La química en la historia,
para la enseñanza

James Watt
The Steam Engine

*Jaime Wisniak**

Resumen
James Watt (1736-1819) fue uno de los más brillantes ingenieros e inventores de su época; su desarrollo y mejoramiento de la máquina a vapor moderna se tradujo en un gigante paso hacia adelante de la tecnología moderna, los procesos fabriles, los medios de transporte y la utilización de la energía de la manera más eficiente. Al él le debemos el condensador separado, la máquina de doble acción, la expansión del vapor, el gobernador de estrangulamiento, la conversión del movimiento recíprocante en movimiento circular, la válvula flotante para regular el abastecimiento de agua, y el indicador de máquina. El nombre de Watt está también asociado con una polémica científica que persiste hasta nuestros días, la controversia del agua: quién descubrió que el agua no es una sustancia elemental sino que está formada de hidrógeno y oxígeno en la razón atómica 2:1.

Abstract
James Watt (1736-1819) was one of the greatest engineers and inventors of all times; his development and improvement of the main features of the modern steam engine resulted in a tremendous step forward of modern technology, manufacturing processes, means of transport, and to the utilization of energy in a most efficient manner. To him we owe the separate condenser, the double acting machine, the expansion of steam, the fly-ball throttling governor, the conversion of reciprocating motion into rotary motion, the float valve as a regulator of the water supply, and the engine indicator. The name of Watt is also associated with a scientific polemic that continues until today: the water controversy, regarding who discovered that water was not an elementary substance but constituted of hydrogen and oxygen in the atomic ratio 2:1.

Life and career

Figure 1. James Watt (1736-1819). By permission of Edgar Fahs Smith Collection, University of Pennsylvania Library.

James Watt (Figure 1) was born in Greenock, January 19, 1736 the fourth of the five children of James Watt (1698-1782) and Agnes Muirhead (1701-1753). His three older brothers and sisters died in infancy, and the youngest, John (1739-176), drowned on a shipwreck on a voyage to America, at the age of twenty-four (Carnegie, 1905; Marshall, 1925; Dickinson, 1989).

James' grandfather, Thomas Watt (1642-1734), was "a teacher of the mathematicks" and navigation to the fishermen and seamen of the locality. The landlord of the district appointed him his Baron Bailie, an office, which then had important judicial functions. In addition, he was named Elder of the community, a highly respected and honourable position. Before his death he had established a considerable business in repairing and provisioning ships; repairing instruments of navigation, compasses, quadrants, etc. He married Margaret Shearer (1656-1735) by whom he had six children, of whom only two sons, John (1694-1737) and James (1698-1782), reached maturity. James Watt followed in his father's footsteps as shipwright, contractor, provider, etc., becoming famous for his skill in the making of the most delicate instruments. Like his father, he became a man of position and influence in the community and was universally esteemed.

James Jr. was from the first a sickly boy and showed signs even then of the chronic ill health that was going to distress him through the greater part of his life. His fond mother having lost several of her children born previously was very devoted to him and rather than sending him to a school where he might not be properly looked after, kept him for a time under her own care at home and gave him his first lessons (Carnegie, 1905). Schooling, however, composed only the lesser part of his education; the more significant portion he received in his father's shop, where he first gained the knowledge of con-

---

* Department of Chemical Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel 84105

Recibido: 17 de julio de 2006; **aceptado:** 5 de octubre de 2006.

temporary craftsmanship—woodworking, metal-working, smithing, instrument making, and model making.

His most intimate schoolfellow was Andrew Anderson, whose elder brother, John Anderson (1726-1796), was the well-known Professor of Natural Philosophy (a term that included physics, experimental philosophy, and physical astronomy). James was given unrestricted access to the Anderson's valuable library, in which he spent many of his evenings (Carnegie, 1905).

At fifteen, James had twice read Wilhelm van St. Gravesandes (1688-1742) book *The Mathematical Elements of Philosophy* (Gravesande, 1720) and had made numerous chemical experiments. Watt's mother passed away suddenly when he was seventeen. At that time, his father business was in bad shape, John, the youngest brother, had taken to the sea in one of their boats and been shipwrecked (1793), leaving only James at home. His father intentions were for James to carry on the business, but when other misfortunes swept away most of the wealth, it was resolved that James would learn a trade.

In June 1754 he was sent to Glasgow to learn the craft of a mathematical instrument maker. It was a profession closely allied to that of his father and his grandfather, and it gave more scope to his mechanical dexterity than he would have got by following either of their trades. Glasgow was far from becoming an industrial city and it was not surprising that Watt did not find someone who could teach him the art he wanted. For this reason he entered the service of a kind of jack-of-all-trades, who called himself an "optician" (he was actually a simple mechanic) and sold and mended spectacles, repaired fiddles, tuned spinets, made fishing rods and tackle, etc. Through George Muirhead (1715-1773), Professor of Oriental Languages at the University of Glasgow, and a kinsman of his mother, James came into contact with other members of the faculty of the university, and, as usual, attracted their attention, especially that of Robert Dick (-1757), Professor of Natural Philosophy, who realized Watt's mechanical abilities and understood that he would not be able to learn nothing of his future craft in Glasgow. For this reason he strongly advised him to proceed to London, where he could receive better instruction. On June, 1755 Watt mounted his horse to ride to London, with a letter of introduction from Dick in his pocket, addressed to James Short (1710-1768), the well-known optician, one of the few men who could have helped Watt at that time.

After arriving in London Watt faced for the first time the problem which would make his life difficult for the next few years. He was an outsider and had never been an apprentice so that he could not even qualify as a journeyman. The city of London still clung to its medieval customs and privileges, chief among which was the right to keep all its trade in the hands of the native-born townsmen, and to forbid any "foreigner" from another town to settle down within its walls to earn his living. The initiative in these matters came generally from the Gilds and Companies, which controlled the various trades carried on in the City. No person could set up in business on his own unless he was a Master and had been admitted as such into the Gild. The normal way of becoming a Master was serving as apprentice for seven years under a bona-fide Gildsman, and then paying the fees for admission to the rank and privileges of Mastership. The Clockmakers of London were a trade of this kind. The mathematical instrument makers were a branch of the Company of Clockmakers and had the same rules. Jamess only way was to bind himself by a legal contract as apprentice to a member of the trade. Since Watt was not interested in serving for seven years he used the good services of Short to find someone who take him for much less time. Short introduced him to John Morgan, mathematical instrument maker of Finch Lane, Cornhill, who was willing to take him for a year and teach him all he wanted to learn in return for twenty guineas and his pupil labour, to compensate his master for the violence he was doing to conscience (Marshall, 1925). In a letter to his father Watt described his master "as being of as good a character, both for accuracy in his business and good morals, as any in his way in London. Though he works chiefly in the brassway, yet he can teach me most branches of the business, such as rules, scales, quadrants and similar."

