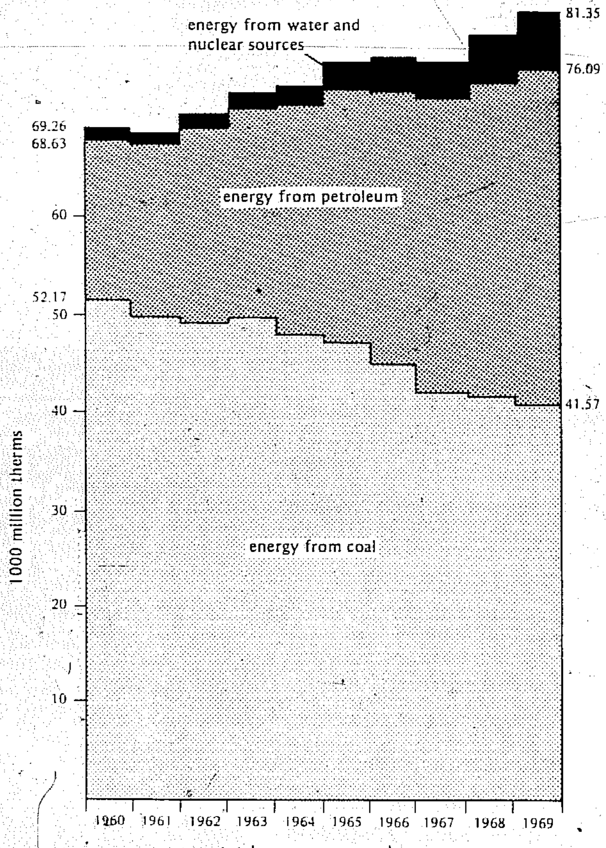


Fig 2.78 Energy produced in the United Kingdom

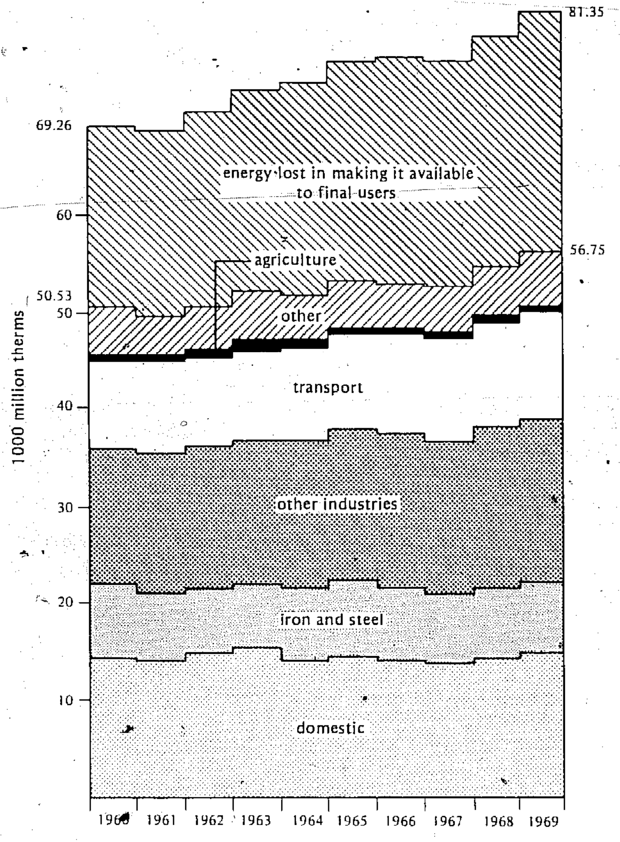


Fig 2.79 Energy consumed in the United Kingdom

Table 3

Year	*Total electric energy produced (billion kW hours)*	*Hydro energy produced (million kW hours)*
1950	769.1	297.6
1951	856.5	323.4
1952	915	343.1
1953	996.6	350
1954	1066.3	371.3
1955	1201.7	393.9
1956	1307.7	421.7
1957	1377.3	439.4
1958	1424.2	483.2
1959	1552.5	493.4
1960	1684.1	536
1964	2220.9	608.1

other sources of energy. Unfortunately, in utilizing the energy some is lost in transforming it to a convenient form for supply to the final user. For example, there are energy losses at each transformation of energy in burning a fossil fuel to raise steam to power turbines driving electrical generators which supply electrical energy via transmission lines to industrial and domestic users. Fig 2.79 shows the total energy consumed by final users (indicating the losses from the total energy consumed on the previous figure). It also shows the consumption by the main categories of user.

Since the demand for energy is always increasing, and consuming the reserves of fossil fuels, it seems that eventually it will be impossible to supply the energy required, unless:

1 mankind makes more effective use of the available energy resources, and

2 the energy at present being obtained from fossil fuels is obtained from other sources, such as waterpower.

2.11 WATERMILL SURVEY QUESTIONNAIRE

1 Schedule

Name of mill: Near:

Parish: County:

Ordnance Survey grid references:

River or tributary:

Name and address of owner:

Miller (present or last known):

Occupier of site (if not miller):

2 Site

How is the mill supplied with water:

(a) on a natural watercourse?

(b) by a mill-pond? Approximate area:

(c) how long is the mill-race or leat?

(d) where does the leat leave the natural water course?

What are the by-pass arrangements for diverting excess water?

How does water flow away from the mill:

(a) type of tail-race?

(b) length of tail-race?

(c) where does the tail-race rejoin the natural watercourse?

If the mill is situated by a public road, to where does this lead?

From .... to ....

If not on a public road:

(a) with which public road does the track from the mill connect?

(b) how far is the mill from a public road?

(c) what public right(s) of way is/are there to the mill?

Are there outbuildings on the site (eg stables)?

3 Mill house

Does the mill house adjoin the mill? YES/NO

If YES, what connections are there between the mill and mill house?

If NO, what is the position of the mill house in relation to the mill?

Details of mill house:

number of storeys

materials of constructions;
walls:
roof:

special features:

dates or inscriptions:

4 *Mill structure*

Walls:
materials: special features:

Floors:
number: materials:
means of support:
(It is useful to make a sketch showing which machines and equipment are on each floor)

Roof:
framework: design/shape:
covering materials:

Lucam:
position: materials:

Structural alterations since date of erection:

Datestones or other inscriptions:

Position of datestones etc. :

5 *Water power*

Is mill equipped with waterwheel(s) and/or turbine?

If equipped with waterwheel(s),

number of wheels:

type of wheel:
undershot/poncelet/low breast/breast/high breast/pitch-back/overshot

Located internal/external to building

Protection afforded: covered/partly covered/exposed

Size of wheel:
diameter: width:

Arms (or spokes):
numbers type/section: material:
method of fixing to wheelshaft: compass arm/clasp-arm/other:

Braced/unbraced wheel:

Rims:
material: depth:
number of sections:
method of attaching floats or buckets:

Floats/buckets:
number: material:
type: open/closed/ventilated shape:

Inscription of wheel on....................

Position of inscription:

Wheelshaft:
section:
cross-section dimensions: length:
material: outer bearing: pit bearing:

Sluice, or shut:
type: method of control:

If equipped with a turbine:
type: maker: method of control:
position of control: diameter of driving shaft:

6 *Transmission*

How are stones driven: underdrift/overdrift?

What is the arrangement of the transmission:
through upright main shaft/through layshaft/others.........
(A sketch of the transmission arrangement is useful.)

Pit-wheel: type (spur/bevel/other):
material: construction:
number of arms: fixing to wheelshaft:
overall diameter: number of teeth or cogs:
material of teeth or cogs:

If upright main shaft arrangement:

(a) Upright shaft:
material:
section: cross-section dimensions:
length:
top bearings: foot (thrust) bearing:
inscriptions:

(b) Gears:

	Wallower	*Great spur wheel*	*Stone nuts*	*Crown wheel*
Material				
Construction				
Fixing to shaft				
Material of teeth				
Number of teeth				
Width of teeth				
Overall diameter				

If layshaft arrangement:

(a) Layshaft:
material:
diameter: length:
position of bearings:

(b) Gears

	Pinion on layshaft	*Intermediate gears meshing with*		*Bevel gears on layshaft*	*Stone nuts*
		pit wheel	*pinion on layshaft*		
Material					
Construction					
Fixing to shaft					
Material of teeth					
Number of teeth					
Width of teeth					
Overall diameters					

Method of throwing stone nuts out of gear:

Machine shaft:
material:
diameter: length:
position of bearings:

If driven from crown wheel (in upright main shaft arrangement), pinion on machine shaft:
material:
number of teeth or cogs:
overall diameters:

[illegible] on layshaft, pulley taking drive
material: diameter: face width;

	Pulleys on machine shaft:				
	1	2	3	4	5
Machine being driven					
Material					
Diameter					
Face width..........................					
Construction					
Fixing to shaft					

7 Mill-stones

Number of pairs of stones:
Type (or material):
Outside diameter: Diameter of eye on
Mounted on hurst: YES/NO
Balance weights fitted to runner stone: YES/NO
Inscriptions on stones:

Stone covers:
material: shape:
size, height: diameter or across flats:

	Horse	*Hopper*	*Shoe*
Material			
Length			
Width			
Height			

Is bell alarm fitted?

How is feed to stones controlled?

Governors:
Type: How driven:
Does governor control distance between stones or flow of water onto wheel? (A sketch of the levers and linkages between governor and what it controls, is useful.)

8 Sack hoist

Type:

Method of engaging/disengaging:

(It is useful to sketch the arrangement and also the way (pulleys in roof etc) by which the hoist chain is taken from the hoist drum to the lucam or to above the trap doors in the mill)

9 Machines (eg wire machines, grain cleaners etc)

Type:

Number:

How driven:

10 Auxiliary power

Type: Make: Approx horse power or kW:

How is drive connected to the mill-stones and other machinery?

