# Fuel Cell Research and Development and the Pursuit of the Technological Panacea, 1940-2005

For years following its invention in the mid-nineteenth century, the electrochemical power source known as the fuel cell has excited imaginations. Because fuel cells directly convert chemical into electrical energy and do not randomize energy as heat in the manner of a heat engine, researchers assumed they were largely exempt from the Carnot limitation on efficiency, which holds that there could not be a perfectly efficient heat engine since such devices must lose a portion of their energy as heat exhaust. As a result, scientists and engineers have perceived fuel cells as the "magic bullet" of power technologies. Although private companies and governments spent billions of dollars on research after the Second World War, they largely failed to develop long-lasting and affordable commercial fuel cells.

The fuel cell concept emerged in the mid-nineteenth century when a handful of European researchers began to experiment with reversing the electrolysis phenomenon. Instead of using electricity to dissociate water into hydrogen and oxygen, they attempted to combine oxygen and hydrogen to produce electricity. In 1839, the British lawyer and amateur scientist William Grove and the Swiss physicist Christian Friedrich Schoenbein used platinum foil to catalyze a reaction between hydrogen and oxygen. Grove further elucidated the chemical basis of this reaction in a number of subsequent experiments, referring to his apparatus as a "gaseous voltaic battery."[1]

Little more was done until the 1890s, when European scientists revived the concept in a new series of experiments using coal and coal-derived gases as a source of hydrogen. To chemical and electrochemical experts, it seemed as if the fuel cell had the potential to

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[1] William Robert Grove, "On A Gaseous Voltaic Battery," *Philosophical Magazine and Journal of Science* 21, S.3 (December 1842): 417.

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replace the dominant internal combustion engine technology. The German physical chemist Wilhelm Ostwald exemplified these hopes in a passionate address to a group of engineers in 1894. He presented the idea of direct electrochemical conversion of solid coal to electricity as a possible replacement for the steam engine, a technology Ostwald saw as "incomplete" because it converted only a fraction of the energy in coal to useful work and the rest to waste heat, soot and smog.[2] While a number of experimental electrochemical energy conversion devices were built in the late nineteenth and early twentieth centuries, none approached conventional batteries or heat engines in durability or cost-effectiveness. In 1939, the German researcher Emil Baur remarked how strange it was that advances in fuel cell theory and the state of the technological art made in the 1890s had borne no fruit almost a half century later.[3]

Hopes were rekindled in the late 1950s and early 1960s when the first practical fuel cells were developed in Britain and the United States. Beginning in the early 1960s, the United States federal government began funding work on fuel cells for military and quasi-military purposes in both terrestrial and aerospace applications. A variety of industries also made large investments in hopes of bringing cheap and durable fuel cells to market. By the early 1970s, most had abandoned this work as costs and technical problems mounted. More than half a century again after Baur's observation and twenty years after the first post-war episode of excitement and investment in fuel cells, another wave of optimism rose in the early 1990s. This time, expectations were greater than ever. The automobile industry, the Department of Energy and, by the early 2000s, the White

[2] Wolf Vielstich, Arnold Lamm and Hubert A. Gasteiger eds., "Part 4: Fuel Cell Principles, Systems and Applications," in *Handbook of Fuel Cells: Fundamentals, Technology and Applications; Volume I: Fundamentals and Survey of Systems* (Chichester, UK: John Wiley and Sons, Ltd., 2003), 161-162.
[3] Emil Baur, *Bulletin Schweitz ETV* 30, 17 (1939): 478.

House, saw the electric passenger vehicle as the most desirable application of fuel cell power. They believed the mass-produced fuel cell electric automobile could solve the environmental and geopolitical problems caused by the dependence on fossil-fuelled internal combustion engine transportation. Projections of the imminent mass commercialization of fuel cell automobiles became leavened with utopian rhetoric framing the fuel cell as the basis of the "hydrogen economy," a revolutionary new energy order that would sweep away the old energy and transportation system. By the early 2000s, however, the commercial fuel cell electric vehicle project had been indefinitely postponed as researchers and investors encountered serious technical and financial obstacles.

This paper argues that dreams for a commercial fuel cell have gone consistently unrealized largely because expectations have consistently outpaced the knowledge base. Researchers and their supporters perceived the fuel cell as a hybrid of the conventional galvanic battery and the internal combustion engine, combining the advantages of both without their handicaps. In conventional storage batteries, the electrodes are also the "fuel," and are gradually consumed over time. In contrast, fuel cells use chemical reactants that are stored externally, not within the battery casing itself. Researchers assumed that as long as fuel was supplied, fuel cell electrodes and electrolyte would continue to operate with no chemical deterioration, a state known as "invariance." Although such claims found a ready audience in industry and government as energy use rose dramatically in the years after the Second World War, they have gone unrealized as advances in fuel cell power output have been negated by offsetting penalties in cost, efficiency and durability.

