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MERCURY - THE ELEMENT THAT CHANGED THE WORLD

Abstract: Mercury is a bright silver liquid with an exceptionally high density of 13.6 $g \cdot cm^{-3}$. It has a high surface tension, causing it to form bright shiny globules that roll freely on smooth surfaces. For this reason, it is sometimes called quicksilver. Not surprisingly, mercury has been the focus of insatiable curiosity since the earliest of times, a curiosity that has led to the use of mercury and its compounds in a vast range of applications in the fields of medicine, chemistry, physics and technology. Mercury has played a significant role in philosophical speculations about the nature of metals, and in scientific research. This has led to some remarkable results, from which we benefit on an everyday basis. The purpose of this article is to outline three major scientific discoveries, made during the past four centuries, which exploited the unique properties of mercury. The discoveries are associated with the names of five outstanding scientists - Torricelli, Priestley, Scheele, Lavoisier and Faraday. Using these discoveries as examples, it will be shown that mercury was the key player in the formation of today's technological world.

Keywords: mercury, experiment, discovery, unique, chemistry, physics

Mercury and Torricelli [1608-1647]

Early theories of matter - particulate and continuous

One of the most important questions that has confronted people is: what is matter made of? In this respect, two theories have dominated our understanding of the composition of matter: it is either particulate, or continuous.

A particulate theory of matter was put forward by the Greek philosophers Democritus [c. 460BC - c. 370BC] and Leucippus [fl. 5th century BC], and independently by the Indian philosopher Kanāda [dates uncertain c. 6th century BC - c. 2nd century BC] [1]. According to this theory, matter is composed of tiny particles called atoms, which cannot be split (from the Greek *atomos* which means *indivisible*). Different substances are composed of atoms with different shapes. Different arrangements of atoms give rise to different substances. A fundamental idea in the early atomic theories was the existence of a void, or vacuum. This was an empty space which was said to exist between atoms, which are constantly in motion.

The atomic theory was very well received by philosophers of that time and indeed, it inspired a huge surge in intellectual and creative activity. Lucretius [c. 99BC - c. 55BC], who was further motivated by another atomist Epicurus [341-270BC], wrote a philosophical discourse, in the form of a poem entitled *De Rerum Natura*. Poems were commonly used in philosophical discourses, since they were more easily assimilated by

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readers. *De Rerum Natura* is considered by many to be one of the greatest philosophical works of all time. In his classic work on the history of science, George Sarton [1884-1956] wrote of Lucretius, "(…) his poem has come down to us in its integrity and is recognised as one of the greatest in world literature." [2]. It deals with a wide range of issues: atoms, the soul, sensation and thought, astronomical and atmospheric phenomena, and the beginnings of life on earth. It is divided into six books, of which the first two are about atoms, their properties and their movement. A short excerpt from a modern translation of this poem focuses on the idea of the void: "Therefore it is by means of invisible particles that nature does her work. Yet it is not true that everything is packed solid and confined on every side by corporeal substance; for there is void in things." [3]. This idea of a void was to become the heart of a centuries-long debate on the nature of matter.

Even though the early atomistic philosophies were coherent, they lacked a fundamental component - the irrefutable argument of experimental evidence. They were thus open to criticism and to other ideas concerning the nature of matter.

An opposing theory, that matter is continuous and therefore a void cannot exist, was put forward by the Greek philosopher Aristotle [384-322BC]. This idea, which had already been incorporated in the philosophy of Parmenides [fl. 475BC], became the cornerstone of Aristotle's celebrated four elements theory. This in turn was an elaboration of the four elements theory of Empedocles [c. 494-c. 434BC]. In the Aristotelian system, all changes are said to occur in the sublunary world, in which matter is composed of four elements: earth, fire, air and water. Changes can only occur when matter moves or flows. For this to occur, matter must be continuous and must therefore fill all space. Aristotle knew that his proposition that "a void cannot exist" was highly contentious, and he made many references to it e.g. "Though some say that there is void because it is necessary if there is to be change, in fact, if one considers carefully, it is rather the opposite that results: that if there is void it is not possible for *anything* to move" [4].

Aristotle's philosophy was based on decades of observations of natural phenomena such as chickens hatching from eggs, volcanic activity, iron rusting, the growth of plants, the movement of fish, earthquakes and volcanoes, and meteorological phenomena. At heart, he was a biologist and viewed the world through analogue eyes. It is from this perspective that he interpreted all changes in terms of matter, which filled all space, and which flowed from one place to another.

Aristotle's genius lay in his ability to convincingly construct a coherent body of knowledge which explained all natural phenomena. It was this body of knowledge which was to dominate natural philosophy for almost 2000 years, and which formed the basis for the philosophical system of the alchemists.

The alchemists were primarily experimenters of European, Chinese, Indian, Arabic and Persian origin. They had as their noble aims: the preparation of an elixir (which would give eternal life), a universal solvent (alkahest), and the philosopher's stone. This stone would supposedly transmute base metals into gold, which was considered to be the ultimate symbol of perfection. Other experiments were conducted, in attempts to solve the mysteries of reproduction (homunculus) and resurrection (palingenesis). The alchemists worked with great passion, faith and dedication, frequently in miserable conditions, to try and achieve their goals. And indeed, great progress was made in several fields, including the classification of substances, the improvement of experimental techniques (e.g. distillation, crystallisation), and the preparation of new substances. However, by the end of the

16th century, with a notable lack of success in achieving the main aims of their labours, there had developed a significant scepticism towards the Aristotelian synthesis.

Practical problems in mines

By the start of the 17th century, when populations were beginning to expand, there came an increasing demand for more and better products of the chemical and technological industries, which at that time belonged to the realms of arts and crafts. The products included food (agriculture), fabrics, cosmetics, medicines, adhesives, cleaning agents, paints, dyes, glass, ceramics, jewellery, fuels and metals. To satisfy this growing demand, the need for ingredients and raw materials grew. Ingredients were sourced from plants, fungi and animals, including insects. Raw materials were obtained from the sea, lakes, and from the ground.

The extraction of solid raw materials gave birth to one of the most ancient early technologies - mining. Mining was used for accessing minerals such as coal, sulphur, salt, metal ores and building stone. By the middle of the 14th century, as technology improved, deeper mines were being built. As the mechanical aspect of digging shafts, extracting ores, bringing them to the surface and their subsequent processing made great advances, so new problems, both sociological and technical, developed. These included increasingly uncomfortable conditions to work in, the increasing exploitation of child labour [5, 6], the illumination of tunnels and shafts, and the presence of dust and explosive gases.

One of the greatest problems was that of flooding. Whilst progress had been made with the removal of flood waters from mines, using buckets, ropes and large wooden mechanisms, a new technique was developed during the late Middle Ages - this was a wooden suction pump, a giant version of a syringe. Such a suction pump for raising water had been invented and used by the Arabic engineer and polymath Ismail Al-Jazarī [1136-1206] in the latter half of the 12th century [7]. Whilst early suction pumps were effective and easy to operate, they could only raise the water to a height of about 10 metres. In deep mineshafts, where greater heights had to be contended with, the column of water would break up, and fall out of the pump, back into the mine. The reason for their inability to lift water beyond this certain height, was not understood, and became the focus of intense speculation and experimentation during the middle of the 17th century.

Early mining engineers overcame the problem of lifting water to greater heights by constructing a series of pumps at different levels, as shown in Figure 1. The illustration (woodcut) of this arrangement was published in the monumental work on mining technology: *De Re Metallica* (1556), which was written by the German engineer/metallurgist Georg Bauer, otherwise known as Agricola [1494-1555] [8].

The original diagram is in black and white, but the author has added colours to clarify some aspects of the setup. The pumps (brown, labelled F, D and B) are driven by the large waterwheel (orange). The axle from the wheel is connected via a bent arm to three interconnected pistons, which move simultaneously as the wheel turns. Water, which is pumped out of each cylinder, is coloured blue. This remarkably ingenious feat of engineering was used in locations such as the Rammelsberg mine in Goslar in Lower Saxony. The mine, which was on the edge of the Harz mountains, was particularly rich in a variety of ores including those of silver, copper, lead and zinc.

