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5 From the birth of fuel cells to the utopia of the hydrogen world

Pierre Teissier

In May 2007, five members of the European Parliament proposed the Written Declaration 16/2007 to establish “a distributed green hydrogen economy” and to implement “a third industrial revolution in Europe” by 2025 (Guidoni et al. 2008). Hydrogen is expected to replace hydrocarbons and become the major source of energy of the global economy. Oil, as well as natural gas, coal and wood are carbon-based fuels, whose combustion in heat engines converts chemical energy into mechanical power (Loeve and Bensaude-Vincent 2016, 000). The steam engine, improved by James Watt in the 1760s, was the first of these heat engines, fuelled by coal. This allowed the ‘first industrial revolution’ during the nineteenth century in Europe: the exponential growth of coal combustion sustaining the exponential growth of industrial activities, especially in textile and mining. From the 1880s onward, the electrical dynamo – a new device converting mechanical force into electrical power – allowed the building of power plants, in which heat engines were combined with dynamos to convert the chemical energy of coal into electricity. This was an important step in the ‘delocalization of power’¹ through electrical networks. In the meantime, the internal combustion engine led to the massive development of the motor industry, where the multiplication of private cars in operation on the roads during the twentieth century. By the late 1960s, petroleum had become the primary source of energy in the world. In two centuries (1770–1970), heat engines and power plants replaced wind and water mills to provide energy for humanity. The thermal forces of petroleum and coal replaced the mechanical forces of water and wind. Despite a few whistle-blowers who worried about the exhaustion of oil and coal in the subsoil and the poor conversion efficiency of heat engines, the industrial carbon-based economy grew rapidly.

The ‘hydrogen economy’ of the third millennium

Gradually, however, experimental clues convinced more observers that an unnatural warming of the global climate was on the way (Weart 2008). The issue became a hot topic, and a large independent group of scientific experts – the Intergovernmental Panel on Climate Change (IPCC) – came together from 1988 onward to establish a worldwide analysis of the situation. All the IPCC successive reports converged to stress the influence of greenhouse gases of anthropogenic origin,

especially carbon dioxide. Carbon dioxide is an atmospheric gas produced by the respiration of living organisms. It is responsible, with other gases like water and methane, for the natural greenhouse effect that sustains life on earth. It is also a product of the combustion of hydrocarbons and coal. The massive growth of heat engines in operation throughout the world had increased the level of carbon dioxide in the atmosphere by around one-third, compared with that before the industrial era. This man-made increase of carbon dioxide has “very likely” resulted in global warming during the twentieth century, as stated by the fourth (2007) and fifth (2014) IPCC reports.² Carbon-based fuels were made responsible of the climate change. Their relative consumption, in a given country, was proportional to the degree of industrialization and of wealth. For most rich countries, oil and coal have become ‘politically incorrect’ in the public opinion. Under European leadership, the 1995 Kyoto Protocol tied countries willing to reduce their domestic greenhouse gas emissions. Nevertheless, the global emission kept increasing. While the self-regulation of carbon emissions reached an impasse at the global scale, the European Union (EU) committed in 2008 to cutting its own emissions to 20 percent below 1990 levels by 2020.

The time was ripe for the EU to strike up an ‘energy transition’ from the carbon economy of the twentieth century to the hydrogen economy of the twenty-first century (Rifkin 2002, 2011).³ Newspapers presented a black and blue opposition between the ‘dark dirt’ of carbon-based fuels and the azure cleanness of water-based fuels. High-technology multinational companies like United Technologies Corporation advertised childish visions of the hydrogen economy (Figure 5.1).

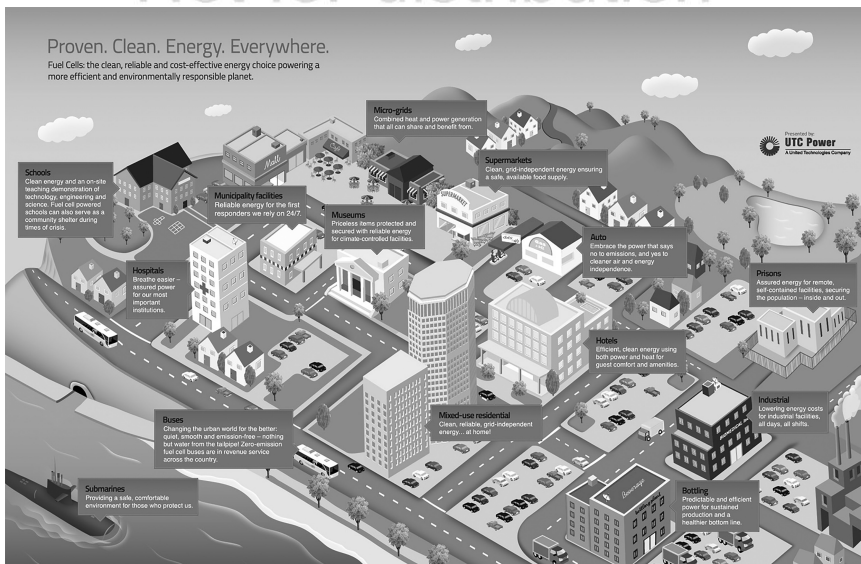


Figure 5.1 Advertisement for the hydrogen economy, UTC Power, 2013.