## Towards A Theory of Postwar Fuel Cell Research and Development

There has been almost no scholarly work on the history of fuel cell research and development, though there is a wealth of archival material and scores of handbooks, manuals and conference proceedings. The authors of such works, many of who are engineers and technicians formerly or actively engaged in research, often express concern with the technology's unusual past and, sometimes, incredulity that it has not yet been commercialized. Perhaps not surprisingly, they generally treat the history of fuel cells as an afterthought, confining it to subsections or appendices. These researchers are concerned with the future, not the past, and regard fuel cell research and development as an ongoing saga that will one day be crowned with success. In rationalizing "failure," these sources tend to focus on what they consider "objective" technical factors, such as expensive materials or faulty design. This is the approach taken by A.J. Appleby and F.R. Foulkes in their *Fuel Cell Handbook*, widely considered to be the authoritative account of fuel cell technology.[4]

The French sociologist Michel Callon was the first scholar to conduct a serious socio-political analysis of fuel cell research and development. Focusing on the French electric car programs of the 1960s and 1970s, his primary concern was how the politics of research and development, particularly the role of state intervention, gave rise to new technologies. The genesis of the French electric car program served to illustrate how alliances between government, industry and academe helped shape science and technology policy. As British and American demonstrations of fuel cell prototypes excited worldwide interest in the late 1950s and early 1960s, French scientists, policy analysts, industrial researchers and the state electrical utility believed a "technological

[4] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), viii.

revolution” was in the making. Each group saw a fuel cell program as a way to achieve their objectives. For patriotic science and technology planners, it would help bridge theory and technique, enhancing national prestige through the expansion and enrichment of the field of electrochemistry. The politically powerful electrical utility became involved mainly to support its dream of developing a commercial electric vehicle. It concentrated on a small fuel cell suitable for an automobile rather than a large one that could be used as a generator, a technology the utility believed could be used to undermine its monopoly on the production and distribution of electricity.[5]

Callon raised general points relevant to the rise of postwar fuel cell research and development. The most important are the forging of broad fuel cell coalitions in which “everyone’s interests were taken care of,” a process that involved simplifying the technical issues at stake, and the impression early British and American projects had on French science and technology elites. Callon was less interested in the origins of the “technological revolution” or the conduct of fuel cell research and development within the laboratory, especially the dynamics of simplification and how they related to alliance building and the generation of expectations and enthusiasm.[6]

Gerrit Jan Schaeffer’s doctoral dissertation is one of the few other notable studies in this field. Viewing the history of fuel cell research and development as a sequence of

[5] Michel Callon, “The State and Technical Innovation: A Case Study of the Electric Vehicle in France,” *Research Policy* 9 (1980): 362-366.
[6] Callon, “The Sociology of an Actor-Network: The Case of the Electric Vehicle,” in *Mapping the Dynamics of Science and Technology: Sociology of Science in the Real World*, eds. Michel Callon, John Law and Arie Rip (London: Macmillan Press, 1986), 29-31. Callon’s primary objective was to use French fuel cell research and development as a case study to help illustrate the so-called “actor-network” theory of power relations in science and technology communities. More than seven years after Callon first began examining French fuel cell communities, he elucidated the role of technological simplification as a key element of coalition-building. He held that diverse coalitions supporting fuel cell research formed only after the relevant technical issues had been simplified. He suggested that such coalitions weaken once the true degree of electrochemical complexity in fuel cell development becomes apparent to the respective parties.

"contingent and dramatic episodes," Schaeffer focused on European fuel cell programs, recapitulating some of Callon's original case studies in more detail. Like Callon, Schaeffer traced expectations that triggered European research programs to demonstrations staged in 1959 by British and American researchers and did not relate these case studies to the larger history of post-Second World War fuel cell research.[7] This is an important omission, for the United States has devoted more resources to developing fuel cells than any other country. Schaeffer also had little to say about Francis Thomas Bacon, the English mechanical engineer whose fuel cell he acknowledges played an important role in informing expectations in the pivotal year of 1959. Finally, Schaeffer attributed the persistence of post-war fuel cell research and development to the sheer number of programs and volume of scientific papers and demonstrations. These, he claims, attracted a continual stream of new players to the field.[8] However, this tautology revealed little of the motives of researchers and sponsors in pursuing fuel cell development and the ways in which expectations were generated.

Any comprehensive study of fuel cell research and development must be rooted in the history of industrial research in general and in industrial laboratories in particular, for it was in that environment, with a few important exceptions, that the vast majority of the work on fuel cells was done after the Second World War. There are a number of outstanding issues within the historiography of industrial research that bear upon the history of fuel cells and fuel cell research and development in important ways. These include the processes by which people have conceptualized the interaction between science and technology and particularly the ways they have defined the role of "pure

[7] Gerrit Jan Schaeffer, *Fuel Cells for the Future: A Contribution to Technology Forecasting From a Technology Dynamics Perspective* (Ph.D diss., University of Twente, 1998), 155.
[8] Ibid., 181.

science" in this relationship. These problems coalesce in the so-called "linear model" of innovation, a concept that poses knotty epistemological and ontological problems. The historian of science and technology David Edgerton notes that the linear model refers to a belief in the origin, process and effects of innovation; "pure" or "basic" science is the source of innovation, which unfolds sequentially, with scientific discoveries informing "applied" research that, in turn, leads to the production of technology.[9] The linear model has frequently been associated with work practices in the first industrial laboratories that emerged in the early twentieth century, above all with the novel institutional structure some scholars have referred to as the "golden triangle." This describes the close partnership between military agencies, industrial laboratories and universities.[10] Though fuel cell research and development has occurred largely within industrial laboratories, these were nevertheless firmly rooted in post-war golden triangle structures both in Britain and the United States, hosting a form of research that was fundamentally interdisciplinary and which maintained important links with universities and a variety of government agencies.

