A Historical Perspective of Fuel Cell Technology in the 20th Century

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ABSTRACT

The development of fuel cells over the last century has been heavily influenced by external factors. Initially, fuel cells were seen as an attractive means for the generation of power because the efficiencies of other technologies were very poor. However, as the efficiency of these other technologies rapidly improved, the interest in fuel cells waned. Then, when the "space race" began in the late 1950s fuel cells were rapidly developed for deployment in space. More recently, significant technical progress in fuel cell technology has made fuel cells appear more viable than ever for a variety of applications. Additionally, concerns about energy resources and the environment have elevated interests in generating power with even higher efficiencies and lower emissions, and this has also raised the interest level in fuel cells. Although some interesting work was done on fuel cells during the first half of the 20th century, it appears that almost nothing was published on this subject in ECS publications during this period. This is not surprising, given that most of the early work on fuel cells was conducted in Europe and the Society was primarily an Ameri- can institution in the early days. In fact, the initial publication of the Society was known as the Transactions of The American Electrochemical Society until 1930 when the word "American" was dropped from the name of the organization to reflect the increasing global composition of the membership and the title was changed to transactions of the electrochemical society.

Keywords—Fuel cell

# INTRODUCTION

In honor of the 100th anniversary of The Electrochemical Society, a retrospective look at the development of fuel cell technology over the past 100 years is presented. The development of fuel cells can be traced back over 160 years to Sir William Grove’s invention in 1839. The history of these very early years have been described elsewhere.1-3 Additionally, comprehensive technical reviews of fuel cell technology are also available ~see, for example, Ref. 4 and 5!, as well as recent review articles on the latest developments.6,7 Therefore, this paper will emphasize the progress on fuel cells that has been presented in the Journal of The Electrochemical Society ~JES! and other ECS publications throughout the Society’s first 100 years. This historical review includes all the major types of fuel cells, which are named according to the electrolyte employed in the cells: the alkaline fuel cell ~AFC!, the polymer-electrolyte fuel cell ~PEFC!, the phosphoric-acid fuel cell ~PAFC!, the molten-carbonate fuel cell ~MCFC!, and the solid-oxide fuel cell ~SOFC!. We will review the significant advances that have occurred and how these developments have been influenced by external factors. Research groups that have made substantial contributions to these developments and the fuel cell literature in ECS publications will be given special emphasis. vehicles. Behavioral and non-financial preferences of individuals on different technologies and mobility options are also important (Lavieri et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib161), Li et al [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib170), McCollum et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib189), Ramea et al [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib250)). EV adoption beyond LDVs has been focused on buses, with significant adoption in several regions (especially China). Electric trucks also are receiving great attention, and Bloomberg New Energy Finance (BloombergNEF) projects that by 2025, alternative fuels will compete with, or outcompete, diesel in long-haul trucking applications (Moore and Bullard [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib199)). These recent successes are being driven by technological progress, especially in batteries and power electronics, greater availability of charging infrastructure, policy support driven by environmental benefits, and consumer acceptance. EV adoption is engendering a virtuous circle of technology improvements and cost reductions that is enabled and constrained by positive feedbacks arising from scale and learning by doing, research and development, charging-infrastructure coverage and utilization, and consumer experience and familiarity with EVs.

**Fuel Cell Development in the Last 100 Year**

The development of fuel cells over the last century has been heavily influenced by external factors. Initially, fuel cells were seen as an attractive means for the generation of power because the efficiencies of other technologies were very poor. However, as the efficiency of these other technologies rapidly improved, the interest in fuel cells waned. Then, when the ‘‘space race’’ began in the late 1950s fuel cells were rapidly developed for deployment in space. More recently, significant technical progress in fuel cell technology has made fuel cells appear more viable than ever for a variety of applications. Additionally, concerns about energy resources and the environment have elevated interests in generating power with even higher efficiencies and lower emissions, and this has also raised the interest level in fuel cells. Although some interesting work was done on fuel cells during the first half of the 20th century, it appears that almost nothing was published on this subject in ECS publications during this period. This is not surprising, given that most of the early work on fuel cells was conducted in Europe and the Society was primarily an American institution in the early days.8 In fact, the initial publication of the Society was known as the Transactions of The American Electrochemical Society until 1930 when the word ‘‘American’’ was dropped from the name of the organization to reflect the increasing global composition of the membership and the title was changed to Transactions of The Electrochemical Society.Electrochemical Society Active Member. z E-mail: Tom.Fuller@UTCFuelCells.com 1 UTC Fuel Cells, formerly known as International Fuel Cells ~IFC!, is a subsidiary of United Technologies Corporation ~UTC!

