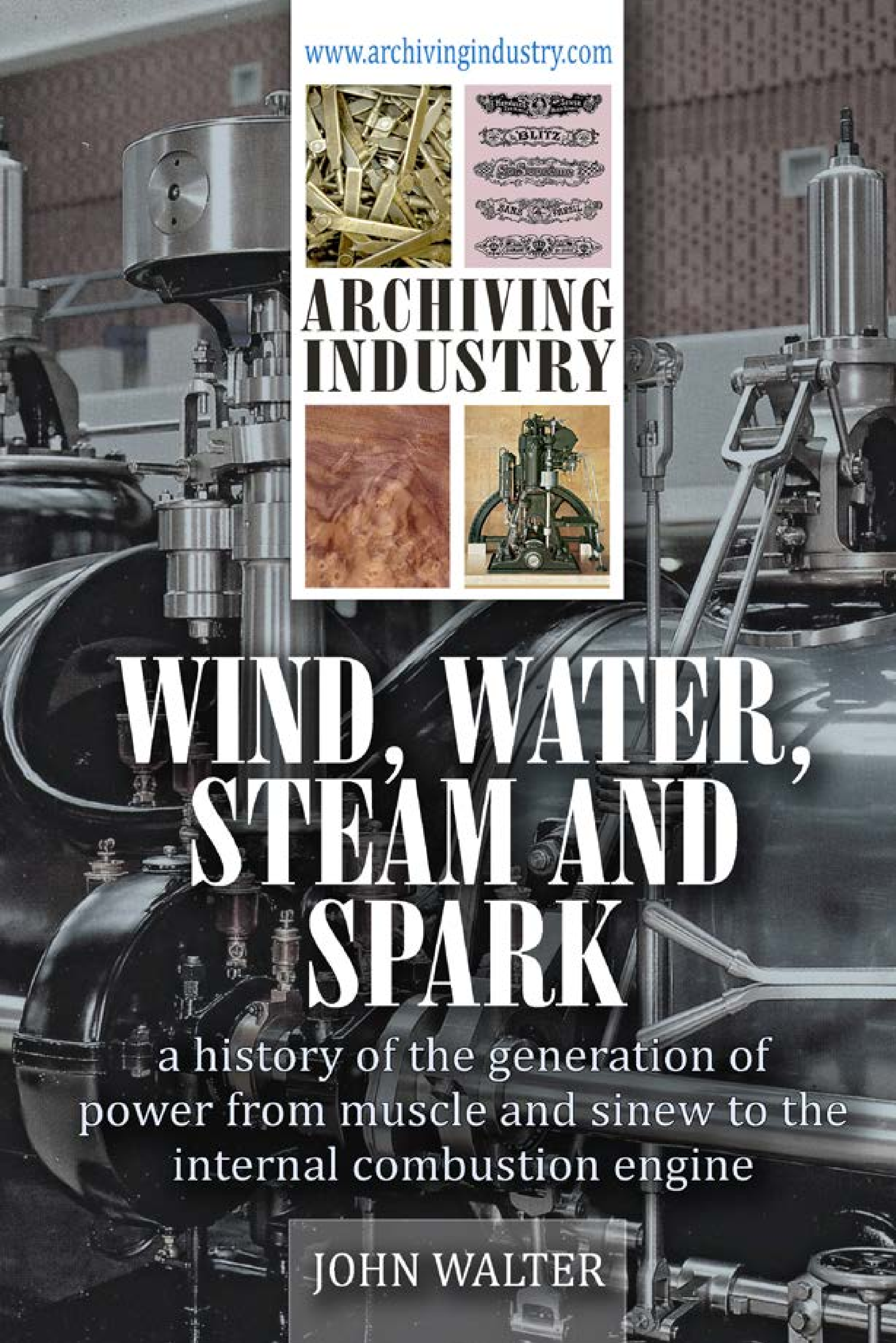

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WIND, WATER, STEAM AND SPARK

a history of the generation of power from muscle and sinew to the internal combustion engine

JOHN WALTER

WIND, WATER STEAM & SPARK

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a history of the generation of power from muscle and sinew to the internal-combustion engine

JOHN WALTER

CHAPTER ONE

from muscle and sinew to the watermill and the wind-engine

In the first century AD, Hero of Alexandria, writing in his Mechanica, summarised the technological aids available at that time to supplement the muscles of men and beasts of burden: the wedge, the wheel and axle, the screw and the compound pulley, all of which were merely variations of the lever. The origins of them had been lost in antiquity, though each embodied mechanical advantage to ensure that a small force applied through a great distance was transformed into a larger force acting through a much smaller range. The result was that the operator used substantially less effort to move a load, but did so much more slowly than he would otherwise have done.

MUSCLE

Gradually, the basics of mechanics emerged and attempts were made to exploit them. Levers were used in beam presses in Greece as early as 1500 BC—to extract juice from grapes or olives—and in the oars of the Greek galleys, some of the most modern being pivoted in rowlocks mounted outboard of the hull for greater efficiency.

The wheel and axle allowed the development of the tread-wheel and its near relative, the animal gin (or 'engine'), by concentrating comparatively small effort applied at the circumference of the circle to become a much greater force at the axle. Donkey mills were used to crush ore by the fifth century BC, and then to grind corn by the third century BC. The rotary motion of the tread-wheel was particularly useful, and attempts had been made to convey it through primitive trains of peg-and-lantern gearing by the time of Christ. Unfortunately, the manufacturing technology of the time was unable to make gears that were accurate enough to avoid excessive transmission losses.

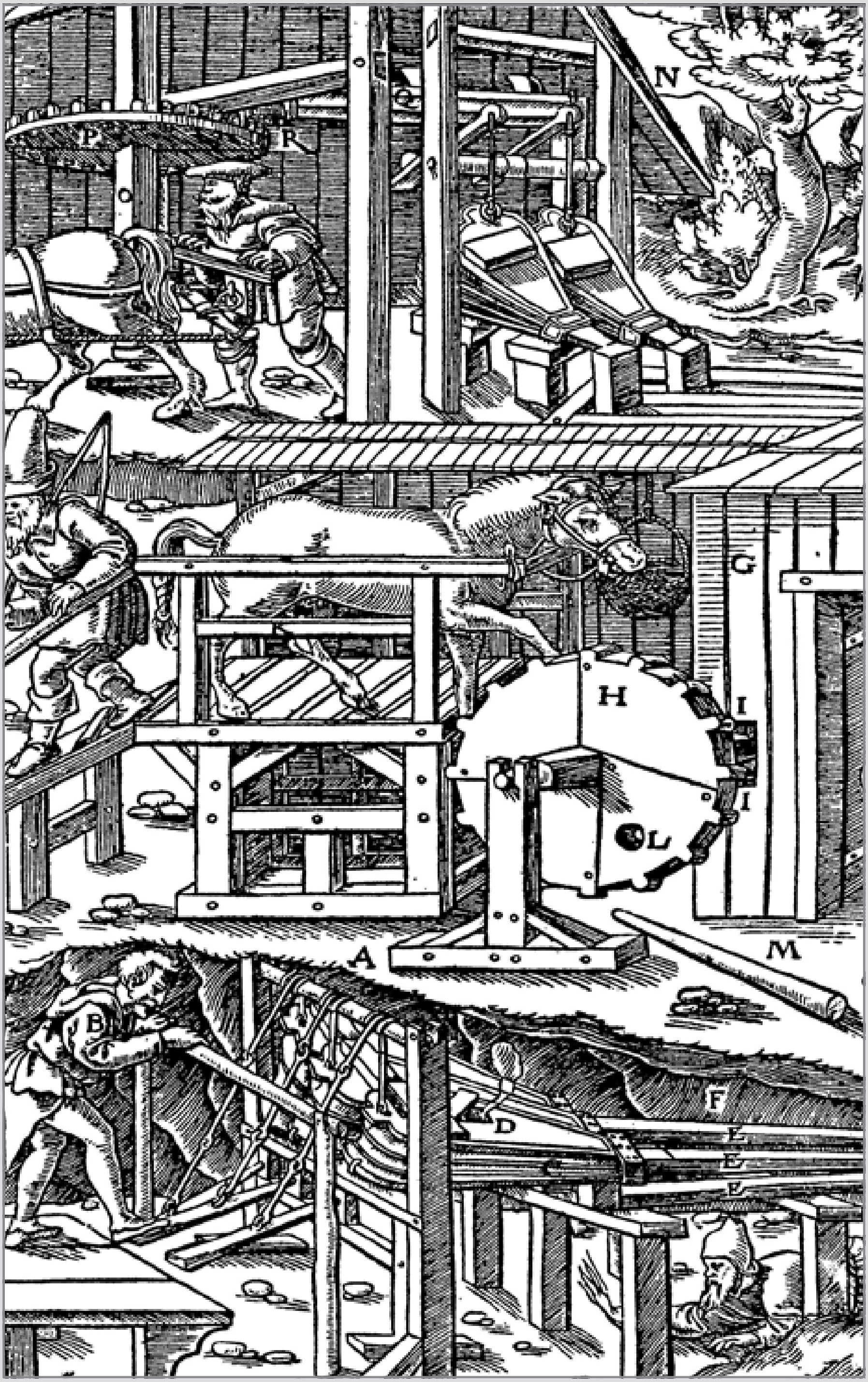
Tread-wheels have been used into recent time. Medieval engineers still built tread-wheel cranes which would have been familiar to a Roman of the first century AD. The Harwich Crane, the last of its type to survive in Britain, was built about 1670 for use in a dockyard; two 16ft diameter tread-wheels on a single axle provided the source of power. A surviving donkey mill in Carisbrooke Castle in the Isle of Wight dates from 1687, and, at a less public level, donkeys, horses and even dogs toiled to supply water or drive small machinery into recent times. A donkey mill worked until 1899 at Saddlescombe Farm, near Brighton; and animal gins were still being made in backward areas—e.g., the Far East or southern Africa—into the twentieth century.

Efficiency was helped by development of the universal joint by Robert Hooke, in the seventeenth century. This allowed portable horse gear to be used on uneven ground. Radial shafts connected with a spur wheel, which rotated the universal-jointed drive shaft through a crown wheel. Typical of recent animal-powered machinery was a South African horse mill dating from the middle of the nineteenth century. The roundhouse contained a vertical wooden shaft supported in the floor by a stone bearing. The horse was hitched to a boom held to this main shaft by iron strapping. As the horse plodded round, guided by a cane linking its bridle with the main shaft, the large spur-peg wheel at the top of the shaft rotated a lantern gear attached to the bottom of the millstone spindle at much greater speed.

The spindle ran up through the stationary bed-stone to drive the runner, the gap being adjusted when necessary by a wedged tentering beam. (Some horse mills were driven by rope and pulley instead of gearing, but the principles were otherwise much the same.)

The wheel-and-axle principle, often allied with gearing, was also used on capstans, hoists and cranes. A particularly useful embodiment was in the jack, often credited to Leonardo da Vinci on the basis of *Codex Atlanticus* illustrations, but probably developed early in the fifteenth century.

The popularity of the jack has endured largely owing to its simplicity. The earliest examples relied on a crank handle attached to a pinion wheel with very few teeth—often only three or four—which drove a larger pinion meshing with a rack on the jack-bar. A pawl-and-ratchet safety mechanism prevented the jack slipping backward when the winding effort was removed. The bar-type jack was supplemented in the nineteenth century by a screw jack, which substituted a threaded rod for the bar and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a worm gear for the jack pinion. However, though mechanically operated jacks have been made in many forms, the operating principles remain the same.

Mediaeval man had few sources of power available to him other than muscle, wind and water. However, the idea of a spring had been appreciated for thousands of years. In a most basic form, bent saplings had undoubtedly been used to provide power—perhaps to lift small items, or provide some kind of recovery from a repetitive action.

This was very different from merely using a counterweighted arm to perform useful work (e.g., the *shaduf* water lifter of Egypt and the Near East) and eventually led to the pole lathe. In this, a foot treadle connected to a springy pole by a cord, twisted around the work piece, provided the downward power or cutting stroke. The whip in the pole then pulled the treadle upward, rotating the work piece back to the starting position ready for the next cut.

Similar principles were applied to a wide range of low power machines, including the spinning wheel and the sewing machine. They are particularly interesting in the application of cranks to transfer reciprocating action of the treadle to rotate a shaft. The appearance of a crank on an atmospheric engine in 1780–1 caused James Watt great distress, as it had been patented by a business rival—even though the prior existence of treadle lathes and similar machinery should really have invalidated the claim.

Another embodiment of the spring lay in the bow, a combination of whippy wood and a drawstring which had been known since Palaeolithic times. Arguably the most important military weapon from pre-dynastic Egypt to the Middle Ages, the bow was originally made from a single piece of wood. However, more robust composite patterns were subsequently perfected by the Persians from laminates of wood and animal sinew, providing greater power within modest dimensions, and the quest led to the crossbow.

Medieval crossbows were derived from Greek and Roman siege equipment powered by twisted cord, hair or sinews. The earliest of these dated back to the era of Alexander the Great and perhaps beyond him to the Phoenicians. Roman legions customarily had rock throwers and spear hurlers working on the same principle.

The greatest improvement in the crossbow was the introduction of wrought iron or steel to make the bow, which apparently originated in the most advanced Italian city states at the end of the tenth century. The use of bronze springs instead of twisted sinews had been suggested by Ctesibius of Alexandria in the third century BC, though the poverty of contemporary metallurgy meant that nothing of lasting significance had been achieved.

By the fifteenth century, however, the crossbow had become powerful enough to pierce chain mail armour and often required a separate windlass or crannequin to retract the bowstring. Eventually, metal springs were perfected sufficiently to allow the introduction of successful spring-driven clocks. The earliest is credited to Peter Henlein, said to have been working in Nürnberg (Nuremberg) at the end of the fifteenth century.

'Clockwork'—the spring trains that allowed clocks to work—was rapidly extended to other uses, not least being the so-called wheel locks fitted to firearms and tinder lighters. However applications were restricted by the need to periodically wind or 'span' clockwork mechanisms and their inability to provide much power.

The same strictures applied to 'weight drive'. Use of counterweights to ease arduous or repetitive jobs was well established, and it was soon realised that the potential energy in a suspended weight (even if only a boulder) could be converted to rotary motion. Among the uses were to drive the 'turret clocks' in the days before springs became universal, and to turn roasting spits.

WATER

The tread-wheel and the animal gin were very useful, but still required muscle power and could not be guaranteed to sustain work continuously. A better source of energy was clearly to be provided by the elements, though the state of technology once again hindered exploitation for a long time. Earth had almost nothing to offer medieval man, and no constructive use of fire could yet be seen. Only wind and water held promise.

Exploitation of water is an ancient art. King Sennecharib of Assyria built an aqueduct as long ago as the seventh century BC, to be followed by Greeks and Phoenicians until systems were being built by the third century BC which could handle pressures twenty times that of the atmosphere (20 bar). This was largely due to the use of hollowed stone pipes.

The Romans built some of the most spectacular aqueducts, from Aqua Appia of the third century BC, largely underground, to the triple storey arcading of the Aqua Claudia. The spectacular arcades of the Pont du Gard, erected in the first century AD in Nîmes in south-western France, testify to the finely-honed skills the Romans could bring to aqueduct construction. However, though they succeeded in supplying water at the rate of about 200 million gallons daily to a city whose populace numbered about half a million at the peak of its power, the Romans never exploited water-power on a grand scale.

Though embodied in the Clepsydra or water clock as early as *c.* 300 BC, what exploitation there was by even the third century AD relied on the waterwheel. The oldest form of watermill is the Norse or Greek pattern, which was distinguished by a vertical shaft and angled, flat or scoop shaped vanes immersed in a stream. They seem to have originated in the upland districts of the Near East, where fast running streams abounded, but migrated rapidly across Europe—perhaps owing to Phoenician traders. Thus they became more popular in Scandinavia than in southern Europe, where they were quickly superseded by the more efficient horizontal wheel.

The drive shaft, held in a sturdy frame, ran upward through the bed (fixed) millstone to drive the runner stone. Corn could be crushed between the stones, though the potential of these small mills was so limited that their output was almost always consumed in the immediate locality. The direct drive meant that runner stones rotated at the same speed as the stream turned the shaft, which meant that movement was often uncommonly slow. Norse mills survived in parts of Norway, Iceland, the Hebridean islands and similarly isolated districts into the twentieth century. One in Sandness in the Shetlands worked until at least 1933.

The vertical wheel Roman or Vitruvian mill, set on a horizontal axle, seems to have been derived from the noria—a water lifting wheel developed in Persia in the seventh century BC. This had originally consisted of clay water pitchers lashed around the circumference of a wooden wheel. The machine was rotated by man or animal power to provide water for irrigation. Some magnificent norias survive in the Islamic world (e.g., the twenty-metre wheel in Hama in Syria) though the 'Great Wheel' erected in Toledo shortly before 1154 AD has been lost.

Variations of this system had already spread throughout the Near East when Vitruvius described an improved scoop blade wheel in the first century BC. But he then proceeded to describe how the current in a fast flowing stream could be used to drive this wheel automatically, the goal

being to derive power from the central axle instead of simply lifting water. The Vitruvian waterwheel drove millstones through gearing—generally at the ratio of 5:1—and were eventually adapted to many differing purposes as the availability of slaves decreased.

The design of the waterwheel showed a steady progression. The earliest mills were of traditional bladed undershot type, rotating the wheel simply by immersing it in a suitable fast running stream. This simple solution sufficed until it was discovered that overshot water supply was more efficient, not least because the weight of the descending water in the buckets added to the power generated from the current flow. Other variations included breast shot wheels, where the water from the mill race was delivered at roughly axle level (divisible into low and high breast sub variants), and the back shot or pitch back wheel in which the motion of the wheel was reversed by a high water delivery on the mill race side of the axle.

Important improvements in the design of the waterwheel were made in the eighteenth and nineteenth centuries by inventors such as John Smeaton, William Fairbairn and Thomas Hewes; and one of the greatest advances in undershot wheels was made in the 1830s by Jean Victor Poncelet, who promoted curved 'scoop' blades and a curved under race to improve efficiency.

Early wheels were made entirely of wood, which made them large and heavy in relation to their power. The rise of the iron industry in the early eighteenth century permitted cast iron naves to be used, running on wrought iron axles. This eventually led to the introduction of wheels made entirely of iron, often excepting the paddle blades.

Overshot wheels often required changes to be made not only to the design construction of the mill but also to the mill site. The need to deliver water above the wheel led to the damming of water courses to form mill ponds; to the construction of channels ('leats') and chutes to convey water to where it was wanted; to the development of by passes and sluices to prevent flooding or divert water away from the mill when required; and to the building of suitable tail races to drain waste water away from the wheel. The overshot wheel was a revolutionary advance, capable of generating much greater power than anything tried before it.

The use of watermills outside Rome was slow to gain momentum, until the social structure of the Empire began to change in the fourth century AD. Shortage of labour persuaded the once hostile authorities to look again at the new source of power. The power of a typical small Roman undershot watermill, with a wheel diameter of seven feet, has been estimated at about 3hp. Its grinding capacity was reckoned to be forty times as great as a donkey or two man mill.

By 350 AD, overshot mills were being made in great size even in remote provinces. One on the river Rhône, near Arles in what is now southern

France, had sixteen 9ft diameter wheels. Each drove a pair of corn grinding stones, hourly capacity being rated at about three tons. This was far more than the immediate hinterland could use, and so it is clear that a trade in flour had been created.

The Romans were also responsible for the introduction of the floating mill, which was originally designed to outwit besiegers who cut water supplies by damming or diverting streams. The floating mill was little more than an undershot wheel slung between two moored boats facing into the tideway. It has been suggested that the idea was adapted from attempts to make an oxen propelled paddle boat in the fourth century AD. The floating mill was much less powerful than the overshot type, but had sufficient advantages in certain situations to survive in Europe into the nineteenth century.

They included tide mills, a medieval invention, originating in Europe some time prior to the Norman invasion of England in 1066. Mills of this type were eventually found around the European North Sea coast; on both sides of the English Channel; on the French Atlantic coast; in Greece; in Portugal; and along the eastern seaboard of the U.S.A. Some were even to be found driving Guyanese sugar mills until recent times. The tide mill was comparatively rare in Britain. However, a tide mill survives in Carew Castle in Wales; another built at the confluence of the rivers Lea and Thames in 1776 worked for nearly 160 years.

Most tide mills worked by confining water in a dammed or banked pond as the tide ebbed, then releasing the water to drive the mill wheel. The major disadvantage of a tide mill of this type was that power could only be generated within the tidal cycle, and thus the mill stood idle for much of the working day. A better solution was to build a mill on a dam barring a tidal inlet or bay, then use separate or convertible wheels to generate power as the tide ebbed and flowed. However, suitable sites were few and far between, and were also vulnerable to storm damage.

The *Domesday Book* of 1086 recorded more than 5600 watermills in England, south of the River Trent alone. Their popularity rapidly spread far beyond corn grinding to ore crushing, furnace blowing, hammering or sawing wood. This ubiquity helped to improve gearing, and promoted the growth of many ancillary trades. Among the most impressive medieval constructions was London Bridge waterworks, which first supplied water on Christmas Eve 1592 and continued to do so until the bridge was finally dismantled in 1822. The potential of hydraulic power had even been demonstrated when a jet of water was fired high over the waterside church of St Magnus the Martyr as a publicity stunt.

The Machine de Marly, installed on the Seine in 1681–2 to supply water to the gardens of Louis XIV in Versailles was one of the engineering wonders of the seventeenth century. Rated at about 75hp, the waterwheels drove batteries of bucket pumps through trains of rocking levers.

A typical eighteenth century flour mill derived its power from the axle of the waterwheel, which ended in a crown geared pit wheel. This drove the vertical main shaft through a wallower gear. A large spur wheel on the main shaft in turn drove the runner stones through small pinions called 'stone nuts', which could often be disengaged by jack rings. A small crown wheel on top of the main shaft could be used to drive auxiliary machinery or a sack hoist.

The design of the waterwheel lay dormant until important improvements were made in the eighteenth century. John Smeaton gained the Royal Society's Copley Medal in 1759 for his investigations, which showed that an overshot wheel could be nearly three times as efficient as undershot rivals.

Other steps were taken by Thomas Hewes and William Fairbairn, the latter contributing the ventilated bucket in 1828 to increase power by as much as a third. One of the greatest advances in undershot wheels was made in the 1830s by Jean Victor Poncelet, whose curved 'scoop' blades and curved under race to improved efficiency considerably.

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The watermill, large though not especially powerful, retained its importance long after the steam engine had made its appearance. Indeed, the primary role of many early engines — particularly the Newcomen type atmospherics — was simply to return wastewater from the tail race to the mill pond. Far from killing the watermill, the Second Industrial Revolution raised it to new heights of efficiency. Suitable water powered systems were still being installed in the middle of the nineteenth century, even though the water turbine (q.v.) was making inroads on their popularity.

One of the most impressive survivors is the Lady Isabella wheel erected in 1853–4 in the Isle of Man by the Great Laxey Mining Company. Designed by Robert Casement to drain mines that had been dropped to 600ft, the wheel had a diameter of 72 ft, a width of six feet, and 168 buckets holding about thirty gallons of water apiece. Water was supplied from a reservoir to a delivery tower beside the wheel.

At a speed of 2 rpm, the Isabella wheel could develop about 200hp and lift 250 gallons of wastewater per stroke from the base of the mine shaft. The dimensions of the machinery were such that the balance box attached to the pump rods contained no less than fifty tons of iron scrap.

Little more than a sophisticated water wheel with divided buckets, rotated by high presure water jets, the Pelton Wheel was discovered almost by accident in the Californian goldfields in the 1870s by an English born mining engineer named Lester Pelton. The mechanism proved to be outstandingly successful, and Pelton Wheels developing 500hp were being made in quantity by the beginning of the twentieth century.

The nineteenth century also witnessed the rise of the water turbine, which was a direct descendant of the waterwheel. The turbine was the greatest single step forward in the use of water power, and could be considered almost as an enclosed waterwheel. The basic theoretical work was done in the middle of the eighteenth century by the Swiss mathematicians Leonhard and Albert Euler, but practical application had to await the Frenchman Benoît Fourneyron.

By 1827, Fourneyron had produced a prize winning 6hp outward radial flow turbine. By the mid 1830s, Fourneyron turbines were operating with heads of 350ft, running at speeds of 2000rpm or more. However, the comparative scarcity of heads of water of this magnitude in Europe — excepting in the Alps, Pyrenees and other mountainous districts — allowed the Fourneyron turbine to lose ground to the rival Jonval pattern. Introduced in 1843, this had an axial (lengthwise) flow and was better suited to low head operating conditions.

Next to be introduced was the inward radial flow design. The pedigree of this system was lengthy; conceived by Poncelet in 1826, the first successful machine (still somewhat primitive) was patented by Samuel Howd of New York City in 1838. Significant improvements were made by the American James Francis in 1849, and James Thompson patented his 'Vortex Wheel' in England in 1852.

The development of the water turbine occurred at much the same time as the development of the Bramah Press and the hydraulic ram, the latter being patented in France by Montgolfier and then perfected in Britain in the 1820s by James Easton. The applications of hydraulic power ranged from accumulators and water-engines to the riveters and shears that were indispensable in nineteenth-century industry, and to the recoil-suppressing mechanism fitted to many heavy guns.

The utility of hydraulic power in cranes, hoists and lifts did not pass unnoticed, and soon many docks had been suitably equipped — e.g., London, Glasgow and Birkenhead — and Woolwich Arsenal also benefited greatly. Experience of dockyard installations encouraged attempts to provide hydraulic power municipally. A pioneering step was taken in Hull in 1875, where pipes had been laid under the city streets to consumers who paid for supplies on a metered basis.

The success of the Hull scheme encouraged the incorporation in London in 1882 of the General Hydraulic Power Company, to supply water-power to the bustling Thames-side district from Vauxhall in the west to the West India and Surrey Commercial docks in the east. Steam-driven pumps installed in Falcon Wharf, by London's Blackfriars Bridge, delivered water into two accumulators with a bore diameter of 20in and a 23ft stroke. These were loaded to supply water pressurised at 700lb/sq.in to the mains.

Many hydraulic supply systems worked successfully for decades, despite leakage from high-pressure mains. Rapid progress with electrical supply systems based on steam, gas or oil engines soon swept large water-based schemes away, but a niche was found for hydraulic power elsewhere.

Development of suitable control systems based on oil instead of water allowed the guns of the battleship USS *Virginia* (commissioned in 1906) to be controlled hydraulically, and the introduction in the 1920s of self-contained hydraulic units opened a new vista.

Interest in pressurised-water power waned rapidly in the late nineteenth century, but the sudden rise of the turbine and efficient generating equipment (which was virtually simultaneous) increased enthusiasm for electricity obtained from the power of water. Many successful attempts had been made to harness water turbines to drive machinery mechanically — either directly or through hydraulic systems — by the time the first hydro electric schemes were tried in Switzerland in the 1880s.

The most important of the earliest schemes, and in many ways the most newsworthy, was the attempt to harness Niagara Falls. Thanks to pioneering work undertaken in Europe, the American authorities embarked on the Niagara scheme in 1886. Predictions had shown that four per cent of the river flow, from a head of 140ft, would generate 120,000hp; some observers stated confidently that they believed that 200,000hp would even be possible.

Development work was protracted, however, and the first machinery was not installed until 1894, when three Geyelin Jonval turbines each developing 1100hp at 260rpm were installed by R.D. Wood & Company of Philadelphia for the Niagara Falls Paper Company. The power company also originally intended to use Jonval pattern axial flow turbines, but when power was generated for the first time in 1895, 11,000hp Fourneyron outward flow units were used. Power requirements soon outgrew supply, and so the original turbines were replaced by Francis inward flow units in ?1905.

Britain was slow follow to these leads. Several small-scale hydro-electric schemes had been tried by 1890, but the first important station was commissioned in 1894 to supply the city of Worcester. Built on the site of Powick Mills, this combination of hydro- and steam-electric alternators relied on a head of barely ten feet on the River Teme. The plant consisted of four 125kW Mordey-Victoria alternators driven by three 286hp steam engines, plus two 160hp, one 100hp and one 60hp water turbines. The Powick station operated successfully for some years, but was dogged by perpetual fluctuations in the height of the river and was closed c. 1927.

Although large scale Pitt River and Big Creek hydro electricity schemes were completed in California in the early 1920s, and the Boulder (later Hoover) Dam project was completed on the Colorado river in 1934, enthusiasm for hydro electricity had waned in many countries by the beginning of the Second World War, as it required special water supply conditions to repay the colossal capital investment required in the plant and machinery.

The commercial generation of hydro electrical power had been effectively challenged by rapid improvements in alternative systems, and was fated to remain unfashionable for many years — a pity, as it offers a sustainable source of power at comparatively little cost in environmental damage.

Interest has also focussed on tidal barriers, such as that strung successfully across the Rance estuary in Brittany, and on sea-borne schemes. Technical problems have dogged all of the rollers, floats, 'nodding ducks' and other maritime schemes which have taken the great step from drawing board to reality, but research continues to overcome them.

Water turbines divide neatly into two major classes: impulse and reaction. The impulse turbine is essentially simple. It consists basically of allowing the weight of water from as great a head (or fall) as possible to convert to kinetic energy by passing through a discharge nozzle to form a high velocity jet. This is then allowed to strike buckets on the periphery of a wheel (or 'runner'), which thereafter turns with great speed. The earliest turbines of this type were inefficient, but the Pelton Wheel — in its perfected or 1889 patent form — increased efficiency to more than eighty per cent.

The simple impulse turbine was difficult to regulate, owing to the pressures on the nozzle. Popular means of regulation have included fitting additional nozzles or by using sliding blades to control flow. Alternatively, more than one runner could be fitted to a single driving shaft. Turgo turbines rely on a jet striking obliquely on one side of the runner, then passing through to be discharged on the other side. However, the system is not suited to large sizes.

Reaction turbines work by allowing water to accelerate within the runner to discharge at high velocity, creating a reactive force which turns the runner on its shaft. Reaction turbines, owing to the many variations possible in their construction, can be adapted to almost any applications.

They have also been made in colossal sizes. Water from the head is customarily accelerated to the entry port (‘gate’) of the turbine through a spiral, and then led at enhanced velocity into the runner.

Modern reaction turbines are classed according to whether water flow is axial or radial, even though a radial entry turbine may well have axial discharge. The axial flow Propeller Turbine, with fixed blades, has been particularly popular in North America, where heads are often low and the flow can be very large. The individual turbine units are customarily vertical, though comparatively low power means that multiplication is common. Typical of the most important installations is the St Lawrence Power Station, operation jointly by the USA and Canada, which has more than thirty individual turbines.

Patented in 1920 by Viktor Kaplan, an Austrian engineer, the axial flow Kaplan Turbine offered a runner with adjustable blades. These allowed the operator to adjust the blade angle to suit variations in water flow, significantly improving performance.

WIND

The origins of the windmill are still disputed. Claims that its rudiments were known in the ancient world have never been resolved, and may lie instead in the wind turned oriental prayer wheels. The idea had travelled westward to Persia by the seventh century AD, and had taken firm root within three hundred years. The most obvious characteristics of the Persian Mill were the vertical axis of the wind shaft and the use of a large number of fabric covered sails.

A typical flour mill consisted of a squared two storey building, often with a vertical slit in an appropriate wall to direct the wind onto either a single sail or at least one side of the cylindrical sail disc. Shutters were introduced at an early stage to control the amount of wind that could reach the sails. Alternatively, especially if the mill was sited in an area where the wind direction varied, the sails were mounted tangentially.

The wind shaft ended in a large peg spurred wheel, which drove several smaller shafts keyed to the runner stones. These were generally placed on the second storey floor above the main drive wheel. Though Stephen Hooper erected a few comparable mills in Britain, beginning in Margate in 1787, Persian style windmills only penetrated in numbers into

the eastern Mediterranean margins. Much more common elsewhere was the European Mill, with a wind shaft which was nearly horizontal.

The slight inclination of the shaft — no more than ten degrees — allowed the base of the supporting frame or tower to be tapered outward to gain strength, and bring the centre of gravity of the mill more towards the centre of the tower. This ensured that wear in the bearing would not tip the sail disc forward to a point at which the mill itself overbalanced or collapsed.

Presenting all the sail faces to the wind simultaneously allowed these mills to develop far greater power than Persian predecessors, though they were more difficult and expensive to build. The earliest examples seem to have been made in the twelfth century, but had become commonplace within a hundred years.

It has often been claimed that the windmill was introduced in Europe only after the Third Crusade (1189–92), but the earliest datable references in Britain are said to refer to the use of a windmill in 1165, during the construction of Orford Castle in Suffolk. A written reference to a windmill in Weedley in Yorkshire dates from 1185, and another regarding one in Bishopstone, Sussex, comes from 1191. No European sources can provide earlier information, though one document in France has been tentatively dated to c. 1180.

Owing to the fixed orientation of the sail disc, some means had to be found of turning the mill to the wind. The earliest solution was the Post Mill, with the body and sails of the mill suspended from a sturdy vertical post around which they could turn.

Some of the earliest mills were mounted on an openwork frame of sturdy timbers, but most of the later ones were boarded or bricked-in to provide storage. The mill bodies were customarily protected either with weatherboarding or tiles.

Among the differing post mills were some with the cross-trees and quarter bars either sunk into a pit dug below the body or filled in with earth to present the appearance of a mound. Briefly popular in the twelfth and thirteenth centuries, these had important drawbacks: lowering the body to ground level restricted the sail span, and thus the power that could be developed, and the timbers were much more susceptible to rot.

About 1430, the Dutch developed a hollow post mill. The drive shaft ran down through the main supporting post, which was usually supported in the floor dividing the mill from the storage area beneath it.

The grindstones were sometimes placed in the lower chamber and driven from above. Only a single example of a mill of this pattern survives in Britain, erected on Wimbledon Common in 1817 but subsequently rebuilt in an altered form. It took the form of a small octagonal smock mill on top of a grinding house. The Dutch Wip mill was much like a post mill, but had a small box like body carried on a high frame of cross trees and quarter bars. The tail pole was generally attached beneath the body.

The post mill was joined in the fifteenth century by the Tower Mill. The earliest remains of this type in Britain—near Burton Dassett in Warwickshire—may date from 1470–85. Though many mills of this type were clad in wood (known as 'smock mills' or 'frock mills' in England), a majority were built of stone or later brick. Smock mills were usually octagonal, with sloping or 'battered' sides to make the design neither top heavy nor needlessly cramped at ground level.

The tower mill was sturdier and easier to maintain than its predecessors. The roles of the post and revolving body were taken by a small rotatable cap, apparently introduced in Flanders about 1560. Hybrid mills were also made, often by reconstructing post mills when they were moved to a new site. Typically, these were altered so that the body rotated on wheels or castors running around the 'curb' or support wall top.

Turning the mills to face the prevailing wind — known as 'luffing' or 'winding' — was originally done by hand, helped by an extended tail pole stretching up to the mill body or mill cap. To ease the effort, simple and (later) geared winches were provided; these could be mounted on posts driven into the ground in an arc around the base of the mill. Some mills had hand chain gear, which usually drove a cog ring in the curb by way of a horizontal worm gear.

A fan controlled method was patented in 1745 by Edmund Lee. The vaned fan was mounted either in a frame constructed on the back of the post mill body (the 'fan carriage') or the tower mill cap ('fantail'). Wheels were added to the base of the tail pole, to run around a circular track around the base of the mill or mill cap. The fan was set at ninety degrees to the sail disc. Whilst the sails faced into the wind squarely, the fan played no part; as the wind veered, however, unbalanced pressure caused the fan vanes to revolve. This drove a bevel geared shaft which in turn rotated the wheels on the tail pole carriage to turn the mill body or mill cap around its central axis. When the sails once again faced the wind, the pressure on the fan side ceased and the mill stopped revolving.

The fan carriage and fantail became almost universal in Britain, though it was slow to influence practice elsewhere. More than fifty years passed before fantails were used in Europe, and then only a few Danish and Dutch millwrights followed the lead. Some English tower mills relied on pinch bars bearing in sockets on the inner wall of the tower to rotate the cap, or on a windlass driven pawl meshing with a cog ring inside the curb.

Windmill sails were originally made of canvas stretched over a simple wooden frame — often triangular — whenever the mill was set to work. Gradually, however, a barred rectangular frame became common; sails were initially threaded alternately under and over the bars, perhaps mimicking earlier use of rushes or dried grasses.

Eventually, a standard sail evolved with a sturdy wooden spine or ‘sail stock’ to which a support or whip was strapped. The short sail bars were attached at ninety degrees to the whip and strengthened by thin lengthwise spars called uplongs or — if they provided the outer edge — ‘hemlaths’. The canvas was usually attached by rings to an iron sail rod and cleats on the whip.

By the end of the eighteenth century, sails were being made with a broad leading edge to catch the wind, auxiliary shutters being patented by Catchpole in the 1850s and installed for the first time on Buxhall Mill, Suffolk, in 1860. A distinctive streamlined edge was developed by the Dutchman Dekker in 1924.

The traditional methods of setting the sails and then making adjustments by partly furling (or ‘reefing’) them, often by pulling cords running down the sails’ length, was wasteful of time and effort. Sudden squalls, however, could wreak havoc with canvas sails unless the miller was quick to take action.

In 1772, Andrew Meikle, a Scottish millwright, patented the Spring Sail. Canvas stretched over sail bars gave way to wooden slats, which could be tipped within the frame by the action of a small pinion in a rack on the central control rod. The rod was kept under tension by spring gear.

Alternative methods were tried in the eighteenth century, including a centrifugal self reefing gear in 1780 and Hooper’s roller reefing system of 1789 which found some success in Yorkshire. The development of William Cubitt’s rod and weight Patent Sail, patented in 1807, swept most of them away as it allowed adjustments made without stopping the mill. The first applications seem to have been in Norfolk, almost simultaneously on Cooke’s smock mill in Stalham and the Horning mill.

The secret lay in the insertion of a sliding 'striking rod' in the centre of the wind shaft. The rod was controlled by a balance weight hung from a chain around a wheel. A pinion on the axle of the chain wheel meshed with a rack cut into the tail of the striking rod. The rod protruded through the end of the wind shaft to end in a spider, from which a lever and a bell crank controlled the adjuster rods of each sail. As the striking rod slid outward, it tipped the bell crank and reduced the angle of the shutters; if the wind dropped, the weights on the chain wheel could be used to retract the striking rod and close the shutters to catch more wind.

Several mills used combinations of the Spring and Patent sails, often made locally. Patcham Mill on the outskirts of Brighton was one such site. The first annular sail was designed in Britain in 1855 by Jeremiah Ruffle. Made by Chubb of Colchester, the first two examples were fitted to a Haverhill and Boxford mills in Suffolk in 1861. Perhaps inspired by the triangular jib sails popular for centuries in Crete and Asia Minor, it proved to be exceptionally powerful, but too expensive to maintain to encourage widespread distribution. Only four full size nineteenth century windmills are known to have been fitted with annular sails, but they had an incalculable effect on wind pumps.

The most important factor in the rotation of the sails was the discovery that they had to be set at an angle to the sail disc (called 'weather') to perform efficiently. Tests undertaken by John Smeaton, published in 1759, suggested that the best results could be obtained by reducing weather from about eighteen degrees at the heel to seven degrees at the tip.

Virtually all English mills had four sails, but there were occasional exceptions. A few five-sail mills were made, even though the sail disc could not be balanced if a sail broke; there were at least thirty six-sail mills, eighteen of which are known to have stood in Lincolnshire; and six or seven eight-sailers. An eight-sail mill survives in near-working order in Heckington in Lincolnshire. Elsewhere, twelve and even sixteen sails were to be found.

The largest of the English mills — indeed, the largest ever built in Europe — was Southtown Mill in Gorleston, near Yarmouth, Norfolk, which was built in 1812 and demolished in 1905. The base of the mill tower had a diameter of 42ft, height to the top of the cap being 122ft; the sail span was 84ft. The largest survivor is the eight storey Sutton Mill in Stalham, Norfolk, built in 1789 but reconstructed in 1857; it is 92ft high with a 73ft sail span.

Most windmills operate similarly, though variations could be found in the final drive. The sails turned on their axle or wind shaft to transfer the rotary motion to the vertical main shaft by means of a large brake wheel on the wind shaft and a meshing gear, known as a 'wallower wheel', on the main shaft. The style of the teeth showed a steady progress from crown peg and spur to the cast iron bevel gearing of the nineteenth century.

Take off gearing, crown or spur, was often keyed to the main shaft to drive sack hoists and other auxiliary machinery. The main shaft ended in a large spur wheel, which could lie above or below the grinding floor. This drove the paired millstones through the 'stone nuts', which were generally small spur gears designed to translate the speed of the wind shaft, 12–15 rpm, to the 120–140rpm necessary to grind corn efficiently.

Millstones driven from above were generally controlled by the brake wheel, whereas those driven from below often had a jack ring to disconnect the stone nuts from the spur wheel. Over driven stones were often rotated by a two legged fork (the 'quant') attached to the stone nut spindle, the runner being held clear of the bed stone by a bearing ('mace') and a support collar ('gymbal') which pivoted on a mace head.

The brake gear, originating in the sixteenth century, usually consisted of a strap linking a series of wooden segments. This was placed around a special collar on the wind shaft or the brake wheel itself, being applied by a weighted beam controlled by ropes or chains.

The alignment of the beam could be adjusted by allowing the base of the shaft to rotate in a bridge box, and automatic regulation of the gap between the stones — a process known as 'tentering '— was also introduced. The bridge box was attached to the bridge tree, which was pivoted in the main frame of the mill. The bridge tree was joined at its free end to another pivoting bar called the brayer. The operating lever was a steelyard with a fork at one end to engage the governor and, at the opposite end, a series of notches in which the eye of the tentering screw running through the brayer could be slipped. The steelyard was pivoted in the eye of a hanging rod.

The governor was a flyball pattern of the type introduced by James Watt on even his earliest steam engines, and was thus the first robotic automaton. However, much scorn was poured by millwrights on credit given to Watt, pointing to the prior use of the governor in mills, but the earliest patent — granted to Thomas Mead in 1787 — is virtually contemporaneous with Watt's work. There is also a suggestion that this type of governor may have been tried on atmospheric engines in the early 1760s, and thus that its provenance is not yet clear.

When the mill began to overrun, the balls of the governor rose and raised the spindle collar accordingly. This swung the steelyard outward to move the brayer and the bridge tree downward, effectively moving the runner stone closer to the bed, though the movement was very small.

The position of the fulcrum and the geometry of the moving bridge tree/brayer frame ensured that movement in the collar was reduced two hundred fold by the time it reached the stones. Yet it forced the miller to check the gap between the stones periodically, in case the pressure grew too great, created too much friction and charred the cereal. The tentering screw was used to adjust the gap between the stones, according to grain quality and moisture content.

The most important function of the governor was to guard against failure in the drive mechanism. If something snapped and the governor ceased to rotate, the flyballs dropped and the gap between the stones was increased.

Most of the earliest windmills ground corn. Later, however, water pumping became common. From the middle of the fifteenth century onward, many thousands of wind pumps were used to keep the sea at bay in the Netherlands. At least eight thousand are said to have been at work there early in the eighteenth century. An assortment of pumps was used, but the simplest (and eventually the most common) was the scoop mill. This used an adaptation of the Vitruvian scoop wheel to raise water between two vertical stone or brick walls, clearance between the scoops and the walls being kept to a minimum to minimise spillage. Windmills were also used to drive sawmills, crush ore, and drive winding drums in mines.

Major limitations of the windmill included siting in areas which caught the wind but were otherwise often inhospitable; difficulties in driving external machinery; and surprisingly low power in relation to size. It has been suggested that a large mill with a sail span of a hundred feet could only generate about 10hp in a wind of 20mph.

Even the finest nineteenth century mill is reckoned to have been capable of no more than 30hp, but the average of all the mills active in England at this time was probably only about eight horsepower. The power required to drive each pair of stones was about 2 hp. As the power of even a large mill was appreciably less than an average horizontal engine of the 1850s, therefore, the decline of the traditional windmill was inevitable.

The first wind-engines and wind pumps were minor variants of the standard windmill, much of Dutch practice being introduced into eastern England by the Dutch engineer Cornelius Vermuyden in the seventeenth century. The earliest pumps used crown peg and lantern gearing to transfer motion from the wind shaft to the main shaft, and then from the main shaft to a shallow lift scoop wheel.

The true wind pump, however, required a reciprocating action to drive bucket or bucket and plunger pumps. This motion was obtained in the simplest designs simply by cranking the wind shaft to receive the lengthy pump rods.

Larger and more sophisticated pumps retained a conventional drive, by way of a brake wheel and a wallower. Bevel gearing was then used to drive a supplementary multi throw crankshaft coupled directly to the pump rods. Eccentric and eccentric wheel driven pumps were also used. In the Netherlands, particularly, a small linear wind pump called a Tjasker was coupled directly to an Archimedean screw.

Improvements made in metalworking techniques in the nineteenth century allowed wind pumps to be made in such large quantities that they formed an enduring image of the flatlands of the USA, southern Africa, the arid tracts of Australia and other areas where water was badly needed or to be kept at bay.

The sails were usually short and often annular. They were mounted on wood trestles in the case of the earliest examples, or alternatively on braced metal tube frames. Fantails were customary, as were central shafts geared to reciprocating pumps or scoop wheels.

Amedée Durand (1789–1873) began work in the 1820s, and by the end of the following decade had already designed his first wind engines. An article in the *Gazette du Village*, in January 1864, shows a machine of this type. It also claims that the machines had been invented 'more than twenty years previously' (i.e., prior to 1844) by Durand, 'membre de la Société impériale et centrale de France'. One wind engine, sited on the roof of the Hôtel de Ville, had been raising water to supply the commune of Verberoy (Oise) for fifteen years; and another was erected in Montbron in the Gironde in 1850. These undoubtedly pre-dated the work of Halladay by many years and undermines the latter's claim to novelty.

Durand wind-engines were distinguished by canvas sails spread over wooden frames, giving an appearance similar to many mills that can be seen working in southern Europe from Portugal to Crete. However, the blade disk 'trailed' behind the main vertical pivot and a system of levers attached to the sails allowed them to rotate axially to shed the wind. A weight-and-chain mechanism returned the sails to their original position when the gusts abated.

The *Gazette du Village* article shows the power head mounted on a pyramid made of four stout wooden beams, with vertical pump-rodding running down through a central vertical post. Access to the control mechanism is reached with the assistance of a series of horizontal bars (probably nothing but wrought-iron rods) running through one of the supports. The writer concludes that 'The wind-engine of Mr Durand is, in our opinion, the simplest and most perfect of the engines of this type; it is self-regulating, and it is a time-saver which …is a supreme recommendation.'

Machines of this type were built in small numbers in the 1840s and 1850s and, though made almost entirely of wood (and not particularly durable), probably gave good service. An improved variant now credited to Prosper Dellon, made largely of metal, was then erected in quantity in the departments of Aude, Gard and Hérault in the 1870s and 1880s.

Credit for the development of the first commercially successful self-regulating wind pump is customarily given, especially in North America, to the attempt made by Daniel Halladay 'to improve on the pylon-mounted cloth-sail windmills built by German immigrants in Iowa.' Born in 1816 in Marlboro, Vermont, Halladay was far from the untutored farm-mechanic he is often portrayed. Instead, he had served an apprenticeship as a machinist in Ludlow, close to his birthplace in the cradle of the American engineering industry, and had been employed as a machinery erector in the government-owned armoury in Harper's Ferry, Virginia. By 1851, Halladay had attained sufficient status to attend the Great Exhibition held in London as a representative of "Captain Ericsson's Caloric Engine".

Halladay returned to the U.S.A. to create a 'machine works' in Ellington, Connedcticut, where he had soon perfected his 'Self Regulating Wind Mill', relying on weighted blades which pivoted out of operation if the wind blew too strongly. A company was formed to make the wind engines in quantity, but had soon moved to Batavia, Illinois, to be nearer the rapidly-expanding market for irrigation systems that was to be found on the Great Plains. Ultimately, huge quantities of these single-rotor machines were made: the United States Wind Engine & Pump Company of Batavia, Illinois, was still making 'Halladay Standards' as late as 1929.

Whether Halladay should be regarded as the true pioneer or simply lucky to be in the right place at the right time is arguable. Though his U.S. Patent 11629 of 1854 was a landmark, the work of Durand and others in Europe prceded it by as much as twenty years. And it may not be entirely coincidental that the Halladay engine appeared *after* its designer had returned fron his trip to Britain. A case can be made for seeing any wind engine simply as a logical progression from the English windmill of the industrial age, which had been transformed to the point of self regulation by a fantail driving onto the curb-ring and by a variety of roller-, spring- and proprietary sails. Perhaps Halladay had seen some of these developments at first hand.

In addition, Halladay was not the only experimenter active in the U.S.A. in the mid 1850s, where patents were granted to Francis Peabody of Salem, Massachusetts (no. 12870 of 15th May 1855), Benjamin Frantz of Waynesborough, Pennsylvania (no. 13247 of 10th July 1855) and Frank Johnson of Brooklyn, New York (no. 14099 of 15th January 1856) were among those dating from the period. One explanation is that many inventors were seeking to provide an answer to a very obvious problem. Unfortunately, the omission of application dates from these earliest patents obscures the true chronology; it was now unknown for years to elapse between an application and a grant.

Several of the earliest North American wind engines were marketed commercially—including the Peabody-type 'Essex Wind Wheel'—but Halladay's success swept most of them away. A notable exception was the 'Eclipse', designed by the Reverend Laurence Wheeler of Beloit, Wisconsin, and patented in the U.S.A. on 10th September 1867 (no. 68674). Wheeler's design had a small fixed fantail, projecting laterally from behind the rotor disc to pivot the assembly through ninety degrees if the wind blew too strongly. Weights returned the rotor to its original position when the wind abated.

The first of these machines came to Europe immediately after the American Civil War ended in 1865, and it is believed that a Halladay example was displayed at the Paris exhibition of 1867, where many wind engines, including a French *pananémone*, demonstrated their capabilities in Billancourt.

Huge numbers of imported American wind engines (and copies made with or without the benefit of a licence) were subsequently sold throughout Continental Europe. So many were sold and erected by distributors and

agricultural suppliers, however, that the origins of individual machines can be difficult to determine. Their success has also often obscured the development of superior designs, particularly in France.

Whereas the Halladay Standard and the Eclipse made money simply by selling in large numbers, the Éolienne Bollée was initially aimed at the much more limited market: the rich. Conceived as a pumping engine, the first commercial sale of a Bollée was made in 1872 to Vicomte Jacques de Rougé, to be installed in the vegetable garden (*jardin potager*) of the Château des Rues in Chenillé-Changé. It was followed by many similar installations. In 1898, however, after the aristocratic market had largely collapsed,[°] Auguste-Sylvain Bollée sold the wind-engine business to Édouard-Émile Lebert. Lebert saw greater potential in the communal market, introducing a quadrangular pylon-mount to supplement and then replace the elegant staircase-encircled column favoured by his predecessor.

Designed and made by bell-founders, the Éolienne Bollée was a first-class product. It was undeniably expensive, but, apart from a few comparatively minor weaknesses, proved to be durable; production was limited to about 375 machines, with rotor diameters ranging from 2.5 to seven metres, but about eighty of them still survive in conditions ranging from relic to working order.[°]

Though the French market was ultimately to be satisfied by American-style single-rotor wind engines, imported or made in France once patent protedction had lapsed, there were many much more interesting designs. A little-known engineer named Jassenne had exhibited a wind engine in Paris in 1855, claiming novelty in the position of the disc of eight blades, which was not only comparatively small, but also at the base of an open-ended frustrum (truncated cone). The intention was to funnel wind into the cone, effectively concentrating its effect on the blades.

These power units were winded by a fantail in the form of a winged beast, and built on a conventional open-frame wooden pylon with a balustraded platform. Jassenne is said to have made his machines with rotor diameters of 1.75m, 2.5m and 3.5m; he also claimed a phenomenal '70 per cent' efficiency (at a time when windmills customarily struggled to exceed 20 per cent) and outputs of 0.33cv, 0.5cv and 1.25cv from his éoliennes in a wind of 6 m/sec. Contemporary commentators treated Jassenne's remarks that as much as 3cv–12cv could be produced in a 21 m/sec wind with justifiable scepticism, yet it is likely not only that some of his wind engines operated successfully.

The exceptionally low cost of these simple single-rotor engines ensured that they found countless uses. Among the most efficient of them was the Aermotor, patented in the U.S.A. by Thomas Perry of Chicago, Illinois (no. 000000), which had curved sheet-metal blades and an all-metal tower. Consequently, Perry's design was not only known as the 'mathematical mill' but was claimed to develop greater efficiency than its rivals.[°] The Aermotor Windmill Company was formed in 1888 by Perry and LaVerne Noyes to exploit the patent, but sales were disappointingly slow: only 45 machines were sold in the first year of trading. By 1900, however, more than 220,000 of them had been erected!

The popularity of these windmills—which found countless uses—was so great that trials were organised to test their efficiency. Typical was a competition undertaken in March 1903 in Ealing, London, by the Royal Agricultural Society. Open to wind pumps of less than four horsepower, the competition began with more than twenty different designs. However, as one of the stipulations was that any breakdown requiring specialist attention immediately ended participation, only six of the windmills progressed to the final stages.

The winner was a 16ft diameter wind pump entered by Goold, Shapley & Muir Co. Ltd of Brantford, Ontario. Costing 70, it had eighteen blades grouped in threes, and drove a long stroke bucket pump. Its performance included lifts of 1428 gallons in a wind of six mph, 3608 gallons at nine mph and a praiseworthy 10,047 at 24 mph — more than double the lift of even the best of its rivals.

Next came two pumps entered by leading English manufacturers, Thomas & Son of Worcester (second prize) and John W. Titt of Warminster (third). Each had 16ft diameter sail discs and 24 individual blades, price being 77 and 61 7s 6d respectively. Performance was similar to the Canadian pattern at speeds below 15 mph, but neither managed to lift more than 5000 gallons at 24 mph.

However, these low cost units, which were only marginally less powerful than small windmills of traditional design, were easy to erect and maintain. Variations are still being made, and have had important influences on the design of the current generation of aero generators (q.v.).

CHAPTER TWO

the steam engine from its origins to the work of Newcomen and Watt

Many claims have been laid to the invention of the steam engine, often wrongly and almost always contentiously. Claimants have included Hero of Alexandria and the Marquis of Worcester, and the latter, though irrefutable evidence is lacking, may well have produced a precursor of Savery's engine at about the time of the restoration of Charles II to the throne of Great Britain in 1660. But the true father of the steam engine is now generally regarded as Frenchman Denis Papin.

Born in Blois in 1647, Papin was practising as a doctor of medicine when he was appointed assistant in the Académie des Sciences laboratory in 1671 under the tutelage of founder member Christiaan Huygens. In 1675, fearing religious persecution, Papin (a Huguenot) fled to England. Recommended by Huygens to Robert Boyle, the Frenchman collaborated in the development of a double-acting air pump with a foot stirrup and automatic flap valves.

About 1681, Denis Papin produced his 'Digester'—a pressure cooker intended to soften bones—and invented the safety valve to reduce the dangers he foresaw in high pressures. He then created a vacuum by the explosion of a gunpowder charge, using the power to lift weights or raise fountains. However, the gunpowder engine of *c.* 1688 was a failure, as substantial amounts of air remained in the cylinder after ignition. The inventor then turned his attention to water.

An experimental model was pictured in *Acta Eruditorum* in 1690. It consisted of a closed cylinder (measuring about 2½ × 10in) containing a piston with a rod protruding through the top plate. A hefty weight was attached over a wooden pulley frame to an eye in the top of the piston rod. The cylinder was then partially filled with water and placed over the fire. When the water eventually turned to steam, the piston rose to the top of its stroke until a detent on the top plate sprang into a retaining notch in the rod. This held the piston securely in its raised position whilst the source of heat was removed.

Pouring cold water over the cylinder condensed the steam to water and created a vacuum beneath the piston. When the spring detent was eventually withdrawn to release the piston rod, therefore, the piston was instantly drawn downward by the vacuum.

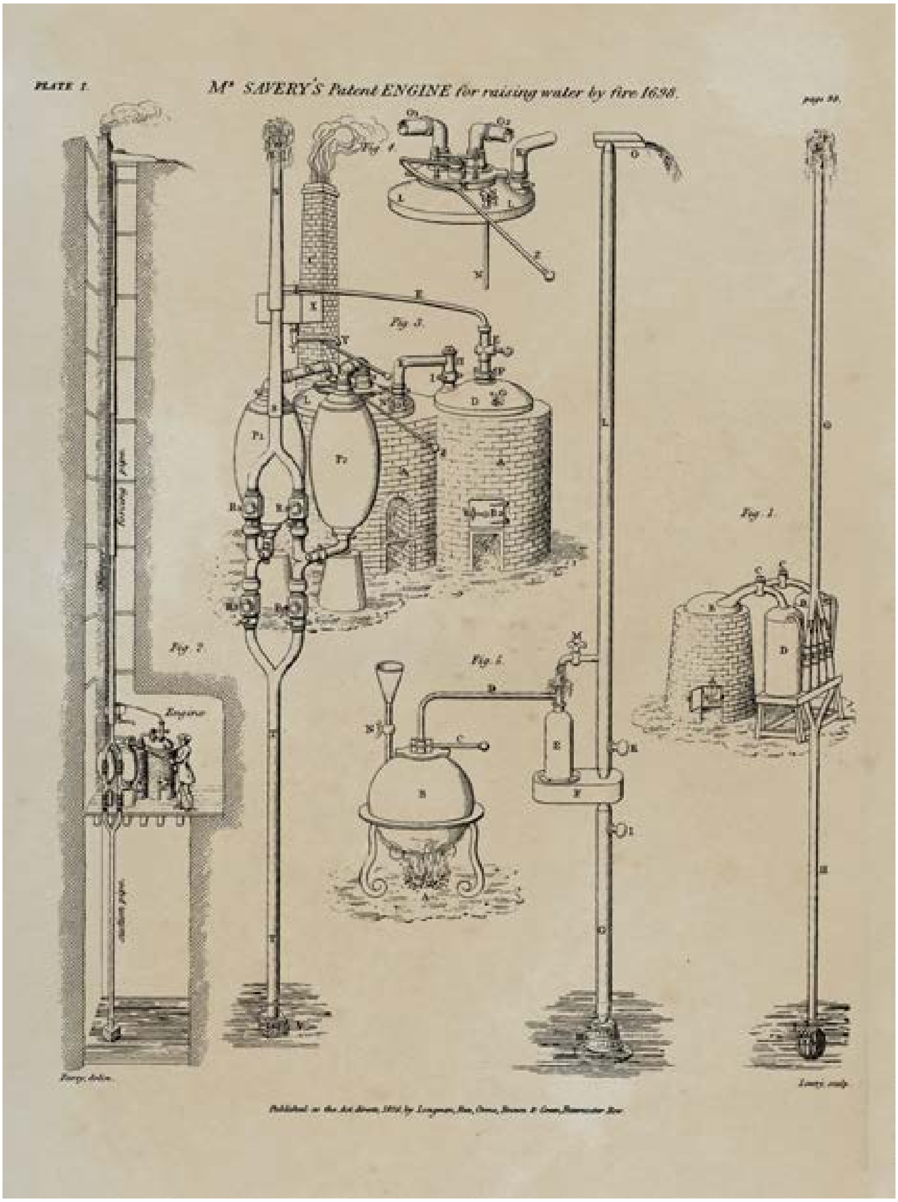
As this action raised the weight, no great problem would have been posed in connecting the engine to a pump, or even to obtain rotary motion. But each piston cycle took a minute, owing to inefficient condensation, and so the machine remained nothing more than an experimenter's toy. Yet the underlying principles of Papin's vacuum engine were to be embodied in the later Newcomen pattern, and the unfortunate Frenchman—who was fated to die in obscurity in 1715—undoubtedly deserves the credit, usually denied him in Britain, that is customarily given in Europe.

