CORNISH ENGINES

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The application of steam power was a major technological development which drove a fundamental change in society in the 18th and 19th centuries. Steam power was the catalyst for the industrial revolution and much development took place in Cornwall where steam engines were used to pump water out of mines.

Early Developments

The first substantial application of steam power was by Thomas Newcomen whose first beam engine may have operated at Huel Vor tin mine as early as 1710, although this is not well documented. Another of his engines, erected at Dudley Castle in Staffordshire in 1712, is generally taken to be the first application in Great Britain.

There were many earlier developments which led up to this first practical application of steam power:

- In the first century AD Hero of Alexandria built a device known as the Sphere of Aeolus which consisted of a rotating ball which was spun by steam jets. At the time this was regarded as a curiosity rather than something which had practical application.

- In the 17th century there were important discoveries about atmospheric pressure. Evangelista Torricelli who was an assistant to Galileo found that atmospheric pressure was only able to support a column of water of 10m in height and for more dense liquids this height was proportionally reduced.

- In 1654 Otto Von Guericke demonstrated a device which consisted of a piston in a cylinder. The piston was connected to a rope and a team of 50 men tried to raise it against the pressure exerted on the top of the piston by the atmosphere. They managed to raise it halfway but were unable to hold it up. Some of the elements of a steam engine were already in place!

There were several further steps toward building the first practical steam engine, the most important being in 1698 when Thomas Savery was granted patent rights for *'An invention for raising water and occasioning all sorts of mill work by the impellent force of fire'.* Savery's device consisted of a chamber which was filled with steam from a boiler. A pipe ran from the chamber down into the water which was to be sucked up. The steam in the chamber was condensed and water was sucked up by the resulting vacuum and prevented from returning by a valve. Steam was then admitted into the chamber which forced the water up a delivery pipe. Savery described his pump as ‘the miner’s friend’ but it does not seem that it was used to pump water out of mines.

Denis Papin working in France had built an experimental engine in 1690 which operated by allowing steam inside a cylinder underneath a piston to condense as it cooled. As it condensed the pressure of the atmosphere forced the piston down.

The First Commercial Engines – Thomas Newcomen

The next development was by Newcomen who was probably aware of these previous developments and which we may presume informed his efforts.

Newcomen served an apprenticeship as an iron monger and blacksmith in Devon, probably Dartmouth, where he spent about 10 years developing his engine. This consisted of a vertical cylinder with an inverted piston which was connected to a pivoting beam. Steam was admitted to the cylinder which allowed the weight of the pumping rods connected to the other end of the beam to raise the piston. Water was sprayed into the cylinder when it reached the top of its stroke and this condensed the steam creating a vacuum under the piston. The pressure exerted by the atmosphere on the top of the piston forced it down, the piston pulled down on the pivoting beam, and the other end of the beam lifted the pumping rods. This was the power stroke of the engine.

A Swede named Martin Triewald later recorded that the condensing water spray had been discovered by chance when a solder joint in a cooling water jacket around the cylinder failed. The resulting spray accelerated the condensation of the steam and greatly increased the speed of the engine. The engine was typically located in an engine house with the beam pivoting on a gudgeon located on the massive front wall of the engine house. The beam projected out of the front of the engine house and as has already been explained is attached to the pumping rods.

In retrospect Newcomen’s developments can be seen as just one step in the evolution of steam power but are of great significance since they represent the first practical widespread application of steam in an industrial setting. There were several technical problems to be solved in the design and operation of these engines. Ensuring an adequate seal between the piston and cylinder was a challenge, especially since some of the cylinders were to become as big as 70 in

(1778mm) diameter and accurate boring at this diameter was impossible with the equipment available at the time. (1/16 in was considered an accurate bore). Later, engineers achieved a tighter fit by shrinking a wrought iron piston ring onto the piston just as a rim was fitted to a wagon wheel.

Boilers were similar to those used by brewers and generated steam at a pressure only slightly greater than that of the atmosphere, about 2-3 psig (14-21 Kpa). At first these were made of copper with a lead top, then all copper and finally of iron. Massive wooden blocks wrapped with old rope served to stop the travel of the piston at the end of its stroke. Initially the engines cycle was controlled by manual valves. The repeated heating and cooling of the cylinder caused problems with maintaining an adequate seal and also represented an efficiency loss.

