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Fuel Cells: A Challenging History

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Abstract. Professional and popular journals present fuel cells as the salvation of transportation and electric power infrastructures; the ultimate rechargeable battery. Engineers and investors alike find them attractive as a modern and elegant alternative to other electrical generators. On three occasions since W. R. Grove's initial research around 1840, widespread adoption of fuel cells seemed imminent. Each time, technical challenges in materials and systems integration, along with advances in other electrical technologies frustrated advocates' hopes. Despite successful development of several different types, commercialization remains limited to niche applications. After 180 years fuel cells remain outside the mainstream of power generation technology. This paper presents an overview of that history. The author discusses basic challenges that have faced developers, and suggests how present research may benefit from past experience.

Keywords. Fuel cells, gas batteries, electrochemical technology.

> *...we concluded that the economical production of powerful currents for commercial purposes ... did not seem to be a problem likely to be readily solved....*
> —Charles R. Alder Wright and Charles Thompson, 1889.[1]

INTRODUCTION

Fuel cells have captivated and frustrated researchers and investors since 1839. A device that quietly combines hydrogen and oxygen to produce electricity and water would solve many problems in a world dependent on electric power. Scientists spent decades learning how fuel cells generate electricity, and engineers built them into submarines, automobiles, a farm tractor, and other devices. Humans traveled to the moon with fuel cells. Yet after 180 years of work, Wright and Thompson's conclusion remains valid. Significant commercial adoption remains elusive due to high costs, intractable technical difficulties, and competition from other technologies.

The seeming simplicity and potential benefits of fuel cells nurtures optimism rarely deterred by persistent obstacles.[2] In the 1890s, the 1960s, and around 2000, technical journals and the popular press described fuel cells as nearing commercial viability.[3] On each occasion, development faltered and significant diffusion failed to occur. Encouraging test results and occasional high-profile successes obscured vital facts: fuel cells come in non-interchangeable types that must function within larger technical and economic systems. Today, a few are in low-rate production for automotive engines and stationary power. Though prototypes proliferate, fuel cells remain niche products. Perceived technical elegance does not convey success in the laboratory or in the marketplace.

Rather than a triumphal march from discovery to market, fuel cell history provides a sobering counter to progressive views of technology development. After a technical review, this article discusses four distinct periods of fuel cell work. Examining the past brings perspective to current events by highlighting recurring factors that hindered adoption. The situation of fuel cells as components in technological systems—requiring other devices in order to operate, while meshing with existing infrastructures—served as one factor.[4] Another is the influence of public and professional perceptions on expectations, including the persistent myth that fuel cells are simple devices on the verge of mass production. The article also presents important differences in socially- dependent contexts, such as differing economic and technical circumstances of each period, so as to avoid the fallacy of cyclical history. Setting the recurring factors in their changing contexts helps explain why fuel cells continue to fascinate despite many disappointments.[5]

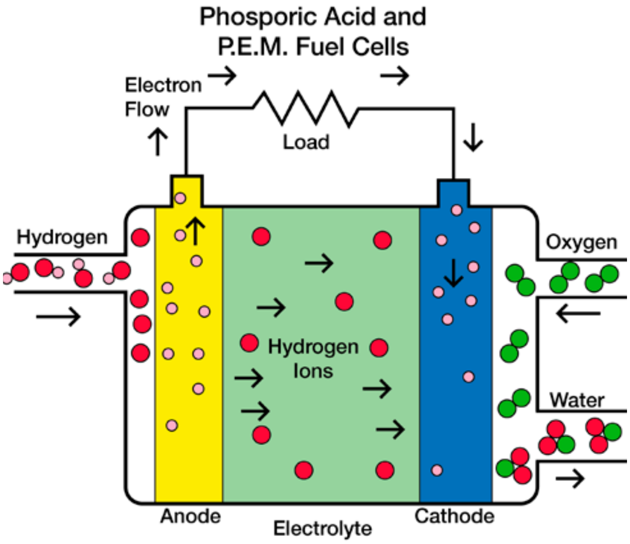

Figure 1. Diagram showing basic fuel cell components. Smithsonian image.

AN ELEGANT TECHNOLOGY

Engineers often refer to an especially efficient process or device as elegant. From the beginning, many admirers declared fuel cells (originally called gas batteries) elegant.[6] Like batteries, they generate direct current electricity through chemical action. Several types exist and their operational details vary in important ways. Figure 1 shows one type and depicts the general components and operating principle. Fuel cells contain two electrodes, an anode and a cathode respectively, each treated with a catalyst, often platinum. Hydrogen introduced at the anode and oxygen supplied to the cathode interact with the catalyst that facilitates the chemical action. An electrolyte separates the electrodes allowing passage of ions through the cell, while electrons routed externally provide electric power. Recombination of gases generates waste heat and water.

The operating process reverses electrolysis, in which an electric current separates water into hydrogen and oxygen. Pure hydrogen can be pumped into a fuel cell directly or extracted from a hydrogen-containing fuel by a reformer. Likewise, cells can use pure oxygen or air. Engineers must manage waste water and heat, control reaction products that can damage catalysts, and prevent the internal leakage of gases and electrolytes. Ideally cells emit no pollutants or greenhouse gases, though environmental challenges exist in mitigating the impact of cell fabrication and disposal, as well as in obtaining and delivering hydrogen fuel. Individual cells yield only a modest amount of electricity. Arranging cells in stacks boosts total output to as much as five megawatts. A power inverter changes the direct current to alternating current, if desired.

Fuel cells are typically classed by the form of their electrolyte. The principle types are: alkali, phosphoric acid, proton exchange membrane (PEM), molten carbonate, and solid oxide. Some types are more appropriate than others for certain applications, and each presents specific technical challenges. Molten carbonate and solid oxide cells operate at relatively high temperatures and are usually classed together. High temperatures reduce the need for expensive catalysts and pure fuels. But cells and auxiliary equipment tend to be large and immobile, and reuse of waste heat can be critical to overall system efficiency. Acid, alkali, and PEM cells operate at lower temperatures and can be more compact and portable. But fuel purity becomes an issue and the power output is reduced.[7]

Far from simple devices, each type's history grew ever more distinct through time though some common features emerge. Specific technical problems as well as general issues like making and distributing hydrogen fuel vexed generations of researchers.