Watt devoted all his time to mechanical work until late hours, six days a week, and taking no leisure. All these took a heavy toll on his health; he caught a severe cold during the winter and was afflicted by a racking cough and severe rheumatic pains. With his father's approval he decided to return home to recuperate, taking good care, however, to secure some new and valuable tools, a stock of materials to make many others, which "he knew he must make himself", together with a copy of Edward James Stone's (1831-1897) translation of Nicholas

Bion's (1652-1733) book on the construction of mathematical instruments (Bion, 1723). Once in Glasgow Watt faced again the rigid rules of the trade. The Incoporation of Hammermen, to which a mathematical instrument maker must belong, considered Watt an intruder on their privileges and prevented him from working in the trade because he had not spent seven years as apprentice.

Watt was saved from this requirement by a twist of destiny. In 1755 the University of Glasgow received news that a graduate of the university, Alexander Macfarlane, and a rich merchant who had established an observatory at Port Royal, Jamaica, had bequeathed all its valuable instruments to the institution. Classes in physical astronomy had recently been started, and the gift was most opportune, but the sea voyage had somewhat affected the operation of some of the instruments. Professor Dick requested from Watt to stay in town to clean and put them back in order, which Watt did promptly. For this service he was paid five pounds, the first contract money ever earned by Watt in Glasgow.

The university charter, gift of the Pope in 1451, gave absolute authority within the area of its buildings, where the writ of the Hammermen did not run. When, shortly afterwards, it was heard that Watt had been refused leave to have a workshop in the town, the University took him under its protection and on December 6, 1757, gave him a room within the walls of the College, thus he was able to evade the jurisdiction of the corporations of tradesmen through an appointment as "mathematical instrument maker to the university" (Marshall, 1925). This was not an unsual act by the University, she had allowed others previously to set up workshops in her quarters, i.e., Donald Govan, printer of the first Glasgow news sheet, the brothers Robert (1707-1776) and Andrew (1712-1775) Foulis, and Alexander Wilson (1714-1784), the type founder (Dickinson, 1989). His room fronted High Street, where he could offer for sale to the public the instruments he made in his workshop. Following the example of his first master in Glasgow he made and repaired spectacles, fiddles, flutes, harps, guitars, and barrel organs. Although Watt did not know music, he devoted himself to a study the mathematical theory of music, coupling it with his mechanical skills. One of the results was a small wind organ he made for Professor Joseph Black (1728-1799) (Carnegie, 1905).

Of all the friends he made at this time the two who most deeply influenced his future were Black and John Robison (1739-1805), who first directed his attention to the steam engine.

The quality of Watt's work made his business very successful. In order to develop it further he went into partnership, in 1759 with John Craig, who undertook to provide most of the capital needed for expansion and to do all the commercial transactions, which Watt, then as ever afterwards, detested. They started with a stock and cash worth £200 and about five years later were making gross sales up to £600 a year and kept a staff of sixteen men at work. It was Watt's reputation as a universal mechanical expert that brought so much business to his shop. In 1760 the partners opened a shop in Saltmaker and Watt himself rented a house on Delftfield Lane, outside the university grounds (Marshall, 1925).

On June 10, 1763, Watt was made a master of the Lodge of Free and Accepted Masons of Glasgow.

Most opportunely, at this juncture, came Watt's marriage, in July 16, 1764, to his cousin Margaret Miller, a lady to whom he had long been deeply attached. More than one intimate friend has said to the doubt whether he could have triumphed without Mrs. Watt's sunny nature and sweet serenity, which spurred him to new efforts. In 1773 Watt's wife died in childbed in his absence. In July 1776 he married again, this time to Ann McGregor (1750-1832), the daughter of James McGregor, a Glasgow dyer, who was the first in Britain to use chlorine for bleaching, which Claude Louis Berthollet (1748-1822), had developed and communicated to Watt. Two children were born from this marriage: Gregory (1777-1824) and Janet (1779-1894) who passed away without getting married, Ann Watt lived to be 82 and enjoyed the fruits of her husband's success and fame.

In 1766, before his second marriage, Watt closed his shop at the university and opened a land surveying and civil engineering office in Glasgow, where he practiced as a surveyor and civil engineer until 1774. Although these jobs did no pay well, they brought in a more regular income than the chance sales of his little shop. His first undertaking of any size was a 9-mile long navigable canal to connect Glasgow with the collieries at Monkland. The survey was completed in 1769 and he was then asked to supervise the work of construction, at £200 a year, a job on which Watt was engaged until 1772, when the project was stopped. He also built a bridge over the Clyde, reported upon its proposed deepening, and improved the harbours of Greenock and Port-Glasgow (Marshall, 1925). Watt also made surveys for a canal between Perth and Coupar Angus, for the well-known Crinan Canal (as requested by the Commissioners of the Forfeited States) and other projects in the Western Highlands. The Perth Canal was forty miles long through a rough country, and took forty-three days, for which Watt's fee, including expenses, was $400 (Carnegie, 1905). Watt was also commissioned to survey and estimate for a canal from Fort William to Inverness, following the line of the Caledonian Canal afterwards built by Thomas Telford (1757-1834). This was the last and most remarkable of Watt's civil engineering works.

If any difficulty of a mechanical nature arose, people came to Watt for a solution. Thus did in 1811 the Waterworks Company when it failed to get pipes for conveying water across the Clyde to stand, the channel of the river being covered with mud and shifty sand, full of inequalities, and subject to the pressure of a considerable body of water. Watt suggested devised an articulated cast iron suction pipe fitted where necessary with revolving ball and socket joints, and moving like a lobster's tail, adopting itself to the form of the river bed. Watt stated that his services were induced solely by a desire to be of use in procuring good water to the city of Glasgow and to promote the prosperity of a company, which had risked so much for the public good. These were handsomely acknowledged by the presentation to him of a valuable piece of plate (Carnegie, 1905).

During most of his manufacturing activities Watt was beleaguered with financial difficulties. Capital was essential to perfect and introduce in the market the steam engine he had developed. During the first stages, Black had been lending Watt the money necessary to carry out his experimentys, but larger sums were needed. To try to solve the problem Black introduced Watt to John Roebuck (1718-1794), a Birmingham physician who had listened to the lectures given by Black and was looking at the application of chemistry to the processes of industry. His first commercial success was a factory for the manufacture of sulphuric acid by a new process, established at Prestonpans. He then turned his attention to the production of iron in Scotland. Roebuck seemed to be the ideal partner for furthering Watt's engine, he had leased some large coal mines, which eventually had become flooded. The atmopsheric engine that tried for pumping out the water was not enough. Roebuck also stood to gain by Watt's invention, since the chief obstacle to progress in his industry was the limit to the efficiency of water-power as a means to work the bellows that drove the air into the blast furnaces. Finally, his establishment could easily be adapted to the manufacture of engines on a large scale. By the spring of 1768 Watt had made a small engine with which Roebuck was so impressed that he agreed to take the risk and became a partner with Watt. He undertook to pay his outstanding debt of £1000, to bear all future cost of experiments, and of securing a patent. In return for this he was to have two-thirds of the property of the invention (Marshall, 1925).