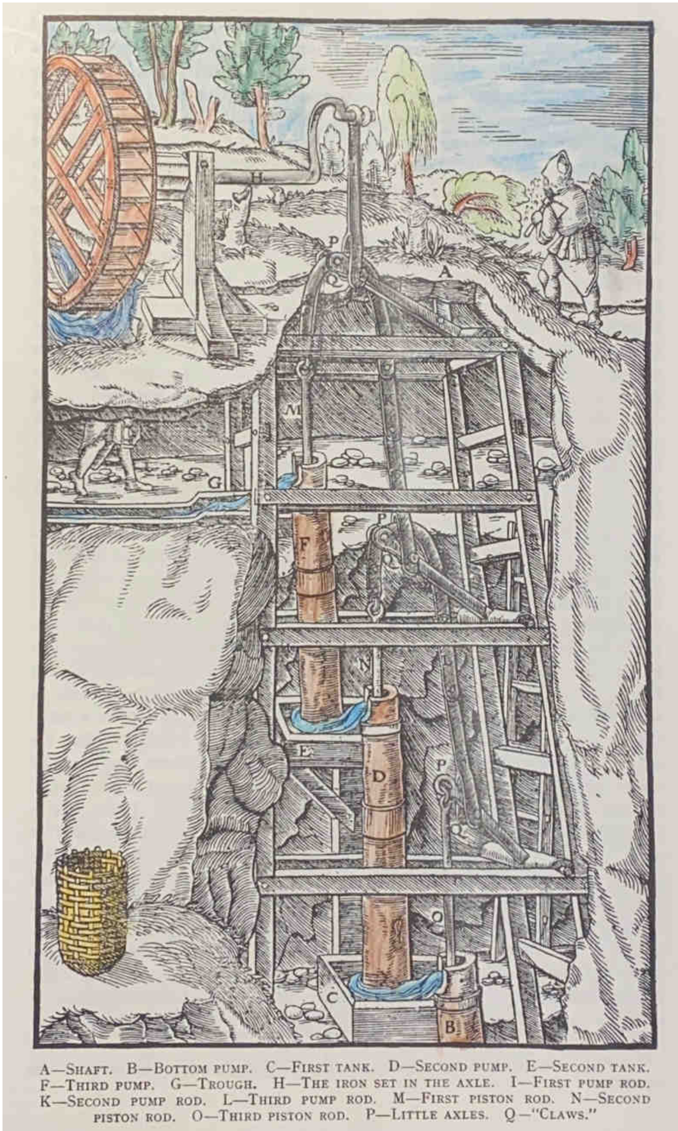

Fig. 1. A series of wooden suction pumps for extracting water from mines [8]

A similar problem with raising water was encountered in Tuscan wells, which were rich in excellent mineral waters. In the early part of the 17th century, Florence, the regional capital of Tuscany, was beginning to thrive as a hub of experimental science. Its principal grand master was Galileo Galilei [1564-1642]. Galileo had already established himself as an outstanding experimenter and had distinguished himself in a wide variety of fields including motion, heat, optics, mechanics, hydrostatics and astronomy.

Galileo, then Torricelli

In 1635, the Duke of Tuscany, who had used suction pumps for irrigation and for the construction of decorative water fountains, asked Galileo to tackle the issue of these wooden pumps: why were they only able to suck water to a height of 10 metres? Galileo was unable to solve the problem. Two thoughts nevertheless occurred to him: firstly, that air has weight (this was a novel idea at that time), and that therefore the atmosphere, which was known to consist of a thick envelope of air surrounding the Earth, could hold the water up by counterbalancing it. Secondly, he considered the idea of whether a vacuum could be formed above the water in a "more than 10-metre-high" vertical closed cylinder.

Evangelista Torricelli [1608-1647] was the next person to undertake an investigation of the water pump mystery. He was born in Rome, and at an early age displayed a great intellectual ability. As a promising student, he studied under the Benedictine monk Benedetto Castelli [1578-1643]. Castelli in turn had studied under Galileo, and Torricelli befriended Galileo in the latter years of his life. He thus had an excellent springboard from which he could take on the challenge of the pump. Figure 2 shows a contemporary portrait of Torricelli.

Fig. 2. Evangelista Torricelli (courtesy of Encyclopedia Britannica)

Torricelli's experiment

Torricelli's master stroke in this respect, was to use mercury and a long (about 1 metre) glass tube, which was sealed at one end. This was to serve as a model of the wooden suction pump. He surmised correctly, that by using mercury, which was about 14 times as dense as water, the height of the mercury column would be much more manageable that the 10 m column of water. Furthermore glass, unlike wood, was completely impermeable to water and to air. The manufacture of a suitable glass tube would have required great skill, but this was possible due to great advances in glass fabrication techniques, which had been made by Venetian craftsmen during the preceding two centuries [9]. Torricelli was fully aware of both the practical and theoretical implications of his undertaking. An artist's impression of his experiment is shown in Figure 3 [10].

Fig. 3. "Torricelli demonstrates the vacuum. When the upper ends of the tubes are raised to the vertical, the mercury, which originally filled them, remains approximately 30 inches above the surface of the mercury in the bowl, leaving an empty space, which when the tube is lowered once more becomes filled with mercury" [10]

He was delighted with the results of his efforts, which he summarised in a letter to Michelangelo Ricci [1619-1682], dated 11th June 1644. Ricci was a young open-minded mathematician and theologian, a friend of Torricelli, who had a keen interest in scientific advances of that time. Some excerpts from the letter are given below: "(…) Many have said that [the vacuum] cannot happen, others that it happens, but with the repugnance of nature, and with difficulty; (…) We live submerged at the bottom of an ocean of elementary air, which is known by incontestable experiments to have weight, (…) We have made many glass vessels such as those shown at A and B, wide, and with neck of two ells (the original text reads *due braccia*, which has also been translated as cubits, which are about 23 inches [11]) long. When these were filled with quicksilver, their mouths stopped with the finger, and then turned upside-down in the vase C which had some quicksilver in it, they were seen to empty themselves and nothing took the place of the quicksilver in the vase which was being emptied. Nevertheless the neck AD always remained full to the height of an ell and a quarter and a finger more (…) While the vessel AE was empty, and the quicksilver, though very heavy, was sustained in the neck AC, we discussed this force that held up the quicksilver against its natural tendency to fall down. It has been believed until now that it was something inside the vessel AE, either from the vacuum, or from that extremely rarified stuff; but I assert that it is external, and that the force comes from outside. This reasoning was confirmed by making the experiment at the same time with the vessel A and with the tube B, in which the quicksilver always stopped at the same level AB" [12]. The diagram of Torricelli's apparatus, as it appeared in a handwritten copy his letter, is shown in Figure 4.

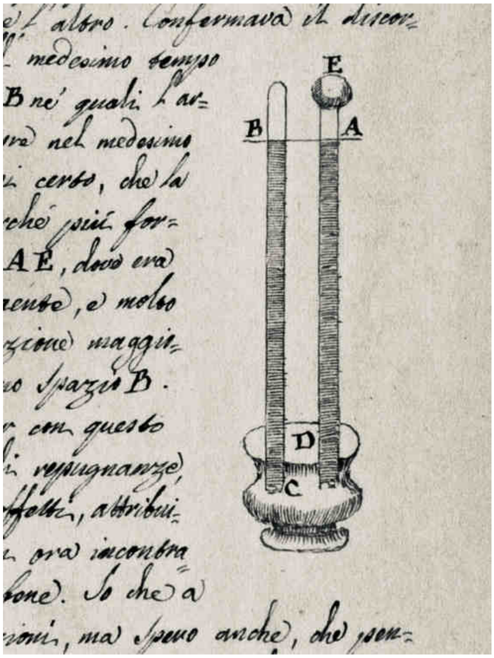

Fig. 4. A fragment of a copy of Torricelli's original letter to Ricci, which shows a sketch of his experimental arrangement (courtesy of the Museo Galileo, Florence)

Torricelli was fully aware of the implications of his experiment: he had demonstrated the existence of a vacuum, and he had deduced that air has weight. Furthermore, he had made the first measurement of atmospheric pressure, as "an ell and a quarter and a finger more" (today this translates as 29¾ inch). He had thus solved the mystery of mining pumps, by providing an explanation as to why water cannot be lifted by a suction pump to a height of more that 10 metres. Furthermore, he provided experimental evidence to fuel the debate on the idea that "Nature abhors a vacuum".

