W. R. GROVE, THE FUEL CELL AND THE HYDROGEN ECONOMY

Sir John Meurig Thomas

Abstract

William Robert Grove (1811–1896), the inventor of the 'Grove cell', was born in Swansea and trained for the law. As a gifted mathematician and scientist, he played a pioneering role in the development of fuel-cell technology in the nineteenth century, alongside contemporaries such as Michael Faraday. This article surveys Grove's life and accomplishments, in particular his invention of the first-ever fuel cell and his award of the Royal Society Medal in 1847. The article assesses the scale of Grove's contribution to modern physics and the development of the emerging hydrogen economy.

Introduction

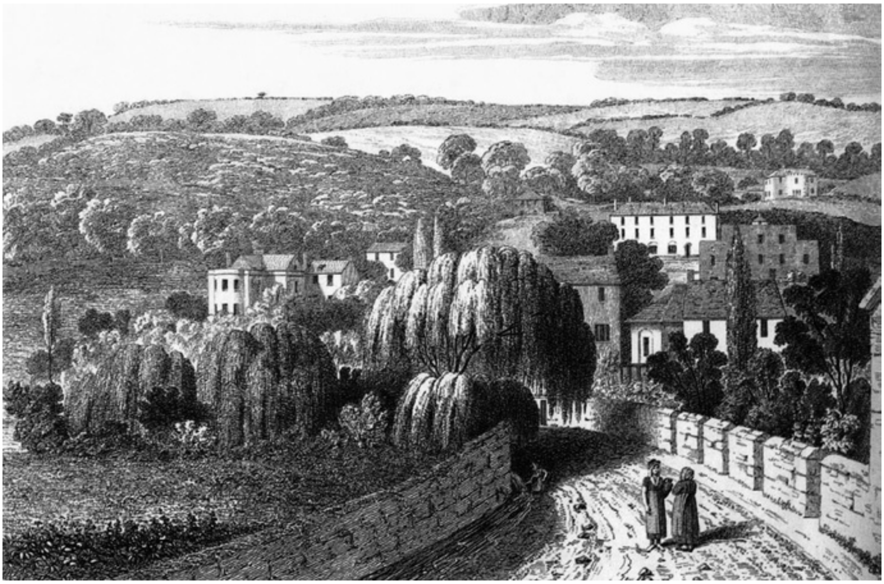
There are several reasons why I accepted, with enthusiasm, the invitation to present this lecture. The first is because W. R. Grove is one of the very few Welshmen who made major and everlasting contributions to the physical sciences, in topics not far removed from my own interests. The second is that, like me, he began his scientific career in Swansea. Thirdly, he had strong associations with the Royal Institution of Great Britain (in Albemarle Street) and with the Chemical Society (now the Royal Society of Chemistry), of which he was one of the founders in 1841. Fourthly, he played a leading role in the Royal Society, who awarded him its Royal Medal (in 1847) and who invited him to give one of its premier lectures, the Bakerian, in 1846.

That universal source of instant knowledge – Wikipedia – tells us that he was PC, QC, FRS, FRSE; that he was a judge, and that 'he anticipated the general theory of the conservation of energy' – which is the same as the first law of thermodynamics – and that he invented a powerful electrical battery (the Grove cell). And that he also invented the first-ever fuel cell, otherwise known, especially in his time, as the gas voltaic battery (see later).

I am now a great admirer of Grove also because he was, in turn, a great admirer and friend of one of my heroes, Michael Faraday, one of the greatest scientists who ever lived.[1] Indeed, as we shall see, it was Faraday who was among the first to learn of Grove's invention of the fuel cell.

1 John M. Thomas, *Michael Faraday and the Royal Institution: The Genius of Man and Place* (New York and London: Taylor and Francis, 1991).

[Fig. 1] *Statue and plaque in Swansea, W. R. Grove's home town [Copyright J. V. Tucker]*



[Fig. 2] *The Willows and Mount Pleasant in Swansea, as it was in the early 1800s [Copyright J. V. Tucker]*

Early Life

W. R. Grove was born in Swansea, the only child of John Grove, a magistrate and deputy lieutenant of Glamorgan, and his wife Anne, née Bevan. His early education was in the hands of private tutors, foremost among them being the Rev. Eli Griffiths. He attended Brasenose College, Oxford, to study Classics; but it is thought that, while at Oxford, his mathematical interests were cultivated by Baden Powell. He graduated in 1832 and in 1835 he was called to the bar in Lincoln's Inn. In that year he joined the Royal Institution, and shortly thereafter he was a founder of the Swansea Literary and Philosophical Society – the forerunner of the Royal Institution of South Wales (a body still in existence).