Eventually Roebuck's business also ran into of financial difficulties and could not longer bear the costs of experiments on the engine. forcing him to sell his part of the society with Watt to Matthew Boulton (1728-1809) of Birmingham. It was found that in the ordinary course of business Roebuck owed Boulton a balance of $6,000. Boulton agreed to take the Roebuck's interest in the Watt patent for the debt. The contract was to continue in force for twenty-five years, from the 1st of June, 1775, when the partnership commenced. This partnership led to the successful commercialization of Watt's steam engine. With the beginning of the new century, 1800, the original partnership of the famous firm of Boulton and Watt expired, after a term of twenty-five years, as did the patents of 1769 and 1775. The term of partnership, which had been fixed with reference to the duration of the patents, was renewed by their sons, James Watt, Jr., Matthew Robinson Boulton, and Gregory Watt. The young men had intelligence and character, a careful education, and knowledge of foreign languages; they proved to be successful managers and led the firm to higher profits than ever (Carnegie, 1905).

From 1795 onwards Watt withdraw gradually from active participation in the business, having accumulated a substantial fortune; in 1804 his happiness was tremendously shocked when his brilliant son Gregory died of tuberculosis.

Many honours were offered or bestowed on him. Robert Jenkinson, Lord Liverpool (1770-1828), then Prime Minister, offered Watt a baronetcy, honour he declined. Twice Watt was asked to take the office of sheriff, in 1803 that of Staffordshire, and in 1816 that of Radnorshire, both of which were declined because he had shrank from public life and felt unfitted for such a duty. He finally found it necessary to declare that he was not a member of the Church of England, but of the Presbyterian church of Scotland, a reason, which in that day was conclusive. In 1816 he was in his eighty-first year, and no difficulty seems then to have been found for excusing him; for it seems the assumption of the duties was compulsory. He was honoured in his lifetime by the formation in Greenock in 1813 of the Watt society. Many societies honoured the great inventor. Watt was a member of the Lunar Society of Birmingham, a fellow of the Royal Society of Edinburgh, the Royal Society of London, member of the Batavian Society of Rotterdam, correspondent of the French Académie des Sciences, and then one of the eight Foreign Associates of the same (Carnegie, 1905).

The University of Glasgow conferred the degree of LL.D. upon him in 1774, and its great engineering laboratory bears his name (Carnegie, 1905). In return in 1808 he founded the Watt Prize in Natural Philosophy and Chemistry, saying: "Entertaining a due sense of the many favours conferred upon me by the University of Glasgow, I wish to leave them some memorial of my gratitude, and, at the same time, to excite a spirit of inquiry and exertion among the students of Natural Philosophy and Chemistry attending the College; which appears to me the more useful, as the very existence of Britain, as a nation, seems to me, in great measure, to depend upon her exertions in science and in the arts."

As told by Carnegie (Carnegie, 1905), in 1816, Watt donated a large number of scientific books to his hometown Greenock to initiate a public library devoted to the instruction of the youth of the city. Nowadays, the library contains over 15,000 volumes and is a valuable adjunct of the Watt Institution, founded by his son in memory of his father, which is today the educational centre of Greenock. Its entrance is adorned by statue of Watt, funds for which were raised by public subscription.

On August 25th, 1819, at the age of eighty-four, Watt passed peacefully away at Heathfield, and was buried in beside Boulton in Handsworth Church, on September 2nd. The Watt Chapel was built subsequently.

On June 18, 1824, as a result of a public meeting in London, a statue of him was executed by Sir Francis Legatt Chantrey (1781-1841) and placed in Westminster Abbey. Lord Liverpool, the Prime Minister presided and announced a subscription of five hundred pounds sterling from His Majesty. The result was a colossal statue, which bears the following inscription, from the pen of Henry Peter, Lord Brougham (1778-1868):

> NOT TO PERPETUATE A NAME
> WHICH MUST ENDURE WHILE THE
> PEACEFUL ARTS FLOURISH
> BUT TO SHEW
> THAT MANKIND HAVE LEARNT TO
> HONOUR THOSE
> WHO BEST DESERVE THEIR GRATITUDE
> THE KING
> HIS MINISTERS, AND MANY OF THE
> NOBLES
> AND COMMONERS OF THE REALM
> RAISED THIS MONUMENT TO
> JAMES WATT
> WHO DIRECTING THE FORCE OF AN
> ORIGINAL GENIUS
> EARLY EXERCISED IN PHILOSOPHIC
> RESEARCH
> TO THE IMPROVEMENT OF
> THE STEAM-ENGINE
> ENLARGED THE RESOURCES OF HIS
> COUNTRY
> INCREASED THE POWER OF MAN
> AND ROSE TO AN EMINENT PLACE
> AMONG THE MOST ILLUSTRIOUS
> FOLLOWERS OF SCIENCE
> AND THE REAL BENEFACTORS OF THE WORLD
> BORN AT GREENOCK MDCCXXXVI
> DIED AT HEATHFIELD IN STAFFORDSHIRE
> MDCCCXIX

In 1882 his name was given a permanent place in the vocabulary of science at the suggestion of Werner Siemens (1816-1892), who, in his Presidential Address to the British Association, made the following proposal: "The other unit I would suggest adding to the list is that of power… It might be appropriately called a Watt, in honour of that master mind in mechanical science, James Watt."

The steam engine

From 200 B.C.E to 1600 C.E. steam was little more than a toy. Many models of heat engine had been proposed, most of the suggestions were based on steam as the working sustance. All these contraptions were not practical becuase the inmense power of heat proved dangerous to generate an difficult to apply. In 1615 Salomon de Caus (1576-1626), an engineer and architect under Louis XIII of France, who came to England in 1612 and was employed by the Prince of Wales to embellish his gardens at Richmond, published a book entitled *Les Raisons des*

Forces Mouvantes, Avec Diverses Machines tant Utile que Plaisante (De Caus, 1615), in which he illustrated his proposition: "Water will, by the aid of fire, mount higher than its source," by describing a machine designed to raise water by the expanding power of steam. De Caus took a metal globe and partly filled it with water through a cock, which was then closed. Through the top of the globe he inserted a vertical pipe, the lower end of which came down nearly to the bottom of his globe and was therefore under the water. Then he applied the fire. The heated air and steam pressed on the surface of the water in the vessel and forced it to flow up the pipe and out as a jet from the top. The result was a toy fountain. It was of no practical use, and could hardly be called an engine, but it is worth describing as being the simplest example of one of the methods of raising water with the aid of fire (Marshall, 1925).