In the immediate aftermath of the Torricellian experiment, in which mercury had played a key role, the floodgates were opened for a flurry of new experimental and philosophical activity. One of the most important experiments in this field is described below.

Barometer on a mountain

Torricelli's assertion that air has weight and that it exerts a great pressure "at the bottom of an ocean of elementary air" fired the imagination of enlightened philosophers. Blaise Pascal [1623-1662] was one of them. He reasoned that air pressure should decrease with increasing height above ground, since there will be a shorter column of air at the greater heights, which should weigh less, and hence should exert a lower pressure. Brilliant thinking indeed, for an experiment in which the stakes were very high! For if successful, it would provide the final nail in the coffin for the theory that a vacuum cannot exist, and the idea that air has no weight.

To carry out this experiment was going to be a great challenge: the highest mountain possible (i.e. the one that would give the greatest chance of a successful result) would have to be chosen, which would not be too difficult to climb, and the weather conditions would have to be favourable. The experimenter would have to carry 16 pounds of mercury (in a sealed vessel, taking great care not to drop the vessel and not to spill any mercury), together with a bowl and long glass tubes, which were sealed at one end. Once at the top of the mountain, the apparatus had to be carefully set up. The chosen mountain was the Puy de Dôme in the Massif Central in France. Its height at that time was estimated to be some 500 fathoms. (This is 3000 feet. The actual height is 4800 feet.)

The experiment was carried out on September 19th, 1648, by Pascal's brother-in-law Florin Perier [1605-1672], who took with him five assistants, who would also act as witnesses. With great foresight, Perier designed a control experiment: he set up a barometer in a monastery at ground level - the height of the mercury column registered 26 inches and 3½ lines. Perier asked that one of the monks should monitor the height of the mercury column frequently throughout the day, to verify that its height remains unchanged.

Fig. 5. Blaise Pascal's experiment with a barometer (courtesy of the Congress/Science Photo Library)

On that day, the weather looked good, and the expedition set out at 8 am. When they reached the summit of the Puy de Dôme, Perier set up the tubes with mercury and read the height of the column. He could barely believe his own eyes: it was 23 inches and 2 lines, which was far lower than anything he had expected. The colossal impact of this result is best summarised in Perier's own words: "(…) thus between the heights of the quicksilver in these two experiments, there was a difference of three inches and one-and-a-half lines; which ravished us all with admiration and astonishment, and surprised us so much that for our own satisfaction we wished to repeat it. That is why I did it, very exactly, five times more at various places on the summit of the mountain, (…)". As W E Knowles Middleton has put it: they "were witnessing one of the great moments in the history of ideas, (…)" [13]. Figure 5 shows an artist's impression of this experiment.

In the years which followed, a huge surge of new experiments, discussions, controversies and ideas occurred. These are brilliantly elucidated in chapters 3 (The Extraordinary Effervescence) and 4 (Seventeenth-Century Experiments and Speculations) of Knowles Middleton's book, mentioned above.

Debates on the nature of matter

Whilst a key idea in the Aristotelian system, i.e. that "Nature abhors a vacuum" was experimentally proven to be wrong, it did not immediately cause an outright rejection of his system. For human nature is such that new and apparently convincing experimental results can take a long time to be accepted and assimilated. Furthermore, the existence of tiny invisible particles from which all matter is made had certainly not been verified. As a further complication to the evolving theories, ideas that: (i) matter is particulate and; (ii) that nature cannot tolerate a vacuum, were not considered by some philosophers to be mutually exclusive.

To illustrate how complex this evolution of ideas was, some of the outstanding natural scientists/philosophers of the 17th and 18th centuries are listed below, together with some of their important scientific contributions and views on issues concerning the nature of matter and the existence of a vacuum.

- Pierre Gassendi [1592-1655] was a French liberal thinking philosopher, theologian, mathematician and astronomer, who strongly supported the idea of atoms and the existence of a void.
- Rene Descartes [1596-1650] was a French philosopher/mathematician who developed a mechanistic theory of the universe and firmly rejected the idea of a vacuum, but believed in the idea of corpuscles, which were particles that, unlike atoms, could be split.
- Otto von Guericke [1602-1686] was a German natural scientist and mathematician, who devised one of the most spectacular experiments of all time - the Magdeburg Hemispheres experiment [1650]. By showing that two teams of four horses, each pulling in opposite directions, could not pull apart two hemispheres which were joined together at their flat rims to form a sphere which had been evacuated, he demonstrated the enormous and ubiquitously acting atmospheric air pressure. He acknowledged the existence of a vacuum, but he was not an atomist.
- Robert Boyle [1627-1691 was an Irish natural philosopher who is renowned for his experiments with air and pressure, and for his rejection of the Aristotelian elements (Earth, Fire, Air and Water), replacing them with the definition of an element as a substance which cannot be broken down into simpler substances. This was published in his celebrated work: *The Sceptical Chymist* [1669]. Boyle was a strong supporter of

the idea of corpuscles and constructed vacuum pumps to investigate a wide variety of phenomena in conditions of reduced pressure. These experiments, however, did not fully convince him of the existence of an absolute vacuum. Boyle invented the term "barometer" - it is derived from two Ancient Greek words: *baros* [weight] and *metron* [measure].

- Christiaan Huygens [1629-1695] was a Dutch mathematician, physicist and engineer, who was the first to propose that light is propagated in the form of waves, which must move through a medium - thus he did not accept that a vacuum can exist.
- Blaise Pascal [1623-1662] was a pioneering French mathematician and was especially interested in experiments with atmospheric pressure He accepted the idea of a vacuum, but not the idea of atoms.
- Robert Hooke [1635-1703] became inspired by the idea of corpuscles to the extent that he made microscopes with the intention of seeing them. Although he could not verify their existence, he made remarkable progress in the field of microscopy and discovered cells in living organisms as well as producing remarkable drawings of insects, plants and fossils. Like Boyle, he did experiments with vacuum pumps but never became convinced of the idea of an absolute vacuum.
- John Mayow [1640-1679] was a physician and chemical philosopher, who was particularly interested in the role of air in combustion and respiration. He elucidated a theory in which nitro-aerial particles in the air enabled it to support combustion and respiration. Isaac Newton [1643-1727] conducted pioneering work in the fields of mathematics, gravity, motion and optics and is thus considered to be the founder of modern physics. He believed that a vacuum could exist and used the idea of corpuscles in his explanation of the nature of light and its propagation.

Throughout the latter half of the 17th and the 18th centuries, the experimental work of natural scientists enabled greater insights into the nature of matter to be achieved. From this intellectual ferment, which had been precipitated by the inspired use of mercury, a new world evolved - a world which was to become increasingly devoid of mystical speculation and false claims.

This work culminated in 1808 with the publication of one of the most celebrated scientific theories of all time: John Dalton's atomic theory. In this theory, atoms were defined as the ultimate, indivisible, unique (for every chemical element) particles, of which all matter was constituted. With the publication of the atomic theory, a new era was entered. This was the beginning of the era in which chemistry became elevated to the status of an exact science.