3 Water turbines

The demand for more power in nineteenth century Britain was largely satisfied by the use of steam engines, helped by the availability of cheap coal. The situation was very different on the Continent, particularly in France where there were vast water-power resources and it was in that country, early in the nineteenth century, that the name 'turbine' originated (based on the Latin *turbo:* 'I spin'). At first the term seems to have been generally applied to any vertical-shaft water-driven device, but in time 'turbine' came to signify something different from the waterwheel, although it is difficult to give a rigid definition. The following list shows the normally accepted differences between turbines and waterwheels:

- Turbines occupy a much smaller space.
- Turbines rotate at high speed so that often no intermediate gearing is required.
- Some turbines (ie reaction type) can work under water.
- Turbines can be made to work equally well under large and small heads of water.
- Efficiencies of turbines are much higher (in excess of 60 per cent).
- Turbines can be made to give far greater power than is practical with waterwheels.

There are two main types of water turbine:

1 *Reaction turbines,* where the pressure (or potential) energy in the water at the inlet is converted to velocity (or kinetic) energy as the water flows over the vanes of the wheel or 'runner'. All the water passages of a reaction turbine are full of water.

2 *Impulse turbines,* where all the energy of the water is converted into velocity before entering the wheel (by emerging through a restriction such as a nozzle or guide vanes). Impulse turbines run only partially filled with water.

Some turbines are hybrids (or transition types) in that they work partly by impulse and partly by reaction.

3.1 EARLY TURBINES

Barker's Turbine

As early as 1740, Dr Robert Barker, a member of the Royal Society, had invented a reaction waterpower device There is considerable doubt as to whether Barker's Mill (fig 3.1) was ever put to practical use because of its low power output. However, a description of a mill at Nörten, near Göttingen, Germany, driven by a similar device conceived by J A Segner (and hence known as Segner wheels) was established in 1750. Almost a hundred years elapsed before the principle of the invention was effectively used in Whitelaw's 'Scotch' turbine (see page 87). However, Barker's Mill gave mathematicians and scientists almost endless scope for argument about the theory of its working. The Swiss mathematicians Leonhard Euler and his son Albert investigated its action and claimed optimistically that they had discovered how to make hydraulic reaction machines which were able to produce 'the whole effect' of which water was capable. Because of some errors in their conclusions, no practical turbine resulted from their work.

Fourneyron's turbine

Early in the nineteenth century, the French Societé d'Encouragement pour l'Industrie Nationale offered a

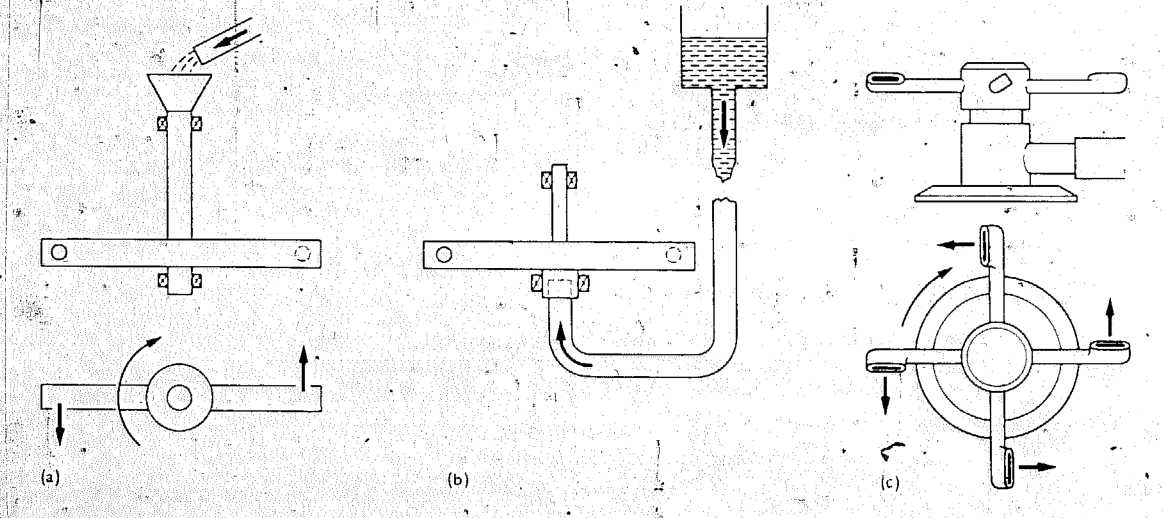


Fig 3.1 (a) The principle of Barker's mill, c 1740, (b) Barker's mill as improved by M L'Abbé Pupil c 1775. By introducing the water to the rotating arm from underneath, it was possible to use a head of water much greater than the height of the rotating vertical tube in (a), (c) Modern version of Barker's mill, as used for lawn sprinklers

prize of 6000 francs (about £250) to the inventor of a machine which could generate much greater power than the existing waterwheels. At that time, there were in France numerous examples of horizontal waterwheels which were a considerable improvement on the primitive 'Greek' or 'Norse' mills described earlier (page 10) and were of two basic types: roue volant, fig 3.2a, and roue a curves fig 3.2b.

By this time the mathematical and scientific arguments had established that, to obtain maximum efficiency, the water should enter the wheel without any turbulence and leave with only sufficient velocity to get it clear of the wheel. Experimenting with this principle, Benoit Fourneyron built an outward flow turbine (the water entering at the centre and escaping at the circumference) with a ring of stationary guide vanes, curved in the opposite direction to the vanes of the rotating wheel. The turbine was erected at Pont sur l'Ognon in 1827 and Fourneyron won the 6000 franc prize. His turbine is shown in fig 3.3.

There seems to have been some prejudice against Fourneyron's turbine, and it is not until 1834 that we find record of his next machine, to blow an iron furnace, using a fall of only 18 cm to give 5–6 kW at efficiencies varying between 65–70 per cent. After this, his turbines were built to work on larger falls between 19 m and 43 m. In 1837 he installed a 42 kW turbine, with a runner only 0.4 m diameter rotating at over 2000 rev/min to drive a spinning mill. Subsequently, he built a great number of turbines of this type for many parts of the world. The design was used in the USA and was the basis of the turbines designed by