There, fuel cells played the same role as heat engines for carbon economy by converting the chemical energy of hydrogen into electrical power. A fuel cell was an electrochemical generator that produced electrical power from the chemical reaction of two gases, hydrogen and atmospheric oxygen. There was an oxidation at the anode: hydrogen was oxidized according to the following half-reaction, $\text{H}_2 = 2\text{H}^+ + 2\text{e}^-$. There was a reduction at the cathode: oxygen was reduced according to the following half-reaction: $\frac{1}{2}\text{O}_2 + 2\text{e}^- = \text{O}^{2-}$. In between the anode and the cathode, the electrolyte allowed the electrical contact and prevented the mixing of the compounds. Instead of emitting carbon dioxide like heat engines, fuel cells produced water by the sum of the two half-reactions: $\text{H}_2 + \frac{1}{2}\text{O}_2 = \text{H}_2\text{O}$.⁴ The electrons released by hydrogen gave electrical power. Heat was also released by the electrochemical reaction. In the 2000s, engineers and industrialists could design operational prototypes and commercial products with a conversion rate of energy up to 90 percent.

The fuel cell had thus become a multifunctional device providing water, heat and power with a high-energy efficiency. This aroused enthusiasm among policy makers and industrialists in the beginning of the third millennium. Fuel cells were expected to constitute the first node of the hydrogen network.

It is not a trivial matter, however, to turn expectations into reality. The hydrogen economy remains a magic formula with no impact on the world. Words are reluctant to be turned into things. It is not like in the antique tale of Genesis, where the God of the Bible once said, “Let there be light. And there was light.” The implementation of the hydrogen economy would have required a Creator to turn the wish into reality. But there is no such a thing as a demiurge in the third millennium. The fuel cell seems to resist all efforts and attempts to create a clean ‘hydrogen world’. To make this long and erratic story short, let us use a parody of the seven-day creation of ‘the heavens and the earth’ in the biblical Genesis. In this parody, the creature plays the leading part instead of the missing Creator. Each metaphorical day sets up a new context in which the ‘hydrogen creature’ is reconfigured and the desired ‘hydrogen world’ remodeled. The tale shows at the same time a process of individuation and the ‘recalcitrance’ of the fuel cell.⁵

To render the dialogue between expectations and resistances, a voice is given to both the context, through impersonal phrases, and the ‘hydrogen creature’ speaking for herself, *with ‘I’ at the end of each day*. The following narrative adopts and adapts the Genesis frame to tell the creation of the ‘hydrogen world’ from the perspective of the ‘hydrogen creature’. The dialogue between the creature and the environment aims to avoid three usual preconceptions imposed by the biographical genre: the permanence of things, the essence of beings and the continuity of time. Instead, it displays the changing patterns of the fuel cell and the correlated ‘hydrogen world’ in an attempt to characterize their ontologies.

A parody of the seven-day Genesis of the ‘hydrogen world’

Day 1 – Let there be hydrogen

Day 1 took place in 1787 when the ‘flammable air’ isolated by Henry Cavendish was renamed ‘hydrogen’ in Paris. The word ‘hydro-gen’ (*hydro-gène*) was coined

in 1787 by four French chemists – Louis Bernard Guyton de Morveau, Antoine-Laurent Lavoisier, Claude-Louis Berthollet and Antoine de Fourcroy – authors of the *Méthode de nomenclature chimique*.

Hydrogen appeared among the five elements, which were ‘the closest to the state of simplicity’ and provided the basis for the formation of all compound substances. This first class included: light, caloric, nitrogen, oxygen and hydrogen (Guyton de Morveau et al. 1787).⁶ The Book of Genesis mentioned only the first one when “God saw how good the light was” to distinguish day from night, and omitted the four other ones. Fortunately, Lavoisier came to complete God’s works and all was in order! Caloric, the principle of heat took over a number of functions of phlogiston, while nitrogen (generator of nitrous compounds) and oxygen (generator of acids) replaced the usual denominations phlogisticated air (*air phlogistique*) and dephlogisticated air (*air déphlogistique* or *air vital*). The new denomination hydrogen (generator of water) disqualified the elementary nature of water inherited from the Aristotelian tradition.⁷ At the same time, it opened up the possibility of obtaining this inflammable gas through a decomposition of water. The public demonstration of the composition of water orchestrated by Lavoisier and Jean-Baptiste Meusnier de la Place in February 1785 at the Paris Academy of Science resulted from the diversion of a campaign of experiments initiated two years earlier to explore means of production of inflammable air for the Montgolfier brothers’. The initial goal was to show that the production of large amounts of hydrogen to fill the balloons of aerostats with lighter-than-air gas was possible. However, the reform of chemical language downplayed this property for emphasizing the property of generating water and promoting analytical chemistry based on the concepts of simple and compound bodies.

In the Book of Genesis, light drew a clear boundary between Day and Night. In the first day of the hydrogen world, the Book of French chemists made the relation between Words and Bodies transparent. It also created the two airs – oxygen and hydrogen – that would allow me to breathe soon. However, I still lacked an ontological determination that would come during the second day.