Barometers in science and in education

So great was the impact of the Torricellian barometer, that it immediately found application for the study of the weather - meteorology. It thus became a vital tool in weather forecasting. Figures 6a and 6b show closeups of a beautiful barometer (from the author's private collection) made by Baird & Tatlock in London in c.1910. The pressure reading of 29.10 inches (739.1 mm) of mercury was taken on a windy day.

With the invention of balloon flight by the Montgolfier brothers in 1783, a new dimension was added to studies of the atmosphere. In this context, on December 1st, 1783, the French physicist Jacques Charles [1746-1823] took a barometer with him on the first ascent in a hydrogen balloon. Its purpose was to investigate the change of atmospheric pressure with increasing altitude, an aim which was admirably accomplished, and which provided a wealth of new information about the structure of the earth's atmosphere.

a)

b)

Fig. 6. a) The supremely accurate scale, incorporating a Vernier gauge, of a Fortin barometer, showing an atmospheric pressure reading of 29.10 inches of mercury, b) mercury reservoir, showing the ivory pointer, centre right, used to make zero adjustments

Because of its key role in the understanding of air pressure, and its role in ideas concerning the nature of matter, the Torricellian vacuum experiment has occupied a front-line position in the school teaching of physics. Figure 7 shows the diagram of the Torricellian experiment from A.F. Abbott's world-renowned textbook [14].

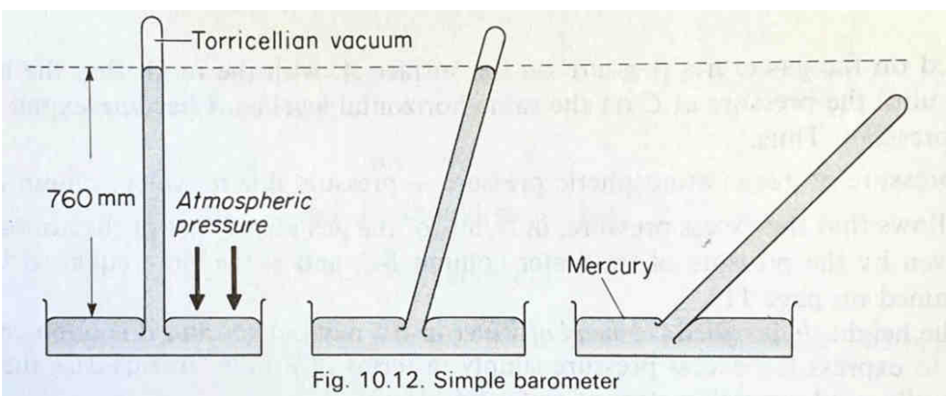

Fig. 7. Torricelli's experiment, from Abbott's physics textbook [14]

These beautifully clear diagrams show how, upon moving the long tube full of mercury from a tilted to a vertical position, the mercury level sinks in the tube, to attain a maximum height of 760cm. This height of mercury is supported by the weight of the earth's atmosphere, and the space above the mercury is empty, i.e., it is a vacuum.

This simple experiment, taught in schools throughout the world, demonstrates the unique role of mercury in a pivotal scientific discovery.

Mercury and three chemists - Priestley [1733-1804], Scheele [1742-1786] and Lavoisier [1743-1794]

Until the beginning of the 17^{th} century, air was not considered worthy of investigation. It was, after all, one of the four Aristotelian elements which were supposed to constitute all matter. However, from the mid 1640s until the mid 1670s, air became the focus of a huge wave of experiments and philosophical debates. [15] These debates were centred on an aeriform life supporting substance which was associated with nitre. Thus, nitre occupied the centre stage for research during the middle of the 17^{th} century. Major figures in this research included the Oxford luminaries Robert Boyle [1627-1691], Robert Hooke [1635-1703] and John Mayow [1641-1679].

This great wave of interest was initiated in Prague in 1604, by a treatise which was published that year. It was called *Novum Lumen Chymicum* (A New Light on Alchemy) and was written by the secretive Polish alchemist Michael Sendivogius [1566-1636]. Between 1604 and 1787 this work went through 56 editions in 5 European languages [16]. Sendivogius had emphatically and convincingly suggested a new interpretation of alchemical philosophy. The main thrust of his philosophy was centred on nitre, the key component of gunpowder - invented by the Chinese a few centuries earlier. It was this ingredient which enabled a mixture of charcoal and sulphur, which would normally burn with a mundane flame, to explode with great violence. What was it about nitre that caused this extraordinarily different type of combustion? Whilst Sendivogius did not provide an outright answer to this question, he certainly made a convincing case for its further investigation. He stated, for example, that: "(…) there is in the Aire a secret food of life (…)" [17]. Furthermore, "(…) it is the water of our dew, out of which is extracted the saltpetre of the philosophers, by which all things grow and are nourished (…)" [18].

For centuries, the focus of the alchemists' work had been on metals, and attempts to prepare the Philosopher's Stone, which could transmute base metals into gold, and thus lead to spiritual and bodily perfection. From 1604, with the impact of the Sendivogian system, the new direction of study became air and nitre [19]. For all their work in this field, the Oxford luminaries were inhibited by their conceptual framework - this included the idea that air is an element - and the limitations of the chemical possibilities offered by nitre (potassium nitrate).

Today we know that potassium nitrate is a solid chemical "store" of oxygen, which is released during its thermal decomposition in accordance with the equation:

$$2KNO_3(s) \longrightarrow 2KNO_2(s) + O_2(g)$$

potassium nitrate → potassium nitrite + oxygen

Using all the techniques at their disposal, and with ingeniously designed experiments, the 17th century chemists achieved all that was possible with nitre: they clearly identified a component of air that could support respiration and combustion. But they could not pinpoint this component of air. This was not because of their intellectual limitations, but because of the substance they were using - nitre. Nitre did not lend itself to an experiment in which it could absorb the “food of life” from air, and then reemit it in a subsequent experiment.

Thus, despite all the achievements of these early chemists and physiologists, the enigma of the “secret food of life” remained. This was clearly stated by one of the first chemistry professors, an outstanding teacher of chemistry, Hermann Boerhaave [1668-1738], in his celebrated textbook of chemistry *Elementa Chemiae* [1732]: “air possesses a secret occult virtue (…) That in this virtue the secret food of life lies hidden, as Sendivogius clearly said, some chemists have asserted. But what it really is, how it acts, and what exactly brings it about is still obscure. Happy the man who will discover it!” [20].

Phlogiston

The time was ripe to reconsider the process of burning by using other substances, new apparatus, new techniques, new experiments, and new people. Two German chemists, Johann Joachim Becher [1635-1682] and Georg Ernst Stahl [1659-1734], fulfilled these requirements. Based on their observations of the burning in air of phosphorus, sulphur, charcoal and a variety of metals, over a period of some thirty years, they developed an entirely novel theory of combustion. At the core of this theory was a new, somewhat vague concept - phlogiston, which was supposed to be the “matter and principle of fire”. According to this theory, combustible substances were rich in phlogiston, which escaped during burning. This idea stood to good reason since, in the case of the burning of wood, straw, paper, charcoal and coal, flames rose upwards, and the fuel all but disappeared.

There were, however, different kinds of substances that could be burnt - these were the metals. Since ancient times, metals were known to change into powdery solids, called calxes, when strongly heated in air. The change could be accompanied by flames, sparks, a glow or no emission of light at all. Furthermore, it had been noted that calxes were heavier than the metals from which they were derived. This weight increase during calcination had been described by Geber in the 8th century, and additionally by Jean Rey [1583-1645] in 1630, by John Mayow in 1668, and Robert Boyle in 1673 [21]. The explanation of this weight increase was very difficult. Some observers suggested that fire particles had weight, whereas others such as Rey, suggested that the weight increase was due to “thickened air” which “mixes itself among the calx” [22].