Historians of technology generally concur that the "linear model" does not accurately describe the actual course of technology development at any stage of history, observing that the science-technology relationship has been much more complex. Michael Aaron Dennis, for example, has argued that it becomes pointless to distinguish "where science ends and technology begins, or vice versa," given the increased use of technological

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[9] David Edgerton, "'The Linear Model Did Not Exist:' Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," *The Science-Industry Nexus: History, Policy, Implications*, eds. Karl Grandin, Nina Wormbs and Sven Widmalm (Sagamore Beach, MA: Science History Publications/USA 2004), 32.

[10] Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993), 2.

instruments to produce scientific knowledge from at least the nineteenth century onwards, as well as the more recent trend of workers in modern industrial laboratories employing scientific methodology to understand the physical principles of technology.[11]

There is also little dispute that the linear model was invoked by a relatively small but influential group of academic scientists and engineers in Britain and the U.S. as a means of leveraging increased government support for basic science after the Second World War.[12] It was further popularized by politicians and the media, becoming part of the popular consciousness. The ideological, institutional and technological consequences of linear thinking, however, are less clear. Noting that a formal linear model has never been drafted by science and technology policy elites, Edgerton reasons that the concept was wholly the creation of academics, who preferred setting it up as a straw man to a more incisive investigation of the nature of technological innovation. For him, the effects of the linear model, uniformly negative, have been restricted almost entirely to the realm of historical and sociological studies of science and technology.[13]

A more widespread view, articulated by Harvey Brooks, is that *belief* in the linear model has had a pervasive and lasting effect on the organization and planning of technology development in the West.[14] Science and technology policy planners may

[11] Michael Aaron Dennis, "Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science," *Social Studies of Science* 17 (1987): 490.
[12] The science journalist Daniel S. Greenberg was one the earliest critics of both this trend and the linear model; see *The Politics of Pure Science*, new ed. (Chicago: The University of Chicago Press, 1999), 29-31.
[13] Edgerton, "'The Linear Model Did Not Exist:' Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century," 31-34.
[14] Harvey Brooks, "The Evolution of U.S. Science Policy," in *Technology, R&D, and the Economy*, eds. Bruce L.R. Smith and Claude E. Barfield (Washington, D.C: The Brookings Institution and American Enterprise Institute, 1996), 21. For works that address the influence of linear thinking in the politics, practice and organization of science and technology, see David Edgerton's *Science, Technology and the British Industrial 'Decline,' 1870-1970* (1996), Daniel S. Greenberg's *The Politics of Pure Science* new ed. (1999) and *Science, Money and Politics: Political Triumph and Ethical Erosion* (2001), David Hounshell and John Kenley Smith's *Science and Corporate Strategy: DuPont R&D, 1902-1980* (1988) and Daniel

never have developed a formal linear model, but, steeped as they were in its ideology, they often applied linear modes of management to inherently non-linear processes of science-based technology development, with important consequences for the conduct of research and development. Glen R. Asner demonstrates this in his examination of the Department of Defense's so-called Independent Research and Development program. Launched in 1959, it massively increased funding for undirected basic research in industrial laboratories. In an effort to reassert managerial control over weapons development programs, the Pentagon strictly defined "basic research," "applied research" and "development," linking them sequentially as a prescribed mode of technology innovation and requiring that contractors separately account for their research and development costs. This led many to restructure their weapons development along linear lines, physically isolating research, development and manufacturing.[15]

Such dynamics also governed the conduct of postwar fuel cell research and development. While the structure of British and American fuel cell golden triangles differed significantly, their managers shared similar assumptions of technological progress. Both attempted to impose linear management protocols on the non-linear interdisciplinary practices of fuel cell laboratories, with important consequences for the epistemology and conduct of research and development and for the configuration of the technological products. Consequently, the terms "basic research," "applied research" and "development" in the history of fuel cell research and development cannot be treated as absolutes: they have meant different things to different actors at the same time, or

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Kevles' *The Physicists: The History of A Scientific Community* (1971) and "K1S2: Korea, Science, and the State," in *Big Science: The Growth of Large-Scale Research* (1992).

[15] Glen R. Asner, "The Linear Model, the U.S. Department of Defense and the Golden Age of Industrial Research," *The Science-Industry Nexus: History, Policy, Implications*, eds. Karl Grandin, Nina Wormbs and Sven Widmalm (Sagamore Beach, MA: Science History Publications/USA, 2004), 3-12.

different things to the same actor at different times.

In developing my analysis, I also draw from themes in business and economic history and from various sub-disciplines in the history and sociology of science and technology. While sociologists and historians have generally concentrated on "success" stories, they have paid greater attention in the last 20 years to the "losers" of history. In the technological context, success and failure are relative terms; some literature focuses on technologies that have failed with sudden catastrophic results, as in the collapse of a bridge or building or crash of a vehicle of some kind.[16] Other work explores technologies that have "died out" or remained marginal in society, typically in relation to devices that have "succeeded." This includes almost every imaginable sort of artifact including household appliances, computers, machine tools, a wide variety of vehicles and batteries in certain applications, to name only a few.[17] The history of fuel cell development most resembles the latter of these cases. While catastrophic failures of fuel cells have commonly occurred during laboratory tests, practical fuel cell power plants have performed reliably enough in certain roles. Developers have achieved success with highly specialized and costly fuel cells in niche roles, particularly in the U.S. space program. However, plans to commercialize fuel cells on a large scale, let alone grand schemes of a whole new energy system based on widely available commercial fuel cells, have not

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[16] For example, see Henry Petroski's *Success Through Failure: The Paradox of Design* (2006), *Design Paradigms: Case Histories of Error and Judgment In Engineering* (1994), *To Engineer is Human: The Role of Failure in Successful Design* (1992), Harry Collins and Trevor Pinch's *The Golem at Large: What You Should Know About Technology* (1998) and Charles Perrow's *Normal Accidents: Living With High-Risk Technologies* (1984).