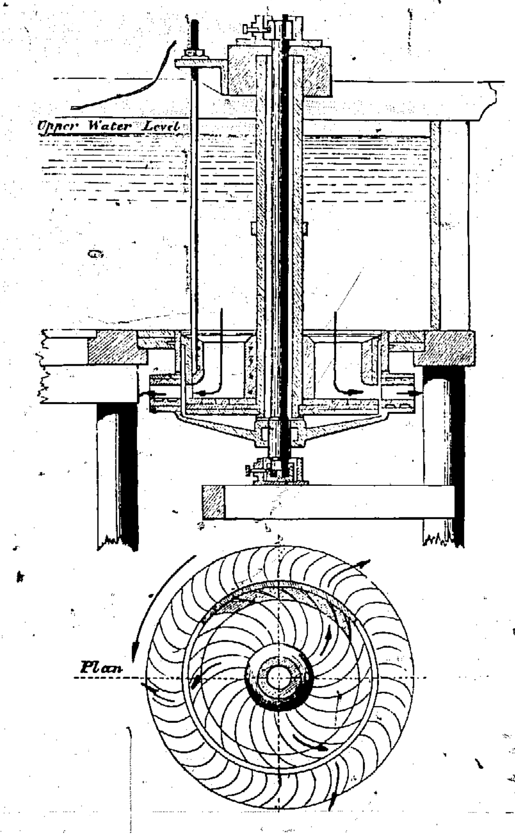


Fig 3.3 Fourneyron's turbine built on the outward flow principle

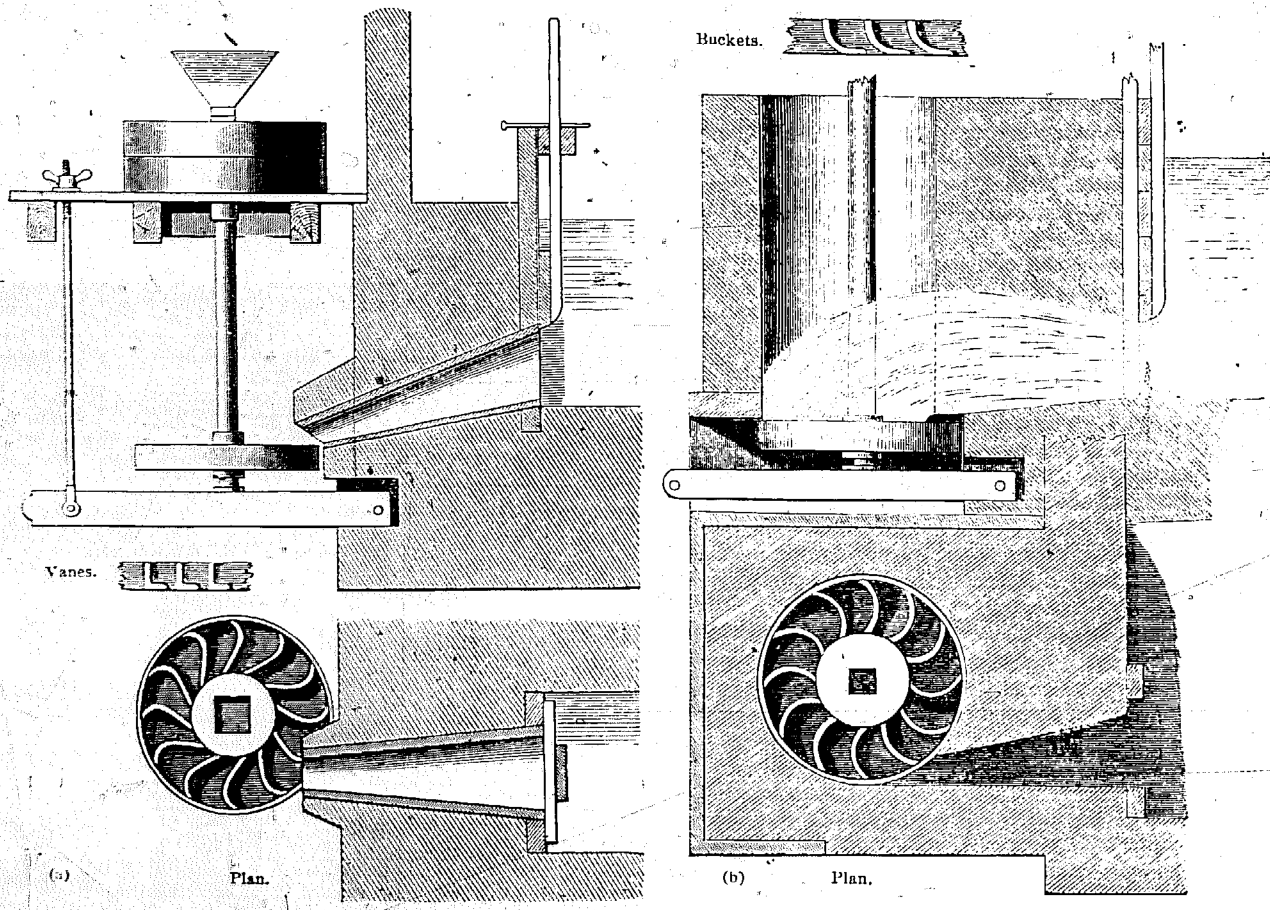


Fig 3.2 (a) Roue volant; (b) roue a curve

From *On the power of water to turn mills*, by J Glynn, 1853

Mr Williams Cullen and made by Mr McAdam of Belfast, one of which, with a head of 14 m, was claimed to give 93 kW with an efficiency of 92 per cent. It is generally considered that the Fourneyron-type turbine could achieve efficiencies of up to 75 per cent with a head of water of anything from 0.3 to 105 m, but only when delivering full power.

A contemporary account of a Fourneyron turbine at work expressed 'surprise that the small wheel did not burst in the spiral masses of water which rushed from it and threatened to destroy the surrounding walls'. In 1844 Boyden, having realized that these 'spirals' were wasting a lot of energy, which could be giving more power, improved the efficiency by about 6 per cent by adding a diffuser. This was an annular casing around the outside circumference of the wheel. This casing had a cross section increasing towards the outlet so that some of the kinetic energy of the water leaving was converted into pressure energy, so increasing the effective head. In the USA, the Fourneyron-type machine was usually known as the Boyden turbine.

Whitelaw's Scotch turbine

Earlier in 1839, James Whitelaw had patented another outward-flow reaction turbine which was an improved version of Barker's Mill (fig 3.4).

In Whitelaw's improved version, the arms were bent to an S-shape following an Archimedian spiral such that, when the turbine was rotating at the speed to give the highest efficiency, the water flowed outward in a straight path. The water flowed into the arms from underneath, as shown in fig 3.4, with the following advantages:

- The weight of the rotating parts could be arranged to balance the hydraulic upthrust (and to avoiding trouble with thrust bearings).
- Far greater heads could be utilized than if the water was delivered into a central tube, as with the original Barker's mill.

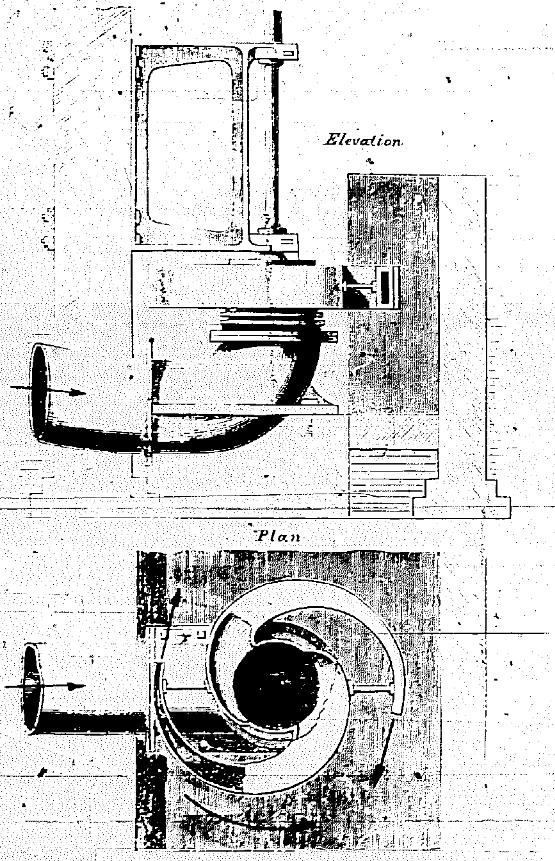


Fig 3.4 Whitelaw's Scotch turbine

Whitelaw also provided his turbine with an effective method of governing. To each end of the rotating arm were fitted movable deflector plates. These were held clear of the orifices by means of springs. Each plate had a weight attached to it, and if the speed rose too high the centrifugal force on the weight overcame the force exerted by the spring and the deflector moved across the orifice, so reducing the effect of the jet, and the speed would decrease. Whitelaw's first turbine was installed at Nethercraig near Paisley and developed only a few horse power, but the second, at Greenock in 1840, developed 45 kW at 90 rev/min when working under a head of 9 m. The cost was given as £500 compared with £1700 for a conventional waterwheel of the same power.

The efficiency claimed was 83 per cent, but this was challenged from America where, in 1830, a Mr Calvin Wing was supposed to have made a turbine almost identical to that of Whitelaw, giving an efficiency about the same as that of an undershot waterwheel. It seems that Whitelaw's turbine was a mediocre, even if interesting, design, and that the number built in the next fifteeen years or so was a tribute to the character and salesmanship of its inventor rather than to the effectiveness of the turbine.

The outward-flow turbine has two major disadvantages:

- It is inherently unstable (as the water flows outwards it enters regions of successively increasing volume).
- It is difficult to govern (to keep a constant speed) particularly when not fully loaded.

3.2 OTHER TURBINE DEVELOPMENTS

This led to the development of turbines using axial flows and inward flows. Poncelet proposed an inward-flow radial turbine in 1826 but the type did not become practical until twelve years later in New York (see Samuel Howd, next column). In 1837 Henschel proposed an axial flow turbine and was followed by the Jonval turbine of 1843 and later, the Fromont turbine see figs 3.5 and 3.6). The water flowed down through a fixed 'wheel' of curved blades on to the moving blades of the 'propeller' below. (The term 'propeller' was used in the Official Catalogue of the Great Exhibition of 1851, and this type was the forerunner of the modern propeller turbine and the subsequent Kaplan turbine – see page 93.)

At this time, the so-called tub-wheel was in use in America. This was virtually a Norse-type waterwheel, completely surrounded at its periphery with a 'tub'. The wheel was placed at the bottom of this and the water entered at the top. By fitting it with a cover containing guide passages, the tub-wheel became essentially a Jonval turbine.

In these axial flow machines it was possible to divide the stationary 'wheel' into concentric compartments, so that for speed regulation at low speeds the compartments could function separately. The Jonval turbine was well suited to the conditions of large quantities of water under low or medium heads that were then being exploited in Europe and America (where it was introduced in 1850).

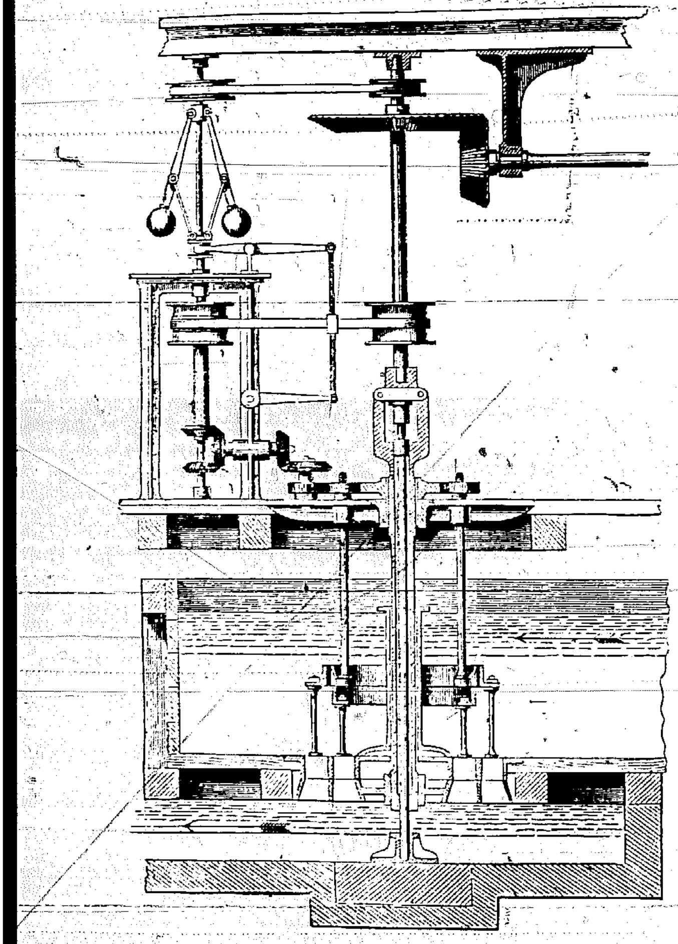


Fig 3.5 Fromont turbine, with 2 m diameter, fixed, upper wheel, and giving 40 kW. The governor (upper left) controls, through gearings, rings, and rods, the position of the sluices in the openings in the fixed wheel of the turbine