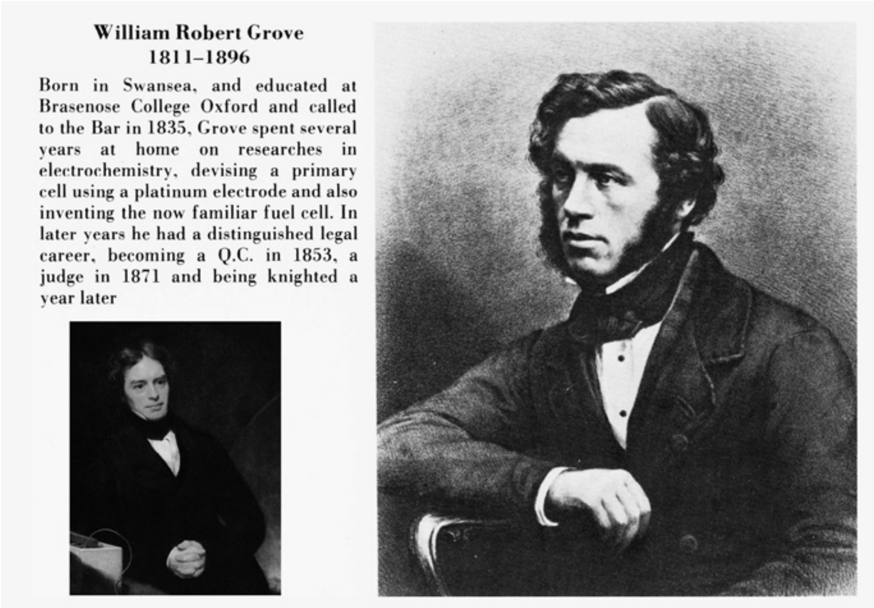
In 1837, Grove married Emma Maria Powles, and while on their honeymoon on the continent he ruminated upon various scientific topics. Shortly, thereafter, he published his first scientific paper on the topic of new voltaic combination.[2] Although he had qualified as a barrister, his deep interests, at this stage in his career, were in natural philosophy (the term then used for what are now regarded as the physical sciences). He conducted several experiments on voltaic cells while in Swansea. He developed a novel form of electric cell, which was later designated the Grove Cell, or the Grove intensity cell, shown schematically in Fig. 4.

It consists of a zinc rod (as one electrode) that dips into sulphuric acid, and another electrode made of platinum dipped in nitric acid; these two acids, and the electrodes that dipped into them, are separated by a porous ceramic pot.[3] Grove's battery, which gave an electromotive force (emf) of about 2 volts, was so popular that he demonstrated it at the Académie des Sciences in Paris in 1839. He also exhibited it a little later at the meeting of the British Association for the Advancement of Science in Birmingham. And Michael Faraday invited him, on 13 March 1840, to describe it at a Friday Evening Discourse at the Royal Institution. So striking were his presentations that he was soon proposed for a Fellowship of the Royal Society by such eminent scientists as Charles Wheatstone. He was elected FRS in 1840.

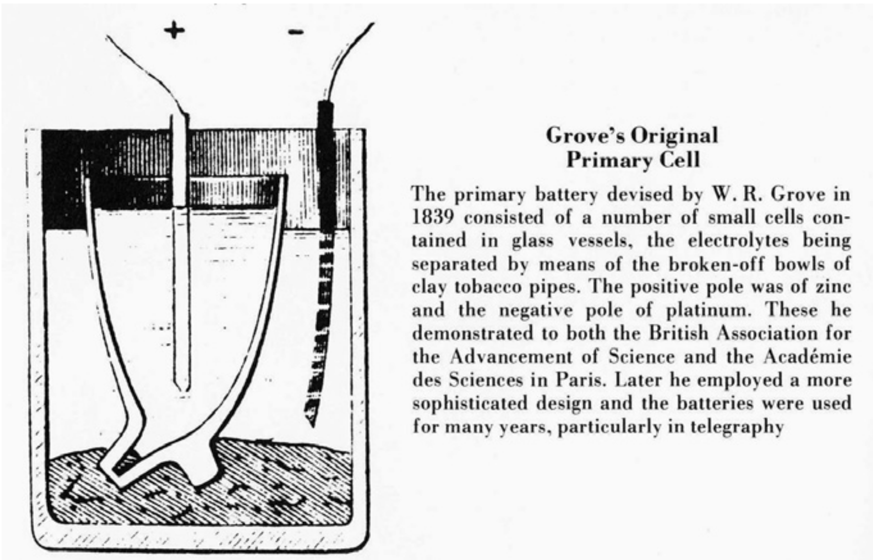
In 1841, Grove became the first professor of experimental philosophy at the London Institution (an establishment formed in 1819, but which ceased to exist over a century ago). In 1840 he had collaborated with another FRS, John Peter Gassiot, on experiments in photography. It is interesting to note that, possibly because of his legal turn of mind, Grove presciently observed:

> It would be vain to attempt specifically to predict what may be the effect of photography in future generations. A process by which the most transient actions are rendered permanent, by which facts write their own annals in a language that can never be obsolete, forming documents which prove themselves – must inference itself not only with science, but with history and legislation.[4]

2 W. R. Grove, *Philosophical Magazine*, 13 (1838), p. 430.
3 The porous pot was made from a clay pipe.
4 Grove made these remarks in the London Institution, 19 January 1842.



[Fig. 3] *Reproduction of a well-known photograph and brief biography of Grove, popular in the mid twentieth century [Copyright Royal Society]*



[Fig. 4] *Schematic illustration of the components of Grove's so-called intensity cell that generated an electromotive force of ca. 2 volts [Copyright Royal Society]*

Grove's tenure of the Professorship at the London Institution

One of the first major lectures that Grove presented at the London Institution was a survey titled 'The Progress of Physical Science', a quite expansive subject, especially for a man who was by training a classicist and by profession a barrister. But, because of his deep interest and activity in electro-chemical phenomena, he was well equipped to expound on this topic.