Day 2 – A missed crucial experiment

The second day opened in Paris on October 22, 1838. At a Monday session of the French Academy of Sciences, Antoine-César Becquerel, physics professor of the Musée d’histoire naturelle, read two short notes on a marginal subject of electrochemistry. The field of electrochemistry had developed since Alessandro Volta’s pile invented in 1800. A voltaic pile was a stacking of two alternating metals (zinc/copper) separated by moist cardboard. It generated an electrical fluid when its two ‘poles’ were connected to a conducting loop of platinum wire. It was later renamed the ‘voltaic battery’ when it replaced the common electrical generators of the time, the Leyden jars, usually associated in battery to increase their power. In the mid-1830s, Michael Faraday established a new nomenclature: the ‘poles’ became the ‘electrodes’, one positive at high tension, called ‘cathode’, one negative at low tension, called ‘anode’, the liquid solution in which electrodes were plunged being

the 'electrolyte'. The voltaic current flowing in the circuit from the cathode to the anode could decompose the chemical compounds of an electrolyte and produce simple bodies at each electrode (Pancaldi 2003, 130). This reaction known as the electrolysis of water (HO) produced hydrogen gas (H) at the cathode and oxygen gas (O) at the anode.⁸ The equation was the same as for the thermal decomposition of water from the 1785 demonstration of Lavoisier: $\text{HO} \rightarrow \text{H} + \text{O}$.

Natural philosophers disagreed about the nature of the forces involved in electrolysis. For Volta, the "contact between, for example, silver and tin [gave] rise to a force, an exertion, that cause[d] the first to *give* electrical fluid, the second to *receive* it."⁹ This 'contact theory' suggested an inexhaustible 'electromotive force' (EMF) generated by the contact of two different metals, which was in contradiction with the limited lifetime of a battery. It was challenged by a 'chemical theory' in the 1830s who assumed that the voltaic current resulted from a chemical transformation of the electrodes and the electrolyte (Kragh 2000, §3). It was in this controversial context about the nature of voltaic electricity that Becquerel read two short papers in 1838. The first was an extract of a letter by a university professor of physics and chemistry from Basel, Christian Friedrich Schönbein. After he had performed the electrolysis of muriatic acid (HCl) in a U-tube electrolyte, Schönbein was intrigued by the detection of weak 'secondary currents' in the opposite direction to electrolysis (Becquerel 1838). The second extract of a communication by a well-known physiologist and physicist of Forli, Carlo Matteucci noticed that two platinum plates covered by hydrogen and oxygen gases generated a current 'from hydrogen to oxygen' in an acid electrolyte (Matteucci 1838). It was the opposite direction than expected.

The two brief notes read at the French Academy of Sciences were part of an international debate about 'secondary effects' in electrochemistry. 'Secondary' referred to weak currents or polarities, which required delicate measurements and had opposite direction or polarity to usual phenomena like voltaic currents and electrolysis. For Schönbein and Becquerel, the origin of the phenomenon was chemical; for Matteucci, it was contact (Snelders 1975, 198; Kragh 2000, 138). In an article published in January 1839, Schönbein stressed the importance of the electrode materials to generate 'secondary' effects (Schönbein 1839, 43–45).¹⁰ Platinum played an active role in "the union of hydrogen and oxygen," contrary to gold and silver. The article concluded that "the secondary currents produced [...] by polar wires [were] due to chemical action, i.e. (in the cases mentioned) to the union of oxygen with hydrogen, or to that of chlorine with hydrogen." One month later, Grove demonstrated that when two platinum plates plunged into an acid electrolyte were put under two tubes of gas, one of oxygen, the other of hydrogen, a current was generated from the platinum in oxygen (cathode) to the platinum in hydrogen (anode).¹¹ As the glass tubes remained lowered, the volumes of hydrogen and oxygen decreased and the level of water rose. The interpretation was obvious for a supporter of the chemical theory like Grove: hydrogen and oxygen combined to form water ($\text{H} + \text{O} \rightarrow \text{HO}$).¹² By repeating this experiment in series, Groves envisions "to effect decomposition of water by means of its composition." Then electrochemists expected that a 'crucial experiment' would reveal

the circularity of natural forces through the composition and decomposition of water. Instead, they found a ‘secondary’ type of electrochemical phenomenon. A distant composition of oxygen and hydrogen generated a delicate current flowing in the direction opposite to the usual one. Chemical forces could be converted into electrical forces.

The second day of the hydrogen world did not last enough time to set a crucial experiment that would have given the key to the mystery of natural forces. Natural philosophers designed, instead, an unexpected device with a tube-and-plate structure stimulated by electrical and chemical fluids. Thus my body was filled with humors and, at the twilight of the second day, I was waiting for the following dawn to breathe.

Day 3 – The first breathing battery

The third day, Grove left his research on ‘secondary’ effects for a couple of years when his design of a specific voltaic battery gave him access to the Royal Society in 1840. The ‘Grove cell’ was made of a zinc electrode in dilute sulphuric acid connected to a platinum electrode in concentrated nitric acid. It was the most powerful battery of its time. Powerful batteries, like the Daniell, Grove and Planté cells, were useful as electrical generators for the industry of electro-deposition and telegraph. When appointed professor of experimental philosophy at the Royal Institution, Grove published a full article devoted to the ‘Gaseous Voltaic Battery’ (Grove 1842, 417). The first name of fuel cells made them acquainted with the lineage of batteries that originated with Volta’s work.