Meanwhile, other researchers actively refined competing types of electrical generators.[8] In a world of limited resources, societies typically made choices based on economics rather than technical elegance with the result that fuel cells remain marginalized.

DISCOVERY OF A PUZZLE

In the 1790s, Alessandro Volta of Italy (1745-1827) stacked discs of alternating metals such as zinc and silver to create "piles" that produced a steady, continuous electric current. His work inspired experimenters worldwide who improved on his discovery.[9] Advances came rapidly and in 1838, Welsh jurist and scientist William Robert Grove (1811-1896, figure 2) devised an eponymous wet cell battery. He used a platinum electrode immersed in nitric acid and a zinc electrode in zinc sulfate. Grove cells proved popular with early telegraphers; American Samuel F. B. Morse (1791-1872) used them to power his 1844 "What Hath God Wrought" demonstration.[10]

While experimenting with his new batteries, Grove arranged two platinum electrodes such that one end of each was immersed in a container of sulfuric acid. He sealed the other ends separately in containers of oxygen and hydrogen, and then measured a constant current flowing between the electrodes. The sealed containers held water as well as the gases, and he noted that the water level rose in both tubes as the current flowed. Christian Schönbein of Germany (1799-1868) independently noted a current in his experiments with platinum and various gases about the same time.[11]

Figure 2. Portrait of William Robert Grove. Woodburytype by Lock and Whitfield. Smithsonian Institution Libraries.

Grove decided to "effect the decomposition of water by means of its composition" and assembled several sets of electrodes in series, as seen in figure 3. Energy lost as heat eventually stopped the process but Grove's experiment attracted attention. He named the new device a gas battery and published several papers on his experiments.[12] He noted however, that "I have never thought of the gas battery as a practical means of generating voltaic power."[13]

Grove's discovery challenged a scientific community still defining basic principles of chemistry, electricity, matter, and energy. Gas batteries were, as Wilhelm Ostwald (1853-1932) of Germany wrote, "a puzzle" for those struggling to understand what caused current to flow from some substances but not others.[14] And it intensified a controversy between proponents of two competing theories. Contact theory, proposed by Volta to explain the pile and "defended" by Johann Poggendorff (1796-1877) and Christoph Pfaff, required physical contact between substances in order for current to flow.[15] A rival theory supported by Grove and Schönbein held that a chemical reaction generated electricity. Arguments between the two camps became quite acrimonious.[16]

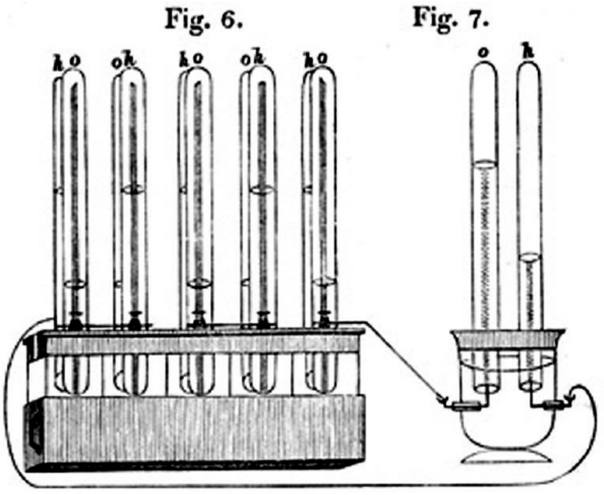

Figure 3. Grove's apparatus for "the decomposition of water...by means of its composition." W. R. Grove, *Trans. Roy. Soc.* **1843**, 133, plate V, p. 93.

The debate faded as knowledge advanced. Concluding that the gas battery was "of no practical importance," Ostwald recounted the solution of the puzzle. "The answer is contained in the fact that oxidizing agents are always substances that form negative ions or make positive ions disappear; the reverse is true of reducing agents. Oxygen and hydrogen are nothing more than oxidizing and reducing agents."[17] Ironically both theories held some truth. Later fuel cell researchers noted that chemical reactions in gas diffusion electrodes take place in "the contact zone where reactant, electrolyte and catalyst meet."[18]

The controversy's details are less important here than the fact of its existence. Ostwald was correct. No practical device emerged from that era, despite several attempts. The primary importance of the gas battery in the mid-nineteenth century lay in spurring research that refined scientific theory. As scientific understanding improved, researchers shifted to making something useful. While that focus contributed to basic science—there was certainly more to be learned—research turned to developing better materials and more efficient designs. But by century's end, Ostwald's countrymen Ludwig Mond (1839-1909) and Carl Langer (1859-1935) noted that "very little attention has been given by investigators to the [gas battery]."[19]

ENGINEERING AND EXPERIMENTS

Public and professional interest in fuel cells briefly surged in the years around 1900 as several researchers looked for novel ways to produce electricity. Mond and Langer worked to increase gas batteries' electrical output by means of an earthenware panel soaked with sulfuric acid and fueled with coal-derived "Mond-gas." But then they chanced to discover "the carbonyl process for refining and purifying nickel, and [their] attention was diverted away from fuel cells to the foundation of the great nickel industry."[20] This would not be the last time that fuel cell researchers turned to other work deemed more important or more amenable to success.

Englishmen Charles R. Alder Wright (1844-1894) and Charles Thompson (1861- 1892) developed a similar fuel cell about the same time. They made progress but reported that internal gas leaks interfered with attempts to increase voltage output, "even with only infinitesimal currents." They concluded,

> *our results were sufficiently good to convince us that* if the expense of construction were no object, *so that large coated plates could be employed, enabling currents of moderate magnitude to be obtained with but small current density, there would be no particular difficulty in constructing [cells] of this kind, competent to yield currents comparable with those derived from ordinary small laboratory batteries; although we concluded that the economical production of powerful currents for commercial purposes by the direct oxidation of combustible gases did not seem to be a problem likely to be readily solved, chiefly on account of the large appliances that would be requisite.*[21]

Their concern with "powerful currents for commercial purposes" reflected the increasing influence of industrial age goals and organizations on electrical research. Wright and Thompson worked during a period of rapid electrification. They understood that producing "currents of moderate magnitude" held little attraction for industrialists who wanted to electrify factories and whole cities.[22] After publishing their results, both turned to other work. Thompson led research at a soap manufacturer. Wright, a physician, is remembered as the inventor of heroin.[23] Neither returned to fuel cells.