**Development of Large-Scale Electricity Generation and Distribution**

The large-scale distribution of electric power began at the end of the nineteenth century. Although Michael Faraday had discovered electromagnetic induction in 1831 ~i.e., the basic principle of a generator!, it took a number of other developments to establish largescale generation of electric power. But, by the mid-1870s electric arcs were illuminating the streets of many major cities in Europe and America. Initially, power transmission was limited to relatively short distances and power-generation stations were relatively small. However, with the development of an ac system, principally due to the contributions of George Westinghouse and Nikola Tesla, the era of large-scale power generation and transmission was born. And, in 1896, power generated by a pair of high-speed turbines at Niagra Falls was transmitted 26 miles to the city of Buffalo, NY. However, early electric power generators were very inefficient. For example, the coal-burning generation station built by Thomas Edison in 1882 in lower Manhattan converted only about 2.5% of the available energy into electricity. Even in the 1920s the overall thermodynamic efficiencies of reciprocating steam engines was approximately 13-14%, and steam turbines obtained just under 20%. These poor thermal efficiencies provided one of the major motivations for the pioneers of fuel cell development. In fact, in 1894, Ostwald10 pointed out the wastefulness of the steam engine and expressed the hope that the 20th century would become the ‘‘Age of Electrochemical Combustion.’’ This still visionary paper also emphasized the reduction of emissions with the elimination of the burning of fuels: ‘‘kein Rauch, kein Russ’’ ~no smoke,.

# Early Fuel Cell Development Efforts

Given that a major fuel at the turn of the century was coal, it is not surprising that much of the work on fuel cells at this time was focused on using this energy source. Both direct and indirect coal fuel cells were investigated. Ludwig Mond, who founded the International Nickel company and other chemical industries in England, had developed a process in which coal and coke were used to derive a gas containing a large proportion of hydrogen. With the assistance of Dr. Charles Langer,11 they pursued the dream of scaling-up Grove’s gas battery into something that would deliver useful power from converted fuels, whereas Grove had only considered ‘‘effecting the decomposition of water by means of its composition.’’12 Unfortunately, impurities in Mond’s industrial gas poisoned the fuel cell’s platinum-black catalyst and the high cost of the required loadings of this catalyst made this alternative power-generation technology cost prohibitive. ~Both of these problems continue to challenge fuel cell developers to this day.! Mond and Langer did make some interesting advances that significantly increased the power density of the fuel cell by greatly enhancing what Grove referred to as the ‘‘notable surface of action.’’ For example, they employed a porous matrix to contain their liquid electrolytes and they introduced the use of powdered electrocatalysts like platinum black. Other researchers pursued the direct coal fuel cell. W. W. Jacques built relatively large carbon/air batteries capable of delivering up to 1.5 kW in 1896. Unfortunately, the lifetime of these cells was limited because they employed molten alkali elec.

The Sputnik launches in 1957 and the ensuing ‘‘space race’’ that followed was undoubtedly one of the most significant historical events to influence the development of fuel cells. The requirements for space applications, namely a lightweight and very high efficiency power plant ~to reduce the amount of fuel and oxidant required!, are uniquely met by fuel cells, especially given that cost is not an overriding factor. This new application spurred the development of both AFC and PEFC power plants. It is interesting to note that the very first fuel cell used in a practical application was a PEFC, which is the same fuel cell type that is currently the focus of many of the major development programs attempting to develop fuel cells for terrestrial applications. The PEFC was invented at General Electric ~GE! in 1955 by William Grubb,15,16 who was looking for new applications for ionexchange membranes ~See Fig. 1!. 17 These early PEFCs utilized hydrocarbon-based polymers that have limited lifetimes in a fuel cell environment. The polymer-electrolyte membranes were composed of polystyrene-divinylbenzene sulfonic acid cross-linked with an inert fluorocarbon film. The life-limiting factor of these cells was the oxidative degradation of the Cu bonds in the membrane, particularly the a-H sites where the functional groups are attached. Despite this limitation, GE developed this technology into the power plant that was successfully deployed in the U.S. Gemini program beginning in 1962. Another drawback of these early PEFC cells were the high loadings of platinum catalysts required. The AFC, operating at elevated temperature and pressure, required less expensive catalysts. Three 28 V power plants provided all the onboard electrical power to the Apollo Command and Service Modules, Fig. 2. The AFC developed by Pratt and Whitney for the Apollo program operated at a higher temperature ~260°C!, higher KOH concentration (;85%), and lower pressure ~near atmospheric! than the Bacon cell. The anodes and cathodes were still porous Ni and lithiated NiO, respectively, but improvements in their structure provided comparable performance at lower operating pressures.1 On the other hand, the electrodes used in the Orbiter AFC, which are still in use on the Space Shuttle missions, contain noble metals ~Pt/Pd anodes and Pt/Au cathodes! that are bonded with PTFE to Ag-plated Ni screens. The PTFE ~which was not available when the Apollo electrodes were developed! is used to form a more stable three-phase interface ~electrode/electrolyte/gas! than could be obtained in previous electrodes. Commercialization of Fuel Cells Unlike some other so-called ‘‘spin-off’’ technologies ~i.e., technology developed for space applications that subsequently become the basis of commercial products!, fuel cells are not yet a major commercial success. In fact, the only commercially available fuel cell power plant, UTC Fuel Cells’ ‘‘PC-25,’’ is based on a different technology ~PAFC! than the AFC-based power plants UTC makes for NASA. So, why are fuel cells still considered a relatively exotic technology? Fundamentally, there are no insurmountable technical obstacles that prevent fuel cells from enjoying commercial success. And, the inherent advantages of fuel cells ~e.g., high efficiencies and low emissions! relative to other electricity generation methods makes them quite attractive. The main obstacle has undoubtedly been the cost of this technology. Additionally, the requirement of operating on re