In 1842 he gave another wide-ranging lecture on 'The Co-relation of Physical Forces', a subject which he later developed and expanded into his publication, *The Correlation of Physical Forces* (see Fig. 6). This dealt with the inter-convertibility of various forms of energy, and was, in effect, an early account of the first law of thermodynamics: energy can neither be created nor destroyed, it can only be converted from one form to another.[5]

Grove was thus the first scientist to record the inter-relationships between the various forms of nature: heat, motion, light, magnetism, electricity, chemical affinity, etc. In his book, he wrote:

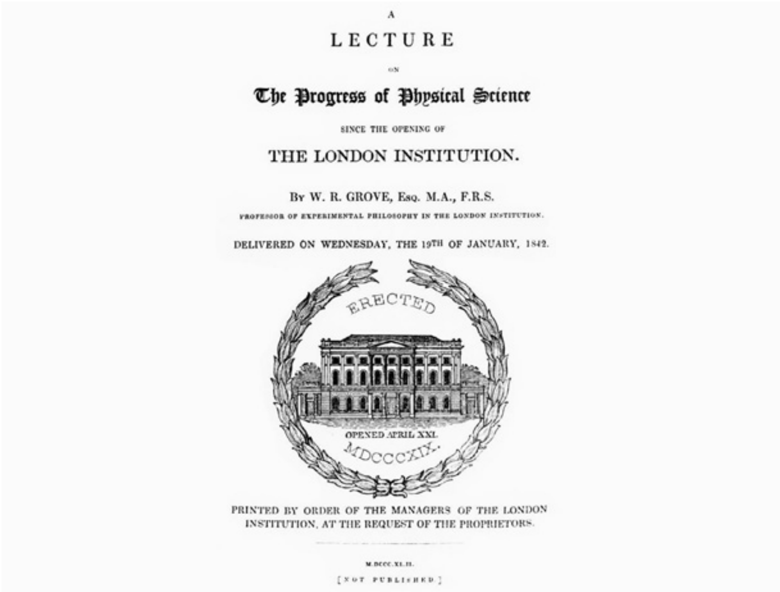
> Light, heat, electricity, magnetism, motion and chemical affinity are all convertible material affections; assuming either as the cause, one of the others will be the effect: thus heat may be said to produce electricity, electricity to produce heat, magnetism to produce electricity, electricity magnetism; and so of the rest. Cause and effect, therefore, in their abstract relation to these forces, are words solely of convenience. We are totally unacquainted with the ultimate generating power of each and all of them, and probably shall ever remain so; we can only ascertain the normae of their action: we must humbly refer their causation to one omnipresent influence, and content ourselves with studying their effects and developing, by experiment, their mutual relations.

Grove's book proved to be a resounding success. It was translated into other European languages and it ran to six editions. Its lucid style is redolent of a deeply cultured and broadly educated man. The first few notes at the end of the book reflect this fact (see Fig. 7).

Many other European scientists, notably Mayer and Helmholtz[6] in Germany, were at that time pursuing in their own ways their endeavours concerning the law of the conservation of energy. In the UK and elsewhere, however, there were several sceptics, and this meant that Grove encountered critical opposition to his views. In due course, however, he, Mayer, Helmholtz and others triumphed. It is noteworthy that in later editions of his book, Grove gave a charming account of the situation in which he initially found himself when he proposed his concepts on the correlation

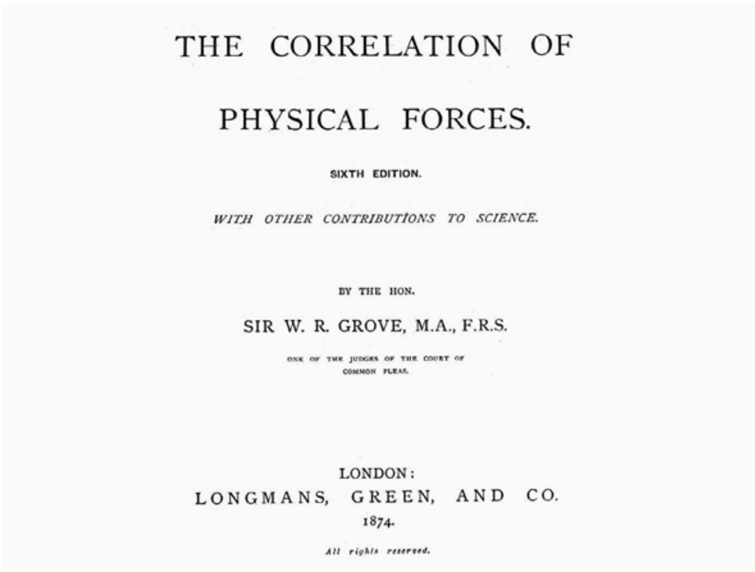
5 At that time, and for a decade or so later, most natural philosophers, Helmhotz especially (see note 6), talked of the forces of nature when, effectively, they were concerned with energy.

6 H. L. F. von Helmholtz (1821–94), German physician, physiologist, and physicist, one of the greatest scientists of the nineteenth century.


A
LECTURE
ON
The Progress of Physical Science
SINCE THE OPENING OF
THE LONDON INSTITUTION.
By W. R. GROVE, Esq. M.A., F.R.S.
PROFESSOR OF EXPERIMENTAL PHILOSOPHY IN THE LONDON INSTITUTION.
DELIVERED ON WEDNESDAY, THE 19TH OF JANUARY, 1842.

PRINTED BY ORDER OF THE MANAGERS OF THE LONDON INSTITUTION, AT THE REQUEST OF THE PROPRIETORS.
M.DCCC.XL.II.
[NOT PUBLISHED]

[Fig. 5] *The announcement of one of Grove's major lectures delivered in 1819 at the London Institution [Copyright London Institution]*


THE CORRELATION OF
PHYSICAL FORCES.
SIXTH EDITION.
WITH OTHER CONTRIBUTIONS TO SCIENCE.
BY THE HON.
SIR W. R. GROVE, M.A., F.R.S.
ONE OF THE JUDGES OF THE COURT OF COMMON PLEAS.
LONDON:
LONGMANS, GREEN, AND CO.
1874.
All rights reserved.