Details of Newcomen's Dudley Castle Engine of 1712 were well documented. It had a cylinder bore of 21in (533 mm), a stroke of 6 ft (1.8 m) and operated at 12 strokes per minute. At each stroke the pump raised 10 gallons of water 153 ft. A major benefit of the steam engine was that by facilitating the removal of water from mine workings, it was possible to exploit deeper deposits of ore.

As we have seen, there were reports that the first Newcomen engine in Cornwall ran at Wheal Vor near Breage from 1710 until 1714, but this cannot be confirmed, and the veracity of this claim has been called in to question. But despite the uncertainty about the first steam engine in Cornwall it was probably operating by about 1715.

In 1727 there were only 5 Newcomen engines operating in Cornwall. Their slow acceptance was entirely due to prohibitive fuel costs which were due to three reasons: taxation on coal, the cost of transporting coal to Cornwall and the high coal consumption of Newcomen's engines. Finally, as the result of petitions from Cornish mine adventurers, the tax on coal was abolished in 1739, by which time there was only one engine working. By 1758 at least twelve engines were at work, this number being increased by a further sixty when Pryce, writing in 1778, stated that *'Mr. Newcomen's invention of the fire engine enabled us to sink our mines to twice the depth we could formerly do by any other machinery.'* Whilst Newcomen's engines had enabled the mines to reach depths which had been unthinkable seventy years earlier, they continued to be very expensive to operate.

John Smeaton, who is best known as a civil engineer responsible for among other things, the Eddystone Light House and Charlestown Harbour, devised a performance measurement for steam engines – ‘duty’. This was defined as the number of pounds of water which could be raised a distance of one foot by burning a bushel (94 lbs) of coal. Newcomen’s early engines had a duty of 2 to 3 millions. Smeaton’s part in the development of the steam engine was in refining the proportions of the Newcomen engine to increase the duty. He found the major impediments to performance were poorly designed boilers, ill fitting pistons and faulty valve gear. By 1775 there were 60 engines working in Cornwall and 100 in the Tyneside area and the duties of the best performing engines had been improved to between 10 and 12 millions.

The pumps used for dewatering mines were called *bucket pumps*, which we recognize as lift pumps. Their pistons were known as buckets. They pumped on the up-stroke, when a clack or valve in the bottom of the pipe opened and allowed water to enter beneath the piston. At the same time, the piston lifted the column of water above it, which could be of any distance. The piston could only ‘suck’ water to a theoretical maximum of 33 ft (10m) which was the height of a column of water which could be supported by the pressure of the atmosphere, but this only occurred at the bottom of the shaft. On the down stroke, a clack in the bucket opened, allowing it to sink through the water to the bottom, where it would be ready to make another lift.

Watt’s Developments

The next important developments in steam engine technology were initiated in 1763 when James Watt, an instrument maker who had a workshop in the University of Glasgow, was asked to repair a model of Newcomen’s engine used at the University. By 1765 he had recognized that a major source of inefficiency was the heating and cooling of the piston and cylinder on every stroke and he developed an elegant solution in the form of a separate condenser. In his own words:-*‘If a communication were opened between a cylinder containing steam and another vessel which was exhausted of steam and other fluids, the steam, as an elastic fluid, would immediately rush into the empty vessel, and continue to do so until it had established equilibrium or otherwise, more steam would continue to enter until the whole was condensed’.* He patented this concept which gave the company of Boulton and Watt a virtual monopoly on the manufacture of engines until the patent expired in 1800.

An early benefactor was Dr John Roebuck who had Watt build an engine for his coal mine at Bo’ness. Watt lacked practical experience with large scale machinery and the engine which was started in1768 did not run well. Roebuck experienced financial difficulties and work on the engine was abandoned in 1770. At this point Watt occupied himself with other work until a second benefactor, Mathew Boulton owner of the Soho Works just outside Birmingham offered him a partnership. The Soho works manufactured all kinds of metal goods such as door knockers and corkscrews and had hitherto been powered by water. Boulton recognized the potential for the steam engine, both as motive power for his own endeavours, and for industry in general.

