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Grove Medal acceptance address

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In accepting the Grove Medal, I decided to describe some of my personal experiences and those of my company, with a brief summary of fuel cell development over the past four decades and a glimpse of the future.

Exactly 40 years ago this month (September 99), I entered the laboratory for electrochemistry at the University of Amsterdam and was introduced to the concept of the fuel cell. There, under the supervision of Professor Ketalaar and Broers, I studied the carbonate fuel cell and the course of my future was determined.

I am a chemical engineer, someone the Dutch described, who, when in the presence of engineers, talks about chemistry and in the presence of chemists talks about engineering. Today, I will talk about both.

After leaving Holland, a place for which I have the greatest affection, and where our first son was born, my wife and I went to California.

There, working in the Aerospace industry, at the dawn of the space age, I had the good fortune to be able to experiment with a great variety of fuel cell systems employing a broad range of fuels and oxidants. Even today, most fuel cellers would be surprised at the power that can be derived from a hydrazine–nitrogen tetroxide alkaline fuel cell. Lifespan, both of the fuel cell and its operators, is another question.

Coming down to earth, I spent the next 8 years at the Institute of Gas Technology where the emphasis, as in Holland, was on the carbonate fuel cell using natural gas as fuel.

In general, the decade of the sixties was a period of great activity for fuel cells. PEM and alkaline fuel cells based on Mr. Bacon's technology were used for manned space travel and 60 US companies and many in Europe were engaged in R&D. Oil companies everywhere sought a magic fuel cell fuel and the first large commercial initiative — TARGET — was initiated in 1967 to place a fuel cell in every home — a 9-year project which was a technical success but not economically feasible.

In 1970, I started Energy Research, together with some colleagues. Initially, our focus was on low-temperature fuel cells and zinc batteries. This year, we spun off our battery business and changed the name of Energy Research, effective this month, to FuelCell Energy, to emphasize our focus on the commercialization of our Direct Fuel Cell.

In the first decade of the company, we developed small 30–60 W alkaline fuel cells and small methanol-fuelled phosphoric acid fuel cell power plants. In the early eighties, these PAFC units matured rather successfully into a family of 3- and 5-kW power plants producing either AC or DC electricity whose goal was to replace noisy engine generators for the US Army (Fig. 1). At the onset of a first production contract, I remember very well a visit from the new Army colonel from the Logistics Command. He had two goals — to become a general and make the Army dependent only on a single fuel. He was very impressed with the quiet operation of the power plant. He told me, ''Dr. Baker, I like this machine but have one very small request, I need it to operate with diesel fuel''. One year and a million dollars later, our lean mean portable methanol machine added a few hundred pounds of balance of plant, our wolf became an elephant and the Army lost interest. We learned two very valuable lessons — a fuel cell power plant must be able to use a readily available fuel and the balance of plant can kill you, i.e., keep it simple.

Outside the company, the seventies saw many US and European companies drop out of fuel cell activities. Those that remained focused on the PAFC, MCFC and solid oxide fuel cells at various levels of intensity.

Still, at the beginning of the eighties, our basic PAFC fuel cell stack technology was there and our air-cooled system required less balance of plant than others, so we teamed with the Westinghouse to develop megawatt class

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Fig. 1. 5-kW PAFC power plant and FCE Fort BeVoir (Army) engineers.

utility power plants that would operate with natural gas fuel.

In-house, we began the basic research work on the Direct Fuel Cell, based on the carbonate fuel cell, a first love.

After several years, both Westinghouse and ourselves mutually concluded that the low-temperature PAFC system would not be cost competitive even in large sizes and we terminated our joint efforts. We became friendly competitors in the greener pastures of the higher-temperature fuel cells.

Somewhat sobered by both the military and commercial PAFC experience we knew the key to success had to lead down the path of power plant simplification and the elimination of as much balance of plant as possible.

Our basic research showed that it was possible to operate by directly feeding natural gas to the carbonate fuel cell without first converting it to hydrogen in an

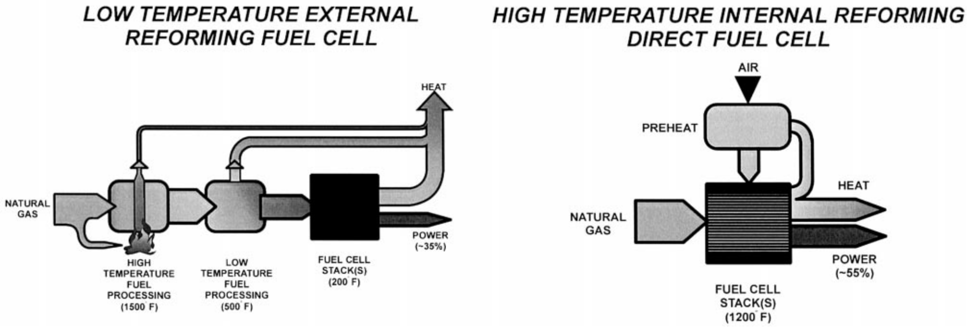

Fig. 2. Comparison of low- and high-temperature fuel cells.