[17] See, respectively, Ruth Schwartz Cowan's *More Work for Mother: The Ironies of Household Technology From the Open Hearth to the Microwave* (1983), Paul Ceruzzi's *A History of Modern Computing* (1998), David Noble's *Forces of Production* (1986), Bruno Latour's *Aramis, or, The Love of Technology* (1996), David A. Kirsch's *The Electric Vehicle and the Burden of* History (2000), Gijs Mom's *The Electric Vehicle: Technology and Expectations In the Automobile Age* (2004) and Richard H. Schallenberg's *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (1982).

come to fruition.

### Tests, Assumptions and Expectations

Any history of fuel cells must also engage with the branch of the history and sociology of technology that focuses on the construction and uses of technological tests, one based on earlier work in the sociology of science dealing with the construction of scientific experiments. Sociologists and historians understand the testing of theories and technology as interpretive processes in which the generalized results do not necessarily reflect the natural properties of materials or technologies but rather the assumptions of laboratory workers mediated by external social, political, cultural and economic factors. As such, the results are "always open to challenge."[18] I posit that the reasons research and development has persisted despite the repeated failure to produce fuel cells as cheap and durable as incumbent internal combustion and battery power technologies have to do with the ways that British, American and, more recently, Canadian research communities have used tests to draft standards of success.[19] These research communities, I argue, have collectively acted as the leading of generators of expectations for an affordable and robust commercial fuel cell in the post-Second World War period.

Donald MacKenzie and Trevor Pinch's studies of how people test technology offer several generalizations useful for the case of fuel cells.[20] For a variety of reasons,

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[18] Trevor Pinch, Malcolm Ashmore and Michael Mulkay, "Technology, Testing, Text: Clinical Budgeting in the U.K. National Health Service," in *Shaping Technology/Building Society: Studies in Socio-Technical Change*, eds. Wiebe E. Bijker and John Law (Cambridge, MA: The MIT Press, 1992), 273.
[19] Classic studies of tests and experiments include Steve Woolgar and Bruno Latour's *Laboratory Life* (1976), Edward Constant's *The Origins of the Turbojet Revolution* (1980), Trevor Pinch's *Confronting Nature: the Sociology of Solar Neutrino Detection* (1986), Steven Shapin and Simon Schaffer's *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life* (1986) and Donald MacKenzie's *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (1990).
[20] MacKenzie holds that testing is an important means by which people come to develop knowledge of artifacts, which in turn helps determine how they are designed and how widely they are adopted in society. As such, testing is a process of shaping rather than revealing facts. He observes the tendency of research

designers of tests have desired unambiguous results and total control over "potential disturbing factors," producing conditions dissimilar to those the technologies will likely encounter in real-world conditions and allowing inferences to be drawn between certain artifacts and others in their class.[21] Pinch describes this as a process of making "similarity judgments," a mode of simplification whereby researchers set aside those things that "make for differences" on the basis of a wide range of assumptions. He describes three different kinds of test to which people subject technology, all of which involve making similarity judgments projecting future performance. Prospective testing determines the feasibility of design and can involve scale models, full-scale prototypes and manufactured goods before they are released into the marketplace. Current testing assesses equipment that is already in wide use; and retrospective tests are designed to diagnose the causes of failures of in-service technologies.[22] The conventions of reporting "successful" tests often involve omitting all reference to the circumstances in which the test was executed.

Though British and American fuel cell research and development communities in the postwar period employed all three types of testing outlined by Pinch, prospective testing has dominated. This is because so few fuel cell systems have gone through the entire cycle of development and been placed into production. This, in turn, is both the cause and

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communities to treat technological knowledge, like scientific, mathematical and medical knowledge, as "hard fact," when the conventions of technology-testing are actually the product of decisions made on the basis of tradition, experience and vested interests, in short, a wide variety of non-technical factors. Justifications for technological choice made on the basis of technical superiority or greater efficiency cannot be considered absolute, given that definitions of superiority and efficiency may vary in different contexts and circumstances; Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance* (Cambridge, MA: The MIT Press, 1990), 9-10, 340-381.

[21] MacKenzie, "From Kwajalein to Armageddon? Testing and the Social Construction of Missile Accuracy," in *The Uses of Experiment: Studies in the Natural Sciences*, eds. David Gooding, Trevor Pinch and Simon Schaffer (Cambridge: Cambridge University Press, 1989), 414-415.