In 1663, Edward Somerset (1601-1667), second Marquis of Worcester, published a curious collection of descriptions of his inventions, written in an obscure and particular language, and entitled *A Century of the Names and Scantlings of Inventions by Me Already Practiced* (Sommerset, 1663). In it Soomerset collected every ingenious device he had ever met with in life, literature or legend, and boldly claimed that he possessed the secret of each without venturing to explain what that secret was. The book contains several shorthand alphabets and codes, several portable fortifications and repeating pistols, a watch that goes for ever, a perpetual motion, a torpedo, an "artificial bird," "a most conceited tinder box," and an automatic horse that a man may ride "using the decent posture with bon grace." Among these marvels are some machines for raising water, mostly by buckets working over wheels and pulleys. Two of these are interesting, Number 68 called "A Fire Water Work," and Number 100. Number 68 was clearly a steam engine on the principle of De Caus, only differing from his in that it had a separate boiler for generating the steam. Number 100 is not clearly enough described to be reconstructed, but it seems to have been some kind of water wheel worked by a man whose strength was multiplied by a system of weights and pulleys. The apparatus of Worcester was actually used for the purpose of elevating water for practical purposes at Vauxhall, near London (Marshall, 1925).

A story repeated in many books is that In the year 1825, the superintendent of the royal Spanish archives at Simancas furnished an account which had been found in the archives, of an attempt made in 1543 by Blasco de Garay, a Spanish navy-officer under Charles V, to move a ship by paddle-wheels, driven, as was inferred from the account, by a steam-engine. Nothing is known of the form of the engine employed, it only having been stated: "a vessel of boiling water formed a part of the apparatus." Actually, as discussed in detail by Hernández Molina in his book (Hernández, 1996), the story seems to be a misinterpretation of the facts. Reading of all the old documents of the Spanish authorities of the time shows clearly that Blasco de Garay's engine was totally mechanical in nature; men located inside the vessel operated a mechanism that transmitted movement to an external wheel.

Real progress began with the work of Dionysius Papin (1674-1712), a French doctor who fled from his country in 1681to escape the persecution of Protestants, settled in London, and became a Fellow of the Royal Society. The chief obstacle to the use of atmospheric pressure to drive a machine was the difficulty of producing the necessary vacuum in an adequate vessel. To Papin belongs the credit for having thought of employing steam to achieve this goal. He took a cylinder, open at the top like a shell case that has been converted into a flower vase, and fitted it with a piston. He put a little water in the bottom of the cylinder, lowered the piston until it rested on the surface, and set it over a fire. As the water boiled, the piston was raised to the top, while the cylinder became full with steam. There it was locked with a catch and the fire was removed. As the cylinder cooled, the steam condensed and became once more a layer of water on the bottom, leaving a vacuum under the piston. When the catch was released the piston made a powerful stroke, driven down by the pressure of the atmosphere, which now had no resistance to overcome. The contraption was again put over the fire and the cycle repeated. Papin remarked that the manner of using his engine to "discharge iron bullets to a great distance, to propel ships against the wind," and so forth, "would be too long here to detail; but each individual must select the construction of machinery appropriate to his purpose" (Marshall, 1925).

The actual breakthrough came with the water raising machine developed by Thomas Savery (1650-1716), a military engineer and also a clever clockmaker. He had often travelled about in Cornwall, and had seen for himself the difficulties the tin miners were having in keeping their mines clear of water. The workings had reached a depth at which the old pumps ceased to function and there was pressing need for something more powerful. Savery tackled this problem as a practical man and invented an engine, patented in 1698, which was actually introduced into some of the mines. In Savery's engine, steam acted directly upton the surface of the water, the pressure of the steam forced the water from the pumping chamber through a pipe line in which there was a crude check valve to prevent a reversal of flow. After the pumping chamber had been cleared of water, the steam supply was cut manually. Next cold water flowing over the chamber condensed the steam. A partial vacuum was created which caused a new portion of water to be sucked in. Because of the direct contact of steam and cold water, the loss of condensation of steam was very large. The cycle was repeated as many times as necessary. In this way he could get the water up about 10 meter. The steam that was condensed represented a substantial loss in efficiency and in addition, there was no way of eliminating the air that accumulated in the cylinder. A simple analysis of the operation, in today's terms would classify Savery's engine as a pump and not as a steam engine.

The fact that a steam engine had actually been used, with some measure of success, to drain a mine estimulated other enterprising men to design better machines. Thomas Newcomen (1623-1729), a Dartmouth blacksmith, undertood the shortcomings of Savery's and proposed to build an engine that would simply provide the power, and then to use it to drive an ordinary suction pump, which would raise the water. This engine was the first successful atmospheric pumping engine. In this geometry the cylinder was also filled with steam, except that it had an open end. A piston moving up and down was connected by means of a heavy chain to one end of a great beam oscillating about a central pitvot (like the beam of a balance). This beam was counterweighed at the other so under it it would pull the piston up. Connection of the cylinder to a steam source would result in steam being drawn into the cylinder. As soon as the cylinder was full of steam, the supply would be cut and the steam condensed like in Savery's engine. The resulting vacuum would force the piston down, thus providing the power. Steam was reamitted and the cyle restarted. A later important modification permitted elimination of the air that accumulated in the cylinder. The first successful model was completed in 1705 and the first engine was set up at Wolverhampton in 1712 (Marshall, 1925). Newcomen's machine was safe, reliable and basically simple, it was powerful, and economically competitve with other means of pumping water, using about 20 pounds of steam per horsepower-hour (Cardwell, 1971). Analysis of the operation shows that steam was only used to force the heavy piston upward, no other work being done by it. All the pumping was done on the downward stroke. The cylinder got cooled between each stroke, leading to a wastage of about four-fifths of all the steam used.

Both Savery and Newcomen were inspired by the desire to provide a mechanical menas for pumping water from the coal mines, but Newcomen conceived the idea of also driving machinery.

As told by Carnegie, in the case of the steam engine a quite important improvement came very curiously. Humphrey Potter was a boy employed to turn off and on the stop cocks of a Newcomen engine, a monotonous task, for, at every stroke one had to be turned to let steam into the boiler and another for injecting the cold water to condense it, and this had to be done at the right instant or the engine could not move. Potter realized that the oscillation of the beam and the operation of the valves occurred in a regular manner. He thereupon rigged up strings between beam and valves in such a manner that the movement of the beam controlled the valves, the first instance of automatic valve action. The steam engine henceforth was self-attending, providing itself for its own supply of steam and for its condensation with perfect regularity. The cords of Potter gave place to vertical rods with small pegs, which pressed upward or downward as desired (Carnegie, 1905).

Watt's interest in the possibilities of generating power from steam appears to have been aroused before 1760, without being influenced by the engines available at that time. Together with Robison he carried out experiments with a Papin digester, in 1761 or 1762. He used a syringe with a plunger as a makeshift cylinder and piston and found that the pressure of steam from a digester was enough to cause the plunger to raise about fifteen pounds, a considerable weight. Watt did not pursue his experiments further, realizing the impossibility of building a boiler that would stand the necessary high pressures for any length of time (Cardwell, 1971).