external fuel processor. We knew, of course, that thermodynamics was on our side since the electrochemical oxidation of methane would be a zero entropy change reaction. Like 21 in blackjack, zero entropy is as good as it gets (Fig. 2).

Kinetics were less certain since we would be processing the methane at about 600°C, or about 200°C lower than conventional steam reforming usually takes place. Serendipity helped. The electrochemical and chemical reactions in the anode of a carbonate fuel cell operate in a complementary fashion. Firstly, the endothermic reforming reaction consumes steam and produces hydrogen while the exothermic electrochemical reaction consumes hydrogen and produces steam. The current produced by the fuel cell essentially drives the non-equilibrium reforming and complete conversion of natural gas is achieved at a relatively low temperature.

An added bonus is the partial cooling of the fuel cell by the endothermic internal reforming reaction, reducing the amount of coolant and parasitic power required.

The eighties saw a pick-up of activity especially in Japan. Most of the major efforts, both in the US and Japan, were directed at the PAFC for stationary power application in sizes from 200 kW to megawatts. Economics remain elusive and perhaps the single greatest lesson learned was to avoid complex pressurized systems.

Now, it was the nineties, the next step for us was the scale-up of stacks and full power plant integration. Ongoing support from the Department of Energy made this possible. The first demonstration outside our facilities took place at utility grid-connected sites in Denmark and California, respectively. Beginning at the 8-kW level, at Elkraft in Denmark, in 1989, we moved rapidly to 20- and 70-kW power plants at a Pacific Gas and Electric site in California in 1990 and 1991 (Fig. 3). Meanwhile, back at our facilities, we were operating 125-kW 250-cell stacks. The latter became the building blocks for our 2-MW class power plants in Santa Clara, CA (Fig. 4). This plant was designed in 1994, built in 1995 and operation began in 1996 and ended 1 year later as required in 1997. The balance of

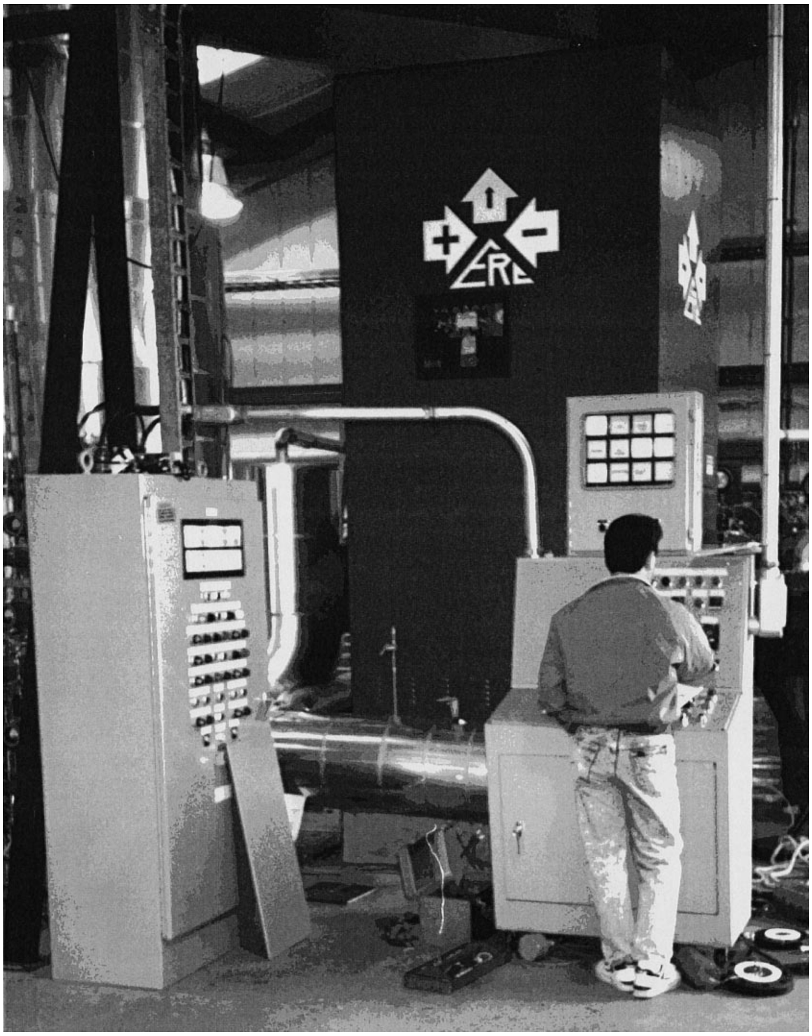

Fig. 3. 70-kW DFC™ power plant at PG&E site in California in 1991.