In order to explain the increase of weight during calcination, Becher and Stahl drew on alchemical philosophy, in which spirits played a role, and proposed the idea that phlogiston had negative weight. They argued their case convincingly and constructed a whole body of knowledge to support it. For almost a century, Becher and Stahl’s phlogiston theory became the front runner for solving the mystery of combustion and many other chemical phenomena [23].

Yet it had significant drawbacks: no-one had ever captured phlogiston, and the theory lacked quantitative experimental evidence, especially in connection with the calcination of metals. It was precisely this process, the calcination of metals, which focused the attention of the next generation of chemists onto this class of substances for subsequent investigations on the nature of combustion.

Priestley and Scheele open new horizons

At the beginning of the 17th century, the study of gases was still in its infancy. Chemists did not have the means of capturing the gaseous products of combustion or of measuring the change in the volume of air involved during the process.

This began to change in 1727, with the publication of a work entitled *Vegetable Staticks*. Its author was Stephen Hales [1677-1761] who was vicar of St Mary's church in Teddington. His scientific interests included plants, and the way they interacted with air whilst growing. Furthermore, he quantitatively studied the amounts of different kinds of air which were released during certain chemical reactions e.g. the action of heat on red lead or nitre (produce oxygen) or the reaction between iron filings and sulphuric acid (produces hydrogen). For this purpose, he devised an ingenious apparatus, which involved the collection of the different kinds of air by downward displacement of water. He also used mercury, a very novel technique at that time, for measuring the volume of fixed air which was released during the fermentation of peas [24].

Hales' work had a great influence on Joseph Priestley [1733-1804] who, like Hales, initially studied theology and the classics. Priestley developed a passionate interest in experimental science whilst living in Nantwich in 1758 and became especially interested in "different kinds of air" after moving to Leeds in 1767. In 1770, he developed a particular fascination for atmospheric air: "I am now taking up some of Dr. Hales's enquiries concerning air" [25]. Using a newly acquired large burning lens (12-inch diameter, with a focal length of 20 inches) [26] he undertook experiments to investigate the gaseous products of the thermal decomposition of several substances. The lens was very convenient, clean and fast to use - it focused the sun's rays to reach temperatures of about 600 °C, and no fuel was required. The substances Priestley investigated included nitre (potassium nitrate), red lead (calx of lead) and calx of mercury.

He obtained an extraordinary result with the calx of mercury. This had already been prepared in the 11th century by an unknown Spanish Arab, as a red powder which forms on the surface of mercury, which had been exposed to heat in air for 40 days [27]. This calx was well known to apothecaries, who used it for the preparation of ointments, and to alchemists, who associated it with the Philosopher's Stone.

Here is an extract from Priestley's notes on the experiment which caused a sensation: "On the 1st of August 1774, I endeavoured to extract air from *mercurius calcinatus per se*; and I presently found that, by means of this lens, air was expelled from it very readily (…) But what surprised me more than I can well express, was, that a candle burned in this air with a remarkably vigorous flame [28]". A diagrammatic representation of his experiment is given in Figure 8 [29]. Priestley was staggered with this result - it was, after all, a truly remarkable experience to see a dramatic increase in the size and intensity of a candle flame. He could not wait to share this newly acquired knowledge.

At this time, Paris had become a renowned centre for chemical investigations. It was here that Antoine Laurent Lavoisier had already established himself as an outstanding experimenter. By a fortuitous set of circumstances, Priestley, who had learnt French, met Lavoisier in Paris in October 1774 [30]. Here he described his sensational experiment with red calx of mercury, calling the gaseous product "dephlogisticated air". This meeting sparked a profound effect on the imagination of the young Lavoisier, as will shortly be shown.

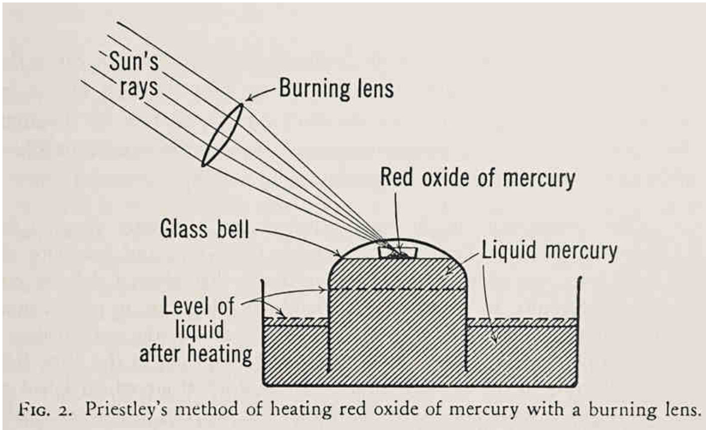

Fig. 8. Priestley's experiment on the thermal decomposition of calx of mercury [29]

Upon returning to England, Priestley continued his investigations further, as he described in his diary in March 1775: "On the 8th of this month I procured a mouse, and put it into a glass vessel, containing two ounce-measures of the air from mercurius calcinatus. Had it been common air, a full-grown mouse, as this was, would have lived in it about a quarter of an hour. In this air, however, my mouse lived a full half hour" [31]; Priestley did many more experiments with his dephlogisticated air, which he had obtained from *mercurius calcinatus per se*. He found, to his continued amazement, that flames burnt better and that mice lived longer than in ordinary air. After breathing it, he said: "I fancied that my breast felt peculiarly light and easy for some time afterwards. Who can tell but that, in time, this pure air may become a fashionable article in luxury. Hitherto only two mice and myself have had the privilege of breathing it" [32].

Yet, despite these remarkable experiments, the enigma of the aerial "secret food of life" continued to perplex him. The issue was extremely complex and involved many other substances including those which we would recognise as nitric acid, mercurous nitrate, nitrous oxide, nitric oxide, nitrogen dioxide, charcoal and carbon dioxide. Ultimately, Priestley was unable to disentangle the huge body of experimental results which had accumulated and was therefore unable to ascertain that air was a mixture of gases, of which his "dephlogisticated air" was a component. Thus, he was not in a position to formulate a universal theory of combustion. For Priestley, who discovered dephlogisticated air, which is today known as oxygen, phlogiston still ruled.

At roughly the same time as Priestley was conducting his experiments, the Swedish apothecary Carl Wilhelm Scheele conducted similar experiments on the thermal decomposition of the calx of mercury. He had, in fact, decomposed this calx two years before Priestley, but his results were not published until 1777. Scheele called his gaseous product *Feuerluft* i.e. "fire air". He was a phlogistonist, and like Priestley, was unable to formulate a general theory of combustion. He corresponded with Lavoisier and undoubtedly inspired him in his own research.

In addition to his discovery of *Feuerluft*, Scheele was an unbelievably prolific worker and discovered a huge number of compounds and reactions. Scheele died at the young age of 43, probably poisoned by his own experiments [33].

Enter Lavoisier

Antoine Lavoisier, who was born in Paris and had studied astronomy, botany and geology, started experiments with combustion in 1772 [34]. In 1774, after his meeting with Priestley, Lavoisier became passionately inspired to take up the hunt for a full and logical explanation of the aerial "food of life", and its role in respiration and combustion.

In this respect, Lavoisier had a couple of trump cards up his sleeve, which were to play a decisive role in his work. Firstly, because he worked as a tax collector at the time, he was familiar with "balancing the books". He applied this philosophy to chemical reactions: "(…) in all the operations of art and nature, nothing is created; an equal quantity of matter exists both before and after the experiment; (…) Upon this principle, the whole art of performing chemical experiments depends" [35]. This "Law of Conservation of Mass", as it is known, was central to Lavoisier's thinking. His second trump card was his recognition of the paramount importance of accurately measuring the volumes of gases and the masses of reagents. Additionally, he recognised the importance of recording prevailing temperature and pressure conditions during his experiments. Lavoisier was furthermore a brilliant logician, and was able to construct and execute experiments, which would lead him to indisputable facts about the nature of combustion, and the role of air in it.