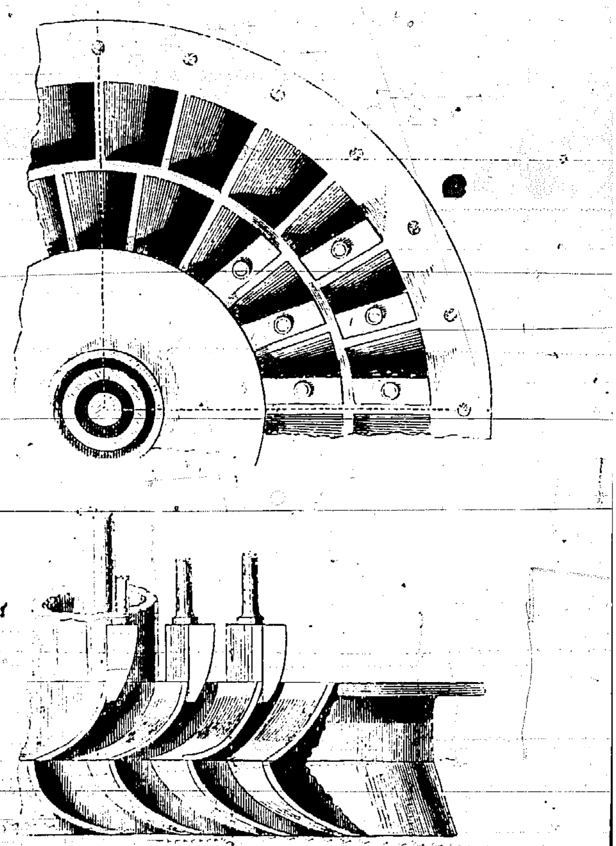


Fig 3.6 Part of the Fromont turbine showing six of the forty-two sluices used to control the amount of water passing through the turbine

Centre vent turbines

In 1838 Samuel B Howd of New York State took out a patent for an inward flow turbine (usually referred to nowadays as a 'centre vent' turbine). It was obviously designed for cheapness, with guide-vanes of wood and no provision for speed regulation. J B Francis in 1849, introduced a modified form by carefully designing the stationary guide vanes and the runner blades to give shockless entry to the runner and minimum velocity in the water leaving it. See fig 3.7.

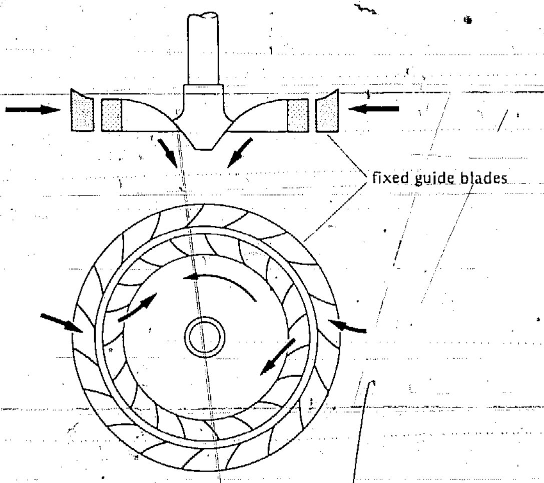


Fig 3.7 Arrangement of 1849 type of Francis centre vent' turbine

Vortex turbine

Almost at the same time, James Thomson (professor of engineering at Queen's College – now Belfast University) introduced his *vortex turbine*, for which he was granted a patent in December 1850. This turbine (see figs 3.8 and 3.9) had many novel features, most of which have been incorporated in designs of turbines produced during the following hundred years.

The features included:

1 Movable guide blades to maintain a good efficiency with flows of water much smaller than that for which the turbine was designed. The guide blades were pivoted near their inner ends so that they were approximately in balance. The pivots were extended through the casing and coupled together so that all the guide vanes could be adjusted together. This adjustment was effected either by hand or by an automatic governor. Later, the whole arrangement of pivoted guide vanes became known as a *wicket gate.* See fig 3.10.

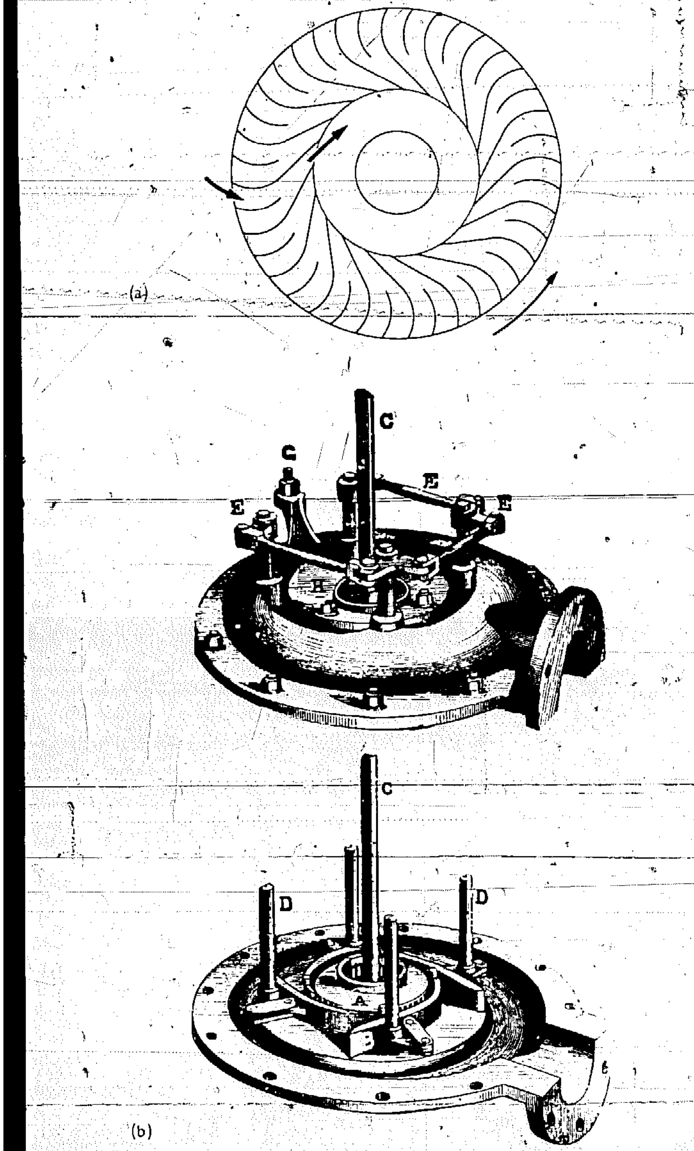


Fig 3.8 Thomson vortex turbine. (a) Principle of operation, (b) contemporary illustration

From Gilbert Gilks and Co Ltd catalogue, c 1895

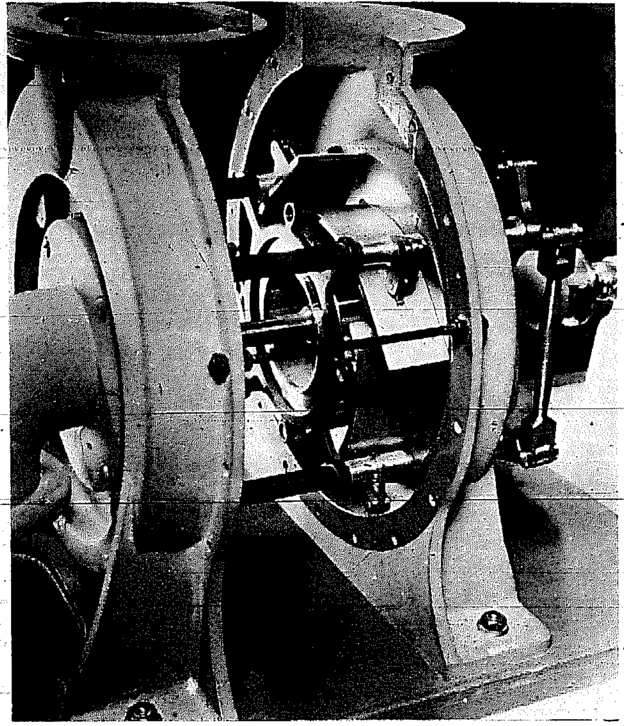


Fig 3.9 Thomson turbine with casing apart and arranged to show the four curved guide vanes which can be turned simultaneously by the linkages seen outside the casing on the right. The water flowed into the turbine through the opening at the top and out of the angled discharge pipe on the left. The drive shaft, from the multi-bladed runner in the centre of the picture, is carried between the links on the right of the turbine.

Photo by courtesy of Gilbert Gilkes and Gordon Ltd

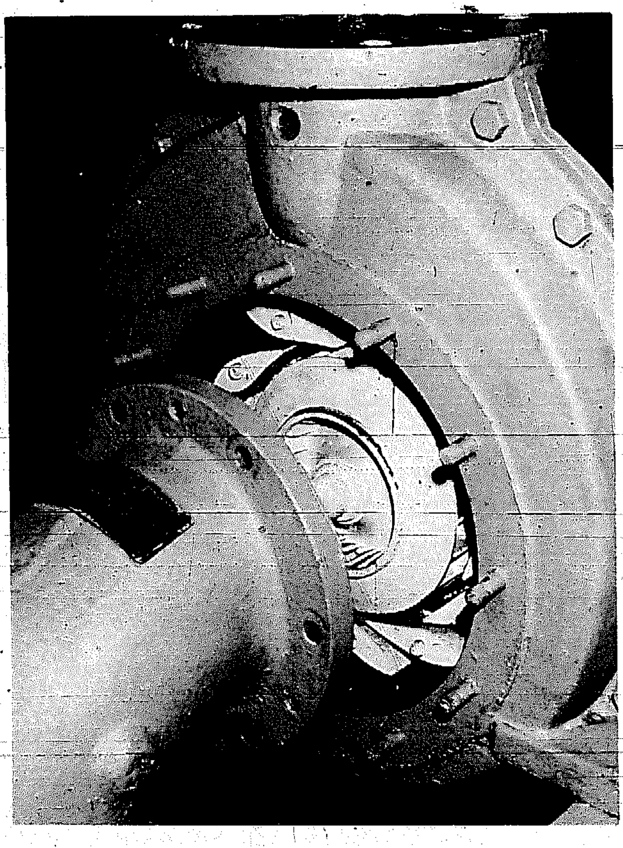


Fig 3.10 A later form of the Thomson turbine with a number of movable guide vanes of aerofoil shape

2 A spiral casing to maintain a uniform velocity of water passing between the guide blades (because of manufacturing difficulties the cases were usually circular with the wheel positioned off centre away from the inlet, so giving a partial compromise between a circular and spiral design).