[Fig. 6] *Grove's most influential publication: his book on the correlation of physical forces which contained a qualitative statement of what later became to be known as the First Law of Thermodynamics [Copyright London Institution]* of forces (see Fig. 8).

At the London Institution, Grove accomplished much else, as evidenced by the work that he described in his Bakerian Lecture to the Royal Society in 1846.[7] Grove was one of the first, if not the first, to demonstrate that a platinum catalyst served to facilitate the combination of hydrogen and oxygen to yield water, as well as facilitating the decomposition (at high temperatures) of water into its component elements. (The thermodynamic principle of microscopic reversibility, which was not enunciated as such until the 1920s, demands that this be so.) While at the London Institution, Grove also devised a simple filament lamp, in which a platinum wire, held in a vacuum, lit up when an electric current (delivered by a Grove cell) was passed through it.

Perhaps the most noteworthy achievement that Grove perfected at the London Institution was his invention of the fuel cell, which he designated both as an 'unusual voltaic pile' and as a 'gas voltaic cell' (Figs 9a and 9b). In October 1842, he wrote to Michael Faraday at the Royal Institution (Fig. 9a). He called it a 'pile' because the first-ever battery to be created (by Volta)[8] was composed of a pile of alternating discs of silver and copper, as schematized in Fig. 9b.

What, in effect, this arrangement, devised by Grove, actually does is to combine hydrogen and oxygen electrochemically in a silent and efficient way, using the platinum foils as catalysts to facilitate the two processes shown at the bottom left and top right of Fig. 10.

Normally, when hydrogen and oxygen gases are brought together in the presence of a powdered platinum catalyst, they combine with explosive violence. The overall reaction (see Fig. 10) is:

$$2H_2 + O_2 \rightarrow 2H_2O$$

But the Grove fuel cell operates in such a way that the individual processes at each electrode are:

At the anode $2H_2 \rightarrow 4H \rightarrow 4H^+ + 4\varepsilon$. At the cathode: $O_2 + H_2O + 4\varepsilon \rightarrow 4OH$.

There is first dissociation of the H2 molecules to yield four hydrogen atoms, which, in turn, liberate four electrons and four protons. A proton is symbolized as H^+ and an electron, the smallest particle leaving a negative charge, as ε. In Fig. 10, we show how the overall processes taking place in this fuel cell give rise to the flow of electrons in an external circuit. This is how Grove's cell generates energy.

7 Grove's Bakerian Lecture was entitled: 'On Certain Phenomena of Voltaire Ignition and the Decomposition of Water into its constituent Gasses by Heat', and it was read to the Royal Society on 19 November 1846. The Bakerian Lecture is the Royal Society's premier lecture in the physical sciences. It originated through a bequest of Henry Baker in 1775. It is for an annual oration or discourse which is to be spoken or read by one of the Fellows. Grove was awarded the Royal Medal of the Society in 1847.

8 Alessandro Volta (1745–1827) of Como in Italy announced the discovery of his eponymous pile in a letter that he wrote to the President of the Royal Society, Sir Joseph Banks, in March 1800.

NOTES AND REFERENCES
TO THE CORRELATION OF PHYSICAL FORCES.

PAGE

5. THE reader who is curious as to the views of the ancients regarding the objects of science, will find clues to them in the second book of ARISTOTLE'S Physics, and in the first three books of the Metaphysics. See also the Timæus of PLATO, and RITTER'S History of Ancient Philosophy, where a sketch of the Philosophy of LEUCIPPUS and DEMOCRITUS will be found.

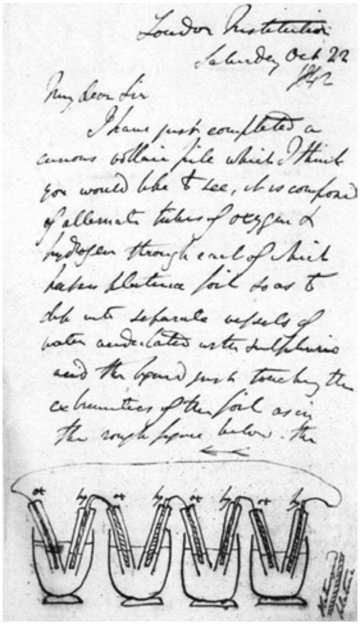
6. BACON'S Novum Organum, book ii. aph. 5 and 6.

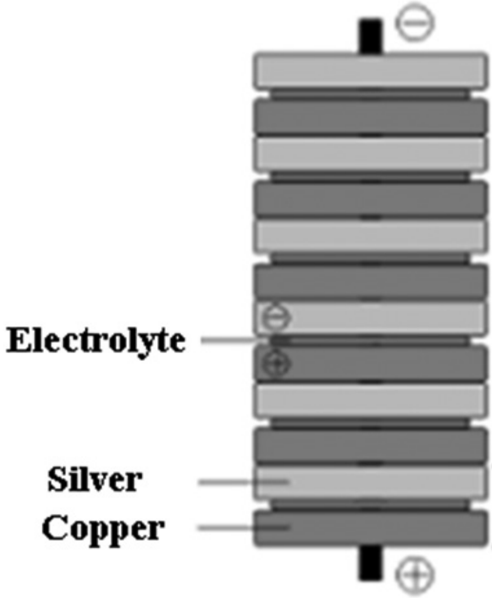
7. HUME'S Enquiry concerning Human Understanding, S. 7, London, 1768.