A few others did take an interest in fuel cells however, even one industrialist. Steam research during the 1800s led to higher efficiencies in coal-fired electrical generating plants. A major driver of fuel cell development since the 1880s has been the desire to escape Carnot heat-cycle limits in electrical plants. Some researchers hoped that fuel cells might enable the direct conversion of coal into electricity. They pursued that goal vigorously, leading to a burst of research and publicity.

American Thomas A. Edison (1847-1931), sought many ways to cut costs and improve the efficiency of generating electric power for his new lighting system. He spent over two years investigating the direct conversion of coal and received several patents, but found himself facing "an insurmountable obstacle." He could not have been encouraged when the experiments resulted in "all the windows [being] blown out of his laboratory."[24] Edison rarely wasted time on inventions that showed little profit potential and soon moved on to other work.

In late 1894, the French team of Louis Paul Cailletet (1832-1913) and Louis J. E. Colardeau (?-?) described a gas battery that used "precious metals" in sponge form to absorb gases, but deemed the process impractical.[25] At the same time Wilhelm Borchers (1856-1925) of Germany described an apparatus for "direct production of electricity from coal and combustible gases."[26] American Charles J. Reed (1858-1943) critiqued Borchers' work, then wrote two papers of his own on this "most promising" use of gas batteries.[27] Economic questions persisted, however. One editorial noted that given the low price of coal, even if Borchers' system gave 100% conversion efficiency consumers would see less than a 10% reduction in electricity prices. "[Assuming] that the [technical] problem were really solved, it does not follow, as is often asserted, that a revolution in the electrical industry would result."[28]

That reminder of economic reality soon fell by the wayside. William W. Jacques (1855-1932), an American electrical engineer and chemist, "startled the scientific world and general public," in 1896, "by his broad assertion that he had invented a process of making electricity directly from coal." Jacques generated current via a "carbon battery" in which air injected into an alkali electrolyte reacted (or so he believed) with a carbon electrode. The apparatus, illustrated in a trade journal (figure 4) at the time, consisted of 100 cells arranged in series and placed on top of a furnace that kept the electrolyte temperature between 400-500 °C.

Jacques claimed 82 percent efficiency for his carbon battery, but critics soon pointed out that he had failed to account for the energy used heating the furnace or driving the air pump. They calculated an actual efficiency of only 8 percent. Further research indicated that the current generated by his apparatus came not through electrochemical action, but rather through thermoelectric action.[29] Even had Jacques' battery worked as well as claimed it left unanswered the economic question raised by Borchers' critics. Nonetheless, the desire to convert plentiful and inexpensive coal directly into electricity by way of an electrochemical process continued in the twentieth century.[30]

Around this time, the use of fuel stocks like coal and manufactured gas gave the fuel cell its modern name. A follow-on article labeled Borchers' device a "fuel battery," in recognition of the "combustible gas" he used.[31] Though the term gas battery remained in use for a time, newer generations came to call it a fuel cell. And experimenters in the years around 1900 found fuel cells to be far more complex than Grove's gas battery.

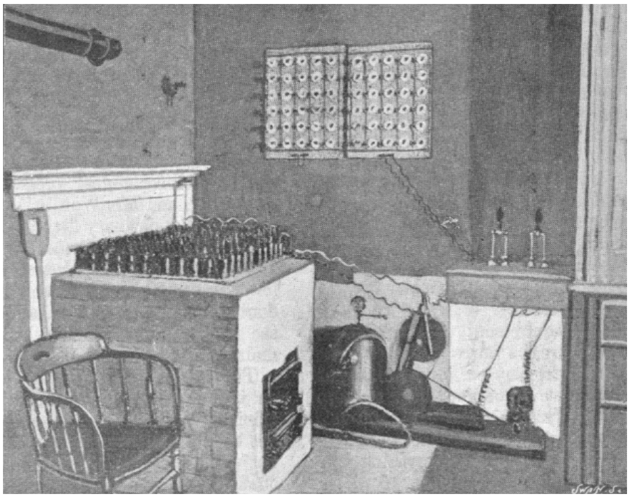

Figure 4. William Jacques' carbon battery apparatus showing the furnace at left with carbon cells on top, and air pump at center bottom. *Electr. Rev.* (London) **1898**, 42, 128.

Despite the flurry of work, fuel cells faded from the scene for reasons modern developers would recognize: costly materials and unfavorable economics.

COMPETITION

Ordinary batteries, for example, provided a less expensive alternative for important markets that needed low power devices. As with Morse's use of Grove's first battery, practical applications supported many battery producers, creating economies of scale. Aside from telegraphy, Alexander Graham Bell (1847-1922) and others used batteries to power telephone call stations and switchboards. The use of inexpensive materials like lead and the ease of refilling and refurbishing primary cell batteries also drove costs down.

Aside from single-unit applications such as telephones, electrical utilities in cities and towns connected large numbers of batteries into banks to buffer and regulate current on distribution grids. That application increased demand for batteries, attracted investment, and spurred research. In the larger scope however, most utilities required generators that produced bulk power, and neither batteries nor fuel cells could produce electricity at that scale.[32]

Nor could either efficiently produce the alternating current that many utilities wanted for their electric light and power systems. Though direct current proved useful for heavy motors and industrial applications, utility executives like Samuel Insull (1859- 1938) of Chicago's Commonwealth Edison pushed equipment makers to improve ac generator technology. In 1904, Insull opened Fisk Street Station that featured new steam turbine generators rated at 5 MW each.[33] The power industry's focus on steam and hydroelectric generators left little interest in low-power devices like fuel cells, although it did ultimately boost battery development in a roundabout way.

Utilities struggled in the early years to find customers for electricity generated outside of evening or morning hours when lighting demand peaked. Insull and others pushed daytime use of appliances like fans and irons, and equipment like pumps and elevators in order to keep generators spinning and improve return on invested capital. They identified automobiles as a potential market for so-called off-peak power. Early internal combustion engines were noisy, dirty, and unreliable, and many people saw battery-powered electric vehicles as the wave of the future. In the 1900s and 1910s, many utilities supported the idea of recharging electric vehicles overnight for urban use during the day.