The ‘gas battery’ (Figure 5.2) became a ‘peculiar’ type of battery that, unlike others, generated electricity from gaseous fuels, namely hydrogen and oxygen. A

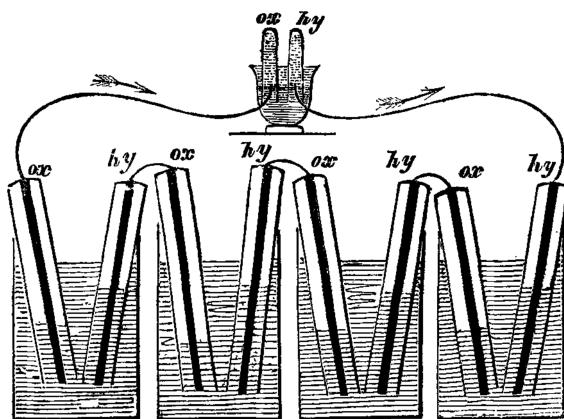


Figure 5.2 First published picture of the gaseous voltaic battery, W. Grove (1842).

Source: Wikimedia Commons

series of at least twenty-six pairs of electrodes was able to produce gaseous oxygen ('ox') and hydrogen ('hy') in the two separate glass tubes. Water was thus electrolyzed from its elementary parts. In the electrodes, the volumes of hydrogen and oxygen decreased and the water level rose, while in the separate tubes, the volumes of hydrogen and oxygen increased and the water level was lowered. The gas battery started breathing, with the electrodes breathing in gases and the separate tubes breathing out gases. Indeed, the battery sometimes coughed and hiccupped, since the delicate anatomy was weak, brittle and leaky. But the respiration process "exhibit[ed] such a beautiful instance of the correlation of natural forces" (Grove 1846). It helped "establish that gases in combining and acquiring a liquid form evolve sufficient force to decompose a similar liquid and cause it to acquire a gaseous form." As for the partisans of the 'chemical theory', this was the proof that the contact theory was wrong: Where is the contact in this experiment, if not everywhere? This made the gas battery theoretically 'more perfect' than other batteries. It became a 'phenomeno-technical' instrument: a scientific tool used to unravel natural phenomena by producing 'purified' – theoretically constituted – technical effects.¹³ Chemical forces were turned into electricity, which was used to decompose the molecule of water.

During the third day of the hydrogen world, I was given a Christian name and a nice portrait for Christmas 1832, and breathing capacities. Yet, as Salman Rushdie (1995) once said, "Suspiro ergo sum. I sigh, therefore I am. [...] We inhale the world and breathe out meaning." This ontological certificate made me so happy that I agreed to reveal the conversion of natural forces to philosophers. It was a pretty good job and I thought they would give me a break. Unfortunately, industrial entrepreneurs took over from philosophers to make me work harder the following day.

Day 4 – A prayer for a coughing generator

The fourth day opened with the attempt by Ludwig Mond to turn the gas battery into an electrical generator for industry. A German-born chemist-industrialist, Mond, established a successful production of soda and ammonia in England. Among many research projects, he studied gas batteries with his assistant Carl Langer. In 1889, they announced "a new form of gas battery" in the *Proceedings of the Royal Society*. The platinum surface of electrodes was known to have a catalytic effect by fixing and also dissociating the gaseous molecules of hydrogen (H₂) and oxygen (O₂). Mond and Langer stressed "the necessity of maintaining the condensing power of the absorbent unimpaired" by preventing the surfaces of the electrodes from getting wet by the electrolyte. They copied "dry piles and batteries" and trapped the sulphuric acid electrolyte in a porous material.¹⁴ The "quasi-solid form" of the electrolyte limited the electrode surfaces becoming wet without modifying its conducting properties.

Mond and Langer's program led to practical improvements: air, instead of pure oxygen, and coal gas, instead of pure hydrogen, were being tested; platinum black

was preferred to platinum to increase the contact surfaces between gas and electrodes; the EMF was stabilized between 0.7 and 1V, the power between 1.5 and 2W, and the operating temperature around 40°C. Yet they failed to regulate the life time of the gas battery (Perry and Fuller 2002, S59). Impurities of the gaseous fuels poisoned the electrode surfaces and made the gas battery misfire after a while. On the scientific side, Mond and Langer pointed to significant differences between the measured EMF and the calculation based on ‘Thomson’s theorem’ and concluded that future researchers would succeed in matching empirical and theoretical values.

In the 1880s, scholars and industrial entrepreneurs were mainly concerned with conversion efficiency. From thermodynamics, they knew that more energy was needed to prepare a given amount of hydrogen by the electrolysis of water than could be generated from the same amount of hydrogen by a gas battery. This was a major drawback for industrial applications. However, the gas battery soon became a “solid compact block with no openings except the entrances and exits for the gases” (Mond and Langer 1889, 300). The liquid electrolyte trapped in a porous solid was separated from gaseous fuels. The device was carefully sealed and partitioned to prevent leaking and the mixing of fluids. The gas battery became dry. However, in spite of endless quantitative controls, its operation remained erratic and smoky. When they understood how reluctant the gas battery was to black-boxing, the industrialists closed their programs and the scholars arranged the ‘gas cell’ on the shelves of science.¹⁵

The fourth day of the hydrogen world was not a bed of roses. Industrialists persisted in improving my delicate body to design a robust engine. But all their surgical operations failed to fix my respiration at a constant pace and intensity and to prevent me from coughing. Smoking was my pleasure, and I didn't want to become an industrial application. I was right indeed, since when I came on the job market the following day, I was left unemployed.