# Fuel Cells in Space

Similarly, ride-hailing—matching drivers with passengers at short notice for one-off rides through a smartphone application, which date back to Uber's introducing the concept in 2009—is an attractive alternative to traditional transportation solutions. These mobility-as-a-service solutions cater to the consumer's need for quick, convenient, and cost-effective transportation and may lead to drops in car-ownership and driver-licensure rates (Garikapati et al [2016](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib91), Clewlow and Mishra [2017](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib45), Movmi [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib205), Walmsley [2018](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib305), Henao and Marshall [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib123), Arevalo [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib15)). After just over 10 years, ride-hailing is widely available and extremely successful, with hundreds of millions of consumers worldwide and 36% of U.S. consumers having used ride-hailing services (Mazareanu [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib187)). While most ride-hailing vehicles today are ICEVs (in line with the existing LDV stock), many ride-hailing companies are exploring electrification opportunities (Slowik et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib272)). EVs offer a number of potential advantages as high vehicle usage promotes a more favorable business model for recovering the higher EV purchase price by leveraging cheaper fuel costs (Borlaug et al [2020](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib24)). At the same time, long-range vehicles and effective charging solutions are required for ride-hailing companies to transition to EVs (Tu et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib295)). Moreover, EVs can mitigate additional fuel use and emissions related to increased travel, mostly due to deadheading, which is estimated to be ∼85% (Henao and Marshall [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib123)). EVs also provide access to restricted areas in some cities (driving some regional goals for ride-hailing electrification). For example, Uber aims for half of its London fleet to be electric by 2021 and 100% electric by 2025 (Slowik et al [2019](https://iopscience.iop.org/article/10.1088/2516-1083/abe0ad/meta#prgeabe0adbib272)).makes terrestrial applications somewhat more challenging and complex than the systems used in space. Fortunately, a lot of technical progress has been made that help address these issues and should enable fuel cells to enjoy widespread use in the near future.18 Additionally, market forces are making the attributes of fuel cells look more attractive. For example, distributed power generation is expected to begin supplanting large centralized power stations due to a variety of factors ~e.g., increased power demand, the need for high quality power, deregulation of the power industry, less susceptibility to terrorist attack, and environmental concerns!. The automotive industry is also looking to obtain substantially higher efficiencies and lower emissions than can be obtained by internal combustion engines. Fuel cells have been identified as one of the most promising technologies that can deliver these desirable attributes, and almost all the major automakers have recently made substantial investments into fuel cell development. Fuel Cells and ECS Much of the recent progress in fuel cell technology has been documented in the Journal and other ECS publications. Therefore, the remainder of this article will focus on some of the major advancements that have been presented in ECS publications, with an emphasis on particular groups of researchers who have made substantial contributions to the fuel cell literature. ~For more exhaustive reviews of fuel cell technology the reader is referred to the references given in the introduction of this paper.! Figure 3 shows the number of paper published in the journal which contain the phrase ‘‘fuel cell’’ in the title. There are undoubtedly many more papers of direct relevance to fuel cells, however, so this data are not precise. They do, however, give us a qualitative picture of the activity in fuel cells in the Society.