Improvements in combustion engines and the creation of gasoline production and distribution infrastructures ultimately pushed electric vehicles aside, but that business model drove investment in battery research.[34] Edison developed his alkali batteries in hopes of entering the market via a route untapped by other inventors. Not for the last time, utilities or auto makers determined that component expense and the need for a continuous fuel supply made fuel cells an inferior choice compared to batteries. No mass market developed and fuel cells faded from the scene.

BACK TO THE LAB

Laboratory work continued during the early decades of the twentieth century. Karl Siegl (?-?) of Germany published a paper describing his gas battery work on the eve of the Great War. After the war, John G. A. Rhodin (1872-1941) of Britain returned to the idea of direct conversion of coal by asking, "Can the heat of combustion of coal be turned directly into electric energy?"[35] While fuel cells generated less interest outside the lab than in the 1890s, scientists explored several novel designs, leading to the diversification of fuel cell types.

Emil Baur (1873-1944) of Switzerland (with students at Braunschweig and Zurich) conducted wide-ranging research into different types of fuel cells during the first half of the twentieth century.[36] Baur and Hans Preis experimented with solid oxide electrolytes using such materials as zirconium, yttrium, cerium, lanthanum, and tungsten. Less electrically conductive than they hoped, their designs also experienced unwanted chemical reactions between the electrolytes and various gases, including carbon monoxide.[37] In the 1940s, Oganes K. Davtyan (1911-1990) of the Soviet Union added monazite sand to a mix of sodium carbonate, tungsten trioxide, and soda glass "in order to increase [electrolyte] conductivity and mechanical strength." This design also experienced unwanted chemical reactions and short life ratings, but work on high temperature devices by Baur, Davtyan and others paved the way for both molten carbonate and solid oxide fuel cells.[38]

Fuel cells in general, however, remained a solution in search of a problem. As Europe plunged toward the Second World War, a suitable problem suggested itself to British scientist Francis T. Bacon (1904-1992). Bacon suggested that fuel cells would be a good substitute for batteries on submarines, where hydrogen gas from damaged batteries could reach dangerous concentrations in the enclosed environment. Bacon set to work at King's College but after a short time the Royal Navy, battling German U-boats, reassigned him to a sonar project. Although promising, fuel cell research again gave way to other priorities.

No applications emerged during the war, but the research of Bacon and others set the stage for a resurgence of interest in fuel cells afterwards.[39] The onset of Cold War competition between the US and the USSR spurred increased investment in many technologies with potential military use, including fuel cells. During the 1950s and 1960s designers tested cells containing different electrolytes in a range of applications. At the same time, research investment in competing technologies reduced or eliminated other prospective fuel cell applications.

MANY POSSIBILITIES

After the war, Bacon moved to Cambridge and for the next twenty years experimented mostly with alkali electrolytes, settling on potassium hydroxide. KOH performed as well as acid and was less corrosive to the porous gas-diffusion electrodes he used.[40] Bacon's work showed good results, but nuclear energy better satisfied the power requirements for his original application. As demonstrated by USS *Nautilus* in 1954, compact nuclear reactors allowed submarines to stay submerged for extended periods without refueling. The new technology provided far more electric power than fuel cells and by 1960 the Navy deemed nuclear a superior alternative.

At the time, that seemed only an isolated example with little impact on fuel cell development. A post-war economic boom in the US unleashed a flood of ideas for civilian applications that leveraged Cold War military research. The popular press reported many fuel cell prototypes under development, from DeSoto's "Cella 1" concept car (figure 5) and Exide Battery's "Racer" to Electric Boat's submersible.[41] In 1959 Allis- Chalmers demonstrated a farm tractor powered by a stack of 1,008 alkali cells based on Bacon's work (figure 6). Generating 15 kW, the tractor could pull about 1400 kg (3000 lb.). Supported by the US Air Force, Allis-Chalmers pursued fuel cell research for some years, also testing a golf cart and a fork lift.[42]

Battery maker Union Carbide also experimented with alkali cells in this period. Karl Kordesch (1922-2011) and colleagues built on 1930s work by George W. Heise (1888-1972) and Erwin A. Schumacher (1901-1981), to make alkali cells with carbon gas-diffusion electrodes.

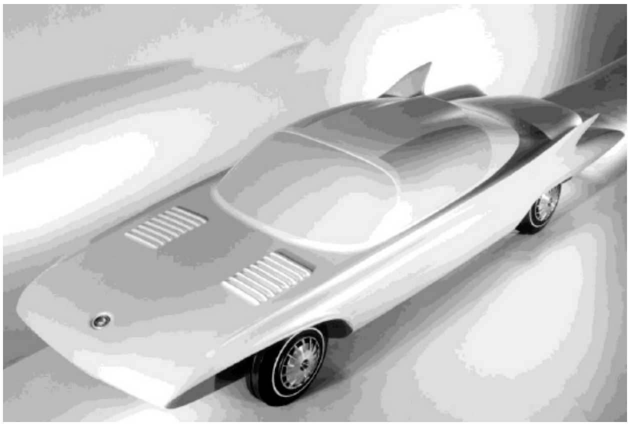

Figure 5. DeSoto "Cella 1" concept model, ca. 1959. From the Science Service Historical Images Collection, courtesy De Soto.

They demonstrated a mobile radar set for the US Army and designed fuel cells to run an undersea base. Kordesch turned heads in Cleveland, Ohio by driving around in a converted Austin A40 automobile powered by batteries and an alkali fuel cell.[43] Union Carbide also provided cells for General Motors' experimental "Electrovan" (figure 7).[44]

Amid the work on alkali cells researchers did not abandon acid electrolytes, and many turned to phosphoric acid. In 1961, Glenn V. Elmore (1916-2009) and Howard A. Tanner tested an electrolyte of 35 percent phosphoric acid and 65 percent silica powder pasted into a Teflon gasket. "Unlike sulfuric [acid]," they noted, "phosphoric acid is not reduced electrochemically under cell operating conditions."[45] The US Army explored the potential of phosphoric acid cells that ran common fuels like diesel as well as unusual fuels like hydrazine (figure 8). An industrial partnership known as the Team to Advance Research for Gas Energy Transformation, Inc. supported research in phosphoric acid cells for the electric power industry, and developed a series of power plants ranging from about 15 kW in 1969 to nearly 5 MW in 1983.[46] Unfortunately phosphoric acid proved a poor conductor of electricity. That among other issues slowed the pace of development.