By 1778 the first Watt engine had been installed at the Chacewater Mine, later part of Wheal Busy. By 1783, 21 Watt engines were at work in Cornwall with only one Newcomen engine left. By 1790 there were 45 Watt engines.

Watt's next development was to make a double acting engine in which steam was alternately supplied to each side of the cylinder while the other side exhausted to the condenser. This doubled the power output of the engine. Remember that these engines operated with low pressure steam, very close to atmospheric pressure, so that for a single acting engine, on the inlet stroke the piston was raised by the force of gravity acting on the other end of the beam, or the momentum of the flywheel in the case of a rotary engine. The power was generated by atmospheric pressure on one side of the piston vs. the reduced pressure created by the condenser on the exhaust stroke. In a double acting engine each stroke was driven by the steam pressure (only slightly higher than atmospheric pressure) acting against the reduced pressure created by the condenser.

The double acting engine required a new means of transmitting the motion from the piston rod to the beam. For a single acting engine this had been accomplished by a chain linkage under tension which converted the linear motion of the piston rod to the rocking motion of the beam. On the inlet stroke, the weight of the pumping gear pulled the beam down at the outdoor end and the indoor end pulled the piston rod up as steam was admitted to the cylinder. On the exhaust/power stroke the piston rod pulled the indoor beam end down and the outdoor end in turn pulled the pump rod up.

Watt devised a linkage which would transmit power both pushing and pulling, and this was known as his parallel motion. Writing to his partner, Boulton he says: *'I have started a new hare. I have got a glimpse of a method of causing a piston rod to move up and down perpendicularly by only fixing it to a piece of iron upon the beam without chains or perpendicular guides or untowardly frictions,* *arch heads or other pieces of clumsiness. I think it a very probable thing to succeed and one of the most ingenious simple pieces of mechanism I have contrived.'*

Commercial engines which had been built so far only created reciprocating motion, but in 1780 James Pickard used a crank in conjunction with a Newcomen engine and immediately patented his idea. Boulton could see the utility of steam powered rotary motion. His Soho works complex had used water power. Watt's solution (quite possibly invented by William Murdoch but patented by Watt) to the problem of converting reciprocating motion to rotary motion was by means of an arrangement known as a sun and planet gear. A stationary gear attached to the end of a connecting rod engaged with a similar gear on the drive shaft. As the other end of the connecting rod moved up and down the planet gear end moved around the sun gear; for each revolution of the planet gear the drive shaft makes two revolutions.

Watt's first crank engines were built in 1794, the year Pickard's patent expired, but he continued to build sun and planet gear engines until 1802. Watt also developed the application of a pendulum governor to his engines. This had previously been used to regulate the speed of windmills. A set of weights were individually suspended from a point on a vertical rotating shaft. Centrifugal force tended to pull the weights outwards from the shaft while gravity tended to pull them downwards and when these forces were in equilibrium the weights assumed a certain position relative to the shaft. If the shaft sped up the centrifugal force increased but of course the gravitational force remained the same so the weights assumed a new position, higher and at a greater distance from the shaft. A linkage attached to the weights could be used to regulate a steam valve. This could obviously only be applied to the new rotative engines.

Watt is also credited with devising the horsepower as a definition of the rate at which an engine was capable of doing work. It has been alleged that Watt inflated the value relative to the actual power output from a horse to avoid any negative comparisons of engine performance. In other words, a 50 HP engine would have more power than 50 horses! A horsepower is 33000 ft-lb/min, so it is the power required to raise 33000lb one foot in one minute or to raise 1 lb 33000 ft in one minute or anything in between.

Boulton and Watt's business practices were just as savvy as Watt's inventiveness; first the patent which effectively denied the right of producing external condenser engines to the competition, second the way in which engines were sold such that the customer paid for the materials and provided the labour for erection to engineering specifications set out by the Company and third a royalty of one third of the value of coal saved compared with an atmospheric engine and which was paid on an ongoing basis. Watt is one of the most significant figures in the development of steam power, but there is also a strong case for saying that his patent stifled development by competitors for 30 years. Fortunately for his competition the patent expired in 1800 and an application for its extension was denied.