Watt's real break came from quite a different quarter. Among the apparatus belonging to the Natural Philosophy Class of the University of Glasgow there was a small replica of the Newcomen fire engine, which was not in working conditions. In the winter of 1763-1764 Professor Anderson asked Watt to repair it. Watt not only fulfilled the request but also took the opportunity to become thoroughly familiar with the construction and modus operandi of the engine. During this work he became aware that the engine was able to perform only a few strokes on load before it ran out of steam and stopped. In addition, he took notice of its enormous consumption of steam, which he understood immediately was due to the fact that the cylinder went through a series of cooling and heating cycles. These observations puzzled him, as the engine of which the little model was supposed to be a replica, worked satisfactorily. Watt knew that cold metal condenses steam and he was well aware that the little cylinder became quite hot when full of steam. He therefore reasoned that the toy cylinder "exposed a greater surface to condense the steam in proportion to its content" than a big cylinder and would, therefore, cool down and condense much more readily. Owing to the scale effect the small cylinder engine could not work as efficiently as the big one (Cardwell, 1971). Another important difference between the commercial engine and the model was the material of construction of the cylinder: in big engines it was made of cast iron, in the model of brass, a better conductor of heat. Therefore energy was being wasted in heating the cylinder.

When weighing all these differences Watt realized not only that the model was more wasteful than a real engine, but also that even in a full-sized engine with a perfectly proportioned cylinder of the most suitable material there would still be a substantial waste of energy and loss of power, arising from the very principle on which the machine worked. In order to quantify the influence of the different factors, Watt embarked in a series of elaborate experiments on the effect of construction materials, the nature of heat, and the properties of steam (Marshall, 1925). The obvious solution to the problem of the material of construction was to machine the cylinder of a material, which, while strong enough to stand the wear and tear of continued use, had a much lower heat capacity than iron or brass. In his first experiments Watt fabricated the cylinder of wood soaked in oil and then baked, and obtained a clear decrease in the amount steam required. Unfortunately, the wood cylinders were incapable of repeated use, they warped and cracked, forcing Watt to return to the use of metallic cylinders. From the limitations of the Newcomen engine it was clear that for maximum economy the cylinder must not be cooled down; only enough cold water to condense the steam should be injected since any excess will cool the cylinder down and waste heat. The problem, therefore, was to determine the optimum amount of condensing water (Cardwell, 1971).

From the conversations Watt had had with Black he knew that mixing one kilo of steam at 212°F with one kilo of water at 52°F should yield two kilos of lukewarm water at 132°F. But the experimental data on the engine showed that the amount of condensing water per cycle was larger than the amount evaporated from the boiler in the form of steam. In order to solve this riddle he decided to measure the excess heat in steam by bubbling it through a known weight of water at room temperature until it boiled; the gain in weight of the water represented the steam condensed. His experiments led to the surprising conclusion that water converted into steam could heat six times its own weight of cold water up to the boiling point. Further consultation with Black explained the differences on the basis of the newly developed concept of latent heat. The weight of cold water multiplied by the rise in its temperature gave Watt a figure for the latent heat of vaporization of water, which was close to what Black had obtained.

Watt's measurement of the latent heat of evaporation enabled him to compute exactly how much water should be injected to condense all the steam without cooling the cylinder down. But he found that when the engine was operated at this theoretical maximum of efficiency there was a serious loss of power. The engine was now economical but no longer powerful (Cardwell, 1971). Watt now calculated the volume of steam generated for each stroke of the piston, compared this with the volume needed to fill the cylinder, and found that it was three or four times as great. In fact, as much as three-quarters of the steam was being wasted. The defect was not due to some detail in the machine; it was fundamental. To condense the steam and create a vacuum, the cylinder had to be cooled. When fresh steam was admitted for the next stroke it went on condensing, uselessly, until it had heated the cylinder up to its own temperature.

Watt knew, from William Cullen's (1710-1790) experiments that lowering the pressure resulted in a lowering of the boiling point of water. The vapours generated in the boiling process vitiated the vacuum. The problem reduced then to determine the pressure of the steam that was generated by the hot condensing water inside the cylinder. Watt proceeded then to measure the vapour pressure of water as a function of the temperature, from very low pressures up to the atmospheric one. He presented the results in the form of a graph, a very unusual procedure for those days: “From these elements I laid down a curve in which the abscissa represented the temperatures and the ordinates the pressure, and therefore found the law by which they were governed sufficiently near for my then purpose.” Watt thus found that with the amount of injection water used in the Newcomen engine, a drop of the interior temperature from 140° to 175°F, a very considerable backpressure would be met with. The meaning of these results was very clear, he could not, at the same time, keep the walls of the cylinder boiling hot, have a pool of near-boiling water at the bottom and a near-perfect vacuum insider. In such, hypothetical circumstances the hot water must boil, generating steam and so destroying the vacuum. The water would go on boiling until the appropriate pressure was reached, and the more “economical” the engine, the greater the opposing pressure must be. In a brilliant stroke of imagination Watt realized that the only way of fulfilling both requirements was to have two cylinders in place of one; the first to be kept hot all the time, the second cold. Having thus resolved the dilemma Watt was immediately able to sketch out the practical details of his improved engine: the true steam engine (Cardwell, 1971).

When asked how he had come to the idea of two cylinders he recalled a conversation where he told Robert Hart, an engineer in Glasgow: “I should like much to know where the idea first struck you, and what led you to it? Watt answered: “It was in the Green of Glasgow. I had gone to take a walk on a fine Sabbath afternoon. I was thinking about the engine at that time. When the idea came into my mind, that as steam was an elastic body it would rush into a vacuum, and if a communication was made between the cylinder and an exhausted vessel, it would rush into it, and might be there condensed without cooling the cylinder. I then saw that I must get quit of the condensed steam and injection water I had not walked farther that the Golf-house when the whole thing was arranged in my mind.” |Thus was thought out the separate condenser, the greatest improvement ever made in the steam engine.

Watt now turned to the waste of power represented by the flow of steam from the cylinder into the condenser. Watt recognized that because of the expansive power, steam needed not be admitted into the cylinder during the entire stroke; steam supply from the boiler should be cut off before the piston had travelled more than a fraction of the way down the cylinder. The steam would go on driving the piston down, though with steadily diminishing pressure as its volume increased, until when the piston reached the bottom of the cylinder, the steam pressure would be only marginally above the residual pressure in the condenser (Watt’s expansive power principle) (Cardwell, 1971).