[Fig. 7] *Excerpts from the end notes of Grove's book, which illustrate the extent of his learning and general (especially classical) knowledge [Copyright Longmans, Green and Co.]*

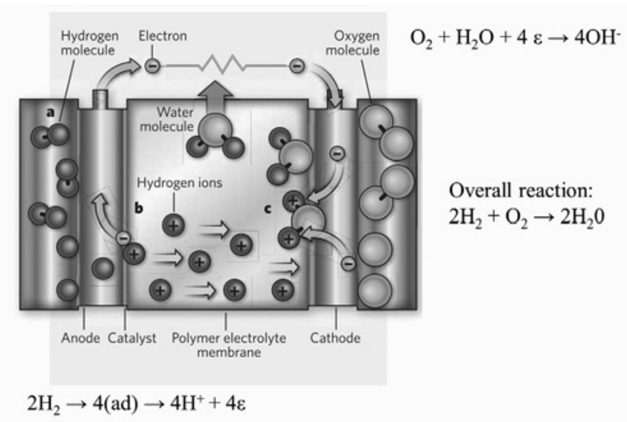
Every one is but a poor judge where he is himself interested, and I therefore write with diffidence; but it would be affecting an indifference which I do not feel if I did not state that I believe myself to have been the first who introduced this subject as a generalised system of philosophy, and continued to enforce it in my lectures and writings for many years, during which it met with the opposition usual and proper to novel ideas.

[Fig. 8] *A charming and magnanimous paragraph contained in Grove's Preface to the Fifth Edition of his book [Copyright Longmans, Green and Co.]*


London Institution
Saturday Oct 22
1842
My dear Sir
I have just completed a
curious voltaic pile which I think
you would like to see, it is composed
of alternate tubes of oxygen &
hydrogen through each of which
passes platina foil so as to
dip into separate vessels of
water acidulated with sulphuric
acid the liquid just touching the
extremities of the foil as in
the rough figure below. The



[Fig. 9a, left] *'I have just completed a curious voltaic pile which I think you would like to see, it is composed of alternate tubes of oxygen and hydrogen through each of which passes platina foil so as to dip into separate vessels of water acidulated with sulphuric acid, the liquid just touching the extremities of the foil as in the rough figure below' [By kind permission of Royal Institution]*
[Fig. 9b, right] *Voltaic Pile [Copyright J. M. Thomas]*



[Fig. 10] *Illustration of the individual processes that take place in a typical polymer membrane fuel cell which 'burns' hydrogen in oxygen, silently and in separate compartments. Modified from L. Schlapbach,* Nature*, 460 (2009), p. 809.*

I demonstrated how the fuel cell works during my BBC TV Royal Institution Christmas Lectures presented in December 1987 (and broadcast nationally in January and March of 1988). Fig. 11 is a 'still' from the programme that depicts the essence of the diagram shown in Grove's letter of 1842 (shown in Fig. 9b).

Fig. 12 is taken from Grove's publication in *Philosophical Magazine and Journal of Science*, 1842.

W. R. Grove and the Royal Society

As mentioned earlier, Grove was elected to the Fellowship of the Royal Society at the early age of twenty-nine, in 1840. Apart from the distinction of being awarded the Society's premier lectureship in the physical sciences (namely the Bakerian) and the even greater honour of being awarded the Royal Medal, his association with the Society is renowned for three other reasons. First, he protested – initially in an anonymous missive – about the rather random procedures for the election of new FRSs. At that time there was no upper limit in any given year for the number of newly elected Fellows. He advocated, and the Council of the Society accepted, that a fixed number only should be elected in a single year.

Second, as a Vice-President of the Society, he initiated other reforms concerning the manner in which the Society conducted its affairs. Third, it was Grove, along with the President, Baron Wrottesley, and his associate J. P. Gassiot, who were the individuals delegated by the Council of the Society to visit Michael Faraday in May 1857 to offer him the Presidency. Faraday turned down this offer, as he felt that both his scientific activity and his own ethos would be compromised by accepting to become PRS (see Fig. 13).

[Fig. 11] *Photograph of the set-up used in the 1987 Royal Institution Christmas Lectures presented by J. M. Thomas, showing tubes containing platinum electrodes and (alternately) oxygen and hydrogen and undulated water. Compare Fig. 12*

The status of Grove's fuel cell today

Grove's gaseous voltaic cell is now known (after Ludwig Mond made the suggestion in a famous paper that he published with Langer in 1889)[9] as a *fuel cell* – the first-ever devised, and it is now of enormous technical and scientific interest, as described below. The 'fuel' for Grove's cell is hydrogen, and air can be readily substituted for pure oxygen. Mond and Langer's paper bemoans the fact that, despite the 'lucid account' given by 'Lord Justice Grove' in many early papers, and despite several subsequent investigations by other eminent scientists (notably Lord Rayleigh), no really effective manufactured fuel cell had been commercialized when they wrote their paper in 1889.

Since a fuel cell circumvents the thermodynamic limitations associated with a thermal cycle (such as combustion engines) its efficiency much surpasses that of the internal combustion engine. This fact prompted the eminent German physical chemist, Ostwald,[10] in 1894 to predict that the fuel cell would ultimately displace internal combustion as a source of energy. As a consequence, a wide variety of applications has already been made (mainly using the H2/O2 cell) in, for example motor vehicles, fork lifts, submarines, buses, motorcycles, boats, and even aeroplanes. Nowadays, Japanese companies (e.g. Panasonic) are manufacturing units (the size of a fridge-freezer) to generate energy for domestic purposes, the fuel cell being natural gas or liquefied petroleum gas (LPG) that is first converted to hydrogen. A variant of the breathalyser, which detects ethanol in the blood, uses the principles of the fuel cell. We return below to the future vital importance of fuel cells.