In one of these experiments, he conducted and gravimetrically analysed calcination reactions in sealed glass vessels. For example, he heated tin and lead in air, in sealed vessels, until they had formed a calx. Although he found that the mass of the sealed glass vessel with contents remained the same before and after the experiment, Lavoisier noted that air rushed into the vessel when it was broken. He thus drew the conclusion that a part of the air was taken in during the calcination of the tin [36]. This observation, which only a very skilled experimenter would have made, enabled him to draw an important conclusion about the nature of calcination - a part of the air is chemically combined with the metal during its calcination. After experimenting with mercury, tin and lead in calcination reactions, he found that the calx of mercury was the only one which could be reversibly and quantitatively decomposed.

Here is part of his account of the experiment in which he quantitively synthesised the calx of mercury: "I took a matrass (A, fig. 14. Plate II) of about 36 cubical inches capacity (…) I introduced four ounces of pure mercury into the matrass (…) Having accurately noted the height of the thermometer and barometer, I lighted a fire in the furnace MMNN, which I kept up almost continually during twelve days, so as to keep the quicksilver always almost at its boiling point. (…) At the end of twelve days, feeling that the calcination of the mercury did not at all increase, I extinguished the fire (…). The bulk of the air (…) at the commencement of the experiment was about 50 cubical inches. At the end of the experiment (…) was only between 42 and 43 cubical inches; consequently it had lost about 1/6 of its bulk. Afterwards, having collected all the red particles, formed during the experiment, from the running mercury in which they floated, I found these to amount to 45 grains" [37]. The apparatus for this experiment is represented in Plate 4, fig. 2 from the collection of beautiful plates, illustrating Lavoisier's chemical laboratory ware. These plates were appended to the end of his treatise and were drawn by his wife, Marie-Anne Paulze [1758-1836]. Figure 9 shows the arrangement of the furnace, matrass (flask), trough filled with water/mercury, and graduated bell jar for measuring the change in volume of air [38]. Judging by the amounts of reagents and products (four ounces of mercury have a volume of 8 cm^3, and 36 cubic inches is about 600 cm^3) this apparatus must have been small, with the furnace about 60 cm high.

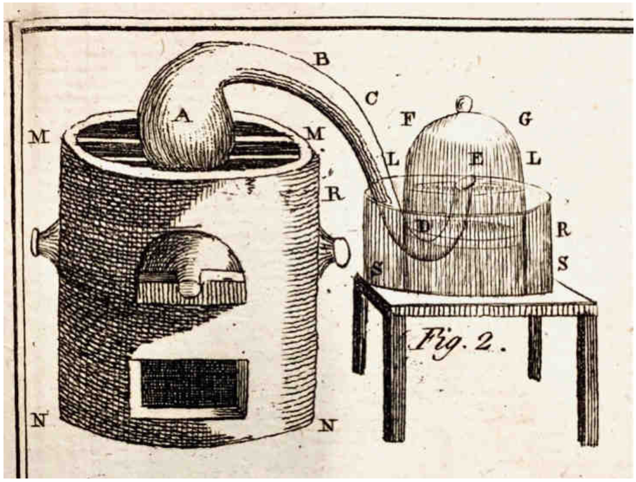

Fig. 9. Lavoisier's apparatus for preparing the calx of mercury [38]

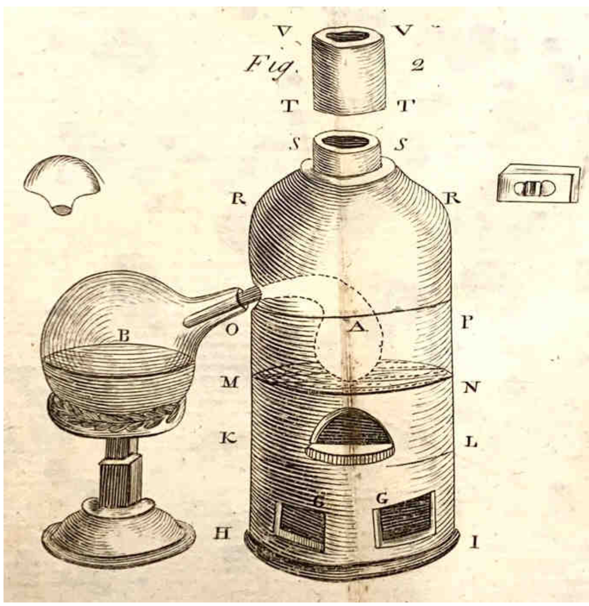

Fig. 10. Reverberatory furnace used by Lavoisier for the decomposition of the calx of mercury. The receiver would have been different - as in the first experiment (Fig. 9) [40]

Lavoisier described the follow-up experiment, in which he quantitively decomposed the calx, as follows: "I took the 45 grains of red matter formed during this experiment, which I put into a small glass retort, having a proper apparatus for receiving such liquid, or gaseous product, as might be extracted: Having applied a fire to the retort in a furnace, I observed that (…) When the retort was almost red hot, the red matter began gradually to decrease in bulk, and in a few minutes after it disappeared altogether; at the same time 41½ grains of running mercury were collected in the recipient, and 7 or 8 cubical inches of elastical fluid, greatly more capable of supporting both respiration and combustion than atmospherical air, were collected in the bell glass" [39]. The furnace which Lavoisier used for this experiment was of the reverberatory type, and a diagram of it is shown in Figure 10 [40].

That he used a reverberatory furnace, and not a burning glass, as Priestley had used for this experiment, may be inferred from comments which Lavoisier had made in earlier experiments on the reaction of metallic calxes with charcoal: "(…) which I placed in a reverberatory furnace of proportionate size" [41] and "I put into a retort of the same size as before (two cubic inches) one ounce of *mercurius calcinatus per se*, alone; I arranged the apparatus the same way as in the preceding experiment, (…)" [42]. By referring to the "preceding" experiment, Lavoisier is clearly implying the use of a reverberatory furnace. By using this furnace in conjunction with suitable glassware, he would have been in a position to accurately measure the volume of "elastic fluid", which was released during the decomposition of the calx of mercury.

Using the results of these two experiments, Lavoisier was able to make the ground-breaking discovery that **air is a mixture** of two gases. He stated this quite clearly: "CHAP. III. *Analysis of Atmospheric Air, and its Division into two Elastic Fluids; the one fit for Respiration, the other incapable of being respired.* From what has been premised, it follows, that our atmosphere is composed of a mixture (…)" [43]. Furthermore, he was able to formulate a universal theory of combustion, which, much simplified, states that: "when substances burn, they combine with oxygen to make new compounds, called oxides".

The Lavoisierian chemical theory, with its far-reaching applications, underpins the whole of today's chemistry. For this reason, Lavoisier is rightfully called the "father" of modern chemistry.

To achieve this great breakthrough, he used the unique substance mercury, and he was aware of its special role in his work. He expressed this quite clearly: "As all the oxyds of mercury are capable of revivifying without addition, and restore the oxygen gas that they had before absorbed, this seemed to be the most proper metal for becoming the subject for conclusive experiments upon oxidation" [44]. The last part of his chapter 8: "Of the oxidation of Metals" is devoted to a detailed explanation of his two experiments described above, which he considers should become core components of chemistry courses. "As, of all experiments upon the oxidation of metals, those with mercury are the most conclusive, it were very much to be wished that a simple apparatus could be contrived by which this oxidation and its results might be demonstrated in public courses of chemistry." [45]

Using today's chemical language, we can represent the unique reversible reaction of mercury with oxygen, as follows.

$$2Hg(l) + O_2(g) \underset{600\ ^\circ C\ (5\ minutes)}{\overset{350\ ^\circ C\ (12\ days)}{\rightleftharpoons}} 2HgO(s)$$

Conclusion

Using nitre as the key substance, the 17th century chemical philosophers achieved absolutely everything that was possible in identifying and characterising the Sendivogian “hidden food of life” in air. With hindsight, it is possible to see that whatever experiments they did, they were never going to be in a position to establish the fact that air is a mixture of two gases, one supporting respiration and combustion (20 %), and the other, suffocating flames and life (80 %).