[22] Trevor Pinch, "'Testing-One, Two, Three…Testing!'" Toward a Sociology of Testing," *Science, Technology & Human Values* 18, no.1 (winter 1993): 27-31.

consequence of the material practices of these communities, which have unfolded in a linear manner both as a result of the management techniques of their patrons and the unique nature of fuel cell technology. While government, industry and the financial community have devoted considerable resources researching fuel cells and associated technologies, such support has been intermittent, as evidenced in the two postwar boom-bust cycles. The limited availability of electrochemical expertise and uncertain access to funding has made commercial fuel cell research and development a speculative and tenuous enterprise. Electrochemistry, the basis of fuel cell technology, was the pauper of post-war American science. Theoretical physics, dramatically and successfully applied in the Second World War and decreed a national security priority by the federal government during the Cold War, dominated all scientific fields. Far fewer resources were available for electrochemistry, which remained relatively poorly understood. This had not always been the case. Electrochemistry flourished in the U.S. in the late nineteenth century, when storage batteries were widely used as load-levelers in early direct current central power stations in order to smooth the often uneven power output of early generators. But in the first two decades of the twentieth century, the practice of electrochemistry declined as reliable electromagnetic generating systems in large central stations dominated the production and distribution of electricity and as the basic automotive lead-acid storage battery became standardized. As the historian Richard H. Schallenberg has observed, American electrical engineers were no longer stimulated to think in terms of electrochemical solutions to problems.[23]

[23] Richard H. Schallenberg, *Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage* (Philadelphia: American Philosophical Society, 1982), 391.

Although the federal government would spend large sums on fuel cell development in the 1960s, mainly in the space program, it did little to foster a post-secondary or polytechnic electrochemical training base. With few career opportunities available in American industry or government, electrochemical engineering offered little prestige. So unpopular was the profession that fuel cell programs in the 1960s were plagued by a labor shortage.[24] Planners resorted to retraining physical chemists and chemical engineers and importing European electrochemists.[25]

Securing capital and expertise was thus a constant concern of fuel cell developers. This helped foster the psychosocial conditions that validated and reinforced the notion of "technological breakthrough," which involved dramatic demonstrations of power output obtained on simple laboratory fuel cells. High power output became the chief criterion of a successful fuel cell and the key driver of expectations. This preoccupation with power stemmed from two factors: the respective ways researchers distinguished between and classified fuel cells and storage batteries and the political economy of fuel cell research and development communities. Batteries and fuel cells operate on similar physical principles, combining a chemical fuel and oxidant in an electrochemical reaction that yields electrical current and a chemical waste product. As noted earlier, batteries have their own self-contained chemical reactants. Storage cells combine these reactants to

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[24] In 1963, an official with the Advanced Research Projects Agency observed that there were only four academicians in the U.S. specializing in electrode phenomena specifically relating to fuel cells, with a combined output of under 40 students per year: Yeager (Western Reserve), Bockris (University of Pennsylvania), Tobias (University of California), and Delahay (Louisiana State University); John H. Huth, "Comments on the Interdepartmental Energy Study," 8 October 1963, Box 4, Project Lorraine-Energy Conversion, 2-4, 1958-1966 Official Correspondence Files-Materials Sciences Office, Advanced Research Projects Agency, accession number 68-A-2658, RG 330, National Archives and Records Administration II, College Park, MD.

[25] *Energy Research and Development and National Progress: Prepared for the Interdepartmental Energy Study by the Energy Study Group under the direction of Ali Bulent Cambel* (Washington, D.C.: U.S. Government Printing Office, 1965), 308.

produce electricity and waste products, which build up within the battery and reduce its efficiency as it discharges. The cell is then “recharged” with externally produced electricity, which dissociates the wastes back into the original chemical constituents. Such devices are said to be “reversible.” They are measured in terms of their capacity to store electricity relative to their volume and supply it for a given period of time. This is typically expressed in terms of watt-hours per liter or “energy density.”

In contrast, fuel cells are merely a kind of energy converter with no intrinsic storage capacity at all. Their chemical fuel is instead stored in external tanks; the fuel cell itself has no measurable “energy density.” Researchers have consequently developed alternate means of rating the technology: “current density,” the amount of electricity produced in a given area of the chemical reactor as the result of an electrochemical reaction, measured by milliamperes per square centimeter or amperes per square meter, and “power density,” the ratio of power available for useful work to weight or volume, measured by watts per kilogram or liter. Importantly, these units of measurement are not expressed in terms of a time relationship, as with conventional storage batteries. Many researchers simply assumed that as long as fuel was supplied to fuel cells, they would continue to operate invariantly, with no internal chemical deterioration over time, unlike batteries. Indeed, fuel cells have instead struck most chemical and electrochemical engineers as having more in common with the conventional internal combustion engine than the storage cell or battery.[26] They have instead posited fuel cells as a hybrid of battery and heat engine,

[26] John O’M. Bockris and Z. Nagy, *Electrochemistry for Ecologists* (New York: Plenum Press, 1974), 64-65.

combining the best features of both in a sort of electrochemical engine that consumes fuel and produces electricity in a single irreversible electrochemical reaction.[27]

In fact, not only are fuel cells subject to similar sorts of chemical side reactions and deterioration over time that afflict batteries, they are, in essence, technological systems, miniature chemical plants requiring fuel storage and/or production systems. These subsystems are complex technologies in their own right. However, during the initial stage of postwar fuel cell research and development programs, researchers typically set them aside, concentrating instead on improving the power output of the fuel cell energy converter. This occurred for two reasons: fuel cells had to be made powerful before they could be considered practical; but it was also much easier to boost the power of fuel cells than to develop them as fully integrated miniature chemical plants. Consequently, advances in fuel storage and production technologies have historically trailed those in fuel cell energy converters.