The greatest invention of all, the condenser, is fully covered by Watt’s first patent of 1769 (Watt, 1769, 1775). Steam was only used to force the heavy piston upward, no other work being done by it. All the pumping was done on the downward stroke. The condensation of the spent steam below the piston created a vacuum, which facilitated the fall of the piston. This caused the cylinder to be cooled between each stroke and led to the wastage of about four-fifths of all the steam used. It was to save this that the condenser was invented, in obedience to Watt’s law, as stated in his patent “the cylinder should be kept always as hot as the steam that entered it” (Carnegie, 1905).

Watt’s inventions led directly to further improvements of equal importance: the sun-and-planet-gearing system to translate the engine’s reciprocating motion into rotary motion without employing the common crank; the application to the steam engine of the double-acting principle that was then commonly used in pumps; the parallel motion with which he connected a rigid piston rod to the wobble. The double acting principle came to change the original engines, which had only one driving stroke, the downward one. A closed cylinder communicated at both ends with the boiler, when the piston was at the bottom, the steam above it was in an enclosed space in which a vacuum could be created by condensation, exactly as for the downward stroke. This gave the engine two driving strokes instead of one (Watt, 1781; Marshall, 1925).

The “double-acting” engine was followed by the “compound” engine, of which Watt says: “A new compound engine, or method of connecting together the cylinders and condensers of two or more distinct engines, so as to make the steam which has been employed to press on the piston of the first, act expansively upon the piston of the second, etc., and thus derive an additional power to act either alternately or conjointly with that of the first cylinder”.

Future operations necessarily depended upon the extension of the patent, six of the fourteen years for which it was granted had already passed. Many rivals were trying to either copy Watt's engine directly or making small changes, which were anyhow in infringement of the patent. Under these circumstances the partners decided to apply for an Act to extend the patent for a period of twenty-five years. Small prepared the petition for a Bill and presented it to the House of Commons on February 23, 1775. In its passage it met with violent opposition from many of the most powerful members of the House, representing the mining interest. The owners of the mines were in increasing trouble due to increase flooding as the pits went down and down into the earth; the mines of Cornwall were approaching their useful life. They were all looking for termination of the original patent in order to stop paying royalties to Watt and Boulton. On October 25, 1781 the patent extension was finally granted for a term of twenty-four years and it covered "certain new methods of producing a continued rotative motion around an axis or centre, and thereby to give motion to the wheels of mills or other machines". The mechanical modification was necessary to overcome of the difficulties experienced in working the steam wheels or rotatory engines described in the first patent of 1769. No less than five different methods for rotatory motion are described in the patent, it has the singular property of going twice round for each stroke of the engine, and may be made to go oftener round, if required, without additional machinery." In all of these Watt recommended that a fly-wheel (see below) be used to regulate the motion, but in the specification for the patent of the following year (Watt, 1782) his double acting engine produced a more regular motion and rendered a fly-wheel unnecessary, "so that," he says, in most of our great manufactories these engines now supply the place of water, wind and horse mills, and "instead of carrying the work to the power, the prime agent is placed wherever it is most convenient to the manufacturer" (Watt, 1781). According to Carnegie (Carnegie, 1905) this patent marks one of the most important stages in the development of the steam engine. It was at last the portable machine it remains today, and was placed wherever convenient, complete in it and with the rotative motion adaptable for all manner of work.

In addition to the steam engine itself, Watt developed some critical auxiliary elements that helped tremendously to control and measure the utilization of power. Two of them are the speed governor, and the indicator diagram.

The governor is an application of the centrifugal principle to controlling the speed of engines. Before Watt others had used it to regulate water and windmills; Watt's contribution consisted in its improvement and application to the steam engine (he called it whirling regulator). The apparatus is built of two heavy revolving balls swinging around an upright rod. The centrifugal force on the balls depends on the revolving speed; the faster the rod revolves the farther from it the balls swing out, and vice-versa. This movement can be transmitted to the steam valves to regulate the amount of their opening accordingly: the higher speed of the engine, the less steam admitted, the slower the speed the more steam admitted. In this manner, the engine can be made to run at any desired uniform speed. Before the development of the governor regular motion was impossible and steam was an uncontrollable variable.

The indicator card gives an accurate measure of the work done in the cylinder, provided the passageways to the indicator are large enough in diameter and short enough that fluid friction is negligible. François Arago (1786-1853) explained the problem solved by the indicator as follows (Arago, 1840): "The barometer being adapted only to ascertain the degree of exhaustion in the condenser where its variations were small, the vibrations of the mercury rendered it very difficult, if not impracticable, to ascertain the state of the exhaustion of the cylinder at the different periods of the stroke of the engine; it became therefore necessary to contrive an instrument for that purpose that should be less subject to vibration, and should show nearly the degree of exhaustion in the cylinder at all periods. The indicator was found to answer the end sufficiently. A cylinder about an inch diameter, and six inches long, has a solid piston accurately fitted to it, so as to slide easy by the help of some oil; the stem of the piston is guided in the direction of the axis of the cylinder. The bottom of this cylinder has a cock and small pipe joined to it which, having a conical end, may be inserted in a hole drilled in the cylinder of the engine near one of the ends, so that, by opening the small cock, a communication may be effected between the inside of the cylinder and the indicator."

Miscellaneous

The illness of his daughter (consumption) and son (tuberculosis), followed by their deaths prompted Watts to study remedial medicine by inhalation and collaborate with Dr. Thomas Beddoes (1760-1808) who, in 1798, had established the Pneumatic Institute in Clifton, where he started applying new method of medical treatment of consumptive patients (gas inhalation), based on gas systematic application of Joseph Priestley's (1733-1804) "factitious airs," or gases. Watt designed an apparatus for the inhalation of mixtures of carbon dioxide and oxygen for diseases of the respiratory system. An interesting detail is that in 1798 Beddoes hired 20-year old young Humphry Davy (1778-1819) as his research assistant; Davy quickly added nitrous oxide to the armamentarium.

In his leisure hours Watt invented an ingenious machine for drawing in perspective, using the double parallel ruler, then very little known. In this machine the paper is held on a vertical board supported by three legs and commanded by a parallel ruler in which there is a pencil socket and at the upper end an index. Lighting on the object the outline is followed by the index and the pencil marks the lines. Watt reports having made from fifty-to-eighty of these machines, which went to various parts of the world (Carnegie, 1905).

Among the profitable branches, which Boulton had encouraged Watt in introducing at Soho, was the copying-press, based on transfer printing, invented by Watt in I778, and which we use to this day (Watt, 1780). The copy is done on thin paper so that it can be read the right way by looking at the back. In July of that year he writes Dr. Black that he has "lately discovered a method of copying writing" instantaneously, provided it has been written within "twenty-four hours. I send you a specimen and will "impart the secret if it will be of any use to you. It "enables me to copy all my business letters." He kept this secret for two years, and in May, I780, secured a patent after he had completed details of the press and experimented with the ink to obtain the right ingredients (Carnegie, 1905).