Day 5 – Unemployment on the market place

In the morning of the fifth day (early twentieth century), while gas batteries were considered hopeless for industrial applications, a few dreamy engineers envisaged ‘gas operated vehicles’.¹⁶ Among them, a mechanical scientist from Cambridge, Francis Thomas Bacon, contracted an obsessive interest for gas battery in the 1930s and collected information on it during his spare time. On reading a 1933 comprehensive survey on ‘fuel couples’ by two German chemists, Emil Baur and Jakob Tobler, he decided that basic electrolytes would give better results than acid electrolytes and chose nickel, which was much cheaper than platinum to use as electrodes (Baur and Tobler 1933).¹⁷ As he failed to convince his employers to launch a ‘hydrogen-oxygen cell’ project, he resigned from his post in Newcastle¹⁸ and followed his freelance enthusiasm for the gas battery until he was enlisted by the admiralty into the war effort. After World War II, he got financial support from the Electrical Research Association (ERA)

to set up a small research group studying the gas battery at Cambridge University. His team included electrochemists, inorganic chemists, theoretical physicists and engineers. In eight years (1946–1954), they overcame a series of empirical obstacles and built “a six fuel cell battery [. . .] using 5 inch diameter electrodes and operat[ing] at 200°C and 400 p.s.i. [27 atm.] achieving individual cell EMFs of 0.8V at 230 mA.cm⁻².” The ‘Bacon cell’ (Figure 5.3) was patented in February 1952.¹⁹ It was a masterpiece of engineering work; the over-pressurized black-box held around forty-five distinct parts, including pipes, gauges and valves. Bacon’s long-lasting research overcame the recalcitrance of the gas battery. This successful black-boxing made the gas battery a mobile and reliable device.

Bacon felt confident enough to publish a seminal article on “Recent Research in Great Britain on the Hydrogen-Oxygen Fuel Cell” for electrical engineers (Bacon and Forrest 1954). He renamed the ‘gas battery’ as a ‘fuel cell’ to emphasize its aptitude for refueling.²⁰ Contrary to other electrochemical cells whose energy was packed *inside* the box, the energy came from *outside*. This made the fuel cell highly dependent on surroundings. No private industry wanted to fund research on an electrical generator that could not operate autonomously. Therefore the ERA withdrew its support in 1956. By contrast, the (British) Welfare State funded Bacon’s program through the National Research and Development Corporation (NRDC). Bacon’s team could design a 6-kW operating generator with forty 150-W fuel cells exhibiting 60 percent efficiency which was ready in August 1959. Still, there was no employment for fuel cells on the marketplace, and the NRDC withdrew.

Tom was a stubborn chap. I couldn't help myself but trust him. He had worked hard for two decades to turn my weak body into a reliable machine. Yet, in the evening of the fifth day of the hydrogen world, I was still jobless on Earth. Waiting for the divine providence to do something for once, I was about to blaspheme against the dark Heaven when my attention was attracted by an odd light slowly crossing the dome of the sky.

Day 6 – Space and glory

In the sky of the sixth day, flew Sputnik, an artificial satellite launched in October 1957 by the Soviet Union. This was the Cold War, and the United States counterattacked. In October 1958, the National Aeronautics and Space Administration (NASA) was created to take the lead of the space race and launch space flights. Space was a cold, airless, hostile environment where there was no room for heat engines. Electrochemical generators were the only candidates to supply onboard energy. NASA experts recognized that fuel cells presented three advantages over batteries: a higher electrical output for the expected duration of missions (one to ten days) (Bacon and Fry 1973, 439); two fuels, hydrogen and oxygen, which were also used for spaceship propulsion; and a subproduct, water, which could provide drinking beverage and