THE SAVERY ENGINE

It is no longer known whether Papin influenced Thomas Savery, who took the first step toward perfecting the steam engine. Comparatively little is known about Savery, who was descended from a family settled near Totnes in the sixteenth century, excepting that he was born in the village of Shilston Barton in 1647—the second son of a local landowner, denied a landed inheritance and thus fated to work for his living. Thomas Savery may have had an acquaintanceship with the Cornish tin and lead mining industry, from which his courtesy title 'Captain' may have been gained, though unproven links with military service have also been claimed.

On 14th July 1698, he was granted Letters Patent to protect the exploitation for fourteen years in England and Wales of a 'New Invention for Raising Water'. After a small working model had been demonstrated to James Brydges and Sir Godfrey Copley, but before the patent was granted, Savery petitioned the House of Lords to extend protection. Royal assent was given to the Bill on 6th May 1699, the unparalleled 21-year extension giving Savery a virtual monopoly until 1733.

An engine was demonstrated to members of the Royal Society in June 1699, illustrations in the *Proceedings* revealing this to have been a small two chamber machine with independent manually operated steam cocks. This model was subsequently displayed to King William III and, by the



ABOVE: the perfected two-chamber Savey engine, reproduced from an engraving published in 1828 in John Farey, *A Treatise on the Steam Engine*. The depth from which water could be raised is realistic, but the height to which it is subsequently forced errs on the side of optimism. Consequently, machines of this type failed to answer their principal purpose: mine drainage.

time an appropriate patent had been granted in Scotland on 25th January 1701, the Savery engine was said to be capable of lifting twenty tuns of water hourly through fourteen fathoms (84ft)—equivalent to about 1·9hp.

Though sometimes now seen as a gentleman's toy, capable only of raising fountains, Savery's engine was specifically developed to drain mines. This was a problem that increasingly dogged exploiters as demand grew for coal, tin, lead and other metals. Rapid exhaustion of the seams nearest the surface required shafts to be sunk and adits to be driven if the valuable ores were to be extracted from deep within the ground.

Leaflets produced *c.* 1699 to promote new ownership of the Escair Hîr silver mine in Cardiganshire mentioned the existence of the Savery engine, though there is no evidence that one ever worked in Wales. Clearly, however, its existence was known outside London circles. Several variants of the twin chamber engine were made, differing only in the design of the pipe work and the steam system. The perfected version, which could work continuously, relied on a lever formed into a geared sector to operate twin steam cocks in unison. This was a much more efficient method than working them independently. Savery also promoted smaller single chamber engines—often claimed to have been the earliest patterns, though it is more likely that they were marketed simultaneously with the two-chamber type.

In 1702, Savery briefly advertised regular demonstrations of his invention in London periodicals. He was also involved in promotion of *The miners friend* [sic], a small-format 84 page booklet published in London by Samuel Crouch of Cornhill. This praised the virtues of the engine for draining mines, or to return water to waterwheel head races to provide rotative power.

From 1703—perhaps earlier—to about 1707, Thomas Savery lived in London in Salisbury Court, in the Parish of St. Bride's, Fleet Street, a few yards from Dorset Steps leading down to the Thames. Here he installed a two chamber engine, probably with the boiler, furnace and steam receivers in the basement. Water was lifted from the Thames by suction, about twenty feet, and forced 30 feet upward to a water tank in the roof eaves. From this broad specification, an operating pressure of 20–25 lb/sq.in and a steam temperature of 126–130° C have been be deduced.

Full size Savery engines were installed in London in the grounds of Sion Hall and Campden House. No details of the former survive, but the latter was apparently a small single-chamber machine developing about two thirds of a horsepower. Unfortunately, no authentic engine survives. The drawing (fig. 1) represents the Savery-type engine installed *c.* 1712 in the grounds of Campden House. Water was heated in the spherical boiler to create steam, which was allowed to fill and heat the empty reservoir. The admission valve was then closed, whereupon cold water could be poured over the receiver to condense the steam. This formed a vacuum in the receiver, allowing atmospheric pressure to propel water up the delivery pipe until the receiver was virtually full. Reopening the admission valve allowed steam to flood into the top of the receiver. This forced water back out of the receiver box, but the presence of a non return flap valve beneath the receiver directed the water up through another flap valve into the rising main. Eventually, water was delivered out of the main into a 'launder' or channel, thence into a tank. The cycle could be completed four times in a minute, lifting a total of about fifty gallons.

Limited by the inability of the suction phase to raise water by more than 25–28ft, the Savery engine could not lift high enough to drain mines that may have been sunk hundreds of feet. However, the machines were compact, cheap to buy, simple to operate and comparatively easy to maintain. These benefits persuaded many men to produce similar engines, including Desaguliers—a notably vocal critic of Savery—whose 'improved' design of 1717 was little more than a copy not only of Savery's ideas but also of Papin's safety valve. Several Desaguliers engines are said to have been made, including one installed in St Peterburg for Tsar Peter I, but they had no lasting effect on the history of the steam engine.

Leupold promoted a high pressure Savery type machine about 1720, dispensing with suction lift entirely, whilst a Frenchman named Gensanne subsequently developed a self-acting engine with 'tumbling bob' valves inspired by the Newcomen atmospheric engine. Several Gensanne engines were made in the 1740s, one example in Fresne, near Condé, being described by Belidor in Architecture Hydraulique.

Small Savery type engines were made in Manchester by Joshua Rigley in the 1760s, often surviving into the nineteenth century, whilst Cornishman John Nancarrow produced his own highly individual design of Savery engine in 1797 by separating the condenser from the pump body. One of the last large scale applications was patented in 1818 by John Pontifex, a machine of this type being installed in the City Gas Works, London, in 1822.

The patenting of the Pulsometer pump in 1875 was the final and most successful embodiment of Thomas Savery's ideas. Many thousands of these fast running twin-chamber steam pumps were made until the beginning of the Second World War, finding special favour with engineering contractors for site drainage.

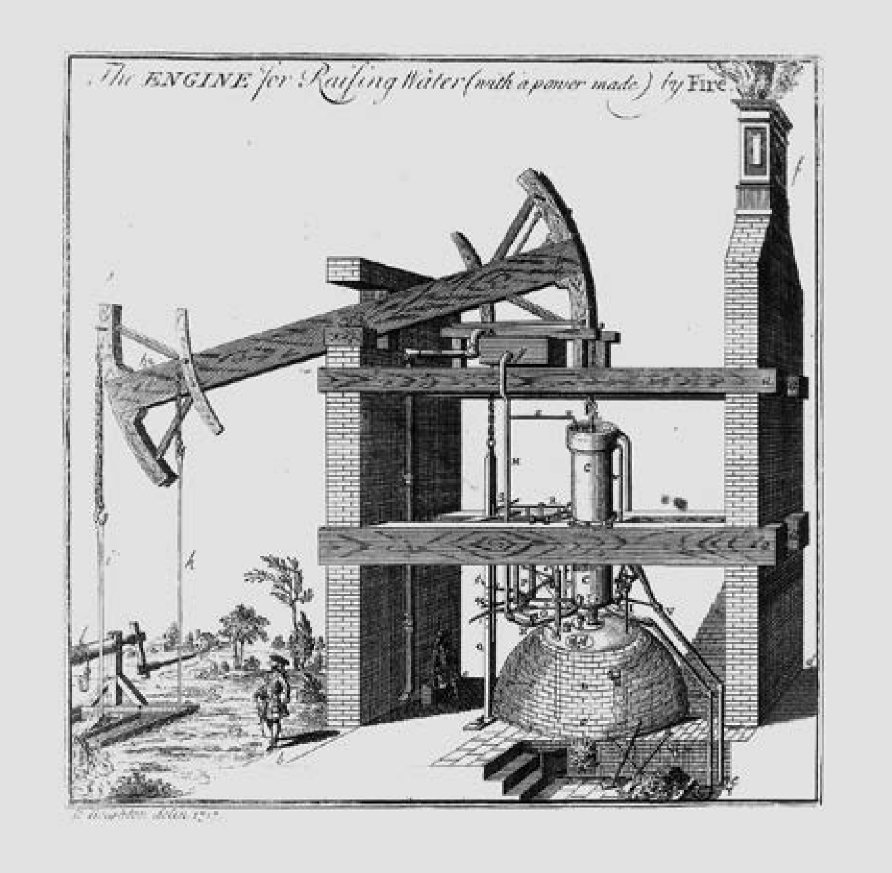
THE NEWCOMEN ENGINE

The inability of the Savery engine to drain mines efficiently drew attention to these problems. The first great advance was found in the Newcomen Engine, but Thomas Newcomen remains almost as shadowy as his near contemporary Savery. Born into a Baptist family in Dartmouth in 1663, Newcomen is said to have been apprenticed to an ironmonger in Exeter before returning to his home town to trade on his own account. By 1690, he had hired 'plumber and glazier' John Calley as an assistant.

The development of the distinctive Newcomen engine must have been lengthy, but, frustratingly, few details survive. Links have been claimed and just as strongly disclaimed with Papin or Savery, but Newcomen and Calley—starting with a vague appreciation of atmospheric pressure and the vacuum—plodded gamely onward until their 'Fire Engine' worked well enough to be marketed commercially.

Seventeenth century ironmongers were also small scale manufacturers, and Newcomen was no exception. Yet the process of perfecting the engine may still have taken ten years. One man who knew the inventor personally, the Swedish engineer Mårten Triewald, subsequently suggested that work had begun independently of Savery but with the same goal of reducing 'the heavy cost of drawing water' (for mine drainage). Stephan Switzer, writing in *Hydrostaticks and Hydraulicks* in 1729, claimed that work on the atmospheric engine had started in the 1690s but also that Savery—with privileged access to Court—obtained his all-enveloping patent before Newcomen and Calley had even heard of his machine.

The Newcomen engine was much larger and more robust than its delicate looking Savery rival, and soon proved to have greatly superior pumping capacity. The first full-size engine is often said to have been installed near Dudley Castle in 1712. However, the absence of fundamental design changes in later Newcomen engines suggests that a prototype was built elsewhere to test the principles. This may have been erected in 1710 at Wheal Vor tin mine near Breage, but there have even been claims that



ABOVE: the engine erected in 1712 by Newcomen & Calley in Coneygree Park, near Tipton in Warwickshire. It was soon famous enough to be the subject of prints taken from a 1719 vintage engraving by Thomas Barney.

a turf-burning engine was to be found a year or two earlier in Balcoath Mine near Helston.

The essence of the Newcomen engine lay in the introduction into the cylinder of low pressure steam, only fractionally above atmospheric level, and in the consequent creation of a vacuum by condensing the steam as rapidly as possible. In his *Descriptive History of the Steam Engine*, published in 1828, Stuart illustrated what he claimed to be the earliest form of the Newcomen engine. The boiler is clearly later (possibly a substitution for the original), but hand operated valves and a water jacketed cylinder testify convincingly to a first step towards perfection. However, working the engine manually depended too greatly on the skill of the minder, and the cold-water jacket could not have been an efficient condenser. Operation would undoubtedly have been slow and hesitant. The design had been improved by the time an engine had been installed in the vicinity of Dudley Castle. Triewald tells that the most important change was the accidental discovery that condensation was greatly improved when water from the jacket entered the cylinder, allegedly through a casting flaw. The resulting vacuum was so strong that the beam chain broke, and the piston smashed its way out of the base of the cylinder to wreck the boiler.

This prototype showed sufficient promise for development work to continue. It had soon been improved by incorporating a water-injecting pipe in the base of the cylinder, vastly increasing power, and only then was a full-size engine erected in 1712 in Coneygree Park, near Tipton in Warwickshire.

This installation was soon famous enough to be the subject of prints taken from a 1719-vintage engraving by file-maker Thomas Barney. Barney entitled his work 'THE STEAM ENGINE near Dudley Castle. Invented by Capt: Savery & Mr Newcomen. Erected by ye later. 1712', the inclusion of Savery's name arising from the nature of his 1698 patent. This forced Newcomen, whose invention may have been an infringement, to agree mutually beneficial terms.

TABLE ONE:

The first ten Newcomen engines

1. Balcoath Mine, Wendron, Cornwall; built by Thomas Newcomen, c.1709*
2. Wheal Vor, Breage, Cornwall; built by Thomas Newcomen, c.1710*
3. Coneygree coal works, Tipton; built by Thomas Newcomen in 1712 ('Dudley Castle')
4. Little Brace shaft, Griff Colliery; built by Thomas Newcomen in 1714
5. Woods Mine, Hawarden, Flintshire; built by Thomas Newcomen in 1714 or 1715
6. Moor Hall, Austhorpe, Leeds; built by John Calley in 1714–15
7. Broseley (?), Shropshire; built by Stonier Parrott in 1715*
8. Stone Pit, Ginns, Whitehaven; built by Thomas Newcomen in 1715
9. Yatestoop Mine, Winster, Derbyshire; built by George Sparrow in 1717
10. Lord Mansell's Colliery, near Swansea; built in 1717

Notes: an asterisk (*) indicates uncertain attribution, identification or date. In addition, Henry Beighton erected an engine in late (?) 1717 at Oxclose, Washington Fell, County Durham, but it is not known whether this machine was finished before the Mansell colliery engine. Thus it should be considered as an alternative 'no. 10'.

The Coneygree atmospheric engine had been moved twice by 1752, ending its days at Willingsworth as a replacement for an unsuccessful Savery pump. It served until the 1780s, though nothing of it remains and even the original site has yet to be conclusively identified. Mårten Triewald, who saw the engine at work, recorded that the cylinder had a 21-inch bore and an 82-inch stroke. Steam was taken from an asthmatic 673-gallon boiler 5 feet in diameter by 6ft 1in high. However, twelve strokes of the pump lifted 120 gallons each minute from a depth of 153 feet.

The parts were massive, but only the cylinder, which had to be accurately bored, placed any burden on existing technology. The remainder of the machinery could be made by traditional blacksmithing and carpentry techniques. Newcomen engines were slow, ponderous and coal hungry, converting less than one per cent of the heat energy into work. But waste coal was plentiful at colliery heads and so this particular drawback—which would have been vitally important in remote districts such as Cornwall—was not immediately apparent. It is probably no coincidence that Newcomen engines were initially concentrated in the coalfields of Warwickshire, North Staffordshire, the Tyne and the Wear. Improvements had been made to the basic engine design even before the deaths of John Calley, in 1717, and Thomas Newcomen in 1729. Apart from the search for greater power, major advances were soon made in valve gear and the method of counterbalancing the pump rod weight.

Problems encountered with the Newcomen engine installed in Stone Pit, Whitehaven, Cumberland, typified those facing the erectors. The engine was built for colliery owner James Lowther by Newcomen, assisted by Thomas Ayres and John Meres, an agreement being signed in October 1715. The 17 × 96-inch[1] cylinder was completed by the beginning of 1717, and, despite persistent teething troubles and an exceptionally severe winter, the engine had soon managed to pump most of the waste water clear of the mine.

In April 1717, however, the failure of sodden timber props (deprived of the support of waste water) allowed the colliery workings to collapse. The iron plates of the boiler were rapidly corroded by acidic water supplies, patching failing to answer until the boiler had been lined with lead. In desperation, Newcomen then obtained a lead-topped iron boiler from Stonier Parrott—but this had failed by the end of 1718 and the original

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[1] Unless expressly specified to the contrary, or obvious in context, the cylinder dimensions given only as '26-inch' refer to the diameter of the bore.

boiler, by then repaired, was pressed back into service. Yet James Lowther still considered the engine a success. An attentive visitor to the pit in 1725 remarked that it was working at fourteen strokes per minute, lifting 140 hogsheads of water hourly.

Rights to the exploitation of the Savery patent passed to his widow in 1715, together with potentially damaging debts. To safeguard Martha Savery's future, therefore, the 'Proprietors of the Invention for Raising Water by Fire' formed themselves into a joint stock company. In addition to Thomas Newcomen (and possibly also Calley), the committee comprised 'gentlemen', a mercer and a tallow chandler. The Proprietors were reluctant to license construction of more Newcomen engines, preferring to retain a monopoly and shares in mine profits which the contracts almost always provided. Few erectors risked trading independently until the Savery patent expired in 1733.

By the eighteenth-century standards, commissioning a Newcomen engine required huge capital investment. The most important component was the cylinder, which was originally cast in brass by bell- or cannon-founders until the Coalbrookdale company offered satisfactory iron castings from about 1720 onward. Brass foundries on Tyneside were among the best, competing with Coalbrookdale until cylinder dimensions grew too large.

Accounts relating to the erection in 1726 of an engine to serve Edmonstone Colliery in Midlothian, by John and Abraham Potter, reveal that the 29-inch cylinder contributed £250 to a total bill of £1007 11s 4d. However, this did not include the cost of building the engine house; and to put these sums into their true perspective, the erectors' assistants were each paid a miserly 15/– (75p) per week.

Edmonstone must have been an especially desperate case; the Potters claimed not only £200 per annum to maintain the engine but also, for eight years from the date of the agreement, a half share of the net profits of the mine. If the engine failed to keep the workings dry, the erectors could remove it without penalty to themselves. Excessive royalty or premium demands did much to restrict the distribution of the atmospheric engine, yet about ninety had been made by Newcomen's death in 1729. Despite carping and often inaccurate criticism from the scientific fraternity—particularly the embittered Desaguliers—hard-headed mine owners were often fulsome in their praise.

Knowledge of the engines spread abroad with Britons and their students. John O'Kelly signed a contract to build an engine in Jemappe sur Meuse, Belgium, in 1720; J.E. Fischer von Erlach, son of the Viennese Court architect, is believed to have erected an engine in Cassel *c.* 1721 after visiting England; Isaac Potter built an engine in Königsberg (Nová Bana) in 1722; and English-trained Mårten Triewald built the Dannemora engine, the first in Sweden, in 1727.

Fischer von Erlach continued to erect engines throughout the Habsburg empire, latterly with assistance from Isaac Potter. One early engine drove fountains in gardens owned by Prinz von Schwarzenburg until the 1770s. With cylinder dimensions of 24 × 108in, working at sixteen strokes a minute, it could lift eight thousand gallons hourly to a 75-feet head. The piston had a leather seal and the serpentine flue passed twice around the boiler before reaching the chimney.

Among the most impressive of the earliest Newcomen engines in Europe were those erected in Windschacht, in the Chemnitz district of Hungary, where Fischer von Erlach and Isaac Potter completed a brace in 1733 and then two more in 1735. Designed to raise water from depths as great as 900ft, the engines required additional counter-weighted 'balance beams' to equalise the great bulk of their massive pump rods. By 1737, a larger engine with a 36-inch diameter cylinder was raising water 212 feet into an adit which was itself 1043 feet below ground level—showing the tremendous progress that had been made in the thirty years since Savery

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TABLE TWO:

The first ten Newcomen engines abroad

1. Jemeppe sur Meuse, Belgium; built by John O'Kelly in 1721
2. Cassel, Germany; built by Fischer von Erlach, c.1721*
3. Königsberg, Hungary; built by Fischer von Erlach and Isaac Potter in 1722
4. Vienna, Austria; built by Fischer von Erlach in 1723
5. Passy, France; built by John May and John Meres in 1726
6. Dannemora, Sweden; built by Mårten Triewald in 1727
7. Cachan près d'Areueil, France; built by Germain Bosfrand and 'Potter' in 1727
8. Vedrun (sic), near Namur, Belgium; built by George Saunders in 1730
9. Fresnes, near Condé, France; built by George Saunders and associates in 1732
10. Windschacht, nr Chemnitz, Hungary; by Fischer von Erlach and Isaac Potter, 1733

Note: an engine is said to have been begun about 1722 by Richard Jones on the Tagus, near Toledo in Spain. Whether it was ever completed is disputed. The Jemeppe sur Meuse engine was moved a few years after completion to Péry.

had raised water a few feet from the Thames into the eaves of his house.

By 1725, use of hammered iron plates was improving the construction of boilers and deadweight safety valves were being fitted on Newcomen engines. The expiry of Savery's master patent in 1733 then gave fresh impetus to the development of atmospheric engines and their accessories. In 1736, for example, Payne proposed the flash boiler with which he experimented unsuccessfully for many years. However, the complexities of construction were beyond the capabilities of the technology of the time and the Payne boiler—ahead of its time—was abandoned.

Among the first viable attempts to use a steam engine for marine propulsion was made in this period. In 1736, Jonathan Hulls of Campden, Gloucestershire, patented a rudimentary tugboat that is said to have been tested on the River Avon at Evesham in 1737. Hulls used a Newcomen-type atmospheric engine in conjunction with a stern-mounted paddle wheel, loose rods being attached to the paddle-wheel shaft to act as punt poles. The piston was weighted, useful work being done on condensation, driving the paddle wheel through piston rod and ratchet gear, but the project failed and nothing further was heard.

The Newcomen engine had an open-top cylinder containing a piston connected with an operating beam or 'Great Lever' pivoted centrally. The outer end of the beam generally projected beyond the engine-house wall to connect with the pump rods. Chains running around curved vertical extensions—'arch heads'—on each end of the beam held the piston and pump rods as near vertical as possible throughout the operating cycle.

The underside of the cylinder was connected directly to a round-top boiler, steam being admitted through a valve in the connecting tube. Operating pressure was only a few pounds above atmospheric level, but counterbalancing the pump rod ensured that this was sufficient to raise the piston. An additional counter-weight was commonly encountered in deep mines, where the weight of the rods was too great to balance the beam and piston mechanism.

The auxiliary weight was often a supplementary beam fitted above the Great Lever on European engines, but was commonly placed at ground level in Britain. Additional pump-rod weight helped to pull the piston up to the top of the cylinder above the steam, simultaneously lowering the bucket-pump rod into the pit.

When sufficient steam had entered the cylinder, the valve was shut. Assuming that enough steam remained in the boiler, a buoyed valve opened the injection cock to allow a jet of water into the cylinder. The reduction in temperature condensed the steam to water, and a surprisingly powerful vacuum was created beneath the piston. This immediately sucked the piston downward, pivoting the beam, lifting the pump rod and delivering water to the pump head. The condensate ran out down the eduction pipe, any moisture remaining in the cylinder being expelled by the next admission of steam.

Water to feed the injection system, and seal the piston by pressing a leather cup outward, was raised to an elevated cistern by a force pump attached to a diminutive supplementary arch head on the main beam.

The first engines may have been manually operated, but Newcomen and Calley had soon developed a weighted-lever system driven from a plug rod suspended from the beam. The introduction of automatic valves is often (if wrongly) attributed to the 'lazy boy' Humphrey Potter, who seems simply to have discovered how to interconnect the valves to isolate the buoy from the cycle. Thus the engine not only became entirely automatic but also ran faster as long as the boiler could sustain steam pressure, though the power of the vacuum was reduced. Improved boiler designs eventually solved steam supply problems permanently, but only some years after the first engines had struggled to address their tasks.

Some eighteenth-century writers, notably Desaguliers, have credited Henry Beighton with the introduction of automatic valve gear. Beighton substituted a simple toothed sector for the original weighted 'Y' lever, but this was retrograde: the best steam valves were opened and shut rapidly, instead of in a gradual creeping motion. Beighton gear may have been retained for injection cocks, but was soon abandoned for steam valves.

The early Newcomen engines were feeble machines. As many experimenters rapidly discovered, they were at their best in large sizes; one 1729 vintage trial of an atmospheric engine against a Savery-type machine of similarly restricted dimensions was widely advertised in favour of the latter.[2]

An atmospheric engine in the Science Museum collection, with a cylinder diameter of 21 inches, was rated at about 4·8hp at twelve strokes per minute; and an indicator diagram taken in May 1895 from a 66-inch

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2. However, the Newcomen-type engine, with a 6 × 24in cylinder, was a working model built for Desaguliers by brass-founder 'Gun' Jones; Jones may simply have lacked sufficient knowledge to make it work properly and the results of the trial have been questioned. It was virtually impossible to compare Savery-type receivers directly with the Newcomen cylinder.

survivor erected in the mid-eighteenth century at Ashton Gate, Bristol, returned 38·5hp (51·4ihp) at ten strokes.

The mechanical efficiency of the latter was surprisingly good—about 75 per cent—but the overall efficiency proved to be a disappointing one per cent, even though improvements had been made to the Ashton Gate engine in the nineteenth century. However, as even the biggest and best windmills rarely generated more than ten horsepower, large Newcomen engines provided a significant advance in power generation.

One problem was the inability of metal founders to supply enough large cylinders. Consequently, some collieries were ringed with smaller engines. A survey in the Tyne & Wear coalfield in the early 1730s revealed that Byker pit had six engines, Long Benton had five, and at least three other sites had four apiece. By 1760, more than 350 Newcomen type engines had been erected. Initially concentrated in the Midlands and north-eastern England, they had spread into Devon and Cornwall after the remission in 1741 of a punitive coal duty. By 1778, at least seventy engines had been built in Cornwall alone, including a 70-inch pattern installed in Herland Mine in 1753. Among the leading the erectors of the day were Jonathan Hornblower, John Nancarrow and John Budge.

The first atmospheric engine to be erected in North America was ordered in England in 1749 by Colonel John Schuyler, whose copper mine had been driven too deep for horse pumps to drain. The major engine components were dispatched from London in June 1753 in the charge of Josiah Hornblower, building work being completed in March 1755. The engine worked successfully for some years, but was twice damaged by fire and acquired a new cylinder each time it was rebuilt. In its final guise, it could lift 134 gallons per stroke from a depth of one hundred feet.

Newcomen engines were also erected in Russia. Nikolai Polsunov is said to have begun construction in 1763 of an engine with two cylinders with an improbable 2-inch bore and a 108-inch stroke. It is hard to imagine this curious machine working efficiently, but, completed after its designer's death, it apparently drove iron furnace bellows for many years.

Typical of the emerging entrepreneurial English engine builders was William Brown, who built 22 in northern England and three in Scotland in 1756–77. Brown—by realising the importance of adequate steam supply—deserves to be recognised as the first to provide suites of boilers to replace the single haystack or wagon top. Using three of the four boilers provided, the fourth being kept in reserve, Brown's 74-inch Walker Colliery engine made 8–10 strokes per minute on a daily consumption of 6–7 tons of coal. Water was raised 534 feet in three stages.

The largest engine operating in the middle of the eighteenth century was a water-returning machine in the Warmley Brassworks, Bristol. Supplied from Coalbrookdale in 1761, its cylinder had a 74-inch bore and a length of 120 inches. Four 29-inch diameter bucket pumps were used to raise nine thousand hogsheads of water hourly through eighteen feet.

Though James Brindley (1756) and Sampson Swaine (1763) developed new boilers—Swaine's was made of moorstone (granite) blocks with three large copper flues—no significant advances occurred until John Smeaton became interested in the technical development of the atmospheric engine.

Smeaton was a contemporary of James Watt, beginning his experiments almost as Watt created the separate condenser, but was dead before this threat had truly overcome the atmospheric engine.

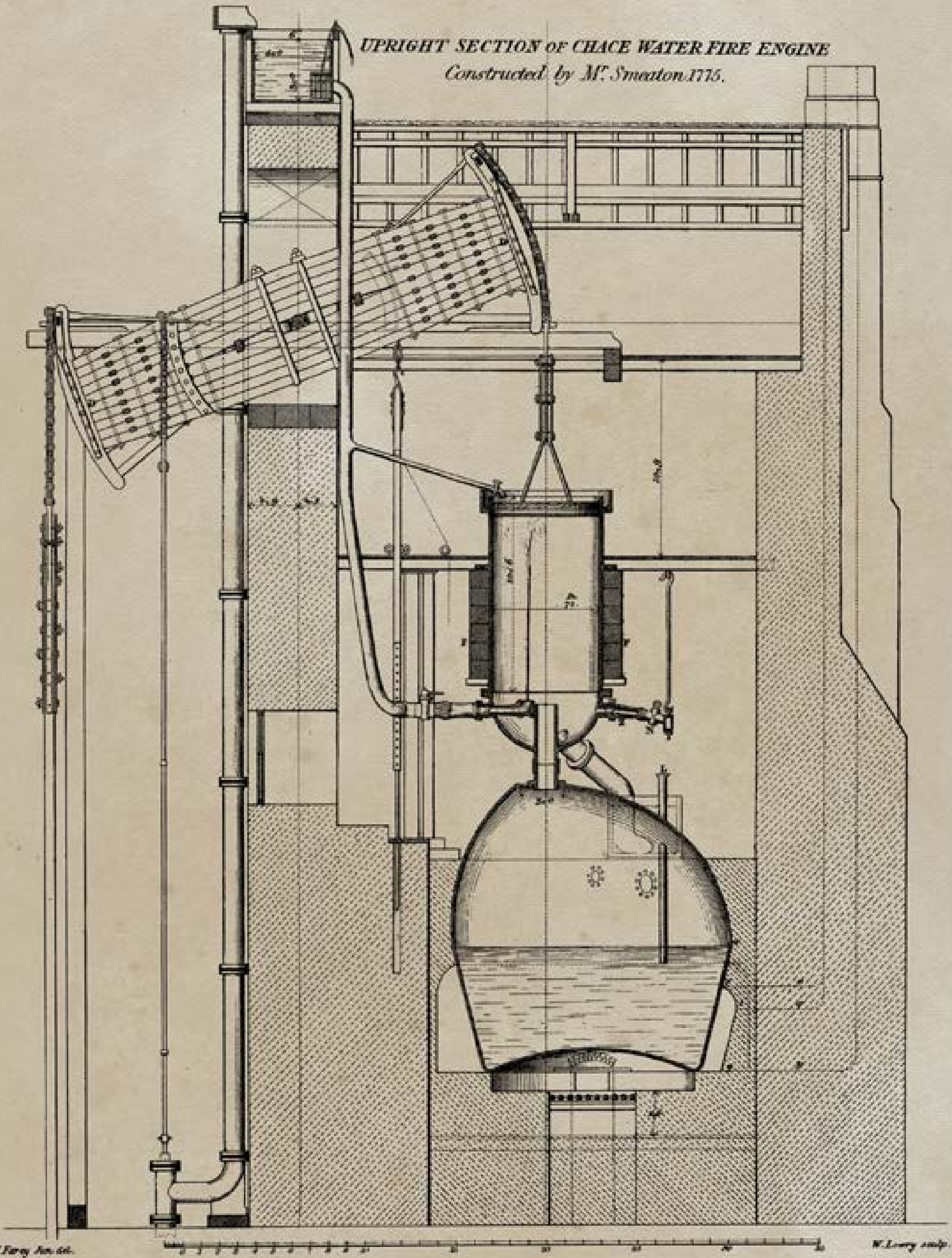
His first full-size engine was installed at New River Head, Islington, in 1767. Unfortunately, it failed to reach expectations, owing to misjudgement of the ideal bore/stroke ratio. Smeaton, undeterred, began a thorough investigation into the causes of failure. He had soon established the concept of 'Duty'—the weight of water in pounds which could be lifted to a height of one foot on a standard measure of coal (then usually a bushel of 84lb). 'Great Product' was the volume of water raised one foot high in a minute, providing a useful means of comparing the output of engines which differed greatly in construction.

Testing fifteen atmospheric engines in the Tyne & Wear coalfield revealed that performance did not depend solely on cylinder diameter. Thus the 75-inch engine returned a Duty of 4·59 million (37·6hp), compared with 5·88 million (40·8 hp) for a supposedly less powerful 60-inch example.

Smeaton soon discovered that power was limited by badly bored cylinders; poorly sealed pump and cylinder pistons; constricted steam admission pipes; poor valve timing; badly made boilers; grates which were placed too low to heat the boiler satisfactorily; and piston strokes which were too short in relation to the length of the cylinder.

Working in close association with the Carron Company, where accurate cylinder boring machinery had challenged the Coalbrookdale monopoly, Smeaton built several greatly improved Newcomen type atmospheric engines. These included the Long Benton Colliery machine of 1772, with cylinder dimensions of 52 × 84in, which gave a Duty of 9·45

UPRIGHT SECTION OF CHACE WATER FIRE ENGINE
Constructed by Mr. Smeaton 1775.



J. Farey Jun. del.

W. Lowry sculp.

Published as the Act directs 1826 by Longman, Rees, Orme, Brown & Green, Paternoster Row.

million when running at twelve strokes per minute. A 72-inch engine was erected in Chace Water in 1775, and a 66-inch pattern began pumping duties in Kronshtadt in Russia in 1777.

Smeaton engines usually had hemispherical cylinder bases and laminated wooden beams. The cistern supplying the cylinder injector was raised into the eaves of the engine house to increase pressure, and the hot well was improved to double as a rudimentary feed-water heater. A 'pet cock' was added in the eduction pipe to bleed air into the cylinder when the engine was running under light load, restricting the volume of steam admitted by reducing the strength of the vacuum. This was regarded as a better solution than tinkering with the valve gear settings or altering the length of the piston stroke.

A cataract or 'Jack-in-the-Box', apparently originating in Cornwall, was added to control the injection cock. It comprised a cold-water tank containing a small weighted cup which overbalanced when full to open the injection port, empty itself, and then return to its original position. The cataract was usually disconnected, allowing the engine to run automatically at full speed. If less power was needed, however, the minder could engage the cataract and set the frequency of the piston strokes by controlling the flow of water to the pivoting cup.

The jerky movements of the Newcomen engine were unsuited to rotary motion. Even Smeaton recommended using the engines in conjunction with waterwheels if a steady turning movement was required. Yet several attempts were made to make rotative atmospheric engines. Mårten Triewald had tried unsuccessfully in Sweden in 1730, as had George Richardson in England in 1734.

Working at Hartley Colliery in Northumberland, Joseph Oxley experimented in 1763 with a ratchet-drive winding engine, but the motion was so erratic that the mine owners soon reverted to a waterwheel. A ratchet mechanism developed by John Stewart in 1766 was also a failure, even though it had been used on a sugar cane mill sent to Jamaica c. 1768. Matthew Wasbrough of Bristol developed a pawl-and-ratchet drive for his machine tools in 1778, seeking a Boulton & Watt engine to drive it. However, the order was declined owing to pressure of work and Wasbrough built a Newcomen-type engine of his own. One of these patent ratchet engines was subsequently delivered to James Pickard's metalworking factory in Snow Hill, Birmingham.

Pickard was himself granted a Scottish patent for a pawl-and-ratchet mechanism in April 1779, which may indicate that he was backing Wasbrough financially. The unreliable ratchet gear was soon replaced by a primitive crank and flywheel drive, though the precise nature of this has been disputed; Pickard patented a method of carrying a crank over dead centre in August 1780, relying on a weighted pinion geared into the crank disk, but James Stead is sometimes credited with this particular invention. It is possible that the entrepreneurial Pickard was backing Stead as well as Wasbrough.

Though the torque of Pickard's crank system was irregular, it exploded the myth that cranks—well known even in 1780—could not be compatible with steam engines. Probably in an attempt to have a competitive patent annulled, James Watt claimed that Pickard had only heard of the crank when Richard Cartwright, a Boulton & Watt employee, described Watt's design to the minder of the unsatisfactory Wasbrough ratchet engine in the Snow Hill workshop.

A few of the Newcomen engines built towards the end of the eighteenth century were intended for maritime use. Among the earliest experimenters was the American James Rumsey, who in 1784 demonstrated a model to George Washington in Bath, Maryland. The original intention to use pole propulsion was subsequently abandoned in favour of a hydrojet, relying on a steam-driven pump to force water through narrow orifices. The earliest known trial of Rumsey's full size vessel occurred in December 1787.

John Fitch of Windsor, Connecticut, working at the same time as Rumsey, presented his model to the American Philosophical Society in Philadelphia in September 1784. It was also demonstrated to George Washington, shortly before Fitch sought protection for his invention from the State of Virginia. The first full-size boat, 34 feet long, dates from this period. It was propelled by a chain and sprocket mechanism, which transmitted power from the engine to the gears controlling two banks of six canoe-type paddles. A small atmospheric engine with a 12-inch cylinder provided the power.

Fitch produced his third design in 1789, allowing the Steam Boat Company to ply the sixty-foot vessel between Philadelphia and Burlington; a larger boat was substituted in 1790. Fitch was granted a French patent on 29th November 1791, whilst Rumsey tried a steamboat on the Thames in 1792. However, Rumsey died unexpectedly shortly afterwards and his work was not perpetuated. By 1795, John Fitch was experimenting with a propeller driven boat on Collect Pond, New York, but success still eluded him. He committed suicide in 1798 before his visions could be realised: a sad end to an eventful and productive career.

THE LAST ATMOSPHERIC ENGINES

Atmospheric engines of surprisingly basic design were still being made in the 1820s, though their boilers had not only been improved but also separated from the engine houses, and 'pickle pot' condensers had often been added after Watt's separate condenser patent expired in 1800.

A 42-inch Newcomen engine erected in 1795 at Elsecar, near Barnsley, was not superseded by electric pumps until 1923 and even then was retained for ten years as an emergency stand-by. It retains an air of antiquity in its preserved state, despite a replacement 48-inch cylinder dating c. 1801 and extensive nineteenth-century modernisation which included fitting of drop valves, addition of parallel motion, and substitution of a cast-iron beam for wood.

Also long-lived were the 36-inch engine installed in 1806 in Caprington Colliery in Stirlingshire, which had been built about 1775 by the Carron Company and lasted until 1901. A 54-inch example at Westfield, Yorkshire, worked from 1823 until 1934; a 1750s 66-inch engine in South Liberty Colliery of the Ashton Vale Iron Company, Bristol, was working well enough in 1895 to permit indicator diagrams to be taken; and a 48-inch engine installed in 1776 by the Coalbrookdale Company in Old Handley Wood Pit, Shropshire, lasted after a move to Staveley Colliery until 1879. All three had been modernised in the nineteenth century, when parallel motion, cast-iron beams, new valve gear, and pickle pot condensers were fitted.

Other well-known survivors include an engine erected *c.* 1760 at Cannel Mine, Bardsley, near Ashton under Lyme. Though derelict by 1830, the major components of the engine (known as 'Fairbottom Bob') survived to be purchased by Henry Ford in 1930. It was then restored for display in the Dearborn Museum in Michigan.

A single-cylinder engine erected in 1791 at Oakerthorpe Colliery, Derbyshire, by Francis Thompson, was moved to nearby Pentrich in 1841, condemned in 1918 and given to the Science Museum; and a second-hand 22-inch engine, believed to have been made by Jonathan Woodhouse about 1815, worked in Hawkesbury, Warwickshire, from 1821 until 1913.

Remnants of the Hawkesbury atmospheric engine were gifted in 1963 to the Newcomen Society by the British Transport Commission, to be reconstructed in Dartmouth in time to celebrate the 300th anniversary of the inventor's birth (1967).

THE FIRST WATT ENGINES

The son of a shipwright, ship owner and chandler, James Watt was born in Greenock in 1736. Watt was a poor scholar, excelling only in mathematics, and was apprenticed to an optician before being advised to go to London to learn the instrument maker's trade. After working for one year with John Morgan of Finch Lane, Cornhill, he returned to Glasgow in 1756 to renew contact with the university. Skilful repair work and the friendship of Joseph Black, professor of anatomy and chemistry, soon allowed Watt to open a workshop within the university precincts.

In 1760, Watt was asked to repair a defective model Newcomen engine. Eventually, with the help of Dr Black, who had formulated the theory of latent heat, Watt not only grasped the underlying principles of the atmospheric engine but had also realised that the loss of latent heat was a serious flaw.

The development of a separate condenser was the first great breakthrough, representing the greatest single advance made in the history of the steam engine. Steam had previously been condensed within the cylinder itself, but alternately heating and cooling the cylinder body was extremely wasteful: even the best atmospheric engine converted only one per cent of the energy supplied to it into work. Great strain was placed on the joints, even though steam pressure was only slightly greater than atmospheric level.

Watt suspected that steam would rush from the cylinder into the supplementary chamber if cold water could be injected into the chamber to form a vacuum. A roughly-made model worked well enough to establish the principle, but the inventor had trouble making the great leap from small scale experimentation to an engine large enough to be useful. His problems were then eased by John Roebuck, a former Glasgow university student who had also been one of the founders of the Carron ironworks.

When Roebuck became associated with drowned coal and salt mines in Borrowstouness (Bo'ness), he discovered that the existing Newcomen type atmospheric engine was unable to drain them. He mentioned the problems to Joseph Black, whereupon Black told Roebuck about James Watt's developments. Roebuck had soon decided to finance construction of a full size engine with a separate condenser.

An experimental engine was built near Kinneil House in 1765/6. It had an inverted cylinder measuring about 18 × 60in, a distinctive plate type condenser, a separate air pump and a single manually operated valve. Its power could be demonstrated by lifting a boulder attached to the piston rod. Another design—probably never exploited—had an upright cylinder operating a pump by way of a short chain running over a large diameter pulley wheel; a rotary engine also originated in this period.

Experiments continued with differing piston seals, condensers and air pumps until, by 1769, Watt was ready to apply for a patent. Drawings prepared in this period show a single cylinder engine with a closed cylinder connected with a small condenser attached to an air pump. The condenser and pump were immersed in a cold water tank. The piston drove onto an arch head attached to the beam end, and the steam valve separated the base of the cylinder from the condenser chamber.

Roebuck, meanwhile, having paid debts accrued by Watt and Black, was willing to finance the patent application. The perfected Kinneil engine, finished in 1770, used an 17·875in diameter cylinder to drive a bucket pump with a diameter of 18 in and a length of 25ft. Problems with the piston packing soon showed that the tin cylinder had been made badly out of true.

When the engine was made to work at six strokes per minute, on acceptably little steam, it stopped virtually every time the pipe condenser was connected. The problems persisted even after improvements had been made to the condenser, until it was discovered that the condenser worked much better if air was allowed to remain in the chamber instead of flooding it on each exhaust stroke.

Unfortunately, John Roebuck soon overreached himself and was declared bankrupt. The incomplete Kinneil engine became the property of James Watt in return for discharging debts, but the project was then enthusiastically championed by Matthew Boulton of the Soho manufactory in Birmingham. With a manufacturing background, Boulton could see the commercial potential that lay in the separate condensing engine.

Watt left Scotland for Birmingham in May 1774, and the Kinneil engine, which had been dismantled, was re erected in Soho to return water to the head of the wheel that drove the grinding machinery. The engine retained its copper bottomed tin cylinder and a surface condenser made of tubes. The cylinder may have had a steam jacket, and a single Newcomen type oscillating sector valve controlled admission and exhaust simultaneously. The valve had a single central cavity which connected with ports in the base plate.

Trials continued until the worst problems had been solved. The tin cylinder was replaced with a new iron casting with an internal diameter of about 18in and a stroke of 60in, the condenser was improved, and a better piston seal was developed.

Eventually, the engine began to operate satisfactorily; by the summer of 1775, running at 14–15 strokes per minute, it was managing to raise 16,000 cubic feet of water on a hundredweight (then 120lb) of coal.

The patent protecting the separate condenser, granted in 1769, would expire in 1783 and expose the Watt engine to imitation. Matthew Boulton realised that this would be financially disastrous if completion of the design was delayed, persuading Watt to petition parliament to extend protection just as Savery had done at the end of the seventeenth century.

TABLE THREE:

The first ten Watt single acting engines

Note: excludes the experimental Kinneil engine of 1770, re-erected in the Soho manufactory in 1774

1. New Willey ironworks, Broseley; erected by John Wilkinson, 1776.
2. Bloomfield Colliery, near Tipton; erected by Perrins, 1776. 50in cylinder.
3. Brewery of Cook, Adams, Wilbey & Sagar, Stratford le Bow, London; erected by Joseph Harrison and James Hadley, 1776. 18in cylinder.
4. Hawkesbury Colliery, Bedworth; 1777. 58in cylinder.
5. New Willey ironworks, Broseley; erected by John Wilkinson, 1777. Known as 'Topsey Turvey', this engine had an inverted cylinder.
6. Wheal Busy (also known as 'Wheal Spirit'), Chacewater, Cornwall; erected by Thomas Dudley, 1777. 30in cylinder.
7. Wilson House, Lancashire; erected by John Wilkinson, 1777 or 1778.
8. Gunton (?), Norfolk; erected by Boulton & Watt, 1777/8. Built for Sir Harbord Harbord; 6 in cylinder.
9. Torryburn, near Dunfermline, Fifeshire; erected by Henderson & Symington, 1778. 44in cylinder.
10. Snedshill Colliery; erected by John Wilkinson, 1778.

The partners were successful, but only after voluble opposition to the extension on the grounds that the Watt design was only a minor variation of the 'Common [Newcomen] Fire Engine'.

The Bill received royal assent in May 1775, extending the life of the 1769 patent until 1800. Watt gained time to perfect his separate condensing engine, but industrial development in the late eighteenth century was thereby hamstrung by encouraging Boulton & Watt to threaten many rivals with litigation. Consequently, far too many promising designs were still born, including the earliest Hornblower compounds.

The success of the rebuilt Kinneil engine allowed Boulton & Watt to advertise commercially. A simple injector or 'jet' condenser had replaced the tube pattern, without reducing efficiency; the oscillating sector valve had been superseded by 'drop' patterns; the cylinder base became cast iron instead of copper; and the air pump was improved.

The first engine to be erected was a 38in pattern in the New Willey blast furnaces, near Broseley in Shropshire. These were owned by ironmaster John Wilkinson who, just a year earlier, had introduced a cylindrical boring mill. Wilkinson built his own engine to Watt's designs, requiring Soho to supply only a key minor parts.

The operation of the single acting engine is explained on the accompanying drawing. Starting with the piston in its rest position at the top of the cylinder, all three valves (steam, equilibrium and exhaust) were opened to allow steam to pass through the engine, warming the components and expelling unwanted air. The equilibrium valve was then closed and the condenser jet was activated to create a vacuum beneath the piston. Steam at boiler pressure—still only slightly above atmospheric level—then pushed the piston downward to the base of the cylinder.

When the piston reached the bottom of its stroke, the equilibrium valve was opened whilst the admission and exhaust valves were closed. Part of the steam in the cylinder flowed out of the equilibrium valve and under the piston, equalising the pressure. This allowed the weighted pump rods to pull the piston up the cylinder, where it waited until a cataract capsized to close the equilibrium valve. Admission and exhaust valves then reopened, allowing the operating cycle to begin again.

The first two strokes of the piston were worked manually, but the plug tree thereafter worked the valves automatically. A description of the original Broseley engine explains how the earliest single acting machines were made.

Building engines with cylinders as large as the 50in pattern erected in 1776 to drain Bloomfield Colliery, near Tipton, was ambitious. However, even the earliest of them operated satisfactorily after teething troubles had been overcome. The separate-condenser engine was much more efficient than even the best open cylinder atmospherics.

The Bloomfield Colliery engine was put to work to drain a drowned ninety foot shaft, where the standard 14 in diameter pump was expected to lift waste water from depths as great as 360 feet. A trial of the engine in Hawkesbury Colliery, by arbitrators assessing premiums, decided that the Watt machine was 'better than the old Common [Newcomen] engine' by a factor of about 4 to 1.

The first engine to be sent abroad went to Jary of Nantes in 1779, but little of the earliest engines emanated from Soho excepting the valves, valve gear and other vital components. The cylinders were often cast in Coalbrookdale whilst the remaining fittings were usually commissioned independently by the erectors. Consequently, variations were often to be found in the construction of steam jackets, air pumps, condensers, beams and framing.

The earliest engines suffered from broken parts and were often out of action for long periods. Yet still they worked impressively enough to lead the steam revolution. Detail improvements attributable to James

Watt included the glass water gauge of 1775 and anti-friction metal in soft packing, introduced in 1778. By 1780 Watt had also pioneered the wagon boiler, offering far more heating surface than its predecessors, and then went on to produce an efficient smoke consuming furnace in 1781.

Completing the simple single-acting engine encouraged Watt to experiment with the expansive properties of steam. Cutting the steam supply early in the stroke let piston travel be completed simply by allowing the steam already in the cylinder to expand. A 33in engine erected in Soho to test the theory worked too violently until changes had been made, including the addition of a steam jacket, alterations to the valves, and revisions to the plug tree.

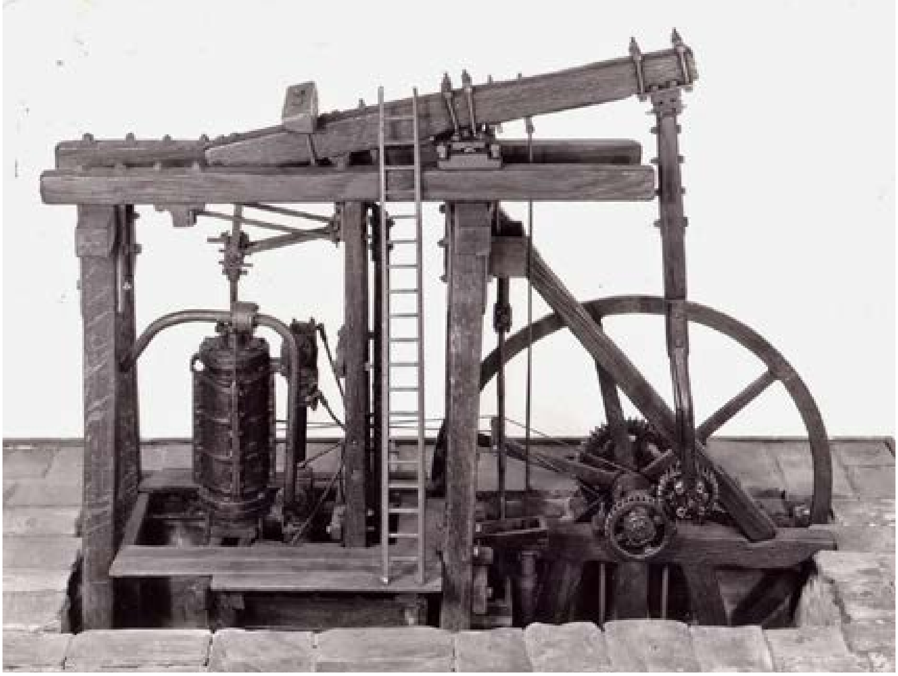
However, despite the care lavished on it, the expansive engine was not an immediate success. Watt lost interest in the late 1770s, much to Boulton's irritation—he could see its merits—and did not resume work until goaded by news of Jonathan Hornblower's two cylinder proto-compound.

In 1782, James Watt received a patent protecting several ideas: expansive working; methods of equalising variations in the power generated during each piston stroke of an expansive engine; a flywheel driven by a pinion and segment on the arch head; and rod and crank drive. The last claim was applied specifically to pumping engines, as Watt was well aware that the patent granted in 1780 to James Pickard had been applied only to rotative machines.

A curious 'Double Engine' was created in this era, but, although one was built and tested, the project ended in disaster. The machine was reconstructed as two separate single-cylinder engines. One interesting feature of the original design was its ability to run as a compound—albeit inefficiently, as the cylinders were of equal size just as Hornblower's had been.

THE DOUBLE-ACTING ENGINE

The life of the expansive engine was short, owing to the development of the double acting pattern in 1782–3. The idea had occurred to Watt some years earlier, and a drawing of an engine capable of admitting steam alternately above and below the piston had even been prepared for a House of Commons committee in the mid 1770s. The resurrection of the idea



was largely due to Matthew Boulton, who wanted a rotative engine which not only evaded Pickard's crank drive patent but also ran more smoothly than single acting types.

The relevant patent dated from March 1782, though completion of the first full size engine was delayed until the winter of 1782/3. It had an 18 × 18in cylinder and ran at the surprisingly high speed of sixty strokes each minute. A high speed engine with a 12 × 12in cylinder was also apparently tested in 1783, running at the unprecedented speed of 100 strokes per minute. It had a trunk piston and may also have had an early form of slide valve.

Short stroke operation, championed by James Watt but mistrusted by Matthew Boulton, proved to be beyond the technology of the time and was soon abandoned. The emergence of high speed reciprocating engines late in the nineteenth century eventually showed that more merit lay in Watt's view than had been apparent in the 1780s.

The admission of steam alternately above and below the piston was easily arranged once the geometry of the valves had been perfected. The valves were customarily worked by allowing the air pump rod to double as a striker, which replaced the original plug tree. Valves were opened as rapidly as possible by drop weights and an escapement inspired by clockmaking techniques. Accompanying drawings make the events easier to understand.

A major problem lay in transmitting the reciprocating piston thrust to the beam. The beams of preceding single acting designs—Watt's among them—were balanced so that the chain linking the piston rod to the arch head was always under tension. With an upward piston stroke, however, chain linkage would simply buckle.

One solution relied on a toothed piston rod extension meshing with a sector on the arch head, but this was prone to damage. It was soon replaced by a direct link between the piston and the beam, even though maintaining vertical movement in the piston rod required an additional intermediate bar. Guide bars were used to regulate the movements, but were difficult to machine accurately and increased friction. The addition of subsidiary rods—for the air pump, or a separate valve plug-tree—heightened the problems. Watt eventually devised a simple solution which allowed the piston rod head to move virtually in a straight line.

James Watt regarded his method of producing 'right lined motion from a combination of motions around centres' as his greatest single contribution to mechanical engineering. A rotative engine built in 1784 for Coates & Jarratt of Hull was the first to include the original form of parallel motion.

TABLE FOUR:

The first ten Watt double acting engines

Excluding the experimental example built in Soho in 1782/3 and the Whitbread engine of 1784, which was not converted to double acting until 1795.

1. Cotes & Jarratt, Hull; 1784. A rotative engine with a 15in cylinder.
2. Stonard & Curtis; 1785. A rotative engine with an 18in cylinder.
3. Wheal Towan, Cornwall; 1784 5. A pumping engine with an 18in cylinder.
4. Wheal Crane, Cornwall; 1784 5. A rotative engine with a 14.3/4in cylinder.
5. Wheal Fortune, Cornwall; 1785. A pumping engine with a 45in cylinder.
6. Walker, Chester; c.1785. A rotative engine with a 20in cylinder.
7. Robinson, near Papplewick, near Nottingham; c.1785. A rotative engine with an 18in cylinder.
8. Albion Mills, London; 1786. A rotative engine with a 34in cylinder.
9. Wheal Messa, Cornwall; 1786. A pumping engine with a 42in cylinder.
10. Wheal Mount, Cornwall; 1786. A pumping engine with a 20in cylinder.

Three bar motion worked satisfactorily, but the engine frame had to be extended to accommodate it. The gear was rapidly redesigned to work within the length of the beam, but was rapidly superseded by the perfected 'jointed parallelogram' or parallel motion. This was first used on an engine supplied to the brewery established by Samuel Whitbread in Chiswell Street, London. The installation dated from 1784, part of an enlargement of the premises begun in 1778 by John Rennie. This particular engine survives in preservation in Australia.

The completion of the double acting engine occurred almost simultaneously with an effective evasion of Pickard's crank type rotative drive. The first engine to be built with sun and planet motion was a single acting 42in example supplied to John Wilkinson in March 1783 to drive a tilt hammer. The mechanism comprised a small cog ('planet'), fixed on the end of the beam rod, which ran around the interior of a large toothed disc ('sun') attached to the flywheel.

This mechanism was used even after Pickard's patent expired in 1794, though Boulton & Watt had made a few crank drive rotative engines in an earlier era. The perfected sun and planet was reversed, so that the 'planet' ran around the outer periphery of the 'sun' gear. This had the advantage over the crank of making two turns of the flywheel for every stroke of the beam.

Boulton & Watt engines were invariably fitted with drop valves until slide valves appeared about 1801. In addition, many engines made after 1799 had eccentric driven valve gear, an invention usually attributed to William Murdock—who may also have been responsible not only for the 'D' slide valves, but also for an experimental piston valve tried in 1783 without success.

James Watt is widely credited with the first application of the flyball governor to a steam engine, though it may have been tried at least once on a Newcomen type engine in the 1760s and millwrights have also occasionally laid claim to paternity. The Centrifugal Speed Governor was apparently designed in 1788, the first application being on the 'Lap Engine' which drove the polishing machinery in the Soho manufactory.

Operation was regulated by balls attached to pivoting arms, which were rotated (usually at greater than engine speed) by a drive belt taken from a pulley on the crankshaft. If the mechanism began to run too fast, the balls moved outwards; this motion closed a butterfly valve in the supply pipe, restricting the steam flow and slowing the engine. If the mechanism began to flag, the balls dropped and the flow of steam was increased.

The flyball governor was simple and surprisingly efficient; by 1793, it was being copied by rival manufacturers. Watt had realised that similar governors had already been used to regulate the grinding speed of millstones, and had not deemed his design to be worth patenting.

Other innovations attributed to James Watt include the engine stroke counter and the indicator. However, the counter may have been adapted from a pedometer made by Wykes & Green of Liverpool, whilst the improvement of the indicator—by adding a pencil and moving board—was due to John Southern, Boulton & Watt's chief draftsman. Credit for addition of a rotating barrel to the indicator, also often given to Watt, is more probably due to John McNaught of Glasgow in 1828–9.

The attractive qualities of the double-acting Boulton & Watt engines, with parallel motion and the flyball governor, soon spread them widely. About five hundred engines had been made when the first national census was taken in 1801, though an accurate total is impossible to deduce owing to difficulties distinguishing those that had been built from those that had been planned (and also, occasionally, from confusion between Newcomen and Watt-type machines). Estimates range from 458 to 512.

Improvements due to Watt brought a rapid rise in performance. An analysis of Newcomen type engines made by Smeaton in 1769 gave an average Duty of 5·59 million, and Smeaton's own improved engine gave 9·45 million in 1772. However, Duty of 12·5 million to be obtained by Smeaton from a Watt engine in 1774 and 22·6 million by Watt himself in 1779, even though boiler pressure was still rarely about 5lb/in above atmospheric level.

Indicator diagrams taken from a replica of the Soho 'Lap Engine' of 1788, created by the Deutsches Museum in Munich in 1912, gave an indicated horsepower of 20·15 — or about 14·1ehp assuming a mechanical efficiency of seventy per cent. The overall efficiency of 2 per cent compared well with one per cent attained with Newcomen engines. The original Lap Engine, after new valves had been fitted in 1833, had been rated at 13·75hp.

The Watt engines created a great impression on the industrial scene of the time and were distributed widely throughout Britain and Europe. A few even found their way to the New World, where Robert Fulton fitted a 24in engine imported from Boulton & Watt in his paddle steamship Clermont (1807).

NINETEENTH-CENTURY BEAM ENGINES

By the beginning of the nineteenth century, Watt's all pervading influence had led to technological stagnation. Others were left to make rapid strides once the separate condenser patent had expired.

Power could be increased by raising working pressure, but only Richard Trevithick in Britain and Oliver Evans in North America were actively promoting this approach in the early 1800s. The introduction of the Woolf cast iron boiler and the central flue Cornish pattern showed that pressures of 25–40lb/in could be generated in safety, but the metallurgy of the day was often unable to cope with the strain imposed by high pressure steam. Serious accidents delayed universal acceptance of the principles for many years.