Fig. 4. Four-stack 500-kW DFC™ module under construction at FCE.

plant, consisted of water treatment, two heat exchangers, a steam generator, natural gas cleanup equipment, automatic controls and a DC–AC inverter rated at 13 000 V output (Fig. 5). The fuel cells consisted of four 500-kW modules. Each module consisted of four 125-kW stacks made with 250 six-square-foot cells. Fuel and air distribution to the 4000 cells was perfect. Its operation has been described in various technical presentations in the US, Europe and Japan (Fig. 6). The plant, the largest fuel cell plant of any kind, operated in North America and the largest advanced fuel cell power plant in the world, set records for environmental quality, efficiency, power quality, etc. and received awards from the Electric Power Research Institute and the American Public Power Association. Sponsorship of the project came from DOE and EPRI, both long-term sponsors, the company and six utility companies led by the City of Santa Clara Municipal Utility. Meanwhile, at the company, we have focused on automating our manufacturing and further increasing our basic stack size while improving quality control (Fig. 7). Our new stacks produce twice the power of the Santa Clara stacks at half the weight, and are the basic building blocks for our megawatt-size power plants and our partner's, MTU, 250-kW cogeneration plant (Figs. 8 and 9). The latter has leapfrogged our own design to further reduce the balance of plant by incorporating fuel and air recycle systems within the fuel cell module vessel. In Japan, Mitsubishi Electric, a development partner, is now testing their own 200-kW power plant.

After extensive testing of pre-commercial and commercial modules in 1998 and 1999, we are moving aggressively to commercialize this Direct Fuel Cell™ power plant (Fig. 10). We intend to expand our production facility to about 50 MW/year by 2001 and continue our focus

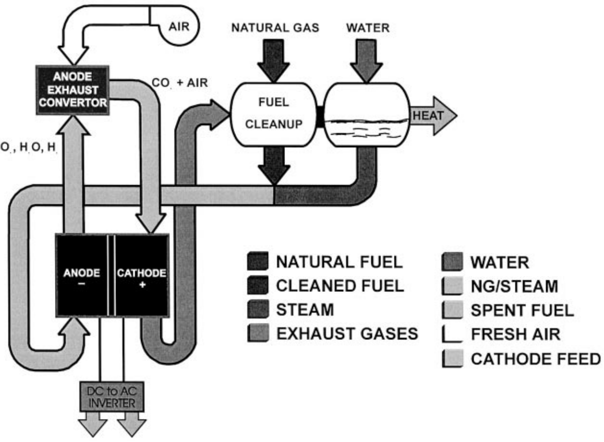

Fig. 5. Schematic Santa Clara, CA 2-MW DFC™ power plant.

Fig. 6. Direct Fuel Cell™ power plant demonstration at Santa Clara, CA.

on cost reduction. It is our belief that the world market for stationary fuel cell power plants is very large. Our megawatt-class power plants are now about one-tenth the size of the Santa Clara power plant. The ability to operate on a broad range of ubiquitous fuels ranging from natural gas to coal gas to biomass waste with relatively simple