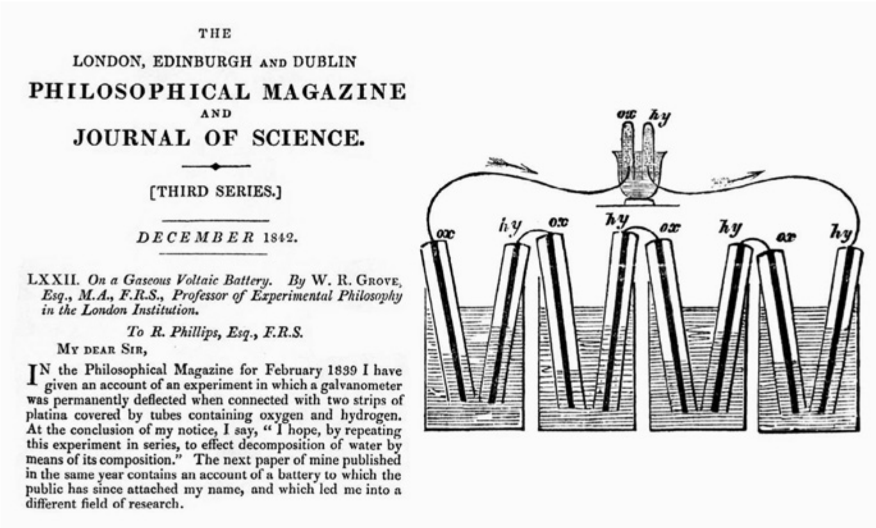
All fuel cells consist (as did Grove's original one) of three components: the two electrodes and an electrolyte to conduct ions between them. Grove himself demonstrated that it was not just hydrogen that could function as a fuel, which is oxidized by oxygen or air to generate the electromotive force (voltage) as energy, but also carbon monoxide (the overall reaction then being $2CO + O_2 \rightarrow 2CO_2$) and some hydrocarbons (like ethylene and ethane, i.e. C2H4 and C2H6 respectively). Grove also showed that some solid materials such as sulphur and phosphorus could also function as fuels. He demonstrated, too, that a fuel cell could also be constructed in which hydrogen combining with chlorine was the overall reaction: $H_2 + Cl_2 \rightarrow 2HCl$.

Enormous efforts have been made worldwide in the last half of the twentieth century and in the present one to exploit Grove's ingenious invention and extensions of it. It transpires that it is much more difficult to assemble a fuel cell using methanol, ethanol (i.e. methyl alcohol and ethyl alcohol), and hydrocarbons such as those present in petroleum than one using hydrogen. But such cells do exist, and the so-called direct methanol fuel cell (DMFC) is now used commercially,[11] albeit not very extensively. However, methanol is often used as a hydrogen carrier

9 L. Mond and C. Langer, *Proc. Roy. Soc. London*, 46 (1889), p. 296.

10 W. Ostwald, *Zeitschrift für Elektrochemie*, 1 (1894), p. 122.

11 G. Zehl, P. Bogdanoff, L. Dorbandt, S. Fletcher, K. Wipperman and C. Harting, *Journal of Applied Electrochemistry*, 37 (2007), p. 1475.



THE

LONDON, EDINBURGH AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[THIRD SERIES.]

DECEMBER 1842.

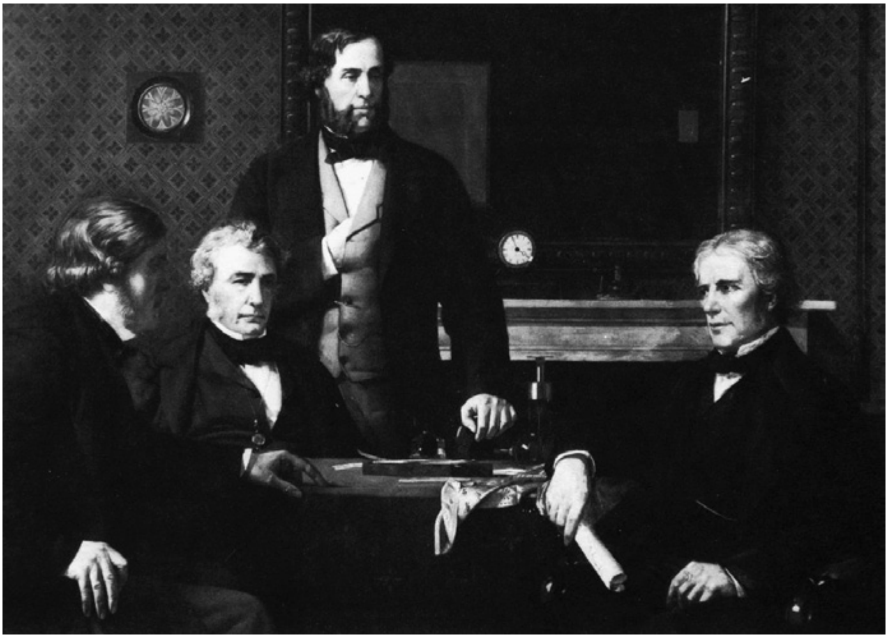
LXXII. *On a Gaseous Voltaic Battery. By* W. R. Grove, *Esq., M.A., F.R.S., Professor of Experimental Philosophy in the London Institution.*

To R. Phillips, Esq., F.R.S.