Interest in high temperature fuel cells resurged after WWII due to their greater tolerance for fuel impurities.

Dutch scientists Gerard H. J. Broers (1920-2003) and Jan A. A. Ketelaar (1908-2001) began building on the prewar research of Baur and Preis, and Davtyan. They decided that limits on solid oxide conductivity and life expectancy made short-term progress unlikely so focused instead on electrolytes of molten carbonate salts. By 1960, they demonstrated a cell that ran for six months using an electrolyte "mixture of lithium-, sodium- and/or potassium carbonate, impregnated in a porous sintered disk of magnesium oxide." However, they found that the molten electrolyte was slowly lost, partly through reactions with gasket materials.[47]

Francis Bacon also began working with a molten cell, using two-layer electrodes on either side of a "free molten" electrolyte.[48] Other groups tested semisolid or "paste" electrolytes, and investigated diffusion electrodes rather than solid ones. Texas Instruments made molten carbonate cells for the Army that ranged in output from 100 W to 1 kW (figure 9). The promise of a cell with a stable solid electrolyte that could tolerate a variety of fuels sustained modest interest in solid oxides. Research-

Figure 6. Allis-Chalmers fuel cell tractor, 1959. From the Science Service Historical Images Collection, courtesy Allis-Chalmers

Figure 7. Sample Union Carbide KOH fuel cell for General Motors "Electrovan." NMAH catalog no. 2007.3061.01. Smithsonian Image.

Figure 8. A soldier refuels a 300 W hydrazine fuel cell, ca. 1964. Courtesy of the US Army Mobility Equipment R&D Center.

ers at Westinghouse experimented with a cell using zirconium oxide and calcium oxide in 1962.[49]

WHEN PRICE IS NO OBJECT

The post-WWII work produced prototypes and conference papers, but little in the way of practical devices. Fabrication costs continued to run high and substitute power sources existed for most potential applications. Only in the mid-1960s did an application emerge that took advantage of fuel cells: the US space program. Batteries sufficed for the first piloted spacecraft, the Soviet Union's Vostok and US' Mercury. But National Aeronautics and Space Administration (NASA) planners knew that batteries would be too heavy for lunar expeditions, and fuel cells gave the added advantage of producing potable water. When reaching the moon became a political priority, concerns about costs receded. NASA ultimately used two types of fuel cells, a novel design from General Electric (GE), and a derivative of Bacon's cell made by Pratt & Whitney.

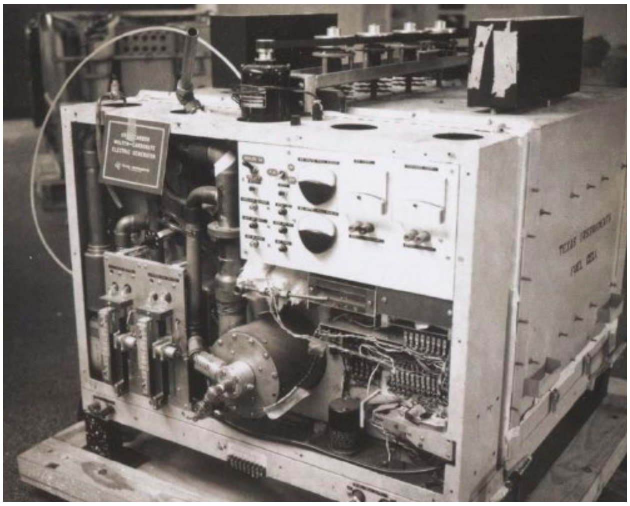

Figure 9. Texas Instruments 1 kW molten carbonate fuel cell. NMAH catalog no. 330031. Smithsonian image.

W. Thomas Grubb (1923-1994) and Leonard Niedrach (1921-1995) at GE developed a polymer electrolyte in the form of a thin, permeable sheet. In 1962, the company introduced the proton exchange membrane (PEM) fuel cell, proposing small units for the military. The unit ran on hydrogen made by mixing water and lithium hydride contained in disposable canisters. Though compact and portable, the cells' platinum catalysts were expensive.[50] The expense did not deter NASA officials who liked the compact size and chose PEM cells for Project Gemini. Missions lasting up to fourteen days would test in earth orbit equipment and procedures needed for lunar flights. Unfortunately for GE, their model PB2 unit experienced problems including internal cell contamination and oxygen leakage through the membrane. The first four short duration Gemini flights used batteries while GE hurriedly fixed the problems. Their new model P3 performed poorly in Gemini 5 but served adequately on six later flights.[51]

The PEM cells' problems boded ill for NASA's very fast schedule to reach the moon. Rather than risk additional delays, the agency chose Pratt & Whitney's alkali cells for Project Apollo's service module. The company had licensed Francis Bacon's patents in the early 1960s and moved into production (figure 10). The alkali cells performed well for Apollo, and a decade later space shuttle designers chose an updated version. Ultimately five shuttles made 135 flights between 1981 and 2011 with electrical power provided by alkali cells.

Powering spacecraft allowed researchers to gain operational experience with fuel cells. They could accept

Figure 10. Apollo fuel cell assembly at Pratt & Whitney. From the Science Service Historical Images Collection, courtesy Pratt & Whitney.

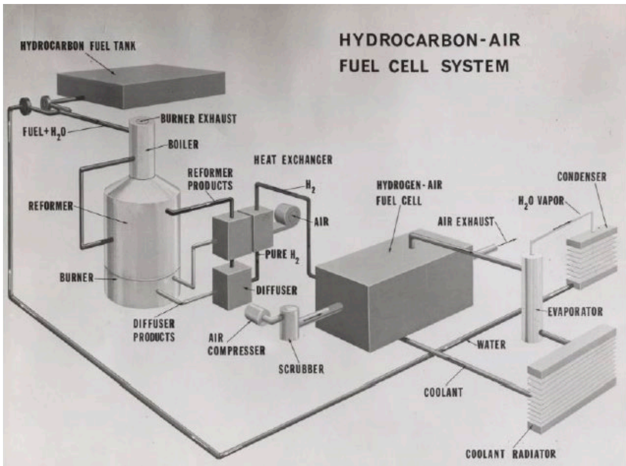

Figure 11. Diagram of fuel cell system. Courtesy of US Army Engineer Research & Development Laboratories.

high costs since few practical alternatives existed. Driven by politics, scientists and engineers spent the money needed to improve cell performance. But space applications proved too limited a market to support that level of research.