Another of Watt's recreations in his days of semi retirement was the improvement of lamps. In August 1857 he wrote a detailed letter on the subject to Aimé Argand (1755-1803), the famous inventor of the Argand burner, and also constructed some lamps, which proved great successes. In 1858 he invented an instrument for determining the specific gravities of liquids, which was generally adopted. One of Watt's inventions was an improved method of readily measuring distances by telescope, which he used in making his various surveys for canals (Carnegie, 1905). In his telemeter one perpendicular and two horizontal hairs were place in the focus of the eye piece of a telescope, through which sights were taken on two disks, one fixed and one movable, on a rod located at a known distance from the observer. The telescope was turned until the horizontal hairs covered the red stripes and the perpendicular hair was parallel to the rod. The divisions on the rod showed the distance, which could be ascertained to less that within 1/100 part of the whole distance. Watt's method is very similar to the one used today by surveyors.

From 1804 onwards Watt was kept busy for some time developing a machine for copying irregular objects such as busts. The idea originated from a machine he had seen in Paris capable of tracing, in the same or on reduced scale, objects in slight relief the dies of medallions The principle of the French machine was a rapidly revolving tool guided by linked bars, which passed over the original. Watt modified this design by mounting the work and the original on axes so that they were capable of a complete turn in step with one another. After much labour and many experiments he did get some measure of success, and made a large head of Locke in yellow wood, and a small head of his friend Adam Smith (Carnegie, 1905).

Watt's career as a scientist was centred on his interest in chemistry. He performed numerous experiments, was in contact with several of the foremost chemists of the day, including Black, Joseph Priestley (1733-1804), and Berthollet, and occasionally ventured into the realm of theory. Shortly after Henry Cavendish (1731-1810), made public his findings about the burning of inflammable air and the formation of water, Wattcame forward with the claim that he had announced the same result on a previous date (Watt, 1784ab), and afterwards, Louis Antoine Lavoisier (1743-1794) declared that he had discovered the compound nature of water before, and independently of either (Lavoisier, 1781). A controversy accordingly arose in which Cavendish and Watt disputed with each other the priority of the discovery while at the same time they rejected Lavoisier's arguments regarding the identification of the composition of water. This dispute, to be called later the water controversy, not only was not settled during the lifetime of the claimants, every so often it continues to flare again in the literature

(Schofield, 1963; Miller, 2002) This "paternity" controversy was caused a series of fortuitous events. Cavendish reported his findings to Priestley, who repeated the experiments and reported them to Watt. In a letter written to Joseph Black (1728-1799) in June 1788, Watt refers to some experiments of Priestley in which the dephlogisticated and inflammable airs were exploded in a copper vessel, producing water, which always contained nitric acid: "It appears, however, that more than 9 tenths of the liquor thus produced is water, which probably in its own form constitutes the greater part of the mass of all sorts of air. I think it highly probable that the acid proceeds from the inflammable air, and the dephlogisticated air acts the same part that it does on the burning of sulphur and phosphorus." It is clear that Watt regarded water as constituting "the greater part of the mass of all sorts of air" and it seems that he regarded it as pre-existing in the two gases. The water controversy has been described in detail in a previous publication (Wisniak, 2004).

Watt also did experiments during the 1780s that contributed to the commercial application of the process, which Berthollet had discovered, of bleaching textiles with chlorine (Berthollet, 1789). Among others, Berthollet passed on the details of his discoveries and operating methods to Watt, who introduced it into the works of his father-in-law at Glasgow. Good results were achieved in the bleaching of 500 pieces of cloth and in 1788 as many as 1500 pieces of cloth were bleached at one time under Watt's direction. Soon afterwards, other British bleachers adopted the process. Watt tried unsuccessfuly to convince Berthollet to obtain a joint patent in England. Berthollet rejected the proposal with the remark, "Quand on aime les sciences on a peu besoin de fortune" (when you love science you have little need for fortune). Another of Watts contribution to the textile industry is a drying-machine for cloth, consisting of three cylinders of copper over which the cloth must turn over and under while cylinders are filled with steam, the cloth to be alternately wound off and on the two wooden rollers, by which means it will pass over three cylinders in succession.

Watt also developed an indicator liquid for testing acidity based on red cabbage leaves. In a short paper published on the subject (Watt, 1784c) he stated that "the infusion of tournesol, or an artificial preparation called litmus, is not satisfactory with nitrous acid, for a mixture of phlogisticated nitrous acid with an alkali will appear to be acid, by the test of litmus, when other tests, such as infusion of the petals of the scarlet rose, of the blue iris, of violets, and other flowers will show the same liquid to be alkaline, by turning green". Watt found that an infusion of red cabbage leaves in dilute sulphuric cid, neutralised before use with chalk or potash, filtered and mixed with alcohol, gave a blue liquid, which became red with acid and green with alkali, and that the reaction was not vitiated by nitrous acid.

In 1787 Jean Henri Hassenfratz (1755-1827) and Pierre Auguste Adet (1763-1832) published their book Méthode de Nomenclature, Proposé par MM. de Morveau, Lavoisier, Berthollet, and de Fourcroy (Hasserfratz, 1787), which outlined the new systematic chemical nomenclature reform, as well as a scheme of chemical symbols. Shortly thereafter, Watt, then an active member of the Lunar Society of Birmingham(they met at 2 PM on the Monday nearest to the full moon), set down his own ideas in a unpublished manuscript, entitled Essay on a New System of Characters for Chemical Subjects. In this essay Watt paid tribute to the efforts of Hassenfratz and Adet to find a simple way to represent chemical elements, compounds, and reactions, but claimed that he had developed a better procedure, which made the characters more easily written and applicable to both the old and the new systems of chemistry. In addition Watt's procedure emphasized the operations of chemistry, which had been neglected by Hassenfratz and Adet, as well as the various physical states of compounds. The suggested nomenclature not only defined symbols for the elements and their compounds but also included an imagery for chemical operations such as sublimation, distillation, boiling, and so on, as well as for the physical state of the compounds. As stated by Larder (Larder, 1970) these symbols were intended as a laboratory shorthand notation and speeding communication in writing to other scientists, rather than for publication and accordingly were not meant to be exhaustive but only deal with the most frequently used and well established compounds.

Although probably logical according to their time, Hassenfratz and Adet's symbols were not used widely because of the technical problems associated with their use in printed matter. Watt's intention was to introduce as many distinctive symbols as necessary, so that there was no danger of confusion between them and so that they could be easily remembered. Watt considered that compounds which remained undecomposed, particularly those which had been hitherto been considered as simple substances, needed be given only a single symbol. Thus a genus could readily be developed to include such classes as acids, alkalis and so on, with a specific initial letter to distinguish the individual members; his chemical symbols could be used both within the older chemical framework, as well as within the new (Larder, 1970).