My dear Sir,

In the Philosophical Magazine for February 1839 I have given an account of an experiment in which a galvanometer was permanently deflected when connected with two strips of platina covered by tubes containing oxygen and hydrogen. At the conclusion of my notice, I say, "I hope, by repeating this experiment in series, to effect decomposition of water by means of its composition." The next paper of mine published in the same year contains an account of a battery to which the public has since attached my name, and which led me into a different field of research.

[Fig. 12] *Another illustration of the essence of Grove's fuel cell published (as shown on the left) in Philosophical Magazine, December 1842 [By kind permission of the Philos. Magazine]*



[Fig. 13] *Deputation from the Council of the Royal Society to Michael Faraday (seated at right) offering him the Presidency of the Society, which he refused. Grove is standing at centre [Copyright Royal Society]* in certain systems, i.e. it can be made to release hydrogen. The so-called 'Hotspot' technology of the Johnson-Matthey Company entails using a catalyst that first dehydrogenates methanol to release hydrogen, and another catalyst that burns off the residual carbon monoxide.[12]

Very many different types of fuel cells are now in use and under development. They have been developed for a multiplicity of different purposes. Considerable impetus for the design of new fuel cells (based on hydrogen) came from the late 1970s when the US National Aeronautics and Space Administration (NASA) decided that the preferred battery for space flights was the H_2/O_2 cell, and individuals like F. T. Bacon in the UK and organizations like General Electric (Schenectady), Pratt and Witney, and the McDonald Aircraft Companies in the US produced viable batteries that consumed hydrogen and oxygen for the generation of energy and the production of drinking water in space vehicles for astronauts. The Gemini and Apollo space programmes relied significantly on extensions to Grove's original fuel cell.

In the interests of compactness and efficiency a solid electrolyte is invariably used to conduct the ions in the cell itself; and the most popular variants are (conducting) polymer membranes. Solid-oxide fuel cells are popular; so are ones that utilize molten carbonates and other molten salts as electrolytes. In the so-called archetypal H_2-O_2 proton exchange membrane fuel cell (PEM FC) design,[13] a proton-conducting polymer membrane (such as the commercial product Nafion, which is a derivative of the well-known plastic Teflon but has the property of acting as a conductor of protons, just like a solution of sulphuric acid, and thus serves as the electrolyte) separates the anode and cathode compartments. (This was sometimes designated as a solid polymer electrolyte fuel cell [SPEFC] in the 1970s.)

Much effort has been expended recently to enhance the life of proton-exchange membrane (PEM) fuel cells. One solution entails increasing the life of Pt/C catalysts using proton-conducting polymer (e.g. perfluorosulfuric acid) stabilized carbon support. Pt-free catalysts made from earth-abundant materials would be desirable, and encouraging progress has recently been made by a joint Chinese-Swedish group in designing a highly effective and less expensive copper-copper oxide coating on thin supports of platinum.[14]

The hydrogen economy

Much has been written about the merit of the hydrogen economy.[15] What, in essence, it entails is the abandonment of the use of fossil-derived fuels – so as to 'decarbonize' energy production (and thereby cease to generate carbon dioxide)

12 P. G. Gray and M. I. Petch, *Platinum Metals Review*, 44 (2000), p. 108.
13 C. Cheng, S. Mu, X. Chen, H. Lu, M. Pan and P. P. Edwards, *Electrochimica Acta*, 56 (2011), p. 2156.
14 M. Wang and L. Sun, *ChemSusChem*, 3 (2010), p. 551.
15 See Cheng et al., *Electrochimica Acta*, 56 (2011), p. 2156; A. G. Dutton, *Wind Engineering*, 27 (2003), p. 239.

and to use hydrogen instead for the central feature of energy production and for transportation and heating. It means that hydrogen would be used extensively in fuel cells. Although hydrogen does not occur naturally, nowadays, it is becoming increasingly feasible to produce it by electrolysis of water. Even though the process of electrolysis is not very efficient, there are now many renewable sources of energy – solar, wind, hydro- and geothermal – that can be used to liberate hydrogen from water. For example, the solar panels and the so-called photovoltaic assemblies make it possible to generate large supplies of hydrogen. As a consequence, hydrogen re-fuelling stations are being established on an increasing scale in many countries, notably the US, Denmark, Germany, Norway, and, rather more slowly, in other countries within Europe. This hydrogen is used increasingly in fuel-cell vehicles (motor cars and trucks) where the propulsion comes from the electricity produced by a fuel cell (see Figs 14 and 15).

In several countries, government-industry consortia have been established to draw up firm plans for the introduction of the hydrogen economy. In no country on earth is there a more systematic drive towards the hydrogen economy than Japan. I am grateful to Professor Yasuhiro Iwasawa, Director of the Innovation Research Centre for Fuel Cells, University of Electro-Communications, Tokyo, for providing me with information pertaining to the realisation of the hydrogen economy in Japan. Fig. 16 sets out the strategy, formulated by the Ministry of Economy, Trade and Industry (METI) of Japan, for the realization of the hydrogen economy. Note, in particular, that by the mid-2020s, it is expected that there will be 160 hydrogen refuelling stations (of the kind shown in Fig. 14) in Japan.

Although many fuel cell vehicles utilize (on-board) compressed or liquid hydrogen containers, this option is far from ideal. First of all the energy per unit volume of liquid or compressed hydrogen is rather small. It is much less than the intrinsic energy locked up (as hydrogen) in many compounds of hydrogen, both inorganic and organic. For example, so-called amidoboranes that consist of the elements lithium, nitrogen, boron, and hydrogen, of chemical composition $LiNH_2BH_3$ or $NaNH_2BH_3$, are quite effective storage materials, as are simple hydrides like MgH2 (magnesium hydride). The disadvantage that these relatively high energy content hydrides possess is that, on exposure to air or water, they tend to be pyrophoric (i.e. liable to ignite), which therefore makes them unsuitable as on-board storage materials.