Technical hurdles remained intractable and researchers struggled to find a replacement for expensive platinum catalysts. Fuel cells still could not compete with other power sources in markets where costs mattered.

Another factor became clear during the post-WWII period: fuel cells were just one component in holistic power systems. Figure 11 shows a representative example. As Eisler points out, though Bacon and others chose to ignore this issue, fuel cells required ancillary equipment like reformers, hydrogen storage tanks, and inverters.[52] All those pieces, themselves complex, had to function compatibly when interconnected.

Modifications to one affected the others, increasing costs and complicating integration into the host device. If the application required the fuel cell assembly to function within a greater system, such as an electric power or transportation infrastructure, an external layer of compatibility issues arose. All power sources face these systems issues, but they add another disincentive to the high costs of adopting fuel cells.

In the 1960s, specialty markets proved too small to generate the economies of scale necessary to reduce fuel cell production costs. Potential mass markets took advantage of less expensive alternatives. Internal combustion engines could power cars, tractors, and motorbikes more economically than fuel cells. Gas turbine engines for aircraft were adapted for electric power stations; one was even displayed next to a fuel cell at the 1964 World's Fair (figure 12).[53] Propane engines could power fork lifts, batteries could run small submersibles and golf carts. Military users liked the idea of fuel cells but not well enough to add hydrogen fuels to their logistic supply chains.[54] They also grew wary of unfulfilled promises when technical and operational difficulties persisted.[55] Some companies (Allis-Chalmers, DeSoto), failed while others (Texas Instruments, Philco) ceased fuel cell research. Public and corporate interest waned and fuel cells' prospects again faded.

ENERGY & ENVIRONMENT

After the 1973 oil embargo, interest in new power sources rebounded and kept money flowing into fuel cell research. Two potential markets attracted significant investment: stationary electric power and automobiles. Utilities and auto makers faced the challenge of satisfying customers who demanded lower costs and less pollution.

Attempts to meet those demands led to another round of fuel cell prototypes and demonstrations during the 1990s and early 2000s. Press releases promised near term availability of commercial products, and indeed a few did emerge for backup and auxiliary power. However, as before, investment in competing technologies resulted in advances to alternatives that made fuel cells less attractive, hindering widespread adoption.[56]

Electric power utilities faced many difficulties beginning in the 1960s, including blackouts and soaring construction expenses.[57] High oil prices led utilities to abandon that fuel where possible but replacements often seemed no better. Nuclear technology faltered in the aftermath of the Three Mile Island meltdown and the Chernobyl disaster. Coal plants needed to install expensive equipment to control emissions that created acid rain and smog, offsetting the low cost of fuel. Renewable sources like solar and wind power were intermittent and expensive, while few acceptable sites remained for new hydroelectric plants.

Also, a backlash against large scale technical infrastructures led many people to question the basic concept of centralized power systems. Plans to expand high voltage transmission grids became politically contentious, especially near scenic or historically sensitive areas. Advocates of decentralized systems argued that small generating plants situated near users would reduce transmission losses, be less expensive to build, and limit the impact of malfunctions.[58] That idea came to be known as distributed generation.

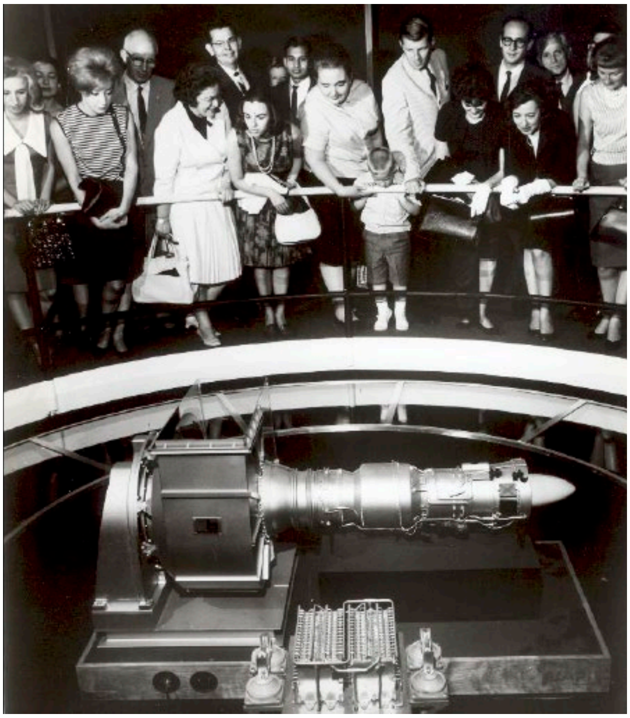

Figure 12. Fuel cell and gas turbine at the 1964 World's Fair. From the Science Service Historical Images Collection, courtesy American Gas Association.

Fuel cells held promise for distributed generation in two ways: as additions to localized power grids, and as stand-alone generators. Manufactured in relatively small, modular units, fuel cells' cleanliness made them especially attractive to pollution conscious urban planners. Nearly 200 fuel cells had been installed in Japan by 2001, including phosphoric acid units of up to 200 kW capacity, similar to the unit in figure 13.[59] In the late 1990s, the US Department of Energy worked with industry groups on several demonstration projects. One cogeneration unit coupled a solid oxide fuel cell with a microturbine, while a demonstration plant in Santa Clara, California, tested a molten carbonate stack.[60]

One urban plant demonstrated how non-technical problems could disrupt fuel cell adoption. Using mostly public and some private funding, Consolidated Edison built a 4.8 MW molten carbonate power plant in New York's Bedford–Stuyvesant neighborhood (figure 14). An extended period of inspections and reviews, spurred by local residents' fears about the underground storage of naphtha fuel, delayed the plant's opening date beyond the life of the fuel cells. Faced with the need to replace the expensive cells, Con Ed instead demolished the plant.[61]

Increased adoption of computer information systems led users to demand more electricity and better system reliability. Power fluctuations and outages created expensive service interruptions in commercial and industrial operations. Generating power onsite, fuel cells reduced demand on electric grids and provided backup power during blackouts. Police in New York City's Central Park were at first unaware of a 2003 blackout when their sta-