Important valve gear improvements had also been made in this era, particularly when the inventive William Murdock introduced the eccentric, but the double acting rotative engines pioneered by Boulton & Watt still dominated the industrial landscape as the eighteenth century closed.

Watt engines, like the Newcomen patterns before them, were large machines. Almost without exception, they were built into the engine house walls and could not be moved without extensive deconstruction. Transferring engines to another site was only undertaken when a mine was exhausted, for example, or flooded beyond economic redemption.

Lesser trades could also benefit from steam engines, but were unable or unwilling to commission a 'house built' example—the cylinder barrel of the 74-inch Warmley Brassworks engine, cast in Coalbrookdale in 1761, alone weighed six tons. Smaller machines were clearly needed.

By 1803, Fenton, Murray & Wood of Leeds were offering substantial free standing or 'Independent' engines with their beam gudgeons supported on four inclined columns joined at the column heads. Another innovation was the short 'D' type slide valve, patented by Matthew Murray, which was driven by a crank eccentric, a rocking layshaft, and a toothed sector.

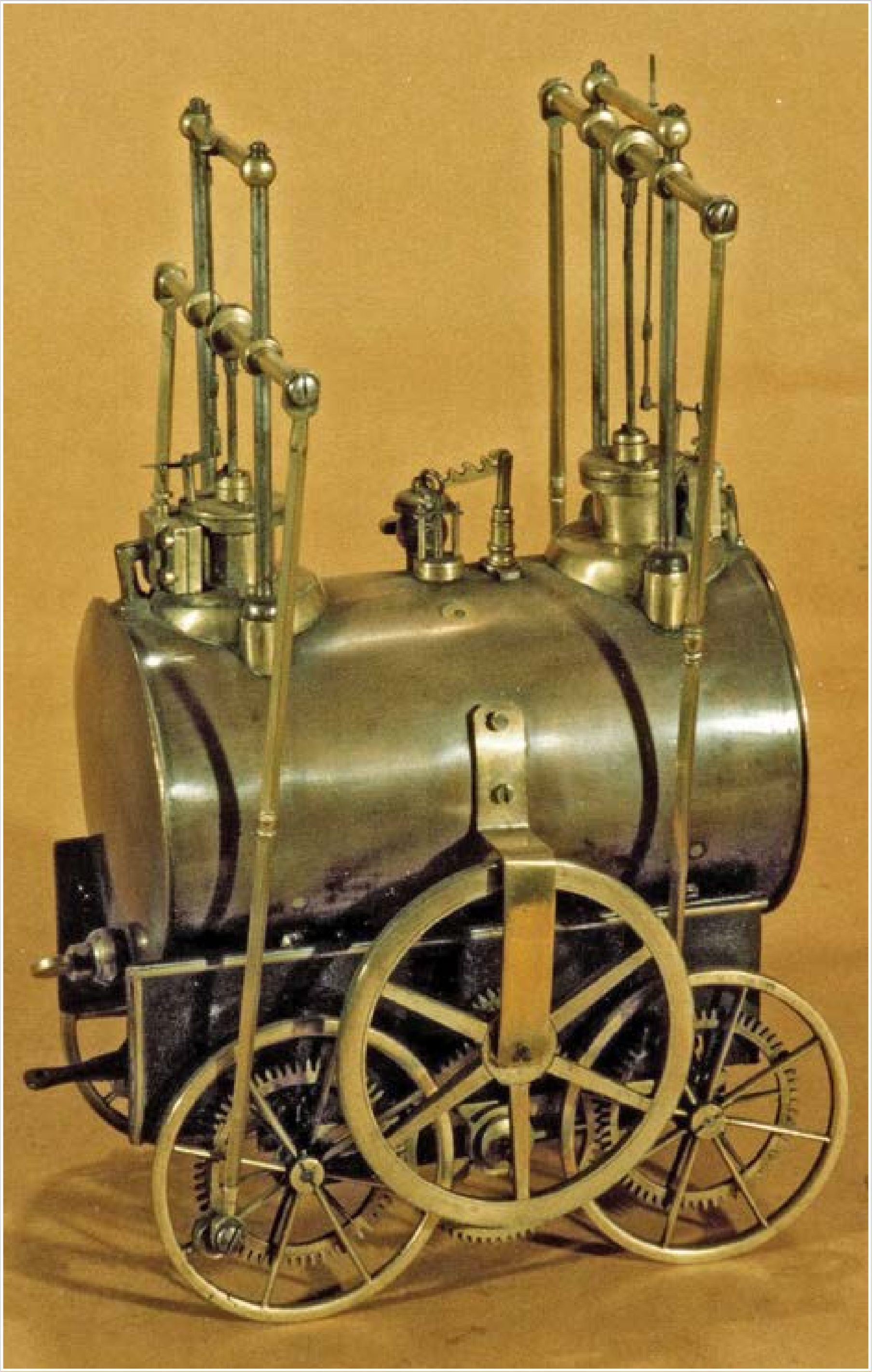
The earliest free standing engines had several pillars supporting the entablature—two, four six or even eight—but a single central column ultimately sufficed for small engines and 'A' frames (originating prior to 1800) were used for all but the largest. One twelve pillar machine from Dancer's End, near Tring, survives in the Kew Bridge collection.

Most of these engines were still securely bolted to the engine house floor, in which accessories such as condensers or the air and feed pumps had still to be sunk. Though the mode of construction had freed them from the walls of the engine houses, therefore, pillar and 'A' frame engines were not necessarily entirely self contained.

The introduction of supporting columns raised the steam engine from a clumsy wood and iron prototype to an object of surprising elegance. This did not escape even the earliest manufacturers, amongst whom Henry Maudslay was a notable aesthete.

Decoration was controlled partly by the ironfounders, increasing in complexity as working of iron improved. The earliest pillar type beam engines were characterised by plain columns, though not necessarily cylindrical and often displaying circumferential ribs. These gave way to classical inspiration. The fluted columns and plain capitals of the Greek Doric order were always popular—especially in 1845–70—though the more decorative Corthinian gained increasing favour in the middle of the nineteenth century.

A few engines made in 1840–50 borrowed from Egyptian or Etruscan art. A notable example was a machine made for Marshall's Mill in Leeds, perhaps the most impressive example of Egyptian style architecture ever erected in Britain. The influence of the Gothic Revival movement was



far more common. Originating in the 1760s, this was established by the second quarter of the nineteenth century and is often found on table and side lever engines. Though it had lost much of its impetus by 1880, some of the last beam engines to be made in Britain still displayed Gothic features.

Municipal pumping stations, in particular, were created with such great attention to detail that they were aptly described as 'Steam Cathedrals'. The similarities between church architecture and the installations financed by prosperous civic authorities were emphasised by stained glass, rose windows, wood panelling, polychrome tiles, marble and gilding. The result could be a stylistic nightmare, but the skill with which the stations had been built was never in doubt.

Typical of the decorated sites was Whitacre pumping station, built in Staffordshire in 1883–5 and demolished in the 1950s. The entablatures of the inverted vertical compound engines installed by James Watt & Company were raised on bastardised Egyptian lotus head columns, whilst the inspection galleries were supported with gilded winged eagle brackets. By comparison with Whitacre, the entablatures of the engines erected in the Goldstone pumping station in Hove (now the British Engineerium) are in a very restrained Greek Doric style.

Though the Goldstone No. 2 engine was installed in 1876, when desires for decoration were reaching their peak, the need to match the style of No. 1 engine house—ten years older—was the most important limiting factor.

By 1800, the first steps to harness the self propelling potential of the early steam engines had been taken. The first real steps towards the modern transport system were taken by pioneers such as Richard Trevithick, who designed the first railway locomotive and a steam carriage, and by John Fitch, William Symington, Robert Fulton and others at sea.

ROAD VEHICLES

Though many attempts were made in the early nineteenth century to provide steam carriages, almost always intended to replace the stagecoach, few of them embodied beam engines. Horizontal or vertical cylinders driving onto the crankshaft through rod and crank systems were much more popular, as they were generally lighter and more compact.

STEAMBOATS AND STEAMSHIPS

One of the first applications of a Boulton & Watt engine to marine use is said to have been made in France. Jacques Périer allegedly tried a steamboat on the Seine in 1775, but this was apparently powered by an atmospheric engine. However, the Marquis Jouffroy d'Aubans tried a boat propelled by duck's foot paddles on the Doubs in 1776; this had a single acting engine purchased from Boulton & Watt. Seven years later, in 1783, he tried an improved design on the river Saone but not until Watt's separate condenser patent finally expired in 1800 was real progress made.

The grant of a patent on 14th October 1801 allowed William Symington to design the steamship *Charlotte Dundas*, but this vessel relied on a single acting horizontal engine which drove directly onto an overhanging crank pin to revolve the paddle wheel by way of slide bars, a crosshead and a connecting rod.

The Watt engines created a great impression on the industrial scene of the time and were distributed widely throughout Britain and Europe. A few even found their way to the New World, where an engine imported from Boulton & Watt was fitted by Robert Fulton in his paddle steamship *Clermont*, built in New York in 1807 by Charles Browne.

Clermont represented a major advance on previous steamboats, as she was 150 feet long and displaced about a hundred tons. The engine was a rotative pattern with a 24 × 48in cylinder, relying on the influence of the flywheel to smooth the otherwise jerky motion to paddle wheels which were fifteen feet in diameter. In August 1807, *Clermont* ran successfully on the Hudson River from New York to Albany at an average of four knots.

Though heavy in relation to their power and wasteful of precious shipboard space, beam engines were particularly popular in North America as they were ideally suited to riverboats. The engines of these shallow draught vessels were customarily mounted at main deck level, so excessive vertical dimensions were happily traded for simplicity.

Though low boiler pressures were retained in European steamships for many years, the 'A' frame 'Walking Beam' riverboat engines pioneered in 1822 by Robert L. Stevens were regularly operated at 60–65lb/sq.in. A few were even pressed to 100lb/in or more.

Thus the beam type marine engine, rapidly superseded in Europe by the side lever, remained popular in the USA until the beginning of the twentieth century.

RAILWAY LOCOMOTIVES

The earliest engines designed by Richard Trevithick had horizontal cylinders (q.v.), but these had been superseded by 1808. *Catch Me Who*

Can, demonstrated on a circular track in London in 1808, had a single vertical cylinder buried in the rear of the boiler to drive onto the rear wheels through a rod and crank assembly.

Trevithick abandoned his railway experiments after the failure of *Catch Me Who Can* to demonstrate enough superiority over horses to persuade the public of the merits that lay in locomotive engines. Almost all of his immediate successors favoured beam or half beam designs. The earliest commercially successful machines of this type were undoubtedly the rack and pinion examples based on a patent granted in April 1811 to John Blenkinsop, manager of the Middleton Colliery in Leeds. Though the railway did not last long in its original rack drive form, it was the prototype of all later rack and pinion systems.

Two similar engines were made in foundry in Leeds owned by Fenton, Murray & Wood, the first entering service on 15th August 1812. Detailed design is generally credited to Matthew Murray. The locomotives each weighed about five tons, and were powered by two vertical single acting cylinders (said to have had a 9in bore and a 22in stroke) that drove the toothed pinion that revolved between the carrying wheels. Suitable teeth were cast into the outside surface of the rails.

Blenkinsop & Murray engines could haul ninety tons on level track, and even succeeded in taking a fifteen ton load up a slope. Several had been made by 1815. The third Middleton Colliery engine had double acting cylinders (its predecessors were rebuilt to this form), and eccentrics operated the valves instead of the original tappet gear.

A fourth Middleton locomotive was fitted with a wooden condenser cistern above the boiler to receive steam exhausted from the cylinders, which otherwise frightened horses. Blenkinsop locomotives survived on the Middleton railway until 1834, when a brief return to horse traction was made before edge rails were laid for more conventional adhesion-type locomotives.

At this early stage of railway history, the best method of propulsion was still to be discovered. This allowed some very strange designs to be produced. On 30th December 1812, for example, a patent was granted to William and Edward Chapman to protect a vertical cylinder chain haulage locomotive engine, the reduction of pressure on the track arising from the use of multiple axles, and the mechanical equalisation of load on the wheels by mounting them in pairs on swivelling trucks or bogies—an idea subsequently widely claimed as novel in Britain and the USA.

The oldest Chapman engine, possibly a four wheeler, was built prior to February 1813 by Phineas Crowther in the Ouseburn Foundry, Newcastle upon Tyne, but was soon reconstructed with an additional axle. The four wheel wood frame truck was attached to the underside of the boiler by a spherical pivot. One six wheel example subsequently ran on the 4ft 5in gauge tramway in Hetton Colliery. It had two 8 × 24in cylinders and a cast iron return flue boiler pressed to about 60lb/sq.in. Power was apparently taken from the cylinders by side levers driving chain wheels, guide pulleys and binding wheels. The machine was rebuilt as a geared adhesion type 0–6–0 about 1817. The pivoting four wheel truck was apparently retained, some play being allowed in the gears to accommodate lateral play.

In May 1813, Chapman & Buddle produced a promotional pamphlet containing drawings of an improved eight wheel chain drive engine. An engine of this type may have been tried in Hetton Colliery in October 1813, but no other Chapman pattern engine is known to have been used until, on 21st December 1814, one built by Phineas Crowther pulled eighteen wagons—a load of 50–60 tons—up a 1 in 115 incline in Lambton Colliery. An account in the Newcastle Chronicle for 24th December confirms that the engine was an eight wheeler running on two four wheel trucks, but failed to describe the drive system.

Chapman's chain haulage system was not successful enough to survive against simpler methods of construction and rapidly disappeared. The development of its successor, the adhesion engine—relying on weight and friction between its wheels and rails to pull loads—is generally credited to William Hedley, Viewer of Wylam Colliery. However, as a patent granted to Hedley in 1813 mentions rope or chain haulage, the design of an eight wheel locomotive run in the colliery in 1814–15 is open to doubt. It may have been similar to the Chapman engine tried in nearby Lambton.

Writing in 1836, Hedley claimed to have built his first four wheel engine in March 1814 after experimenting with a man-power 'adhesion truck'. He also claimed that the engines (several of them were made) were too heavy for the track and had to be rebuilt as eight wheelers, before reverting to 0–4–0 configuration when edge rails were laid in 1828.

Two surviving locomotives are credited to Hedley, blacksmith Timothy Hackworth and wheelwright Jonathan Forster: *Puffing Billy* in the Science Museum in London and *Wylam Dilly* in the Royal Scottish Museum in Edinburgh. Possibly made in Newcastle by Phineas Crowther, the former weighs about 8 tons 6 cwt in running order. Both engines now have four wheels and Fremantle parallel motion. However, though patented in 1803, Fremantle gear did not become commonplace until protection expired in 1817. This and other details suggest that their current appearance, arising from rebuilding in 1828–9, hides their original form. Thus the influence of Hedley on the development of the locomotive engine is difficult to gauge.

Two cylinders driving through half beams became customary in this period. Even Stephenson used them on his Killingworth and Stockton & Darlington engines until improved forms of drive were developed. These included a bell crank lever, featured on Stephenson's *Experiment* of ?1827; and a dummy crankshaft used in some of Hackworth's earliest designs.

Finally, Timothy Hackworth fitted the piston rod directly to the wheels of *Royal George* (even though a parallel motion was retained) and coupled the six axles together. Stephenson's *Lancashire Witch*, built for the Bolton & Leigh Railway in 1828, was the first to embody inclined cylinders and a cross head to support the piston rod.

The advent of springs had much to do with the re location of the cylinders. Combining springs and vertical cylinders was soon found to be a poor idea, as the engine tended to lift from the track each time the pistons thrust downward. At speed, this could be so dangerous that the cylinders were placed diagonally—but even this proved to be unsatisfactory, and they were soon moved until they were nearly horizontal.

Other innovations in the formative period of the locomotive engine included the provision of better valves (the conventional 'D' type was patented by Matthew Murray in 1802), multi tube boilers, and a rudimentary appreciation of the blast pipe.

THE CORNISH ENGINE

The Boulton & Watt engines erected in Cornish mining districts prior to the 1790s were ponderous machines relying on sheer size to fulfil their tasks. As boiler pressure was only slightly above atmospheric level, the engines relied more on the creation of vacuum than use of steam to work effectively.

The Cornish Engine was a sophisticated revival of the Watt expansive pattern of the 1770s, which had enjoyed success briefly before superseded by the double acting pattern. The major difference was the great increase in steam pressure, and the addition of a third or 'equilibrium' valve.

The first large Trevithick high pressure engines were twice as powerful as Watt's even though steam pressure was only 6–10lb/sq.in. Tests with pressures as high as 145lb/sq.in, undertaken in Coalbrookdale in 1802, showed that greater potential lay in the single acting engine than had been realised. If the admission of steam was stopped early in the movement of the piston, expansion completed the stroke—saving not only steam but also fuel.

An 11 × 42in Trevithick vertical engine, made for a London cannon foundry in 1803, took steam at 40–45lb/sq.in. It ran successfully at 26–27 rpm, but was overshadowed by a serious high-pressure explosion in Greenwich only a few months later.

The growing reputation of the high-pressure system was challenged by less drastic means in Dolcoath Mine in 1806, when a 'trial' of a large low pressure Boulton & Watt condensing engine operating at 4lb/sq.in against a vertical Trevithick 'Puffer' working at 25lb/sq.in resolved in favour of the former in the proportion of 120:55. Trevithick, who had not been invited to witness what was doubtless a selective comparison, immediately raised the operating pressure of his Puffer to 40lb/sq.in and a recalculation on the basis of three separate tests resolved as 147:35 in favour of the high-pressure engine. The controversy rumbled on until Trevithick, recovering from illness and near bankruptcy, returned to Cornwall from London in 1810.

Experiments with three pumping engines in Dolcoath Mine were particularly interesting. The oldest, the 45in Carloose Engine, was a conventional Newcomen-type atmospheric example; Wheal Gons had a 63in improved atmospheric engine erected by John Budge about 1774, with a stroke of 93in; and there was 63in Boulton & Watt double acting machine dating from 1780. All three engines had all been tested in 1798, when Duty of the Carloose, Budge and Boulton & Watt engines were returned as 5–6 million, ten million and sixteen million respectively. Watt had been contemptuous of the old engines, but raising their boiler pressures in 1799 had improved performance considerably.

In 1812, Trevithick replaced the globe boilers installed in 1799 with his cylindrical pattern. Pressed to 40lb/sq.in, these helped to reduce coal consumption from 6192 bushels in 1811 to only 4752 a year later. After trials and tribulations, the engines were all adapted to work expansively. This wrought a further improvement in the work of the Carloose and Stray Park engines, the latter re erected from Wheal Gons. As the modified Stray Park machine returned Duty as high as 31 million, the 45in Carloose and 63in Boulton & Watt engines were replaced in 1816 with a new 76in single acting expansive engine with a distinctive double beat steam valve. This was soon giving a Duty of forty million.

The prototype of all Cornish Engines, this Dolcoath pioneer served until 1869—virtually without a break—and inspired the spread of single flue high pressure boilers throughout Cornwall.

The Cornish engine was single acting, relying on tappets on the plug rods to control the valve events. A typical operating mechanism contained one or two vertical plug rods and three horizontal layshafts. Each oscillating layshaft controlled an individual valve. The engine was started by operating the cycle manually, but began to work automatically as soon as a satisfactory vacuum was created in the condenser. When the piston neared the top of its stroke, the exhaust valve opened the pipe to the condenser; steam beneath the piston immediately expanded into the chamber, where it was condensed by a jet of cold water. This created a vacuum. Simultaneously, the admission valve allowed high pressure steam to enter above the piston. Thus the piston and the beam began their downward strokes together.

The steam supply was cut at a pre-determined fraction of the piston travel, allowing expansion — aided by the vacuum — to complete the downward stroke. A tappet on the plug rod then closed the exhaust valve, barring the path to the condenser, and the equilibrium valve opened to allow the partially expanded steam to enter the by pass or valve tube. This reduced the pressure in the cylinder. Denied access to the vacuum in the condenser by closure of the exhaust valve, the piston was pulled back up the cylinder by the weight of the pump rods. Steam flowed out underneath the piston as it moved, equalising pressure on each side.

Just before the upward stroke was completed, the equilibrium valve closed and the final travel of the piston was cushioned by a small amount of residual steam. The Boulton & Watt engines used in Cornwall prior to the introduction of Murdock's 'D' type slide valve in the early 1800s had simple 'drop' or poppet valves. These not only gave an effective seal, but were also easy to operate. However, when steam pressures increased, greater effort was needed to open the valves against the force being applied to their large heads.

An answer was found in the so called 'Double Beat' pattern, which, as the drawings show, had two separate seats. The first valve of this type is said to have been designed by Joseph Hornblower, but had never been exploited. The model eventually found its way into the possession of Jonathan Hornblower, and a modified version was incorporated in an engine erected in Wheal Busy by Samuel Moyle. Moyle was the Hornblowers' nephew.

The Cornish valve was improved by Arthur Woolf, who enlarged the steam passages whilst simultaneously adjusting the area of the seats so that operation required very little effort. These valves were highly efficient, an improved form being patented in 1839 by Nicholas Harvey and William West, and survived until the last Cornish Engines were made in the early 1900s. Their influence can also be seen in horizontal engines made from 1870 onward.

The immense size of the cylinders taxed nineteenth century casting techniques to their limits; consequently, though the engines operated reliably, straps, kingposts and bridles were sometimes added to strengthen the beams. Excepting the 100in engine, which was not installed until 1871 and trussed in 1880, the surviving Cornish Engines in the Kew Bridge pumping station were all modified after a crack was found in the beam of the East Cornish machine in December 1862.

A fractured lattice beam had blocked the shaft in Hartley Colliery only few months earlier, with the loss of more than 250 lives to an undetected casting flaw. Many owners were forced to reinforce the beams of their engines, and castings of this type were rapidly superseded by wrought iron fabrications. Another potential weakness of the Cornish Engine lay in the direct connection of the pump rods to the beam. If pump rods broke or a water main fractured, losing the load on which the balancing of the components depended, the outboard beam end would slam upward

TABLE SIX:

Ten manufacturers of Cornish Engines

Bells, Lightfoot & Company, Newcastle upon Tyne
John Davies & Company, Tipton
Harvey & Company, Hayle
Holman Brothers & Company, Camborne
J.E. Mare, Plymouth Foundry, Plymouth
Neath Abbey Iron Works
Nicholls, Williams & Co., Tavistock
Perran Foundry, Hayle (Falmouth?)
Sandys, Carne & Vivian (later Sandys & Vivian), Copperhouse Foundry, Hayle
West & Son, St Blazey

TABLE SEVEN:
Engine performance

Unless stated otherwise, Duty is obtained from a Cornish Bushel of 94lb coal.

17·0	Average of Cornish Boulton & Watt engines, 1798
15·7	Average of eight selected Boulton & Watt engines installed in the Cornish tin mines, August 1811
21·5	63in Dolcoath Great Engine (Boulton & Watt) with Trevithick's improvements, *c.* 1814
26·75	45in Carloose or Shammal engine with Trevithick's improvements, *c.* 1814
31·25	63in Stray Park engine with Trevithick's improvements, *c.* 1814
40·0	76in Dolcoath Engine (Trevithick), 1816
45·0	Wheal Chance Combined Engine, 1816
48·0	76in Dolcoath Engine (Trevithick), 1819
40·3	Treskerby Combined Engine, 1820
87·0	80in Wheal Towan engine (Cornish type erected by Samuel Grose), 1827
96·0	Highest Duty reported in 1843 (the average for the year was about 60 million)

and the piston could be driven out through the base of the cylinder. As this could be disastrous, engines were often provided with buffers or stop beams to minimise damage. Many of the water pumping stations relied on elevated stand pipes — Kew's was 138ft tall — to ensure that operation could continue after a burst main.

The advent of the Cornish Engine improved Duty greatly, competitive spirit being honed by the publication of monthly reports. In 1824, John Taylor had organised a trial in Wheal Alfred of a two cylinder Woolf compound (40 × 78in and 70 × 120in) against "Taylor's Engine", a 90in single cylinder Cornish pattern also constructed by Arthur Woolf. Duty was very similar, the compound averaging about forty million in 1825 compared with 42 million for its rival. However, though the performance of the compound was restricted by the limited capacity of its boilers, Taylor preferred the simpler single cylinder pattern.

Subsequently removed from Wheal Alfred to the Consolidated Mines, where it was soon renamed "Woolf's", the 90in engine gave a Duty of 67 million in November 1827 after the valves had been altered and the cylinder had been lagged with wood.

John Taylor held Woolf in high regard, crediting him with the much of the improvement in the drainage of the Consolidated Mines. The three engines working in 1825 had returned average Duty of thirty million apiece, whereas the five erected by 1829 were each exceeding fifty million. And, in addition, the consumption of 17,034 bushels of coal in 1825 had been reduced to only 10,600 by 1829. This alone saved the owners more than £3000 yearly.

The first authenticated Duty of more than a hundred million was attained in Cornwall in 1827, and the 80in engine owned by Fowey Consols returned 125 million on a 94lb bushel of coal in 1835. Performances of this magnitude could hardly pass unnoticed—or, indeed, unchallenged—outside Cornwall. One important visitor was Thomas Wicksteed, who was commissioned in 1838 by the East London Waterworks Company to find a suitable pumping engine. He was sufficiently impressed by what he saw in Cornwall to erect an 80 × 120in machine in Old Ford Works, where it was found to raise 2½ times as much water as the existing 60 × 95in Boulton & Watt engine.

This performance was not quite as good as the result suggested, as the cylinder volume of the Cornish Engine was more than twice that of its rival. However, fuel consumption dropped appreciably and thus a considerable improvement in economy was made.

Cornish cycle engines proved to be sturdy and efficient, and were made in large quantities. Many existing Watt machines were subsequently converted simply by changing the valves and adding new high pressure boilers. One of the best features of Cornish Engines was the ease with which the cut off point could be adjusted, allowing more steam to be admitted as mines deepened and the weight of pump rodding increased.

Cornish Engines became very popular with the water supply industry until Woolf and McNaught compounds gained favour for the way they could handle fluctuating loads. Ironically, the ultimate success of the Cornish Engine had owed much to the dedication of Trevithick's rival Arthur Woolf. A 112in Cornish engine was erected in the Battersea pumping station of the Southwark & Vauxhall Waterworks Company in 1857, but the limits of expansion in a single cylinder had been reached and the future lay instead in multiple expansion.

Most Cornish Engines were built in classical form, with a vertical cylinder driving a beam, but less conventional examples were also made. Two 40in Bull type engines supplied to Kew Bridge in 1845, by Sandys, Carne & Vivian, had 'grasshopper' or half beams. They were not especially successful and had been removed by 1856.

Two of the twelve single cylinder engines used to drain the railway tunnel beneath the Severn had cylinders inverted to drive directly onto the plug rods, and at least one inverted cylinder engine—erected in Fairplay Iron Mine in the Forest of Dean—drove onto a rocking beam to magnify the pump stroke. This 72-inch example is said to have been built by the Neath Abbey Iron Works. Two cylinder machines were also made, though those attributed by James Sims were usually tandem forms of the Woolf compound (q.v.).

Among nearly twenty surviving Cornish engines are some remarkable machines. The oldest will be found in the Crofton pumping station, near Great Bedwyn in Wiltshire, where water was pumped into the Kennet & Avon canal. Originally built by Boulton & Watt in 1812, it was converted to the Cornish cycle when a new Cornish Engine was installed nearby by Harvey of Hayle in 1844. Both engines have 42-inch cylinders, the strokes being 93 and 96 inches respectively.

The oldest surviving purpose built Cornish Engine is the 1846 vintage 90 × 132in engine in Kew Bridge pumping station, which was designed by Thomas Wicksteed and built by Sandys, Carne & Vivian of Hayle. This machine raised about 470 gallons of water per stroke, delivering about 3½ million gallons in a 12 hour shift.

Among the most interesting survivors is the 70-inch engine in Prestongrange colliery in Midlothian, now the Scottish Mining Museum. The engine was originally made in 1853 by J.E. Mare of the Plymouth Foundry, for the Wheal Exmouth & Adams United lead mine on the edge of Dartmoor, but moved first to Old Wheal Neptune and then to the Great Western Mine. When the latter closed, Harvey of Hale refurbished the engine, cast a new beam (which is dated 1874), and despatched the rebuild to Leith by sea. The engine worked in Scotland into the 1950s.

The largest surviving single-cylinder engine is the 100 × 132in example built by Harvey for the Kew Bridge station in 1871. This delivered 717 gallons per pump stroke: approximately five million gallons in a twelve hour shift.

A Cornish Engine erected in 1836 by Francis Trevithick for Périer, Edwards & Chappert in Chaillot, near Paris, was the first of many machines to be exported. Typical of these was an 85-inch Harvey engine erected in Real del Monte mine in Mexico in 1873, whilst a 90-inch engine, also made by Harvey, went to the Rio Tinto mines in Spain in 1893. Some went to South America, and at least one made the interminable sea voyage to South Australia.

An impressive overseas representative is the 50-inch Ookiep copper mine engine, made by Harvey in 1882 to the designs of John Hocking, which worked until 1919 and was restored in the 1960s. This engine could be double-acting if required, but there is no evidence to show that this was ever tried.

The largest of all the survivors is usually reckoned to be the Dutch Cruquius Engine, but this was an annular compound (q.v.).

CHAPTER THREE

compounding and other challenges to the supremacy of Boulton & Watt

Though even the earliest of the Watt engines improved greatly on the performance of the Newcomen design, there were always those who believed they could provide something better. A few twin-cylindered atmospheric engines had been tried, without conspicuous success, and the advent of the Hornblower compound engine in the early 1780s was enough the alarm Boulton & Watt. Realising that their supremacy was being challenged, the inventor and his partner took every opportunity to discourage riovals. This was facilitated by the terms of the separate-condenser patent, which were sufficiently all-embracing to defeat most competitors until protection lapsed in 1800 and the floodgates opened. Political influence was also used to block advances, and it is hard to see the last decade of the eighteenth century as a period of great enlightenment.

Virtually without exception, Boulton & Watt engines had only one cylinder. Attempting to evade Watt's separate condenser patent, therefore, several enterprising engineers produced two cylinder designs. Among them was Adam Heslop, born in south western Scotland, who spent most of his adult life in Cumbria.

In July 1790, residing in Ketley, near Wellington in Shropshire, he received a patent for his two-cylinder atmospheric engine. At least fifteen of these machines were erected in Cumbria from *c.* 1793 until 1810 or later. The first three are said to have been built in Workington by the Seaton Iron Works, but the later examples were the work of Heslops, Johnson, Millward & Company of the Lowca Iron Works in Whitehaven.

The Heslop engines had a hot 'Receiving' cylinder connected with an intermediate arch head near the pump rod assembly, allied with a cold 'Working' cylinder beneath the opposing beam end as 'used in the Common Fire Engine'. Steam was admitted to the hot cylinder at about 3 lb/sq.in above atmospheric pressure, which allowed the counter-weighted beam to raise the piston. Simultaneously, the piston in the cold cylinder was lowered, immersed in a water tank, and raised the pump rodding.

The eduction valve blocking the connecting pipe between the cylinders was then opened, allowing steam to flow from the hot cylinder. This reduced the pressure sufficiently for the counter weights to reassert themselves and begin to tip the beam, lowering the pump rods and pushing residual steam back towards the connecting pipe. The eduction valve was then closed. When the piston in the cold cylinder had reached the top of its stroke, an injection of cold water formed a vacuum and the piston was drawn down.

As the movement of the piston began, the valve was opened to admit a fresh charge of steam beneath the hot cylinder piston. Thus each stroke of the Heslop engine was driven partly by steam lifting the hot cylinder piston, but largely by formation of a vacuum in the cold cylinder allowing atmospheric pressure to force its piston downward.

The Heslop system was an improvement on the Newcomen atmospheric system, but could not compete with Watt. The latter apparently regarded the 'cold cylinder' of the Heslop engine as an infringement of the separate condenser patent and may have been able to prevent production for a few years. The case is, however, not proven. The variable cylinder proportions of the Heslop engines—from 11:10 to 9:5 in favour of the hot cylinder—suggests that Heslop had no real grasp of multi-stage expansion where the reverse proportions are more desirable, and this may hold the key to the lack of long-term success.

One Heslop engine survives in the Science Museum collection. Originally erected in the 1790s at Kells Pit, Whitehaven, it had been re erected at nearby Wreah Pit by 1837. Changes made to its design (according to *Engineering* in January 1879, shortly before it ceased working) had included renewal of the original beam; addition of an air pump; plugging of the snifting valve; the addition of links and a cross-head guide for the cold cylinder; and the replacement of the cast-iron flywheel with a wrought-iron example.

An attempt to obtain an indicator diagram was largely unsatisfactory. Data suggested that the pressure in the hot cylinder, initially at 16½ lb/sq.in, had dropped to about atmospheric level during the cold cylinder piston stroke before being condensed to form a vacuum. The cylinders measured approximately 34 × 34in (hot) and 25·4 × 39in (cold).

Best known as an erector of single-cylinder Newcomen type engines in the Midlands, Francis Thompson also built a few two-cylinder rotative engines of his own 1792-vintage design. Most drove textile mills, the largest, in Davidson & Hawksley's Mill in Arnold, having two cylinders with 40-inch bores and 72-inch strokes. This particular machine is said to have run at about eighteen strokes per minute, driving the 18-foot flywheel by way of a crank and connecting rod, but, as speeds as high as 45 rev/min. have been claimed, gears may also have been interposed.

The opposed cylinders were separated by an air gap, the upper cylinder being inverted and the piston rod carried upward through a packed gland in its base. Steam was admitted beneath the lower piston in the normal way, the power or vacuum stroke being transmitted to the arch head by two chains. As the vacuum drew the lower piston downward, so steam was admitted above the upper piston, which was connected to the third or central arch head chain by an upward extension of the piston rod. This transmitted the power stroke of the upper piston, which was moving up instead of downward. When the beam moved to its lowest position, steam was admitted beneath the lower piston and condensed above the upper piston. The operating cycle, therefore, was based on steam admission in one cylinder and simultaneous condensation in the other, giving alternating up/down power strokes.

Obsolescent by the time they appeared, Thompson engines could not compete with the first generation of Boulton & Watt rotative engines.

Bateman & Sherratt engines had two vertical open-topped cylinders, relying on racks on the piston rod extensions to drive a toothed flywheel. The racks oscillated the wheel, which was connected to a short beam and thence, through a connecting rod and a crank, to a rotating layshaft. A similar design patented by Isaac Manwaring provided the basis for the Hornblower & Maberley closed cylinder type (q.v.).

The first Bateman & Sherratt engine—with 36-inch bore cylinders and a 48-inch stroke—was erected in Thackeray's Mill, Garratt, Manchester, in 1794. Work was stopped in 1796 by an injunction granted in favour of Boulton & Watt, after as many as twelve engines may have been completed.

The first steamboat to have been run successfully in Britain was driven by a two cylinder atmospheric engine, patented in 1787 by William Symington. An Edinburgh banker, Patrick Miller, had built a three-hulled boat propelled by manually-operated paddle wheels between the hulls, but was keen to develop a self-propelled version.

The three-hull vessel was replaced in 1788 by a double-hull pattern, large enough to support a two cylinder atmospheric engine patented in 1787 by William Symington. The engine was placed in one of the hulls, with an externally fired boiler in the other, and drove two paddle wheels mounted in tandem between the hulls. The vessel made its first trip on Dalswinton Loch, near Dumfries, on 14th October 1788. Its engine had two 4½ × 18in cylinders with piston rods extended upwards between guides. Each was also connected to the other with a chain running over a pulley or drum. As the pistons worked alternately, the drum rocked backward and forward.

This oscillating motion was conveyed to the paddles by rudimentary chain and sprocket drive. Each paddle shaft carried two loose pulleys with teeth on their inner flanges; between them lay a fixed disc with two pawls. As the chains from the driving drum oscillated the pulleys, pawls engaged the ratchet teeth to ensure that the paddle wheels revolved continuously in only one direction.

The cylinders sat in a tank, doubling as the condenser, and each contained a small auxiliary air pump piston at their lower ends. The air pumps were driven by a small underlever beneath the tank. Each cylinder had separate admission and exhaust valves operated by weighted tappets controlled by a reciprocating plug rod hung from a chain attached to a lateral extension of the main drive drum shaft. Power was generated by atmospheric pressure on top of the piston during the down stroke.

Symington built a larger engine in 1789, but Miller was unimpressed and the partnership came to an end. The engines were regarded as infringements of patents held by James Watt—particularly in the method of condensing exhausted steam—and work ceased for some years.

HORNBLOWER ENGINES

Attempts were being made by the 1780s to provide steam engines with two cylinders, arising partly from technological limitations—two small diameter cylinders were easier to make than one large one—and partly from a desire either to reduce strain on components or smooth operation. It was also often seen as a way of evading Watt's separate condenser patent.

Jonathan Hornblower the Younger obtained an English patent in 1781 protecting the expansion of steam in successive cylinders. A high pressure cylinder was placed inboard of a low pressure cylinder beneath the arch head. Beginning with both pistons at the tops of their cylinders, steam was admitted into the high pressure cylinder to force its piston downward. Opening a valve at the end of the stroke equalised pressure on both sides of the high pressure piston. The low pressure cylinder was empty at this stage.

As the weighted beam pulled the high pressure piston upward, steam was transferred beneath the piston through a connecting tube. When the valve closed at the top of the stroke, new steam was admitted above the high pressure piston. As the piston was forced downward, low pressure steam beneath it was pushed out through the steam tube and into the low pressure cylinder. Thus the second stroke consisted of new high pressure steam acting on the small piston and residual low pressure steam acting on the larger one.

When the pistons had reached the bottom of the stroke, equilibrium valves opened to equalise pressure on both sides of the pistons as they moved upward again. The valves closed at the top of the stroke, allowing fresh steam to be admitted above the high pressure piston. The cycle then started again. As the high pressure piston descended, it pushed the previous charge of low pressure steam into the second cylinder; and the low pressure piston in turn transferred the residual pressure of the last admission but one to the condenser.

An experimental Hornblower engine was apparently being tested in 1779, but the first to be operated commercially was erected in Radstock Colliery, near Bristol, in 1782. James Watt was furious at this attempt to flout his Cornish monopoly, sending his trusted lieutenant William Murdock to report on the Hornblower system whilst suggesting to the mine owner that the two-cylinder engine infringed the separate condenser patents.

Murdock reported that the Hornblower engine was neither particularly efficient nor a real threat to the double-acting Watt pattern. Whether Murdock was merely saying what Watt wished to hear is difficult to judge, but Jonathan Hornblower built another engine—at Tincroft Mine, Cornwall, in 1790—and then erected at least eight more before abandoning the two-cylinder design when his patent expired in 1795. He had petitioned Parliament in 1792 to extend the term of his patent, but the move was blocked by Watt's lobbyists.

Hornblower engines, which were more complicated than Watt's, failed to make an impression on the history of the steam engine largely because the operating pressures were too low to use two-stage expansion efficiently.

THE WOOLF ENGINES

Cornishman Arthur Woolf, born in Camborne in 1766, is due credit for the first truly successful compound or multi stage expansion engines. Unlike Joseph Hornblower twenty years earlier, Woolf realised that the diameter of the low pressure cylinder had to be enlarged to compensate for the reduction in steam pressure. This proved to be a major step forward, even though his explanation of the theoretical principles was mistaken.

Woolf is said to have been been apprenticed to a cabinet maker, but then went to London to become a staircase maker of repute. His excellent workmanship was to be reflected in the erection of a Hornblower & Maberly Pendulum Steam Engine in Newbottle Colliery in County Durham. Returning to London in 1796, Arthur Woolf was asked to instal a Hornblower & Maberly Watt type rotative engine in the Griffin Brewery of Meux, Reid & Company in Liquorpond Road, Clerkenwell.

Woolf subsequently became resident engineer in the brewery, designing, amongst other machines, an efficient waste steam water heater and a complicated method of obtaining rotary motion without using a flywheel.

Among his most important innovations was a distinctive multi flue cast iron boiler, patented in 1803 though experimentation continued until 1815. Several iron tubes were placed across the furnace, connected by necks to a longitudinal main receiver pipe, whilst Robinson's patent fire grate simultaneously improved combustion and reduced the emission of smoke. The Woolf boiler could withstand pressures of 35–45lb/sq.in, which was considerably greater than anyone excepting Trevithick in Britain and Evans in the USA was promoting in this period.

Investigation led Woolf to the mistaken conclusion that the expansion of steam could be deduced directly from gauged pressure. He decided that steam at 5lb/sq.in would expand to five times its volume at atmospheric pressure; at 40lb/sq.in, therefore, volume would be forty times greater. This quirky law of expansion was a keystone of an English patent granted to Woolf in 1804.

The prototype compound engine was an adaption of a small 6hp rotative engine which had been purchased from Fenton, Murray & Wood of Leeds to assist the 1796 vintage Hornblower & Maberly Griffin Brewery engine. A tiny high pressure cylinder was added, together with a patent boiler capable of supplying steam at 25–30lb/sq.in. Woolf was greatly influenced by Trevithick's single cylinder high pressure engine, and was apparently intending to drive a second piston with steam which would otherwise exhaust directly to the atmosphere.

The ratio of the volumes of the high- and low pressure cylinders of the experimental engine was an unsatisfactory 1:18. Power was disappointingly low, though the engine was extremely economical to run. Consequently, Woolf built a new engine in 1804. Made largely from components supplied by Fenton, Murray & Wood, this was intended to generate 36hp on the basis of cylinders measuring 8 × 36in (high pressure) and 30 × 60in (low pressure); steam was supplied at 40lb/sq.in.

The new engine was completed in the summer of 1805, but was still much less powerful that Woolf had hoped. This was largely due to the

TABLE FIVE:

The first Woolf compound engines in Cornwall

1. West Wheal Fortune, St Hilary, 1812; a winding engine, first duty reported in May 1813 as 5.3 million.
2. A 10hp installed `near Marazion' in 1812
3. Wheal Vor, 1812; the 9hp engine from the Lambeth workshop, serving as a winding engine. The first duty was reported as 5.9 million in September 1813
4. East Shaft, Wheal Abraham, 1813; a winding engine, first reported in October 1813 with a duty of 10.9 million
5. Wheal Abraham, 1814; a pumping engine first reported in October 1814 with a duty of 34 million (reached 52.2 million after adjustment)
6. Blewett's Shaft, Wheal Abraham, 1815; a winding engine first reported in September 1816, with a duty of 5 million
7. Wheal Vor, 1815; a pumping engine built by the Neath Iron Works, first reported with a duty of 45.1 million in October 1815
8. Wheal Vor, 1815; a stamp engine with a duty of 13.7 million in February 1817
9. Wheal Abraham, 1816; a pumping engine reported in July 1816, duty 23.8 million
10. Crinnis, near St Austell, 1818; a pumping engine first reported in May 1819

Note: the supposedly 1816 vintage Tadpool Engine at Wheal Unity was converted from an old single cylinder pumping engine and is, consequently, omitted from the list.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cylinder volume ratio of 1:23. However, when the machine was dismantled, the bore of the low pressure cylinder was found to be rough. Instead of questioning his basic expansion principles, Woolf sought to correct the manufacturing faults and find piston seals which would cure steam leaks. The changes undoubtedly made a great improvement in the Griffin Brewery compound engine. Woolf arranged for Trevithick to test it in March 1808, after a new 12 × 40in high pressure cylinder had been fitted and the low-pressure cylinder had been bored out to a diameter of 30 in.

The cylinder volume ratio of 1:9·7 enabled a Duty of about 22 million to be reckoned at a boiler pressure of 40–42lb/sq.in. This was an excellent result for a comparatively small engine, though Trevithick suggested that performance would be improved by enlarging the boiler. Soon after Trevithick's experiments, by grinding malt, John Rennie tested the Woolf engine against a Boulton & Watt rotative machine of comparable power. He concluded that the Watt engine was superior in the proportion of about 4:3, persuading the proprietors of the Griffin Brewery to purchase a 30hp Boulton & Watt rotative engine to replace the temperamental compound.

Owing to the friendship of Rennie and Watt, the objectivity of this particular trial is difficult to judge. Affidavits were sworn in 1811 by the brewery's engine superintendent that the Watt engine took four hours longer to complete work done by the Woolf pattern in 17–18, using four bushels of coal hourly instead of only two. He also estimated that increased coal consumption was costing Meux, Reid & Company £1000 annually. Writing in 1817, Bryan Donkin rated the Woolf and Boulton & Watt engines 18:11 in favour of the compound.

Disappointed by the rejection of his compound engine and a change in ownership of Meux, Reid & Company, Woolf left the brewery in the summer of 1808. By 1809, he had formed a partnership with Humphrey Edwards of Mill Street in Lambeth. A few small compound engines were newly built and some older single cylinder engines were converted in Edwards' workshop, until, by 1811, a standard pattern had been evolved by trial and error.

Manufacturing quality was outstanding—joints were caulked with iron cement and beams were cast iron. In particular, Woolf's improvement of metallic piston packing developed by Edward Cartwright was particularly successful. A typical 16hp Woolf & Edwards engine had 9 × 30in and 16 × 40in cylinders, running at 27–28 rpm on a steam pressure of 35–40lb/sq.in.

An encouraging test was made in this era by a committee comprising, amongst others, Richard Trevithick, Henry Harvey of Hayle Foundry, James Burton and John Penn. A 9hp Woolf engine with 7 × 36in and 14 × 36in cylinders, installed in the Lambeth workshop, was tried against an 8hp Boulton & Watt machine in Battersea Distillery. For each bushel of coal, the Woolf engine ground 17·3 bushels of wheat compared with only 5·9 for its rival—though the value of the results was muddied by the age of the Battersea engine, which was not in ideal condition.

The cylinders of the Woolf engine were usually placed vertically, with the smaller high pressure inboard of the larger low pressure unit. Owing to the position of the rods beneath the beam, the high pressure piston had a shorter stroke than its larger low pressure equivalent. An equal stroke design with the two cylinders side by side, driving a common linkage, was less popular. The cylinders of later engines were often jacketed to increase efficiency.

The cycle of the single acting Woolf engine was much the same as the original Hornblower proto compound (q.v.), but double acting patterns were also made. Beginning with the beam in its uppermost position, steam was admitted above the high pressure piston and the pistons moved downward. When they had reached the bottom of the operating stroke, valves opened to connect the cylinders and link the low pressure cylinder with the condenser.

Steam was admitted beneath the high pressure piston; as the piston rose, the steam above the piston, by now expanded to a lower pressure, was pushed through the connecting valve to emerge beneath the low pressure piston. An upward stroke of the beam ensued.

Fresh steam was admitted above the high pressure piston, forcing the components down again. As residual steam beneath the high pressure piston was transferred above the low pressure piston, the steam remaining beneath the latter, which by this time had lost almost all of its expansive force, was exhausted to the condenser.

Woolf was convinced by 1811 that his engine was ready to compete with the established manufacturers in Cornwall, an opinion Edwards may not have shared. The partnership was dissolved. Arthur Woolf returned to Cornwall but Edwards eventually settled in France to promote the Woolf engine and a simplified cast iron boiler with great success.

Though development of the compound engine continued, Woolf also supervised the work of existing single cylinder engines in Crenver, Oatfield and Wheal Abraham. By 1813 he also had the 48in engine at Wheal Vor and the 45in example at Wheal Vrea under his control.

Some single cylinder Watt engines were altered to conform with the 1804 Woolf patent, using cast iron boilers to generate higher steam pressure. Duty of these engines was greatly increased, but the strain on parts intended for much lower pressures was often too great for the old engines to bear.

The performance of Woolf compounds deteriorated noticeably after a few years. As they were much more expensive than Watt or Trevithick rivals, the reputation of Woolf's engines began to suffer. The problems were generally due to ignorance of what today would be termed 'preventive maintenance'. High pressure operation involved high temperatures, but these caused the primitive lubricants to congeal. Increased friction placed a greater strain on the moving parts, and required more attention to the metallic packing of the piston than the mine captains customarily gave.

John Farey tested the Woolf engine at Wheal Abraham — the first in Cornwall to have a cast iron beam and parallel motion on the pump rod — after it had been overhauled in the summer of 1818. A Duty of 65 million (47·8hp) could be obtained at a pressure of 62–68 lb/sq.in if steam was cut off after two thirds of the high pressure piston stroke.

Many Cornish mine owners were impressed more with the distinctive Woolf boiler than the compound engine, which went into rapid and terminal decline. The inventor was forced to sue several copyists shortly before his patent expired in 1817, and the difficulties in gaining compensation greatly reduced his circumstances.

Woolf also made an experimental Trevithick type (or 'Cornish') boiler, which proved to be so successful that Harveys of Hayle were persuaded to open a boiler making plant. Woolf, who was already working as factory superintendent, designed most of the production machinery. His attention turned to the single cylinder Cornish engine in the early 1820s, when work began on three machines (one 70in, two 90in) installed for the great mining entrepreneur John Taylor in the Consolidated Mines, Gwennap.

Failing health and the sudden death of his first wife persuaded Woolf to retire from active business in 1830. He was not a rich man, but married again and ultimately died peacefully in Guernsey in the autumn of 1837.

The compound engine was a short-lived failure in Cornwall, where its complication was unnecessary, but a handful of English manufacturers kept faith with the smaller rotative engines. These were particularly valued for even torque and the beneficial reduction in the temperature range within each cylinder. Amongst the best known of the earliest makers were J. & E. Hall of Dartford; Horn & Company of Westminster; Wentworth & Company of Wandsworth; and Eastons & Amos (later Easton, Sons & Amos and then Eastons & Anderson) of London.

The huge success of Woolf's brainchild in Europe was due entirely to his one time partner. Humphrey Edwards went to France soon after the partnership had split in 1811, receiving a French patent protecting the two stage expansion engine and the cast iron boiler in May 1815. Sales were brisk, the engines being made initially in the Lambeth workshop and then—after Edwards had left for the Continent—by J. & E. Hall of Dartford. The emigré engineer eventually became a partner in the long established Chaillot foundry, which thereafter traded as Scipion Périer, Edwards & Chappert.

The total number of Woolf engines introduced to France by Edwards alone is believed to have been about three hundred, the oldest examples being imported from England and the remaining two thirds being made in Chaillot. Other European manufacturers copied the idea; totals must have run into thousands.

So popular did the basic system become, ironically, that virtually all mid nineteenth century compounds were Machines à Vapeur Woolf in France. A modified version of the Woolf boiler reappeared in Britain as the 'Elephant' but could not challenge the established Cornish and Lancashire patterns.

A few vertical tandem compound beam engines were built in France and elsewhere in Europe in the middle of the nineteenth century. The larger low pressure cylinder was generally placed directly on top of the high pressure unit, often sharing a common piston rod and a single slide valve. Though still be touted on railway locomotives as late as 1900, it was needlessly complex, difficult to balance and awkward to seal.

More than thirty Woolf engines remain in Britain, ranging from an engine built for Basford Works by J. & E. Hall of Dartford in 1838, with cylinder diameters of 7 in and 15in, to a mighty 30in/48in quartet installed in the Abbey pumping station in Leicester by Gimson & Company in 1891. Goldstone No. 2 Engine—an 1875 vintage product of Eastons & Anderson of Erith—is amongst the largest, with cylinders measuring 28in and 46in.

The oldest surviving Woolf engine (still in working order) was installed by Wentworth & Son in the Ram Brewery, Wandsworth, in 1835, though a substantial rebuild in 1863 makes it difficult to gauge how much of the original remains. The newest is a 18in/29in pattern installed in Tees Cottage pumping station in 1904 by Teasdale Bros. & Co. Ltd of Darlington.

Most large Woolf engines were house built, but substantial numbers of free standing machines were made. These include a six column engine, built by Eastons, Sons & Amos in 1864 and currently owned by the Birmingham Museum of Science and Industry. There were also 'A' frame patterns, among them an engine made in 1893 for the Addington pumping station by Glenfield & Kennedy of Kilmarnock and now in Strumpshaw Old Hall Museum.

THE MCNAUGHT ENGINE

A patent granted in 1845 to John McNaught, a partner in J. & W. McNaught of Bury (later Rochdale), enabled many existing low pressure engines to accept the high pressure steam necessary to improve efficiency. Realising that the old engines were not always strong enough to simply admit high pressure steam, McNaught added a small diameter high pressure cylinder on the flywheel side of the central pillars. This had two advantages; the working pressure in the old cylinder could be maintained at existing levels, and the strain on the beam during the operating stroke was partially overcome by the balancing effect of the new piston rod.

One of the earliest applications of the McNaught principle seems to have been made to side lever marine engines made by J. & G. Thomson of the Clyde Bank Foundry in Glasgow. A second high pressure cylinder was squeezed into the space beneath the crank, driving directly onto the crosshead by side rods. A few of these engines were installed in flax and jute mills in Fifeshire and Angus in the middle of the nineteenth century.

'McNaughting' was sometimes applied to horizontal engines, transforming them into tandem compounds, but problems occasionally arose when space in existing engine houses was too limited to accommodate another cylinder. A few beam engines were compounded by adding a horizontal pusher engine in an ante chamber, driving directly onto the crankshaft. Supplementary cylinders could also be mounted horizontally on the engine bed plate alongside the existing vertical cylinder, and one or two were even bolted directly onto engine room walls. 'Pusher' conversions were popular in the Lancashire weaving industry, where the roofs of sheds were usually low, but only one engine of this type survives.

McNaught engines were the first 'Receiver Compounds', with a reservoir of low pressure steam in the large diameter pipe connecting the cylinders. This was popularly believed to be more tolerant of variations in load than the Woolf system, where the two cylinders were connected as directly as possible.

Many new McNaught engines were made from 1845 onward, even though the compactness of the Woolf engine was preferred in water pumping stations. McNaught compound beam engines lost ground rapidly, and had become rare by 1890 even though comparable horizontal engines were still being built in the 1930s. The last McNaught type engine may have been a triple expansion machine installed in 1904 in an Oldham mill owned by Lee & Wigley Ltd. Built by Buckley & Taylor to the design of J.H. Tattersall, it had cylinders of 28 × 36in (high pressure), 32 × 48in (intermediate) and 44 × 72in (low). The high and intermediate pressure cylinders were grouped together, Corliss valves being used throughout, and 1000hp could be indicated when the engine was running at 35 rpm on a steam pressure of 160lb/sq.in.

The sole remaining McNaught compound, with cylinder diameters of 18in and 24in, belongs to the Bradford Industrial Museum. Originally designed as a single-cylinder slide valve pattern, built by William Bracewell & Company of Burnley in 1867 for E. & A. Matthews of Eastburn in Keighley, it gained a high pressure cylinder and Corliss valves when compounded about 1900.

Alternative methods of 'compounding by addition' appeared as soon as the McNaught patent expired. Evan Leigh patented a conversion of his own in 1863, specifically intended for engines where the bed plate was too weak or too cluttered to accept a new cylinder. The beam was extended out over the flywheel and a narrow long stroke cylinder was added. At least four sets of engines were made by Musgrave of Bolton in the 1860s, but the system never became popular.

A similar method briefly promoted in the mid 1870s by James Bagshaw & Sons of the Victoria Foundry, Bagshaw, Leeds, relied on a replacement beam with a beak or horn above the flywheel gudgeon. The new high pressure cylinder was inclined to clear the sweep of the crank and drove directly onto the beak.

OTHER COMPOUND ENGINES

James Sims succeeded to his engine erecting business on the death in 1834 of his father, William. The expiry in 1818 of the multi stage expansion patent granted to Arthur Woolf had allowed William and James Sim to develop a compound engine of their own, the two cylinder machine being erected in Poldice in 1824. Annular construction allowed the small diameter high pressure cylinder to lie inside the large low pressure unit.

The engine worked economically, but required improvement in too many details to attract commercial attention. However, James Sims continued experimenting until 1841, when he was granted a patent to protect a tandem compound with the high pressure cylinder on top of the low pressure unit.

"Sims' Combined Engine", as it was called, was subsequently made in small numbers. The best known example was built by Harvey of Hayle for the Crofton pumping station, to supply water to the Kennet & Avon Canal. The diameters of the high and low pressure cylinders were 21in and 42in respectvely.

Another machine was erected in Par Consolidated Mines ('Par Consols') in 1843 and a larger engine, with cylinder diameters of 60in and 100in, was working in St George's by the end of 1844. A second machine in Par Consols, apparently dating from 1845, was apparently a Bull type inverted vertical driving directly onto the pump rods.

Sims' Combined Engines enjoyed a brief heyday in the water pumping industry, being installed in Coventry, Ipswich and Lincoln in addition to their native Cornwall. However, their lives were often short as the success of the McNaught system and the successful reintroduction of the Woolf compound from France soon eclipsed Sims engines. The worst feature of these tandem compounds seems to have been the stuffing box and gland between the cylinders, which were notoriously difficult to seal.

Among the most famous Cornish-cycle engines were the three giants erected in the Netherlands to drain the flooded Haarlemmeer. A commission sent to England in 1840 learned that the fuel consumption of a Cornish engine was typically only about 2lb/ihp/hr, which was about one seventh of the average figure obtained from typical Watt type Dutch pumping engines.

Acting on behalf of the Dutch government, Gibbs & Dean ordered the first engine from Harvey of Hale. Erected in Leeghwater in 1844, this machine drove eleven shallow lift pumps from a series of cast iron beams projecting radially from a castellated roundhouse. It was replaced by a diesel engine in 1912. An eight beam engine built by the Perran Foundry (under sub contract to Harvey) was installed in 1846 in Cruigmur, near Amsterdam. This lasted until 1893. The third and last machine—the preserved eight beam Cruquius Engine—was commissioned in 1849.

The Cruquius Engine had an immense 144in diameter low pressure cylinder, with a 132in stroke, built concentrically with the central 84in high pressure cylinder. The pistons of these three Dutch giants were so large that an erector and his entire family are said to have eaten their Christmas Dinner in one of the low pressure castings.

The high pressure piston had a single rod, placed centrally, whereas the low pressure had four. Owing to the absence of pump rodding, the lift being only a few feet, the beams were balanced by the central 'spider' crosshead, the pistons, and the piston rods.

These annular compounds were started by admitting steam at 60lb/sq.in beneath the high pressure piston, raising the indoor beam end upwards and depressing the pump rods ('outdoors'). As the pistons neared the upper limits of their stroke, the equilibrium valve opened to allow steam from beneath the high pressure piston to flow above both the high and low pressure pistons, equalising the pressure at a greatly reduced level. This allowed the weight of the crosshead, piston and piston rods to bring the inner beam ends back downward.

When the pistons reached their lowermost position, fresh high pressure steam was admitted. This raised the pistons again, the open equilibrium valve allowing all residual (or low pressure) steam to collect beneath the annular low pressure piston.

When the pistons reached the top of the cylinders, the equilibrium valve closed and the exhaust valve opened the path to the condenser. Residual steam rushed into the condenser to be turned back to water, and the resulting vacuum added its effect to the suceeding downstroke.

The Cruquius Engine could raise about 120 million gallons of water in a twelve hour shift, working at eight strokes per minute. Indicated horsepower was about 965, fuel consumption being 2·5lb/ihp/hr.

CHAPTER FOUR

the quest for efficiency: life after James Watt

Though the Scotsman James Watt (1736–1819) is widely and perhaps justifiably regarded as the father of the steam engine, there is also little doubt that his was a 'dead hand' on development until the separate-condenser patent expired in 1800. Thereafter, with the enveloping monopoly of Boulton & Watt finally broken, many enterprising inventors sought new solutions to improve efficiency and reduce the size of engines, boilers and accessories.