My colleagues at the University of Oxford, led by my collaborator, Professor Peter Edwards, in the Inorganic Chemistry Laboratory there, and I have recently explored a novel and potentially very valuable storage material, namely conventional wax.[16] Wax, typical formula $C_{36}H_{74}$, is a part-constituent of petroleum. We have discovered a simple method that uses a cheap catalyst to release hydrogen from such a wax by utilizing microwave radiation:

$$C_{36}H_{74} \rightarrow 36\ C + 37\ H_2$$

16 S. Gonzalez-Cortes, D. R. Slocombe, T. Xiao, A. Aldawsari, B. Yao, V. L. Kuznetsov, E. Liberti, A. I. Kirkland, M. S. Alkinani, H. A. Almegren, J. M. Thomas and P. P. Edwards, *Science Reports*, 6 (2016), p. 5315.

[Fig. 14] *A fuel cell car at a hydrogen pump at a 'petrol' station in Washington DC. The General Motors and Shell companies are backing the test to promote the technology [*International Tribune*, 12 November 2004]*

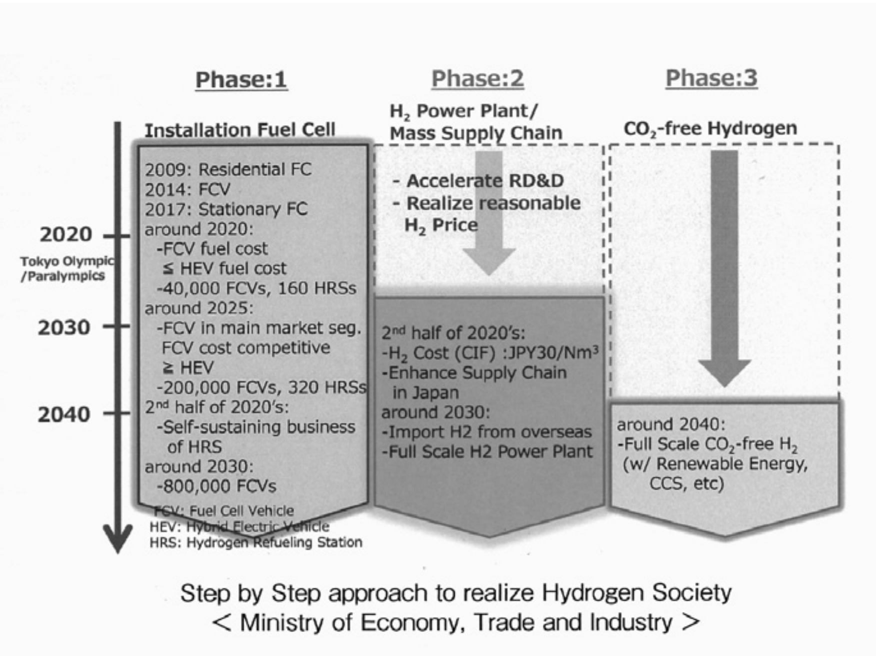
[Fig. 15] *Hydrogen is hailed as a non-polluting synthetic fuel that could replace oil, especially for transport applications. The technology to make this a reality – particularly hydrogen-storage materials – has been a long time coming, but the first commercial vehicles might now be only a few years away. [Schlapbach,* Nature*, 460 (2009), p. 809]. The Chicago Transit Authority has had, since 2001, zero-emission fuel cell propelled public transport.*

Much work still remains to be done to develop this approach so as to provide a viable, safe, benign and readily available hydrogen-storage material.

Envoi

In view of the enormous practical interest that fuel cells currently elicit, it is ironic that Grove himself once remarked: ‘Science to me generally ceases to be interesting as it becomes useful.’ Another noteworthy fact pertaining to Grove’s contribution to natural philosophy is that when the journal *Nature* published Grove’s obituary, the first paragraph was a quotation from Michael Faraday’s paper published in 1846, ‘On the Magnetisation of the Ray of Light and the Illumination of Magnetic Lines of Force’:

> I have long held an opinion almost amounting to conviction, in common I believe with many other lovers of natural knowledge, that the various forms under which the forces of matter are made manifest have one common origin; or in other words are so directly related and mutually dependent that they are convertible, as it were, into one another, and possess equivalents of power in their



[Fig. 16] *‘Step by step approach to realize Hydrogen Society’ (based on METI report, Tokyo, 2016) [By kind permission of Professor Yasuhiro Iwasawa]*

> action. In modern times the proofs of their convertibility have been accumulated to a very considerable extent, and a commencement made of the determination of their equivalent forces.[17]

This was an appropriate quotation, for it encapsulates the ideas that were in the minds of Grove's contemporaries, especially Faraday, Joule, and the German natural philosophers, Hehmholtz and Mayer. It is appropriate to add that this paper of Faraday's was of extraordinary importance. It was the one where he showed that light has a magnetic component. If this were not so, modern telecommunications like radio, television, mobile phones, tablets, and the internet would not be possible.

Acknowledgements

I am grateful to Professor J. V. Tucker of Swansea University for presenting me with the photographs that appear in Figs 1 and 2. I am also greatly indebted to Professors Y. Iwasawa, Tokyo, and P. P. Edwards, Oxford, and to Dr G. P. Owen for invaluable assistance. I dedicate this article to the memory of my late friend, Sir Ralph Kohn.

17 M. Faraday, *Phil. Trans. Roy. Soc. Lond.,* 1 (1846), p. 211.