In this sense, the history of fuel cell research and development provides an interesting contrast with the development of electrical grids as described by Thomas P. Hughes. He coined the term "reverse salient" as an analytical metaphor to account for the expansion of these technological systems, analogizing the process of innovation to a military front. While the front may generally advance, it does so asymmetrically. In certain places,

[27] For example, see A.D.S. Tantram, "Fuel Cells: Past, Present and Future," *Energy Policy* (March 1974): 56; John O'M., Bockris and Amulya K.N. Reddy, *Modern Electrochemistry 2B: Electrodics in Chemistry, Engineering, Biology and Environmental Science,* 2nd ed. (New York: Kluwer Academic/Plenum Publishers, 2000), 1811; Ballard Power Systems, Inc., *Annual Report* 1996 (1997), *Annual Report* 1997 (1998*), Annual Report* 1998 (1999), *Annual Report* 1999 (2000), *Annual Report* 2000 (2001), *Annual Report* 2001 (2002), *Annual Report* 2002 (2003).

pockets of resistance retard overall progress and are focused on by engineers accordingly. When these areas are mastered, the front may again advance.[28]

In contrast, the reductive focus of fuel cell researchers on reverse salients mainly within the fuel cell energy converter has tended to build expectations and attract a wide variety of sponsors while inhibiting the development of fuel cell systems. The resulting linear linkage between progress and funding typically broke down as researchers made fuel cells larger and more complex. Early experiments generally employed simple laboratory cells using pure hydrogen and oxygen. These reactants were expensive, but yielded high current densities. Increasing power output became the standard benchmark of progress and the chief political capital of researchers, attracting sponsors and investment. As researchers gained more experience with fuel cells, they made two important judgments about their nature, with important consequences for the future conduct of research and development. They learned that fuel cells had the same level of efficiency regardless of size, unlike conventional heat engines. Researchers came to believe that fuel cells could be used in a wide range of applications ranging from tens of watts to tens of millions of watts. The second judgment was more contentious. Successful demonstrations of fuel cells using hydrogen led researchers to expect similar progress on larger and more powerful fuel cells using cheaper but more chemically complex carbonaceous and hydrocarbon fuels. Together, these judgments gave rise to the notion of the fuel cell as a "universal energy converter" capable of employing a wide variety of hydrogenous fuels in a number of applications and working equally well in all. This is perhaps the key factor facilitating the process of alliance-building that Callon noted in the

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[28] Thomas P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, MD: Johns Hopkins University Press, 1983), 14.

French context, attracting a wide variety of sponsors including the battery, chemical, oil and auto industries, as well as gas and electric utilities and military organizations.

As researchers devised more complex testing regimes for more sophisticated fuel cells, however, they discovered that such technologies worked well in only certain contexts and applications. Making fuel cells durable and affordable, an expensive and time-consuming process known as "engineering research," involved a completely different non-linear political economy than early-stage research and development.[29] Engineering research involved long tests of scaled-up fuel cells in realistic operating conditions. Here, success was no longer gauged solely in terms of dramatic increases in power output but by slow incremental improvements in durability and cost-effectiveness. However, larger hydrogen fuel cells behaved quite unlike simpler equipment used in short-term tests, displaying adverse physico-chemical reactions over longer periods of time. The same could be said for hydrocarbon fuel cells, except that their performance and durability were inferior to hydrogen fuel cells. Matters became still more complex when fuel cells of all types were integrated with fuel production and/or storage systems and mated with appliances. This imposed stresses on the fuel cell energy converter that varied according to the demand for power, with further unpredictable consequences in terms of interactions between materials. Once the pace of breakthrough power demonstrations slowed as research communities struggled to make fuel cell systems cost-effective and durable, the result was typically a "crisis of expectation," in which government and industry sponsors scaled-back or withdrew their patronage.

[29] The term first appears in the literature in a report produced by Ernst M. Cohn, NASA's director of electrochemical system from the early 1960s to the mid-1970s; "Primary Hydrogen-Oxygen Fuel Cells For Space," 7, June 1967, Record Number 13761: Propulsion, Auxiliary Power: Fuel Cells, 1961-1999, Reports, Press Clippings, NASA Headquarters Archive, Washington, D.C.

The judgments research and development communities made of the similarity between laboratory and full-sized fuel cells and between hydrogen and hydrocarbon fuel cells were further conditioned by "technopolitics," the "strategic practice of designing or using technology to constitute, embody or enact political goals."[30] While British and American fuel cell researchers belonged to distinct technopolitical cultures with differing institutional priorities, they nevertheless shared similar assumptions and definitions of "research" and "development" and standards of what constituted a successful fuel cell.

## Postwar Fuel Cell Programs

The origins of the chain of expectations in post-Second World War fuel cell research and development can be traced to Francis Thomas Bacon, the English mechanical engineer widely acknowledged in the technical literature as the "father" of the first practical fuel cell.[31] Between 1932 and 1959, Bacon, supported by the Electrical Research Association from 1946-1956 and the National Research Development Corporation from 1956-1959, developed a device using a pressurized alkaline electrolyte. This allowed him to dispense with costly platinum as a catalyst, which is required by fuel cells employing acidic electrolytes, and use cheap nickel instead. The tradeoff was that while acidic cells had some tolerance for carbonaceous fuels, alkaline cells could only use costly pure hydrogen. Rejected by British industry, the "Bacon cell" sparked a wave

[30] Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II* (Cambridge, MA: The MIT Press, 1998), 15.