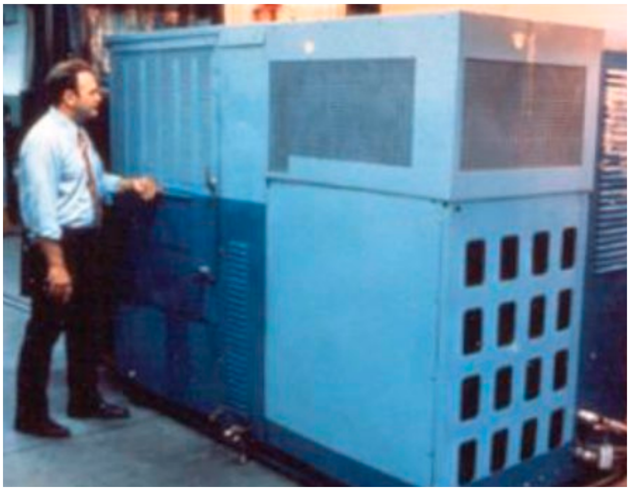

Figure 13. UTC 40 kW model PC-18 phosphoric acid fuel cell, 1979. Courtesy of the US Department of Energy.

Figure 14. Artist's rendering of the 4.8 MW Bedford–Stuyvesant fuel cell power plant. NMAH catalog no. 2008.0006.03. Smithsonian image.

Figure 15. Plug Power house with PEM fuel cell in attached enclosure, 2001. Smithsonian image.

tion's fuel cell kept lights and computers on. Seeking to tap the residential market, a company called Plug Power in 1998 demonstrated a stationary PEM unit in the Albany, New York house seen in figure 15. Promoted as the "first permanent home installation," the 5 kW power plant powered the home for about two years. The company partnered with GE and Detroit Edison with the goal of marketing a residential fuel cell by 2002.[62]

It seemed in the early 2000s that fuel cells might finally be finding a practical niche in stationary power, as several companies began selling commercial units. Advances in other technologies upset those plans, however. A substantial boost in natural gas supplies due to fracking led utilities to install more gas turbine power plants. Cost competitive wind turbines gave them yet another option to replace coal and nuclear plants. Breakthroughs in photovoltaics coupled with mass production dramatically cut the cost of solar cells. Utilities began installing solar farms for local use or to feed the grid. Many people installed solar panels to generate electricity for use or sale to local utilities during the day, while taking grid power in sunless times.

Manufacturers integrated small solar panels on equipment like road signs, replacing combustion generators and eliminating the need for either petroleum or hydrogen fuel.

AUTOMOTIVE CELLS

Like electric companies, car makers also needed to cut pollution and improve fuel efficiency. Unable to quickly adopt alternative fuels, they designed lighter cars with smaller engines, while pushing national governments to maintain oil supplies.[63] They also began to experiment, often under duress, with possible replacements for internal combustion engines. A compact fuel cell that emitted only water vapor held obvious attraction. Though high temperature and alkali cells would be ill-suited for cars, PEM cells looked promising. By 2002, major manufacturers were testing prototype fuel cell cars—and making grandiose promises, as Hultman and Nordlund noted.[64]

Transporting some form of hydrogen fuel constituted a major challenge. Few people would tolerate cars with exposed hydrogen tanks like Kordesch's Austin. One either needed a reformer to extract hydrogen from a fuel that existing stations could sell or to create a hydrogen distribution infrastructure. Either option would be difficult and expensive. Making, compressing, and storing hydrogen entailed high energy costs, cutting overall system efficiency.[65] Reforming fuel onboard the vehicle, as with a methanol fuel cell, provided one way to address the issue. However, byproducts of the reforming process poisoned cell catalysts, a familiar problem, and corrosion problems required use of an acid electrolyte.[66] The byproducts also belied claims of a non- polluting engine.[67]

Centralized refueling stations for urban trucks and buses, like the battery recharging stations of the early 1900s, seemed a reasonable first step. H-Power, Georgetown University, and the Energy Department adapted a 50 kW Fuji Electric phosphoric acid cell for transit buses and began test runs in 1994 (figure 16). Phosphoric acid cells require an extended warm-up period, making them better suited for commercial vehicles than for personal cars. Four years later, Georgetown, Nova BUS, and the US Transportation Department began tests of a bus powered by a 100 kW cell from a joint venture of Toshiba and United Technologies.[68]

Figure 16. H Power phosphoric acid fuel cell bus, 1996. Courtesy of the US Department of Energy.

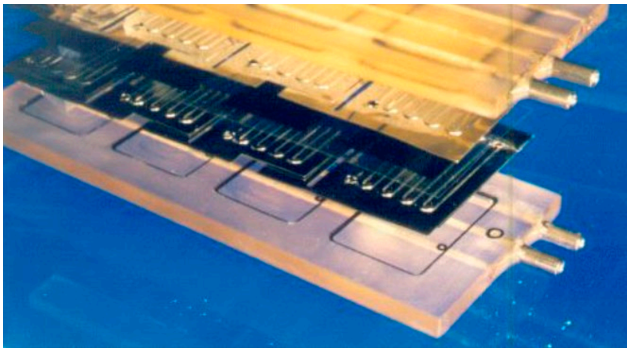

Figure 17. Micro-fuel cell by Fraunise ISE for mobile phone. Courtesy of Fuel Cells 2000.

During this time an unexpected cost hurdle emerged. One of the most expensive materials in many fuel cells, platinum, also proved critical for the catalytic converters that car makers needed to control engine emissions. Increased demand for platinum raised the price of the already expensive metal. Replacing an internal combustion engine with a fuel cell might eventually remove the need for catalytic converters and substitute one platinum containing product for another. But such a shift might take decades, and that pushed cost reductions too far out for most investors, reducing the attraction of automotive fuel cells.

Another option was to find a bridge technology that could work with the existing petroleum infrastructure. In 1997, major auto makers began to promote gas-electric hybrid vehicles that used a small gasoline motor in combination with an electrical generator to recharge batteries or power electric motors. They also invested at least as much in battery research as in fuel cells. The Tesla electric automobile in 2003 along with the company's massive battery factory in Nevada shows how sustained research and investment in both product and power source might lead to economies of scale.

Commercially available hybrids and battery powered cars began moving a market that might have supported mass production of fuel cells in a different direction.