Watt revisited Cornwall in 1781 to make an inspection of all the engines. His evenings were spent designing "road steam-carriages". He filled a quarto drawing-book with different plans for these, and covered the idea in one of his patent specifications (Watt, 1784c). Boulton suggested in 1781 that the idea of rotary motion should be developed, which Watt had from the first regarded as of prime importance. It was for this he had invented his original wheel engine, and in his first patent of 1769 he describes one method of securing it. It occurred to him that the ordinary engine might be adapted to give the rotary motion. He prepared a model upon his return to Soho, using a crank connected with the working-beam of the engine for that purpose, which worked satisfactorily. There was nothing new in the crank motion; it was used on every spinning wheel, grindstone and foot-lathe turned by hand, but its application to the steam-engine was new (Carnegie, 1905).

Among the many possible applications of his steam engine, Watt considered the locomotive steam carriage although with reservations because he had calculated they would consume twenty pounds of coal and two cubic feet of water per horsepower on the common roads. In his seventh "new improvement," in his patent of 1784 (Watt, 1784c), he describes "the principle and construction of steam" engines which are applied to give motion to wheel "carriages for removing persons, goods, or other" matter from place to place, in which case the engines "themselves must be portable." Writing on this subject, George Williamson says (Williamson, 1856): "Watt's early interest in locomotive steam-carriages, dating from Robison having thrown out the idea to him, was never lost. "

The application of steam for propelling boats upon the water was, at this time (1788), attracting much attention. In 1770 Watt suggested and sketched a screw propeller for boats. The only record of any earlier suggestion of steam is that of Jonathan Hulls (1699-1758), in 1736, which he described in a pamphlet entitled "A Description and Draught of a Newly Invented Machine for carrying Vessels or Ships Out of or Into Any Harbour, Port or River, against Wind or Tide or in a Calm" (Hulls, 1737). Watt described a large barge equipped with a Newcomen engine to be employed as a tug, fitted with fan (or paddle) wheels, towing a ship of war, but nothing further appears to have been done. Boulton and Watt were urged to undertake experiments but did not take action until Robert Fulton (1765-1815) in person ordered an engine from them from his own drawings, intended for this purpose. It was shipped to America early in 1805, and in 1807 placed upon the Clermont, which ran upon the Hudson River as a passenger boat, attaining a speed of about five miles an hour. This was the first boat ever propelled by steam successfully for commercial purposes. It was subsequently discarded because the revolving paddle wheels caused waves that threatened to wash away the canal banks (Carnegie, 1905).

References

Arago DFJ, Éloge Historique de James Watt, *Mém. Acad. Roy. Sci.*, **17**, 61-88 (1840).

Berthollet CL, Description du Blanchiment des Toiles et des Fils par l'Acide Muriatique Oxigéné, et de Quelques Autres Propriétés de Cette Liqueur Relatives Aux Arts, *Ann. Chim.*, **2**, 151-190 (1789).

Bion N, Traité de la Construction et des Principaux Usages des Instrumens de Mathématique, Paris, 1723. Translated by Edmund Stone, as *The Construction and Principal Uses of Mathemtical Instruments*, London, 1758.

Cardwell DSL, *From Watt to Clausius*, Cornell University Press, Ithaca, 1971; p. 40-55.

Carnegie A, *James Watt*, Doubleday, New York, 1905.

De Caus S, *Les Raisons des Forces Mouvantes, Avec Diverses Machines tant Utile que Plaisante*, Frankfort, 1615.

Dickinson HW & Jenkins R, *James Watt and the Steam Engine*, Encore Editions, London, 1989.

Gravesande W van St, *Physices Elementa Matemática*, Leyden, 1720-1721.

Hassenfratz JH & Pierre Auguste Adet PA, *Méthode de Nomenclature, Proposé par MM. de Morveau, Lavoisier, Berthollet, and de Fourcroy*, Cuchet, Paris, 1787.

Hernández Molina R, *El Ingenio de Blasco Garay* (1539-1543), Servicio de Publicaciones, Universidad de Cádiz, Cádiz, 1996.

Hulls J, *A Description and Draught of a Newly Invented Machine for Carrying Vessels or Ships Out of or Into*

Any Harbour, Port or River, Against Wind or Tide or in a Calm, published by the author, London, 1737.

Larder D F, An Unpublished Chemical Assay of James Watt, Notes and Records, *Royal Soc. London*, 25, 193-210 (1970).

Lavoisier A, Mémoire Dans Lequel on a Pour Object de Prouver que l'Eau n'est Point une Substance Simple, un Élement Proprement dit, mais qu'elle est Susceptible de Décomposition & de Recomposition, *Mém. Acad. Royale Sci.*, 468-494 (1781) (Published in 1784).

Marshall TH, *James Watt*, Morrison C. Gibb, Infield, England, 1925.

Miller DP, Distributing Discovery "Between Watt and Cavendish: A Reassessment of the Nineteenth-Century Water Controversy", *Ann. Sci.*, **59**, 149-178, 2002.

Schofield RE, Still More on the Water Controversy, *Chymia*, **9**, 71-76 (1963).

Somerset E, *A Century of the Names and Scantlings of Inventions by Me Already Practiced*, J. Grismond, London, 1663.

Watt J, *New Invented Method of Lessening the Consumption of Steam and Fuel in Fire Engines*, British Patent No. 913 (January 5, 1769).

Watt J, *Extension of Patent No. 913*, British Patent No. 913 (May 22, 1775).

Watt J, *A New Method of Copying Letters and Other Writings Expeditiously*, British Patent No. 1244 (February 14, 1780).

Watt, J, *Certain New Methods of Applying the Vibrating or Reciprocating Motion of Steam or Fire Engines to Produce a Continued Rotative or Circular Motion Round an Axis or Centre, and Thereby to Give Motion to the Wheels of Mills and Other Machines*, British Patent No. 1306 (October 25, 1781).

Watt, J, *Certain New Improvements Upon Steam or Fire Engines for Raising Water, and Other Mechanical Purposes, and Certain New Pieces of Mechanism Applicable to the Same*, British Patent No. 1321 (March 12, 1782).

Watt J, Thoughts on the Constituent Parts of Water and of Dephlogisticated Air; with an Account of Some Experiments on that Subject, *Phil. Trans.*, **74**, 329-353 (1784a).

Watt J, Sequel to the Thought on the Constituent Parts of Water and Dephlogisticated Air, *Phil. Trans.*, **74**, 354-357 (1784b).

Watt J, On a New Method tof Preparing a Rest Liquor to Shew the Preference of Acids and Alkalies in Chemical Mixtures, *Phil. Trans.*, **74**, 419-422 (1784c).

Watt J, *Certain New Improvements on Fire and Steam Engines, and Upon Machines Worked or Moved by the Same*, British Patent No. 1432 (April 28, 1784d).

Williamson G, Memorials of the Lineage, *Early Life, Education, and Development of the Genius of James Watt*, Printed for the Watt Club, Greenock, 1856.

Wisniak J, The Nature and Composition of Water, *Indian J. Chem. Technol.*, **11**, 434-444 (2004).