For the complete analysis of air, an experiment would have to be devised, which would use a substance that would easily combine with atmospheric oxygen at one temperature, and release the same amount of oxygen at another temperature. There is only one substance which could fulfil this role: mercury. And only one person who had the practical knowhow, the theoretical background and the enlightened mind to be able to accomplish this: Lavoisier.

After the countless number of experiments which had been conducted by countless numbers of chemists over a period of almost two centuries, Lavoisier had finally solved the enigma of the secret aeriform “food of life”, which, in 1778, he named oxygen. The word oxygen is derived from two Greek words: *oxys* and *genes*, which mean “the acid maker”, and was coined on the basis of Lavoisier’s knowledge of the acidic oxides of carbon, sulphur, phosphorus and nitrogen. Yet, in this case, his logic did not stand the test of time, since today it is known that not all acids, e.g. hydrochloric acid, contain oxygen. In another similar statement which has today been shown to be incorrect, Lavoisier included heat (Calorique) and light (Lumière) in his list of the elements. The fact that a scientist as great as Lavoisier was able to make statements, which are today known to be incorrect, reflects the colossal difficulty which has always confronted scientists. This is all the more reason why they and their achievements should be accorded great respect.

It was a great tragedy then, that Lavoisier, who as a tax collector was considered to be an enemy of the state, was executed by the guillotine during the French Revolution [46]. “Thus perished, at the age of fifty-one, one of the most remarkable men in the history of science. (…) The news of this great crime profoundly affected the intellectual world” [47].

Today we live in a world of internal combustion engines which power ships, yachts, aircraft, rockets, cars, trucks, lorries, buses and tractors; a world of Bunsen burners, gas cookers, central heating systems and industrial chemical plants; a world in which giant steam turbines turn huge generators that supply electricity to our doorsteps. For all of this, we can thank Lavoisier and mercury.

Mercury and Faraday

Mercury in laboratories

Throughout the ages, mercury was extracted from its dark red ore - cinnabar, for which the chemical name is mercury(II) sulphide. In the 4th century BC, it was obtained by grinding cinnabar with vinegar. In the Roman era, techniques had been developed, in which the cinnabar was decomposed by roasting it in furnaces, and liquid mercury was collected by condensing its vapours. It was used for a wide variety of purposes.

In alchemical laboratories, which existed from the Middle Ages until the 18th century, mercury was used in attempts to make the philosopher’s stone and to prepare a wide variety of medicaments. These activities of the alchemists were summarised succinctly in 1810, by the outspoken Scottish historian of chemistry, Professor Thomas Thomson [1773-1852]: "Mercury was the metal from which the alchymists conceived the greatest hopes, and which they exposed to every possible torture during their researches after the philosopher's stone. The introduction of medicine occasioned a scrutiny no less varied than obstinate, after the paroxysm of the alchemists was over" [48]. Figure 11 shows mercury, being poured into a Petri dish.

Fig. 11. Pouring mercury into a Petri dish

In chemical laboratories, from the 18th century onwards, in which the philosophy and aims of experiments were fundamentally different from those of the alchemists, mercury was highly valued for its physical properties. It became especially useful in the emerging study of "different kinds of air", or gases as they became subsequently known. Thus, Robert Boyle used mercury for his experiments on the variation of the volume of air (to which he referred as an elastic fluid) with pressure. From these experiments he formulated his celebrated Boyle's Law in 1662. Joseph Priestley, who dramatically improved techniques for the manipulation of gases under water, introduced the use of mercury to collect soluble gases: "In experiments on those kinds of air which are readily imbibed by water, I always make use of quicksilver, in the manner represented in Figure 8, (…)" [49]. Figure 12 shows Priestley's setup for generating a gas which is soluble in water, and collecting it over mercury [50].

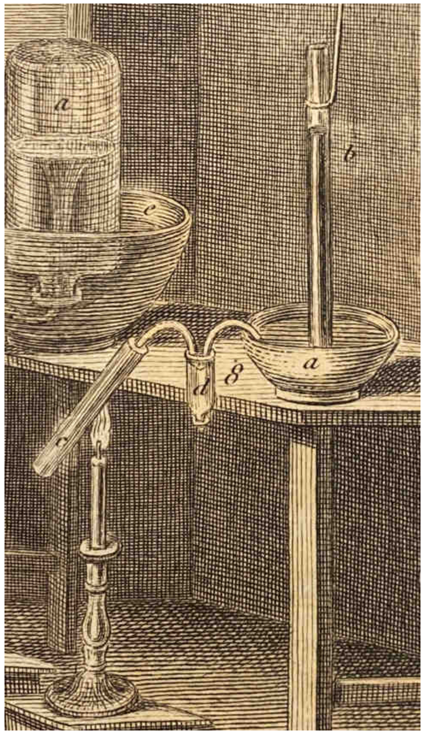

Fig. 12 This inset from the backplate (Fig. 8) shows a tube *c* being heated, a condensate collector *d*, a glass bowl of mercury *a* and a long, inverted glass tube (baton) *b*, partly filled with mercury, for collecting the gas [50]

This apparatus would have been perfect for making ammonia, which Priestley called *alkaline air*. "Accordingly I mixed one fourth of pounded sal ammoniac, with three fourths of slaked lime; and filling a phial with the mixture, I presently found that it completely answered my purpose. The heat of a candle expelled from this mixture a prodigious quantity of alkaline air" [51]. Sal ammoniac is today known as ammonium chloride, and slaked lime is calcium hydroxide. The tube d collected condensed water vapour and ammonia gas was collected over mercury in tube b.

Priestley was also able to prepare, collect and investigate hydrogen chloride (marine acid air), sulphur dioxide (vitriolic acid air) and silicon tetrafluoride (fluor acid air), all of which are soluble in water [52]. At the beginning of the 19th century, mercury was a common laboratory material.

Enter Faraday

A particularly special laboratory was housed at the Royal Institution (RI) of Great Britain in London, which had been founded in 1799 by Sir Benjamin Thompson (Count Rumford). The purpose of the Institution was to enable scientists to interact with members of the public via educational lectures and workshops. One of the most important scientists, who became involved with the RI in 1813, was Michael Faraday. Faraday was not only an extraordinarily gifted experimenter, but also an outstanding educator [53], and became widely known and adored through his popular science lectures for families with children. He was also an expert in handling mercury and used it in a wide variety of applications [54]. Little was he to know at the beginning of his career, that soon he would be exploiting yet another property of mercury - its electrical conductivity.

The year 1800 had seen a colossal scientific breakthrough - Alessandro Volta published the results of his experiments in which he described a kind of energy - electrical energy, which could be generated by the action of two dissimilar metals which were dipped into a saline solution [55]. This energy could flow down a metal wire. Today this is called *current electricity*. Volta knew about this energy only too well, since he had subjected himself to a range of electric shocks that caused his body to contort and go into spasms. The possibilities which this discovery offered, fired the imaginations of everyone who heard about it.

Among such possibilities were the physical effects of an electric current, especially its effect on a magnet. The reason why this phenomenon drew so much interest, was that it involved invisible forces. Invisible forces - both gravitational and magnetic, had always held a special fascination for people. And it was in this field of invisible forces, that another sensational discovery was made, this time in 1820 by the Danish physicist Hans Christian Oersted [1777-1851]. Oersted initially studied medicine, but his main passions were chemistry and physics. He was appointed professor of physics at the University of Copenhagen in 1806 and maintained contact with many scientists. It was these scientists who fostered Oersted's special interest in the relationship between electricity and magnetism [56].