3 The double discharge arrangement virtually eliminated end thrust which always caused difficulty until effective thrust bearings were invented.

The first vortex turbine was built in 1852 to drive a beetling mill in a linen mill at Dunadry, County Antrim. It was found that the design was readily adaptable for a wide range of heads, from 9–135 m. Numbers of these turbines were built – 439 by the Kendal firm of Williamson Bros between 1856 and 1881.

The disadvantage of the vortex turbine was that it ran slowly on very low heads, and too fast when small powers were required on high heads. So for low heads it was replaced by low-fall higher specific-speed, inward-flow turbines based on the designs of J B Francis.

Mixed-flow turbine

The turbine as originally constructed by Francis was a true radial inward-flow wheel with fixed guide vanes. After discharge from the wheel or 'runner', the water was turned to flow away axially. The runner had a comparatively small depth with a large number of vanes which necessitated a wheel of rather large diameter and low speed to obtain sufficient power. Subsequent developments led to a reduced wheel diameter to increase the speed, and a greater depth of runner with a smaller number of vanes extending nearer to the centre of the wheel so that the water was discharged more axially as it left the runner. Thus was evolved the mixed-flow or 'American' type of wheel (fig 3.11). There were numerous patented variations, some with adjustable guide blades, such as the 'River' patent turbine produced by Joseph Armfield of Ringwood, Hampshire. The company continues to trade as Armfield Engineering Limited. See fig 3.12. These reaction turbines ran full of water and the entire machine was always placed below the level of the supply water. At first they were also placed below the tail-water level but it was found more convenient, for inspection and maintenance, to have the machine above this level. The water was then discharged from the turbine by a pipe known as a suction or draft tube, the lower end of which is submerged in the tail-race water. It was found that by making the draft tube in the shape of a divergent cone, the velocity of the water to the tail-race was decreased and the performance of the turbine was improved.

Girard turbine

When high heads were encountered, impulse turbines were adopted. Zuppinger, in 1846, developed such an impulse wheel, and Schwamkrug proposed another design in 1850. These were followed by the impulse turbine introduced by Pike Serard about 1850 (see figs 3.13 and 3.14). It was made in either the horizontal or vertical-shaft form, and the water was admitted through one or more jets to the inside of a wheel similar to that of a Fourneyron turbine. These turbines were used extensively in high head developments up to

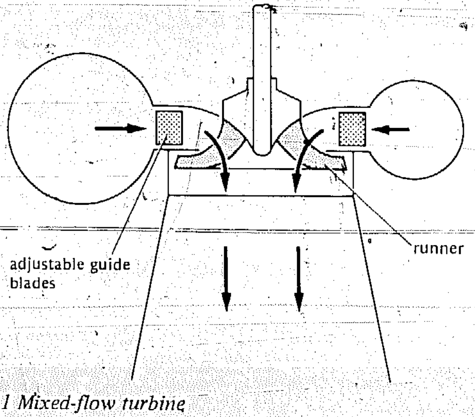


Fig 3.11 Mixed-flow turbine

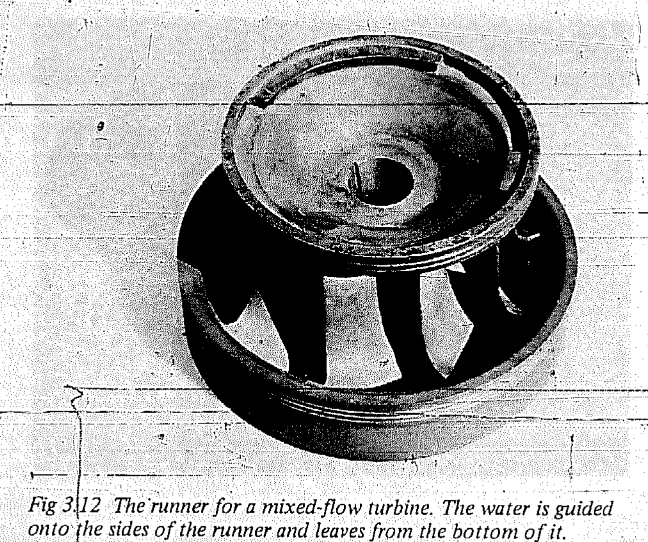


Fig 3.12 The runner for a mixed-flow turbine. The water is guided onto the sides of the runner and leaves from the bottom of it.
Courtesy of Armfield Engineering Ltd

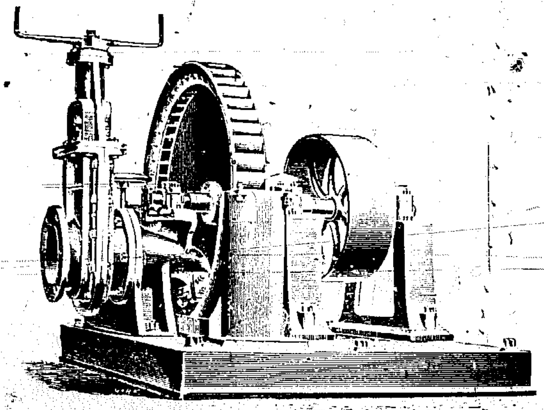


Fig 3.13 Girard turbine as shown in an advertisement by Gilbert Gilkes and Co Ltd, c 1895

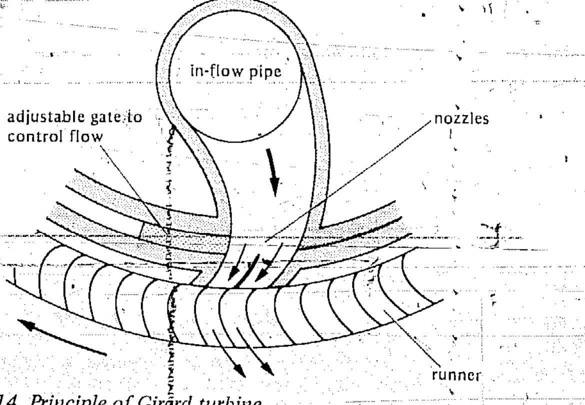


Fig 3.14 Principle of Girard turbine

the end of the nineteenth century. The first Girard to be manufactured in Britain was a 430 kW machine at Greenock, installed in 1881, and which ran until 1950. This was probably the United Kingdom's most powerful water turbine until well into the twentieth century.

Pelton wheel

About 1870 another type of impulse turbine, the Pelton wheel, was developed through observation of an accident to a waterwheel working in the Californian gold field. High pressure jets were used for mining and also for developing power by directing the jets onto crude waterwheels with flat blades. This was as inefficient as the early undershot waterwheels, and efficiency was improved by fitting curved buckets. It is said that one day, instead of the full force of the jet hitting the centre of the buckets, the jet became accidently directed onto the side of the wheel, striking one edge of each bucket and being discharged at the other.

To everyone's surprise the wheel picked up in speed and power, but with the disadvantage of side thrust along the wheelshaft. After a good deal of trial and error, Lester Pelton evolved the central partition bucket which he patented in 1880 (fig 3.15). The full effect of the change of momentum of the water was not at first achieved because the following bucket interfered with the jet to the bucket on the radius perpendicular to the line of action of the jet. This was overcome by using ellipsoidal cut-away buckets patented by Abner Doble in 1899. With the addition of a spear or needle nozzle the Pelton wheel of today was evolved (figs 3.16 and 3.17).

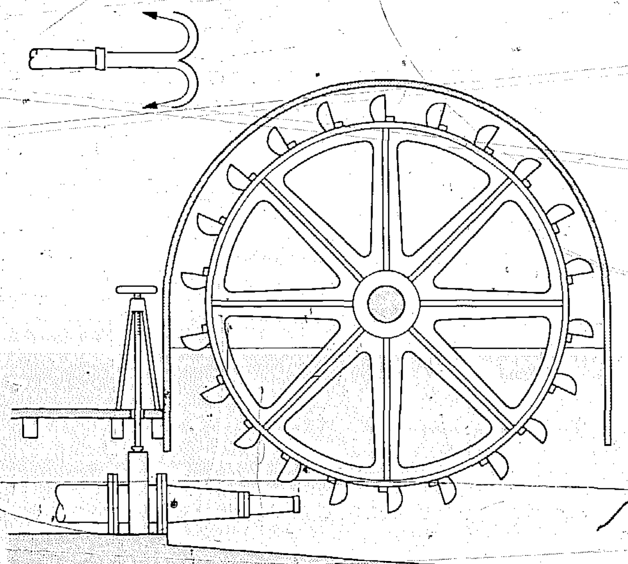


Fig 3.15 Pelton wheel. Shape of buckets shown at top left

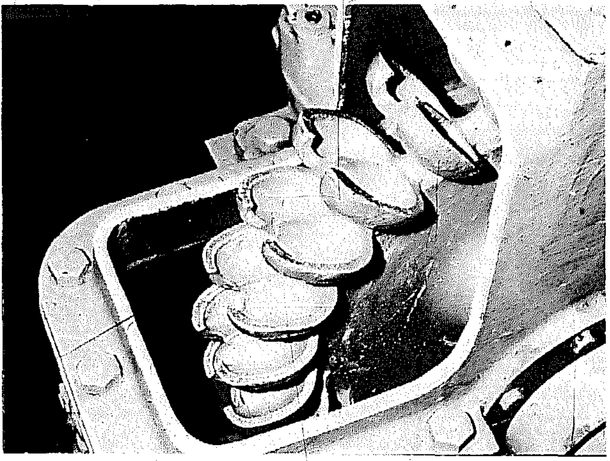


Fig 3.16 Pelton wheel with cut-away casing to show the double hemispherical cups forming the buckets, and the cut-away on each bucket, ensuring that they do not interfere with the water jet until they are virtually perpendicular to it