Advances in battery technology also disrupted another potential market: portable electronics. Several companies experimented with micro fuel cells they hoped could replace rechargeable batteries in cell phones, laptop computers, and portable audio players (figure 17). Millions of small electronic devices created environmental concerns about the disposal of used batteries containing toxic materials like cadmium and mercury.[69] A Motorola engineer at a 2001 conference reported problems with water transport in cells for phones, but claimed progress on a cell for laptop computers.[70] Before commercial products could be introduced though, new nickel-metal hydride and then lithium-ion batteries changed the market. Despite the latter's thermal problems, batteries were easier to integrate into electronic devices than micro fuel cells.

One 2013 study found 109 firms in nine countries engaged in fuel cell research partnerships.[71] Despite all that effort and publicity, by the early 2010s fuel cells again fell out of favor. Plug Power demolished their test house in 2002 and shelved plans for residential PEM fuel cells. The Tennessee Valley Authority reactivated a closed nuclear facility instead of installing a regenerative fuel cell system. Auto makers, who promised affordable fuel cell vehicles in showrooms by 2004, quietly pulled back from all but a few high-priced models. US government funding for fuel cells was cut in 2008, with one official citing "four miracles" needed to bring the technology to market.[72] Even in spacecraft like the International Space Station, high efficiency solar panels rather than fuel cells provided power.

LESSONS OF NON-CYCLICAL HISTORY

Nearly two centuries after Grove's discovery, fuel cell researchers have made significant advances even while the basic concept remains unchanged. Thrice during that period fuel cells seemed on the verge of widespread adoption only to fade from view. History never repeats, despite the tired old adage. So how are we to take lessons from an account that seems to do just that? One key is to look for changes in the larger societal contexts within which technologies exist, especially economic and political changes, while remembering that human nature tends to persist. Understanding context helps explain historical differences. Understanding people helps explain historical similarities.

One lesson is to look beyond functional elegance to mundane economics. Since 1839 people have been captivated by the idea of combining hydrogen and oxygen to generate electricity and water. There simply must be a way to use that idea, so fuel cells have always been a solution in search of a problem. Yet technical elegance is neither necessary nor sufficient to produce a return on investment. Every time engineers found a seemingly realistic use for fuel cells, a competitor better met users' needs. Internal combustion engines, steam turbines, photovoltaics, and batteries all set technical and economic challenges for developers. But each of those power sources attracted additional investment that advanced their capabilities when a compatible application proved commercially successful. Advocates should pay close attention to alternate technologies and business models because there are no uncompetitive applications for fuel cells.

Nineteenth century researchers would recognize many difficulties their descendants struggle with. The need for expensive rare earths, especially platinum, is one; the need for readily available pure gases is another. Yet the technical environs within which those difficulties exist have changed. Inexpensive solar cells may enable efficient production of pure hydrogen. Recent experiments with aqueous fuels based on recyclable boron hydride may offer a sustainable fuel distribution infrastructure without the energy loss of compressing hydrogen.[73] Still, the basic material costs must be dramatically reduced for fuel cells to become commercially competitive.

Today's researchers do face hurdles many of their predecessors did not. For one, the need to design equipment that meets established standards. Whether those are electrical, manufacturing, or safety standards, once in place new devices must operate within those set parameters. Standards can advance quality and promote efficiency. Setting standards is an act of control that can eliminate some competitors and raise costs for others.[74] Standards internal to fuel cell technology have been crafted, but engineers must also account for external standards like building codes that affect other power sources as well.[75]

A related difference is the need for economic compatibility with associated system components. Fuel cells must work with power inverters and control equipment; ideally those should already exist in manufacturers' product catalogs. Special versions of those components can be made, but that introduces additional design, testing, fabrication, and certification costs that are counterproductive. Incompatible variations between fuel cell types exacerbates the problem.

Fuel cell researchers today enjoy advantages their predecessors could only dream of, such as computer-aided design and fabrication tools. The ability to model physical and chemical interactions before making experimental devices speeds research. Additive manufacturing may permit economical production of complex component designs. Researchers today also have the internet, a high-speed global communications system that permits far-flung collaborations. Access to searchable digital archives makes the results of ongoing and past research readily available. Changes in information technology shift the basic nature of scientific and engineering research in ways that should not be underestimated.

One of the most enduring human features of fuel cells is the feeling among advocates that solutions are close. In 1884, Edison gave himself five years to find an answer, and expected some "lucky" person would succeed.[76] In 1960, two GE engineers felt that use in "special applications...within the next five years" was "likely."[77] In 2010, a Penn State engineer commented on the "fickle" nature of US government support, giving another five-year estimate "to make hydrogen technologies consumer- ready."[78] In 2013, a policy analyst recognized that companies, "always believed things could be fixed with a little more time and a little more money;" and then proposed a major national research program "to uncover the secrets of the fuel cell."[79]

In part those feelings stem from technical naiveté conflating fuel cells that run on pure hydrogen with those that run on other fuels, a definitional difference that Eisler noted.[80] The economic and energy problems that made pure hydrogen a poor fuel choice have not been solved by research on reforming coal, gas, or petroleum fuels.

Technical advances provided a dose of positive reinforcement but failed to meet users' immediate needs as well as other technologies. A cold accounting for recurring optimism may indeed be "disheartening for young [engineers]," but it is also essential to avoid another round of wasted money and dashed hopes.[81] Practical fuel cells will not emerge from the lab unless they can be produced and operated sustainably in both environmental and economic terms.

Other similarities and differences exist, and we cannot predict how this story will unfold. Perhaps fuel cells are doomed to perpetual impracticality. Perhaps persistence will finally lead to mass adoption. Few people doubt the unsustainability of fossil fuels, only the timing of when they will run out or be abandoned to mitigate climate change. So demand for clean, low-cost power sources seems assured. Perhaps batteries and renewables will meet that demand. Perhaps a politically-driven shift away from combustion engines coupled with low-cost hydrogen generated using cheap solar power will radically alter energy costs in favor of fuel cells. We shall see.

In the meantime, we should approach with care the advice of Jons Jakob Berzelius as recalled by John Rhodin in 1926. "Let us patiently search Nature, she always gives an answer if we search long enough."[82] Sometimes patience indeed pays off. But as generations of fuel cell researchers can attest, sometimes nature refuses to cooperate and the answer is not what we want to hear.

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