[31] See, for example, H.A. Liebhafsky and E.J. Cairns, *Fuel Cells and Fuel Batteries: A Guide to their Research and Development* (New York: John Wiley & Sons, 1968), 18; John O'M Bockris and S. Srinivasan, *Fuel Cells: Their Electrochemistry* (New York: McGraw-Hill, 1969), 26; Bernard J. Crowe, *Fuel Cells: A Survey* (Washington, D.C.: National Aeronautics and Space Administration, 1973), 8-9; A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook* (New York: Van Nostrand Reinhold, 1989), 10; Karl V. Kordesch and Günter Simader, *Fuel Cells and their Applications* (New York: VCH Publishers, 1996), 2, 58, Gerrit Jan Schaeffer, *Fuel Cells for the Future: A Contribution to Technology Forecasting From a Technology Dynamics Perspective* (PhD diss., University of Twente, 1998), 98-99; *Handbook of Fuel Cells: Fundamentals, Technology and Applications; Volume I: Fundamentals and Survey of Systems*, eds. Wolf Vielstich, Arnold Lamm and Hubert A. Gasteiger (Chichester, England: John Wiley and Sons, 2003), 168-169.

of interest in the United States in the late 1950s on the assumption that it could easily be converted to operate on carbonaceous fuels. Though this proved erroneous, the Bacon cell became an exemplar of fuel cell technology after the American aero-engine manufacturer Pratt & Whitney licensed the technology in 1959 and developed a version for NASA's Apollo moon spacecraft.

For planners in the Department of Defense, the use of hydrogen fuel cells such as the Bacon cell in aerospace applications suggested the feasibility of carbonaceous fuel cells in terrestrial roles.[32] In the 1960s, the Advanced Research Projects Agency (ARPA) played a key role defining and popularizing notions of the fuel cell as a universal energy converter. As part of "Project Lorraine," the Department of Defense's program of research on advanced terrestrial power source technologies, ARPA and Army planners created a requirement for a general-purpose, all-weather fuel cell capable of using the so-called "logistics fuels," chemically complex compounds including gasoline, diesel and jet fuel common in the military supply chain. Moreover, this power source was to be built on a strict timeline and on a limited budget.[33]

As in the British program, a gap emerged between expectations developed in relation to laboratory work and the actual needs of end-users. Because the logistics fuels were difficult to completely reduce to hydrogen in fuel cells, planners resorted to lighter substances such as cyclopropane, propane and methanol that were relatively tractable, hoping this would provide insight into the electro-oxidation of more chemically complex

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[32] One ARPA official justified this assumption by claiming terrestrial fuel cell systems were "less exotic" than their aerospace counterparts, though they had to be built more ruggedly; John H. Huth, "Program Plan for Electrochemistry: Program Plan No. 4," 1 February 1963, Box 2, AO 247-Monsanto Research Corporation (DA 36-039-SC-88945), 1.

[33] ARPA's spending on fuel cells totaled $14.5 million between Fiscal Years 1960-1964 out of budgets that ranged between $190-$280 million in the 1960s; Memorandum by John H. Huth, "Comments on IDA Report R-103 by R. Hamilton and G. Szego," 2 March 1964, Box 4, Project Lorraine-Energy Conversion, 2; Richard J. Barber Associates Inc., *The Advanced Research Project Agency, 1958-1974*, V-1, VI-1.

fuels.[34] In the meantime, developing light carbonaceous fuel cells allowed researchers to achieve "successes," raise funds and build expectations for commercial sales. Despite much promotion, the resulting fuel cell systems met neither commercial nor military requirements.[35]

Knowledge yielded in the reductive and controlled circumstances of Project Lorraine left industry and Army engineers ill-prepared to face the challenges of developing full-scale prototype hydrocarbon cells. The Army hoped to use such devices with portable radios and radars. As it tested fuel cells in these applications, problems arose that had not been anticipated during Project Lorraine. During the very earliest stages of basic and applied research, workers rarely considered how the electrical load demand of the appliance - the "duty cycle" - might affect the entire system. Different appliances had different duty cycles: radars drew relatively constant amounts of power while radios and vehicles called for it intermittently. Such irregular use, researchers found, imposed great demands on the control equipment necessary for responding quickly to electrical demand, adding fuel, removing waste and maintaining the chemical equilibrium within the fuel cell reactor required for long life. These interrelated systems were additionally stressed when carbonaceous and hydrocarbon fuels were introduced into them. Despite the

[34] J.P. Ruina to Chief, Research and Development, Department of the Army, 7 June 1961, Box 2, AO 247-General Electric; General Electric, "Saturated Hydrocarbon Fuel Cell Program (ERDL), Quarterly Letter Report Number 1, December 1, 1961-March 31, 1962," undated, Box 2, AO 247-General Electric, 2; Memorandum by Charles F. Yost, "Renewal of Program in Electrochemistry, ARPA Order 247, General Electric Company, Contract DA-44-009, ENG-4853,"13 August 1962, Box 2, AO 247-General Electric.