Although Watt certainly understood the potential benefits of increased steam pressure, and his patent included expansive working whereby the steam valve was shut off part way through the stroke, he refused to design and operate engines at any pressure higher than 3 psig, which was a major impediment to improving performance.

The Cornish Engine

In 1781 Jonathan Hornblower patented a 2-cylinder engine and in 1782 installed the first one at Radstock Colliery in Somerset. Several more Hornblower engines were installed in Cornwall, but the owners ended up paying royalties to Watt under his patent. Steam expanded in the smaller high-pressure cylinder, was exhausted into the larger cylinder where it expanded further to do more work. The high-pressure cylinder was attached to the beam closer to the fulcrum than the low pressure cylinder and had a shorter stroke. These engines were operated at pressures close to atmospheric and because of this were unable to derive much benefit from the compound arrangement.

Engine house at The Crowns, Botallack

Cornishman Richard Trevithick pioneered the next major development which was the use of high pressure steam His first high pressure application was a beam winding engine installed at Cooks Kitchen (later part of South Crofty) mine in 1800 which did have a condenser. Another high-pressure engine at Dolcoath exhausted to atmosphere and earned the nickname of ‘the Valley Puffer’.

Trevithick’s boilers were cylindrical with a cast iron shell and an internal wrought iron fire tube with the fire grate at one end of the flue and the chimney at the other and they operated at pressures up to 50 psig (345 kPa). This would become known as a Cornish Boiler. (A later twin flue variant would be known as the Lancashire Boiler). He replaced traditional wagon style boilers with his new design at Dolcoath in 1806.

A major benefit of high-pressure steam engines was that they could do about 4 times as much work as could be done with a Watt engine of similar size. Also, because there was no need for a cumbersome condenser, it made for a very compact unit with a much higher power to weight ratio. This enabled it to be used as a source of motive power for transportation.

The first steam locomotive was built by Trevithick in 1802 and ran on a railway at Coalbrookdale in Shropshire (where Abraham Darby had first pioneered the smelting of iron with coke in 1709). There was an unfortunate accident, somewhat surrounded by mystery, and it seems that the world's first locomotive ended up as a stationary engine. Trevithick went on to many great achievements in the field of steam powered transportation including the steam carriage of Camborne Hill fame in 1801.

Once Watt's patent had expired the stage was set for using high pressure steam in combination with a condenser. This combined the work available from the expansion of the steam and that from condensing the expanded steam. In practical terms it allowed the steam to be cut off early in the stroke, initially one of Watt's ideas but which had resulted in negligible benefit in an engine which worked close to atmospheric pressure with what was essentially 'kettle steam'.

In 1812 he built a single acting high pressure (40 psig 275kPa) condensing beam engine at Wheal Prosper Mine near Gwithian which achieved a duty in excess of 30 millions. This was the Genesis of the Cornish Engine Era.

What is known as the Cornish Engine was a simple single acting beam engine which used the expansive power of the high pressure (40 – 60 psig, 275-415 kPa) in combination with a separate condenser. Steam was admitted to top of the cylinder for between 1/5 and 1/10 of the stroke after which it was shut off and the remainder of the stroke was driven by the expansion of the steam. As the piston reached the bottom of its stroke the equilibrium valve (known by engine men as the Uncle Abram valve) opened which allowed the vapour from the top of the piston to enter the chamber below the piston and at the same time exhaust to the condenser. The weight of the pump rods drove the up or equilibrium stroke. As the piston approached the top of its stroke the equilibrium valve closed, and the steam valve opened slightly before the top of the stroke to allow a live steam cushion to reduce the shock of the change of direction.