After many unsuccessful attempts to demonstrate that there was a link between electricity and magnetism, Oersted finally, to his utter amazement, succeeded in 1820. He discovered that when an electric current flowed down a wire, it could cause the deflection of a magnetic needle. This deflection was a mechanical movement. He had thus achieved one of the greatest dreams of scientists - the conversion of electrical energy into mechanical energy, by means of invisible magnetic forces. This effect became known as the electromagnetic effect, and it immediately inspired a whole number of scientists to a hitherto unthinkable idea - could these invisible magnetic forces be harnessed to induce motion?

In that same year, the French physicist and mathematician Andre-Marie Ampere [1775-1836] showed that the magnetic flux around the wire, which was conducting electricity, was a circular one. This can be visualised as a cylinder of magnetism around the wire. Ampere further discovered that parallel currents flowing in the same direction attract one another. This discovery immediately sparked the next wave of great interest in the scientific community - the idea of circular motion. Could the invisible magnetic flux around the wire that was carrying a current, interact with the field of a permanent magnet in such a way as to cause rotation? If this issue could be resolved, then a new kind of machine could be developed - a motor which is driven by invisible electromagnetic forces.

Among many scientists who took up the challenge to design a device that would convert an electric current into rotary motion through the interaction of magnetic fields, was Michael Faraday. In his experimental work, Faraday had already demonstrated supreme manipulative skills and a colossal intuitive intelligence - by 1819, for example, he had already established himself as the foremost analytical chemist in England [57].

The concepts involved in the project were exceedingly difficult to grasp, since the magnetic field, the electric current, and the direction of the force on the conductor, were all mutually at right angles to one another. It is not surprising that several scientists, including the distinguished chemist and physicist William Wollaston [1766-1828], gave up the chase [58]. Faraday persisted, however, in trying to design an apparatus which would work. After several unsuccessful attempts, on September 3rd, 1821, he achieved a great breakthrough, by obtaining “electromagnetic rotations”, as he described them, in a simple apparatus. A replica of this precursor to an electric motor is shown in Figures 13a and 13b. Crucially, it uses mercury as a liquid conductor of electricity.

a) b)

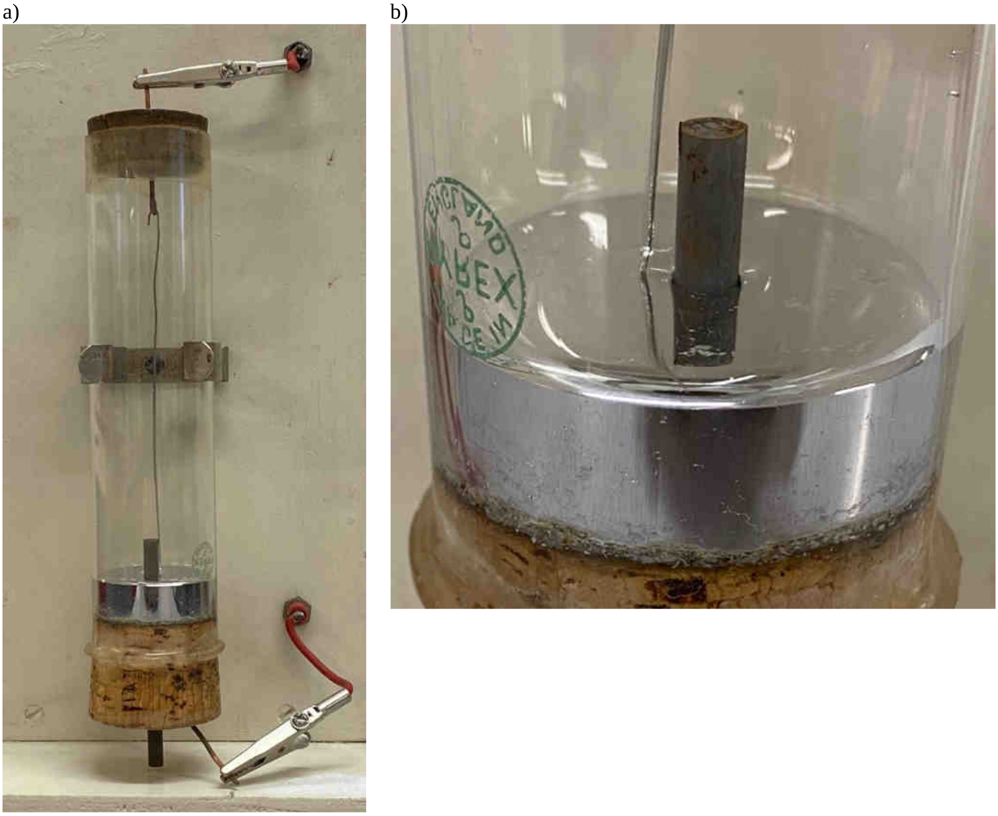

Fig. 13. a) A replica of Faraday’s precursor of the electric motor, and b) a closeup showing the mercury, permanent magnet, and stiff copper wire, which is suspended on a freely moving joint, to enable it to move in circles around the magnet when a potential difference of 3 volts is applied across the terminals. This is used for school demonstrations

Faraday was so excited about this invention, that on Christmas day of the same year, he succeeded in achieving a similar electromagnetic rotation, by using the earth’s magnetic field. This experiment was witnessed by his wife’s brother George Barnard: “All at once he [Faraday] exclaimed, ‘Do you see, do you see, do you see, George’ as the wire began to revolve. One end I recollect was in the cup of quicksilver, the other attached to the centre.

I shall never forget the enthusiasm expressed in his face and the sparkling in his eyes!" [59]. Thus, it can be seen what an enormous amount of excitement is generated by the process of scientific discovery.

The diagram in Figure 14, taken from a school textbook, shows the principal features of Faraday's "electrical rotation" device [60].

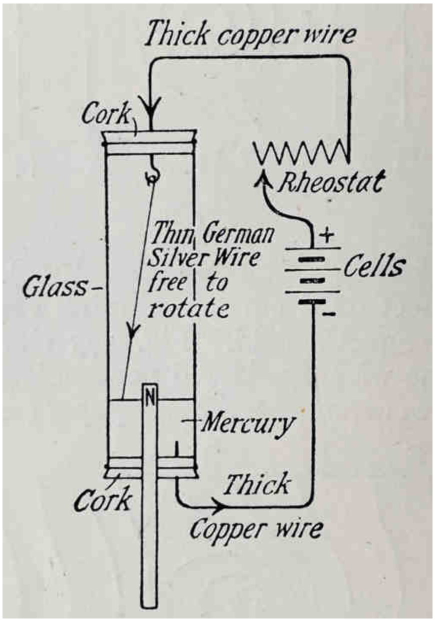

Fig. 14. Diagram showing the elements of Faraday's electric motor precursor. A fixed permanent magnet protrudes through the lower cork [60]

There are four stages in the explanation of how this rotation is achieved: 1. When the circuit is made, an electric current passes through the wire, and induces a circular magnetic field around itself. 2. The North pole of the permanent magnet experiences a magnetic force in the direction of the wire's field. 3. In accordance with Newton's third law of motion: "To every action there is an equal and opposite reaction", the magnet must exert an equal and opposite force on the wire. 4. This force is perpendicular to a line drawn from the wire to the pole and so the wire will rotate in a circle around the magnet.

Who, but the genius of Faraday, could have thought this through, and put it into practice? Michael Faraday was supremely humble and yet one of the greatest scientists of all time. It was he, who exploited the unique electrical and fluid properties of mercury to initiate the development of one of the world's most ubiquitous machines - the electric motor.

Conclusion

– Torricelli's experiment with an inverted tube of mercury (1643) led to a reinterpretation of the nature of matter.

- Lavoisier's theory of combustion (1789), drawn on earlier experiments of Priestley and Scheele, formed the foundation of modern chemistry.
- Faraday's electric motor prototype (1821) led directly to the development of the ubiquitous modern electric motor.

It has been clearly shown that mercury was the key player in each of these ground-breaking experiments. The colossal impact of the work of these scientists continues to affect our everyday lives. Mercury is indeed the element that has changed the world.

Acknowledgements

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