Fig 3.17 Another view of the Pelton wheel with cut-away casing showing, left, the section through the nozzle with the spear inside. The flow of water onto the buckets may be regulated by moving the spear backwards or forwards inside the nozzle, so altering the gap between the tapered sides of the spear and the orifice in the nozzle

3.3 HYDRO-ELECTRIC APPLICATIONS

All of these early turbine installations were employed to drive machinery either directly, or by mechanical transmissions such as gearing or belts and pulleys. Industries desirous of using power from water had to be situated close by, or move to, the source of power. In 1874, the Swiss town of Schaffhausen on the Rhine established works on the river to obtained power for driving the machinery of the manufacturers in the neighbourhood. About 1 MW was obtained from turbines and the power was distributed to the workshops by a costly system of pulleys and wire rope drives. Several other towns tried this system without a great deal of success.

With the development of the electric incandescent lamp, people began to look around for convenient sources of power for driving the dynamos. In 1876, waterpower was utilized in a direct current lighting system comprising arc lamps, each supplied by separate generating sets, illuminating the caves and a kiosk at the Castle Linderhof in Upper Bavaria. The first electrical generating installations in Britain were driven by steam engines, although in 1880 Sir William Armstrong installed a 7 kW Thomson turbine at Cragside, Rothbury, Northumberland, to drive by belt a 90 V dynamo supplying current for Swan lamps illuminating his home. The following year electricity was supplied at Godalming from a hydro-electric installation. In 1884 a Girard impulse turbine was supplied to the Greenock Water Trust where it drove two dynamos for lighting part of the town. This is considered to be one of the earliest municipal hydro-electric schemes in the country. The first hydro-electric plant in the USA was at Appleton, Wisconsin, in 1882, and in the same year the city of Lausanne, Switzerland, was provided with lighting current from generators powered by a 120 kW turbine.

At this time there were limitations to the distance over which power could be transmitted by electrical methods, and in 1882, when it was planned to obtain about 4 MW from the waters of the Rhône at Geneva, Switzerland, the decision was taken to effect the transmission of power by hydraulic methods. When the system was inaugurated in 1886, seventeen turbines (of a planned eighteen) each of 224 kW drove pumps to supply water at pressure through a system of water pipes (which put end to end would be 140 km long) to give power for industrial purposes and for working small private turbines.

However, it was the advent of alternating current electrical transmission systems which really made it possible for electricity generated by waterpower to be utilised a considerable distance away. In 1895 the first really large hydro-electric installation came into operation at Niagara Falls, following proposals to harness the large waterpower potential at this site. Prior to this date, the standard American method of utilizing a large amount of waterpower was to distribute the water to the several consumers by means of a system of head-races with facilities for its discharge at lower level, the water to be used as the owner or lessee saw fit, often in small turbines. This arrangement needed a large continuous body of land suitably located to take the head-races and tail-races, and also for each private turbine owner to sink his own turbine pit.

At Niagara, apart from one large owner (The Niagara Falls Paper Company) the demand for power from the individual was unlikely to justify sinking a turbine pit for each of them, and this was the incentive for the Niagara Falls Power Company to instal a row of turbines in a single spot, and to transmit and distribute the power by electricity. See fig fig 3.18.

Whereas the paper company installed Jonval turbines, the power company started operations with three outward flow turbines each capable of producing in excess of 3.7 MW and coupled by vertical shafts to generators with a terminal

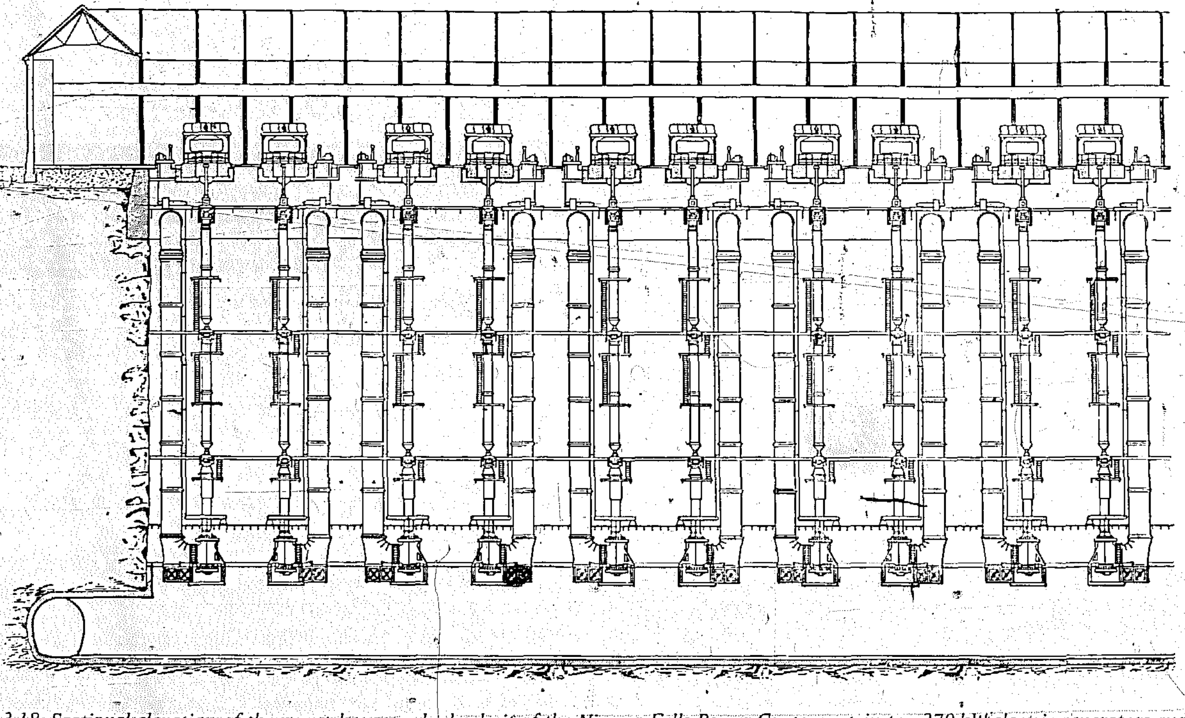


Fig 3.18 Sectional elevation of the power house and wheel-pit of the Niagara Falls Power Co, to contain ten 370 kW electric generators and ten 5000 370 kW turbines

From 'The harnessing of Niagara', *Cassier's Magazine*, 1899 voltage of 2200 V. Each turbine consisted of two Fourneyron turbines, one being set inverted and vertically over the other so as to neutralize the forces on the foot bearing. The fall from the surface of the upper water to the centre between the upper and lower wheels was 10.8 m and the wheels discharged 130 m^3 per second, rotating at 250 rev/min. At 75 per cent efficiency they gave 3.7 MW. These three turbines were built by I P Morris of Philadelphia to the designs of Faesch and Piccard of Geneva, Switzerland.

The reason for the adoption of a European design was that in America it was very unusual for a turbine to be built to order since the volume of trade was such that manufacturers built for stock. The types available had resulted from thorough testing and improvement by trial and error. In general, the American builders shunned high falls, except with the Pelton wheel, which at this time was restricted to the horizontal-axis type and would thus need an elaborate belt and pulley transmission system to the generators 45 m above (this position was to avoid excavating extra rock to accommodate the generators – 3.5 m diameter, 3.5 m high, close to the turbines). On the other hand, European manufacturers usually built to order, their designs being based on calculations, and often for high heads.

The power developed was transmitted up to 30 km and was used to drive machinery in mills and factories, to operate street railways, to supply lighting by arc and incandescent lamps, for electrolytic purposes, and for heating.

The success of the Niagara Falls installation showed that it was no longer necessary to generate power close to the consumer and that it was now possible to utilize some of the vast waterpower resources in remote areas. In the Alpine regions of France, Germany, Italy, and Switzerland, it was often possible to use the water resources by diverting the water through a pipe or tunnel.

In other places, despite adequate water supply and suitable mountains or other elevations to produce the fall, a considerable amount of civil engineering is involved, including the building of huge dams, to ensure that both the necessary flow and head of water are available to drive the turbines at all times and in all seasons. Thus, although hydro-electric stations in operation do not involve fuel costs, they involve colossal expenditure in their construction and in the arrangements for transmission of the power generated.

Kaplan turbine

In 1913 Professor V Kaplan of Sweden patented a propeller turbine for the utilization of low heads (see fig 3.19). Originally this had fixed blades, but soon afterwards he introduced a version fitted with swivel blades by means of which the angle could be varied under the control of a governor whilst the turbine was running. The angles of the inlet and outlet vanes were adjustable without stopping the turbine, so it was possible to obtain an almost constant efficiency of 85–90 per cent over a range from 30 per cent load up to full load under comparatively low heads. Although Kaplan invented the propeller turbine, usually only the adjustable-blade type runner is called a Kaplan turbine. This has pure axial flow, generally with four to six blades without an outside supporting rim. By 1926 a Kaplan turbine of 8.2 MW was in service in Sweden having a 5.7 m diameter runner working with a head of only 6.4 m. (See fig 3.21.)