**IV. Fuel Cells and ECS**

There is a similar increase in activity in the symposia and proceedings volumes with ‘‘fuel cells’’ in the title. The majority of these symposia have been sponsored by the Battery Division, but many other divisions have Future Directions More work is being done on fuel cell development than ever before. Multiple companies around the world are focused on the commercialization of fuel cells for stationary power, and almost all of the major automotive companies have either internal fuel cell development programs and/or they are working closely with other companies to develop power plants for transportation applications. The widespread commercialization of stationary fuel cell power plants appears inevitable, with the only major technological barriers remaining being cost and proven lifetimes. However, because PAFC power plants with suitable lifetimes (;40,000 h) for stationary applications have already been developed, it appears reasonable to expect that the lifetime requirements will be met by fuel cells that operate at even lower temperatures ~e.g., PEFC!. In regard to cost, a major advantage of PEFC is that all the repeat parts ~e.g., MEAs and bipolar plates! can be manufactured by high-volume processes that are already being demonstrated by multiple companies. Undoubtedly, improving the lifetime and cost of fuel cells will be a major focus for many years to come given that continuous improvement in these two critical areas will increase the number of applications where fuel cells are competitive with other power-generation technologies. The cost targets for automotive applications are roughly an order-of-magnitude more demanding than those for stationary applications. This, and other technical challenges, will inevitably delay the widespread introduction of fuel cell powered automobiles. However, demonstration vehicles have already been introduced and many more are in development ~Fig. 9!. The resources being dedicated to these efforts are impressive and will undoubtedly accelerate the commercialization of fuel cells in both stationary and transportation sectors. Another issue that must be resolved before fuel cells find widespread acceptance in transportation applications is the availability of a suitable fuel infrastructure. Hydrogen would be the fuel of choice, but the volume and weight of the various hydrogenstorage technologies still do not compare favorably with liquid fuels. Therefore, efforts to develop fuel cell vehicles that operate on gasoline, methanol, or other fuels are ongoing. Because of the fuel infrastructure issue, fleet vehicles that operate on hydrogen and refuel at a central station will be introduced first. In particular, buses are an attractive application for fuel cells because the cost, volume, and range requirements are not typically as challenging as those for the automotive targets.

**V. General Fuel Cell Topics**

The development of new materials will continue to have a major influence on the development of fuel cells. Just as the introduction of PTFE enabled new GDEs for aqueous-electrolyte fuel cells and the availability of ion-exchange membranes resulted in the creation of PEFCs, the introduction of new materials will enable both improved designs and new types of fuel cells. Currently, an active area of research is the search for new polymer-electrolyte membranes. Ideally, these membranes will possess high ionic conductivity without the presence of liquid water, which will enable them to operate at higher temperatures, resulting in simpler PEFC systems due to improved heat rejection and CO tolerance. At the other end of the temperature spectrum, the development of solid oxide conductors that have suitable conductivity at lower temperatures would be desirable because this might allow alternative sealing materials to be employed in SOFCs and should help mitigate material degradation issues. Other examples of new materials that would aid in the commercialization of fuel cells are advanced electrocatalysts ~e.g., with higher activity, and/or lower cost, and/or improved stability!, lowcost composites with excellent stability and electrical conductivity that could be used to construct bipolar plates, and robust sealing materials ~especially for high-temperature fuel cells!. Finally, the development of advanced hydrogen-storage materials would greatly aid in the introduction of hydrogen-powered vehicles. Another need that is clearly evident to those of us who are working towards the commercialization of fuel cells is a workforce of engineers that have a good understanding of electrochemistry and the design of electrochemical systems. Currently, there are very few engineering programs that offer courses in these subjects, especially at an undergraduate level. However, the development, design, and manufacture of a complete fuel cell power plant involves a lot of engineering work that requires at least a working knowledge of electrochemical principles. Universities that recognize this need and provide quality programs in electrochemical engineering, at both the undergraduate and graduate level, will produce graduates who are in high demand as electrochemistry-based industries, including fuel cells, continue to grow. For example, many chemical engineering departments now offer the opportunity for undergraduates to emphasize a particular area by taking several optional courses in that field ~e.g., biochemical engineering!; a similar program in electrochemical engineering would also appear to be well justified and potentially very beneficial for both industry and the new graduates. Although one cannot project the future of fuel cells over the next hundred years, it can be stated with some certainty that The Electrochemical Society will continue to play a prominent role in the development of fuel cells. Society members will undoubtedly continue to lead research in fuel cell technologies as well as train others in the field. And the meetings and publications sponsored by the Society will continue to be an important forum for the discussion of these developments. Hopefully, when the 200th anniversary of the Society arrives fuel cells will be as ubiquitous as the internal combustion engine is toda

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