SIDE-LEVER ENGINES

Boulton & Watt made about six engines in accordance with a patent granted to William Murdock in 1799. A short rocking bell crank lever beneath the vertical cylinder, driven by side rods attached to the crosshead, transmitted the motion through a link to the flywheel crankshaft. Compact blowing engines of this type were built in 1802–3 for Fulton & Sons of Glasgow and the Perth Foundry Company, relying on additional side rods attached to an extension of the bell crank to operate the air cylinder piston.

The first man to design a readily transportable engine seems to have been Matthew Murray of Fenton, Murray & Wood, who made a few side lever machines from about 1805 onward. Murray's 'Inverted Beam Engine' was built around an iron tank containing the condenser and the pumps. The cylinder was vertical, but the piston rod was connected by a crosshead with rods that ran vertically down outside the tank bed. A transverse bar connected with the operating beam placed centrally beneath the floor of the tank. The beam drove a flywheel by way of a rod and crank, whilst an intermediate box link operated the air pump.

The combination sliding 'D' type steam/exhaust valve, which had been patented by Murray in 1802, was driven by a short oscillating rod attached to the crankshaft. A short toothed sector attached to the valve rod slid the valve across the ports. Unfortunately for Murray, who was a talented engineer, too many of his innovations were embodied in a single patent. Boulton & Watt seized on one comparatively insignificant aspect, and the whole patent was rescinded in an atmosphere of great bitterness.

Offered in sizes as large as 24hp, Murray tank bed side lever engines still required a specially prepared base to accommodate the flywheel and a wall bearing to support the idle end of the crankshaft. Though not especially influential when it was introduced, the Murray engine subsequently inspired the development of tank bed beam engines in addition to a variety of marine engines.

Side lever engines were still being installed aboard ships in the middle of the nineteenth century. Engines of this type were also used on some of the first railway locomotives, though modifications of the table engine (q.v.) were more popular. The forty foot *Comet*, launched on the Clyde in July 1812, was one of the first steamboats to be driven by a side-lever engine. Promoter Henry Bell wanted the vessel to convey guests at his hotel and baths in Helensburgh to Glasgow and back.

The hull was built by Charles Wood, the boiler by David Napier, and the engine by John Robertson. It had a vertical cylinder measuring 12¼ × 16in driving the piston rod and crosshead upward. The crosshead was connected with two half beams—pivoted at their outer ends—by side rods. The flywheel was driven by a connecting rod attached to a transverse bar between the half beams, spur gearing transmitting the motion to the paddles. The slide valve was worked from a rocking shaft by a loose eccentric, which could be slid along the crankshaft to reverse the motion. The pioneering steamship was wrecked on Crinan Point in 1820, but the engine was salvaged.

The perfection of the side lever marine engine is widely credited to Robert Napier, whose first example was built in his yard in Camlachie, Glasgow, in 1823 for the paddler *Leven*. The 31½ × 36-inch single cylinder engine can still be seen in Dumbarton, but most of Napier's later products had two cylinders driving cranks set at ninety degrees to each other to provide even rotation and facilitate starting. Jet condensers were standard, a partial vacuum being maintained by air pumps, and an adaptation of Watt parallel motion was usually used to keep the piston rods vertical.

Paddle steamships with side lever engines soon became popular, and grew rapidly in size. The first cross channel voyage was made by *Margery*, from Newhaven to ?Dieppe in ?1819, and the first Atlantic passage entirely under steam was made in 183X.

However, though changes were soon made to the paddles—the first feathering wheels were designed by Charles Baird in 1815 for service in Russia on the river Neva—progress in engine design was exceedingly slow. There were variations in side lever construction, some taking the form of bell cranks, but the differences were generally confined to detail. But there was undeniably a tremendous growth in size. The mail steamer *Dee* of 18?? had Boulton & Watt engines with two cylinders each measuring 54 × 60 inches, operating at 8lb/sq.in to drive 20ft-diameter paddles fast enough to maintain about eight knots.

Typical Napier side lever engines were fitted in *Britannia* (1156grt), built on the Clyde for Samuel Cunard in 1840. The first steamship to carry mail from England to Boston, Massachusetts, she took a little over fourteen days to cross the Atlantic at an average speed of about 8 knots, using 35–40 tons of coal daily. *Scotia* of 1862, the last paddle steamer to be built for the transatlantic service, had side lever engines with two 100 × 144-inch cylinders supplied with steam at 20lb/sq.in from eight tubular boilers. *Scotia*'s engines developed 4900ihp and drove enormous paddle wheels with a diameter of forty feet.

Side lever engines were popular with ship designers, as they had a lower centre of gravity than the conventional beam engines they otherwise resembled. The marine engines were generally plainer than those used on land, though their entablatures often showed Greek, Egyptian or Gothic decorative influences.

GRASSHOPPER ENGINES

The grasshopper or 'half beam' engine was a near contemporary of the side lever type. It was patented in England in 1803 by William Fremantle, best known for his distinctive parallel motion design, but the first engines seem to have been the Columbians made—independently of Fremantle—by the American Oliver Evans. The claim to novelty lay in a short beam attached by back links (often in ladder or lattice form), pivoted in the bed frame where the flywheel connecting rod would normally lie. The cylinder, rigidly attached to the frame, carried a small auxiliary frame, usually in the form of an 'A', which anchored the bridle rods.

The bridle rods ran forward to the mid point of the beam, acting in concert with the back links to provide a parallel motion. The flywheel, next to the cylinder, was driven by a connecting rod taken from the beam between the gudgeons for the piston rod and the bridle; the air pump was generally driven from pendant rod attached to the beam between the connecting rod and the back links. Most grasshopper engines had slide valves, driven from the crankshaft by an eccentric and a rocking layshaft.

These engines were very popular, as they were compact and could simply be bolted to a prepared masonry base, but power was usually restricted by the comparatively short crank throw. Manufacture continued until the 1880s, some of the best (and some of the largest) being the work of Eastons & Amos and their successors. Several survive in museum collections.

TABLE ENGINES

Credit for the first table engine is generally given to Henry Maudslay, who patented one in 1807, but it is possible that Richard Trevithick was making comparable models as early as 1802. The vertical cylinder of the Maudslay engine was carried above the crankshaft axis on a ‘table’ supported by four sturdy pillars. The piston rod was connected to a crosshead wheel reciprocating in a slotted guideway fitted to a secondary platform, which doubled as the cylinder head support. A pin on the crosshead mated with a connecting rod, which ran down through a slot cut in the table to drive the fly crank.

In the original design, a pair of pivoting beams above the crankshaft drove the air and feed pumps. The steam valve was lifted by a push rod driven from an eccentric on the crankshaft.

Maudslay’s engine was rapidly exploited as a compact power source, driving anything from watchmakers’ lathes to small sugar cane mills. Most of these engines were probably made after the expiry of Maudslay’s patent in 1821. They also often take a simplified form, with the crosshead guides formed integrally with the cylinder cover and simple ‘D’ type slide valves driven by a cam or eccentric on the crankshaft.

The table engine enjoyed a brief period in vogue, but still drove the crankshaft through an unnecessary side rod. It was rapidly superseded after about 1850 by the simpler oscillating and vertical engines, which drove directly onto the crankshaft. Yet thousands of table engines were made by a variety of small scale manufacturers, too many of whom remain anonymous. Survivors continued to operate into the twentieth century and can now be found in museum collections throughout Britain.

OSCILLATING ENGINES

The popularity of engines which required beams or additional rods waned once it had been proven that not only could a crank be driven directly from the piston rod but also that it was largely self regulating. However, the deep seated fear that direct acting engines would wreck themselves persisted long enough to allow table engines to enjoy a brief heyday.

The rise of direct drive systems on land was due to a search for portability, which found a particular outlet in the development of railway locomotives and road vehicles. A major catalyst of change at sea proved to be the screw propeller, which required a fore and aft shaft instead of lateral drive to paddle wheels. The screw had a pedigree stretching back to the early eighteenth century, but its potential was not recognised until the 1830s. Credit for its revival is due largely to Francis Smith and John Ericsson, working independently in Britain and France.

The prospects of the propeller were not initially matched by engines, which ran much too slowly to rotate them efficiently. Though the seventy foot screw steamship *Robert F. Stockton* had been built successfully by Lairds of Birkenhead in 1838, many steam engine makers considered that its direct drive engine (which trials showed to be capable of 50 rpm) ran too fast for safety.

Owing to these technological deficienies, geared engines became popular for a few years—even though cast iron gearing was noisy and wood tooth systems were not particularly durable. By the mid 1840s, however, manufacturing techniques had improved sufficiently to allow engines to be coupled directly to the propeller shaft. The oscillating, vibratory or pendulous engine, invented by William Murdock in 1785, was amongst the first of the direct drive types to become popular.

The piston rod was connected directly to the crankshaft by allowing the rocking motion of the trunnioned cylinder to accommodate the angular displacement of the rotating crank. Steam was generally admitted through one trunnion and exhausted through the other, providing the major drawback of an otherwise simple machine and delaying commercial exploitation for nearly forty years.

1: VERTICAL ENGINES

These enjoyed a brief heyday on land, but wore quickly owing to restricted bearing surfaces. However, production was surprisingly large and engines are still regularly encountered in preservation. Most are built on a simple ‘A’ frame, though pillar supported examples are known. A few inverted vertical examples have also been reported.

The basic principles of the oscillating engine were resurrected in 1827, when Joseph Maudslay patented an improved two cylinder design. The condenser and air pump lay between the cylinders, where they were driven from an auxiliary crank on the paddle wheel shaft. The engine was carried on paired ‘A’ frames, the outer trunnions admitting steam whilst the central trunnion exhausted to the condenser. The slide valves contained in chests on the inner or exhaust faces of the cylinders were driven from separate eccentrics on the paddle shaft. The Thames paddler *Endeavour* of 1829 was one of the first to be fitted with an engine of this type—a 20nhp example made by Maudslay, Sons & Field.

Improvements were made to the oscillating engine by John Penn of Greenwich, who patented an improved valve gear in 1831. By 1853, Penn had developed a distinctive design with three cylinders angled at sixty degrees to each other to give the paddle wheels a smooth turning movement.

The introduction of oscillating engines was viewed with apprehension by ships’ engineers, who regarded their moving parts as additional danger in an already perilous environment. Gradually, however, the simplicity and strength of oscillating machinery became appreciated and engines of this type were built well into the 1860s until enthusiasm for them declined with the advent of the screw propeller. However, paddle steamers continued to use oscillating engines for many years.

The engines of *Pacific* (1469grt), built and engined on the Thames in 1853 by John Scott Russell & Company, developed 1684ihp and weighed 240 tons. The two cylinders, measuring 74 × 84 inches, drove wheels with a diameter of 27 feet to give the ship a speed of more than fourteen knots. The four ‘box’ or rectangular boilers contained 1760 three-inch diameter fire tubes, weighed about 160 tons in working condition, and delivered steam at merely 18lb/in . They were amongst the first multi tube boilers to be used successfully at sea.

The use of tubes—commonplace on railway locomotives since the Rainhill Trials of 1829—had been suggested by the Earl of Dundonald in 1845, but did not become widespread for another ten years.

Among the largest was fitted in Brunel's *Great Eastern* (27,384grt), completed on the Thames in 1858. It had four 74 × 168-inch cylinders, weighed 836 tons, and indicated 3411hp. Some of the most powerful engines of this type, however, were installed in the mail packet *Leinster* (?2000grt), the first of several sisters built for the Holyhead–Kingstown route from 1860. The engines had cylinders of 98 × 78 inches, developing 4750ihp. The cylinders had two valve chests on opposite sides of the trunnions, to balance them properly, and the valves were driven by one loose eccentric per cylinder on the crankshaft.

Eight multi tube boilers, with forty stoke holes and more than four thousand fire tubes, supplied steam at 20lb/in . The valve motion was operated by a sliding rod ending in a curved slot, which received the valve gear slide blocks to ensure that the valve events were isolated from cylinder oscillations. Rack and pinion gear enabled the paddle shaft motion to be reversed. On her trials, *Leinster* made nearly eighteen knots at 25 rpm.

The very low boiler pressures of the day required enormous cylinders to generate enough power. The earliest boilers were so weakly made that relief valves were often provided to prevent them collapsing when the cooling of water produced a partial vacuum. Few sea going ships risked pressures greater than 5–10lb/in until the 1850s.

2: HORIZONTAL ENGINES

Pre-1850 oscillating engines of this type are much scarcer than vertical patterns, perhaps reflecting the concern that their cylinders would wear too quickly. However, small examples proved very popular on children's toys made from the middle of the nineteenth century to the present day. Produced by toymakers great and small, in a vast range of sizes and styles, they are universally known as 'Piddlers' owing to the trails of drips that mark their progress.

As steam pressures increased, oscillating engines became frustratingly difficult to seal and fell rapidly into disrepute. Attempts were still being made in the late 1870s to provide efficient seals into the late 1870s, but were doomed to failure by the very nature of the machines they sought to improve. In one particular design, the bottom of the cylinder was curved to fit a base plate through which steam could be admitted and exhausted as the entire cylinder moved in its arc.

STEEPLE ENGINES

The steeple engine was a variant of the table pattern (q.v.), introduced about 1818–20. The flywheel of the largest table engines often presented a problem, as it often extended beneath the engine bed plate. This created few difficulties with the small machines, which could be raised on brickwork or a sturdy wooden bench, but large machines required a flywheel pit. This in turn restricted their portability.

Steeple engines retained the vertical cylinder, but it was bolted directly to the bed plate beneath the crankshaft. The piston rod was attached to an openwork frame—usually triangular, but occasionally elliptical—which formed a crosshead sliding in the slotted upper extension (or 'steeple') of the frame. A connecting rod ran downward to a crankshaft revolving inside the triangular frame as the piston reciprocated. This allowed the flywheel to be mounted entirely above the bed plate, though a duplicate frame was needed to support the idle end of the crankshaft. Slide valves were customarily driven from a crankshaft eccentric.

Steeple engines were soon adapted to marine use, amongst the first being made by George Forrester & Company of Liverpool for the paddler *Rainbow* in 1837. Robert Napier built some 30nhp single 32 × 42-inch cylinder engines of this type for the East India Company's shallow draught river steamers.

These engines had two piston rods to each piston, which passed upward through the cover plate with one on each side of the paddle wheel shaft, to join a crosshead sliding in tubular guides. The connecting rod drove downward from the crosshead to the crank. The crosshead also drove the air, water feed and bilge pumps through links and levers, whilst reversing was accomplished by Stephenson link motion; this had a toothed link, which could be adjusted by hand wheel and pinion to alter the cut off.

A unique horizontal engine inspired by John Ericsson was installed in the frigate *Pomone* in 1843 by Ericsson's representative in France, Comte de Rosen. The trapezoidal distance piece was retained, but was guided on a horizontal slide frame and connected with two piston rods.

Steeple engines held few advantages over the simpler direct drive vertical patterns of the same era and lost favour for land use in the 1860s. Some of the largest were made for marine use, a role in which they lasted into the 1880s.

Only a single full size steeple engine survives in Britain, made in 1868 and now owned by the Royal Scottish Museum after a life spent in St Leonard's Brewery in Edinburgh. It has a single 7 × 14-inch cylinder with a conventional eccentric driven slide valve, and a flywheel diameter of 6 feet. A few others remain in Europe, one dating from *c.* 1845–50 being maintained in working order in the Technisches Museum in Vienna.

VERTICAL ENGINES

An engine of this type is often regarded as a simplified table engine, but substantial numbers of large scale examples had been made by 1805.

1: THE EARLIEST PATTERNS

A unique beamless Boulton & Watt engine was erected in Halebeagle Mine in the Cornish North Downs district in 1796. It had a vertical 52 × 80in cylinder placed directly above the shaft and drove the pumps through a crosshead, side rods and 'V' bobs. In 1797, Edward Cartwright patented an extraordinary single cylinder vertical engine with counter rotating crankshafts connected with a single crossbar attached directly to the piston rod. Toothed wheels attached to the crankshafts drove a flywheel by way of a small intermediate pinion. The condenser was a narrow tube permanently connected to the cylinder and a primitive surface condenser was immersed in the tank bed. An engine was erected in Wisbech in 1802, but was unsuccessful.

Matthew Murray patented his 'Cycloidal Engine' in 1802, obtaining a straight line piston rod motion from a crank connected to a small toothed wheel rolling within a toothed ring attached to the four pillar frame. The valves were driven from a geared shaft. The engine was too complicated to sell widely and was rapidly overhauled by simpler designs.

A partially reconstructed example owned by the Birmingham Museum of Science and Industry is the only survivor. The true prototype of the vertical engine, however, was patented in 1800 by Phineas Crowther of the Ouseburn Foundry in Newcastle upon Tyne, but very few of his crank and rod pattern seem to have been made.

Richard Trevithick was the first to build vertical engines in quantity, his high pressure non-condensing Portable Agricultural Engine becoming a great success in the West Country and the south west Midlands. The first example, intended to thresh corn, was built in 1812 for Sir Christopher Hawkins of Trewithen. Its single cylinder was buried vertically in the squat boiler, which was set into a brick hearth with an annular flue. A single connecting rod connected the trunk piston with the flywheel crankshaft. The engine was carried on a sturdy wooden frame supported by slender cast iron columns. An oscillating plug type valve was driven by an eccentric on the crankshaft, and steam exhausted into the atmosphere through a long chimney running vertically up through the framing.

No safety features were fitted, but the engines were economical enough to run for six hours before the boiler needed refilling. They developed about 4hp, cost £80, and were claimed to consume coal at a rate of only 2 lb/hp/hr. A few were apparently fitted with an expansion cock worked by an adjustable cam, with beneficial effects on economy.

2: THE POLE ENGINE

This machine was amongst Richard Trevithick's strangest contributions to steam history. Adapted from his pump and hydraulic engines, it consisted of a long, large diameter piston (the 'pole') sliding within an elongated cylinder or 'pole case'. The pole was extended upward to join a crosshead, which drove the pump machinery directly through two side rods.

Though a patent application was not made until June 1815, Samuel Grose had erected the first pole engine four years previously in Wheal Prosper Mine, Gwythian. It had a 16-inch diameter cylinder, an eight-foot pole, and cost 750 guineas. Fed with steam at 100lb/sq.in from two wrought iron cylindrical boilers (3 feet diameter, forty feet long), with external fire grates and enveloping flues, the engine was said to give a Duty of forty million.

When steam was admitted to the base of the cylinder, it began to raise the pole piston. The admission of steam was then stopped to allow the remainder of the upward stroke to be completed by expanding steam, and the exhaust valve was then opened either to the atmosphere or a condenser. This allowed the pole to fall rapidly under a combination of gravity and vacuum (if a condensing engine), operating the plunger pump in the mine shaft.

Pole engines were extremely efficient when new, especially in comparison to the obsolescent machinery they superseded. But they had several poor features. Excessive friction arose between the pole and the pole case, particularly if the fit was poor, and the pole was difficult to seal against the high pressures involved. The exposure of large surfaces to the atmosphere not only caused excessive cooling but also promoted corrosion.

Few of the original Trevithick pole engines enjoyed a long or profitable life. The largest engine—with a pole measuring 33 × 144 inches—was erected in Herland Mine in 1815. The two 5ft 6in diameter boilers, each forty feet long, had a central flue reinforced by external channels through the supporting brickwork. The pump had a diameter of 14½ inches, a 120-inch stroke, and operated at fourteen strokes each minute.

The Herland pole engine was particularly interesting, as it had been erected to demonstrate superiority over not only the 72in double acting Boulton & Watt machine operating since the 1780s—said to be Watt's own favourite—but also a Woolf compound erected in 1814.

Watt had claimed his engine to be capable of a Duty of about 27 million, though this was apparently based on 120lb of coal instead of the customary 94lb Cornish Bushel. A public test in 1798 had returned merely seventeen million. The Watt engine was coupled to a 14-inch diameter pump with an 84-inch stroke, operating at about twelve strokes each minute. The Woolf compound was about as powerful as the Boulton & Watt machine, but cost ten times as much as the Trevithick pole engine.

The major components of the Herland pole engine were made by Hazeldine & Rastrick in Bridgnorth. The cylinder allowed a ten-foot stroke (subsequently increased to 10ft 6in) and could take steam at 120lb/sq.in, though this proved to be too much for the pump rods and was subsequently reduced to 80lb/sq.in, cutting off at about two thirds of the stroke, and then to 60lb/sq.in with the cut off set at a quarter stroke.

A test of the pole engine in March 1816 returned a Duty of 48 million at 100–120lb/sq.in, with a comment that sixty million could eventually be returned. But the trials had been a vision of hell. The boilers leaked steam copiously, particularly when the highest pressures were reached, and onlookers were terrified by steam escaping from the safety valves. The exhaust could be heard five miles away.

The pole engine proved to be more powerful than the Boulton & Watt and Woolf engines combined, approaching the capabilities of the two 80in Watt type engines working in Cornwall. But the Herland Mine engine regularly blew out piston packings and, as the pole wore badly, it was soon abandoned. Metallurgy had once again failed to keep pace with inventiveness.

3: POLE ENGINE CONVERSIONS

Small auxiliary units were added to existing Watt engines, forming a type of compound, but in this respect Trevithick lagged behind his Cornish rival Arthur Woolf. The first conversion seems to have been undertaken in Bere Alston, and others had soon appeared at Wheal Lushington, Poldice and Wheal Diamond. A few Boulton & Watt engines gained pole engine feed pumps (e.g., at Wheal Alfred as early as 1812–13).

A typical 'pole engine compound' in Wheal Chance Mine, Scorrier, converted in 1816, allied a small auxiliary cylinder with the 58-inch diameter original. The pole case was fixed to the bed of the engine between the cylinder and the main beam centre. The altered machine returned 46·9 million Duty in 1817, simultaneously halving the original coal consumption.

4: SIMS' COMBINED ENGINES

A few machines of this type were installed by William Sims, agent for the Cornish United Mines. Born in Chacewater in 1762, Sims had been sent to London in 1811 by the major shareholders in Gwennap Mines to examine the Woolf compound installed in the promoters' Lambeth workshop.

He returned to Cornwall convinced of the virtues of multi stage expansion, but was unable to reach terms with Woolf and instead purchased a half-share in the pole engine shortly before Richard Trevithick left England for South America.

Sims also fitted a few high pressure pole units to existing single cylinder engines, the earliest Combined Engine (installed in Treskerby Mine in 1815) being created by adding a 36-inch short-stroke pole unit was added to a 58-inch Boulton & Watt machine. Duty increased from 17·5 million in 1814, before conversion, to 40·3 million in 1820.

Unfortunately, attention was soon drawn to infringement of Woolf's patent and work ceased after only a few machines had been converted. The shareholders in these mines were forced to pay Woolf £500 damages in settlement of the claims. William Sims subsequently turned to the erection of Cornish cycle engines, assisted by his son James. He died in 1834.

Trevithick departed for the silver mines of Peru in 1815, leaving a catalogue of extraordinary but largely unexploited inventions. He did not return until 1827, with little but his life to show for his adventures. His last engine was an inverted vertical pattern, described below.

5: LATER VERTICAL PATTERNS

Huge engines supplied air for blast furnaces or drove textile mills, but were soon eclipsed by inverted vertical or horizontal patterns. The original vertical type was most popular in north east England, particularly the Durham coalfield. Some two cylinder vertical engines—invariably 'house built'—were erected, as were smaller examples with pillar or 'A' frame supports for the crankshaft bearings.

One of the first maritime applications of a vertical closed-cylinder engine was made in the USA by John Stevens and his son Robert, who built the 24-foot propeller-driven launch *Little Juliana* in 1804. A high pressure multi-tube boiler supplied a single-cylinder vertical engine, which drove a connecting rod attached to the crosshead. The two propeller shafts were geared together to ensure that they rotated in phase. Stevens' paddle wheeler *Phoenix* (1807) became the first steamboat to make a proper sea passage in 1808 and successfully plied the Delaware river for several years.

The popularity of vertical engines increased as steamships grew in size. As ships grew larger, space could be found to mount cylinders directly below the crankshaft or, alternatively, one beneath (driving by side rods or a crank) and another fore or aft driving through side levers. Compromise gradually gave way to the direct drive method, with vertical cylinders set directly beneath the paddle shaft to drive onto cranks.

The first direct-drive steamship seems to have been the paddle frigate *Gorgon* (1111 tons displacement), designed by Sir William Symonds and launched from the Royal Dockyard, Pembroke, in 1837. The engines were made by Seaward & Company. There were two cylinders measuring 64 × 66 inches carried on heavy base plates which not only contained the condensers and hot well, but also formed a mounting for the air- and water-feed pumps. These pumps were worked from rocking levers controlled by the parallel motion that guided the piston rods. The crankshaft was supported with an eight column entablature. Steam was supplied from four large tubular boilers, each with four furnaces; speed was 9·75 knots on 24 tons of coal each day.

The machinery aboard *Gorgon* was successful, but the short conencting rods were undesirable; not only did they strain the parallel motion, but the marked angular displacement during the piston stroke hindered smooth operation. One solution was found in open top cylinders, which allowed a longer rod to be anchored in the piston body almost directly behind the piston head, but obviously restricted the engine to single action. Engines of this type were introduced about 1839, Seaward and Capel producing similar designs at much the same time. Improvements in construction allowed the heavy base plates that had characterised the engines of the 1830s to be discarded, the cylinders being bolted directly to the keel through the intermediacy of the condenser frames. Most were operated by long 'D' type slide valves driven by crankshaft eccentrics and rocking shafts.

Another method of providing a long drive rod within restricted dimensions was the 'return [connecting-]rod engine'. This could be fitted with vertical (or sometimes inverted vertical) cylinders. The piston rods ended in a crosshead, guided by parallel motion, to which the connecting rod was attached. The connecting rod ran upward (often between the cylinders) to drive the paddle shaft, and the auxiliary pumps were often worked from the crosshead by rocking levers or rods.

The 'Siamese Engine' was a variant of the return rod type, patented in 1844 by Joseph Maudslay and Joshua Field. The first examples was apparently installed in the paddle frigate *Retribution* (1641 tons displacement), the twin cylinders of each of the two engines measuring 72 × 96 inches. They were placed in line beneath the paddle shaft, the piston rods being attached to a substantial 'T'-shape crosshead sliding in guides between the cylinders. The connecting rod was pivoted in the tail of this 'T' head and ran upward to the paddle shaft crank.

The annular trunk engine—patented by Joseph Maudslay in 1841—featured vertical cylinders. The trunk piston was designed so that the crankshaft, beneath the engine, could be driven by a connecting rod attached to a crosshead sliding in guides attached above the cylinder top plate. However, the necessity to seal both ends of the cylinder made these engines needlessly complicated and few were made.

THE EARLIEST HORIZONTAL ENGINES

The expiry of the master Watt patent in 1800 allowed Symington to gain a patent of his own on 14th October 1801 and design another steamship, the famous *Charlotte Dundas*. Built by Alexander Hart of Grangemouth, with the patronage of Lord Dundas, the 56-foot vessel had a single hull. The power source was a single-acting horizontal engine with a 22 × 48-inch cylinder, which drove directly onto an overhanging crank pin to revolve the paddle wheel by way of slide bars, a crosshead and a connecting rod. The condenser and the air pump were worked by a bell crank pivoting on the crosshead.

Charlotte Dundas was tried successfully on the Forth & Clyde Canal in 1802, towing a load of 140 tons for nearly twenty miles. Unfortunately, vested interests in established methods of canal haulage persuaded the canal owners that the wash of the steamship would be extremely damaging to the banks and so nothing further was done. Symington became another of many talented pioneers to fade into obscurity, dying unnoticed in London in 1831, and his pioneering vessel was abandoned to rot slowly away.

The true father of the modern horizontal engine was Richard Trevithick who, unlike Symington, was convinced that only high-pressure steam could combine suitably compact dimensions with acceptable power. However, though Trevithick built road carriages and locomotive engines in the first years of the nineteenth century, no real progress was made until the 1820s.

Trevithick had been born in Cornwall in 1771 to a father who managed atmospheric- and Watt-type engines serving the tin mining industry. After a most rudimentary schooling, from which he emerged barely able to read and write, young Trevithick was made engineer at Eastern Stray Park Mine in 1790. His genius was already apparent, but so was the impetuosity that was to dog his life.

In 1791—while still only twenty—Trevithick was asked by a committee of Mine Captains to examine Jonathan Hornblower's compound engine, which was being hailed as a local challenger for the despised Boulton & Watt. Richard Trevithick could only report that Hornblower's machine was neither substantially better nor appreciably worse than its rival.

From 1792 onward, Trevithick associated with Edward Bull in the erection of inverted cylinder engines. These were placed directly above the mine shafts so that the piston rods could be connected directly with the pump rodding. Boulton & Watt served injunctions on Bull and Trevithick in 1796, but were unable to prove that the two men were in partnership.

An infringement suit brought in this period against Hornblower & Maberly was more successful, bringing Trevithick to London to witness proceedings. Whilst in London he met Davies Giddy (later known as Davies Gilbert), a wealthy landowner with a passion for the sciences. Not only did Giddy become President of the Royal Society later in life, but he was also fascinated enough by Trevithick to become the Cornishman's mentor. In 1797, Richard Trevithick married Jane Harvey, daughter of the owner of the Hayle Foundry where most of the castings for the Bull engines had been made, and his future seemed assured.

High pressures intrigued Trevithick greatly, perhaps because they were entirely contrary to the cautious approach of James Watt. Boulton & Watt engines pumped water effectively, but the slow moving sun-and-planet rotatives did not operate the 'whims' (winding drums) as readily.

The first model of a small non-condensing engine driving through a crank instead of a beam was made in 1796. Armed with Davis Giddy's opinion that the loss of vacuum would be partly offset by the absence of an air pump, Trevithick erected his first large engine in Dolcoath Mine in 1798. The cylinder was recessed in the boiler horizontally, and the piston rod, riding in slotted guides, drove a connecting rod coupled to a crankshaft attached to the rope drum. Boiler pressure was 25lb/in , and the engine exhausted steam with a bark that gained it the sobriquet 'Valley Puffer'.

About 1802, probably after experience had been gained with the rudimentary blast pipe of the first steam road locomotive, Trevithick altered the Valley Puffer so that steam exhausted into the chimney. This created additional draught, made the fire burn more fiercely and raised steam more economically.

Construction of these early engines varied, as each was built to an individual specification; cylinders could number one or two, horizontal or vertical, condensing or exhausting directly to the atmosphere. Vertical cylinder machines generally drove beams instead of directly to the cranks. Some engines were quite large and others were surprisingly small. But they were cheap to build and economical to run, even though most had short lives.

The earliest winding engines or 'steam whims' were installed in Cook's Kitchen Mine in 1799–1800. These both had condensers; one even had two cylinders. They were the first of perhaps thirty installed in Cornwall. Operating pressure was still about 25lb/in , steam being supplied from horizontal cylindrical boilers with a single central flue — the original 'Cornish' pattern.

Unfortunately for Trevithick, the explosion of a high pressure drum-type boiler in Greenwich in September 1803 cost four lives. The cause was subsequently found to be a heavy spanner added to the safety valve by the engine minder, to prevent the valve lifting, but this explanation gained much less publicity than the incident itself. Boulton & Watt publicly denounced the dangers of excessive pressures; Trevithick was still regarded as a real threat to their cosy prosperity.

By this time, Trevithick semi-portable engines were being made right across England from Newcastle to Cornwall. The unscrupulous nature of many licensees was reflected in their attitude to the inventor, who had often to threaten them before gaining his dues. Among the most trustworthy contractors were the Coalbrookdale Company and Hazeldine & Rastrick of Bridgnorth. The latter partnership lasted until 1818, when Rastrick began working independently in West Bromwich.

In these semi-portable engines lay the genesis of the railway locomotive and the traction engine. The Coalbrookdale Company were the first to build a horizontal-cylinder engine, designed by Richard Trevithick to run on a wagon way. Work had begun August 1802, but was stopped when the engine was 'first started up'—possibly owing to a boiler failure—and was then abandoned.

In 1804, Trevithick completed a locomotive engine for the Pen y Darren Ironworks near Merthyr Tydfil. The owner of the works, Samuel Homfray, had so much faith in the engine that he bet 500 guineas with Anthony Hill of the rival Plymouth Ironworks that ten tons of iron could be hauled on the 4ft 6in gauge wagon way from Pen y Darren to Abercynon.

The locomotive was successfully tested on 13th February 1804. It had a single 8¼ × 54-inch cylinder and ran at about forty strokes per minute, giving a speed of 4mph. The exhaust steam was turned from the cylinder up the chimney, forming a primitive blast pipe—an invention later claimed on behalf of Stephenson, Hackworth and many others. Steam was distributed to the cylinder through a four-way rotary valve, which was operated by tappets on a rod struck by a lug on the cross head. The only safety feature appears to have been a fusible plug, which may also be due to Trevithick. The plug melted if the boiler water evaporated and the temperature of the boiler wall rose too far.

When the wager run took place on 21st February 1804, the engine successfully pulled five wagons, ten tons of iron and about seventy joyriders from Pen y Darren to Abercynon. The nine mile journey took a little over four hours, on two hundredweight of coal. Undergrowth had had to be cleared from the path of the train, restricting speed; the maximum was about 5mph. On the return journey, however, a bolt holding the axle to the boiler barrel came away and the boiler water escaped.

The locomotive subsequently made several more trips, hauling as much as 25 tons of iron, but was too heavy for the plate way and was eventually relegated to stationary duties. Several other Trevithick engines were constructed, but the last—*Catch Me Who Can*—had a vertical cylinder (q.v.). The failure of a partnership with the unscrupulous Robert Dickinson (to produce cast iron tanks for maritime use) ruined Trevithick financially, and the inventor was never able to perfect his railway locomotives. He returned to Cornwall in 1811 to create the prototype high-pressure pole engine; and the idea of a horizontal engine lay dormant for many years, tempered by fear that excessive friction would wear the underside of the piston and cylinder too quickly.

1: THE FIRST SUCCESSFUL DESIGNS

By 1825, Taylor & Martineau of London introduced a high-pressure horizontal engine commercially. Its design is usually credited to Philip Taylor, working under the tutelage of Arthur Woolf.

The engine had a lattice girder frame bolted to a prepared bed. The piston was connected to a stirrup ended crank rod by a crosshead sliding in slotted guides, relying on wheels on the tips of the crosshead bar to minimise friction. The condenser lay beneath the cylinder, the air pump was operated by an eccentric on the crankshaft, and the Watt type flyball governor was driven by a three speed pulley system.

By the 1840s, as objections receded, the horizontal engine was challenging the supremacy of other direct-acting designs. It lasted even in its simplest single-cylinder simple expansion guise into the middle of the twentieth century.

The typical single-cylinder machine was offered in a range of sizes from a few horsepower up to more than 100hp. The most basic forms had ‘D’ type slide valves driven by an eccentric on the crankshaft, but details varied widely.

The construction of horizontal engines may also give a clue to their age, as early examples often had separate crosshead guide bars bolted to the frame bed; later ones customarily took a simpler cylindrical form. The earliest examples relied on the proven 'D' type valve, whereas many made from the 1860s onward have Corliss semi-rotary valves and post-1870 European engines often had Sulzer drop valves.

2: THE FIRST LOCOMOTIVE ENGINES

The opening of the Stockton & Darlington Railway occurred in 1825, but the earliest engines, exemplified by *Locomotion*, were still generally derived from the table engine and had vertical cylinders buried in the boiler. Though Stephenson introduced the fire-tube boiler for railway locomotives in 1827, the idea apparently being suggested by his backer Henry Pease, it seemed as though the locomotive engine was making very little progress.

The directors of the Liverpool & Manchester Railway, uncertain of whether to use locomotive or stationary engine haulage, decided to announce competitive trials. Four steam locomotive engines appeared, plus the horse on treadmill Cyclopede submitted by John Brandreth. The 0–2–2 *Rocket* entered by George and Robert Stephenson, had diagonal cylinders mounted alongside the firebox, driving directly onto the crank pins through piston and connecting rods. *Novelty*, an 0–4–0 created by William Braithwaite and John Ericsson, was a side-lever design with two vertical cylinders driving the coupled wheels through bell cranks. The 0–4–0 *Sans Pareil*, by Timothy Hackworth, had inverted vetical cylinders driving directly onto the crank pins by way of piston and connecting rods. Timothy Burstall's *Perseverance*, based on his road carriage, was a vertical-boiler 0–4–0 with a two-cylinder table engine driving a dummy crankshaft through side rods. The motion was transmitted to the wheels by gearing.

The victory of *Rocket* ended the first phase of railway locomotive development, and the influence of beam, side lever and table engines disappeared almost overnight. But even *Rocket* was soon improved. The thrust of the original pistons, which were set at too great an angle, tended to lift the wheels clear of the rails at high speed. Horizontal cylinders were clearly preferable, and so all subsequent Liverpool & Manchester Railway locomotives of *Rocket* type followed the modified design, beginning with the delivery of *Meteor* in January 1830. *Rocket* was soon modified to conform.

The use of two cylinders operating out of phase had already been established as a means of allowing a locomotive engine to start even if one crank had stopped on dead centre. It also smoothed the transmission of power to the wheels. Though dummy crankshafts, bell-crank levers and other unusual power transmission systems were all tried, the success of Stephenson's *Planet*—delivered in September 1830—established the classical inside cylindered locomotive design. The cylinders were hidden from view between the flitched or 'sandwich' frames, where they drove a crank axle.

The success of even the earliest railways increased the loads engines were expected to pull. This was answered simply by making the engines bigger; boilers increased in diameter and had more fire tubes, increasing the amount of water that could be turned to steam and allowing cylinders to be enlarged; boiler pressures rose, forcing the development of adequate safety valves; driving wheels were enlarged so that the distance travelled with each rotation grew. Stability problems were solved by adding axles and, particularly, in the addition of bogies or pivoting trucks to guide engines around curves. The first bogie had been patented in 1812 by William Chapman. Isaac Dripps of the Camden & Amboy Railroad was the first to fit a pilot (or 'cowcatcher') and a pony truck, when, in 1832, he converted a Stephenson made 0–4–0 to a 2–2–2.

For all these changes, however, the inside cylinder design pioneered by *Planet* in 1830 remained practically unaltered into the twentieth century. The most important innovations in this period concerned valve gear, which allowed the expansive properties of steam to be used to best effect—increasing power whilst simultaneously reducing the consumption of coke.

The valve gear system patented in 1842 by William Howe is now better known as "Stephenson's", though Stephenson himself, mindful of the controversy that had attended the development of his miner's lamp, always gave credit where it was rightfully due. It was used until the very end of the steam age, alongside a single eccentric mechanism patented in Belgium in 1844 by Egide Walschaert.

One of the most distinctive answers to the problems of ever increasing demands on power, which was often accompanied by increased boiler length and engine weight, was provided by the English engineer Thomas Crampton. Intended to pull modest loads at high speed, Crampton locomotives had a trailing axle immediately behind the fire box, where it was driven (in the earliest designs at least) by outside cylinders placed between the widely spaced carrying axles.

The first of these engines was a 4–2–0 with a driving-wheel diamater of seven feet and 16 × 20-inch cylinders completed in 1846 for the British owned Liege & Namur Railway by Tulk & Ley of Whitehaven in Cumbria. Similar machines were then tested on the London & North Western Railway, culminating the unique 6–2–0 *Liverpool*, built in 1848 by Bury, Curtis & Kennedy. This 35 ton monster, with 8-foot drivers and two 18 × 24-inch cylinders, allegedly attained 75mph with a light train. Unfortunately, the rigidity of its wheelbase damaged the light and poorly laid track, and the ultimate success of the Crampton system was achieved in France.

The favourite horizontal marine engine of the Royal Navy in this era—unchallenged for thirty years—was the return [connecting-]rod pattern, first fitted in HMS *Amphion* in 1844. The twin cylinders were placed across the ship in proximity with the propeller shaft. The pistons each had two rods, between which the main shaft could rotate. The piston rods continued some distance past the main shaft to the crosshead, from which the connecting rod ran back ('returned') toward the piston to drive the main-shaft crank. This achieved the primary goal of marine engine designers inspired by Ericsson's *Princeton*: placing the propelling machinery beneath the waterline to protect it from shell fire.

Return-rod engines were often steam jacketed to reduce heat loss, and generally had link-type reversing gear controlled by handwheel, rack and pinion. Some engines had separate steam-expansion valves, which could be operated independently of the link motion. The expansion valve was generally driven by spur gearing from the crankshaft, could alter the cut off by using a sliding helically-grooved sleeve, and could be thrown out of gear instantly by a clutch mechanism if maximum power was needed in an emergency. Jet condensing was customary.

The horizontal trunk engine was also popular in the navy. The essence of this was the use of a long hollow body piston which allowed the connecting rod to be pivoted in the piston on a gudgeon pin, and drive the propeller shaft crank directly without requiring crossheads of crosshead guides.

Construction of this type had been patented by James Watt in 1784, and had been applied to land and marine engines alike for many years when—in 1845—John Penn patented an efficient double-trunk pattern in which the hollow double-acting pistons reciprocated to drive shafts on both sides of the engine.

This was suited more to two-shaft construction, but could be made to run a single shaft with suitable gearing. Vertical single trunk engines were popular with marine engine builders in the 1850s, but then lost favour.

THE LATER HORIZONTAL ENGINES

By 1850, the 'D' type slide valve pioneered by William Murdock and Matthew Murray had become all but universal. Most valves were driven by eccentrics on the crankshaft, which was also a well proven method. Experience with the earliest Newcomen atmospheric engines had shown that the best steam valves opened and shut as rapidly as possible. Drop or poppet valves were used until the introduction of the slide valve at the beginning of the nineteenth century. However, though slide valves were easily made and simple to maintain, they opened and shut comparatively slowly and could constrict the steam supply until the port was fully open.

At comparatively low speeds, these problems were unimportant. Any slight loss of performance was simply ignored, as the valves and the ports were made large enough to keep them to a minimum. To reach high speeds, however, a new approach was needed.

If steam is admitted during the entire piston stroke, a crank-driven steam engine can be set to rotate a flywheel in either direction simply by moving the crank manually to alternative sides of dead centre. But this method of reversing was far too crude to be useful and so, with the rise of expansive working, valve gear was developed to control the motion mechanically.

1: THE FIRST IMPROVEMENTS IN VALVE GEAR

The earliest of these relied on a loose eccentric, which could rotate on the crankshaft between limits set by two stops. A notch or 'gab' on the eccentric rod could be engaged with a lever connected with the valve spindle. Reversing the motion required the eccentric rod to be disconnected and the valve to be operated manually. When the mechanism began to turn, the rod was dropped back onto the valve rod lever; the eccentric was intercepted by the appropriate stop on the crankshaft to allow the cycle to continue automatically.

This system was superseded by a combination of a fixed eccentric and a gab for each direction. These were eventually linked so that one engaged automatically when the other disengaged. Finally, in 1842, William Howe of Chesterfield joined the eccentric rods with a curved slotted link in which the valve rod tip could slide. Reversing the motion was achieved simply by a rocking lever, which, acting through an intermediate rod, lifted or dropped the link as required.

Owing to the success with which Howe gear was applied to railway locomotives, it became universally known as "Stephenson's"—though Robert Stephenson himself always gave his employees the appropriate credit. However, many other forms of valve gear were designed in this era. Daniel Gooch developed a stationary link motion in 1843, whilst Egide Walschaert patented his first single-eccentric design in Belgium in 1844. Link-type reversing gear had an immediate impact on locomotive and marine engines, but not on stationary-engine practice. A greater advance lay in improving the valves. Attempts had been made to control engine speed automatically, by linking the governor to the valve gear instead of relying on a butterfly throttle valve in the main steam pipe. James Watt had experimented with governor control in the 1780s, but, though the Watt flyball governor was a remarkable performer for its day, sensitivity declined as angular displacement increased. Thus the engines 'hunted' as they ran to the governor, corrections being made too slowly to eliminate surging.

The deficiencies of the Watt governor were highlighted when engine speeds rose. This inspired development of more sensitive designs, amongst the best known being the Porter (1858) and Pickering (1862) types. New flyball governors were still being invented in the twentieth century, and a few engines may even be found with centrifugal systems built into the eccentric on the crankshaft.

Improved steam admission controls were developed by Zachariah Allen in the USA (1834) and Jean Jacques Meyer in France (1842). Meyer gear—which became popular in Europe—usually comprised a small slide on the back of the main slide valve, driven independently by its own crankshaft eccentric. The gear was simple, and could be adjusted manually if the purchaser did not want the complication and expense of governor control.

Alternative adjusters were subsequently patented by Augustus Rider (1868) and Wilson Hartnell (1876), but another approach relied on detent or 'detaching' gear to control a valve. One of the earliest designs of automatic cut-off gear was patented in the USA in 1841 by Frederick Sickels. It was tried on a Mississippi river boat, but its drop valves were not particularly successful. A longer lasting solution was provided by George Corliss.

2: CORLISS VALVES AND DETACHING GEAR

The original Corliss gear was applied experimentally to a beam engine in 1848, and then patented in the USA in March 1849. The first engine to operate with the distinctive variable expansion gear under direct control of the governor had a cylinder diameter of 32 inches and a 72-inch stroke. Its indicated horsepower was about 260.

The design had reciprocating slide valves, admission and exhaust being worked independently on opposing sides of the cylinder block. The key part of the mechanism was a central disc-like 'wrist plate', driven by an eccentric from the crankshaft, which was connected with four valve rods. These rods were linked with levers or toothed segments to operate the valves.

As the disc plate oscillated, its first function was to slide open an exhaust valve. On the admission side, however, the relevant valve rod was connected with the valve sector only by a detent and spring system. As the valve rod rotated to admit steam, the cut off point was reached and a ramped bar—sliding vertically—pushed a lateral bolt to disconnect ('detach') the valve rod from the valve sector. A drop weight closed the steam admission valve instantly.

Additional rotation of the disc plate then operated the second pair of exhaust and admission valves to obtain the reciprocal piston stroke, the engine being double acting. Alterations to the cut off were accomplished manually by altering the height of the ramped bar, using a threaded adjuster rod and an appropriate rack on the bar.

The original slide-valve mechanism was replaced in 1850 by a horizontal derivative. Pins on the valve lever meshed with stops on the valve rod, until disconnected when ramps on the cut-off rod, controlled by the governor, pushed the detaching bolts downward. The valves were weighted to make closure almost instantaneous.

The greatest advance in the earliest Corliss horizontal engine lay in the valves, as the original sliders had been replaced by hollow cylinders oscillating in liners ('semi-rotary valves') to admit or exhaust steam. The central disc-plate was driven by the tail rod of the crankshaft eccentric.

The horizontal gear was improved in 1851. Though it was still driven

TABLE EIGHT:
Operating characteristics of Corliss and other engines

From Uhland's *Corliss Engines and Allied Steam Motors working with and without Automatic Variable Expansion Gear* (1879)

1) Corliss type
22 engines. Power: 12–675hp. Boiler pressure: 45–90 lb/sq.in. Running speed: 30–82rpm. Average maximum cut off: 48 per cent. Most popular governors: Porter (eight engines), Watt (five), Proell (four). Note: several modified Corliss examples could cut off much later in the piston stroke — e.g., Douglas & Grant, 65 and 72 per cent, Kliebisch 75 per cent, B de & Farcot 80 per cent, and Wannieck Köppner 100 per cent or full stroke.

2) Other types of rocking valve
Six engines. Power: 6–80hp. Boiler pressure: 45–150 lb/sq.in. Running speed: 60–125rpm. Average maximum cut off: 79 per cent. Most popular governor: Porter. Note: the lowest extreme cut off was 63 per cent.

3) Flat slide valves
Fourteen engines. Power: 20–100hp. Boiler pressure: 60–75 lb/sq.in. Running speed: 40–85rpm. Average maximum cut off: 64 per cent. Most popular governors: Porter (eight engines), Watt (three). Note: the shortest extreme cut off value was 32 per cent, the longest being ninety per cent.

4) Lift or drop valves
Nineteen engines. Power: 20–300hp. Boiler pressure: 45–120 lb/sq.in. Running speed: 32–100rpm. Average maximum cut off: 69 per cent. Most popular governors: Porter (ten engines), Watt (three). Note: the lowest extreme cut off was a mere 25 per cent, the highest was 100 per cent (full stroke).

5) Combined rocking and lift/drop valves
Seven engines. Power: 15–350hp. Boiler pressure: 60–90 lb/sq.in. Running speed: 32–85rpm. Average maximum cut off: 80 per cent. Most popular governors: Buss (three engines). Note: the maximum cut off exceeded seventy per cent in all seven engines.

from the oscillating disc-plate, the admission-valve drop weights were replaced by weighted pendant rods working in dash pots to buffer their sudden fall. The construction of the valve rods was improved, the position of the detaching spring was revised, and adjustable ramps on the governor-controlled rod were added to control the cut-off point.

The modified valve gear was most sensitive at cut offs shorter than forty per cent of the stroke, which suited Corliss engines to high pressures where a considerable amount of residual steam expansion could be guaranteed. They were less happy under low pressures or widely fluctuating loads, owing to the excessive limitations placed on steam expansion.

The 1858 patent gear was similar to the 1851 type, but the detaching gear was improved. A spring-loaded fork, pivoted on the end of the valve rod, engaged a bell crank pivoting on the valve body. The tail of the fork meshed with the collar on the bell crank until released by a cam on an auxiliary lever, pivoted on the valve spindle, which was rotated by the cut-off rod driven from the governor. This is often known as 'Harris Corliss' gear, owing to its adoption by one particular American manufacturer.
The 1859 patent gear was a considerable departure from its predecessors. It was first seen in Europe at the Paris Exhibition of 1867. The oscillating disc-plate was removed from the cylinder block to a bracket, often in the form of a 'Y', which was fixed to the engine bed.

The exhaust valves were driven conventionally, by rods connected with the oscillating plate, but each admission valve was controlled by a rod running forward to a large spring-plate set into the back of a sturdy bar. This bar was pivoted to the 'Y' frame and attached to the disc plate by a short link. As the disc oscillated, so the link moved the spring-mounting bar backward and forward.

The valve-detaching mechanism comprised a rocking lever controlled by the governor, which pivoted to release the valve-lever rod. The power in the spring plate retracted the valve-lever rod and rapidly shut the valve. The position of the cut off was defined by the governor; as speed rose, and the balls flew farther outward, the rocking lever released the valve-rod latch earlier in the stroke. Conversely, if the engine began to falter, the governor balls dropped to lift the rocking lever and admit more steam to the cylinder on the next stroke.

European-designed Steiner gear, exploited commercially by, amongst others, Maschinenfabrik Crimmitschau, replaced the 1859-patent Corliss pendant gear with horizontal levers. However, this had too many joints, pins and rods to be efficient, and was superseded in 1877 by the simpler Renzsch pattern.

1875-type Corliss gear returned to the cylinder-mounted wrist plate, but the admission-valve rod drove a two legged intermediate lever. The valve lever was connected to the vacuum-type buffer piston by a short rod, the anchor point of which also held the spring-loaded ramped detent. A shoulder on the ramp engaged an adjuster bolt on the two-legged lever.

The detaching gear was controlled by a pivoting auxiliary lever, driven from the governor, which bore on the detent-rod spring through a small roller. The roller could be moved radially to control the point at which the catch on the two-legged lever released the ramped shoulder, allowing the buffer piston to fly shut, rotate the admission valve, and shut off the steam supply. Several forms of this gear were developed by Corliss, differing greatly in detail though not in principle. They were usually—but not invariably—fitted to vertical-cylinder beam engines, most notably the gigantic double engine exhibited at the Centennial Exposition in Philadelphia in 1876 which was misleadingly claimed to generate as much as 3000hp.

Corliss's 1879 design reverted to the oscillating wrist plate on the cylinder body to minimise unequal expansion of steam on opposing sides of the piston. The admission rod drove a serpentine plate attached loosely to the valve seat. The end of this plate carried a boss and a spring-loaded detent which mated with a shoulder on the valve lever.

The detaching mechanism, driven by the governor, comprised a rocking lever connected to a slotted link in which a boss on the detent lever could slide. The cut-off point was varied by moving the slotted link longitudinally; when the detent and the shoulder were released, the valve closed under the influence of the drop weight and dashpot assembly.

Many variations of Corliss gear were made in the USA, amongst the best known being by Jerome Wheelock & Company of Worcester, Massachusetts. Wheelock paired the admission and exhaust valves at the bottom of the cylinder block, with the exhaust valves outboard. Though the performance of the admission valve was marginally inferior to the standard Corliss pattern—communicating with the cylinder only through short exhaust-valve passage—the Wheelock valves could be controlled by rods without requiring a wrist plate. Cut off was controlled by the governor.

3: CORLISS GEAR IN EUROPE

Corliss' ideas were widely copied after making their first appearance in the 1860s. The greatest strengths lay in the reduction of the steam passages—steam being admitted virtually directly into the cylinder through long slotted ports—and in the rapid and accurate cutting of the steam supply. Unlike most link-type valve gear, the exhaust ports were controlled separately in the Corliss system and thus were unaffected by variations in cut off. The Corliss gear was undeniably complicated, but most parts were mounted externally and were comparatively easily maintained.

Many European manufacturers believed they could improve the original design, though alterations were often better in theory than in workshop practice. Spencer & Inglis gear, patented in Britain in the 1860s, relied on rocking steam-admission valves, attached to springs in dash pots and linked with the wrist plate by a multi-part rod assembly. A central stem on the lower part of the rod slid inside an actuating sleeve until two spring clips—one above the rod, the other below—held the two parts securely together. The engagement was controlled by the angular position of a double-cam trigger in relation to the actuating rod, which could be controlled by rods leading to the governor.

The valve rod assembly acted as a rigid strut during the opening stroke of the valve. Once the valve had opened to the cut-off point, however, the trigger pivoted to force the spring clips outward. This broke the connection between the valve rod and the actuating sleeve, allowing the powerful spring in the dash pot to pull the rod and sleeve apart. The valve immediately snapped shut.

Spencer & Inglis gear enjoyed a heyday of about a decade, being used on engines made by Hick, Hargreaves & Company of Bolton, Poillon of Lille and Sigl of Vienna. In Britain, J. & E. Wood of Bolton made Wheelock-type engines with paired valves on the lower edge of the cylinder block. These were oscillated by eccentrics on the crankshaft.

Engines with Corliss valves were made in a wide range of sizes, shapes and styles. Among those being marketed in 1880 were a 17xx × 33-inch engine by Maschinenfabrik Wilhelmshütte of Sprottau, developing 25ehp at 30rpm, and much larger examples. Corliss-type engines made in Europe were often modified to lengthen the cut off, many American patterns being limited to about forty per cent of the piston stroke. European engines were usually capable of handling greater fluctuations in load than their prototypes.

Amongst the best known modifications were made by Karl Kliebisch, whose valves were driven by eccentrics and bevel gears mounted on the frame ahead of the cylinder. The Bède & Farcot system relied on a bevel-gear assembly on the cylinder block, but was rapidly replaced by a comparatively conventional oscillating wrist plate.

4: OTHER EUROPEAN DESIGNS

Some engines had rocking valves operated by link motion instead of detaching gear. These were generally simpler and sturdier than the true Corliss types; and though their performance may have been poorer in theory, the differences were not always noticeable in practice.

Others retained rocking valves, but combined admission and exhaust functions. The Musil engine, patented in Germany and made by Hüttenberger Eisenwerk of Klagenfurt, had only two valves placed transversely beneath the cylinder block. These were driven from an auxiliary shaft geared to the crankshaft. Variations in cut off were controlled from the governor.

The Radinger, made by Simmeringer Maschinen- & Waggonfabriken, had a three-valve system with two admission valves flanking a central exhaust. The valve drive was taken from the crankshaft by gearing and a layshaft. The Hlubek engine, also made by the Simmeringer company, relied on oscillating valves and two pistons within a single cylinder, the rear piston being driven through the rear stuffing box by a crosshead attached to two side rods.

5: DROP VALVE ENGINES

Among the many alternatives to oscillating valves was a reversion to the drop or lift valves pioneered in the eighteenth century. The most advanced of the earliest forms were adaptations of the double-beat patterns featured by the Cornish Engines.

The best known of the many competing systems were made by Gebrüder Sulzer of Winterthur, Switzerland. The earliest was introduced in 1867, but improved in 1873 and again in 1877; driving the valves from layshafts was common to all, though the form of the drive varied. The 1877 version was more suited to high-speed running at long cut offs than its predecessors.

A single eccentric on the layshaft drove each pair of valves, the lower (exhaust) valve being operated by a cam whilst admission was controlled by a system of links controlled from the governor. A pivot on the mid-point of the eccentric lever was attached to a rod pivoted to a crank link attached to the valve stem lever. A second rod ran from a link pivoted to the tip of the eccentric lever to the end of the crank link. The valves were controlled by a trip mechanism operated from a layshaft driven from the crank.

Sulzer-type engines were made by many European manufacturers, particularly Maschinenfabrik Augsburg Nürnberg ('MAN'). A few Europeans also made engines which combined spring loaded drop- or lift-pattern admission valves with oscillating Corliss exhaust valves. This was favoured principally because the compact Corliss design did not protrude beneath the cylinder block. A distinctive expansion gear patented by Wilhelm Proell in 1881 (with its equally distinctive governor) was often fitted to these machines. Others operated their valves by cams or eccentrics driven from a layshaft geared to the crankshaft, relying on governors to control the cut-off point.

6: THE LATER HORIZONTAL-CYLINDER LOCOMOTIVE ENGINES

Technological advances in the middle of the nineteenth century were generally confined to details, such as the introduction of split rings on solid head pistons, credited to John Ramsbottom. Paul Giffard developed the first practicable injector in 1856, when the prolific Ramsbottom produced his duplex spring safety valve. Trials were also successfully undertaken to enable coal to be used instead of expensive coke, the change being almost entirely due to improvements in firebox design.

One of the easiest ways of increasing the power of a railway locomotive was to increase the size of each cylinders, even though this was limited by the restrictions placed by the 'Loading Gauge'—an area in which Britain was particularly hamstrung. In addition, two-cylinder engines, owing to the setting of the cranks out of phase with each other, often developed a noticeable surging effect as first one piston and then the other delivered its power stroke.

This problem was solved by increasing the number of cylinders to three or four, which allowed a much smoother application of power for each revolution of the wheels (four cylinders theoretically balanced perfectly) as well as keeping overall dimensions within the predetermined restrictions.

The first four-cylinder simple expansion engine to serve in Britain was a 4–4–0 designed for the Glasgow & South Western Railway by James Manson and completed in the Kilmarnock shops in 1897. However, there was sometimes little to choose between two- and four-cylinder engines of otherwise similar dimensions, as the limitations on cylinder diameter were often applied by the steam-raising capacity of the boiler.

Excepting quirky and generally short-lived designs with tandem cylinders, two of the four cylinders were generally placed inside the frames supporting the boiler. This often complicated maintenance. Another way of coping with the additional cylinders was provided by articulation. Locomotives were often created by reducing the diameter of the driving wheels to fit within the desired wheel base, but this generally reduced the speed that could be attained without wearing the valve gear unduly. Extending the wheel base to incorporate large-diameter wheels was also tried, but confined the locomotive to well laid main-line track with gentle curves and restricted its utility greatly.