This Drawing is a reproduction of the Original on a reduced scale

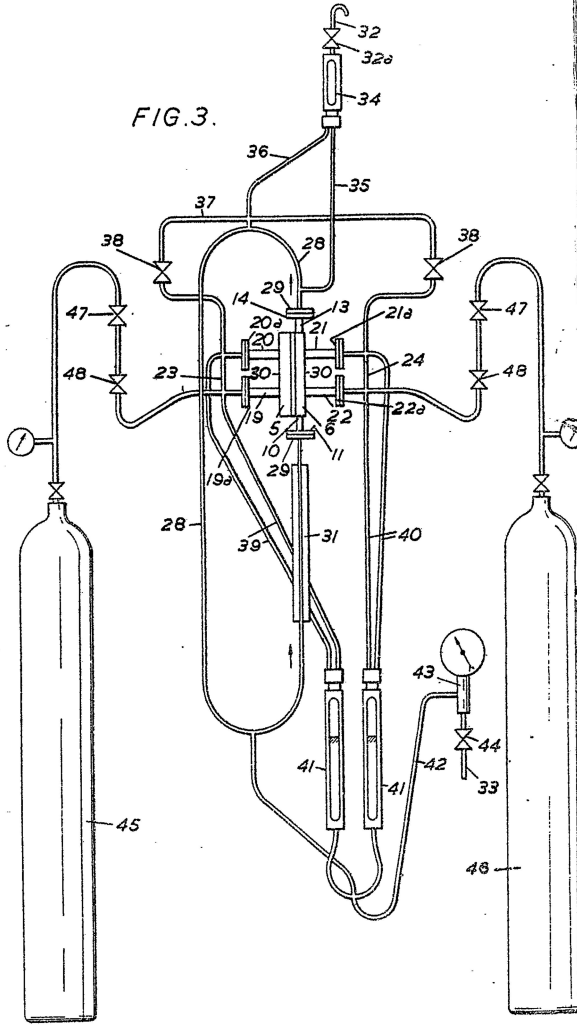


Figure 5.3 Patent representation of the fuel cell, F. T. Bacon (1952).
Source: European Patent Office

AuQ1

cabin humidification (Warshay and Prokopius 1989, 2; Williams 1994, 9). In Gilbert Simondon's terms, the fuel cell could be characterized as a 'hypertelic' machine, a machine over-adapted to one specific environment of use: interstellar space (Simondon 2012, ch. 2).

U.S.-based companies like Leeson-Moos and Pratt and Whitney bought the license of Bacon patents to the British government. A huge network of industrial and scientific institutions was set up around NASA.²¹ Pratt and Whitney hired 1,000 employees to transform the 6 kW Bacon cell into a 1.5 kW power plant (Figure 5.4). The power plant, which would provide on-board electricity for the Apollo program (1961–1975), was composed of thirty-one fuel cells. \$100 million were spent to reach NASA fuel cell requirements. Three Pratt and Whitney 1.5 kW power plants were embarked in each manned flight (1968–1972) (Warshay and Prokopius 1989, 3). During the 1969 Apollo XI flight to the Moon, they provided around 400 kW.h.

U.S. President Richard Nixon warmly congratulated Bacon in 1970: "Without you, Tom, we wouldn't have gotten to the Moon." In 1973, Bacon was elected a Fellow of the Royal Society. In fact, his success resulted from a convergence of scientific, technical, military, political, economic and symbolic forces. One hundred million dollars, ten thousand people and ten years were needed to make the fuel cell a reliable autonomous power plant operating during ten days in the extreme conditions of interstellar space.

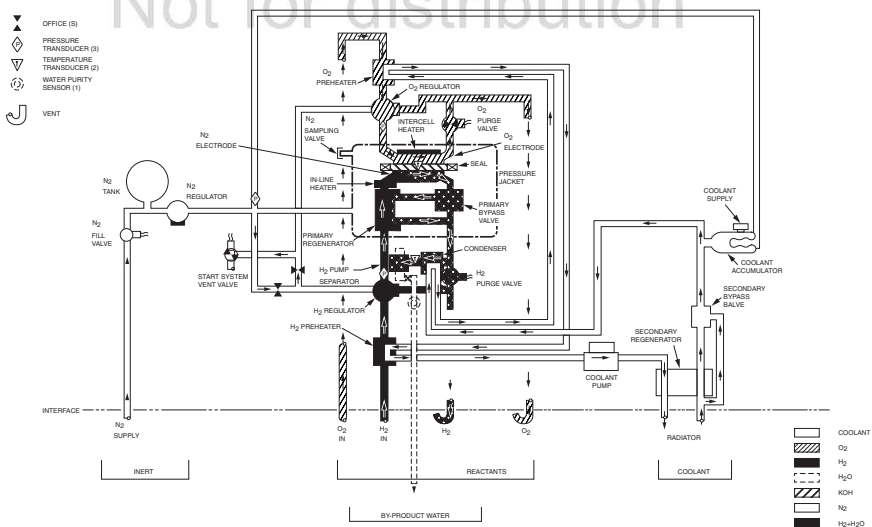


Figure 5.4 1.5 kW fuel cell power plant for Apollo Program, Pratt and Whitney (1967).

AuQ2

Source: A Survey. NASA SP-5115, prepared under contract NASW-2173 by Computer Sciences Corporation, Falls Church, Virginia. Washington, DC: NASA.

In the sixth day of the hydrogen world, Uncle Sam and Uncle Tom on the center stage made huge efforts to overcome my recalcitrance and turn a stubborn creature into a docile robot. Their efforts and money were only rewarded by the tiny amount of power generated during a single-week manned space flight. During the space trip back from the Moon, I was already prepared for the seventh day, the Holy day for everybody to rest. However, instead of the traditional Sabbath, the hydrogen world invented the hydrogen utopia.