Cornish pump at Nourse Mine (Witwatersrand, South Africa)
Source: SA Archives

In 1801 Joel Lean, manager at Wheal Crenver and Oatfield, Crowan was the first to replace bucket pumps with plunger pumps except for the very lowest level, and the arrangement of plunger pumps spaced at an average of 30 fathoms (55m) operated by a single acting beam engine became standard Cornish practice. At about this time engineering works and foundries were established in Cornwall for the manufacture of engines and mine related equipment. The most well known was Harvey's of Hayle, also Copperhouse Foundry of Hayle and Perran Foundry of Perran's Wharf.

These engineering works built Cornish and other design engines, pumps and other heavy equipment for the thriving Cornish Mining Industry and also for mines around the world. There were many famous personalities associated with them. Arthur Woolf from Illogan was an engineer for Harvey's who made important contributions with his compound engine and also in the design of high-pressure boilers. His engines were two-cylinder double acting beam engines and this design became popular later in the 19th century and the Hamilton Water Works Engine is of this type.

William Sims was another respected Cornish Engineer who contributed to the improvement of engine efficiencies.

In 1810 Captain John Davy commenced publication of the 'Engine Reporter' with Joel Lean as registrar and reporter. The duty figures for operating engines were published allowing mine owners and operators to compare performance and also leading to healthy competition and improvement. In 1825 the average duty for the 56 engines reporting was 32 millions (remember the duty for Newcomen's first engines was 2 – 3 millions). The same year Samuel Grose, Engineer at Wheal Hope Gwinear, built a 60 in(1524mm) engine which reported a duty of 45 million. Publication of the 'Engine Reporter' continued for over 100 years.

In 1834 William West's new 80in (2032mm) engine at Fowey Consols achieved a duty of 125 millions operating with a steam cut off of 1/10 the stroke.

Steam power was used for duties other than pumping and these usually involved rotative engines. In 1813 the first steam stamps were installed at Wheal Fanny (Carn Brea). In 1835 the first steam capstan was installed by William West at South Hooe and in1842 the first man engine was installed at Tresavean by Michael Loam.

In Cornwall the beam was known as the Bob. Engine houses were of a rectangular plan. The front wall was of massive granite construction to support the weight of the bob and withstand the stress due to the rocking of the bob; it is known as the bob wall. The cylinder was bolted down to a plinth within the engine house. The chimney was situated at one of the rear corners of the engine house and the boilers were located in an adjacent boiler house. Engine ponds were located nearby to store water for the condenser. The pump rod shaft was located immediately in front of the engine house directly below the outdoor end of the bob. The pump rods were made of Scandinavian or Canadian timber up to 24 inch square at the upper end. It was quite usual that the water would not be pumped all the way to the surface, but it would be raised from the lowest levels of the mine to an intermediate point and discharged through an adit to the surface or the sea.

In addition to Cornwall there were many Cornish Engines built for English Collieries and also for various mines around the world particularly in Australia, South Africa and Mexico.

The largest engines ever built were three annular cylinder compound engines built by Harvey's of Hayle and installed to drain the Haarlem Mere in Holland between 1845 -9. Each had an 84 in (2134mm) inner cylinder and an outside annular piston 144 in (3657 mm); one of them operated 11 radial beams, the other two 8 beams each. One of these has been preserved there is an excellent web site with animated simulations of different parts of the engine – www.cruquiusmuseum.nl

The final chapter of the Cornish Engine story is associated with what is reckoned to be the most significant improvement in human health to date, the provision of clean water and sanitation. As these developments gained rapid acceptance in the 19th century, a further application of the Cornish Engine was for water pumping duties and there were many fine examples of these efficient engines installed in water works and sewage pumping stations. There were 70 engines pumping water in the London area alone.

Finally, here is a table which traces the increase in efficiency as the steam engine was developed. This shows the considerable improvements which were made and shows the tremendous achievement of the Cornish Engine.

Approximate Coal Consumption of Steam Pumping Engines Per Water Horsepower per Hour			
		lb	kg
1725	Newcomen	31.9	14.5
1775	Smeaton	17.0	7.7
1800	Watt	8.8	4.0
1840	Cornish	3.1	1.4
1870	Horizontal Compound	2.0	0.9
1885	Vertical Triple Expansion	1.5	0.7
1900	Steam Turbine	1.0	0.5