[35] For example, General Electric's hydrocarbon fuel cell, unveiled to some fanfare in April 1963, possessed some features attractive for civilian use and others suitable for military requirements, but as a system was unfit for any specific application, civilian or military. Too expensive for commercial use owing to its reliance on platinum catalyst, the device used propane and natural gas, fuels that, while cheap in comparison to hydrogen, were not attractive from the perspective of military logistics; "GE Fuel Cell Advances," *The Wall Street Journal*, 24 April 1963.

importance of control sensors, they were typically the last subsystem to be considered by fuel cell workers.[36]

All the tendencies in fuel cell research and development that played out over some three decades following the end of the Second World War were re-enacted in the socio-economic and political circumstances of the 1990s. This time, expectations coalesced around the fuel cell-powered electric automobile, long the lodestone in the dreams of fuel cell enthusiasts. In an era when clean energy had become an indispensable political consideration in the marketing of automotive technology, a fuel cell electric vehicle capable of combining environmental sustainability with the comfort and convenience consumers had come to expect from gasoline automobiles had considerable popular appeal. In such an automobile, the dream of the fuel cell as a universal energy converter was reborn once more, engaging the massive resources of the automobile industry and, subsequently, the federal government's energy research and development apparatus.

The historical disjunction between dreams of a universal energy converter and the physical limits of fuel cell technology seemed lost on the latest generation of researchers. As technologists struggled to miniaturize automotive carbonaceous fuel cells systems, the automobile industry and then the federal government looked to the hydrogen fuel cell.[37] By the turn of the millennium, the idea of a fuel cell-based hydrogen economy began to

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[36] Preliminary work had not prepared researchers for the challenges of scaling-up fuel control equipment. As one Union Carbide engineer observed, it was one thing to develop a fuel feeder that would operate well "on a relay rack in an air conditioned laboratory," something else again to build one that could withstand "salt-spray test, humidity-cycling test and…environmental extremes;" George E. Evans, "Hydrazine-Air Fuel Cell Controls," in *Proceedings: Twenty-Second Annual Power Sources Conference, 14-15-16 May 1968* (Red Bank NJ: PSC Publications Committee, 1968), 1.

[37] In 2000, Arthur D. Little and the National Research Council concluded that "off-board" fuel reforming might be preferable to automobile chemical plants; Richard K. Stobart, "Fuel Cell Power for Passenger Cars-What Barriers Remain? in *Fuel Cell Technology for Vehicles,* ed. Richard Stobart (Warrendale, PA: Society of Automotive Engineers, 2001), 14; National Research Council, *Review of the Research Program of the Partnership for a New Generation of Vehicles, Sixth Report* (Washington, D.C.: National Academy Press, 2000), 85-87.

gain currency in American popular science culture. In the words of one visionary pundit, such an energy order would "fundamentally reconfigure human relationships," displacing centralized hydrocarbon-based energy production systems and bringing the energy and environmental crises to an end.[38]

Paradoxically, as technical problems in fuel cell technology programs mounted and the automobile industry postponed indefinitely its 2004 target date for commercial introduction of the fuel cell vehicle, the expectations of political elites increased. In the early 2000s, they claimed that the fuel cell automobile was the ultimate solution for sustainable transport, facilitating the reduction of U.S. petroleum consumption, greenhouse gas emissions and dependency on foreign oil.[39] In this sense, the fuel cell-based hydrogen economy was framed as a technological energy utopia, a characteristically American cultural *leitmotif*.[40]

At first sight, the eagerness of the automobile and oil industries to pursue the fuel cell automobile appeared to run contrary to the belief among some analysts that new technologies represent a threat to established interests, causing a reaction that often blocks the spread of new devices.[41] However, political and industrial elites were prepared

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[38] Jeremy Rifkin, *The Hydrogen Economy: The Creation of the World-Wide Energy Web and the Redistribution of Power on Earth* (New York: Jeremy P. Tarcher/Penguin, 2002), 9.

[39] The administration of George W. Bush introduced FreedomCAR (2002) and the Hydrogen Fuel Initiative (2003) as an environmentally-sustainable means of facilitating the expansion of the U.S. light duty fleet while reducing petroleum consumption; U.S. Department of Energy, FreedomCAR and Fuel Partnership Plan, http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/fc_fuel_partnership_plan.pdf; George W. Bush, 28 January 2003, http://www.whitehouse.gov/news/releases/2003/01/20030128-19.html, accessed 22 February 2007; U.S. Department of Energy, *Basic Research Needs for the Hydrogen Economy: Report of the Basic Energy Sciences Workshop on Hydrogen Production, Storage and Use*, 13-15 May 2003, 11.

[40] George Basalla, "Some Persistent Energy Myths," in *Energy and Transport: Historical Perspectives on Policy Issues*, eds. George H. Daniels and Mark H. Rose (Beverly Hills, CA: Sage Publications, 1982), 27; Howard P. Segal, *Technological Utopianism in American Culture* (Chicago: University of Chicago Press, 1985), 1-22.

[41] See, for example, Nathan Rosenberg, "On Technological Expectations," in *Inside the Black Box: Technology and Economics* (New York: Oxford University Press, 1982), 104-119.

neither to launch the new industrial revolution that the commercial fuel cell automobile required nor moderate expectations to accord with the physical limitations of fuel cell technology and their own socio-economic and cultural credos. As such, the most recent fuel cell boom may be interpreted as the latest episode in what the historian of technology Langdon Winner has referred to as the long-standing tradition in the American polity of using technology as a substitute for politics.[42]

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[42] Langdon Winner, *Autonomous Technology: Technics Out-of-Control as a Theme in Political Thought* (Cambridge, MA: MIT Press, 1977), 237.