The provision of flangeless wheels and axles that could move a short distance laterally eased some of the problems, as did the provision of bogies and swivelling trucks. But they were not the entire answer. Articulation seemed a better alternative.

Though Matthew Murray proposed a design unsuccessfully in 1825 (?), the first articulated locomotive to be built was the work of Horatio Allen in 1831–2. This ran briefly on the South Carolina Railroad and had two twin boiler units connected by a central firebox. It had two cylinders and a theoretical 2–2–2–2 wheel notation, but was not especially successful.

In 1851, however, a competition was held in Austria to find a locomotive that could operate a railway line over the steeply graded Semmerling Pass. This attempt to provide an unusually good hill-climbing locomotive produced three differing approaches to articulation: *Seraing*, built by Cockerill of Belgium; *Wiener Neustadt*, by Günther of Vienna; and *Bavaria*, by Maffei of Munich. The Belgian locomotive is generally regarded as the prototype of the Fairlie system, whilst the Wiener Neustadt pre-empted the Meyer.

The Mallet was by the far the most popular method of articulation, usually in multi-cylinder compound form (q.v.). However, though some railways retained faith in compounds until the end of steam in North America (there was little doubt that they ran more economically than their simple-expansion rivals), a majority preferred simplicity in the years after the end of the First World War, when low-pressure cylinders had grown so large that they became increasingly difficult to fit within even the generous North American loading gauge.

By 1919, improvements in manufacturing techniques allowed simple-expansion versions to be made with boilers pressed to new extremes. The two standard Mallets promoted in the immediate post-1919 period

TABLE NINE:

Some British stationary steam engine makers

From trade listings in *Engineering*, 1901

John Abbot & Co. Ltd, Park Works, Gateshead on Tyne
W.H. Allen, Sons & Co. Ltd, Queen's Engineering Works, Bedford
Alley & Maclellan, Sentinel Works, Glasgow
W.H. Bailey & Co. Ltd, Albion Works, Salford, Manchester
Baker Blower Engineering Co. Ltd, Stanley Works, Sheffield
Belliss & Morcom Ltd, Ledsam Street Works, Birmingham
Bever, Dorling & Co. Ltd, Union Foundry, Dewsbury
Brazil, Holborow & Straker Ltd, Vulcan Ironworks, Bristol
Peter Brotherhood, Belvedere Road, Westminster Bridge Road, London SE (sales office)
Campbell & Calderwood, Soho Engine Works, Paisley
Alexander Chaplin & Co., Govan, Glasgow
Clarke, Chapman & Co. Ltd, Gateshead on Tyne
Clay, Henriques & Co. Ltd, Dewsbury
Clayton Engineering & Electrical Construction Co. Ltd, Newton, Hyde, near Manchester
Clayton & Shuttleworth, Lincoln
J. Cochrane, Barrhead, Glasgow
H.J. Coles, London Crane Works, Derby
H. Coltman & Sons, Midland Ironworks, Loughborough
A.F. Craig & Co. Ltd, Paisley
Crow, Harvey & Co., Park Grove Ironworks, Glasgow
Davey, Paxman & Co. Ltd, Colchester
Dempster, Moore & Co., Robertson Street, Glasgow
Alfred Dodman & Co. Ltd, Highgate Works, King's Lynn
B. Donkin & Clench Ltd, Southwark Park Road, London SE
Douglas & Grant, Dunnikier Foundry, Kirkcaldy
Drysdale & Co., Bon Accord Engine Works, Glasgow
Easton & Co. Ltd, Erith Ironworks, Erith
Energising Momentum Engine Co., Westminster Bridge Road, London SE (made elsewhere)
W. Foster & Co. Ltd, Lincoln
J. Fowler & Co. (Leeds) Ltd, Leeds
Fraser & Chalmers Ltd, Threadneedle Street, London EC
Galloways Ltd, Manchester
R. Garrett & Sons Ltd, Leiston Works, Leiston
Grantham Crank & Iron Co. Ltd, Grantham
Greenwood & Batley Ltd, Albion Works, Leeds
Gwynne & Co., Brooke Street Works, Holborn, London EC
Hathorn, Davey & Co., Leeds
Hatley Engine Co., Fairweather Green, Bradford
Hayward Tyler & Co., Whitecross Street, London EC

Heenan & Froude, Manchester
E.S. Hindley, Bourton
R. Hornsby & Sons Ltd, Grantham
Hunter & English, Bow, London EC
Isca Foundry & Engineering Co., Newport, Monmouthshire
Jessops & Appleby Bros. (London & Leicester) Ltd, Leicester and London
T. & R. Lees, Hollinwood, near Manchester
Manlove, Alliott & Co., Nottingham
Marshall, Sons & Co. Ltd, Gainsborough
McOnie, Harvey & Co. Ltd, Scotland Street Engine Works, Glasgow
Richard Moreland & Son Ltd, Old Street, London EC
Napier Brothers Ltd, Hyde Park Street, Glasgow
C.A. Parsons & Co., Heaton Works, Newcastle upon Tyne
Peckett & Sons, Atlas Engine Works, Bristol
Thos. Piggott & Co. Ltd, Springhill, Birmingham
A. Ransome & Co., Stanley Works, Newark on Trent
Ransomes, Sims & Jefferies Ltd, Ipswich
E. Reader & Sons, Phoenix Works, Nottingham
Robey & Co. Ltd, Lincoln
R. Roger & Co. Ltd, Stockton on Tees
Rose, Downs & Thompson Ltd, Old Foundry, Hull
Geo. Russell & Co., Motherwell
Ruston, Proctor & Co. Ltd, Sheaf Ironworks, Lincoln
Scott Bros., Halifax
Ernest Scott & Mountain Ltd, Newcastle upon Tyne
Thomas Shanks & Co., Union Ironworks, Johnstone
Simpson, Strickland & Co. Ltd, Dartmouth
Smedley Brothers Ltd, Eagle Ironworks, Belper
A. & W. Smith & Co. Ltd, Eglinton Engine Works, Glasgow
John Smith & Co., Grove Ironworks, Carshalton
Tangyes Ltd, Cornwall Works, Birmingham
Taylor & Challen Ltd, Birmingham
D. & J. Tullis Ltd, Kilbowie Ironworks, Kilbowie, near Glasgow
E.R. & F. Turner Ltd, Ipswich
Vauxhall Ironworks Co. Ltd, Wandsworth Road, London SW
James Watt & Co., Soho Foundry, Birmingham
Willans & Robinson Ltd, Rugby

by the United States Railroad Administration (USRA) retained compound working, but the 25 Union Pacific Railroad 4–8–8–4 ‘Big Boy’ simple expansion Mallets of 1941–4 were the largest steam locomotives ever built. Made by the American Locomotive Company, Big Boys had four enormous cylinders—23·75 × 32 inches—and 5ft 8in driving wheels. A boiler pressure of 300lb/sq.in gave a nominal tractive effort of 135,375lb.

The locomotives could develop more than 6000hp at the drawbar and could haul hundred-car freight trains weighing up to four thousand tons over a hilly section of the Union Pacific. Though speeds rarely exceeded 40mph, the huge machines could reach eighty if pushed. A typical example of the 1941 batch measured 132ft 10in overall, 16ft 2·5in high, 10ft 10in wide, and weighed a staggering 1,189,500lb. The enormous tenders held 24,000 US gallons of water and 56,000lb of coal.

The only other system to attain international popularity—the Fairlie was a passing fad—was the Garratt, total production of which amounted to about two thousand. Whereas the Mallet was at its best in the USA, all but unencumbered by loading-gauge restrictions and assured of good quality track, the Garratt was favoured in areas where heavy loads had to be hauled over undulating, lightweight track with severe curves.

Patented in 1907 by Herbert W. Garratt, Inspecting Engineer of the New South Wales Government Railways in Australia, the principal claim to novelty was the attachment of a short large-diameter boiler unit to the end of two power trucks. Each truck carried its own water tank or bunker, helping to restrict the strain on the pivots by relieving the boiler assembly of unnecessary weight. The open space beneath the main frames, unencumbered by axles, wheels and valve gear, allowed a deep fire grate and a readily accessible ash pan to be fitted. Together with the excellent proportions of the boiler, these features gave excellent steam raising capacity. In this respect the Garratt was much more effectual than the Mallet.

The first Garratt was a small compound built in 1909 for 2-foot gauge North East Dundas Tramway in Tasmania by Beyer, Peacock & Co. Ltd of Manchester. Most machines of Garratt type were four-cylinder simple expansion, though a few six-cylinder units were made.

Almost all Garratts emanated from the Beyer, Peacock & Co. Ltd factory in Manchester, excepting a few built in France for service in Algeria and a handful built under licence in Spain. The largest was a solitary 4–8–4+4–8–4 Class 10 Ya, built for the USSR in 1932, which weighed 262·5 tons and had a nominal tractive effort of 78,700lb.

The use of multiple cylinders undoubtedly improved power, but did not improve either fuel consumption or thermal efficiency. Alternative methods of improving performance were found in compounding (q.v.), pioneered in France in the late nineteenth century.

Few challenges were offered to the supremacy of the double-acting horizontal cylinder railway locomotive prior to 1914. However, the Midland Railway's Paget was an interesting multi cylinder design, whilst Stumpf machines tested in several countries embodied Uniflow (q.v.) cylinders with central exhaust.

7: THE LATER MARINE ENGINES

Built on the Thames by Ditchburn & Mare of Blackwall, completed in the autumn of 1861, *Warrior* (9231 tons displacement) had a horizontal trunk engine commissioned from John Penn. This had two 104¼× 48-inch cylinders, indicated horsepower during a full power trial held in 1868 being 5267 at 53·14rpm; maximum speed was a fraction over fourteen knots. However, boiler pressures were still very low—*Warrior*'s still supplied steam at only 20lb/in . A later engine made for HMS *Northumberland* by Maudslay, Sons & Field of the Millwall Ironworks in London in *c.* 1867–8 had the two opposed cylinders measuring 112 × 52 inches, driving a 24-foot diameter screw propeller on a single shaft. Indicated horse power was 6545 at 58 rpm.

Trunks reduced the effective diameter of the piston substantially; in the case of *Northumberland*, for example, they had a diameter of only 41 inches. The engines had double-ported slide valves driven from crankshaft eccentrics by link motion, each valve being provided with relief frames on the back surface to reduce friction as the valve face slide over the cylinder block.

The engines also had large expansion valves, cut off in the steam chests and cylinders being controlled by separate eccentric and link motion; the main link motion controlled admission of steam to the cylinders only. Ten cylindrical fire tube boilers, with a total of forty furnaces, supplied steam at a meagre 25lb/sq.in.

The earliest iron hull warships were surprisingly successful, but attempts to put engines of similar power into timber frame ships were less satisfactory. The experiences of the sisters *Lord Warden* (7839 tons displacement) and *Lord Clyde* (7602 tons), the largest and fastest wooden warships ever built in Britain, showed what could happen. *Lord Warden* was fitted with a simple expansion return-rod engine with three 91¼ × 54-inch cylinders ordered from Maudslay, Sons & Field, whilst *Lord Clyde* received a Ravenhill & Hodgson trunk engine with two 116 × 48-inch cylinders. Trials run in 1867 returned 6706ihp at 63·33rpm and 6064ihp at 64·75rpm for *Lord Warden* and *Lord Clyde* respectively, maximum speeds being 13½ knots. Unfortunately, it had not been realised that the trunk engines, with cranks at ninety degrees, put far greater strain on the engine bed mountings than the 120 degree three-crank return rod pattern, in which the power strokes were much better balanced; consequently, the Ravenhill & Hodgson machinery was condemned after only twenty months whereas the Maudslay set served out eighteen trouble-free years.

Marine engine design remained stagnant during the 1860s. *Captain* (7664 tons displacement), for example, completed by Lairds of Birkenhead in January 1870, had trunk engines each with two 80·125 × 39-inch cylinders driving two shafts. Trials had returned 5772ihp at 74·15rpm, giving a speed of nearly 14¼ knots. Steam was supplied from eight rectangular boilers at a pressure of about 30lb/sq.in. Thus the engines offered no real advances on *Warrior*'s.

Despite the revolutionary absence of sails and turret armament, *Devastation* (9118 tons displacement)—completed by Portsmouth Dockyard in April 1873—was still unremarkable mechanically. The engines were Penn horizontal trunk patterns with two 80 × 39-inch cylinders apiece, driving two shafts. Trials returned 5652ihp at 72·83rpm, with a boiler pressure of 30lb/sq.in, which gave a maximum speed of about 13·3 knots.

However, *Devastation* was the last Royal Navy battleship to have engines of this type, as attention had finally turned to compounding, which had been used on passenger ships as early as the 1850s.

8: PERFECTED SELF CONTAINED AND PORTABLE ENGINES

The Great Exhibition of 1851 was accompanied by trials undertaken in Hyde Park with the products of ten manufacturers. First prize was awarded to Hornsby of Grantham, whose engine returned a coal consumption of 6·73lb/hp/hr. The horizontal cylinder lay within the firebox, which continued upward to form a steam dome. Economy was promoted by a feedwater heater placed in the smokebox, and by a cladding of hair felt and wooden slats over the boiler.

Second in the economy trials came the fixed-cylinder Tuxford engine (7·46lb/hp/hr), followed in close succession by the Clayton & Shuttleworth, Garrett and Barrett machines. These were the only entrants to better 10lb/hp/hr, though the Tuxford oscillating-cylinder engine approached it.

Another extreme was exemplified by the Roe portable, which consumed fuel at an extravagant 25·8lb/hp/hr. A machine of this type is credited with 93·9lb from a subsequent trial held in the Sussex town of Lewes—a staggering indictment of its design, as even the 6·73lb of the victorious Hornsby entry in 1851 would have been regarded as very poor by the standards of 1870.

The Royal Agricultural Society trials in 1853 were won by a Clayton & Shuttleworth engine with a horizontal steam-jacketed cylinder inside the smokebox. Fuel consumption was 4·32lb/hp/hr, which was reduced to 3·75lb by a Tuxford engine tested at Carlisle in 1855. The advent of better testing in 1858 was followed by a perceptible rise in the consumption figures, but trials fell into disrepute when some manufacturers refused to participate on the grounds that their rivals were entering specially prepared 'racers'.

Progress during the 1850s is best summarised by the portable engines submitted to the Royal Agricultural Society trials by William Tuxford & Sons. The time needed to raise steam pressure—most of the machines operated at 45lb/in—remained 30–45 minutes throughout the period, but the amount of coal burned per effective ('brake') horsepower reduced from 11·5lb for a 5nhp machine tested in 1849 to 4·05lb for the 8nhp example tried in 1855.

By the end of the 1850s, the portable engine had become established not only for agricultural use but also as a handy source of industrial power. It has been claimed that eight thousand machines were being used by 1851, but it is hard to see how or by whom these could have been made. Eight *hundred* may a better estimate for pre-1851 production, as Clayton & Shuttleworth, the most prolific manufacturer, had made only about 1500 engines by the end of 1855. The company had exceeded an annual output of four hundred machines only a year previously.

Demand highlighted the need for durability, ease of maintenance and economical running; and the earliest engines were speedily replaced by much more efficient designs. Typical of the attention to detail was a patent granted in 1861 to Robey & Scott of Lincoln, protecting a firebox and grate surrounded by a water jacket to improve the steam-raising capability of the boiler. In addition, sludge could easily be drained from the space beneath the fire grate.

Performance of portable engines improved rapidly in the 1860s, allowing the hourly coal consumption per horsepower to drop from

3·59lb (obtained in 1863 from a Tuxford example) to 2·71lb for a Clayton & Shuttleworth machine exhibited in 1872. This improvement was due largely to the introduction of better boilers and more efficient valve gear; Robey portables exhibited at the Smithfield Club Cattle Show in 1869, for example, incorporated automatic expansion gear patented by Robert Robey and John Richardson.

By the early 1870s, the design of portable engines had been stabilised. Experimentation had given way to demands for simplicity. Unfortunately, owing to a desire for uncluttered external appearance, vital components were soon being placed inaccessibly—e.g., exhaust steam pipes were inserted in the top of the boiler, making it impossible to detect if live steam was leaking directly into the chimney.

A return to externally-mounted components marked the final phase of development, whilst refinements in manufacturing techniques allowed cylinders to become liners within comparatively simple castings. This avoided the complicated one-piece designs that had once been universal.

Strengthening firebox crowns guarded against unexpected collapse. Garrett & Sons of Leiston patented a corrugated roof in 1876, whilst Richardson & Wansbrough patented a roof-girder system for Robey in 1900. Another problem to be faced concerned the connection between the cylinder and the crankshaft plummer blocks (bearings). Bolting everything directly to the top of the boiler created a rigid cage to maintain the alignment of the moving parts, but severe stresses were created as the components expanded.

Many manufacturers simply increased the strength of the parts, trusting to experience to provide adequate proportions. Better methods included the provision of stay rods between the cylinders and the crankshaft bearings—often including expansion joints—or allowing the plummer-block brackets to move. Ruston & Proctor patented a 'steam stay', which was little more than a hollow tube designed to expand simultaneously with the boiler, whilst E.R. & F. Turner of Ipswich mounted the brackets transversely so that they could flex slightly to relieve stress.

9: SELF-CONTAINED DESIGNS

'Independent Engines' were often supplied for use on temporary or prepared bases, the degree of adaptability giving rise to terms such as 'semi-portable' and 'semi-fixed'. The simplest form was little more than a standard portable engine without its wheels. The firebox was supported on steel girders forming an ashpan, and a cylindrical steel pedestal doubling as a feedwater tank was placed beneath the smokebox. Machines of this type were known as overtypes, as the cylinders lay above the boiler.

Undertype engines were often preferred for fixed sites even though their construction—with the cylinders in or alongside the smokebox saddle—was rarely favoured in agriculture. Though traction engines and portables were occasionally made in this form, the proximity of the cylinders and motion to the ground was a disadvantage in a muddy field. However, the same layout also allowed the crankshaft to be placed beneath the boiler to lower the centre of gravity. As this promoted smooth running, self-contained undertype engines were popular in industry.

Undertypes were mounted on cast-iron bedplates in the smallest sizes, or on steel girder frames in larger patterns. Robey was just one of the many manufacturers to offer undertype machines. Acccording to a catalogue dating from 1924, they included single cylinder, twin-cylinder simple expansion and two-cylinder compound patterns. The smallest was the No. 4 (8/11bhp), with a single 7×10-inch cylinder and a 48-inch flywheel running at 160rpm. It was 8ft 10in long, merely 4ft 4in wide, and weighed 2 tons 15 cwt empty. [Add details of the largest simple expansion pattern.]

Portable and self-contained engines were often adapted to particular circumstances. Those destined to work in arid areas—such as the interior of Australia—were often fitted with condensers, simple jet patterns being customary on truly portable engines whereas semi-portable examples could accept bulky surface condensers or multi-tube feedwater heaters. These retrieved as much water and waste heat as possible from the exhausted steam.

Condensing engines were about one tenth more powerful than non condensing machines of otherwise comparable specifications, yet consumed 12–15 per cent less fuel. However, chimney extensions were usually necessary to compensate for the loss of exhaust-steam blastpipes; to ensure adequate draught, chimneys could be sixty feet high.

Robey pioneered engines with the motion enclosed in a protective casing, which was greatly favoured in dusty environments. Engines could also be supplied with oil fuel apparatus. Square fire-holes facilitated log burning, and spark arresters—from large conical fittings on top of the chimney to compact mesh patterns or enclosed traps in the chimney base—were commonly fitted on wood burners. The largest engines could feature worm-and-sector chimney lifters, or platforms with steps and handrails along the sides of the boiler. Brakes could be added to the wheels, or chocks provided to prevent unwanted movement.

Many portable engines destined for colonial service, especially if they were to be manhandled over difficult terrain, had cylindrical fireboxes. The standard squared ashpan type protruded beneath the boiler shell and was much more vulnerable to damage than its cylindrical equivalent. Many cylindrical boilers also had detachable tubes and tube-plate assemblies to facilitate cleaning, these features being particularly useful if impure water had to be used. The basic idea was patented in Britain in 1861 by George Biddell and William Balk, working for Ransome & Sims of Ipswich, but is often mistakenly credited to Germans.

10: COMPOUND STATIONARY ENGINES

The success of two stage expansion at sea was reflected on land, where virtually all compound railway locomotives and a large number of stationary engines had cylinders placed horizontally instead of vertically. Experimental work began very early: Daniel Adamson produced a triple-expansion mill engine in 1863 and a quadruple-expansion version in 1874, whilst a single crank triple-expansion engine was made in 1869—to Crosland patents — by the Fairbairn Engineering Company.

The tandem was the simplest compound engine, many being converted from single-cylinder engines by McNaughting. These developments were made possible by improved metallurgy and the widespread introduction of the two flue or Lancashire boiler, patented in 1844 by William Fairbairn and John Hetherington.

These boilers allowed working pressures to rise in safety, but often threatened to damage older low-pressure engines with plenty of life left in them. Adding a new high-pressure cylinder ensured that expanded steam passed to the original cylinder at much the same pressure as the engine had always operated. Most cylinders were simply attached behind the existing one, sharing a new extended piston rod, but they could be added alongside if space was restricted. Some tandem cylinders were linked with spacers, but others were virtually abutted.

New single-crank tandem compounds were made in quantity from the 1880s until the 1920s. Most had the high-pressure cylinder behind the low pressure pattern, but Pollitt & Wigzell of Sowerby Bridge built a few ‘three rod’ engines in accordance with a patent granted in 1870. These had their low pressure cylinder behind the high pressure unit, a common crosshead being driven by side rods.

Most of the earliest tandem compounds had slide valves, though Corliss valves were sometimes used on the high-pressure cylinder. Post-1900 engines usually had Corliss semi-rotary, Sulzer drop valves, or proprietary variations of them.

These engines were made thoughout Europe. Six built by Carels Frères of Ghent, in Belgium, were installed in Lancashire textile mills prior to 1914; and one British company built engines to a Swiss design. The last single-crank tandem compound was built in 1936 by Newton, Bean & Mitchell, for the Heckmondwike mill of Blackburn & Tolson.

Triple-expansion tandem compounds also existed in some numbers. A typical example, made in 1912 by John & Edward Wood of Bolton for the Newton Moor Mills of J.J. Ashton Ltd in Hyde, Cheshire, had a 48-inch stroke and cylinder diameters of 14 (high pressure), 23 (intermediate) and 36 inches (low). It developed 750ihp at 77 rpm, boiler pressure being 160lb/in^2.

Twin tandem engines, usually dating from 1890 or later, were often large and powerful. Inspired by earlier twin single-cylinder installations, the basic type comprised two identical two-cylinder tandem compounds driving a single drum on a central shaft.

An engine installed in Hartford Mill in Werneth, near Oldham, was typical. Built by Urmson & Thompson Ltd in 1907, it had two 21 × 60-inch high pressure and two 44 × 60-inch low-pressure cylinders in matched pairs. Corliss valves were used throughout. Intended to drive 34 ropes around a 24-foot diameter drum, the installation could develop 1500ihp at 65 rpm. Boiler pressure was 170lb/in .

Twin tandem triple-expansion engines were also made, though rarely (if ever) using six cylinders in pairs of three. The high pressure and one low pressure cylinder were usually placed on one flank of the drum, with the intermediate and the second low-pressure cylinder on the other. Alternatively, three cylinder machines were made with the high pressure and intermediate cylinders on one flank and the low-pressure cylinder and the condenser on the other.

The most powerful engines performed impressively. An 1895 vintage product of Goodfellows of Hyde, installed for Ashton Brothers in Throstle Bank cotton spinning mill, could indicate 1400hp at 60 rpm. In its original form it had one high , one intermediate and two low-pressure cylinders with a 60-inch stroke, the cylinder diameters being 21, 31 and 33 inches respectively. The cylinders originally had Corliss valves and Ramsbottom trip gear, but the engine was subsequently modified.

Textile mill engines, considered as a class, were usually conventional. However, J. & E. Wood of Bolton, amongst others, sometimes grouped Corliss-type admission and exhaust valves at the bottom of the cylinder; and Daniel Adamson & Company of Dukinfield made American Wheelock-patent engines in Britain under licence.

Twin tandem compound engines were also popular on the railways at the beginning of the twentieth century, but were soon eclipsed by more efficient systems. The problems of adequate steam supply and sealing the piston rods, which were common to both cylinders, proved to be difficult at the high pressures involved.

In its most basic form, the cross-compound was a two cylinder machine with a crank on each side of the flywheel. A few single crank examples were also made. The design dates back before 1877, when Joseph Clayton & Company of Preston made one for the Stonebridge cotton weaving mill of George Whittle. The valves may be slide, Corliss or Sulzer patterns, usually depending on the age of the engine. Cross-compounds were the most common of all mill engines, being made by virtually everyone excepting Goodfellows of Hyde and Urmson & Thompson. The largest examples, made by Hick, Hargreaves & Company of Bolton, were capable of indicating 4000hp.

11: UNIFLOW ENGINES

The idea of a double-acting engine which exhausted centrally had occurred to several engineers in the 1820s, notably the Frenchman Jacques de Montgolfier and the American Jacob Perkins. Perkins had patented a primitive engine of this type in England in 1827, and a railway locomotive of unknown origin had even run on the South Eastern Railway from 1849 until 1852.

Coping with the complexity of the centrally-exhausting engine lay beyond the manufacturing technology of the early nineteenth century. In 1885–6, however, Londoner Leonard Todd patented his ‘Terminal Exhaust Cylinder Engine’ and ‘Mid Cylinder Exhaust Engine’. The latter was claimed to work more efficiently than conventional double-acting machines and to ‘maintain within itself an improved gradation of temperature extending from two Hot Inlets to its common central Cold

Outlet'. This Todd believed to restrict condensation as steam entered the cylinder, promoting economy.

Todd's engine had a single large-diameter cylinder containing a piston which occupied virtually half the length of the bore. Steam was admitted by slide valves to alternate faces of the piston, expanded, and then exhausted through a ring of ports cut through the periphery of the cylinder at its mid point. Unfortunately, the inclusion of Meyer type adjusters on the back of the slide valves and the use of additional piston cut-off valves operated by the governor were excessive complications.

Todd engines encountered so many troubles that development had been abandoned by the early 1890s. Among the greatest difficulties were the excessive temperature variations between the ends and the middle of the cylinder, which caused jamming if tolerances were too fine or excessive steam leakage past the piston if they were too wide.

Though the germ of success lay within the Todd engine, exploitation was delayed until Johann Stumpf of the Charlottenburg technical school patented an improved version in Germany *c.* 1908. Stumpf called his design 'Una Flow'. It was much more successful than Todd's had been, and was soon being made in quantity. By the summer of 1910, one of the principal licensees, Erste Brünner Maschinenfabrik of Brünn (Brno), then in the Austro Hungarian empire, had made nearly fifty engines.

A 500ihp Stumpf engine made in 1909 by Elsasser Maschinen Fabrik of Mühlhausen, to drive generating equipment, had returned an hourly steam consumption of 10·14lb/ihp. Economy on this scale encouraged the spread of the uni-directional flow ('Uniflow') engine. The first British licensees were Fraser & Chalmers of Erith, the Lilleshall Company of Oakengates in Manchester, John Musgrave & Sons of Bolton, and Robey & Company of Lincoln. Most Continental engines operated their drop valves with cams, but British-made examples usually had eccentrics on a layshaft driven from the crank.

Uniflow engines were strongly built, owing to the need to counterbalance heavyweight pistons and the widespread use of single cylinders. They were also fitted with special relieving valves to restrict the maximum compression attainable in the cylinders. Despite working with a cut-off no greater than ten per cent, which put a very high initial load on the piston, they were popular with the textile industries: uniflow engines occupied far less floor space than conventional multi-cylinder compounds of comparable power.

By the end of the First World War, problems which had dogged the earliest uniflow engines had largely been overcome. Suitable lubricants had been developed, and the differences in temperature between the ends and the centre of the cylinders had been minimised by barrelling the bore. Unequal expansion as the engine attained operating temperature straightened the bore and allowed the piston to run smoothly. Though this had been attained only by complicating manufacture, the uniflow engines had sufficient advantages to ensure sales continued for many years. The last large scale example known to have been made in Britain was exported to Turkey in 1955.

Robey made 'Independent' or semi-portable engines with a single uniflow cylinder. Offered in the 1920s in six sizes from 24/32bhp to 160/216bhp, these were usually superheated. Several attempts were also made to adapt uniflow engines for marine use—without success—or even to propel railway locomotives. The Kolomna engineering works built a freight locomotive in Russia in 1909, whilst Stettiner Maschinenbau AG 'Vulcan' built four 0–8–0 examples for the Royal Prussian Railway Directorate in 1909–10. These were tested against otherwise identical locomotives with conventional piston valves or experimental drop valves, the uniflow proving superior in the proportion 100:119:129.

Chemins de fer du Nord in France and the North Eastern Railway in Britain also experimented with uniflow cylinder locomotives. The British representatives were a short lived 4–4–2 passenger engine and a mixed traffic 4–6–0, nicknamed 'Old Stumpfy', which survived in traffic for eleven years. Both engines were characterised by notably raucous exhaust.

Though they were supposed to be particularly economical to run, this was never evident in practice. In addition, the reciprocating masses of the Stumpf system required careful balancing and may have put too great a strain on the track to mount a successful challenge to conventional designs.

12: COMPOUND LOCOMOTIVE ENGINES

Attempts were often made to improve the thermal efficiency of the railway engine prior to 1900, but rarely with real success. Though experiments with a continuous expansion steam system had been undertaken in the 1860s, the work of an English railwayman named John Nicholson, the first successful embodiment of compounding in a railway engine occurred when Anatole Mallet built an 0–4–2 tank engine in 1876—inspired, no doubt, by the success of Woolf-type compound stationary engines in France.

By 1889, and the Exposition Universelle in Paris, the first steps towards an efficient compound railway engine had been taken. Interestingly, many of the earliest of these had been taken in Britain, but the unhappy experience dealt compounding a blow from which it never recovered.

The principal villain of the piece was Francis Webb, a very skilful engineer who, by the early 1880s, had risen to the position of Locomotive Superintendent of the London & North Western Railway. Impressed by Mallet's small compound tank engine, Webb determined to build comparable engines in Britain. After converting an old engine as a trial, Webb built the three-cylinder 2–4–0 *Experiment* with two high-pressure cylinders outside the frames and a single large low-pressure unit inside. Webb stated the principal goals as a reduction in fuel consumption and the elimination of coupling rods.

Hard running showed that the engine worked satisfactorily, so the first of ?nineteen improved examples emerged from Crewe. These proved to be too light to compare with existing two cylinder simple-expansion engines and were supplemented with the larger 'Dreadnoughts' of 1884, which weighed 42 tons in working order.

From this basis, Webb applied compounding to everything from small tank engines to four-cylinder 0–8–0 freight locomotives. They have received a universally bad press, owing to a combination of badly proportioned cylinders and ineffectual valve gear, and the lack of coupling rods on the earlier express locomotives was also a hindrance. Their epitaph can probably be read in the speed with which Webb's successors scrapped them, even though not all were totally without merit.

Thomas Worsdell built two cylinder compounds for the Great Eastern Railway and then, with greater success, for the North Eastern Railway. They all had two cylinders inside the frames, though the steam chests were often placed outside; the design was based on the Prussian von Borries pattern—itself derived from Mallet's—with a few modest improvements. The goals were increased thermal efficiency and a reduction of stress on the moving parts.

Between 1886 and 1892, more than two hundred Worsdell–von Borries compounds were made; most were 0–6–0 goods engines, but there were also twenty high-speed 4–2–2s. Though not without their constructional problems, these engines were surprisingly efficient. Unfortunately, success on a provincial British railway was not enough to overcome prejudice based on the L&NWR experience.

The greatest exponents of compounding were French—perhaps fittingly, as the initial success of the compound stationary engine had also been gained largely in France. Among the French exhibits in the Paris exhibition in 1889 was a 2–6–0 compound goods engine designed for the Nord railway by Éduard Sauvage. Built in 1887, the engine had a central high pressure cylinder (initially 46cm, then 43 × 50cm) and two 70 × 50cm outside cylinders driving the central driving axle. The low pressure cranks were set at ninety degrees, with the high-pressure crank at 135 degrees to each of them.

Trials achieved a drawbar pull of 4400kg whilst hauling a 540-tonne train up a gradient of 1 in 200, and 620 tonnes were taken up the same slope at 20km/hr. However, owing to its small wheels, with a diameter of only 1·65m, the Mogul was not as influential as its design deserved to have been. It was not perpetuated, even though Sauvage became an influential teacher and remained a fluent champion of compounding for the rest of his life.

A contemporary of Sauvage's modest 2–6–0, all but unnoticed at Paris, was a 2–2–2–0 made for the Nord railway in 1886 by Société Alsacienne de Constructions Mécaniques. Designed by Alfred George de Glehn, this engine had two high-pressure cylinders between the frames, driving the front axle, and two larger low-pressure outside cylinders driving the rear axle.

An inverted form of Walschaert gear was used, and the system of valving permitted the driver to choose two cylinder simple-expansion (using either set of cylinders), four cylinder simple-expansion, or 'reinforced compound' operation where some high-pressure steam could be admitted to the low-pressure receivers to boost power. Ironically in view of the lack of success of the British L&NWR compounds, de Glehn also omitted to couple the driving wheels—for precisely the same reason as Francis Webb had done.

The difference may have been simply that no one dared confront Webb, whereas de Glehn was merely the servant of the railway that commissioned the locomotives from SACM. The 2–2–2–0 was taken by Gaston du Bousquet, newly promoted to the post of locomotive superintendent, for a Nord 4–4–0. This in turn promoted a range of 4–4–2s, 4–6–0s and 4–6–2s which were more than the equal of rival simple-expansion locomotives of otherwise similar dimensions. The saturated 4–4–2 of the early 1900s, which weighed only 65 tons, could take loads of 300–350 tonnes at 75mph and develop 1400ihp at these speeds. Virtually every major French railway was to run compounds, four cylinders being preferred initially, though some engines had two—usually rebuilds of old stock—and post-war SNCF designs invariably had three.

The success of the de Glehn/du Bousquet compounds caused another look to be taken in Britain. The Great Western Railway experimented in the early 1900s with three locomotives imported from France, before settling on four-cylinder simple expansion, but the use of English drivers may have prejudiced the results.

The best work in Britain was done by Walter Smith, chief draftsman of the North Eastern Railway, who modified a Worsdell 4–4–0 to a three-cylinder compound system in 1898. This had a central high-pressure cylinder exhausting to two external low-pressure units, with the 90°:135° crank settings pioneered by Sauvage on the Nord railway in France. Separate control gear was fitted and steam could be admitted to the low-pressure cylinders to start the engine away.

Though well regarded, however, this locomotive remained a solitary prototype on the NER. Its legacy was a handful of three-cylinder compound Atlantics on the Great Central Railway and the Smith/Johnson 4–4–0s on the Midland Railway, the first of which dated from 1902. Richard Deeley then built a slightly modified pattern—the ‘Midland Compound’—after he had succeeded Johnson in 1906. These were popular and smooth-running engines, but were handicapped above 60mph by poor steam-passage design.

Smith’s final design, completed in 1904, was a four-cylinder compound Atlantic with two high-pressure cylinders inside the frames exhausting to two external low-pressure units. Two examples of this first-class design were built for the North Eastern Railway in 1906, one with Stephenson valve gear and the other with Walschaert’s, but the sudden death of Smith brought work to an end. The NER wanted to build more of them, until the rapacious attitude of Smith’s executors forced the substitution of heavy three-cylinder simple expansion locomotives developing comparable power.

Enthusiasm for compounding continued unabated in France after the end of the First World War, owing largely to the genius of André Chapelon, whose 1929 transformation of a Paris–Orléans 4–6–2 verged on miraculous. From an engine which could develop only about 1850ihp, Chapelon obtained 3000ihp at 75mph. Later conversions with streamlined steam passages and oscillating cam poppet valves driven by Walschaert gear raised the indicated horsepower to 3700.

Chapelon's masterpiece was 4–8–4 No. 242A1, which could generate 5500ihp in the cylinders (equivalent to about 4200hp at the drawbar). Coal consumption was a miserly 1·87lb/dbhp at 2200dbhp, rising to only 2·65lb/dbhp at 4000dbhp at 62·5mph. Yet if the Chapelon transformations represented the most efficient form of compound railway locomotive, the largest of all compounds were articulated examples based on a patent granted in France in 1884 to Anatole Mallet.

In 1887, the Decauville company realised that the Mallet system could provide a 60cm-gauge engine which could haul loads equal to its own weight on eight per cent gradients (1 in 12.5), travel safely around curves with radii as sharp as 20 metres, and yet have an axle loading of less than three tonnes.

The Decauville 0–4–4–0T Mallet carried the front power unit on a Bissell truck, pivoted to the frame roughly beneath the mid-point of the boiler. Overall length was only 5·38m, weight in working order being about 11·6 tonnes. High pressure steam was supplied directly to the rear cylinders, then exhausted into a receiver from where it was taken to the front or low-pressure cylinders by a flexible pipe.

Locomotives of this type gained renown on the 60cm gauge 'Inner Circle' track laid at the 1889 Exposition Universelle in Paris, where more than six million passengers were carried without serious incident. Prior to about 1902, no notice of the Mallet had been taken in North America, where the heaviest freight traffic was being moved by large rigid frame locomotives such as 2–10–0s and 2–10–2s, including tandem compounds made for the Atchison, Topeka & Santa Fé Railroad. Unfortunately, the rigid wheel base and high axle loading of these engines confined them to well-laid track with shallow curves.

In 1903, therefore, the American Locomotive Company of Schenectady built the first Mallet to run in the USA—a 0–6–6–0 for the Baltimore & Ohio Railroad. The engine had two high-pressure cylinders measuring 20 × 32 inches, two 32 × 32-inch low-pressure cylinders, and 4ft 8in coupled wheels. A weight of 212·5 tons with its tender made it by far the largest locomotive engine in the world.

Exhibited at the St Louis World's Fair in 1904, the Alco Mallet was the butt of criticism from engineers who were contemptuous of its great weight, the method of articulation, and the design of the flexible steam pipes. When the Mallet entered service after the fair had closed, it proved much more successful than anyone excepting its promoters had anticipated. Minor problems were soon cured and a reputation for great power was gained. A scramble to develop the biggest and most powerful Mallet-type locomotives ensued, the rivalry between the major US railroads being matched only by rivalry between long established Baldwin and the newly-formed American Locomotive Company ('Alco').

About 2,500 Mallets had been built in Europe by 1914, by Decauville and Batignolles in France; by Borsig and Henschel in Germany; by the Hungarian state factory; in the Putilov and Kolomna factories in Russia; and by the Swiss Locomotive Works in Winterthur. A few had even been built in Britain by the North British Locomotive Co. Ltd of Glasgow, beginning in 1907–9 with four 0–6–6–0 engines destined for China.

The largest of all conventional two-unit Mallets—intended to bank 15,000 ton freight trains—were the ten 2–10–10–2 examples built in 1918 for the Virginian Railroad by the American Locomotive Company.

The two standard Mallets promoted from 1919 onward by the United States Railroad Administration (USRA) retained compound working, but their enormous low-pressure cylinders had reached the limits of the loading gauge. Owing to continual improvements in manufacturing technology, which allowed boiler pressures to be raised to 275–300lb/sq.in, many later Mallets reverted to simple expansion. They included the 4–8–8–4 'Big Boys' of the Union Pacific Railroad, built by Also in 1941–4, which were nearly 133ft long and weighed 1,189,500lb with their tenders.

Attempts were also made to perfect the Triplex or Henderson Mallet, with a fixed central power truck and articulated trucks at each end. Exhaust from the central high-pressure cylinders was split between two pairs of low-pressure cylinders positioned on the pivoting trucks. Though this enabled six identical cylinders to be fitted, the added complication proved to the undoing of the Triplex system. Only five locomotives seem to have been made, all by the Baldwin Locomotive Company.

The prototype was *Matt H. Shay*, a 2–8–8–8–2 delivered to the Erie Railroad in 1913. Trials showed that tremendous loads could be hauled on level track—on one occasion, 16,300 tons were drawn at 14mph—but the boiler could not supply steam fast enough to reach higher speeds. This was partly due to a reduction in draught, as the rearmost cylinders exhausted to the atmosphere through an auxiliary chimney at the rear of the tender.

The most powerful railway engine of all time, on the basis of tractive effort, was 377-ton Baldwin made 2–8–8–8–4T Triplex Mallet no. 700 of 1916. This had two high-pressure and four low-pressure 36 × 32-inch cylinders and a nominal tractive effort, with all cylinders working on simple expansion, of 199,560lb. However, the boiler could not supply enough steam at more than 10–15mph, so no. 700 was reconstructed as two separate engines in 1921.

13: COMPOUND MARINE ENGINES

The earliest compound to be tried by the Royal Navy was the unsuccessful six-cylinder 'V' or inverted diagonal (q.v.) pattern tested in the frigate *Constance*. The next to be tried was a 600nhp two crank Woolf-type tandem engine by Humphrys & Tennant, installed in the wooden central battery armoured corvette *Pallas* (3794 tons) launched in Woolwich Dockyard in March 1865. The 51-inch diameter high-pressure cylinders lay outboard of the 99-inch low-pressure cylinders, which lay next to the crank. Trunk pistons gave a barely sufficient stroke of about 39 inches.

Trials undertaken off Plymouth showed that *Pallas* could attain 12·45 knots at 78rpm on 3210ihp, boiler pressure being about 32lb/sq.in. Speed rose to about thirteen knots after changes had been made to the single propeller.

Similar engines were fitted in two large troopships, *Serapis* and *Crocodile*, but the high-pressure cylinders and the piston-rod gudgeons in the trunks wore excessively. Fuel consumption was acceptably low, but the high cost of maintaining the engines told against them so greatly that the compounds were soon replaced by simple machinery.

Another attempt to introduce compounding into the navy was made in the late 1860s with five single-screw 350nhp wooden screw corvettes. The two-cylinder engine fitted by Rennie into the 1831 ton corvette *Briton* (Sheerness dockyard, launched in November 1869), embodying a Cowper reheater between the cylinders, proved to be the most economical. Steam exhausted from the high-pressure cylinder was heated and dried before entering the low-pressure side of the engine. Trials indicated that this engine consumed coal at a rate of only 1·98lb/ihp/hr at maximum power (2149ihp, 13·13 knots), or 1·3lb/ihp/hr at cruising speed (660ihp).

Three sister ships of the Eclipse class (displacing 1755 tons) were also used in the experiments. Launched from Portsmouth dockyard in April 1868, *Sirius* had a two-crank tandem compound engine supplied by Maudslay, Sons & Field. The small diameter high-pressure pistons were set into the face of the larger low-pressure units, which provided a particularly compact arrangement. At 96rpm, with a boiler pressure of about 55lb/sq.in, *Sirius* indicated 2302hp and attained 13·1 knots.

Hms *Tenedos* (Devonport, 1870) had an Elder two-cylinder horizontal compound, each cylinder driving onto a separate throw of the crank. The high-pressure cylinder exhausted into a large receiver doubling as a steam jacket, and thence into the low-pressure cylinder. Power was 2028ihp at 99rpm, with a boiler pressure of 60lb/sq.in. Trial speed was thirteen knots.

The least successful of the experimental engines was fitted in the corvette *Spartan*, launched from Deptford in November 1868. Designed by A.E. Allen and built by J. & G. Rennie, this was said to have been one of the worst powerplants ever commissioned into British naval service. Trials returned a meagre 1582ihp, which made *Spartan* almost a knot slower than her sisters.

Trials were subsequently undertaken with torpedo gunboats before the superiority of the two-stage compound was finally established. One of the earliest successful compound engines was fitted in the unarmoured corvette *Boadicea* (3913 tons displacement), launched in Portsmouth Dockyard in the autumn of 1875. Built by J. & G. Rennie of Blackfriars, London, it had one high-pressure cylinder of 73 × 48 inches and two low-pressure cylinders measuring 92 × 48 inches on the opposite side of the shaft. Steam was admitted to the high-pressure cylinder by balanced slide valves driven from a crankshaft eccentric by a rocking shaft and link motion. A separate eccentric-driven Meyer-type slide valve was fitted to the valve chest to adjust the cut-off point by moving a control lever.

The exhausted high-pressure steam was admitted to the valve chests of the low-pressure cylinders, which were big enough to act as receivers, and thence to the cylinders themselves through double-ported slide valves. Surface condensers were fitted. *Boadicea* had ten single-ended boilers with 36 furnaces, operating at 70lb/sq.in, which gave an indicated horsepower of about 5130 at 14·75 knots through a single screw propeller with a diameter of twenty feet.

By the late 1870s, virtually all of the most important problems had been eliminated. Among the oustanding successes were the Despatch

Vessels *Iris* (3730 tons) and *Mercury*, commissioned in 1878 and 1879 respectively. Each ship had twin shafts driven by two-crank Maudslay, Sons & Field engines derived from those installed in *Sirius*. Recessing the high-pressure pistons into the low- pressure units gave a compact and tidy layout. The engines were supplied from eight oval and four cylindrical boilers, and were intended to indicate about 6000hp at 17 knots. A load of 780 tons of coal was expected to give a range of 6000 nautical miles at ten knots, or about 2000 at maximum continuous speed.

The first trials run with *Iris* gave a disappointing 16·6 knots, even though the engines indicated 7086hp. Changes to the propeller allowed power to rise to 7330ihp and speed to 17·89 knots. Subsequently, more than eighteen knots were obtained from *Iris*, and *Mercury*, benefiting from the improvements, achieved 18·57 knots on 7735ihp. This made each ship the fastest in the world in turn, and amply repaid the faith placed in the compound engine which thereafter became standard in the Royal Navy.

14: COMPOUND PORTABLE AND SEMI PORTABLE ENGINES

Though agricultural needs were usually satisfied with basic single-cylinder simple expansion engines, industrial applications were often much more demanding.

Two-cylinder machines appeared in the 1870s, allowing cylinder dimensions to be reduced whilst simultaneously smoothing operation, but not until Garrett of Lincoln produced the first compound portable engine in 1879 were demands for greater power truly answered. Compounds were more expensive to buy than single-cylinder equivalents, but saving as much as thirty per cent of fuel attracted many purchasers.

Many compounds—and, indeed, single-cylinder engines—were fitted with automatic expansion gear controlled by governors, the Pickering and Hartnell types being widely favoured though proprietary horizontal designs were used by Robey and others.

At the Royal Agricultural Society show in the summer of 1887, a compound 8nhp Davey, Paxman & Company portable engine gained the £200 prize by using only 1·85lb of coal hourly per brake horsepower. This compared with 2·6lb for an otherwise identical single-cylinder simple expansion 8nhp (17 bhp) machine tested at the same time.

Robey's Portable Compound Steam Engine No. 8 was typical of the smaller compounds. Rated at 8nhp, it gave 19bhp when running at its most economical rate and 26bhp at maximum load. Steam was supplied from the boiler at 150lb/sq.in to high- and low-pressure cylinders with diameters of 5½ and 9½ inches respectively, the common stroke being 12 inches. The flywheel had a diameter of 58 inches and ran at 200 rpm. No. 8 was 12ft 3in long, 6ft 2in wide and weighed 5 tons 18 cwt empty. By comparison, the Robey No. 30 Compound (72/96bhp) had cylinder diameters of 10 and 18 inches, an 18-inch stroke, and an 84-inch diameter flywheel running at 133 rpm. The engine was eighteen feet long, 8ft 3in wide and weighed 17 tons 10 cwt empty.

Typical of the semi-portable or independent engines was the Robey No. 65 Compound, with cylinder diameters of 15 and 26 inches. These shared a common 28-inch stroke, power being 156bhp at normal speed (non condensing) or a maximum of 208bhp. The 10-foot diameter flywheel ran at 90 rpm. The basic engine weighed 54 tons 15 cwt empty, but the separate condenser added 3 tons 11 cwt.

Superheating was occasionally offered from *c.* 1905 onward as a simpler alternative to compounding. Engines of this type were capable of excellent economy: an 8nhp Garrett engine tested by *The Engineer* in 1907, for example, returned an hourly coal consumption of only 2·23lb/bhp, evaporated 10·1lb water for each pound of coal, and consumed steam at a rate of 22·6lb/bhp. Published details show that this particular machine had a boiler pressure of 170lb/sq.in, developed 26·3bhp at 200 rpm (with 32 per cent cut off) and had a steam temperature of 510° F.

A superheated 20 bhp machine made by Ruston & Proctor returned 2·02lb coal/bhp/hr when tested in 1911, and a superheated overtype semi-stationary Garrett engine, installed in 1910 in the St Ivel cheese factory in Yeovil, returned an exceptional 1·21lb. Garrett claimed in advertisements that the St Ivel machine combined the 'economy of the suction gas engine… with the reliability, flexibility and overload capacity of the steam engine'.

15: DIAGONAL ENGINES

The first of these was patented by Marc Brunel in 1822. Later very popular, as it occupied less height than vertical systems but was not as long as a horizontal, the diagonal engine could drive directly onto a paddle-shaft crank without ultra-short connecting rods. It did not wear as quickly as an oscillating engine, nor suffer the same steam leaks.

One of the earliest geared engines was a diagonal driving the propeller of Brunel's *Great Britain* (3618grt), launched in 1843. This had four direct-acting 88 × 72-inch cylinders driving upward onto a crankshaft supported in 'A' frames of timber and iron. A large-diameter drum attached to the after end of the crankshaft drove a smaller drum on the inboard end of the propeller shaft. Four sets of chains meshed with wooden teeth on the drum surfaces to rotate the screw, the gearing being set to increase the engine speed of 18rpm so that the screw made three turns for each one of the crankshaft.

Indicated horsepower was about 2000, steam being distributed by piston valves driven by reversible loose eccentrics. A single eccentric was used for the admission and exhaust valves of each cylinder. Boiler pressure was a meagre 5lb/sq.in, steam being generated in a single large cylindrical double-ended boiler with 24 stoke holes. A feedwater heater lay around the base of the funnel. The original *Great Britain* powerplant was replaced by Penn-made oscillating engines in 1847.

The engine of *Harbinger* (848grt), launched in 1851 from the Blackwall shipyard of J.C. Mare & Company for the Cape and East India mail service, was supplied by Maudslay, Sons & Field. It had two opposed 41½ × 27-inch cylinders athwartship, mounted diagonally to drive a central crankshaft. The condenser lay beneath the shaft to form an integral part of the engine bed. Slide valves in chests on top of the cylinders were driven by rocking shafts from the crankshaft eccentrics. The fire tube boilers were pressed to a mere 15lb/sq.in, which allowed ten knots to be maintained at 26–27rpm.

The simple-expansion engines commonly used aboard warships in the 1860s, operating at no more than 20lb/sq.in, usually consumed coal at a rate of 4–5lb/ihp/hr; even the earliest compound, installed in the steamer *Brandon* in the mid 1850s, had returned 3–3½lb/ihp/hr and newer equipment was offering substantially better returns. Economy, therefore, was a major attraction of the compound.

Prior to the introduction of compund engines, no warship was capable of making the translatlantic passage under mechanical power alone. Thus sail still remained supreme, engines being regarded as an aid to manoeuvring and a means of closing the enemy if the wind and tides were unfavourable to sail. Boiler pressures remained conservatively low and machinery was placed below the waterline to guard against shot damage.

The decision was taken in 1860 to convert a group of wooden fifty-gun Fourth Rate Sailing Frigates to accommodate steam engines, boilers and coal bunkers. This required stretching the hulls between the fore and main masts, length between perpendiculars increasing from 170ft to about 250ft. The opportunity was also taken to try a selection of differing engines.

Originally built in 1849, *Arethusa* (3708 tons) was finally undocked in August 1861. The vessel had conventional simple-expansion trunk engines made by John Penn of Greenwich and made 11·7 knots on trials with 3165ihp. *Octavia* (3832 tons, 1849), undocked in August 1861, had a simple expansion return-crank engine by Maudslay, Sons & Field. Her trials returned 2415ihp, equivalent to 11·53 knots.

By far the most interesting powerplant was installed in HMS *Constance*. Originally completed in Pembroke dockyard in 1846, the frigate was undocked in April 1862 with a displacement tonnage of 3786 and a new engine supplied by Randolph & Elder. Each side of this 'V' type design had a high-pressure cylinder flanked by two low-pressure units. A three-throw crankshaft was coupled to the single screw, but trials were beset by problems and initially gave only a disappointing 10·8 knots at 2300ihp. Engine troubles delayed completion of preliminary steaming trials, and not until 30th September 1865 were the three ships readied in Plymouth Sound for a race to Madeira. They were to proceed on identical courses until fuel ran down to a predetermined quantity. By 6th October, when all three were running short of coal, *Constance* lay about thirty miles from Funchal; *Octavia* was some 120 miles behind *Constance*, but forty ahead of *Arethusa*. When the trials were analysed, hourly coal consumption for *Constance*, *Octavia* and *Arethusa* was found to be 2·51lb/ihp, 3·17lb/ihp and 3·64lb/ihp respectively.

The compound engine had demonstrated its superiority as far as fuel economy was concerned, but had given endless trouble. Lubrication difficulties and breakages of parts had been promoted by the boiler pressure, which was higher than customarily accepted in the Navy of the 1860s. Great concern was voiced about the ability of ordinary seamen to understand the complicated machinery and so the first trial of a multi-stage expansion engine ended in failure. Its immediate replacements were almost always horizontal (q.v.).

INVERTED VERTICAL ENGINES

Direct acting machines had been tried in the eighteenth century, when Edward Bull a few inverted vertical examples in an attempt to circumvent

Watt's patents. Bull—who apparently came from the Black Country—had been sent to Cornwall by Boulton & Watt, but became disillusioned when William Murdock was appointed as his superior and soon began to erect engines on his own account. Their cylinders were inverted above the mine shaft, driving directly onto pump rods.

The earliest Bull engine was installed in Balcoath Mine and at least ten are known to have been made. The engines had a particularly efficient double acting air pump, suspected to be Trevithick's contribution, and injected cold water into the exhaust-steam pipe in an attempt to avoid Watt's separate condenser patent. Unfortunately, the courts decided a patent infringement lawsuit in favour of Boulton & Watt, and the Bull engine was abandoned. Edward Bull then produced a hydraulic engine, one of which was being erected by the Wheal Bounty adventurers when the designer died unexpectedly in March 1797. He had not even reached his fortieth birthday.

Bull's influence on steam engine design was comparatively minor; however, it seems that he may be due at least part of the credit customarily given to Richard Trevithick for an effectual water pressure engine. Bull and Trevithick operated in a loose partnership in the 1790s, and it may be simply that Trevithick put into practice after Bull's death ideas which may originally have been due (at least in part) to his late partner.

Bull-type engines reappeared early in the nineteenth century, after the expiry of Watt's separate condenser patent. Some Cornish-pattern examples were made, including two of the twelve pumping engines installed to drain the Severn Tunnel. These had 50in cylinders.

Some of the pumping engines patented about 1875 by Henry Davey and built by Hathorn, Davey & Company of Leeds in 1875–1900 were also of this general inverted-vertical pattern, usually driving beams or half-beams beneath the cylinders.

Richard Trevithick eventually produced a 'closed circuit' engine allied with his patent multi-tubular vertical boiler, which doubled as a clever combination of condenser and superheater. Construction was basically concentric. Cold air was drawn into the closed furnace, allowing exhaust steam to exchange heat with the incoming air. This condensed the steam and simultaneously supplied pre-heated air to the furnace. The condensate passed to the boiler unit to be converted into high-pressure steam at high temperature—a system which could have been beneficial for maritime use, if anyone could have been persuaded to test it extensively.

Trevithick associated with John Hall of Dartford in 1832, but died suddenly in 1833 before anything could be achieved. For all his gifts, he left life practically penniless.

The inverted vertical engine reappeared about 1840, derived by Nasmyth from his 1839 patent steam hammer. Placing the cylinder so that the piston drove downward onto the crank lowered the axis of the flywheel compared with a vertical engine. As the centre of gravity was also lowered, inverted vertical engines ran more steadily at speed than vertical designs.

In its largest sizes, the inverted vertical was widely used as a blowing or rolling mill engine; it was also very popular for maritime and high-speed use, but generally only after it had been doubled or even tripled. For each large engine, however, there were countless smaller examples. These remained extremely popular for use in confined spaces, and were made in large numbers until comparatively recently.

Most were free standing, but some engines were specifically designed for wall mounting and there was great variety in the framing. The earliest patterns generally have angular frames whilst many later examples incorporate a rounded ‘bottle’ type.

1: COMPOUND ENGINES

By the mid 1870s, compounding had become so well established that large and powerful engines were being fitted to ships in a quest for speed. Typical of these were the massive twin-tandem compound installed in *Britannic*, 5004grt, completed in 1874 by Harland & Wolff of Belfast for the White Star Line. Built by Maudslay, Sons & Field, the engine had two 48 × 60-inch high-pressure cylinders above two 83 × 60-inch low-pressure units in paired groups separated by the valve chests. It was 33 feet high and 24 feet long.

The slide valves were controlled from an eccentric on the crankshaft by link motion and an operating rod. Reversing was assisted by a single cylinder auxiliary or ‘slave’ engine, owing to the great weight of the parts. Each high-pressure valve had an additional expansion valve to control the cut off, operated by its own eccentric. The low-pressure cylinders exhausted into a surface condenser. Eight boilers containing 2423 fire tubes supplied steam at 70lb/sq.in, which gave an indicated horsepower of 4971 and a service speed of thirteen knots.

2: MULTIPLE-STAGE EXPANSION ENGINES

Credit for the introduction of the first marine engine of this class, in Britain at least, is customarily given to Alexander Kirk on the basis of the machinery installed in the steamships *Propontis* (1874) and *Aberdeen* (1882). However, the claims remain contentious.

Alexander Carnegie Kirk was a Scotsman, born in 1830 in the small town of Barry, Forfarshire. Apprenticed at an early age to Robert Napier at the Vulcan Foundry in Glasgow, where some of the most successful of the early marine engines had been made, Kirk then became chief draughtsman for Maudslay, Sons & Field in London. The Maudslay firm was renowned, among other things, for its warship engines. However, Kirk soon went back to Scotland to work as chief engineer for Young, Meldrum & Binnie, makers of paraffin oil, and successfully developed a refrigerating machine.

In 1864, Alexander Kirk re-entered marine engineering as works manager of Elder & Company of Glasgow, where he was influenced directly by the pioneering work of John Elder. Randolph & Elder had made some of the earliest compound marine engines, and, indeed, John Elder had patented the basis of multiple-expansion engines in 1862. Kirk continued working in this particular field after the unexpected death of John Elder in 1868, but his claim to fame relies largely on the machinery designed for the steamship *Propontis*.

An old vessel operated by W.H. Dixon of Liverpool, submitted to Elder & Company for refurbishment, *Propontis* had been propelled by a simple-expansion engine made by Smith & Rodger. This engine had been supplied with steam from a low-pressure box boiler, but it is said that, lured by the promise of substantial reductions in coal consumption, Dixon insisted on the use of Rowan & Horton 'accelerated circulation' water-tube boilers and a compound engine.