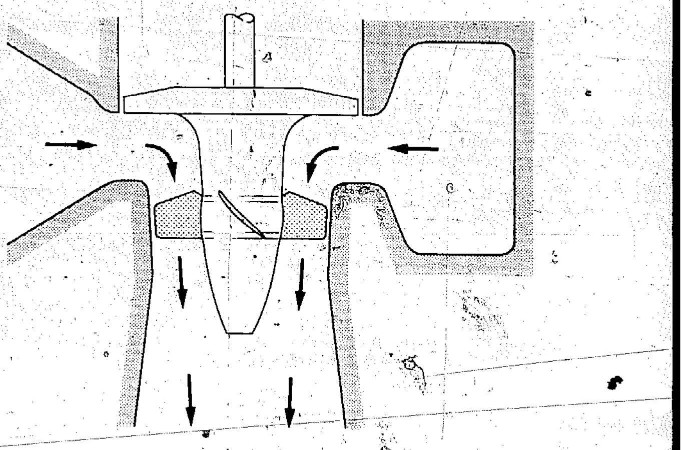


Fig 3.19 Principle of the Kaplan turbine

Banki turbine

An interesting design of turbine, which extracted energy from moving water in two stages, was produced in Hungary by Dr Donat Banki in 1917. It derived its power from the kinetic energy of an inward flow water jet. As shown in fig 3.20, the horizontal blades of the rotor were curved in such a way as to direct the water:

1 inwards and across the open cylindrical space at the centre onto the inner edges of the blades on the other side, and

2 outwards to the tail-water.

Despite its advantages of operating efficiently on a wider range of gate openings than most turbines, and of simplicity and cheapness in manufacture, the design had only limited popularity, mainly in Central Europe.

Tubular turbine

In 1936, the first turbine combined with a generator was constructed. This type, known as the tubular turbine, has a generator enshrouding the runner (or rotating part) of the turbine: the generator rotor and the blades on the runner form a wheel in which the runner blades are the spokes.

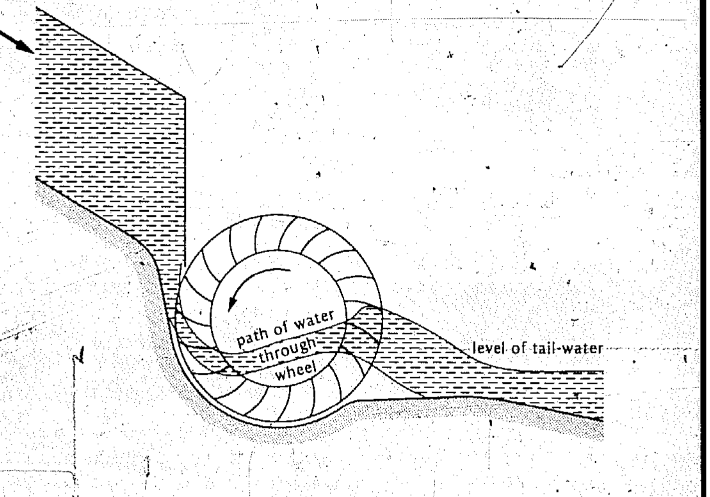


Fig 3.20 Banki turbine

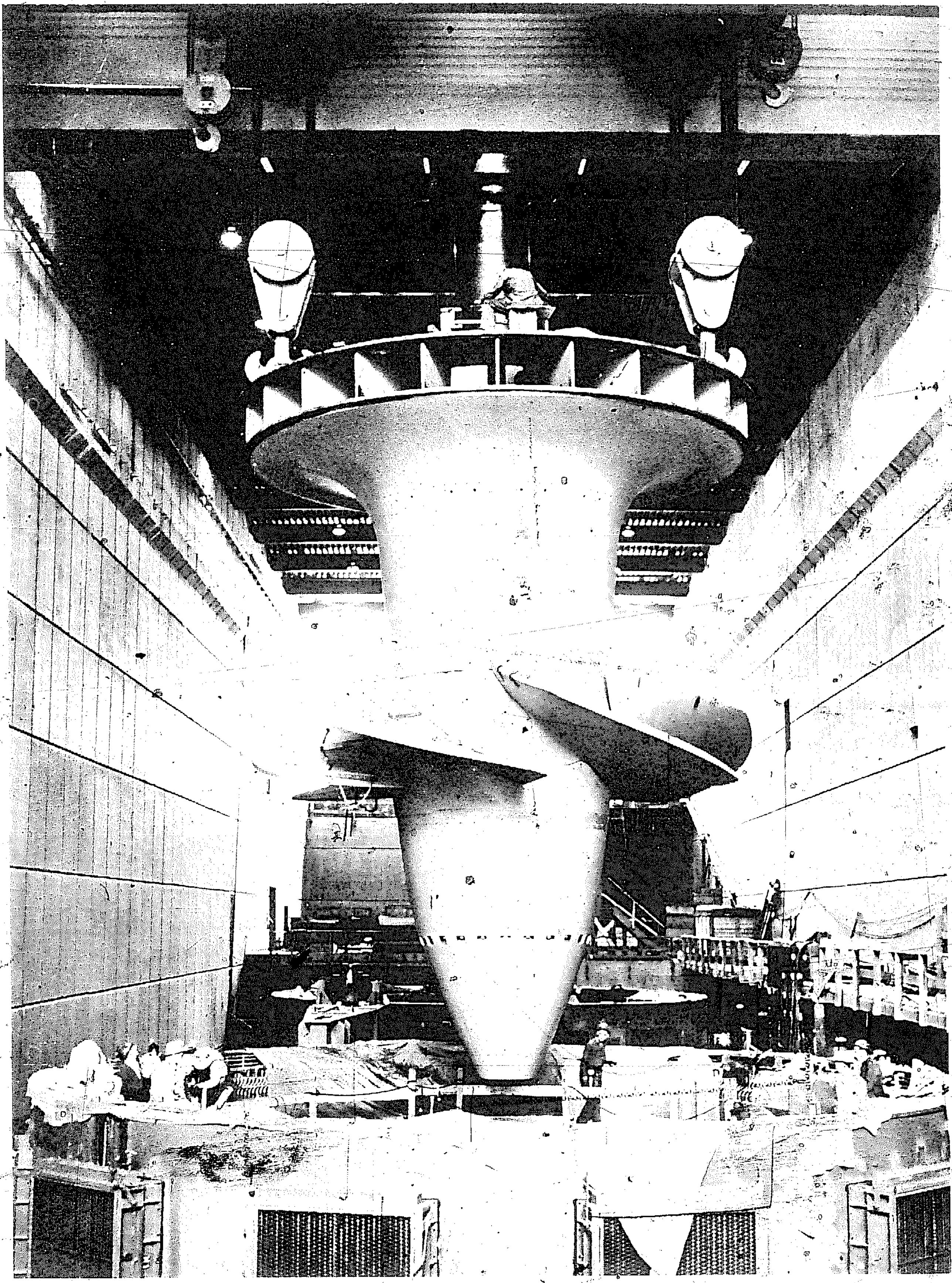


Fig 3.21 The runner for a Kaplan turbine being lowered into position at Priest Rapids, Grant County, Washington, USA. The runner assembly weighs approximately 350 tonnes and has an overall length of 13 m: the diameter over the blades is 7.2 m. The complete turbine gives 98MW when rotating at 85.7 rev/min under a 26 m head and was one of ten similar units erected by the former English Electric Co Ltd at Priest Rapids between 1959 and 1961

Photo By Courtesy of GEC Turbine-generators Ltd

Bulb turbine

Another type of combined turbine and generator is the bulb turbine, fig 3.22, where the generator is an extended hub of the turbine. Although introduced for low capacities by the Swiss firm Escher-Wyss, high capacity bulb turbines have been produced by many firms and are being developed for the utilization of tidal power.

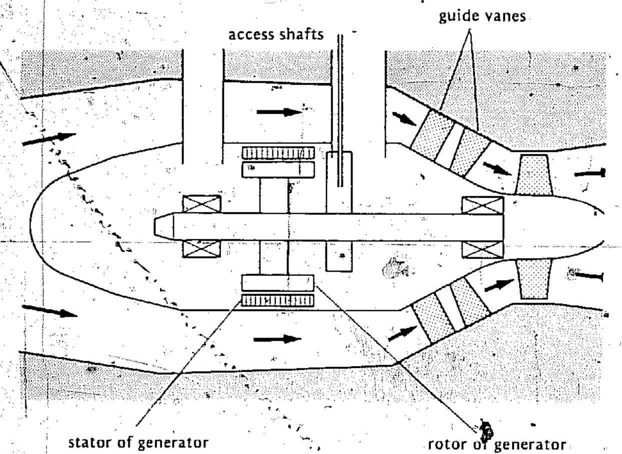


Fig 3.22 Bulb turbine

Deriaz turbine

In the mid-1950s the Deriaz turbine (fig 3.23) was developed to operate under variable heads up to about 180 m giving a flat efficiency/load characteristic together with part-gate stability of operation. The mixed-flow, adjustable-blade Deriaz machine is a cross between the Francis and Kaplan turbines and can be used as a straight turbine, a reversable pump turbine, or an adjustable blade pump. Compared with the Kaplan turbine, the oblique mounting of the runner blades in the hub gives the Deriaz turbine greater mechanical strength and the blade shape is simpler. The generator design is more economical with the Deriaz turbine. On the other hand, the Deriaz is considerably more expensive than an equivalent Francis design for the same heads and output and its peak efficiency is less than that of the Francis machine, but when operating under a wide range of heads the Deriaz has an economic advantage.