Day 7 – No sabbath on earth

Back to Earth the morning of the seventh day, the fuel cell was drafted for military low-energy portable units and submersible vessels (Rogers 1969; Warszawski et al. 1971). It was also recruited by the gas industry to conduct an ambitious program to generate electricity from charcoal and air. Started in 1967, the Target consortium gathered around thirty U.S. gas companies around Pratt and Whitney. Fifty million dollars was spent during six years to design a 12.5 kW fuel cell power plant fuelled with hydrocarbons.²² In Britain, a similar project associated NRDC (renamed Energy Conversion Ltd.), British Ropes, British Petroleum, Guest Keen and Nettlefolds to develop hydrogen-air and zinc-air systems (1968–1973). The 1973 oil crisis curtailed these projects. NASA promoted automotive applications of fuel cells to justify the tremendous space budgets.²³ Yet the Lunar Rover Vehicle itself had been driven by (Planté) lead-acid batteries, not by fuel cells.²⁴ Gas batteries still had lower power than traditional batteries. Their second drawback for terrestrial transportation was their high price: three orders of magnitude higher than market products for the same power range (Crowe 1973, 62). This did not prevent enthusiastic projects from the mid-1960s onward, either by automobile industry (GM electrovan) or by independent scholars (Marks et al. 1967; Kordesch 1971). Fuel-cell-powered vehicles did not find their way to the car industry market that was monopolized by internal combustion engines. There were specific niches for fuel cells: space shuttles, submarine vessels and, for emergency, hospitals and airports.²⁵ No mass-market commercialization was expected by practitioners. In the 1990s, Japan and the United States launched the ‘hydrogen race’.²⁶ The State of California started to build a huge hydrogen infrastructure – ‘the hydrogen highway’ – to equip fuel-cell-powered vehicles on the West Coast. A decade later, the EU firmly joined the race and became a staunch advocate of hydrogen economy. However, worldwide research and development efforts stumbled on ever-disappointing results. They got no significant increase of fuel cell power generation.²⁷

At the sunset of the seventh day, the ‘hydrogen world’ had not been created yet. It remained a utopia since it strongly depended on the need to overcome three technological obstacles: (1) the limitations of the fuel cells themselves, which were highly reluctant to (co)operate; (2) reducing fuels, especially hydrogen, whose synthesis had required the combustion of hydrocarbons in the atmosphere to perform the electrolysis of water;²⁸ (3) hydrogen networks, like the Californian ‘hydrogen highway’, whose establishment were dependant on gas station networks.²⁹ To overcome these three obstacles would have required a deep ‘cultural

shift', and such radical shifts are highly improbable in history.³⁰ The utopia revealed more about the present than the future. Car-makers publicly displayed the 'hydrogen vehicle' of tomorrow – a childish toy – to hide their current polluting business. Politicians announced the 'hydrogen economy' to make people believe they controlled energy systems. Environmentalists advertised possible 'green systems' to fight internal combustion engines and nuclear plants. For the three groups, displaying the affordances of the 'hydrogen world' mattered more than the effective results of the hydrogen creature. With all their hype, the fuel cell became the 'philosopher's stone' of today (Eisler 2009).

Epilogue – Recalcitrance and interdependence

The biblical metaphor of the seven days of creation is helpful to emphasize three major features of the genesis of technoscientific objects such as fuel cells: First, they require a gradual process of individuation. Second, it may be a long, painstaking and possibly endless process. And third, a recurrent key issue lies in conflicting interactions between the fuel cell and its milieu. If according to Simondon the 'concretization' of technical objects is characterized by a successful interaction between the machine and its associated milieu, it is clear that the fuel cell never became a concrete technical object. Each daily interaction between the creature and its environment shaped a new figure of the fuel cell: theory-testing tool, a battery kin, an unstable generator, an open black-box, a low-power stable prototype, a medium-range power plant and the dawn of a new clean industrial era. None of these figures managed to be articulated to the adequate milieu in which material and symbolic forces could have cooperated. While the relation between the creature and its environment was reconfigured at each stage, the fuel cell developed new forms of recalcitrance: the inflammable air versus hydrogen (day 1), secondary effects versus a crucial experiment (day 2), a brittle device versus a gaseous voltaic battery (day 3), a smoky gas battery versus a stabilized generator (day 4), a jobless generator versus a commercial power plant (day 5), a fragile power plant versus a reliable energy supplier (day 6) and an expensive product versus an advertising toy (day 7).

In spite of reconfigurations at each stage, the fuel cell creature kept two constant features throughout the tentative creation of a 'hydrogen world'. The first one is a strong resistance to any form of control, containment and normalization, which accounts for the remarkably slow increase of power of fuel cells (and batteries as well) over two centuries. In this respect, there is a stark contrast between energy technology and information technology. From the 1970s onward, the computer industry doubled the information storage capacity of semi-conducting materials every eighteenth months according to the famous 'Moore's law' (Brock 2006). While this self-fulfilling prophecy allowed the exponential growth of information storage capacities over four decades, the energy storage capacities of batteries barely reached a linear growth during two centuries. Matter matters less for information than for energy. Information has been quickly mastered and disciplined by electronic engineers whereas energy remains a vexing issue challenging human

ingenuity and creativity. The ‘information revolution’ of the last decades of the twentieth century was possible because integrated circuits cooperated with engineers to turn dreams into reality and build the ‘silicon economy’. On the contrary, fuel cells were recalcitrant to cooperate with engineers to turn dreams into reality. The ‘third industrial revolution’ that would bring about the hydrogen economy remains a utopia in the early third millennium.