First patented in 1858 by J.M. Rowan and T.R. Horton, partners in the Atlas Works in Glasgow, a Rowan-pattern boiler—with a steam pressure of 115lb/sq.in—had been fitted in *Thetis*, built by Scott of Greenock in the same year. Trials of the water-tube boiler and an associated two-cylinder compound engine had returned coal-consumption figures as low as 1·02 pounds per horsepower-hour, but the installation was unsuccessful in service. Dixon now wished to use an improved Rowan & Horton boiler capable of generating steam at 150lb/sq.in.

The success of compounding had been due entirely to the need to divide the temperature drop that occurred between the admission and exhaust of steam by adding another cylinder. The thermodynamic advantages of doing so had been proven not only in countless compound or two-stage land engines, but also in marine engines exemplified by the tandem pattern fitted in Alfred Holt's pioneering *Agamemnon*. Even two-stage expansion reduced coal consumption sufficiently to allow voyages between Britain and Australia without excessive re-coaling stops.

Alexander Kirk realised that two-stage expansion would fail to make the best use of steam pressures which many shipowners regarded as suicidal. His solution, which was undoubtedly presaged by Elder's patent (and perhaps also by a body of opinion within Elder & Co.), was to add another cylinder. This created the three-stage or triple-expansion engine, the unit fitted in *Propontis* being among the first to take the classic inline inverted-cylinder form.

Kirk himself admitted that he was 'thoroughly convinced that the great success of the ordinary compound engine of that day over the simple engine, or even the Woolf engine, lay in the range of temperature through which the steam in any one cylinder passed in the course of one stroke being very much reduced [and it seemed] that with the higher pressure [he] must use three successive expansions and divide the total range of temperature into three parts.'

The tramp steamer *Propontis*, 318·4 feet between perpendiculars with a 36·3-feet beam, had a gross registered tonnage of 2083 before alterations and 2132 thereafter. Fed from boilers arranged in four self-contained sections, with a total heating surface of 8700 square feet and a grate area of 121·6 square feet, the new triple-expansion engine drove a single four-bladed propeller. Steam from a high-pressure cylinder with a diameter of 23 inches exhausted successively into an intermediate cylinder (41 inches) and thence to the low-pressure unit (62 inches). The stroke—common to all, of course—measured 42 inches.

Trials began on 4th April 1874, a typical test revealing that pressure within the smallest cylinder, supplied from boilers operating at 110lb/sq.in, ranged from 98lb/sq.in (inlet) to 21lb/sq.in (exhaust). This was equivalent to 274·8 indicated horsepower. The range within the middle or 'intermediate' cylinder, from 30lb/sq.in above to 2lb/sq.in below atmospheric pressure, equated to 276·8 indicated horsepower, whereas the relevant figures for the low-pressure cylinder ranged from 1lb/sq.in above to 12lb/sq.in below atmospheric pressure (355·5 indicated hosepower). A slight imbalance was to be seen within the individual expansion stages, but not great enough to pose operating problems. Indicated horsepower totalled 907·1, though the machinery was classed merely as 250 nominal horsepower. A twelve-hour trial gave 9·5–10 knots at 750 indicated horsepower, 130lb/sq.in and seventy revolutions per minute, coal consumption proving to be only 1·8 pounds per horsepower-hour.

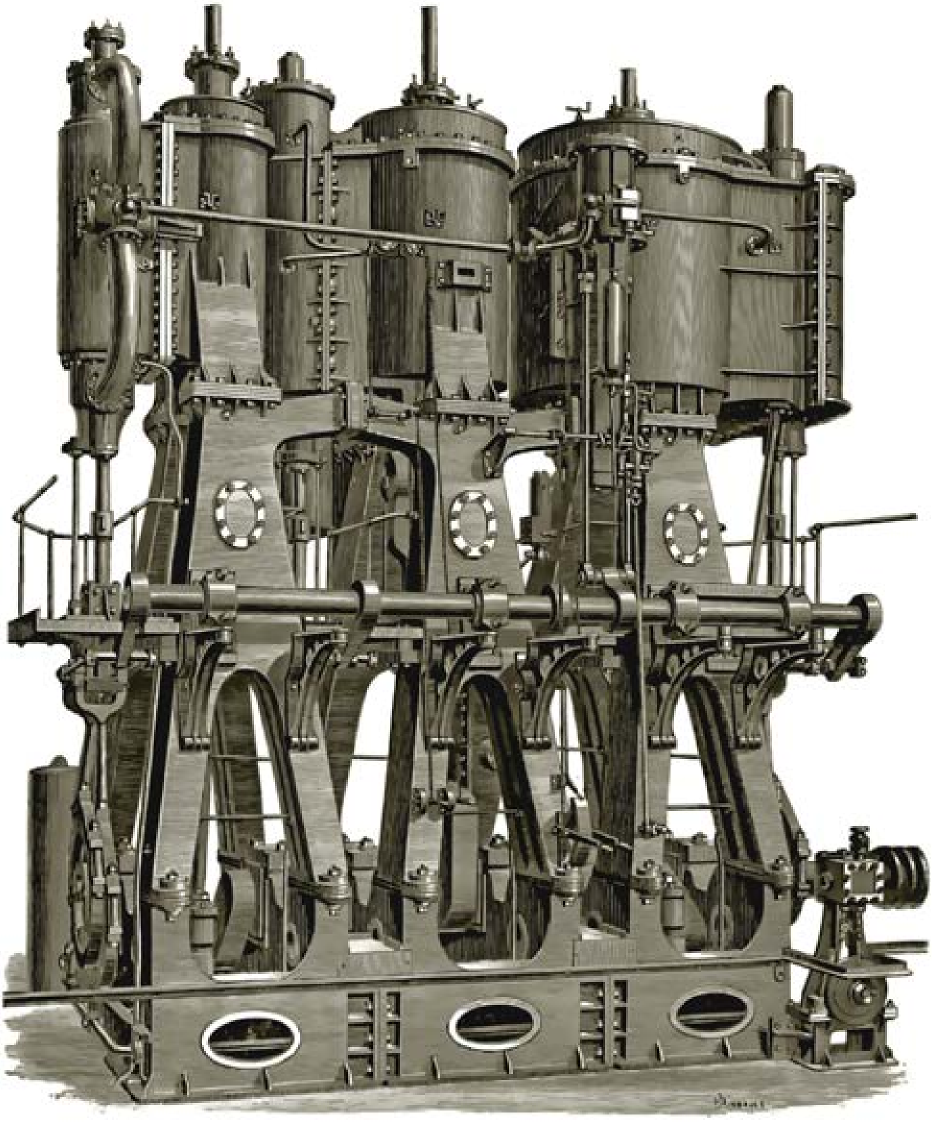
Propontis was duly dispatched on a seven-thousand mile voyage from Liverpool to the Black Sea port of Odessa, returning to Antwerp by way of Malta. The outbound journey was used largely to familiarise the engine-room staff with the machinery. On the return trip, however, trials indicated that as much as 1172 horsepower could be obtained from the engines, and speeds as great as eleven knots could be reached once the expansion gear had been disconnected.

Coal consumption was calculated to be just 1·54 pounds per horsepower-hour at 1100 ihp, once deductions had been made for the needs of the auxiliary machinery. However, only three of the four boilers had been used and the iron division strips, which directed the path of the heat from the grate, proved to be unreasonably fragile.

Unfortunately for Kirk and his employers, though initial signs had been encouraging, the Rowan & Horton boilers were a disappointment in service. Efficient enough when new and in good repair, they deteriorated so rapidly that two serious explosions in rapid succession persuaded Dixon to replace them in 1876 with conventional cylindrical boilers. These were pressed to much lower levels (just 80 or 90lb/sq.in) and reduced the performance of the engine accordingly. Coal and water consumption were undoubtedly lower than they would have been had conventional two-cylinder compound machinery been used, but the gains were obscured by disputes over the boilers.

Setbacks with *Propontis* allowed others to develop triple-expansion engines, stealing a lead. Not until the beginning of 1881 did Alexander Kirk, by then a partner in Robert Napier & Son, find a British shipowner—George Thompson & Company of Aberdeen—willing to risk using high-pressure steam. It was ironic that a business whose success had been forged by legendary tea-clippers such as *Thermopylae* and the iron-hulled *Salamis* should gain renown as a champion of efficient steam propulsion.

Three masts, barque rig, an elegant clipper bow, a figurehead and a bowsprit reflected Thompson's sailing-ship successes, but hid in the steamer *Aberdeen* an ultra-modern engine with cylinder diameters of 30, 45 and 70 inches. Operating with a common stroke of 54 inches,



this differed only in detail from the machinery fitted in *Propontis* some eight years earlier. However, instead of proprietary water-tube boilers, Alexander Kirk fitted two conventional double-ended cylindrical steel boilers with a total heating surface of 7128 square feet and a safety valves loaded to 125lb/sq.in.

The goal was a forty-day passage to Australia. Many pundits scorned the project before trials had been run, opining that the excess of boiler pressure over conventional practice was nothing less than foolhardy, but

Aberdeen proved them all wrong by successfully negotiating speed and economy trials alike. The vessel had a gross registered tonnage of 3616, an overall length of 362·5 feet and a beam of 44·4 feet. A trial undertaken on 21st February 1882—with the steam jackets and feedwater heater in operation—indicated 1944 horsepower, the range of steam pressures in each cylinder being from 108 to 20lb/sq.in (HP); from 28lb/sq.in above to 2lb/sq.in below atmospheric pressure (intermediate); and from 4 to 15lb/sq.in below atmospheric pressure (LP).

A full-power trial indicated 2631 horsepower, a speed of 13·74 knots and a coal-consumption of 1·85 pounds per horsepower-hour: excellent results for a vessel of *Aberdeen*'s type, and a vindication of the faith Thompson, Napier and Kirk had placed in three-stage expansion. Consumption of coal at 'cruising power', 1800 indicated horsepower, was reckoned as just 1·28 pounds per horsepower-hour.

Early in the morning of 1st April 1882, *Aberdeen* left Plymouth, bound for Australia with four thousand tons of cargo and coal. A brief stop was made at Cape Town to replenish the bunkers, and, on 14th May, the ship steamed triumphantly into Melbourne harbour after a passage that had lasted just 42 days. The engine had performed flawlessly, indicating an average of 1880 horsepower and returning an overall coal-consumption rate of barely 1·7 pounds per horsepower-hour. This had allowed *Aberdeen* to use about five hundred tons of coal less than ships fitted with two-cylinder compound engines of comparable power.

Even after travelling in excess of 170,000 miles, equivalent to seven circumnavigations of the globe, *Aberdeen*'s engines showed no more wear than an ordinary compound and, moreover, none of the cutting of the valves or cylinder-walls predicted by opponents of high-pressure steam. By the time William Parker presented a Paper to the Institute of Naval Architects on 29th July 1886, more than 170 merchantmen had already been fitted with triple-expansion engines.

The advantages were so clear-cut that about twenty of these ships had had their two-cylinder compound engines adapted by the addition of a new high-pressure cylinder above the old one: a solution that cleverly avoided the changes in engine-room layout demanded by substituting an 'inline' three-cylinder engine, though problems arose in balancing the thrust of three cylinders onto two cranks.

Alexander Kirk was also renowned for experiments with steel, summarised in papers he presented to the Institution of Naval Architects.

This enabled him to develop steel forgings that were durable enough to be incorporated in the frames of warship engines, beginning with HMS *Nelson* in 1879. The use of steel saved a substantial amount of weight; despite developing more power than the cast-iron framed engines of sister-ship *Northampton*, the machinery of *Nelson* weighed 998 tons compared with 1113.

One-time president of the Institution of Engineers and Shipbuilders in Scotland, honoured in 1877 by the University of Glasgow and the Royal Society of Engineers, Alexander Kirk died comparatively young in October 1882. A popular, genial and generous man, he was soon universally hailed as the inventor of the triple-expansion engine and is certainly due much of the credit for persuading the Royal Navy to adopt machinery of this type. But there were those who knew or supposed they knew differently, and publicity that attended Kirk's death attracted much correspondence in the engineering press. Not all of it was as complimentary as the obituaries had been.

The idea of multiple-expansion was by no means new even at this time. According to the French engineer Anatole Mallet—writing in *Evolution Pratique de la Machine à Vapeur* (1913?)—suggestions had been made in France as early as 1823, owing to the success of the two-cylinder Woolf compounds and a desire to increase steam pressures. Jacob Perkins had patented a forerunner of the triple-expansion engine in England in 1827, and Daniel Adamson had successfully constructed a three-stage mill engine in 1862–3.

The first engineer to make a triple-expansion engine for marine use seems to have been the Frenchman Benjamin Normand (1830–88), elder brother of the better-known Jacques-Augustine Normand. Working independently, Benjamin Normand installed a two-stage compound engine in *Furet* (1860) and had begun building a small two-crank three-stage expansion engine in 1870. Work was interrupted by the Franco–Prussian War, but the engine was fitted in 1871 in *Bâteau Numéro 30* of the Compagnie des Bateaux-Omnibus de la Seine and ran successfully for many years.

Similar triple-expansion engines were then built for *Falconeer* (1871) and *Montezuma* (1872), but details are currently lacking. In 1874, however, Jollet & Babin of Nantes built *Gabrielle* with a two-crank four-cylinder Normand steam engine capable of indicating 400 horsepower. Single high-pressure and intermediate cylinders with diameters of 60 and 90 centimetres (23·6 and 35·4 inches respectively) were placed above two 100-centimetre (39·4-inch) low-pressure units. The stroke was eighty centimetres, 31·5 inches, and a re-heater was placed between the intermediate and low-pressure cylinders to improve economy. The cylindrical boiler operated only at 4·5 atmospheres—merely 64lb/sq.in—which undoubtedly minimised the value of three-stage expansion, but, though evidence remains largely circumstantial, *Gabrielle* seems to have worked economically enough before being lost in the English Channel in the late 1870s.

Benjamin Normand drifted back into obscurity and it is now rare that due credit for the development of effectual triple-expansion is given to France: the country in which the work of Englishman Arthur Woolf, the father (though not the originator) of the compound engine, also won its greatest renown.

Peter Ferguson, then employed by Thomas Wingate & Company of Whiteinch, a Clydeside suburb of Glasgow, claimed to have installed a three-crank triple-expansion engine in the launch *Mary Ann*, and it is an open question whether Kirk, like Ferguson a member of the Institution of Engineers and Shipbuilders in Scotland, would have been aware of this particular development. It pre-dated *Propontis* by at least two years.

A.C. Franklin, another claimant, supervised manufacture of a three-crank engine by the Ouseburn Engine & Works Company of Newcastle upon Tyne in 1873. This had cylinder diameters of 11, 17 and 24 inches, an eighteen-inch stroke, and a boiler pressed to 120lb/sq.in. However, though testing had been undertaken, the intended recipient of the first engine was cancelled and the actual recipient, *Sexta*, built by W. Gray & Company of Hartlepool, did not run her trials until September 1874. Coal-consumption figures as low as 1·518 pounds per horsepower-hour were returned.

Despite short-lived local notoriety, however, the claims made by Franklin were disbelieved in broader ship-owning circles and passed largely unheralded. Yet the prior existence of this particular engine was sufficient to invalidate patent claims registered not only by Alexander Kirk but also by Alexander Taylor, who, though undoubtedly pre-empted by Benjamin Normand, claimed paternity of the two-crank triple-expansion engine.

The first Taylor engine, made by Douglas & Grant of the Dunnikier Foundry in Kirkaldy, was fitted in the 143-feet long steam yacht *Isa* (175 grt) in 1878. Its dimensions were modest; cylinder diameters measured 10, 16 and 28 inches, and the stroke was merely 24 inches. Larger Taylor-pattern engines made by Douglas & Grant were subsequently installed in steamships *Albertina* and *Claremont*, built for Fisher, Renwick & Company of Newcastle upon Tyne in 1882. These had cylinder diameters of 14¼ (HP), 20¼ (intermediate) and 40 inches (LP), and a 33-inch stroke. Steam was supplied from a 'common marine' or cylindrical boiler pressed to 150lb/sq.in, which the manufacturers claimed to have been the first of its type operated at such high levels.

The true genesis of three-stage expansion at sea is perhaps best summarised by an obituary published in *Engineering* on 14th October 1882, which stated: "There may be reason for dispute as to Dr. Kirk's claim to novelty in the introduction of triple expansion, but it is undeniable that he gave a great impetus to the practical use of higher pressures… There is one point, too, which is clear, the arrangement of triple-expansion engines of the *Propontis* and the *Aberdeen* is that now universally adopted. This says much for accuracy in [initial] design."

The success of the triple-expansion engine in mercantile service did not escape the attention of naval authorities, which were impressed by the reductions in coal consumption and consequent increases in range. This was particularly important to the British and the French, with far-flung empires to protect and thousands of miles between coaling stations. However, both traditionally-conservative navies had only just accepted the value of compounding, and fretted about the dangers of high-pressure steam should boilers be struck by shells.

The first European Power to take the risk was Italy, so often the innovator in late nineteenth-century naval matters. The twin-screw protected cruiser *Angelo Emo*, delivered in 1884, was driven by engines designed by Frederick Marshall of Hawthorn Leslie & Company that were intended to indicate 8000 horsepower. However, credit was not entirely due to the Italian navy.

The warship, designed under the supervision of Sir William White, had been built by Armstrong 'on account'—for sale once a buyer could be found, but possibly also to investigate the value of three-stage expansion. The vessel was hawked to Greece while still on the stocks, as *Salamis*, but the contract defaulted before completion; searching for a suitable purchaser, Armstrong soon sold the ship to Italy at a good price. Trials were so successful that the implications could no longer be ignored.

It has often been claimed that triple expansion engines were fitted in the four Second Class Cruisers of the Leander Class, completed in 1885–7, but the only differences between these and *Mercury* (q.v.) lay in the introduction of closed stokeholds and forced draught; the engines remained Maudslay, Sons & Field horizontal tandem compounds. The three-stage expansion machinery of the British turret battleships *Victoria* and *Sans Pareil* was the first to be ordered, but the first warship fitted with a triple-expansion engine to be commissioned into the Royal Navy was the torpedo gunboat *Rattlesnake*, which took much less time to complete. Built by Laird Brothers of Birkenhead, *Rattlesnake* displaced 550 tons, had a length between perpendiculars of about 200 feet, and measured about 23 feet in the beam.

The gunboat was laid-down on 16th November 1885, launched on 11th September 1886 and completed in May 1887. Two engines drove a propeller shaft apiece, and together indicated about 2700 horsepower on trials. This was sufficient to give about 19¼ knots with forced draught. Experiments with near-sisters *Grasshopper*, *Sandfly* and *Spider*, all fitted with two-cylinder Maudslay compound engines, soon showed the advantages of the additional expansion stage. However, *Rattlesnake* had an inline inverted-vertical engine, and many powerful voices were still raised in support of the old horizontal compound engines.

These worked well on comparatively low steam pressures, and their layout suited them to a place deep in the bowels of a warship, safe beneath protection afforded by the waterline; upright engines could not be accommodated so readily, as the projection above the waterline had to be protected with armour plate. Additional protection brought penalties in the form of additional weight, reducing speed, or required economies to be made elsewhere in the ship if speed was to be maintained.

An answer was found in the form of the horizontal triple-expansion engines fitted in the cruisers of the Orlando class. These twin-screw ships were about 300 feet long, between perpendiculars, with a beam of 56 feet, and were each armed with two 9·2-inch and ten 6-inch breech-loading guns. An assortment of small-calibre quick-firers was provided for short-range defence.

The original design had called for two twin-cylinder inverted compound engines, indicating 7500 horsepower, but the advent of triple-expansion engines forced a change. Though predicted load displacement rose from 5000 to 5600 tons, it was hoped that the new engines would raise speed by a knot. They were intended to indicate 5500 horsepower with normal draught, or 8500 horsepower when forced. Fed with steam at 130lb/sq.in, from four double-ended boilers, the engines had a stroke of 42 inches and cylinder diameters of 36 (high pressure), 52 (intermediate) and 78 inches (low pressure).

The first ships of this particular group were laid-down on 21st April 1885 in Glasgow, *Australia* and *Galatea* being entrusted to the Govan yard of Fairfield and the Glasgow yard of Napier respectively. Hms *Australia* was also the first to be completed, in October 1888, but was eventually followed by sisters *Aurora*, *Galatea*, *Immortalité*, *Narcissus*, *Orlando* and *Undaunted*.

The trials were reasonably successful, with the greatest power being developed by *Galatea* (9205 indicated horsepower with forced draught) and the fastest speed by *Undaunted* (19·4 knots when running light). Horizontal engines proved to be efficient enough in themselves, but the limited beam of the cruisers forced them to be placed in tandem, with the port-shaft engine ahead of the starboard unit. Though the profile of the installation was commendably low, friction in the unequal propeller shafts emphasised an imbalance that was usually evident in supposedly identical engines. The experiment was never repeated; all subsequent British warships above the size of a gunboat had engines that were placed either in tandem (driving a single shaft) or side-by-side.

The enormous inverted-vertical triple expansion engines of *Victoria* and *Sans Pareil* still showed a great leap of faith, weighing, in the case of *Sans Pareil*, about 235 tons apiece. The warships were the work of Armstrong of Elswick and the Thames Iron Works of Blackwall respectively, construction work beginning with the laying of the keels in April 1885.

Victoria was launched on 9th April 1887 and completed in March 1890; *Sans Pareil* entered the water on 9th May 1887, though completion was delayed until July 1891. Each warship had a load displacement of 10,470 tons, measured 340 feet between perpendiculars, and had a beam of about 70 feet; armament comprised two 16¼-inch, one 10-inch and twelve 6-inch breech-loading guns, accompanied by an assortment of small quick-firers.

Two engines supplied by Humphrys, Tennant & Company, driving separate propeller shafts, were fed with steam from eight single-ended cylindrical steel boilers with a total heating surface of 19,600 square feet. The boilers were placed in separate compartments, in four groups of two. Each engine was rated at 4000 horsepower on normal draught, which was intended to give a sea-speed of about sixteen knots. Cylinder diameters were 43 (HP), 62 (intermediate) and 96 inches (LP), the stroke measuring 51 inches.

Trials undertaken with *Sans Pareil* in September 1888 gave an average of 8070 horsepower at 87 revolutions per minute, with natural draught and a boiler pressure of 135lb/sq.in. However, the engines could be forced to far higher output: 14,244 horsepower for *Victoria* and 14,482 horsepower for *Sans Pareil*, giving 17·3 and 17·75 knots respectively. Coal consumption, depending on the power being generated, ranged from 1·88 to 2·6 pounds per horsepower-hour.

The success of engines fitted in ships such as *Rattlesnake*, *Orlando* and *Sans Pareil* heralded the triple-expansion era, which, as far as major warships were concerned, lasted until the beginning of the First World War. The subsequent success of the turbine has eclipsed the all-round advantages of triple expansion, which continued to be used in smaller warships (e.g., the corvettes) until 1945.

Where the British led, others soon followed. Most navies kept to a single pattern, fitting triple-expansion engines in small craft—gun- or torpedo boats—before progressing to larger and more powerful units. However, the absence of reliable information from foreign-language sources still hides much of the truth. It is often difficult to determine precisely when propelling machinery was ordered, or how many changes had been made to the specifications before the warships were completed.

The confusion is worst where minor navies are concerned, particularly if machinery was ordered elsewhere. For example, the Chinese built three protected cruisers of the Kai Che class in Foochow dockyard in 1881–8. *Kai Che*, the first of the trio, was launched in 1882 and completed in 1883; she was undoubtedly propelled by a single shaft and a horizontal two-cylinder compound engine. Yet most sources list sister-ships *King Ch'ing* and *Huan T'ai* with triple-expansion engines indicating 2400hp at 14·5 knots.

The explanation is simply that these two vessels were not laid down until 1885, completion being delayed until August 1886 (*King Ch'ing*) and February 1888 (*Huan T'ai*), which allowed ample time for better engines to be purchased. The source of the engines is not known, but may have been W.G. Armstrong & Company: Armstrong laid-down two protected cruisers for the Chinese in October 1885, completing *Chih Yuan* and *Ching Yuan* in July 1887. Each ship had horizontal triple-expansion engines driving two shafts, *Chih Yuan* indicating 6892hp on a forced-draught trial which gave a maximum speed of 18·5 knots.

It seems much more likely that the first triple-expansion engines to be used in the Chinese navy drove six first-class torpedo boats built by Vulcan of Stettin in 1883–4. These apparently had single-shaft machinery indicating 600–700hp.

The first triple-expansion engines fitted in German warships propelled a selection of small single-screw torpedo boats built for comparative trials by the Weser, Vulcan and Schichau yards in 1884–5. The Weser boats, originally numbered *XII–XVII* but later *W1–W6*, indicated about 900–910hp and reached 19·7 knots; the Vulcan examples (*XVIII–XXVII*, later *V1–V10*) were smaller, indicating merely 590hp, and could reach only 17·8 knots; the Schichau group, *XXVIII–XXXII* or *S1–S6*, were the most seaworthy, generating about 870ihp and capable of a little over nineteen knots.

Larger machinery was fitted in the Wacht-class 'avisos', the first, *Wacht*, being laid down in the Weser shipyard in 1886 and completed on 9th August 1888; two-shaft diagonal machinery indicated about 3450hp, giving a speed of 18·5 knots. The first of the Siegfried-class coastal-defence battleships, laid-down in the Germaniawerft shipyard in 1888, was completed on 4th April 1890 with two-shaft inverted vertical triple-expansion engines capable of about 5000ihp. Maximum speed was restricted to 14½ knots, deemed to be sufficient for the limited role envisaged for *Siegfried* and her sister ships.

Though much of the credit for the development of the triple-expansion engine—and the two-stage compound before it—was due to Frenchmen, the French Navy of the 1880s was undergoing a period of introspection. Commitment to technological progress was uncertain, and the inclination to build a series of 'one-off' designs (instead of near-identical sister ships) had not yet been overcome.

The first multi-stage machinery fitted in a French warship was the quadruple-expansion engine installed in 1885–6 in *Ouragan*, described below. Triple-expansion engines were installed for the first time in the protected cruisers of the Alger class. The first ship, *Isly*, was laid down in the Brest dockyard in August 1887 to be followed in September by *Jean Bart* (Rochefort dockyard) and in November by *Alger* (Cherbourg dockyard). The machinery, which drove two shafts, developed about 8000ihp to give a maximum speed of 18·5 knots; *Jean Bart* and *Isly* had horizontal engines, but *Alger*'s took conventional inverted-vertical layout.

The French penchant for something different was clearly shown in the armoured cruiser *Dupuy de Lôme*, laid down in Brest dockyard in July 1888 and eventually completed in 1895. A single inverted-vertical and two horizontal triple-expansion engines were used to generate about 13,000ihp, boosting maximum speed to 19·7 knots. The intention was to use the centre shaft for economical low-speed cruising, the two wing shafts for high-speed cruising, and all three shafts to reach maximum speed.

The first French 'capital ship' to be fitted with triple-expansion engines, the turret battleship *Brennus*, was completed in Lorient dockyard in 1896 after work lasting seven years. Engines indicating about 13,900hp drove two shafts, maximum speed being 17·5–18 knots, but the most important technological advance was a pioneering installation of Belleville water-tube boilers.

The first Italian warship to incorporate triple-expansion machinery of indigenous make seems to have been *Montebello*, the first of four similar protected cruisers ordered in 1885. Laid down in La Spezia navy yard on 25th September 1885, *Montebello* was launched in March 1888 and completed on 21st January 1889. Three-shaft machinery indicating about 3180hp—possibly made by Ansaldo—gave a maximum speed of 18 knots. The first Italian 'capital ship' to be propelled in the same manner was *Sardegna*, the third unit of the Re Umberto class, which was begun in the La Spezia yard on 24th October 1885. Launched in September 1890 and completed on 16th February 1895, *Sardegna* had two enormous inverted-vertical engines generating 22,800hp. Trial speeds reached 20·3 knots.

For a navy not renowned for its readiness to embrace technological advances, the Russians were surprisingly willing to fit triple-expansion engines. The first recipient was the torpedo-gunboat *Leitenant Ilin*, laid-down in the Baltic Works shipyard in 1885 and completed early in 1887. Two-shaft inverted vertical machinery indicated about 3500hp and gave a trials speed of 20·8 knots.

Horizontal engines were ordered for the battleship *Imperator Nikolay II*, laid down in Galerniy Island yard in December 1885 but not completed until July 1891; the first large inverted-vertical powerplant seems to have been installed in the seventeen-knot armoured cruiser *Pamyat Azova*, a product of the Baltic Works (1886–90), which indicated about 8500hp.

The Japanese navy ordered the cruiser *Unebi* in France in the Spring of 1884. Laid-down in the Havre yard of Forges et Chantiers de la Mediterranée in May 1884, the warship was launched in April 1886 and completed six months later. The original twin two-cylinder compound engines had been superseded before construction began by triple-expansion machinery indicating about 6000hp, which was calculated to give a speed of about seventeen knots. *Unebi*, believed to have been seriously unstable, was lost without trace in a typhoon in October 1887.

The first Japanese warship to embody inverted-vertical engines seems to have been *Chiyoda*, a protected cruiser built on Clydeside by J. & G. Thompson. Completed in December 1890, *Chiyoda* had two-shaft machinery developing about 5600ihp; this gave a maximum speed of nineteen knots. The first warship to mount Japanese-made triple-expansion machinery was the 630-ton gunboat *Oshima*, built in the private Onohama yard in Kobe and launched in September 1891. Apparently based on a French Normand prototype, the inverted-vertical engine, driving a single shaft, had a stroke of 15¾in and cylinder diameters measuring 11in (high pressure), 19_in (intermediate) and 31_in (low pressure); trials indicated a maximum of 1216hp and speeds up to sixteen knots.

Among the earliest warships with triple-expansion engines to be supplied to the Spanish navy was the torpedo boat *Destructor*, launched from the Clydeside yard of J. & G. Thompson on 29th July 1886. Inverted-vertical engines driving two shafts gave 3784ihp, and a speed of 23 knots that was particularly notable for its day. At much the same time, however, work commenced on the cruisers *Isla de Luzon* and *Reina Regente*, respectively launched from the Armstrong yard in Elswick and the Clydeside yard of J. & G. Thompson in November 1886 and June 1887. Both vessels—each the first of a class of three—were driven by two-shaft horizontal triple-expansion engines, though power levels differed greatly: *Isla de Luzon* indicated 2627hp, giving 15·7 knots with forced draught, whereas *Reina Regente* obtained 11,500ihp and 20·4 knots.

The first US warships to be designed with triple-expansion engines were the armoured cruisers *Texas* and *Maine*, the cruiser *Baltimore* and the 'dynamite gun cruiser' *Vesuvius*, all authorised by an Act of Congress of 3rd August 1886—though building was slow and neither of the armoured cruisers commissioned until 1895. First to be completed was *Baltimore*, which commissioned on 7th January 1890 with the horizontal engines that were commonly fitted to US warships authorised prior to 1890.

Vesuvius was the first major warship to be built in the USA with inverted-vertical engines, commissioning on 7th June 1890, though the torpedo-boat *Cushing*, a Herreshoff product described below, had been accepted for service on 22nd April 1890; *Cushing* was propelled by unique five-cylinder inverted-vertical quadruple-expansion engines.

Four-stage expansion, despite a pedigree stretching back to the pioneering work of John Elder in the early 1860s, was rarely used in the propulsion of warships. Though the attraction of improved economy at steady speeds was used to good effect in merchant ships prior to 1914, only a handful of engines were tested in naval service. Additional complexity and poor slow-speed economy to be expected in engines designed to develop high power soon proved to be severe handicaps.

A single-shaft quadruple-expansion engine was installed in 1885–6 in *Ouragan*, a seagoing torpedo boat built by Chantiers de la Loire of Nantes as a speculative venture. The vessel was purchased by the French navy on 9th September 1886, and four copies were ordered on 19th December 1888. However, though the novel engine claimed to deliver sufficient power to attain 25 knots, trials were disastrous; only sixteen knots were possible at 1400ihp, and best achieved during the three-year developmental period was 19·21 knots! The engines are believed to have been Normand 'twin tandem' patterns, with the high-pressure cylinder above the low-pressure cylinder and the two intermediate units above each other. However, though compact, two-crank engines of this type proved difficult to balance unless the proportions of the cylinders were judged accurately.

An alternative approach was taken in the USA by the Herreshoff family. Brothers James Brown Herreshoff (1834–1930) and John Brown Herreshoff (1841–1915) are best known for a coil type water-tube boiler, patented in 1874. This was successful enough to allow steam pressure to be raised considerably, encouraging a third brother, the boatbuilder Nathaniel, to develop the steam yacht *Stiletto*, built in 1883 by the Herreshoff Mfg Co. Fitted with a two-cylinder 450ihp compound engine and a water-tube boiler, the yacht gained a reputation as a 'racer' by outrunning the Hudson River Line packet-boat *Mary Powell*—'the Fastest Steamer in America'—in June 1885 and later maintaining 23 knots for eight hours.

Stiletto was purchased by the US Navy in 1887 as 'Torpedo Boat No. 2', serving until 1911, and heightened interest in speed. The Herreshoff family had, meanwhile, developed an 875hp five-cylinder quadruple-expansion engine with a 15-inch stroke and cylinder diameters of 11¼, 16 and 22½ inches. Steam began in the smallest or high-pressure cylinder, then exhausted consecutively into the 16in 'first intermediate' and 22½in 'second intermediate' cylinders before being split equally between two 22½in low-pressure units.

Construction of this type presaged the multi-cylinder triple-expansion engines that were accepted universally for use in torpedo-boats and destroyers prior to the advent of the turbine. Adding a cylinder increased the length of individual engines, but this was of little consequence in ships that were already abnormally long in relation to their beam. In addition, problems accommodating two-shaft installations and large-diameter low-pressure cylinders were overcome without resorting to staggered engines or propeller shafts of unequal length.

Only five of these Herreshoff engines were built: one for each of the yachts *Ballymena*, *Say When* and *Vamoose*, and two for the torpedo boat *Cushing*. The warship was authorised in August 1886, laid-down in April 1888 and commissioned on 22nd April 1890. The yachts could attain 19½–23 knots, though the torpedo boat was measurably faster. But, unfortunately, what the independently-minded Herreshoff family saw as meddling by U.S. Navy in the design of fast small craft soon brought co-operation to an end.

Typical of the largest inverted vertical triple expansion engines were fitted in the fast battleship *Duncan* (13,305 tons displacement), supplied by the Thames Iron Works, Shipbuilding & Engineering Company in 1900. Each engine had four cylinders—33 × 48in (high pressure), 54 × 48in (intermediate) and 63 × 48in (low pressure)—with the high and intermediate pressure cylinders in the centre flanked by a low pressure unit at each end. Steam was admitted to the central pistons by piston valves, and thence to the low pressure pistons by slide valves. The valves were operated by crankshaft eccentrics through Stephenson link motion and valve rods. Belleville water tube boilers raised steam at 300lb/sq.in, economisers heated the feed water, and surface condensers converted the exhaust steam to water.

On acceptance trials in 1903, *Duncan*'s engines indicated 18,000hp at 120 rpm, speed being maintained at eighteen knots. Daily coal consumption was about fifty tons at seven knots, a hundred tons at ten knots and 420 tons at eighteen knots. Coal capacity was normally only nine hundred tons, though 2182 tons could be carried in emergencies.

Among the greatest advantages of triple expansion marine engines was economy. A typical powerplant was installed in the Turret steamer *Nonsuch* (3826grt) launched from the Sunderland yard of William Doxford

& Sons Ltd in 1906 for Bowles Brothers & Company of London. Power was provided by a three cylinder inverted vertical triple expansion engine with cylinder diameters of 24in, 41in and 68in, and a 45 inch stroke. It was rated at 1700ihp and consumed about 2 cwt of coal per mile (1·3lb/ihp/mile) at ten knots. The fixed bunkers held 360 tons of coal, which promised a range of 3600 miles, but when the bridge hold and the reserve bunkers were filled, maximum capacity rose to 1370 tons. Consequently, at least theoretically, *Nonsuch* could have sailed from London to Wellington in New Zealand without refuelling.

3: STATIONARY ENGINES

Triple-expansion engines were also widely used on land, especially to operate water and sewage pumping systems. Others, though less common, were installed in textile mills; still more were associated with the electric power supply industry, and some drove rolling mills.

Built for the Arrow Mill in Castleton, Rochdale in 1907, by J. & W. McNaught of Rochdale, Reliance was a typical cotton spinning mill engine. The three cylinders had a stroke of 48in and diameters of 25in (high pressure), 38in (intermediate) and 60in (low), Corliss valves being fitted on the first two stages and a piston valve on the last. Driving a 22ft forty rope drum, the engine could indicate as much as 1700hp at 75 rpm. Boiler pressure was 180lb/in .

Quadruple-expansion engines were the final flowering of multi-cylinder reciprocating piston steam machinery. Though patented in the 1860s, the first examples were not installed until the 1880s when they enjoyed a brief heyday as replacements for old two crank compounds. Superimposed layout—one high- and one intermediate-pressure cylinder above the second intermediate and the low-pressure units—could be accommodated without using additional floor space.

A typical superimposed-type engine was fitted by the Central Marine Engineering Company in the steamer *Suez* in 1887. Developing 986ihp at 56 rpm, with a boiler pressure of 160lb/sq.in, it had cylinders measuring 22 × 45 inches (high pressure) and 30 × 45 inches (first intermediate) above 43 × 45 inches (second intermediate) and 60 × 45 inches (low pressure) units. By 1900, multiple-expansion engines had grown to colossal size. There were four- or five-cylinder triples, and even some six-cylinder quadruples. Each of the enormous four crank six-cylinder quadruple expansion engines made in 1899–1900 by the Vulcan shipyard in Stettin for the Hamburg

America Line steamship *Deutschland* developed a staggering 36,940ihp at 77 rpm. The high- and intermediate-pressure cylinders were constructed in tandem, then placed between the two low-pressure units. The goal of these quirky arrangemenhts was generally to reduce the diameter of the low-pressure cylinders to manageable proportions by dividing the steam flow between two of them.

A four cylinder in-line engine built by the North Eastern Marine Engineering Company for *Springwell* in 1914 had the 25½ × 54-inch high-pressure cylinder at one end of the block. This exhausted into the first intermediate cylinder (36 × 54 inches) at the opposite end of the block, after which the steam returned to the second intermediate and low-pressure cylinders (measuring 52½ × 54 and 76 × 54 inches respectively) before exhausting into the condenser. The engine indicated 4400hp at 80 rpm, boiler pressure being 220lb/sq.in.

QUADRANT ENGINES

The Guion Line installed 'L'-type machinery in *Wyoming* and *Wisconsin*, built by Palmers in 1870. These had 60-inch diameter high-pressure cylinders placed vertically and 120-inch low pressure cylinders lying horizontally, the goal being to save space in the engine room. *Montana* and *Dakota* of 1875, built by the same Tyneside shipyard, had three cylinder engines in which a vertical 60-inch high pressure and two horizontally-opposed 113-inch low-pressure cylinders drove a single crank. The Palmer engines were all fitted with Corliss valves, but were notably unsuccessful.

Smaller 'L'-form engines were made by Tangye of Birmingham, sometimes compounded but equally often with two identical simple-expansion cylinders. A few nineteenth-century McNaughted compounds (q.v.) also took 'L' form on sites where access or space was restricted.

The immense 'Manhattan Engine', which acquired its sobriquet from its North American origins, was briefly popular in electricity-generating plants before being eclipsed by the turbine. Engines of this type were used to drive the London County Council tramway system, four sets (two engines apiece driving a central flywheel armature) being installed in a power station in Greenwich. Made by John Musgrave & Sons Ltd of Bolton, they had vertical high-pressure cylinders measuring 33½ × 48 inches and horizontal cylinders of 66×48 inches. Running at 94 rpm on a boiler pressure of 180lb/sq.in, they were gave a three phase 6·6kV supply at 25 cycles per second. Normal output was 3·5kW per set.

Operational from May 1906 onward, these engines were large and heavy. Dimensions highlighted by Charles Parsons, whose offer of turbo alternators had been rejected by the London County Council, suggested that they were 47ft 6in high (from the bottom of the flywheel pit) and about 48ft long. Rival turbine equipment measured merely 14ft 6in and 11ft respectively. Parsons was ultimately to have the satisfaction of replacing the cumbersome reciprocating machines by 1922.

Manhattan engines were also built for the British textile industry, notably by George Saxon. A typical example installed *c.* 1906 in the Leigh mill of the Hall Lane Spinning Company had a vertical high-pressure cylinder measuring 27 × 54 inches and a horizontal low-pressure unit of 54 × 54 inces, driving a 22ft 6in forty-rope drum through a common crank. The cylinders had Sulzer-type drop and Corliss semi-rotary valves respectively. Trials indicated that the huge engines could generate as much as 1400hp at 75 rpm.

CHAPTER FIVE

the search for speed, from the high-speed piston engine to the first turbines

The beam engine was not a candidate for high-speed operation, so the changes were applied to the horizontal pattern. The advent of detaching gear and improved valves brought about a great change in the stationary steam engine of the late nineteenth century; improved governing enabled the machines to run more smoothly; efficiency was better; and advances in metallurgy made manufacture easier. However, though the steam engine design had taken great steps forward, running speeds remained comparatively low.

There were undoubtedly many applications where fast-running engines had advantages, but the needs were filled at first by gears or belts. The rapid rise of the electricity supply industry in the 1880s was a great spur to development, as poor transmission of power through gears or belts was reflected in irritating flickering of the arc lamps.

One obvious solution was to couple a fast-running engine directly to a dynamo, but few established manufacturers offered engines running at even 100 rpm prior to 1880. The 1879-vintage survey mentioned previously reflected this bias; of the 68 engines surveyed, only four were rated above this particular benchmark, and the average was a mere 61 rpm. The fastest-running of the group had been an 80hp horizontal engine made by Edward P. Alliss & Company of Milwaukee (125 rpm) and a 34ehp Woolf type horizontal compound by Dinglersche Maschinenfabrik of Zweibrücken (116 rpm).

The first to break with tradition and seek high speed was the American Charles Porter, who had turned from a career in law to become an engineer. In 1858, Porter patented his well-known governor, which had a large central weight on a sliding vertical sleeve or collar. This reduced the tendency of the simple Watt-type flyball governor to overreact to changes in engine speed as loads fluctuated.

The Porter governor was taken by John Allen, who designed a distinctive horizontal engine. This had a shorter stroke in relation to cylinder diameter than normal practice, a much smaller flywheel, and lightweight reciprocating parts. The balanced steam admission and exhaust valves were duplicated, and driven by a valve rod connected with a slotted link on the crankshaft eccentric. Cut off was controlled by the governor, which automatically moved the valve-rod boss in the link slot according to engine speed.

A non-condensing Allen-Porter high-speed engine tested by the American Institute of Mechanics in 1859 returned consumptions of 25·8lb water and 2·87lb coal per ihp/hr. It had a single 16×30-inch cylinder, worked at a pressure of 75lb/sq.in, and was found to indicate 125hp at 125 rpm. This was more than twice as fast as most other horizontal engines of the mid-nineteenth century.

An Allen-made engine was exhibited at the International Exhibition held in London in 1862, where it attracted great attention. The promoters of conventional engines ridiculed its design, claiming that it would soon shake itself to pieces, but were eventually proved to be wrong. After watching a demonstration of an Allen-Porter engine in Paris in 1867, which ran at 200 rpm, John Hick of Hick, Hargreaves & Company said that ‘no amount of testimony would have made me believe that a steam engine could be made to run at such speed, with such absolute smoothness’.

Whether or not British engineers admitted it, the Allen-Porter engine had a profound effect on British practice and many engine-makers produced comparable designs throughout the remainder of the steam period.

Increased speeds forced changes to be made in construction to suppress vibration. A major change was made to the engine bed and frame, which became significantly more rigid. A cylindrical ‘trunk’ crosshead guide replaced grooved or slotted bars, and was soon developed into a massive extension of the cylinder block. The simple Watt flyball governor was usually replaced by improved patterns, most notably the Porter and (in Britain at least) the 1862-patent Pickering type.

Alternative systems of governing included the Hartnell (1876), the Buss (1870), the Hartung (1893) and the Jahn governor of 1912. Some of these are regularly encountered on surviving machinery, the Hartnell pattern being surprisingly common on British made portable and semi-portable engines.

Successful attempts were also made to perfect the shaft governor, which was basically two spring-loaded pivoted blocks or arms attached to the crankshaft. When the engine overran its normal speed, the arms moved outward to shift an eccentric and reduce steam supply; when speed fell, springs moved the arms in towards the crankshaft and allowed the valve gear to admit more steam to the cylinder by lengthening the cut off. Most governors of this type were much more compact than flyballs. The limitations of the traditional horizontal engine were soon reached. One problem lay in the difficulty of balancing single-cylinder machines at high rates of rotation, owing to the large reciprocating masses involved, and another was to obtain satisfactory lubrication of the bearings.

BROTHERHOOD ENGINES

Experience gained at sea, particularly, had shown that balancing was easier if more than two cylinders could be used. These engines started better than single cylinder types—they were never at dead centre—and ran more smoothly. But they were still slow-moving and ungainly. The advent of the compact inverted-vertical compound and then the triple-expansion engine, which was patented in the 1860s, gave a clue to the future of high-speed machinery.

Amongst the first truly successful high-speed engines was the design of Peter Brotherhood, who patented his three cylinder pattern in 1871 (British no. 648/71). The cylinders of Brotherhood's engine were fitted radially at 120 degrees to each other, driving a common overhung and counterbalanced crankshaft. A rotary valve controlled admission and exhaust.

The mechanism was totally enclosed, which facilitated splash lubrication. It was single acting, and the use of trunk pistons with ball-tipped connecting rods made for compactness. Consequently, the Brotherhood engine was small for its power: output ranged from 1 hp at 1000 rpm for an engine with three 2½ × 2-inch cylinders to 55bhp at 500 rpm for one with three 7 × 6-inch cylinders.

Despite the fast running speeds, the units ran very smoothly. This was partly due to the symmetrical layout and partly to the use of single action, which avoided the reversal of stress at the end of each piston stroke that occurred in double-acting designs. The Brotherhood engine soon found a niche as a torpedo powerplant, running on compressed air instead of steam, and as a hydraulic motor.

The successful introduction of the Brotherhood high-speed engine inspired a legion of competing designs. Most were based on the tried and tested multi-cylinder compound marine engine, though horizontal engines were popular in North America.

THE WILLANS ENGINES

One of the most remarkable steam engines to be marketed in Britain in the 1880s was the work of Peter Willans, who produced his first engine in 1873 and his first British patent (no. 974/74) in 1874, whilst working for the Thames Iron Works. Improved by a patent granted in 1880, the engine was a three-crank single acting pattern, distribution to each line of cylinders being controlled by the valves in the adjacent line. A six-way cock allowed motion to the reversed when necessary.

In 1876, Willans and his backers licensed production of the engines to Tangye Brothers & Holman and Hunter & English, for land and marine use respectively. However, Tangye modified the design so greatly that the engines were completely unsuccessful; Willans regarded them as very badly made. Even the earliest Hunter & English engines had trouble with lubrication and their bearings.

Production in the Willans & Robinson factory in Thames Ditton did not begin until 1880; classified by the diameter of the low-pressure cylinder and the length of the stroke, the engines soon became popular with boat builders, as they were powerful, reliable and very compact. A patent granted to Peter Willans & Mark Robinson in 1882 protected an air buffer to prevent knocking at low loads, when the pressure in the steam chest was too low to maintain a constant thrust on the moving parts.

Engine no. 371 was supplied in March 1884 to generate electricity in Buckingham Palace; three others followed at later dates. These were Triple Tandem Specials, embodying both the air buffer and three lines of two superimposed cylinders.

The first patent for the Central Valve ('CV') Engine, granted in 1884, was swiftly followed in 1885 by an improved design. All three cylinders received and exhausted steam through a vertical multi-segment piston valve. The valve housing doubled as the rod for all three pistons. The valves of the 1885 pattern were driven by an eccentric mounted between the two short rods that connected the dummy or 'guide piston' to the crankshaft (the 1884 design drove off the crank web). Most engines had a radial governor attached to the crankshaft at the opposite end from the flywheel.

One of the first CV engines was delivered to the Admiralty in 1885 to drive an alternator aboard HMS *Black Prince*. It was followed by fifteen 5 × 3-inch CV engines to power searchlights, and a niche was soon found commercially to drive generating sets. One of the great advantages of the CV engine was its smooth running, which was largely due to constant thrust on the bearings achieved by an exhaust chamber above the guide piston. The engine operated with equal pressures on both sides of the piston during the up stroke.

By 1887, Central Valve Engines were being offered in a range of sizes from a low-pressure cylinder diameter of 5 inches to 20 inches. They could be built as simple expansion or compound, with single, double or triple cranks. Sizes 'E' to 'I' could also be supplied in triple-expansion guise. With an appreciation of standardisation that was unusual at the time, the diameter of the high-pressure cylinder was the same as the low-pressure cylinder of the next smaller engine but one. This allowed many minor components to interchange, including pistons, piston rings, valves and connecting rods.

An epicyclic reversing gear was patented for marine engines in 1888, and an open-frame variant of the CV engine followed in 1889 to meet an Admiralty specification. This had external piston valves, allowing the steam to work on the top of the high-pressure piston and the underside of the low-pressure unit. Though Willans was able to patent his engine, the existence of an earlier design by W.H. Scott was acknowledged.

A new three-crank tandem compound marine engine appeared in 1891, shortly before Willans' unexpectedly sudden death. Steam was admitted above the high- and low-pressure pistons, and the piston valves outside the cylinder block were driven by a layshaft, itself driven from the crankshaft by spur gearing. The valves were mounted in a separate cradle, which could be moved vertically to adjust the cut off point and even reverse the direction of rotation.

Experience suggested that the maximum size for a Central Valve Engine was about 800ihp, which meant that the largest sizes planned were never built. Their bearings were to have been lubricated by the splash method and would probably have overheated at low speeds.

A test of a three-crank triple expansion engine—with cylinder diameters of 5·4, 10·5 and 13·7 inches, and a 10·3-inch stroke—gave a coal consumption of 1·19lb/ihp/hr and a water evaporation of 11·1lb per pound of coal. The engine had indicated 394·8hp at a fraction under 300 rpm, boiler pressure of 180lb/sq.in reducing to 169·5lb/sq.in on entering the high pressure cylinder and 28·9lb/sq.in in the low pressure cylinder.

Many Willans engines survived hard work for more than fifty years. Two Hunter & English-made marine engines, for example, were still working in the Port of London Authority steam crane *Leviathan* in the 1950s. They had no serious rivals until the widespread introduction of forced lubrication in the 1890s, as the three-cylinder Brotherhood high-speed engine was not suited to large sizes.

OTHER HIGH SPEED ENGINES

One of the most successful of the more conventional inverted-vertical high speed engines was that of George Bellis, based on Belliss & Morcom's successful marine engineering business. The first engine—developing 25hp at 625 rpm—was built in 1890 to drive the machinery in the Bellis & Morcom factory in Birmingham, but soon demonstrated its commercial potential. Based on the proven two-cylinder compound marine engine, its success was assured when Belliss & Morcom's chief draughtsman, Albert Pain, developed a way of forcing lubrication into the bearings under pressure.

The typical two-cylinder Belliss & Morcom engine of the 1890s relied on piston valves driven by an eccentric on the crankshaft by way of a single rod. The forced lubrication system, which operated at pressures of 10–25lb/sq.in, was driven by an oscillating pump.

Tests of a 300bhp Belliss & Morcom Self Lubricating Engine, built for the Waterloo & City Electric Railway Company, revealed that engines of this type could run surprisingly smoothly even under greatly fluctuating loads. Even though the loading was varied instantly from virtually nothing to full, the changes in engine speed never exceeded 2·48 per cent (momentarily) or 1·04 per cent (permanent set)—the latter representing about 7 rpm, as the average running speed had been 384 rpm. Figures returned from non-condensing operation were even better, being 1·82 per cent and a mere 0·65 per cent respectively.

A 200bhp engine—with 12_ and 20-inch diameter cylinders, a 9-inch stroke and a boiler pressure of 120lb/sq.in—gave 194ihp at 365 rpm, 186bhp with a mechanical efficiency of 96 per cent, and consumed water at the rate of 18·2lb/bhp/hr.

The North American high-speed engine could be either a vertical inverted type (typified by the Westinghouse patterns) or horizontal, a design that found very little favour in Britain in this period. Philip Armington and Winfield Sims patented a fast-running horizontal engine in 1888, but the design found greater notoriety as the basis from which the colossal Manhattan (q.v.) engines of the late 1890s grew. Originally intended for heavy-duty pumping use, these engines had one vertical and one horizontal cylinder apiece. The name came from a pioneering installation in an electric power station in New York.

ROTARY ENGINES

The genesis of the direct-acting rotating engine can be traced back to the original aeolipyle of the first century AD, which was the prototype of the reaction turbine.

The invention of the aeolipyle is widely credited to Hero (or Heron) of Alexandria, but there is no evidence to suggest that this is justifiable. It is more likely that Hero was simply recording the existence of a machine which had been made in Greece some time earlier.

The aeolipyle ('Door of Aeolus') was widely copied in antiquity, as an early mechanical toy, though potentially capable of doing useful—if insignificant—work. The principles were rediscovered during the Renaissance, when Giovanni Branca of Santa Casa di Loretto suggested using steam issuing from a nozzle to drive a vaned horizontal wheel. An illustration published in 1629 in *Le macchine…del Signor Giovanni Branca, Cittadino Romana, Ingegniero* shows how the steam could be used to drive two reciprocating pestles by primitive lantern-and-peg spur gearing.

There is no evidence to suggest that the Branca machine was ever made, excepting perhaps as a small-scale model or toy, but it was an early embodiment of the impulse turbine. Though perfection was delayed for more than 250 years, the attraction of rotary engines has never faded. Though problems of sealing leaks and excessive friction were almost impossible to ovecome in the earliest days, many inventors saw that the advantages of a ‘steam wheel’ included extreme simplicity and the ease with which smooth rotary motion could be provided—especially attractive in the era of ponderous reciprocating atmospheric engines, which, disregarding other problems, were extremely expensive to build and maintain.

The widespread use of waterwheels had a profound influence on thinking. They were simple to design and build, but susceptible to vagaries in water supply. Some atmospheric engines, and a few improved Savery-type machines, were even used to return spent water from the mill race to the mill pond. The turbine was also influenced by water-powered designs, in particular by ‘’Barker’s Mill‘‘. This was a simple reaction turbine designed in 1743 by Dr Robert Barker.

Rotary engines were mechanically-driven systems, often embodying blade pistons or flap valves. However, many of the gimcrack schemes were never made; few were mechanically efficient enough to challenge even the Newcomen atmospheric pattern in power and size. One of the earliest ideas was published in the proceedings of the Académie Royale des Sciences in 1699 by the Frenchman Amontons, whose giant Fire Wheel may even have been built as an experiment (though it would undoubtedly have failed to meet expectations). The Amontons Engine was claimed to work by expansion of air but, if it worked at all, it would have done so at least partly by the effects of steam. The illustration shows how greatly its design was influenced by waterwheels.

The cause of the rotary engine was undoubtedly weakened for some time by the comparative success of first the Newcomen atmospheric and then the Watt steam engines. Yet even Watt had developed a Circular Steam Engine in 1766, but was unable to perfect it beyond a working model. A drawing prepared some time prior to February 1769 showed that the circular engine consisted of a hollow box-section annulus containing three pivoting flap valves and sufficient mercury to act as a barrier for steam to press. Thus the power stroke was performed by the entry of steam into the space between a flap valve and the mercury, rotating the wheel until the exhaust point was reached.

Watt introduced his second rotary engine in 1782, but with no greater success than had attended his first experiment. From the development of Cooke’s Rotatory Engine in 1787 to Peel’s of 1823, more than twenty different designs were patented. None enjoyed success, though several undoubtedly made the great leap from a drawing to a model.

Amongst the most worthy were those of Sadler (patented in 1791), which was a form of reaction turbine derived from the aeolipyle; William Murdock (1798), who used two counter-rotating vaned wheels within a steam-tight case; Jonathan Hornblower (1798 and 1805), who relied on oscillating vanes; and Masterman's of 1821, which was another of the many cartwheel patterns.

EARLY TURBINES

After the first development of steam-powered reaction turbines in antiquity and the Branca impulse pattern, neither of which was successful in themselves, progress was confined to water-pressure machines. Most acceptable designs began with Barker's Mill, patented in 1742, but this was little more than an improved version of Hero's aeolipyle of the first century AD.

Kempelen's steam turbine of 1784 was the first since Branca's to be promoted with any vigour, though it failed to make much impression. The device consisted of a spherical boiler set in a brick hearth, which was surmounted by a horizontal tube with holes at the tips through which steam could issue.

This was simply Hero's reaction turbine in a different form; the principal improvements lay in horizontal rotation, which allowed a crown wheel to be placed on the centre-line above the steam pipe to rotate a drive shaft through bevel gearing. Thus the Kempelen turbine was capable of doing useful work in a way its predecessors could not. However, its rotational speed was too low to generate much power and far too much fuel was burnt to be acceptable. James Watt had good grounds to be dismissive of its potential when asked by Boulton to express an opinion.

In 1849, James Nasmyth introduced a 'steam wheel' to drive a circular saw. The turbine wheel—integral with the saw shaft—was a hollow disc with a detachable side plate. Steam was admitted through a stop valve, to pass through the hollow horizontal pipe and into the turbine disc by way of a cone joint. A large coil spring applied sufficient force to keep the joint steam-tight. Steam issued from apertures in the disc, imparting rotary motion to the saw, and passed into the steam chamber surrounding the turbine disc. Exhausted steam departed from the top of the casing, usually bound for a condenser, and the water vapour that had already condensed left by a drain in the base.

Though the turbine saw had comparatively little power, it revolved at speeds as high as 2000 rpm on a steam pressure of about 60lb/sq.in and had enough momentum to cut surprisingly efficiently. Nasmyth also introduced a steam powered turbo-fan, which rotated at much the same speed as the saw.

Kempelen had also claimed a method of using steam supplied from two vessels in turn to propel water into a turbine. There is no evidence that this machine was ever made, but James Watt did patent a comparable system in England in 1784. It consisted of a two-chamber container, roughly conical, into which steam could be admitted alternately. Admission of steam expelled the fluid in the chamber through vertical side vents, whilst the second chamber filled with fluid—water, oil or even mercury—through a flap valve in its base. The alternate entry and expulsion of fluid caused the container to rotate about its vertical axis, drive being taken from the container-stem extension protruding through the enveloping case. Power would once again have been low.

Richard Trevithick's steam wheel was little more than another version of the aeolipyle, but at least had the merits of considerable size and a self contained boiler.

John Ericsson patented a machine in the 1830s which was one of the first to embody fixed vanes to allow the steam to gain additional purchase. Steam could enter from the admission pipe or through the outside of the turbine wheel before escaping by the central axis. (Is this right?) Nozzles were formed in the periphery or body of the rotating chamber.

Working in the 1830s, Alexander Morton patented a turbine in the form of concentric wheels. The final pattern had three wheels with diverging nozzles on their circumference, between the rows of fixed blades or vanes without which the machine would not work at all. Charles Parsons patented a comparable multi-stage reaction turbine in 1890, but it was much less efficient than his better known patterns and was never exploited commercially. Parsons also patented a combination of the Hero and de Laval turbines in which steam entering axially accelerated outwards through the first ring of diverging nozzles to strike another row of plain curved blades. The two units counter rotated with approximately even torque, and could be geared together to drive a common axle. Alternatively, they could be used to drive separate sets of machinery.