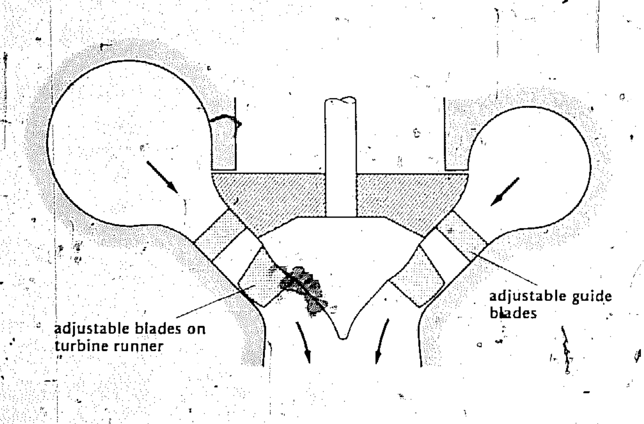


Fig 3.23 Deriaz turbine

The first application of the Deriaz turbine was at the Sir Adam Beck, Niagara, pump-generating station of the Hydro-Electric Power Commission of Ontario, where the first three units, designed to run both as pumps and turbines, were completed in 1957. They each give 34 MW at 92.3 rev/min under a 25 m head as turbines or, operated as pumps, take 41 MW to yield 139 m^3/s at 23 m head. The Deriaz turbine runner is shown with blades open and closed in figs 3.24 and 3.25.

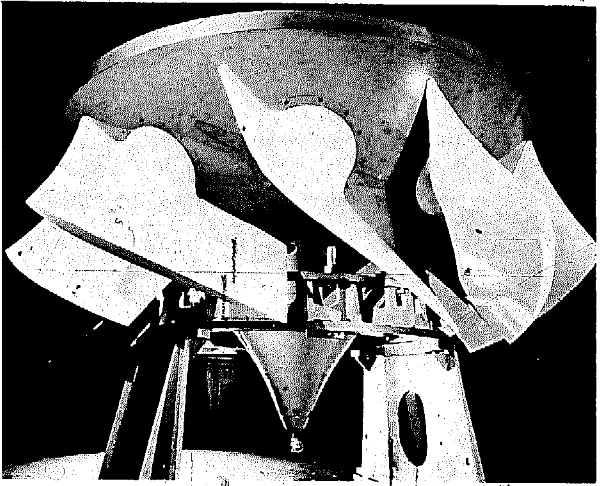


Fig 3.24 Deriaz turbine runner assembly with blades open. The complete turbine gives 80 MW at 150 rev/min under a head of 75 m. It is one of three erected by the former English Electric Co Ltd for the Valdecanas power station of the Hidroelectrica Espanola SA in 1964. The units operate in reverse as pumps, the no 1 unit taking 80 MW to deliver 283 cm^3/s at 72 m

Photo by courtesy of GEC Turbine-generators Ltd

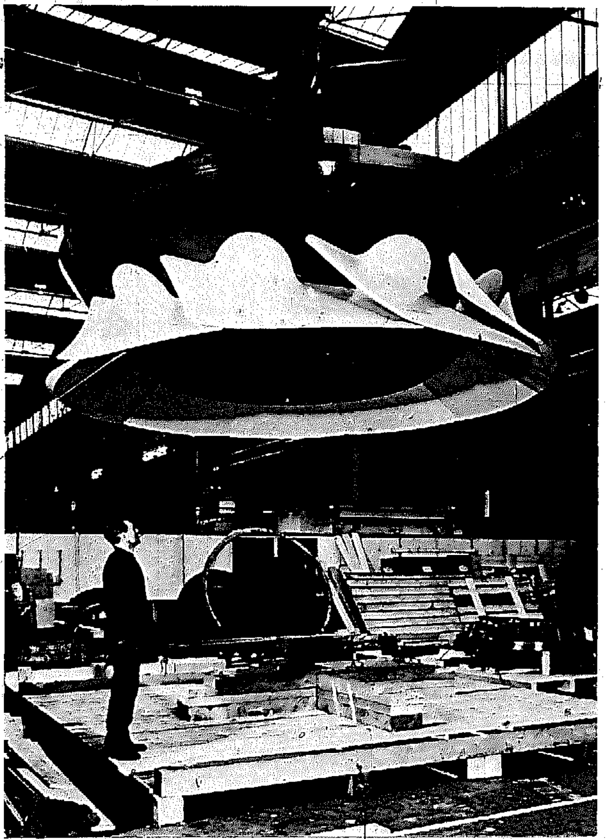


Fig 3.25 The same Deriaz runner shown in fig 3.24 but with the blades in the closed position

Photo by courtesy of GEC Turbine-generators Ltd

At the present time, several types of turbines are constructed depending on the head of water under which they are required to work:

1 For low heads, such as encountered on run-of-river plants, where a dam is erected across a river, the Kaplan turbine is favoured. Before the 1930s this turbine was restricted to heads not exceeding 15 m but much higher heads are now regarded as acceptable. Even during the 1960s a Kaplan-type machine was in use at Bort, France, operating under a head of 69 m (and sometimes 80 m) with a capacity. For variable heads up to about 180 m, the Deriaz turbine may have an economic advantage over the Kaplan and Francis turbines.

2 For medium heads, the Francis turbine* is used. Formerly the range was between 15 m and 300 m but at the lower end Kaplan turbines may now be used and it has been suggested that at heads of up to about 500 m (1700 ft) the Francis turbine has a definite advantage over the impulse-type wheels. At Hemsil in Norway, two Francis turbines, each of 316 MW, work under a net head of 510 m.

3 For very high heads, Pelton and Turgo wheels are used.

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*In this country 'Francis turbine' is used as a classification for wheels receiving water under pressure in a radial inward direction and discharging axially through the centre, having adjustable guide vanes. Some of these Francis turbines have the guide blades in an open flume, but others have them in a volute casing so that many of the features of the Thomson vortex turbine are included.

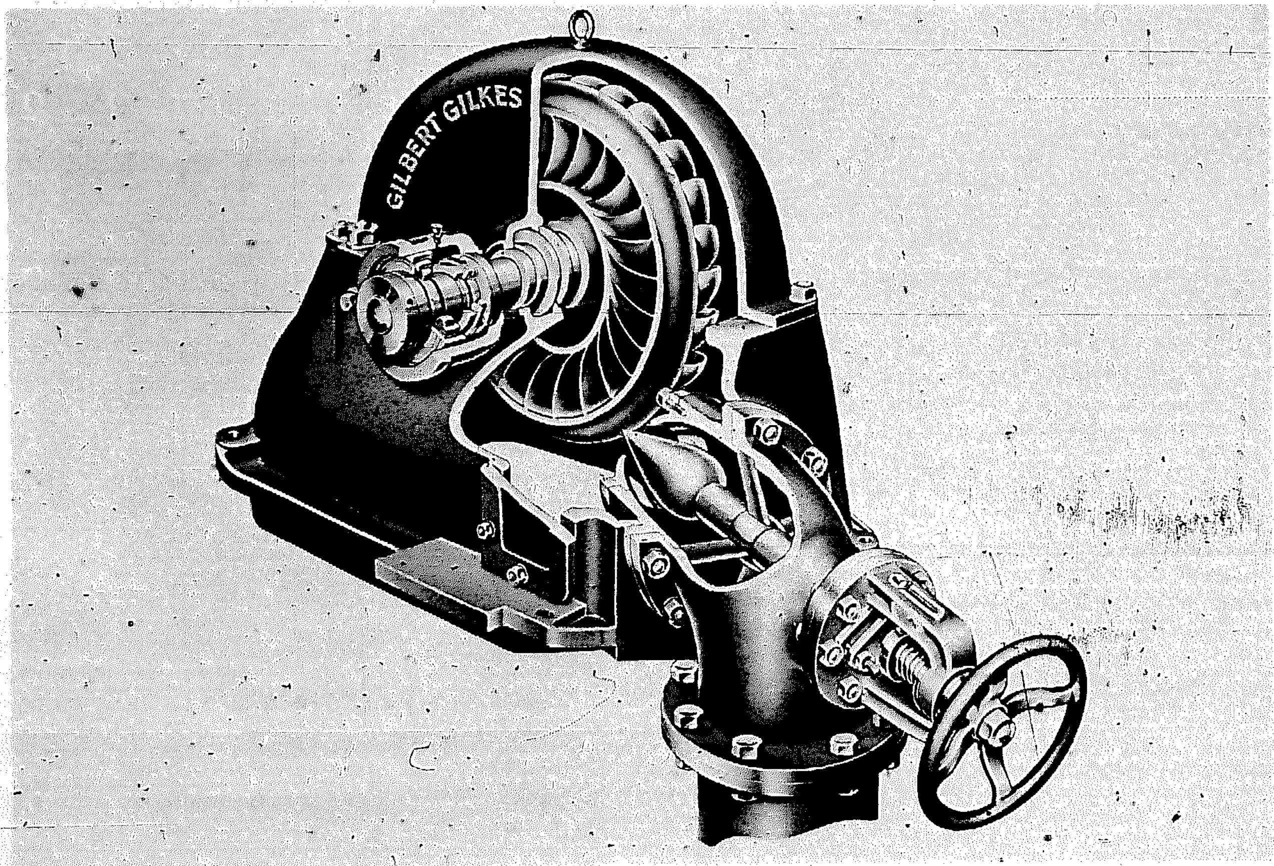

Fig 3.26 Part-sectioned artist's drawing of a 'Gilkes' patent Turgo Impulse wheel where the nozzle is directed at an angle to the plane of rotation of the wheel

Courtesy of Messrs Gilbert Gilkes & Gordon Ltd

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