A second permanent quality of the hydrogen creature is its propensity to connect things together: energies, forces, fluids, chemicals and electrons. The inhalation of vital air and inflammable air allows the fuel cell to generate water, heat and electricity. This production cannot occur without exchanges with its environment. Like living beings and technological artifacts as well, the hydrogen creature cannot live without interacting with its milieu. Even in space, the operation stopped when no more fuel was provided. The production of hydrogen requires energy and the operation of fuel cells requires adequate surroundings. Mond, Bacon and all the champions of the hydrogen economy viewed the question just the other way around. The concept of the ‘hydrogen economy’ is nonsense, relying on the fiction of a self-sufficient machine. Since the ontology of the fuel cell reveals the ‘hydrogen world’ as modern myth, it was legitimate to tell this story through the format of the antique myth of Genesis.

Notes

- 1 The expression *la délocalisation de la puissance* in French is borrowed from Gras (2003).
- 2 “Global atmospheric concentrations of carbon dioxide, methane, and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values [. . .] over the past 650,000 years. [. . .] Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic (human) greenhouse gas concentrations” (IPCC 2007, 37 and 39). “Very likely” refers to a probability higher than 90 percent.
- 3 For a historical survey, see Hultman and Nordlund (2013).
- 4 For the detailed history of water and of the controversies regarding its composition, see Chang (2012).
- 5 The concept of individuation of technological objects was introduced by Gilbert Simondon (2005); the concept of *récalcitrance* by Bruno Latour (2004).
- 6 The French word for ‘nitrogen’ is *azote*, which means ‘that deprives of life’.
- 7 “*L’hydrogène uni à l’oxygène ne forme point un acide, mais cette union constitue l’eau qui, considérée sous ce point de vue, pourroit être regardée comme un oxyde d’hydrogène*” (The union of hydrogen with oxygen does not form an acid, but composes water, which, from this perspective, might be regarded as an oxide of hydrogen) (Guyton de Morveau et al. 1787, 88).
- 8 The Swedish chemist Jöns Jacob Berzelius replaced the symbols used by John Dalton for chemical elements by the initial letters of their names.
- 9 Letter from Volta to Friedrich Gren (1796), cited by Kragh (2000, 134).
- 10 The article was dated from December 1838.
- 11 The postscript of the article dated from January 1839 (Grove 1839, 127–130).
- 12 The interpretation did not appear in the short postscript but was given two months later in Grove’s correspondence to the French Academy of Sciences (Becquere 1839).
- 13 The concept of *phénoménotechnique* was introduced by Gaston Bachelard (2000, §6).

- 14 The porous solid was either “an earthenware plate [or] conducting strips [. . .] filled up with plaster of Paris” (Mond and Langer 1889, 297).
- 15 Early twentieth-century textbooks stressed the theoretical importance of the ‘reversibility’ of ‘gas cells’. See Glasstone (1930).
- 16 The November 18, 1932 issue of *Engineering* held “two articles on pages 605–608, one headed ‘Gas Operated Vehicle’ and the other ‘The Erren Hydrogen Engine’” (Williams 1994, 4).
- 17 The literal translation of *Brennstoffketten* would have been ‘fuel series’ but, according to personal papers of Bacon in the Churchill Archives Centre [NCUACS 68.6.97/B35], the phrase was translated for Bacon as ‘fuel couples’.
- 18 The Churchill Archives Centre mentions a first report in December 1939 [NCUACS 68.6.97/B.36] and a second report extended version of B.36 in January 1940 [NCUACS 68.6.97/B.38].
- 19 The priority date of the patent, entitled ‘Improvements relating to galvanic cells and batteries’, was June 1949. For further information on the 1952 patent GB667298 (A), see the European Patent Office database. Bacon obtained nine patents related to fuel cells between 1952 and 1965.
- 20 On the Web of Science, the phrase ‘fuel cells’ appears in scientific journals in the early 1960s. It was coined after ‘fuel’ from the 1933 *Brennstoffketten* of Baur and Tobler and ‘cell’ from the 1939 ‘hydrogen-oxygen cell’ of Bacon, which derived from electrochemical cells of the nineteenth century. The coining was similar in German (*Brennstoffzelle*) and slightly different in French where *pile à combustible* means ‘fuel pile’.
- 21 From 1958 to 1963, 800 reports were written on fuel cells. NASA SP-120 report 1967, 1.
- 22 TARGET stood for ‘Team of Advance Research for Gas Energy Transformation’ (Crowe 1973).
- 23 More than half the 1973 NASA report on fuel cells by Crowe was devoted to non-space applications.
- 24 The Lunar Roving Vehicle was built by the Boeing Company for \$38 million; see the 1971 Lunar Roving Vehicle *Operations Handbook*, document LS006–002–2H, Huntsville: Boeing, <http://www.hq.nasa.gov/alsj/lrvhand.html> (accessed July 17, 2016).
- 25 In 1980, the fuel cell power plant of the U.S. Orbiter mission had a 12 kW output according to Warshay and Prokopius 1989, 3–4.
- 26 For an international R&D survey, see Solomon and Banerjee (2006, 781–792).
- 27 A survey on Web of Science exhibited an exponential growth of scientific articles containing ‘fuel cell’ in their title from around 100 in 1995 to around 1,400 in 2008.
- 28 96 percent of the hydrogen produced in the world came from hydrocarbons and coals in 2006, and 4 percent from the electrolysis of water, according the website of IFPEN (French Institute of Petroleum and New Energies).
- 29 The concept of ‘path-dependency’ in particular makes clear why past choices matter for future choices. See Kirsch (2000).
- 30 The problem of energy bifurcation was analyzed by Gras (2003).

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