The double unit counter-rotating turbine was patented in England in 1843 by Pilbrow. He also included a claim in his specifications for a series of wheels placed in series. A patent granted in 1848 to Robert Wilson of Greenock—later a partner in Nasmyth, Wilson & Company of Manchester—depicted a turbine in which steam was expanded in server stages successively.

This could be achieved, claimed Wilson, by taking the steam alternately back and forward around a single row of blades; by leading steam radially through rows of blades (either alternately fixed and mobile or counter rotating); or even by leading steam longitudinally through alternated fixed and rotatable vanes. The luckless Wilson had described the principal elements of the successful radial- and axial-flow turbines, but was ahead of his time; the manufacturing technology of the mid nineteenth century was not really capable of providing efficient seals at the high pressures necessary to allow Wilson to put his ideas into practice.

THE PARSONS TURBINE

The perfection of the steam turbine was due to Charles Parsons, who was responsible for the greatest single advance in motive power since Watt's separate-condenser patent more than a hundred years earlier.

An important catalyst was the rise of electricity: the basis of the electric motor had been laid in the 1820s, the first arc lamp had appeared in 1848, and Swan & Edison had produced the incandescent lamp in 1879. The need for steady, fast running engines to drive generators efficiently became of paramount importance.

The first attempts to provide satisfactory sources of high-speed power produced multi-cylinder reciprocating engines. Typical of these was the Brotherhood pattern, patented *c.* 1871, which had three cylinders driving onto a single crank. However, very few steam engines of this type, which were generally characterised by a very short piston stroke, could run at much greater than 500 rpm—a rate at which piston speeds usually became excessive. The engines were also prone to vibration unless carefully balanced, owing to the reversal of motion at the end of each piston stroke.

Parsons' earliest development was a four cylinder high-speed rotary engine with epicycloidal gearing, which resulted in the cylinder block revolving at half the speed of the crank. A prototype was built in 1883 by

Kitson & Company of Leeds, proving to run quite smoothly at 900 rpm when coupled directly to a generator. The pistons were opposed in pairs and had solid one piece connecting rods.

Suspecting that even 900 rpm was too slow to be entirely successful, Parsons turned from reciprocating engines to the turbine. By 1884, enough had been done to justify applying for a patent as it had been realised that single-stage turbines ran much too fast to be harnessed within the technological limitations of the day.

An answer was found by reducing the accelerating effects of pressure-drop across a series of individual stages. This was influenced by water turbine designs. Increasing the annular area of the 'working face' of the turbine or, alternatively, adjusting the pitch of the blades was sufficient to handle increases in volume as the steam traversed each stage. This is generally known as a 'pressure compounded' turbine.

The intention had been to protect turbines in which the steam flowed outwards from the centre (radial flow) or along the turbine rotor (axial flow), but only the latter was included in the master patent.

Steam ran through alternate rings of fixed and rotating blades, the former being fixed to the external casing (the stator) whilst the latter formed part of the rotor. Though habitually described as reaction turbines, Parsons' machines usually combined impulse (when the steam hit the rotating blades) with an element of reaction as the steam traversed the rings of fixed blades. Balancing the axial thrust in the earliest turbine, which ran at a fantastic 18,000 rpm, was eased by admitting steam centrally to exhaust at each end and by providing flexible bearings to adapt to any irregularity in the running of the rotor shaft. A screw pump provided forced lubrication. The pump was primed by a fan, which sucked air into the casing whilst doubling as an extremely sensitive governor.

Parsons also patented the use of his turbine as a compressor, and the linking of a turbine with a compressor to provide one of the earliest workable gas turbines. In February 1885, a steam turbine was installed in the steamship *Earl Percy*—the first of many marine installations, though the advantages were not initially apparent as the machinery ran too fast.

The inventor became a junior partner in Clarke, Chapman & Company of Newcastle upon Tyne in *c.* 1885, but co-operation soon led to disagreement. However, when the partnership was dissolved, Clarke, Chapman & Company retained the most important of the Parsons patents for the remainder of their life. Of the many original claims, only the gas turbine, the multi-stage axial compressor, cooling armatures with oil, and a detachable commutator were returned to their originator. Charles Parsons would have cause to be thankful that he had not included his radial-flow turbine in the the protection sought in 1884.

Parsons pressure-compounded axial flow turbines proved to be efficient electricity producers once generators had been developed to withstand the high rates of rotation. The earliest turbo generators were non-condensing, but condensing versions were available from *c.* 1890. Outputs of 350kW were achieved by the mid 1890s, and 1000kW by 1900. The Parsons turbine was a tremendous success from the very start of production, as the teething troubles were comparatively minor in relation to the immense technological leap the project represented. The turbine had several enormous advantages over reciprocating engines, including the absence of vibration and a progressive reduction in temperature which avoided the problems caused in conventional cylinders by alternate heating and cooling. Once satisfactory seals had been designed, maintenance of turbines was greatly eased even though very high temperatures and pressures had to be sustained.

Another major advantage of turbines was their compact dimensions. Their disadvantages were complexity of blading and the care with which they had to be made. This raised prime cost considerably above reciprocating engines of similar power and, until the great potential of the turbine was widely appreciated, discouraged many potential purchasers.

Great advances were made in generating equipment in the first decade of the twentieth century. Parsons built his first alternating-current generating set in 1903, installed in Newcastle upon Tyne, in which the magnetic field was created by the rotor and power derived from the stator.

Gradually, the turbine made inroads into the market for giant reciprocating-engined generating machinery. But even Parsons' persuasive arguments initially failed to persuade the more conservative agencies to abandon conventional sources of power for the electricity supply industry. Consequently, four massive Manhattan or 'L'-type compounds were installed in 1905–6 in Greenwich power station. These 3500kW units proved to be unsatisfactory; much to Parsons' delight, perhaps, they were replaced by turbines once the First World War had ended.

THE FIRST MARINE APPLICATIONS

The formation in January 1894 of the Parsons Marine Steam Turbine Co. Ltd was specifically undertaken to produce a ship. The result was *Turbinia*, famed for her dash down the lines during the Spithead Diamond Jubilee navy review of 1897 at a speed far in excess of what was expected from 'Thirty Knotter' torpedo boat destroyers.

Success had not come easily. The earliest turbine installation, a single-shaft unit developing the equivalent of 1500ihp, propelled *Turbinia* at only about eighteen knots. Dynamometer trials indicated that the turbine was capable of generating power effectually enough, but showed output to be limited by the single shaft and an inefficient propeller. *Turbinia* was then given a three-shaft system with the high-pressure engine to starboard, intermediate to port and low pressure in the centre. A separate reversing turbine was fitted on the low-pressure shaft, the propelling machinery and associated coal fired boilers contributing half the displacement tonnage of 44. Trials returned 34·5 knots on 2300shp, performance being restricted by the firing rate, as the boiler room was extremely cramped.

Experiments undertaken by the Royal Navy in 1896–7 led to three '33 Knotter' torpedo-boat destroyers fitted with conventional reciprocating engines, but none reached the contract speed even after lengthy experimentation with the machinery and propeller profiles. The warships vibrated excessively and soon proved to be very unreliable.

On 4th March 1898, therefore, the Admiralty ordered the torpedo-boat destroyer *Viper* (344 tons displacement) from the Parsons Marine Steam Turbine Co. Ltd, though the hull was actually built by Hawthorn, Leslie & Co. Ltd. The vessel was completed only a few weeks before the French navy ordered an experimental Rateau turbine to be fitted in the torpedo boat *Libelulle*, being built by Forges et Chantiers de la Méditerranée—but this vessel was not completed until early in 1904 and only attained fifteen knots at sea.

The outer pair of *Viper*'s four shafts, each fitted with two propellers, was coupled directly to the high-pressure turbines, the inner shafts serving the low pressure and reversing units. Trials undertaken without armament returned an impressive 36·83 knots, making *Viper* the fastest ship in the world by a considerable margin. Speed could be maintained without the excessive vibration that had characterised the reciprocating engines of the '33 Knotters'.

Unfortunately, *Viper* was lost on 3rd August 1900 on Renonquet rocks off Alderney in the Channel Islands. When *Cobra* foundered off Flamborough Head on 18th September 1900, with great loss of life, the Royal Navy had lost its only two turbine-powered ships in rapid succession.

Fortunately for Parsons, sufficient data had been amassed to confirm the virtues of turbine propulsion in high-speed warships. The first turbine driven passenger ship was *King Edward* (000grt), launched on behalf of the Parsons Marine Steam Turbine Co. Ltd from the Dumbarton shipyard of William Denny & Brothers in May 1901. The centre turbine of the three-shaft installation, with a single propeller, was driven by the high-pressure unit whilst low-pressure and reversing units were coupled to wing shafts with two propellers apiece.

Unlike the warships, *King Edward* had conventional double-end boilers operating at 150lb/sq.in. A maximum of 20·57 knots was achieved on the Skelmorlie Mile after a series of experiments with differing propeller profiles.

The destroyer *Velox*—a speculative venture by Hawthorn, Leslie—was purchased in 1902 to replace *Viper.* Two propellers were fitted to each of four shafts and the problem of uneconomic performance at slow speed, which dogged all early direct-drive turbine installations, was answered by coupling additional triple-expansion engines to the inner (low pressure) shafts to facilitate cruising and reversing. However, this pioneering multi-engine installation encountered success only when geared turbines were substituted *c.* 1909.

After experimenting in 1904 with near-identical Hawthorn, Leslie destroyers, *Derwent* (triple-expansion engines) and *Eden* (three-shaft Parsons turbines), the turbine was established as vibration-free and considerably more economical than reciprocating engines at high speed.

Attention turned to larger vessels in general, and to the 3300-ton Third Class Cruisers of the 'Gem' class in particular. Comparative trials were undertaken at the end of 1904 between three of these warships before they had been armed. *Amethyst* (Armstrong, Whitworth & Co. Ltd) had turbines supplied by Parsons; her sisters *Topaze* and *Sapphire,* built by Laird & Co. Ltd and Palmer's Ship Building & Iron Co. Ltd respectively, had conventional reciprocating engines.

The contract speed of 21·75 knots at 9000ihp, with forced draught, was easily exceeded; *Topaze* recorded 22·1 knots on 9868ihp; *Sapphire* attained 22·34 knots on 10,200ihp; and *Amethyst* returned 23·63 knots on

14,002shp.

Experience showed that, with a standard load of 750 tons of coal, *Topaze* could travel 7300 nautical miles at ten knots compared with only 5570 for her turbine rival; at fourteen knots the figures were very similar—about 5100 and 4950 miles respectively. At twenty knots, however, the turbine-driven *Amethyst* could travel 3160 nautical miles compared with only 0,000 for her conventionally engined rivals.

The success of Amethyst persuaded the Admiralty to specify turbines for the new 'big gun' battleship *Dreadnought*. Though the two-shaft installation was restricted to 24,700shp and a speed of 21 knots, the new ship was an instantaneous success and rendered every other battleship obsolescent. The new propulsion system not only increased speed, but also saved sufficient weight to allow more guns to be carried.

The first ocean-going passenger ship to be driven by turbines was the Allan Line *Virginian* (10,757grt), built by Alex. Stephen & Sons of Glasgow. Parsons turbines delivering 12,000shp, driving three shafts, were designed to achieve seventeen knots. On trials, however, sister ship *Victorian* recorded a mean of 19·8 knots.

Though the turbine had showed great potential, shipowners were a cautious breed. Anxious not to proceed too quickly into the unknown, the Cunard Steam Ship Company ordered *Caronia* (19,687grt) and *Carmania* (19,524grt) from John Brown & Company of Clydebank, identical in all respects but their engines. Both were completed in 1905.

Caronia had two four-cylinder quadruple expansion engines rated at 21,000ihp, designed to give a service speed of eighteen knots (though 19·5 were achieved on the Skelmorlie Mile). *Carmania* had three shafts, with a high-pressure Parsons turbine in the centre and the low-pressure and reverse turbines coupled to the wing shafts.

Trials showed that the turbine-engined ship was capable of more than twenty knots, though this was subsequently attributed more to the modified 'run' (contours) of the stern than the engines. The consensus was that the quadruple-expansion engines were cheaper and simpler to maintain, but turbines ran more smoothly.

Despite the success of the Cunard ships, some major owners were still not convinced of the merits of turbines. In 1908, therefore, the White Star Line ordered *Olympic*, in which poor slow-speed economy and inability to reverse was countered by fitting additional reciprocating engines. The favoured method, tested in the destroyer *Velox* in 1906, was to exhaust high-pressure steam from reciprocating engines into low-pressure turbines. This arrangement was used in both *Olympic* and *Titanic*, conventional engines driving the outer shafts and the turbines driving the inner pair.

Exasperated by the doubts of influential shipowners, Charles Parsons purchased the old steamship *Vespasian* in 1909. The ship was overhauled and thoroughly tested; the triple-expansion engine was then replaced by a standard turbine geared down 20:1, the original boilers and propeller being retained to validate comparison. The reduction in fuel consumption was found to be about twenty per cent. Thereafter, geared turbines were fitted to most high-speed warships and cross-channel steamers.

PARSONS' RIVALS

An early competitior for Charles Parsons was Carl de Laval, a Swede of French ancestry, whose early experimentation with centrifugal milk separators persuaded him to develop a turbine. After unsuccessfully experimenting with an aeolipyle-type reaction machine, de Laval turned to the single stage impulse type.

Expanding steam in one stage provided de Laval with great problems. However, after striving to produce a satisfactory steam nozzle for what was inevitably a fast running machine, small-scale series production began in Sweden in 1893.

The typical de Laval turbine comprised a single disc of blades, rotated by admission of steam through a series of tangential nozzles. Machines of this pattern were amongst the simplest in their class—lacking the multiple blading of the Parsons turbines—but were usually restricted to low power installations. Owing to this important limitation, de Laval turbines gradually lost favour.

MARINE TURBINES

The French navy was the first in Europe to experiment with turbine power, fitting an experimental Rateau turbine in the torpedo boat *Libellule*, ordered from Forges et Chantiers de la Méditeranée in March 1898 but not completed until 1904. Unfortunately, maximum speed proved to be only fifteen knots. Greater success was encountered with the torpedo boat *293* (94 tonnes), ordered from the Normand yard in October 1902, which reached 27·3 knots with three-shaft Parsons turbines in 1904; and the similar *294* (100 tonnes), ordered in March 1903, which recorded 25·14 knots with two shaft Bréguet-Laval turbines in 1905. However, the French navy had endured many years of neglect and the failure of the indigenous Laval-pattern engine to develop enough power was a great disappointment to its constructors.

The first turbine-engined German warship to enter service had been the torpedo-boat destroyer *S125* (447 tonnes) completed in the Elbing yard of Friedr. Schichau in 1904 and driven by two Parsons turbines. Trials returned 27·8 knots on 6600ihp. Comparisons with near sisters of the 'S120' class, all of which had reciprocating engines, revealed the customary greater economy at high speed and an absence of vibration.

The first vessel to have German-designed engines was *Adler* (562grt) of the Hamburg–Amerika Linie, launched in October 1904. The 1200shp Zoelly turbine driving a single screw gave a speed of 15·5–16 knots.

The first German cruiser to be fitted with turbines was *Lübeck* (3265 tonnes) of the Bremen class, laid down in the AG 'Vulcan' yard in Stettin in 1903 and completed in April 1905—only a few weeks after HMS *Amethyst* had become the world's first large turbine-driven warship. The German vessel was driven by Parsons engines purchased from Britain. Trials returned a maximum of 23·1 knots on 14,035shp.

Though four of *Lübeck's* reciprocating-engined sister ships achieved 23·3 knots on trial, on 11,582–12,205ihp, the turbine installation predictably ran more smoothly at high speed. *Lübeck* initially had four propellers on each shaft, but these were subsequently replaced by two apiece.

The demand for turbines, created in part by the naval race, rapidly outstripped the ability of the Parsons Marine Turbine Co. Ltd to supply them. The rise of competitors became inevitable once the master patents had expired, and it was no secret that the principal navies would seek supplies of their own.

Light cruisers were often built in classes of four or more identical ships, and so provided ideal test-beds for differing turbines. In 1905, for example, the U.S. Navy authorities authorised the scout cruisers *Chester* and *Salem* (3750 tons), fitted with four-shaft Parsons and two-shaft Curtis turbines respectively. These ships were commissioned in 1908, but the troublesome engines in *Salem* were replaced in 1918 by General Electric geared turbines.

The story in Germany was similar. Authorised in 1906–7, the 'Kolberg' class (4362 tonnes) all had turbine drive. Schichau-built *Kolberg* had Melms Pfenninger engines; *Mainz*, by AG 'Vulcan', had American Curtis-type turbines made under licence by Allgemeine Elektrizitäts Gesellschaft (AEG); *Cöln*, from Krupp'sche Germaniawerft, had proprietary Parsons-type turbines; and *Augsburg*, built in Kiel navy yard, apparently had genuine Parsons turbines supplied from Britain. The ships all had four shafts, excepting two-screw *Mainz*. Trial speeds ranged from 26·3 to 26·8 knots on 22,040–31,033shp, but, though these outputs varied greatly, speeds were surprisingly similar.

The four cruisers of the 1908–9 programme, laid down in 1910, were completed in 1912. *Magdeburg* (AG 'Vulcan') and *Stralsund* (AG 'Weser') had Bergmann turbines driving three shafts; *Breslau*, by AG 'Vulcan', had twin paired AEG-Vulcan turbines driving four shafts; and *Strassburg*, built by Wilhelmshaven dockyard, had two turbines designed by the navy engineering department. Trial speeds ranged from 27·5 knots on 33,482shp (*Breslau*) to 28·2 knots on 35,515shp (*Stralsund*).

Ironically, the navy-designed turbines proved to be so successful that every post-1912 cruiser and many other German warships were driven by them.

CHAPTER SIX

the hot-air engine, from the Stirling cycle to the Robinson designs

The nineteenth century witnessed the development and ultimate decline of the hot-air engine, which may yet prove to be a significant source of power. The hot-air engine was a brave, but only partly successful attempt to provide a source of power that was as efficient as a conventional steam engine but much safer to use. Without regular maintenance, steam-engine boilers corroded to a point where they became dangerous, and from the earliest days of Richard Trevithick, Oliver Evans and 'high' pressures, boiler explosions had regularly occurred. The problems became so bad that the first Boilers Explosion Act was passed in Britain to regulate safety. However, the act, its successors and the introduction of compulsory boiler insurance (which entailed regular inspections) were only partially successful; they undoubtedly reduced the incidence of explosions, but death and damage still resulted from carelessness.

In common with the reciprocating steam engine and the internal-combustion engine, hot-air engines work by expanding a heated working fluid to drive a piston-in-cylinder mechanism. This working fluid was almost always air prior to 1900, though some modern engines have used helium or hydrogen.

The proposal in 1824 of an ideal theoretical cycle of operation for any heat engine, by the Frenchman Sadi Carnot, was approached nearer by Stirling type hot-air engines than any steam engine. Unfortunately, Robert and James Stirling were many years ahead of their time and the exploitation of their ideas was handicapped by the technological limitations of the early nineteenth century. Yet the hot air engines were admirably suited to meet domestic and light industrial needs in their heyday. They were cleaner and safer than the steam engine, requiring neither costly steam-raising equipment nor skilled operating staff, and could run on anything from camel dung to Welsh steam coal.

The first momentary flight with a man aboard was allegedly achieved by the Frenchman Félix du Temple at Brest in 1874, in a craft said to have been powered by a hot-air engine. Improvements to specific features—increasing the mean operating pressure, or improving regenerator efficiency—were made in many designs. But no single type of engine incorporated them all to perfection.

The hot-air engine could be used for purposes which ranged from the mundane, such as supplying domestic water, to the bizarre. For example, Jean Schoenner of Paris built silent-running horizontal motors in the early 1890s, to drive gramophones or rotating shop-window displays. The displacer cylinder was mounted directly under the working cylinder, with appropriate cooling fins. The flywheel ran horizontally between adjustable ball bearings and a geared drive powered a spring belt connected to the tilting final turntable drive.

Other applications were found in toys. Ernst Planck of Germany, working in the 1890s, made a simple hot-air engine with a central displacer and side-mounted working piston—which typified many international designs, culminating in the 'Ky Ko'. The Planck engine was designed to drive miniature workshop machine tools as an alternative to the steam and gas engines produced by many other Nürnberg toymakers in the late nineteenth and early twentieth centuries.

By 1900, the hot-air engines that had found so many uses for domestic and light industrial purposes were being ousted by the gas engine, the oil engine and, particularly, the electric motor—all of which offered greater power output for a given size. Almost a century of development had failed to reveal more than a trifling part of the potential of the hot-air engine, development that had been hindered at virtually every turn by metallurgical restrictions and poor understanding of the underlying principles. The hot-air engine had failed to capitalise on early promise, owing largely to poor efficiency and unfavourable power-to-weight ratio. It was to lay dormant on the scrap-heap of invention until resurrected by Philips in the late 1930s to power radio transmitters for use in remote districts.

The premature demise of the hot-air engine concealed that in it lay potentially greater thermal efficiency and specific power than either the steam engine or the internal-combustion engine.

OPERATING PRINCIPLES

Not only were the hot-air engine designers of the early nineteenth century handicapped by a lack of understanding of the principles on which their machines operated, but even the scientists of the day were perplexed. Long after James Joule had established the relationship between work and heat in 1843, many experimenters still believed in the 'caloric theory' which saw heat as an indestructible fluid. John Ericsson, for example, failing to understand the conversion of heat into work, strove for nearly fifty years to create a perfect (but unattainable) regenerator which would capture virtually all the heat put into an engine, returning it to work for virtually nothing.

Consequently, the achievement of Robert Stirling was all the more remarkable in the absence of a sound theoretical basis for his work. As early as 1816, Stirling had grasped the essential design principles to patent a closed-cycle engine incorporating a power piston, a displacer, a regenerator and a compact cylinder arrangement.

OPEN-CYCLE ENGINES

These are generally classified under two groups. *Directly-heated engines*, pioneered by Sir George Cayley in 1807, required a fresh charge of air to be supplied for each cycle. The air was heated directly in a furnace before passing into the cylinder. The *indirectly-heated engines*, promoted by John Ericsson from 1840 onward, relied on the admission of a fresh charge of air for each cycle—but heated it indirectly (i.e., by external combustion) before reaching the cylinder.

CLOSED-CYCLE ENGINES

These use a single charge of air, which is permanently contained within them. They are invariably heated externally, though some of the most modern patterns may be heated internally. The earliest engines of this type were the work of Robert Stirling, beginning in 1815. The 'Stirling Cycle' remains the basis for virtually all closed-cycle hot-air engine designs, even though metallurgical problems hindered the successful application of Stirling's own engines.

Many designers of closed-cycle engines lacked Stirling's innate understanding, promoting unsatisfactory designs which often lacked vital components such as a regenerator. However, as the innate superiority of the Stirling cycle was not appreciated for many years, primitive open-cycle engines were able to compete successfully throughout the entire hot-air engine era.

THE FIRST STEPS

The earliest claim that air could replace the steam used in an atmospheric engine was made in an English patent granted in 1759 to Henry Wood. The specification stated that the engine was to work by 'hot or rarefied air, produced by the air passing through fire, or through red hot pipes, or through boiling water…' Nowhere, however, did Wood state in detail how his machine was to be built, and the idea of a 'caloric engine' remained dormant for forty years.

James Glazebrook patented another open-cycle hot air engines in 1797, incorporating the essence of a regenerator to pre-heat the air charge with waste products from the furnace, but there is no evidence that this was ever exploited. George Cayley was the first man to put theory into practice. His earliest design, patented in 1807 and described in detail in *Nicholson's Philosophical Journal*, consisted of two cylinders in tandem, connecting with a furnace. Air was circulated around the grate to enter above the larger upper or motor piston, power being generated on the downstroke by expansion of the heated air. Simultaneously, the piston in the smaller cylinder drew a fresh charge of air in through a flap valve in the cylinder floor and into the furnace

The Cayley engine had one failing common to all directly-heated designs—the circulation of hot air was accompanied by corrosive cinders, which tended to scour the interior of the cylinder. Little was done with the engine for almost thirty years, as the inventor became obsessed with aeronautics. In 1837, however, he patented an improved form of his 'Furnace Gas Engine' and a few hundred were made in the early 1840s by the Caloric Engine Company.

THE STIRLING ENGINES

Robert Stirling, born in Methven in Scotland in 1790 and educated at the University of St Andrews, is renowned not only as the originator of the closed- cycle hot-air engine but also as the founder of a dynasty of highly successful engineers. After completing a classical education and being ordained as a priest of the Church of Scotland, Stirling was presented to the second charge in Kilmarnock in 1815. There he stayed until taking charge of the Ayrshire parish of Galston in 1824.

Always interested in mechanical devices, Robert Stirling seems to have produced his first closed-cycle engine shortly after moving to Kilmarnock. An English patent was sought in 1816 (no. 4081), but the specifications were never published. It has been suggested that the Enrolling Fee was never paid, and widespread knowledge of this patent was lost until Stirling's original handwritten version reappeared in 1917. Yet its existence had been mentioned in many of the obituaries published after Stirling's death in 1878, and the gist of the Scottish patent—which was also never formalised—had appeared in 1886.

Stirling saw his engine as suitable for breweries, distilleries, dye works and other manufactories 'by transferring heat from one portion of liquid, air or vapour to another'. One of the most important features was the inclusion of regenerator, which he called a 'Displacer', to consume as much heat as possible. The original patent drawings show a single inverted vertical cylinder supported on four columns to drive a crankshaft through a primitive parallel motion, rocking beams and connecting rods. The cylinder contained a motor piston and a large displacer, which were driven ninety degrees out of phase with each other with the displacer leading. The displacer was hollow, had ring or roller bearings to reduce friction, was sheathed in brass, and contained transverse baffle plates to reduce the rate of heat transfer within the body.

A regenerator was created by wrapping wire around the surface of the displacer and an air-bleed valve in the cylinder wall controlled output. The flue from the furnace was carried upward to shroud the entire upper surface of the cylinder, providing the 'hot' end; air temperature was deemed to provide sufficient cooling.

Helped by the inertia of the heavy flywheel, the displacer alternately transferred air from the hot end of the cylinder—where it expanded to drive the motor piston downward—to the cold end, where it contracted to allow the motor piston to rise again. One machine of this pattern was made to pump water in an Ayrshire colliery: undoubtedly the earliest industrial application of a hot-air engine. Rated at merely two horsepower, it was installed in 1818 but lasted only until the single 24×120in cylinder cracked beyond repair in 1820.

Stirling was disappointed with the first engine but, working in collusion with his younger brother James (to whom rather more of the credit customarily given may be due), had soon embarked on a programme of improvements. At about the time that Sadi Carnot was proposing his operating cycle, James Stirling discovered that increasing pressure significantly improved the performance of the hot-air engine. This led to double-acting engines with several cylinders, and a selection of regenerators. Major patents were granted in 1827 and 1840.

At least one Watt type double-acting engine must have been converted to Stirling multi-cylinder operation in the 1820s, but details are lost. This 'Twin Engine', with a double-acting power piston and separate displacer cylinders, was widely copied. However, separating the power piston and the displacer was not only wasteful of space but also reduced the compression ratio. This in turn restricted power.

The solitary double-acting motor piston of the Twin Engine was driven by the expansion of air in the two separate displacer cylinders, acting alternately on the two sides of the piston. The displacer pistons (generally filled with brick dust insulation) transferred air from the lower, hot or furnace end of the cylinders through a regenerator consisting of thin annular baffles to the upper end, which contained tubes through which cold water could circulate.

The 1840-patent system was essentially similar, but the regenerator and refrigerator were contained in a small supplementary casing alongside the displacer cylinder. Air was supplied by a pump at 150lb/sq.in—a frighteningly high pressure for the mid-nineteenth century.

A double-action beam engine in Dundee Foundry was converted to the twin-displacer Stirling system in 1842, and began operating the following year. The power piston measured 16×48in, and an indicated horsepower of 37–45 (depending on source) was obtained at about 30 rpm. This was appreciably greater power than the engine had generated in its steam days, and was achieved with a coal consumption of only about 2.5lb/ihp/hr. Operating pressures peaked at about 240lb/sq.in.

Enthusiasm sooned waned, as the engine regularly burned-out piston seals. After the third major failure in 1846, it was converted to steam. No other large-scale Stirling engines seem to have been made, and the inventor turned his enthusiasm towards scientific instruments. The failure of his hot-air engines, which were far ahead of their time, could be blamed entirely on metallurgical shortcomings. The true explanation of the regenerator action was not given by William Rankine until 1854, when he patented an engine with extended heat-transfer surfaces in collusion with James Napier.

STIRLING CLOSED-CYCLE ENGINES

These inorporated a cylinder with power and displacer pistons, a flywheel with cranks and connecting rods, and a source of heat. The displacer was open at the ends and filled with wire gauze to serve as a regenerator. The cylinder was a closed system charged with air, or a specific gas such as hydrogen, as the working fluid.

When the bottom of the cylinder was heated to working temperature, and the top end was cooled, the engine rotated automatically once started by hand. Thereafter, the displacer moved through the cylinder, pushing air alternately from end to end. When the air was at the hot end, its temperature rose and it expanded to propel the power piston to the top of the cylinder. When the air was at the cold end, its temperature fell and the power piston returned, compressing the air once again.

The work required from the flywheel to compress the air at low temperature was less than that produced by expansion at high temperature, the surplus representing useful output. The wire gauze filling of the displacer acted as a regenerator, reducing unnecessary loss of heat at the cold end of the cylinder. The regenenerator absorbed heat from the hot air when it was being displaced through it to the cold end for cooling, and gave it back to the cold air as it was being returned to the hot end for heating. Unfortunately, temperatures and pressures were too low, resulting in low efficiency and low power output.

Maximum temperatures were limited by the failure of the iron-cylinder 'hot end' and sealing methods were too poor to allow mean operating pressures much above atmospheric levels; advantage could not be taken of the closed cylinder engine's potential for high pressure operation. High temperatures could be achieved in directly heated open-cycle engines, but lubrication was difficult. In addition, grit and unburned carbon carried over from the furnace scored valves and passages, causing friction and wear on the moving parts.

THE ERICSSON ENGINES

John Ericsson, born in Sweden in 1803, was one of the most prolific inventors in the history of mechanical engineering. In many respects—not least being tremendous physical strength and a robust self belief—Ericsson was like Richard Trevithick. The major difference was whereas Trevithick's wanderings in South America proved to be his downfall, Ericsson's journey from Sweden to England and then the New World was his great success. Like his English counterpart, the Swede was a versatile inventor: fire engines, forced-draught boilers, locomotives, warships, screw propellers, hot-air engines and torpedoes were just some of them.

Ericsson was the son of an ironworker. He first found employment on a canal-building project, created by Thomas Telford, before entering the Royal Swedish navy. Realising that there was little chance of making a name for himself in Scandinavia, John Ericsson left for England in 1826 to promote his first 'flame engine'. This was an open-cycle machine relying partly on the expansion of air drawn over the fire grate into the power cylinder and partly on steam generated in a boiler.

The air fulfilled the important secondary purpose of improving combustion in the fire grate before passing through a regenerator and into an air cylinder containing a motor piston. An alternative design mixed the steam and the combustion products before admitting them to each end of the power cylinder alternately. However, these ideas were not sufficiently practicable to attract critical attention. Ericsson (unaware of the original 1816 patent) amused himself by opposing the patent application made by Robert Stirling in 1827 while simultaneously developing new ideas of his own.

Minor reverses scarcely worried the anglicised Swede. His 1833 patent engine was most ambitious. Intended to propel ships, it was to have had two expansion cylinders fed from a furnace apiece, and one compression cylinder supplied from a water-jacketed bath. The regenerator consisted of a series of small-diameter tubes in a large cylindrical casing. A simpler machine of this general pattern was tested by the *Mechanic's Magazine* in November 1833.

Air in the circuit of tubes was heated in the furnace and led into the double-acting power cylinder, which measured about 14×18in, thrusting the 'hot' piston forward to turn the central common crank by means of piston and connecting rods. Operating pressure was about 35lb/sq.in. As the hot piston moved forward, the piston in the 10½×18in compression cylinder moved outward, forcing the previous charge out of the cylinder, into the regenerator and ultimately back into the furnace. As the pistons reversed their motion, accepting new hot and cold charges, the previous hot charge was led back through the regenerator to the cold bath. The result was a continuous cycle of air: from furnace to hot cylinder to regenerator (giving up heat) to cooler to cold cylinder to regenerator (to gain heat) and then back to the furnace again.

Running at 56 rpm, the Ericsson engine indicated 8.36hp. With a mechanical efficiency of about seventy per cent, this gave an effective power of about five horsepower. Thermal efficiency of almost nine per cent was substantially greater than even the best mid-nineteenth century steam engine.

Ericsson made a particular claim for the regenerator in his English Patent of 1833, which allowed ‘a greater quantity of power [to be obtained] from a given quantity of fuel than has heretofore been accomplished’. The engine incorporated the ‘Brayton Cycle’ (q.v.) more than forty years before Brayton made use of it. An improved version was patented in Sweden in 1860, but there is no evidence that machines of this type were ever made in quantity.

The 1853 patent hot-air engine was unquestionably the most ambitious and impressive machine of its type to have been built—but also the most public failure. The basic action came to be known as the ‘Ericsson Cycle’, comprising two constant-pressure (isobaric) and two constant-temperature (isothermal) components. Beginning at the upper dead-point of the motor piston, air was admitted to the supply cylinder through a non-return valve. Reversing the motion then forced air back through the outlet valve into a pressurised air reservoir, then through the upper port on the slide valve and into the regenerator to gain heat before entering the furnace. There it expanded to drive the motor piston upward.

The supply piston rose simultaneously to force another charge into the air reservoir. As the pistons descended, air was forced out of the power cylinder, back through the regenerator to lose heat, out through the lower port in the slide valve, and (if necessary) around the transfer pipe to re-enter the supply pipe through the admission valve. This was potentially a continuous or closed cycle, but, in practice, most engines drew fresh charges of air in with each stroke.

Several large experimental engines were tested on land—including a 60hp engine shown in the Great Exhibition held in London 1851—but Ericsson had far more grandiose ideas. The result was SS *Ericsson*, the 'Caloric Ship'. This 2200-ton ship-rigged two master measured 235ft on the waterline and was driven by paddle wheels amidships. She cost more than $500,000 to build, $130,000 being spent on the engines alone, and Ericsson is said to have gambled a large part of his considerable fortune on success. Power was supplied from an enormous open-cycle engine, with four 168in diameter power cylinders and four 137in supply cylinders. The power cylinders were the largest ever installed in an engine of any type. The paddle shaft was driven by a train of rocking levers and connecting rods, and the regenerators were made of wire-mesh screens containing many millions of individual cells.

Though nominally of six hundred horsepower, the actual power developed by the huge engine is still debated and estimates have ranged from 115ihp upward. It is clear that the vessel failed to develop the anticipated speed by a wide margin, however, and that power was substantially below what had been desired. Modern calculations have suggested about 430ihp, which, assuming mechanical efficiency was about seventy per cent, would amount to 300bhp. Thermal efficiency was an encouraging thirteen per cent.

The Caloric Ship left Sandy Hook in February 1853 for a three-day voyage to the mouth of the Potomac River. Accompanying journalists were encouraged to ride on the huge motor pistons—each weighing fifty tons with their piston rods—as they moved up and down in the open-top cylinders. The US Navy observer was favourably impressed by the smoothness of the engines, but reported that maximum speed did not seem to be greater than eight knots at 9 rpm; the trip had been made in a gale and Ericsson had limited the maximum operating pressure to only 8lb/sq.in. above atmospheric levels.

The major problems arose from excessive heat, with temperatures as high as 450°F being recorded in the power cylinders. This caused considerable oxidation; lubrication was a worry, and the piston seals failed continually under the strain. Seeking greater power and speed, John Ericsson subsequently raised the cylinder pressure to about 15lb/sq.in. by fitting forced-draught blowers and—in May 1854—the Caloric Ship reached an eminently acceptable speed of eleven knots. On the return journey, however, the ship was heeled in a squall, shipped water through the lee engine-room ports (which had been left open for ventilation), and sank in shallow water. Though the wreck had soon been raised, damage was too great to justify reconstruction and *Ericsson* was fitted with a conventional steam engine.

The Caloric Ship was an heroic failure. Coal consumption trials undertaken with the Collins Line steamships *Pacific* and *Baltic*, which gave a daily average of 58 tons, showed the six tons burned by Ericsson's system to great advantage. However, the failure of the marine hot-air engine all but coincided with the development of an effective two-cylinder compound steam engine. The latter soon caught the attention of the ship owners, as it was more economical than low pressure simple-expansion patterns and, crucially, occupied far less space aboard ship.

The failure of *Ericsson* affected the inventor deeply, and the hot-air engine patented in the USA in 1858 (no. 22,281) was by comparison a feeble thing. Intended for small scale industrial and domestic use, it was a single cylinder open-cycle machine. The motor piston and the displacer were driven by a complex linkage coupled to the crankshaft, operating a quarter-turn out of phase with each other. The crankshaft, placed laterally above the front of the cylinder, connected with a flywheel which provided sufficient momentum to overcome the parts of the operating cycle where no power was being developed.

The motor piston was cooled partly by its position at the front of the cylinder while the trunk-type displacer shrouded the furnace and partly by the intake of cold air through valves in its surface. The cycle began when, approaching the end of their strokes, the motor piston and displacer moved close together. As they could still each move forward, the annular non-return valve in the displacer head still allowed hot air to act on the motor piston. At the end of the displacer stroke, the annular valve shut, the exhaust valve opened, and the inward movement of the displacer—moving more rapidly than the motor piston—created enough vacuum between them to suck cold air in through the non-return valves in the motor-piston face.

Continued inward movement of the displacer then expelled the exhaust products of the previous stroke; the motor piston had also begun to move back, but, as progress was slower than the displacer, cold air was still being drawn into the chamber created between the pistons.

Shortly before the displacer reached the limit of its inward travel, the exhaust valve closed. A simultaneous rise of pressure in the cold air chamber also shut the non-return valves in the face of the motor piston. Expansion of the air at the furnace end of the cylinder then raised sufficient pressure, by moving outward, to open the annular valve between the displacer and the air chamber. This equalised the pressure on both sides of the displacer, but heating all the air in the cylinder then thrust the motor piston outward to generate power.

The 1858 patent Ericsson engine was brilliantly conceived, essentially simple, and easy to maintain. However, though compact, it was very noisy and a thermal efficiency of only 2½ per cent was little better than a Watt-type beam engine. A typical machine had an 18in-diameter cylinder; running at 35 rpm, it indicated 1.36hp. Poor mechanical efficiency reduced this to only 0.7hp at the brake. Coke consumption was surprisingly high, about 9lb/ihp/hr, though advertising literature often camouflaged this by claiming that the Ericsson machines used only a third as much fuel as a small steam engine.

These open-cycle externally heated engines were made in the New York iron foundry of Cornelius DeLamater. Between 1858 and 1860, about three thousand Ericsson engines—the first hot-air type to be made in quantity—had been sold by the Massachusetts Caloric Engine Company. Installed worldwide for domestic and light industrial purposes, they proved particularly popular in printing shops and newspaper offices; the use of steam engines in such public places often required licences or special insurance.

Ericsson engines started easily, requiring only 20–30 minutes of pre-heating, and the hot exhaust could be used for heating or drying. They were also used to power foghorns, one being shown at the 1867 Paris exhibition in conjunction with the Daboll horn favoured by the Cunard Steamship Company and the coastguard services in Britain and the USA. Until superseded by Bénier engines, Ericssons and their foghorns had been installed in many lighthouses—e.g., Dungeness, St Catherine's Point off the Isle of Wight, or Ailsa Craig in the Clyde estuary.

Later Ericsson designs abandoned the directly heated open-cycle system in favour of the closed Stirling type. The prototype seems to have been the Sun Motor of 1872, which relied on a large solar reflector to focus sun rays onto the hot end of the cylinder. In 1873, Ericsson told DeLamater he had abandoned open-cycle engines because of continual valve-sealing problems.

Next came a modification of the Sun Motor developed specifically to pump water. This was patented in the USA in October 1880 (no.

226,052), rights being assigned to Cornelius DeLamater and George Robinson. Most engines made after Ericsson's death in 1889 incorporated an improved cylinder and transfer piston patented by Thomas Rider in 1889–90. The motor piston was altered to reduce friction and to make the leather packing easier to replace. The cylinder was extended to give a longer power stroke, and the design of the pump was improved. Engines could be fuelled with gas, wood or sometimes even oil.

The basic engine was a single-cylinder piston and displacer design with an integral pump, the water raised being used for cooling before being expelled from the water jacket into the storage tank. One end of the beam driven by the piston rod was attached to the pump rod, and the other linked with the connecting rod. The displacer was driven—suitably out of phase with the motor piston—by a bell crank connected to the main crank by a short link.

Sales were pleasingly brisk. About five thousand engines had been sold by 1885; twelve thousand by 1890; and 20,000–22,000 when the Rider Ericsson Engine Company was formed in 1902. An 1890 DeLamater Iron Works catalogue offered five Ericsson closed cycle engines. The smallest, with a 5-inch diameter cylinder, occupied a floor are of only 2ft 2in×1ft 2in and stood just four feet high to the top of the flywheel. It weighed about 250lb, and could raise 150 gallons of water to a head of fifty feet on 15 cubic feet of gas. The largest version had a 12in cylinder. Its footprint was 4ft 6in × 2ft 3in, height was about 6ft 6in, and weight in working order totalled 1450lb. Hourly water raising performance (on 8lb anthracite) was about 1500 gallons to the customary 50ft head.

Comparative hourly fuel consumptions of the 6½-inch Denney Improved Ericsson, made by the American Machine Company of Newark, Delaware, were listed as 2½lb coal, 15 cubic feet of gas or a quart of kerosene. For a Rider engine with an 8in diameter cylinder, the appropriate figures were 6lb coal, 58 cubic feet of gas or five quarts of kerosene.

An Ericsson engine tested in 1896 by the Massachusetts Institute in Boston, with an 8-inch diameter power cylinder and an effective stroke of 3.9in, returned 0.20–0.27ihp (94–110 rpm). However, owing to the poor mechanical efficiency of only 27–30 per cent, this was equated to a miserable 0.07bhp.

THE LAUBERAU ENGINE

Frédéric Joseph Lauberau was granted a patent in the USA as early as 1849, though his perfected closed-cycle hot air engine dates from the beginning of the 1860s. The trunk-type motor piston drove the centrally mounted flywheel and crankshaft assembly by way of connecting rods and a rocking lever.

The motor piston was constructed in a such a way that air could be transferred alternately to the hot and cold ends by a small vertical displacer piston driven from the crankshaft. The furnace and the water jacket projected deeply into the motor piston to maximise their effect. The system lacked a regenerator, but the use of a cam to actuate the displacer gave a pause at the end of each displacer stroke, allowing distinct phases of isothermal expansion and compression—and a closer approach to the theoretical Carnot cycle.

A typical 2nhp Lauberau machine was about 7ft 8in high and 8ft long, with a 19.7in diameter motor piston and an effective stroke of about 15.9in. Running at 37 rpm, a machine tested in 1863 returned a thermal efficiency of just 1.8 per cent, the low effective horsepower figure of 0.8 being due partly to excessive friction and partly to heat losses in the needlessly complicated air passages. Fuel consumption proved to be about eleven pounds of coke per ehp/hr. The best-known manufacturer of Lauberau engines was L. Schwartzkopff of Berlin, but there must once been others in France.

THE LEHMANN ENGINE

Introduced in Europe in 1865, but not patented in the USA until June 1869 (no. 91,239), this was a straightforward Stirling-cycle machine with the motor piston and displacer in the same horizontal cylinder, operating about one sixth of a turn out of phase with each other. Supported on a roller, the displacer moved the sealed charge of air from the inward end of the cylinder, set into the furnace, to the water-jacketed outer cold end. The flywheel and crankshaft were driven by rocking levers, reminiscent of the Ericsson open-cycle engine but not as complicated.

The Lehmann engine was less compact than the Lauberau pattern, a typical example being 11ft 2in long and about 5ft 6in to the top of the flywheel. The cylinder had a diameter of 13.2in (25cm) and a stroke of 6.9in (17.5cm), the relevant dimensions for the displacer being 13.5in (34.3cm) and 9.6in (24.4cm). Running at 100 rpm, the indicated horsepower was about 1.5, or 1bhp with a mechanical efficiency of 65 per cent. Thermal efficiency was about four per cent—though twice as good as that of the Lauberau hot air engine, this was needlessly degraded by the absence of a satisfactory regenerator. However, the machines could be started in 15–20 minutes and ran quietly. Their coke consumption was usually reckoned as 10lb/bhp/hr.

A test reported by Fleeming Jenkin in 1884 on a Lehmann type engine with a 145/8×67/8in power cylinder returned 2.37ihp at 106 rpm, equating to 1.34bhp with a mechanical efficiency of just 51 per cent. The maximum operating pressure had been 14.7lb/sq.in above atmospheric level, the highest temperature recorded had been 823°F, and hourly consumption of coal averaged 9.8lb.

A Lehmann engine made by Maschinenfabrik Johannes Arndt of Dessau survives in the Deutsches Museum in Munich. Others were made under licence in Belgium by Jahn & Co. of Boitsfort (which were often marked ‘’Hoffmann’s System“) and in Britain by Sir W.H. Bailey & Co. Ltd of Manchester. The smallest Bailey engines—⅙hp, ⅛hp and ¼hp—were vertical, whereas the ½hp and larger patterns were horizontal.

Lehmann engines were comparatively inefficient, with a weight/power ratio of about five tons per horsepower, but the simplicity of construction allowed them to remain in production for fifty years. By 1877, improved examples with a cam-driven displacer were being marketed by Stenberg of Helsingfors under the name ‘Calorisca’.

THE ROPER ENGINE

Ericsson and DeLamater soon had a collection of rivals, and the open-cycle directly heated engine patented in 1862–6 by Sylvester Roper—another variation of Cayley’s—became particularly popular in the USA. It combined the furnace and the power cylinder in a single casing, with a small air pump mounted separately on the base plate. The pump rod, crankshaft and flywheel were all connected with a rocking beam. As the beam rocked, the air-pump piston rose to draw air into the cylinder through a flap valve in the base plate; as the piston was driven down again, air was forced out of another non-return valve into the furnace.

When the Roper engine was started, the dampers were set to divert all the air through the fire grate, but, once the fire became incandescent, the dampers could be readjusted to send all the air above the grate. Heat expanded the air, which was then admitted beneath the motor piston when the eccentric-driven poppet valve opened. The spent charge from the previous cycle had already been exhausted through the outlet valve into the chimney.

The *Scientific American* reported Roper's claim that his engine accomplished 'what others had attempted and failed…viz., forcing the air directly into the fire, and thereby combining the power of expansion with the power and products of combustion. This is accomplished…by the use of an air pump, close, air tight doors to the furnaces, and poppet valves'. Advertising brochures praised the 'Roper Caloric Engine' on the grounds that it used no water, could not explode, required neither expert attention nor expensive insurance, and ran as smoothly and silently as a steam engine.

The Roper Caloric Engine Company of New York advertised Caloric Engines in four sizes, ranging from a ½hp pattern with a 9 × 9in power cylinder and a weight of 1000lb to a 4hp engine with an 18×18in cylinder and a weight of 4000lb. Daily coal consumption was said to range from 30lb for the smallest machines to about 120lb for the largest, running speeds being 80–90 rpm. The machines were probably made by the assignee of the Roper patents, Elmer Townsend of Boston in Massachusetts.

Tests of a Roper engine undertaken in 1869 for the Great National Exhibition of the American Institute—the machine emerged with a gold medal—suggested that a 3nhp example with a 16×16in cylinder and a 13×17 in pump, running at 85 rpm, gave an effective horsepower of 2.57. The flywheel had a diameter of 60in. A 4hp machine gave 7.01ihp, but needed 1.85hp to operate the pump. However, though power-to-weight ratio was low and thermal efficiency was poor, Roper engines occupied comparatively little floor space and were popular in the New England states into the 1870s. Like other hot-air engines, they were especially favoured by printers: they were easy to start, ran steadily and required very little attention.

THE BUCKETT ENGINE

The basic principles of Cayley's open-cycle engine of 1837 were revived by Buckett in 1881. Promoted by the Caloric Engine & Siren Fog Signals Co. Ltd of London, the engines consisted of a furnace, an air pump and a cylinder in which the power was generated.

After the fire had been lit, air was supplied either by a hand pump or by turning the flywheel manually to create sufficient pressure for the machine to begin turning over automatically. With each stroke, the pump mounted above the crankshaft delivered a charge of air to the furnace. Air supply was split between the annular space outside the firebrick liner and delivery directly above the grate. Dividing the stream intensified the heat generated above the grate and increased operating pressure.

A flyball governor regulated the amount of air supplied above the fire, controlling the pressure and through it the running speed. In the largest machines, the governor also altered the position of the cut off. The valves were driven by crankshaft eccentrics and bell cranks; fuel was fed from the top by a chain and wheel mechanism; and an air jacket not only protected the valve seating from the worst effects of high temperatures but also acting as a pre-heater.

Buckett engines were customarily large, heavy, and somewhat primitive. Tests undertaken in Britain with a 12nhp engine, in 1883, recorded an indicated horsepower of 41.24, but also that more than 21ihp was expended driving the air pump. The effective horsepower was merely 14.39, consumption of gas coke being 2.5lb/bhp/hr. A smaller machine of the same general type, with a 24×16in power cylinder and a 18×16in pump, recorded 10ihp (7.1bhp) at 61 rpm, fuel consumption being much the same as its larger cousin. Thermal efficiency was generally about eight per cent.

THE BÉNIER ENGINE

This was another of the open-cycle 'furnace gas' engines, patented in France c. 1876 and made by Compagnie Française des Moteurs à Air Chaud of Paris. Its construction resembled a small single-pillar steam engine, with the power cylinder, beam, connecting rod, crank and flywheel placed conventionally. The major differences included a horizontal air pump in the bed plate, driven from the crank by a rocking lever. The slide valve was also driven from the crank.

The major claim to novelty lay in the introduction of a small part of the air charge around the lower section of the motor piston, the diameter being reduced to allow a narrow annular chamber between the piston and the cylinder wall. Bénier engines also had automatic stokers, relying on drive from the crankshaft to operate a rotating hopper and a sliding gate. This system was prone to jamming unless the fuel had been carefully graded, but was otherwise surprisingly reliable.

Tests undertaken in 1887 revealed that the Bénier engine with a 13.4×13.8in motor piston making 117 rpm indicated 5.85hp, mechanical efficiency of 69 per cent giving 4.03bhp. Coal consumption was 4.36lb/bhp/hr, better than most engines of its type owing to the air blast directed through up through the fire grate on each inward stroke of the air pump. Thermal efficiency in the 1887 trials was judged to be about four per cent—no better than most Lehmann machines—though the manufacturers of the Bénier engine claimed as much as six per cent in their advertising literature.

Compagnie Française des Moteurs à Air Chaud offered Bénier engines from four to twenty horsepower, hourly coal consumption ranging from 15lb to 50lb. A 6nhp machine exhibited in Paris in 1889 was 3.13m long, 1.39m high and 2.08m high. The engines became quite popular in France, and were adopted in Britain in 1886 by the Commissioners of Trinity House. They were used to operate fog warning signals on headlands. The Genty hot-air engine, briefly touted in France, was somewhat similar externally to the Bénier but had a vertical air-pump cylinder and a pre-heater for the air charge built in to its bed plate.

OTHER CLOSED-CYCLE DESIGNS

An 1845-vintage patent by Charles Franchot described a closed, or Stirling cycle engine with a power piston and a displacer working in the same cylinder. A modified 1853-patent version used two power pistons, one each in the hot and cold cylinders. There was no displacer.

William Newton patented a design for a multi cylinder closed-cycle engine in 1853, with alternate hot and cold cylinders, with individual cycles taking place partly beneath the piston in the hot cylinder and partly above the piston in the cold cylinder. A four (?) cylinder double acting closed-cycle engine of this general type was patented by Sir William Siemens in 1860.

Low power closed-cycle Heinrici motors became popular in the 1890s. Made without regenerators, a typical example produced 0.028hp with a weight/power ratio of 1.5 tons/bhp.

RIDER ENGINES

The closed cycle engine designed by the Philadelphian Alexander Rider originated in 1871, the first patent being assigned to Cornelius DeLamater and George Reynolds of the DeLamater Iron Works. Rights to the perfected version, patented in September 1875 and improved in 1879, were assigned to Rider, Wooster & Company of Walden in New York State.

The engine first gained real notice after the Centennial Exposition had been held in Philadelphia in 1876. Similar in principle to earlier designs by Charles Franchot (1853) and William Siemens (1860), the Rider engine had a vertical cylinder and a vertical displacer, which together supported the small- but-sturdy flywheel. The cylinders, which each contributed to the generation of power, were connected by a short transverse tube containing a regenerator composed of thin baffles.

Rider engines were made by the DeLamater Iron Works, apparently under contract to the Rider Engine Company, and a licence was granted to Hayward, Tyler & Co. Ltd of Manchester, England. Available in ¼hp, ½hp and 1hp sizes, the British-made Rider engine was very popular; about a thousand were made from 1877 until *c.* 1895, and one was even installed in Sandringham for the Prince of Wales.

Catalogues produced by DeLamater in 1890 advertised the 'Improved Rider Compression (Hot Air) Pumping Engine' with motor piston diameters ranging from 4in to 10in. The smallest type occupied a floor area of 1ft 6in×2ft 2in, was 3ft 9in high, weighed 490lb, and could run at 120–200 rpm; the largest occupied 2ft 8in×4ft 4in, stood 7ft 9in high, weighed 3600lb, and ran at 80–110 rpm. The two smallest machines ran only on gas, whereas the larger ones could burn coal or oil; hourly coal consumption ranged from 3lb to 9lb, depending on size.

Most Rider-type hot-air engines were sold for shallow-lift pumping duties, and usually had a Rider Rolling Valve Pump attached to the displacer cylinder. Few reliable performance statistics seem to have been recorded, though the Massachusetts Institute in Boston tested an engine with a 6.7 × 9.5in power cylinder in 1896. This developed 0.58–0.81ihp at 118–143 rpm; however, as mechanical efficiency averaged only 37 per cent, the brake horsepower figure was a disappointingly low 0.18–0.30.

In spite of its poor thermal efficiency, the Rider engine was not only extremely well made but also undoubtedly the most successful of the large hot-air engines. At least eight thousand had been made in the USA by 1902. And though not in itself an advance, the Rider system also paved the way for the great strides made by Philips after 1945.

ROBINSON ENGINES

This small machine was patented in Britain by A.E. & H. Robinson & Co. Ltd of Manchester, but made under licence by L. Gardner & Sons Ltd of Patricroft, and Norris & Henty and Pearce & Company of Manchester. Most of them date from 1885–1920.

The engines customarily had horizontal power cylinders, with ‘trunk’ (q.v.) pistons allowing the piston rod to drive directly onto the crank. The displacer, running a quarter-turn in advance of the motor piston, worked vertically in the cast-iron frame directly above the fire grate. The upper part of the frame had a water jacket.

Robinson engines were made in several patterns, including one with a roller on the displacer-piston rod bearing directly on the motor-piston rod. The ‘parallel motion’ drive pictured here is far more common. The earliest engines and the smallest of the later examples lacked regenerators, though the other machines relied on hollow displacer pistons filled with wire gauze or comparable material.

Some of the smallest engines were heated by gas, whereas the larger ones relied on coal, coke or wood. The half-horsepower version, with a 10in diameter motor piston, ran at about 170 rpm. Fuel consumption is believed to have been quite high, but the small Robinson engines were popular, reliable and surprisingly cheap to run.

CHAPTER SEVEN

internal combustion, from the first steps to the Diesel engine

The term 'internal combustion' is understood here to include gas, oil and petrol engines, and also jet- and rocket-propulsion systems. The essence of these machines lies in the method of generating power. In a steam engine, fuel is burned externally—in the fire grate, outside the boiler itself—to allow steam to be supplied to the cylinders. Internal combustion systems, conversely, ignite fuel that has been admitted directly into the cylinder.

The earliest embodiment of the principles may well have been attempts to regulate the consistency of gunpowder. Even the earliest cannon were primitive open-cylinder internal combustion engines, and amongst the first *éprouvettes* or powder testers were cylinder-and-piston patterns. Power was judged by the height reached by an indicator attached to the weighted piston rod.

Credit for realising that the power generated by the tests had greater potential than a mere indicator is usually given to a French cleric, Abbé Jean de Hautefeuille of Orléans, who suggested in the 1670s that a 'gunpowder engine' could raise water. Hautefeuille intended to explode a charge communicating with a reservoir, relying on the combination of atmospheric pressure and the weak vacuum created by cooling to raise water into a launder. A later attempt, said to date from 1682, used the force of gases directly on the surface of water in a small container.

There is no evidence that Hautefeuille ever made working models. However, Christiaan Huygens *did* demonstrate a gunpowder engine to Jean Baptiste Colbert, Controller General of Finance to Louis XIV and a patron of the Académie des Sciences. This exhibition did not occur until 1680, but Huygens had previously sketched an identical machine in a letter sent to his brother in September 1673.

Huygens' engine was little more than a small chamber beneath a cylinder. When the charge was fired, the piston was forced up the cylinder and expelled air through leather tube valves. The charge residue cooled to create a weak vacuum, which acted in concert with atmospheric pressure to return the piston to its original position. However, though Huygens' assistant Denis Papin developed efficient valves in the mid 1680s, only about three-quarters of the air could ever be expelled from the cylinder. Retaining so much air inhibited the return of the piston, and attention turned instead to the prototype steam engine (q.v.).

A few ever-hopeful inventors persisted with the 'explosion engine'. A ship propelled by gunpowder was patented by Englishman John Allen in 1729, a revolver type multi-charge machine was designed to raise water in the mid eighteenth century, and a multi-cylinder powerplant—substituting blank cartridges for pistons—was used in the 1870s on a model aeroplane.

THE FIRST STEPS

In 1791, John Barber of Nuneaton was granted an English patent to protect a primitive gas engine. The distillation of gas had been discovered in the 1720s, but exploitation had been delayed and the first application of gas lighting (widely credited to William Murdock) was not to be made until 1798 in the Soho manufactory of Boulton & Watt.

Barber sought to generate gas by heating substances such as powdered coal in a retort. Gas was passed into a receiver to cool, mixed with air, and finally pumped into a combustion chamber or 'Exploder'. Flame issued from a nozzle on the Exploder to rotate the vanes of a vertical wheel, drive being taken from the wheel shaft by gears.

Barber claimed that his invention could be used to grind 'Corn, Flint, Manganesse or other Matter and also [for] rolling, slitting, forging and battering Iron and other Metals, turning…Mills for spinning and Engines for turning up Coals, Minerals from Mines of all sorts, stamping of Ores, raising Water, and any other Motion': virtually any of the tasks entrusted to the primitive steam engines of his day. However, the power generating capacity of such a primitive gas turbine was far too small to be useful.

In May 1794, a varnish maker named Robert Street produced a design which—but for the limitations of eighteenth-century technology—could have revolutionised power generation. The 'engine' protected by English Patent no. 1983 foreshadowed late nineteenth-century ideas in many respects, even though it was little more than a power-assisted manual pump. Power was provided by sprinkling turpentine or alcohol onto the base plate of the cylinder, which was kept at red heat above a fire. The piston rested in the top of the cylinder, its movement being constrained by guide bars. The operator raised the piston with a hand lever as soon as the spirits had vaporised, drawing air into the cylinder until the piston uncovered a port containing a naked flame. The turpentine/air mixture ignited to drive the piston upward to the top of the enclosing frame with enough force to operate a small lift pump.

Like Barber before him, however, Street was unable to make the leap from promising theory to marketable commodity. A similar fate befell the Frenchman Philippe Lebon, whose first patent dated from 1799. Lebon intended to use gas obtained from coal in a remarkable double-acting engine. Not only was the charge to be ignited electrically, from a crankshaft-driven exciter, but engine-driven pumps compressed air and gas before the mixture was admitted to the cylinder. The power cylinder was closed at both ends, and the valves were all driven mechanically.

Lebon was murdered during a robbery in 1804, before achieving anything of consequence, but some of his ideas survived. A particular advance was made by Isaac de Rivaz in Switzerland in the early nineteenth century. De Rivaz's passion was a self-propelled road carriage powered by a gas-vacuum engine, developed in 1805 and patented in 1807. The engine had twin pistons working within a single open-top cylinder. The piston rod was extended upward to carry the chain that looped around a pulley on the drive shaft.

The gas was contained in a replaceable leather bag, attached to a short pipe containing a plug cock. An air/gas charge entered the combustion chamber, formed between the pistons as the lower piston was drawn downward, and was fired electrically. The motor piston was immediately forced upward, returning under a combination of gravity, atmospheric pressure and the vacuum created as the combustion products cooled beneath the piston. The piston-rod chain turned the pulley on the upward stroke, but, owing to an intermediate pawl and ratchet wheel, the shaft did not rotate immediately; work was done only when the piston descended, the back axle being turned with an endless rope.

By 1812, de Rivaz had improved his engine by adding a primitive carburettor or 'mixer'. Little more than a closed box containing perforated baffle plates, this accepted gas from bellows and relied on a multi-port valve to supply measured charges to the cylinder. Tests undertaken near Vevey in October 1813 revealed that the vehicle could attain about 5km/hr on twelve piston strokes per minute. The cylinder measured 36.5 × 150cm, and had an effective stroke of 97cm. The piston alone weighed 68kg, but the absence of a flywheel (and power generation only on the downward stroke of the piston) made motion jerky. As range was severely restricted by the small amount of gas carried in the reservoirs, de Rivaz abandoned his carriage, though the patent and the similarity of layout must undoubtedly have influenced Barsanti and Matteucci forty years later.

Many other inventors had tried to produce satisfactory engines. Among them were the Frenchmen Claude and Joseph-Nicéphore Niepce, who demonstrated a boat on the Seine in 1806. This was propelled by a single-cylinder engine fuelled with lycopodium power or pulverised coal dust. And William Cecil, an English clergyman, exhibited his experimental hydrogen powered gas-vacuum engine at a meeting of the Cambridge Philosophical Society in 1820.

THE FIRST SUCCESS

The only internal-combustion engines known to have been sold commercially anywhere in the world prior to 1830 were combinations of atmospheric and internal-combustion principles credited to the Englishman Samuel Brown.

One small engine—rated at merely one horsepower—had been built by August 1824, when the *Mechanic's Magazine* recorded that, at the cost of a cubic foot of gas, it had lifted about three hundred gallons of water through a height of fifteen feet. By 1832, however, several full-size machines were operating. One was raising water in a pump house on the Croydon Canal; another was draining a fen near Soham in Cambridgeshire; and two were operating in Eagle Lodge, Old Brompton, Kensington, London.*

One of the Eagle Lodge machines was said to be capable of lifting 750 gallons of water each minute to a twelve-foot head, requiring four strokes to do so. The engines may all have been made by the Bedlington Ironworks.

* One engine is even said to have been built in Philadelphia in 1828–9, but very little is known about this project excepting that it may have been planned with the assistance of Brown's son.

The earliest of Brown's gas-vacuum engines, patented in 1823, was made in two differing guises. The purpose-built pumping engine had two elongated combustion chambers set inside iron casings, an annular chamber being left between them to act as a water jacket. A cover plate or 'lid' above each chamber served as a seal.

As gas entered the combustion chamber, the lid was raised to admit air. Once sufficient gas had been admitted, the admission valve was closed and the charge was fired by exposure to a flame igniter. The lid was then replaced to confine the combustion products, which, as they cooled, created enough vacuum to lift water from a reservoir at the base of the machine. This passed through a one-way flap valve, into the annular space between the combustion chamber and the outer casing, then spilled over the rim of the chamber to assist cooling. At this point, a valve released the vacuum, allowing water to drain out of the casing onto an overshot water wheel—providing rotary motion—and then back into the supply reservoir. Water from the reservoir was fed through 'timed' or alternately operating valves into float chambers, rods on the floats connecting directly with the beam to control the movement of the combustion-chamber lids. The rods also controlled a small overbalancing box of mercury to ensure notably rapid valve events.

As the machine could be modified simply by omitting the waterwheel and allowing the reservoir to accept drain water, it is suspected that the Croydon and Cambridge engines were of this general pattern. The diameter of the cylinders was 42–44in, but the length of stroke is debatable; it has been recorded as merely 22in, but this should probably be 22 feet—the height of the top of the combustion chamber above the water reservoir.

A two-cylinder engine was also featured in Brown's 1823 patent, with a piston connected to an arch head at each end of the beam. The operating sequence was essentially similar to the pump, except that water was used only to cool the cylinder and promote the formation of a vacuum. One small engine of this type, with 12×24in cylinders, was tried in 1825 in a road carriage which successfully negotiated the notoriously steep Shooter's Hill, south east of London on the road to Dover.

The perfected 1826-type engine, tried on a boat on the Thames in 1827, was a three cylinder vertical in-line pattern. A separate double-acting power cylinder was provided with each combustion chamber. Gas was pumped into the chambers, mixed with air, and then fired. The chamber lids were closed to assist in the creation of a vacuum. The vacuum was then transmitted to the power cylinders through flexible hoses, the power stroke being generated from the difference in pressure between vacuum on one side of the piston and the atmosphere on the other. The creation of vacua on alternate sides of the piston gave six strokes for each three-cylinder combustion cycle.

Brown's goal was a continuous vacuum and, ultimately, a sizeable reduction in gas consumption. The pistons drove directly onto the crankshaft, gimbals allowing the power cylinders to pivot far enough for the piston rods to act directly onto the cranks. The valves were driven from the crankshaft by appropriate levers.

Unfortunately, gas-vacuum engines were cumbersome, expensive to operate and awkward to maintain. Limited production of coal gas would have restricted distribution even if the machines had attracted public attention, and so the project seems to have been abandoned by 1835.

Writing in the *Mechanic's Magazine* in 1826, William Cheverton noted that there was a real need for compact engines which were 'ready for use at any time, capable of being put in motion without any extra consumption of means, and without loss of time'. Brown's engine came close to fulfilling these requirements, but not close enough to challenge the steam engine.

A revival of Brown's ideas occurred when Richard M. Lowne patented an improved twin cylinder gas-vacuum engine in 1861. A flame was drawn through flap valves into the water-jacketed cylinders to ignite a gas/air charge during the outward stroke. The valves then closed, allowing the gases, as they cooled, to create the weak vacuum that acted on the pistons for part of the inward or power stroke. The valves were lifted by levers on rocking shafts, controlled by adjustable springs, and kept shut by atmospheric pressure during the inward movement of the piston.

Claimed to have been 'a marvel of elegance, simplicity, cheapness and power', the Lowne engine was intended to dental drills, coffee mills, mincers and similar small scale machinery. However, although exceptionally cheap, its power was too low and its crudity too great to court popularity.

TO THE DRAWING BOARD AGAIN . . .

An American contemporary of Brown, Samuel Morey of Orford, New Hampshire, also patented a gas-engine design in 1826. This incorporated a primitive carburretor to vaporise alcohol or turpentine; a wire mesh screen to prevent flames being sucked back into the carburretor chamber; and efficient cam-operated lift valves. Driven by side rods attached to crossheads, the crankshaft lay in the base of the frame. A two-cylinder Morey engine was demonstrated in an unsuccessful attempt to attract commercial interest, but all that remains is a small model in the Smithsonian Institution.

It is no longer known whether the 'Gas Exploding Engine' patented in England in 1833 by Lemuel Wright was ever made. Opinion remains divided, even though the precision and detail of the patent drawings suggest that a prototype may have been tested. The machine would have resembled a table-type steam engine (q.v.), with the cylinder mounted on a four column entablature and a double-acting piston driving a crankshaft by way of a crosshead and side rods.

Air and gas were pumped from two auxiliary cylinders attached to the engine base plate into small spherical mixing chambers at each end of the power cylinder. Ignition was accomplished by an external flame, and a flyball governor controlled the speed of the machine by regulating the admission of gas. The cylinder and the piston were both water-jacketed to protect the components from intense heat generated during combustion. The Wright engine also exhausted much of the combustion remnants on each stroke, excepting from the spaces outside the sweep of the piston.

Experiments continued throughout the first half of the nineteenth century, but few of the many gas-engine patents were ever properly exploited. Amongst the most noteworthy was a single-acting engine by William Barnett of Brighton, one of three designs patented simultaneously in April 1838. This was also basically of table-engine design. The air/gas charge was transferred under pressure to the motor piston by separate pumps, and was then fired by a special igniting cock. Barnett was also the first to solve the problem of firing a pressurised charge with a conventional flame-type igniter: the provision of a small transfer port, sealed at the moment of ignition, prevented the flame being blown out each time it was exposed to the charge.

The main power and auxiliary pump cylinders were mounted on top of the table, allowing the motor piston to act upward onto a crosshead and thence on the shaft by way of side rods. The pump pistons were also connected to the crosshead by links, to move simultaneously in phase with the motor piston.

As the motor piston moved downward, exhausting the combustion remnants through a sepcial valve, air and gas were forced through automatic lift valves to mix in the receiver between the table and the underside of the cylinder. As the motor piston reached the bottom dead-point, the exhaust valve was closed and a port between the receiver and the cylinder was opened to admit the pressurised air/gas mixture. The igniter then fired the charge, driving the piston to the top of its stroke.

One obvious disadvantage of the Barnett engine lay in the retention of spent gas in the receiver after the port had closed to allow the motor piston to descend in the cylinder. However, the proportion of residue to fresh charge was not great enough to prevent operation. The inclusion of a scavenge pump in the patent specification suggests that Barnett was aware of the problem, but also that adding complication in a comparatively small machine was not worthwhile.

Barnett's second design was double acting, igniting valves being set into the cylinder walls opposite the admission/exhaust ports. The piston valve was designed to admit the air/gas mixture at one end of the cylinder just as exhaust began at the other. The charge was ignited as the piston reversed its motion, expansion continuing for practically the entire stroke.

The most influential of the Barnett engines, his third, was little more than a revision of the double acting 'No. 2'. The air/gas mixture was admitted to the cylinder shortly before the piston reached the inner dead-point, to be compressed during the remainder of the stroke. Ignition occurred just as the motion was reversed, combustion driving the piston outward until it exposed the exhaust port in the centre of the cylinder and allowed the charge residue to be extracted by a scavenge pump.

It is not known if any double-acting compressing engines were made, and it has been argued that their pressure-controlled valves—substituted for mechanically-driven types—may have made the operating cycle difficult to control. Yet this engine was the first real embodiment of charge compression, expounded in theory by the ill-starred Lebon at the beginning of the nineteenth century. Unfortunately for William Barnett, who had the basis of an efficient design, his schemes also failed to prosper.

Unwanted combustion remnants plagued designers for many years. A proposal was made by Johnston in 1841 to use oxygen and hydrogen instead of the air/gas mixture, seeking to produce water residue, but the difficulties of obtaining gas in sufficiently large quantities restricted this idea to laboratory experiments.

Among many inventors who strove to make satisfactory internal combustion engines in the mid-nineteenth century was Stuart Perry of Newport, New York State, who built turpentine-fuelled engines in 1844 and 1846. The patent model of the older Perry engine survives in the Smithsonian Institution, but commercial acceptance was never forthcoming. Work had stopped by 1850, even though the solitary horizontal-cylinder 1846 machine worked surprisingly well.

A prototype gas engine designed by Alfred Drake was exhibited in Philadelphia in 1843, and an improved version with a single 16×18in cylinder was shown in New York City in 1855 (it only ran successfully for a very short time). Patents were granted in the USA in April 1855 and in Britain in September 1855, the latter to patent agent Alfred Newton, but the Drake machines failed to attract interest even though a few were apparently offered commercially. The Drake engine—a non-compressing design with a water-jacketed cylinder—relied on the admission to the cylinder of a carefully regulated mixture of air and illuminating gas. This was fired by an incandescent tube, the first of its type to be developed. The basic mechanism was eventually converted to oil burning, apparently working successfully.

BARSANTI AND MATTEUCCI

The first engine to achieve any real success was the work of Eugenio Barsanti and Felice Matteucci, who met in 1851. Barsanti, a friar, was lecturing in hydraulics and mechanics at a college in Florence; Matteucci, his partner, was a practising engineer. By 1854—mindful of the work of Isaac de Rivaz in Switzerland forty years earlier—they had developed the first 'free piston' engine. Built by the Bernini foundry in Florence, the prototype had two open-topped vertical cylinders and an 'A'-frame supporting the crankshaft and flywheel. Problems delayed completion until 1856, when the machine was sold to the local railway works.

Patents granted in 1854–7 protected a three-stroke gas engine. The earliest was a vertical open-cylinder gas-vacuum pattern, relying on a rack on the piston rod to drive two pinions. The key to operation lay in the twin pistons, one attached to the rack rod and the other to a short cylindrical rod passing through a gland at the base of the cylinder. The short rod was attached to the drive-pinion shaft by means of a crosshead and side rods.

The initial movement of the lower piston was downward, allowing air to enter between the piston faces. When this 'free piston' had moved far enough, the air valve was closed and the gas inlet opened. The mixture of gas and air that lay between the two pistons was then ignited electrically to project the motor piston upward, rotating the drive-shaft pinion by means of the piston-rod rack. Simultaneously, the free piston was forced downward to expel the residual combustion products from the previous charge.

As it began to move upward once again, a port was opened to allow the combustion products to flow around the lower piston. As the motor piston descended under the combined influence of the vacuum formed beneath it and the pressure of the atmosphere above, the free piston continued to rise and the combustion products were squeezed out of the decreasing gap until the two pistons eventually came to rest face-to-face and the operating cycle could begin again.

The greatly simplifed 1857-type engine discarded the free piston and relied on a rod driven from an eccentric on the crankshaft to operate the slide valve. Changes were also made to the rack mechanism to improve performance, and the perfected engine allowed much better gas expansion than preceding designs. In 1858, however, Giovanni Barsacci developed a horizontal derivation of the original Barsanti & Matteucci engine with opposed pistons and a bevel-gear drive train. Electric ignition was improved by the substitution of a Ruhmkorff coil for the de la Rive multiplier. Benini made an 8hp engine of this type in 1858, and La Società Promotrice del Nuovo Motore Barsanti e Matteucci was formed on 19th October 1860 to exploit the design commercially. A 20hp engine was shown at the Italian Exposition held in Florence (Firenze) in 1861 and a few smaller machines were subsequently made by Escher, Wyss & Company of Zürich.

Ill health forced Matteucci to retire in 1862 and the discovery of severe problems forced a return to the simpler 1857 pattern single-cylinder vertical engine. Trials engines of this type, rated at 4hp, were made by the Bauer Helvetica company of Milan in 1863. Tests were claimed to have shown great economy and an impressive overall efficiency of fourteen per cent. However, the emergence of the Lenoir gas engine in France and the absence of manufacturing facilities in Italy forced the directors of the Barsanti & Matteucci company to contact Société John Cockerill of Seraing (Belgium). Before progress could be made, Barsanti died suddenly in Liége in April 1864 and development came to an end.

Barsanti & Matteucci gas engines were never made in quantity and their place in the history of power has been questioned. The comparative scarcity of illuminating gas in newly federated Italy would have made the machines expensive to run, and it is noteworthy that the remaining directors of the company chose to develop a hot-air engine. Though the basic Barsanti & Matteuci design was subsequently revived in Germany by Otto & Langen, the pioneering work undertaken in Italy in the 1850s remains largely overlooked.

THE LENOIR ENGINE

The first commercially successful gas engine was patented in France on 24th January 1860 by Jean-Joseph-Étienne Lenoir. The original machine, built on the general lines of a small horizontal steam engine, was double acting and relied on electrical ignition.

Its operating principles were scarcely novel; even Lefebvre, who made the Lenoir engine for the promoters, suggested (with rare candour and historical perception) that it "uses Street's patented piston with direct and double action as developed by Lebon, the ignition is like the Rivaz engine, the cylinder is cooled by water as in Samuel Brown's engine, it can be made to run on vaporised hydrocarbons as suggested by…Hazard [Morey]; on it can be found the same clever idea of Talbot's circular distributor. But…the Lenoir engine sucks in gas and air through the action of the piston without requiring any previous mixing, and for this reason it has a proper claim to be patented". This quote is particularly interesting for the recognition it gave to Isaac de Rivaz and Samuel Brown, whose contributions were so soon forgotten.

The piston rod turned the flywheel by way of a crosshead and a forked connecting rod. Two slide valves, one on each side of the water-jacketed cylinder block, were driven by eccentrics on the crankshaft. They admitted a mixture of one part gas to twelve parts air on one side, whilst exhausting the residual products of the previous combustion on the other.

Once the piston had reached the end of a stroke, enough energy had been stored in the flywheel to begin a new cycle. As the piston began to move, with the air port already open, the gas port was opened to allow the charge to be mixed before being sucked into the cylinder by the forward movement of the piston. Firing the charge with a spark—provided by a two-cell battery and a Ruhmkorff induction coil to a spark plug in each end of the cylinder—generated a pressure of several atmospheres, though this was rapidly reduced by the cooling effects of the water jacket. Tests showed that the pressure before ignition, about 10lb/sq.in, rose to a maximum of 60lb/sq.in. The residue of the previous cycle was exhausted from the opposing end of the cylinder at a pressure of 1.5 atmospheres and a temperature of about 200°C.

The exhaust valves were designed with sufficient lead to open before the piston reached the end of its travel. A centrifugal governor controlled running speed by acting directly on the gas-admission valve, but the Lenoir engines were notoriously difficult to lubricate. The piston often became red hot and ignited incoming charges prematurely, promoting erratic running and excessive consumption of fuel.

Tests undertaken in 1861 on a ½hp engine revealed that, with an air/gas mixture of 10:1 and a running speed of 130 rpm, cylinder pressure peaked at 4.87 atmospheres and gas consumption was about 112 cubic feet per bhp/hr. A 1hp engine running at 94 rpm on a mixture of 7½:1 gave figures of 4.36 atmospheres and 96 cubic feet per bhp/hr respectively.

Like most early designs, the Lenoir engine was at its best in large sizes. This was subsequently found to be due to the relationship between cylinder volume and surface area, which became more favourable as diameter increased. However, this factor was so often hidden by inferior design or manufacture that the smallest engines, theoretically the least efficient, often seemed to perform better.

The prototype Lenoirs were made by Hippolyte Marinoni, best known for high-quality printing machinery, which enabled the inventor to avoid perils that had dogged many of his predecessors. The first two engines were rated at 5hp and 20hp. Their success allowed Société des Moteurs Lenoir to be founded in 1862 to market engines made by Lefebvre & Cie and Gautier & Cie of Paris; 143 were being used in the French capital city alone by the end of 1864. A road vehicle with a 1 hp internal-combustion engine had been built in 1862, the first of its type, and another is said to have been sold to the Tsar of Russia.*

By 1865, about 370 gas engines had been made for Lenoir and the Compagnie Parisienne de Gaz, which had acquired rights in 1863. A

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* The existnce of this vehicle has been questioned, as it is said to have 'disappeared on its way to St Petersburg'.

hundred had even been made in Britain by the Reading Iron Works Co. Ltd for the Lenoir Gas Engine Co. Ltd of London; Koch & Company of Leipzig and Kuhn of Stuttgart had made a few in Germany; and small numbers of ½hp machines may have been made in New York City by the Lenoir Gas Engine Company (generally regarded as an importer). The power of European-made engines rarely exceeded 3hp, though some 6hp examples were offered.

The success of the Lenoir engines was brief. Though they usually worked reliably enough and were very easy to start, owing to the absence of compression, their reputation suffered once it had been realised that they were neither as efficient nor as economical as their promoters had claimed. Trials indicated efficiencies of only about four per cent, and showed that half the heat energy was dissipated uselessly into the water jacket surrounding the cylinder. In addition, the spark plugs needed regular cleaning and the electrical-ignition system was prone to fail.

Mindful of progress being made by others, Lenoir worked for many years to improve his basic double-acting design before settling in 1883 on a single cylinder four-cycle compression-type engine inspired by the ideas of his fellow countryman Beau de Rochas (q.v.).

THE EARLIEST RIVALS

Many inventors emerged to lay claim to the basic Lenoir design, including a clockmaker named Reithmann who had obtained a Bavarian gas-engine patent in September 1858.

Pierre-Constant Hugon, a director of Compagnie Parisienne de Gaz Portatif, patented a double acting gas-hydraulic motor in 1858–63—only to abandon it when the Lenoir engine became successful. The non-compressing Hugon gas engine, introduced commercially in 1865, was a vertical single-cylinder design with the crankshaft and flywheel supported by 'A'-frames. The slide-valve assembly was driven by two eccentrics on the crankshaft, and a third eccentric drove the charging pumps.

Hugon's major contribution to gas-engine design was his efficient flame-igniter. This relied on two transfer ports in an auxiliary slider on the back of the main slide valve, one of which was lit at the beginning of each stroke by a permanently-burning gas jet in the engine base plate.

Hugon showed that flame ignition was more efficient than the electrical systems available in the 1860s, but was initially handicapped by his pumps, which relied on rubber bellows and flexible delivery hoses. As these soon deteriorated, the engine was hastily redesigned to accept conventional metal-body piston pumps and a mixing valve.

In 1867, mindful of the success of the Lenoir engine, Hugon produced a horizontal-cylinder machine of his own. Independent tests showed that this engine was considerably more economical to run than those of his principal rival, partly because greater charge expansion had been allowed and partly because the flame ignition system was so efficient. Hugon also solved overheating problems by spraying cold water into the cylinder after each stroke. Tests undertaken in 1861 on a Lenoir gas engine had shown that 53 per cent of the heat generated during combustion dissipated into the water jacket and 30–35 per cent was lost in the exhaust. The Hugon water-spray system, tried in 1866, was found to lose only about twenty per cent to the water jacket, and an additional 24 per cent in the vaporisation of the water injected into the cylinder. This particular Hugon machine, a vertical example rated at 2hp, had a 13×12.8in cylinder and ran at an average of 53 rpm. The air/gas mixture of 13:1 gave a peak cylinder pressure of 48lb/sq.in, a fuel consumption of 91 cubic feet per bhp/hr, and a thermal efficiency of approximately seven per cent.

Hugon engines were made until the early 1870s, ranging in size and power from ½hp to 3hp, but were then eclipsed by the Otto & Langen pattern. A few were built in England by licensees Thomas Robinson & Company of Halifax, but are rarely encountered.

The gas engine developed by Alexis de Bisschop of Paris was the most successful non-compressing design. Essentially a source of restricted power, it had an unusually small footprint and relied on a finned cylinder to promote cooling. The combination cylinder and tubular piston-rod guide was mounted vertically but, unlike the Barsanti & Matteucci and Otto & Langen designs, the flywheel, mounted at mid height, was rotated by a lever and connecting rod. An eccentric on the crankshaft drove the single piston-type admission/exhaust valve through a rocking lever attached to the cast-iron frame. A small flame igniter, placed in a port in the cylinder wall, was exposed by the initial upward travel of the piston to fire the charge. This then forced the piston farther upward, carrying the crank round by a little more than half a turn.

Few Bisschop engines developed more than a third of a horsepower, the most popular being the tiny 'Manpower' (one-twelfth horsepower) varieties. This miniaturisation filled a real need in the days before efficient electric motors became available, but hid a frighteningly large appetite for gas. A consumption of 150 cubic feet per bhp/hr would not have been tolerated in larger machines. Excessive use of fuel was due mainly to the design of the loose-fitting piston, which lacked rings in an attempt to counteract the effects of heat. Gas blow-by was by no means uncommon, but was minimised by keeping the maximum pressure below 25lb/sq.in.

Bisschop engines needed to be heated for ten minutes before starting, most examples incorporating a special gas-jet heater. They were made under licence by Mignon & Rouart of Paris; by J.E.H. Andrews Ltd of Stockport, England; and by Buss, Sombart & Company of Magdeburg in Germany. Total production probably exceeded ten thousand.

THE FOUR-STROKE CYCLE

One of the most significant advances in gas-engine design was made in 1862, when a French patent was granted to Alphonse Beau de Rochas. The inventor had recognised that the major failings of the Lenoir and similar machines were principally the lack of compression, restriction of expansion, and the loss of heat through the cylinder walls. He had also defined four criteria necessary to provide an efficient gas engine—the greatest cylinder volume allied with the smallest surface area (which effectively meant a large diameter piston with a short stroke); maximum piston speed; maximum expansion of the air/gas charge; and the highest pressures that could be obtained in the first phases of expansion. Engines embodying recommendations such as these could use much of the energy that was customarily wasted in slow-moving gas engines, where expansion was restricted and much of the heat simply dissipated into the cylinder walls.

Beau de Rochas believed that only a single-cylinder engine fulfilled his requirements. This, he claimed, would successively draw in the charge of air and gas, compress the charge, ignite it in the ‘dead space’ (at the end of piston travel), and then exhaust the combustion products to the atmosphere. He also sought to generate enough heat by compressing the charge to spontaneously ignite it, but this did not prove efficient enough to be incorporated in workable engines until Herbert Akroyd Stuart and Rudolf Diesel became interested in the 1890s.

Like countless men before him and many others afterward, Beau de Rochas was ahead of his time. His work was eventually recognised by the Academie des Sciences and the Société d'Encouragement pout l'Industrie Nationale, but the commercial awaited the efforts of others.

OTTO AND LANGEN

Nikolaus Otto was born in 1832 in the small rural town of Holzhausen, in the Taunus district of Germany. An early career as a travelling salesman could not quench his inventive spirit, and the introduction of the Lenoir gas engine in France caught his attention. Otto then experimented with a Lenoir copy before progressing to a four-cylinder machine of his own with a twin opposed horizontal layout.

Lack of success soon persuaded Otto to design a vertical gas engine with a closed cylinder and a single crankshaft. Eccentrics on the shaft controlled the valve events, and air displaced above the motor piston was forced into a separate reservoir alongside the cylinder. Power was generated partly by combustion, on the outward (up) stroke, but also, on the inward (down) stroke, by the difference between the air pressure in the auxiliary reservoir and the vacuum created beneath the motor piston as the combustion products cooled. Consequently, the 1863 patent Otto engine gave continuous power—no doubt aided by its heavy flywheel—even though the unequal work done by the two strokes strained the drive train and promoted running which was often very erratic.

The involvement of Eugen Langen was the key to Otto's success. Langen had also noticed the Lenoir engine and the opportunity to promote a locally designed rival appealed greatly to his entrepreneurial instincts. On 31st March 1864, therefore, N.A. Otto & Company was founded and work began immediately to adapt the 1863 patent engine for series production. However, the engine was not perfected until 1867 in circumstances which still attract controversy.

Almost all of the original machine had been abandoned, in detail if not in concept, until it bore a strong external resemblance to the Barsanti & Matteucci engine of the 1850s. These links have been emphasised by some writers and underplayed by others, depending on viewpoint. Otto & Langen undoubtedly had some knowledge of the work that had been undertaken in Italy—their British patent agent, C.D. Abel, supplied copies of the relevant specifications in 1865—and the similarity in layout is too close to be coincidental. Yet the Otto & Langen gas engine did differ substantially from its Italian predecessor.

The slender cylinder doubled as a pedestal, supporting the drive train and the flywheel; the lower part of the cylinder, surrounded by a water jacket, was combined with feet. Langen's major contribution to the design was the efficient overrunning clutch, which was locked to the drive shaft by rollers and wedges only on the downward piston stroke. The slide valve controlling admission and exhaust was controlled by a shaft driven eccentric, a special pawl lifted the piston to admit a new charge, and a rubber bladder was provided to overcome fluctuations in gas supply pressure.

Each charge of air and gas was admitted by a slide valve driven by an eccentric, ignition being controlled by a burner in the valve cover. The flame igniter system was inspired by Hugon, but had been improved in so many respects that it was practically a new design. Igniting the charge projected the piston upward with considerable force, but the clutch detached the shaft wheel from the main drive shaft. The shaft was already being revolved by the energy stored in the flywheel. At the top of the piston stroke, however, the motion abruptly reversed, engaged the roller clutch, and allowed the rack to turn the flywheel directly as the piston dropped back under a combination of vacuum, gravity and atmospheric pressure. The downward stroke also engaged the eccentrics on the layshaft, which could otherwise rotate freely.

The success of the Otto & Langen engine was due to the strength of its components, which succeeded where Barsanti & Matteucci ratchet and pawl mechanism had proved too weak. The drawing explains the operation of the clutch system in greater detail. The first public showing occured at the Paris exhibition of 1867, where the strange-looking machine stood unnoticed among the horizontal-cylinder Lenoir and Hugon patterns. At the last minute, however, the examining committee was persuaded—supposedly by the Prussian representative—to undertake a performance trial before making a decision which would undoubtedly have favoured a French design.

To universal surprise, the noisy and seemingly primitive Otto & Langen engine gained the gold medal in its class by consuming only a third as much fuel as its rivals. Efficiency was due largely to greater expansion of the air gas mixture, which was about four times as great in the Otto

& Langen engine than in a typical Lenoir. Felice Matteucci protested against the award, declaring the German design to be nothing other than an infringement of Barsanti & Matteucci patents, but his protest went unheard.

Small scale manufacture of Otto & Langen engines began immediately, helped by the formation of Langen, Otto & Roosen in 1869 and then by the advent of Gasmotoren Fabrik Deutz (in a suburb of Cologne) in 1872. Smooth transition to series production in the early 1870s owed much to the efforts of Gottlieb Daimler and Wilhelm Maybach, both of whom later achieved great fame in their own right. Maybach is generally credited with redesigning the drive train to incorporate an improved overrunning clutch and a single shaft layout, even though the patent was granted in Daimler's name alone.

That the engine was a great success was due as much to the high standards of manufacture as low gas consumption. Trouble had been encountered with the flyball governor, which had been added to control the exhaust valve after the earliest machines had been completed. The original system worked well enough when new but, once the engine had become worn, running speed began to fluctuate and gas tended to leak past the piston. An answer was found in a governor acting directly on the pawl controlling the piston-lifting rod to correct running speed.

Among the worst features of the Otto & Langen engine was its shape, which restricted power by limiting height. The ½hp version stood 7ft high and weighed 900lb; but the 3hp engine—the largest made by Deutz—was 12ft 8in high and weighed 4450lb. These engines ran at 110rpm and ninety rpm, their pistons making forty and 28 strokes per minute respectively.

The economy of the Otto & Langen engines compared with the Lenoir and similar rivals soon became widely appreciated. Tests of the ½hp engine exhibited in Paris in 1867 gave a gas consumption of about 44 cubic feet per bhp/hr, whereas trials of a 2hp example, reported by Dugald Clerk, gave a maximum cylinder pressure of 54lb/sq.in and a gross gas consumption of 42 cubic feet per bhp/hr. Thermal efficiency was a little over eleven per cent.

Performance improved steadily until, by the mid 1870s, figures of 25–28 cubic feet per bhp/hr were regularly obtained—a quarter of the consumption of the small Lenoir machines. The Otto & Langen engine, therefore, is regarded as the first in which the expansion of the gas/air mixture was used its full potential. Though it was noisy and unstable, owing to vertical layout and the unbalancing effect of the heavy flywheel, sales were brisk. Otto & Langen and Gasmotoren Fabrik Deutz alone made more than 2600 from 1867 until assembly ceased in 1882. Only about 450 machines had been made prior to the formation of the Deutz company, but annual production rose rapidly to peak at 634 in the 1875/6 financial year.

A greater influence than manufacture in Germany lay in the spread of this particular gas engine not only across Europe but also in the USA. The principal British licensees were Crossley Brothers of Manchester, who acquired rights as early as 1869. These engines were promoted initially by Simon & Company of Nottingham until, by 1871, Crossley assumed the dual role of manufacturer and distributor.

Production in Britain amounted to 1400 engines, most being distinguished by a dash pot instead of the rubber gas bladder. Crossley products were all of two-shaft type, but had improvements in their drive train.

About two hundred machines were made for the French concessionaire Éduard Sarazin by Compagnie Parisienne d'Éclairage et de Chauffage. They were never very popular in France, partly because memories of the Franco–Prussian War were far too vivid but also because the steadier-running Lenoir engine was widely preferred. Langen & Wolf of Vienna and the Bauer Helvetica company in Milan made the Otto & Langen in Austria-Hungary and Italy respectively; Schleicher Brothers of Philadelphia held the North American rights. Worldwide production amounted to about 4500.

RIVALS OF OTTO & LANGEN

GILLES DESIGN

This gas engine, often mistakenly identified as French (though Friedrich Gilles may have been Alsatian), was made by Maschinenbau Humboldt of Kalk bei Cöln. A single-cylinder two piston inverted-vertical engine had a crankshaft mounted on the base plate. When the air/gas mixture was ignited, the free piston was thrust upward until it was held on a latch. As the combustion products cooled, the creation of a vacuum pulled the motor piston up and rotated the crankshaft. The upper piston was then released, and the entire mechanism returned to its lower position ready for the admission of the next charge.

The Gilles engine ran much more smoothly than its Otto & Langen rival, but inherent mechanical defects were serious enough to deny it success. The advent of the four-stroke Otto cycle brought its career to an abrupt end.

BRAYTON DESIGNS

The single-cylinder two stroke machine designed by George Brayton, after abortive experiments with turpentine and alcohol fuels, was the first successful gas engine to be developed in the USA. Though it was not especially efficient, it was to form the basis of the world's first practicable oil engine.

The prototype gas engine was built in the autumn of 1871 by the Exeter Machine Works of Exeter, New Hampshire, which was already marketing Brayton's sectional heating boiler. The original engine apparently combined the pump and motor pistons in a single vertical cylinder, but the perfected version—introduced in 1872—had a separate pump chamber. It was soon christened the 'Ready Motor', owing to the ease with which it could be started.

A pump compressed gas and air into a reservoir, from which the mixture was gradually fed into the cylinder through a small pipe, around a protective screen, and across the igniter flame. The ignition mixture was maintained at a higher pressure than the combustion chamber to ensure that the power stroke was a smooth movement, owing to the progressive burning of the charge, instead of a sudden and violent ignition. (This 'Brayton Cycle' has since been successfully applied to gas turbines.)

Fuel-consumption tests on Brayton gas engines subsequently revealed that the compressor pump absorbed a considerable proportion of the power generated in the combustion cylinder. The earliest full-scale independent trial, in January 1872, showed that an engine with an 8×12in cylinder and an 8×6in pump indicated 9hp at 180 rpm. However, the effects of the pump and friction reduced the effective horsepower to only 4.1. Tests undertaken in 1873 with a 5nhp engine revealed that an indicated horsepower of 8.62 was reduced to an effective (brake) value of only 3.98. Fuel consumption was given as an encouraging 32 cubic feet per ihp/hr, but the true value was 69.3 cubic feet per bhp/hr. This gave a poor power-to-weight ratio and made the engine inefficient for its day.

Thermal efficiencies of about seven per cent were better than the original Lenoir engine, but only half that of the competing Otto & Langen pattern. However, the Brayton engine ran much more smoothly than its German rival and was much quieter. Its worst feature was the periodic rupture of the wire-gauze screen protecting the flame (inspired by miners' safety lamps), which allowed blow-back to ignite the air/gas mixture in the reservoir.

Fortunately, Brayton engines were not only strongly made but also incorporated a safety valve; unexpected explosions, therefore, were disconcerting rather than dangerous. To re-start the engine, it was necessary only to purge the reservoir, replace the screen, and reignite the burner.

The engines were marketed in the USA by several differing agencies, including distributors registered in New York ('New York & New Jersey Ready Motor Company') and Philadelphia ('Pennsylvania Ready Motor Company'), though they seem to have been made in Providence, Rhode Island. Production was modest, as work ceased in 1877 in favour of an oil-fuel derivative patented in 1874. Brayton Ready Motors were briefly made in Britain under licence by Simon & Company of Nottingham, beginning in the summer of 1877.

A modified British-made version was exhibited in Paris in 1878 with a small boiler mounted above the inverted vertical cylinder to allow the injection of steam into the cylinder during the operating cycle. The goal was to increase power and improve lubrication, the latter being a recurrent problem of early gas-engine design. Complication was unnecessary, however, and the improved Simon engine (sometimes known as the 'Beechey' after the promoter of the supplementary boiler) was soon abandoned.

THE OTTO ENGINE

Credited to Nikolaus Otto, this machine brought the formative period of the gas engine to a close. Made from 1876 onward by Gasmotoren Fabrik Deutz of Deutz, near Cologne, it was so successful that the its four-stroke operating cycle has become universally known as the 'Otto Cycle'...even though it was really that of Beau de Rochas.

The first Otto engines were horizontal, the influence of contemporary steam-engine design being reflected in an open faced water-jacketed cylinder facing the flywheel. The slide valve was moved transversely across the back of the cylinder by a rotating layshaft, driven from the end of the crankshaft by bevel gearing. The shaft also drove a pendant flyball governor and a cam-actuated exhaust valve.

The cycle consisted of a first outward stroke to draw the air/gas mixture into the cylinder; a second return stroke to compress the charge; ignition at the inner dead point; a third outward or power stroke; and then a fourth return stroke to exhaust the residual combustion products. A cam on the rotating layshaft lifted the exhaust valve when necessary.

The original slide-valve mechanism was much too complicated. The burner, contained in the cover plate, had its own gas supply pipe. Another pipe supplied the air/gas charge to the cylinder, and a third connected with a tiny intermediate flame chamber in the slide valve itself. The ignition sequence was also quirky. The permanently-lit burner contained in the slide cover was offset from the charging port so that there was no direct communication between them. The auxiliary chamber in the valve, containing gas from its own small pipe, was moved sideways until it aligned with the burner in the slide cover. This ignited the gas in the chamber. When the valve slid back far enough in the reverse direction, it communicated the gas in the auxiliary chamber (now alight) with the charging port. The main charge fired and the piston was thrust toward the flywheel.

A major drawback of the single-acting four stroke engines was that power was generated only for half a revolution of the crankshaft, leaving 1½ turns to be accomplished only by the momentum of the substantial flywheel. Another problem lay in the retention of substantial amounts of residual gas in the cylinder after the exhaust stroke—there was a large unswept compression space behind the piston—though Otto believed that this cushioned the piston and promoted longevity.

The largest Otto engines were also notoriously difficult to start, and so were often fitted with air-compressing pumps and storage reservoirs to turn the motion for the first cycle. Yet the design was a huge success: Gas Motorenfabrik Deutz had made (or licensed) more than 45,000 of them by 1895, representing a total of about 200,000hp. Licences had been granted by this date to Crossley Brothers of Manchester; to Compagnie Française des Moteurs à Gaz of Paris; and to Schleicher, Schumm & Company of Philadelphia.

Improvements were soon made. The idiosyncratic ignition system proved to be a particular weakness, and the two-stage burner system was speedily substituted by ignition tubes or electrical firing gear. The high costs and limited distribution of illuminating gas inhibited sales as the Otto engines became popular, but this particular problem was solved by the development of self contained producer-gas generators.

Not surprisingly, owing to their popularity, Otto gas engines were extensively tested. Trials undertaken in Germany in 1878 revealed that 3.2hp and 6hp machines, running at 180 rpm and 159 rpm respectively, consumed gas at 38–40 cubic feet per ihp/hr. This was high compared with some rival designs, ironically including the obsolescent Otto & Langen pattern, but was steadily reduced. By 1887, a 14ihp engine tested in Glasgow was consuming only 19.4 cubic feet per ihp/hr, and a 30bhp Deutz-made example tested in 1895, running at 200 rpm, returned 16.3 cubic feet per ihp/hr. Consumption of weaker producer gas was usually far higher, but the fuel was cheap in comparison with illuminating gas.

TWO- AND SIX-STROKE DESIGNS

A major weakness of the Otto cycle engine was perceived in the limitation of power to one stroke in four. In 1880, therefore, Dugald Clerk produced his first two-stroke machine. A return was made to an auxiliary chamber (which Clerk called a 'Displacer') alongside the cylinder, in which air and gas could be mixed. The displacer piston operated ninety degrees in advance of the motor piston. The cylinder, which was generally enveloped in a water jacket, was closed by a conical compression chamber into which the charge was delivered by a transverse slide valve operated by a bell crank driven from a crankshaft eccentric.

The displacer piston, moving outward, drew a mixture of gas and air in through a valved filter beneath the cylinder block. Gas supply was cut before the end of the displacer stroke, which was then completed by taking in pure air. As the displacer reached mid stroke, the motor piston began its outward travel, moving until it uncovered the exhaust ports cut around the periphery of the cylinder towards the outer dead-point.

This reduced pressure within the cylinder to atmospheric level. However, as the displacer had returned sufficiently to compress the air/gas mixture, the admission valve opened to allow the combustion products of the previous charge through the exhaust ports. The return of the motor piston then closed the exhaust and compressed the charge. Ignition at the inner dead-point then reversed the motion and allowed the operating cycle to begin again.

A small transfer port in the valve body allowed a flame constantly alight in a chamber in the cover of the slide valve to communicate with the compression chamber. A tiny grating in the base of the transfer port regulated the supply of gas, air being drawn in from the atmosphere through a narrow pipe in the cylinder block. The running speed of the Clerk engine was governed by a flyball device, driven from the crankshaft, which controlled a sliding grid placed between the paired valves in the tube delivering the charge mixture to the displacer cylinder. A compressed air reservoir facilitated starting.

Clerk engines were made in several sizes, but rarely exceeded 12hp. Tests showed that gas consumption ranged from 29.8 cubic feet per ihp/hr for a 2hp example running at 210 rpm to 20.4 cubic feet for a 12hp engine running at 130 rpm. Heat efficiency was generally about twelve per cent.

The Clerk two-stroke cycle was moderately successful, but did not allow sufficient expansion of the air/gas charge to be entirely satisfactory. Though the expulsion of a substantial amount of residual combustion products before each power stroke began was beneficial—and undoubtedly better than the standard four stroke Otto system—improvements were still possible.

An alternative approach was taken by the Beck gas engine of ?1888, which worked on a six-stroke cycle. The first outward stroke controlled admission of the air/gas mixture; the second return stroke compressed the charge; ignition was then followed by the third (outward) stroke, and the fourth (inward) stroke exhausted the combustion products. This was little more than the Beau de Rochas cycle, but Beck then added a fifth outward scavenging stroke, admitting pure air to cleanse the cylinder, and a sixth inward stroke to expel the air. This not only improved the richness of the charge, but also reduced fuel consumption.

Beck engines had slide valves driven from a crankshaft eccentric, and an insulating layer between the water jacket and the compression/ignition chamber to retain as much heat as possible. Their major disadvantage was that only one of the six strokes generated power, which made governing engine speed very difficult. A heavy flywheel was required to store sufficient momentum to deal with the remaining five strokes. Trials undertaken with a 4hp Beck gas engine revealed fuel consumption of

21.4–26.8 cubic feet per ihp/hr, depending on running speed. Indicated horsepower peaked at about eight at 207 rpm, brake horsepower being 6.3.

A double-acting six stroke gas engine was made briefly in the 1890s to Griffin patents by Dick, Kerr & Co. Ltd of Kilmarnock. This had the advantage over the Beck pattern of two power strokes in every six, which promoted smoother running and easier governing. However, though the six-stroke Griffin engine had some very good qualities, the maker had soon converted it into a simpler four-stroke Otto type derivative simply by omitting the scavenger.

THE ATKINSON DESIGNS

James Atkinson was another of the leading British experimenters active towards the end of the nineteenth century. His engines, though four-stroke patterns, were quite unlike any of his rivals and could be recognised at a glance.

Recognising that the water jacket and the high temperature of the exhaust were principal sources of heat loss, the inventor decided to design the piston and crank so that the stroke could vary according to the specific requirements of the individual portion of the operating cycle.

One of Atkinson's most important claims was that the expansion of the ignited charge was accomplished in an eighth of a revolution, instead of roughly half as in the Otto system. Whereas admission customarily occupied the same volume as expansion in conventional four stroke engines—e.g., each occupied virtually the total swept volume of the cylinder—Atkinson contrived to expand the charge to almost double its original size. The reduction in the portion of each revolution given over to expansion restricted the amount of heat lost through the cylinder walls into the water jacket.

DIFFERENTIAL ENGINE

The earliest Atkinson gas engine was an Otto like pattern with incandescent tube ignition, but was abandoned before production began. It was replaced by the prototype of this odd-looking machine, revealed at the Inventions Exhibition of 1885. The Differential Engine had a single cylinder, mounted horizontally at the base of the frame, which contained two opposed pistons. These were attached to the crank by two connecting rods, two links and two connectors.

Beginning with the two pistons at their farthest to the right, expelling the residual combustion products during the exhaust stroke through ports cut through the periphery of the cylinder, clockwise rotation of the flywheel began to move both pistons towards the left. Owing to the clever geometry of the links and pivots, the left or pump piston moved more rapidly than its consort. This created a chamber between the pistons into which the air/gas mixture was admitted. The pump piston then stopped, allowing the following motor piston to compress the charge. Ignition occurred at the point of maximum compression, driving the motor piston back to the right with considerable force before the pump piston could begin its delayed rightward travel. The ratio of admission/compression to expansion/exhaust was usually about 1:1.7.

The Differential Engine was an interesting machine to watch in motion, the manic whirling of links and rods being unmistakable. Unfortunately, the complexity of the drive train was a particular weakness of Atkinson's design—excellent though it was in many other respects. The engines ran uneconomically when lightly loaded and were apt to rattle when the pivots began to wear.

CYCLE ENGINE

This replaced the Differential engine in 1886. Though a single-piston design, the Cycle Engine nevertheless retained the unequal-stroke operation pioneered by its predecessor. The major change was the replacement of the duplicated multi-link drive with 'Link and Toggle Motion' comprising a connecting rod, two cranks and a connecting lever. The admission and exhaust valves were operated by cams on the crankshaft, relying on a flyball governor to disconnect the valve-operating rod if the engine began to overrun.

The Cycle Engine could also run roughly when worn, but was surprisingly economical. Trials undertaken in the 1890s generally revealed an hourly gas consumption of about 20–23 cubic feet per ihp. A range of engines tested in 1894 by the Royal Society of Arts confirmed that the Atkinson design was miserly with fuel, the return of 19.22 cubic feet per ihp/hr being the lowest recorded. A Cycle Engine tested in 1891 in conjunction with a Dowson gas producer system indicated 21.95hp and consumed anthracite at the rate of only 1.06lb/ihp/hr.

UTILITÉ ENGINE

Unfortunately for Atkinson, but not surprisingly in view of its compexity, the Cycle Engine also failed to challenge the established Otto type patterns. It was replaced in the early 1890s by the Utilité, which was essentially a refinement of the preceding designs seeking greater durability. This, too, was unable to loosen the increasing stranglehold being applied by conventional four-stroke machines, and so Atkinson, despairing of success, entered employment with his arch-rival Crossley.

OTHER BRITISH GAS ENGINES

The Stockport engine, made by Andrews & Company, appeared in 1883. It was originally offered as a single acting two-stroke machine with two opposed cylinders, one containing a motor piston supplied with an air/gas charge from the other, which operated as a separate compressor pump. Each cylinder contained a trunk piston, which kept dimensions compact enough to drive a central crankshaft.

About two thousand engines of this type were made. They had two slide valves, one working vertically to admit the charge (driven by an eccentric on the crankshaft) and another, travelling horizontally, which carried the flame type igniter. The pistons reciprocated to allow the outward stroke of the pump to draw the charge through the admission valve, as the motor piston, on its inward stroke, expelled the residue from the previous cycle from the exhaust port. When the motion was reversed, the inward stroke of the pump compressed the charge into a receiver formed in the bed plate. The pressure of the charge was sufficient to open a valve into the cylinder, allowing the entry of the new charge to help expel the remnants of its predecessor. The mixture was compressed and then fired as the motor piston reached the inner dead-point, allowing the succeeding outward stroke to drive the flywheel around.

Andrews also made a double-acting engine with two motor pistons and two pumps, driving onto a single two-crank shaft. The pump pistons were driven by the smaller of the cranks slightly in advance of the main or motor crank. A third type of engine had a single vertical cylinder and a differential pressure piston. The charge was admitted and compressed in the top or large diameter section of the cylinder, then transferred beneath the piston to be fired and exhausted in the small diameter section.

SUCCESS IN THE MARKET PLACE

After the hesitant start with Lenoir and Otto & Langen machines, the success of the gas engine was assured once the availability of gas improved. The existence of natural gas—'Marsh Gas', methane—had been known for hundred of years. The deposition and subsequent petrification of sediment trapped in underground pockets the vast quantities of gas that had been created by heat and slow chemical decomposition. Gas was often found in conjunction with oil-bearing strata, most notably in North American oilfields and along the margins of the Caspian Sea. Attempts had been made to provide gas-lit street lamps in the New York town of Fredonia in 1821, but the earliest successful attempt to use natural gas occurred in Heathfield, in the English county of Sussex, in 1898. There, gas was found at a depth of three hundred feet in a bore hole being sunk to find water. It was used to light the nearby railway station and several domestic buildings, and also to power a few small gas engines housed in the immediate vicinity.

The Heathfield gas, which was more than ninety per cent methane, had a higher calorific value than illuminating gas, and the engines would have operated particularly efficiently. Tests of a 595bhp four-cylinder inverted vertical gas engine made the Snow Pumping Works, undertaken in the USA in the Spring of 1901, suggested that consumption was as low as 9.1 cubic feet per bhp/hr. The thermal efficiency of this particular engine, estimated as about 24 per cent on the basis of the brake-horsepower figure, was much better than even the best conventional steam engine.

Coal was the most popular source of illuminating or 'town' gas, which was manufactured on a grand scale by distillation in closed retorts. However, gas of this type was expensive enough to encourage alternative sources. A cheaper method was found simply by burning coal. 'Producer Gas', as this was called, was obtained by forcing a blast of air through an incandescent charge of fuel, but was not rich enough to drive machinery efficiently. An answer was found in 'water gas', which was generated in much the same manner but substituted a jet of steam for the air blast. Though much more richer than producer gas, water gas still had half the calorific value of town gas. It was appreciably cheaper than town gas, but four times as expensive as producer gas and could only be produced intermittently from a single generator.

An answer to the problem was found by combining the generation of producer and water gas, obtained by injecting air and high pressure steam simultaneously into anthracite or gas coke at red heat. The principal advantage of this system was that gas could be supplied continuously.

Attempts were made in the early 1900s to obtain gas from ordinary coal, and even from sawdust. The Mond system pioneered by Brunner & Mond of Northwich in Cheshire—often on a huge scale—successfully handled bituminous coal slack. A major disadvantage lay in the excessive quantities of carbon monoxide produced by these manufactories, which was far greater than the amount produced by illuminating gasworks.

Many different types of 'power gas' were advertised, but only a handful were distributed on a large scale. There were three basic patterns. In the low pressure system, air was sucked into the generator by the partial vacuum ('suction') formed by the action of the motor piston. The high-pressure systems relied on the air/steam charges being draw into the generator by a steam jet or forced in to it by a fan.

Typical of the small high-pressure systems was the plant patented by J. Emerson Dowson in 1878 (?). Made by Crossley, the perfected design consisted of a tall cylindrical generator filled with anthracite or gas coke, and a closed-grate boiler to generate steam. Superheated steam entered the base of the generator only after passing at high velocity through an injector, taking with it a strong air current.

Gases generated within the anthracite charge combined with oxygen supplied in the air/steam charge and rose to the top of the generator tower. They then passed through a water trap and scrubbers into a gas holder. Production of gas was controlled automatically by a valve on the air injector, which allowed steam and air to vent into the atmosphere if pressure in the gas holder rose too far.

The low-pressure suction gas plant made by the National Gas Engine Co. Ltd was typical of its class. A charge of anthracite was loaded into a cylindrical generator lined with fire brick and surrounded by an annular vapouriser, an air heater, and a feed-water heater. Air was drawn through the air heater into the vapouriser, where it became saturated with steam before being drawn up under the firegrate and then up through the incandescent fuel. The resulting gas was led from the top of the furnace to enter the base of the scrubbing tower through a water trap. It rose through a filter of coke, saturated with water trickling constantly downward from a spray mounted under the top plate of the scrubbing tower. The gas then travelled from the scrubber to enter the engine by way of a small intermediate expansion box.

In 1906, the Royal Agricultural Society tested fourteen suction gas plants at the Derby Show. The victor was the 20bhp National unit, followed closely by the 15bhp Crossley. Consumption of coke or anthracite averaged 1.1–1.6lb/bhp/hr, water being used at an hourly rate of 0.75–1.5 gallons per brake horsepower according to load. Fuel consumption 'per bhp/hr' reduced as load increased, whereas the use of water increased commensurately.

A Scotsman named MacCallum patented an interesting coal-burning derivative of the gas engine in 1894, a few being made by D. Stewart & Co. of Glasgow, but the success of this approach was delayed until the advent of pulverised fuel which could be sprayed directly into the cylinder.

Gas engines were comparatively cheap to buy and were relatively easy to maintain. They were far less dangerous than steam engines, could be operated at short notice, and had a higher thermodynamic efficiency. Power grew rapidly. The largest Otto & Langen engine of the early 1870s was rated at about 3hp, stood about 13ft tall and weighed about two tons; a 20hp four-cycle Otto engine was made in 1881, a 100hp Simplex in 1889, and 200hp was being regularly exceeded by 1898.

A survey undertaken by the Belgian engineer Mathot, published in 1910 in *Construction and Working of Internal Combustion Engines*, noted that seven principal European gas engine manufacturers—Crossley, Ehrhardt & Sehmer, Otto, Körting, Société Alsacienne, Cockerill and Maschinenfabrik Augsburg–Nürnberg—had between them made 814 'large' engines by 1908. The aggregate indicated horsepower was 689,000, which gave an average of nearly 850hp per machine. These were staggeringly impressive figures by the standards of even a decade earlier. Ehrhardt & Sehmer had made 59 engines averaging 1183hp; Vereinigte Maschinenfabrik Augsburg–Nürnberg had made 215 averaging 1192hp apiece.

Mathot estimated the aggregate global gas-, oil- and petrol-engine horsepower to be a little over four million; taking 12hp as an average, therefore, more than 335,000 engines would have been made in little more than forty years.

Crossley, beginning in 1868 with the upright Otto & Langen engine and then progressing in 1877 to the horizontal four-stroke Otto machines, had made more than sixty thousand gas engines by 1909 aggregating 1.04 million horsepower. They ranged from a small 1.2bhp single-cylinder vertical to a large tandem horizontal engine rated at 680bhp. The largest engines offered in Britain at this time were 2500bhp horizontal double-tandem units made by the Premier Gas Engine Co. Ltd of Sandiacre, near Nottingham.

COPIES OF THE OTTO ENGINE

The Otto engine was undoubtedly the most influential of all gas-engine designs, and was soon a target for copysists. The inventor was forced to pursue many rivals through the courts, but the results of litigation were surprisingly variable.

The case brought in France against the promoters of the Simplex (q.v.) engine was dismissed on the understandable grounds that the patent granted in 1862 to Beau de Rochas took priority over Otto's. In Britain, however, a similar defence failed on the grounds that the existence of a copy of the patent in the British Museum was not in itself sufficient to consider the four-stroke idea to be in the public domain. Few Otto type engines were made in Britain until the expiry of the master patent in 1890, excepting by accredited licensees Crossley. The influence of the patent also explained why so many successful attempts were made to promote alternatives (e.g., the Atkinson machines).

Though the four stroke Otto-cycle engines were all basically similar, details varied greatly. British-made machines, expecially those made before 1900, usually incorporated flame or incandescent-tube igniters; in continental Europe, however, electrical ignition was far more common. However, many later British gas engines also featured induction-coil or magneto ignition, and substantial numbers of older machines were eventually rebuilt. Typical of the thousands of Otto cycle engines built in the last decade of the nineteenth century were those built by Campbell of Halifax. The company's range extended from . . . to . . .

EARLY OIL AND PETROL ENGINES

The petrol type Simplex was one of the first engines to be tried in a vehicle, when Frenchman Éduard Delamare-Deboutteville fitted a stationary engine in a four-wheeled hunting brake in 1883. The experiment was eventually abandoned, as the carriage proved to be too fragile for the weight of the engine. A rubber-tyred tricycle followed, but its frame collapsed under the weight of the engine.

The first successful purpose built petrol-engined car was built in 1885 by Rhenische Gasmotorenfabrik Karl Benz of Mannheim. The three-wheel vehicle was driven by a single cylinder xxhp water-cooled engine with electrically-operated ignition and an inlet valve driven from the crankshaft. Patented on 29th January 1886, the car also had an efficient differential gear. First demonstrated publicly in July 1886, the Benz vehicle attracted only cursory attention.

More successful was the four-wheeled motor vehicle built in 1886 by Gottlieb Daimler, on the basis of a horse-drawn carriage. In 1887, Daimler built the first motor vehicle to be powered by a twin-cylinder high speed 'V'-form engine, with which the vehicle attained 17.5 km/hr. In 1889, Daimler patented an engine with inlet valves in the piston crown, aspiration apparently being through the crank case.

COMPRESSION-IGNITION ENGINES

Englishman Herbert Akroyd Stuart patented the first commercially successful compression-ignition engine in 1890, made by Richard Hornsby & Sons of Grantham from 1892 onward. The first sale was made to the Newport Sanitary Authority. The earliest engines required an external heater for the cylinder until they had run long enough to be self-sustaining; and fuel was injected into the chamber by a special plunger-pump system. By 1892, Hornsby & Sons had made an experimental high-pressure version of the Akroyd Stuart compression-ignition engine which could be started from cold without external heat, representing a great step forward.

The high-pressure compression-ignition engine developed by Dr. Ing. Rudolf Diesel, sales manager of the Linde Ice Making Company, was patented in Germany on 28th February 1892. After agreements had been reached with Krupp and Maschinenfabrik Augsburg, the prototype was run in the latter's factory on 10th August 1893. A succession of teething troubles then delayed the start of series production until 1899. The earliest engine had a compressed-air fuel injection system.

A high pressure compression-ignition (Diesel) engine built by the St Louis Iron & Machine Works began work in the Anheuser Busch Brewery in September 1898, the first of its type to enter commercial service anywhere in the world, and production of four stroke compression-ignition Diesel engines commenced in the factory of Maschinenfabrik Augsburg in 1899.

The world's first two stroke compression-ignition engine was made by the Diesel Motor Co. Ltd of Guide Bridge, Manchester, and successfully demonstrated on 25th March 1901.