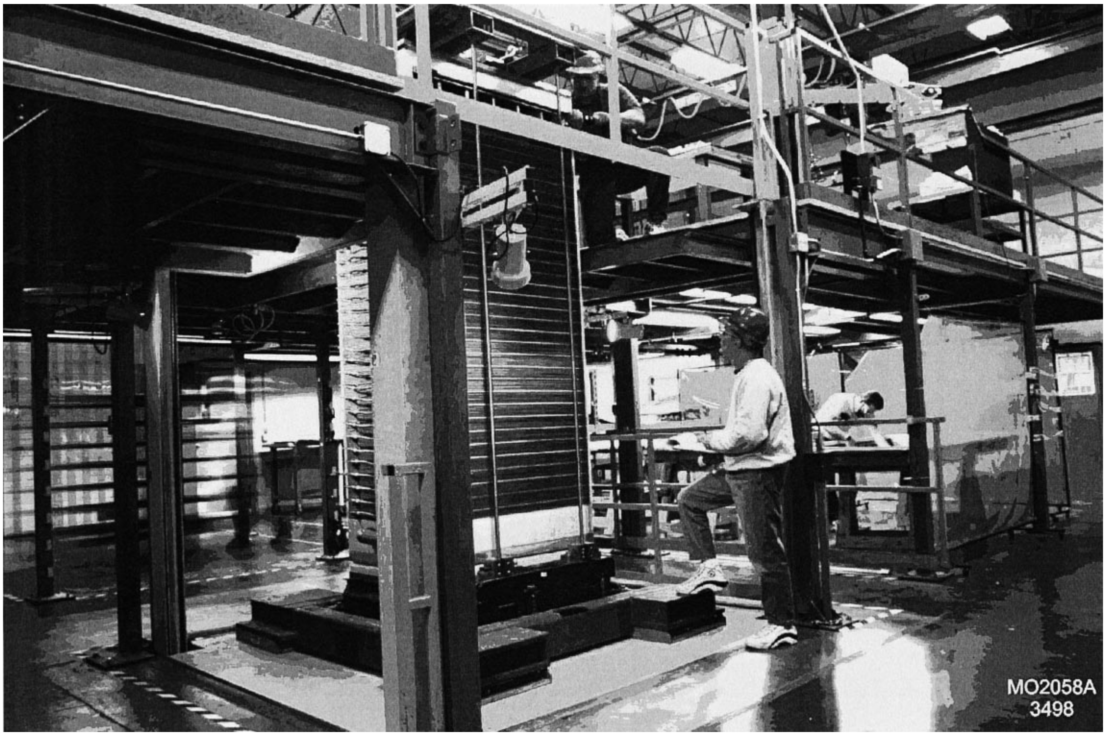

Fig. 7. Fuel cell stack assembly at the FCE manufacturing facility.

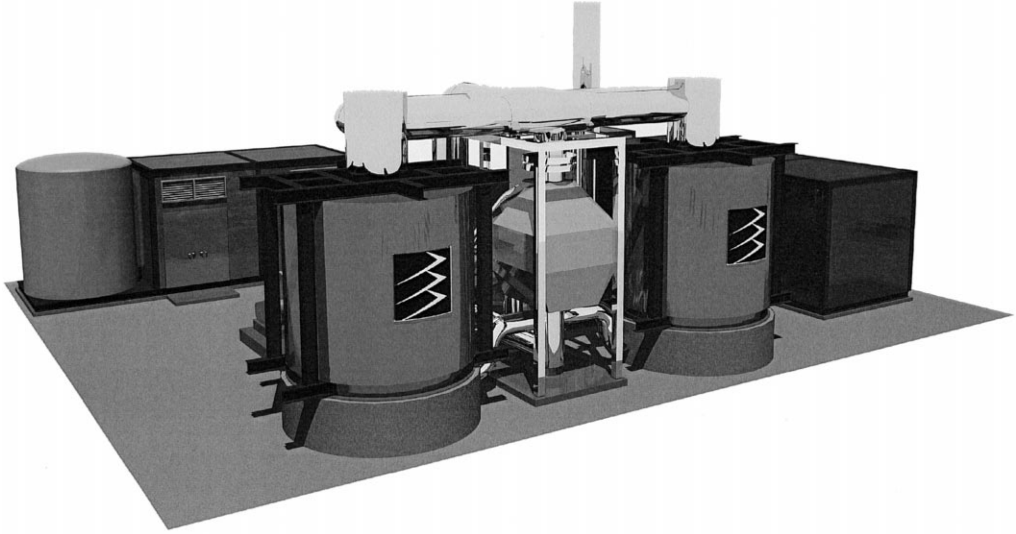

Fig. 8. 3-MW electric/cogeneration power plant.

balance of plant is a great advantage. We also believe that the cost per kilowatt of balance of plant drops rapidly with increasing plant size. Efficiency of 55% for single-cycle Direct Fuel Cell power plants are readily achievable. Combined-cycle Direct Fuel Cell power plants can achieve 70% (Fig. 11). This combination of characteristics are unique to high-temperature systems. The ability to achieve high efficiency is the discriminating factor in determining the lifecycle cost of electricity and establishes the allowable capital cost for the power plants (Fig. 12).

The nineties reflect rather substantial development efforts in the US, Japan and Germany on high-temperature fuel cell power plants. Also, there has been a resurrection of a greatly improved PEM fuel cell stack, which shares a balance of plant somewhat similar to the phosphoric acid system and is nearing the final stage of development.

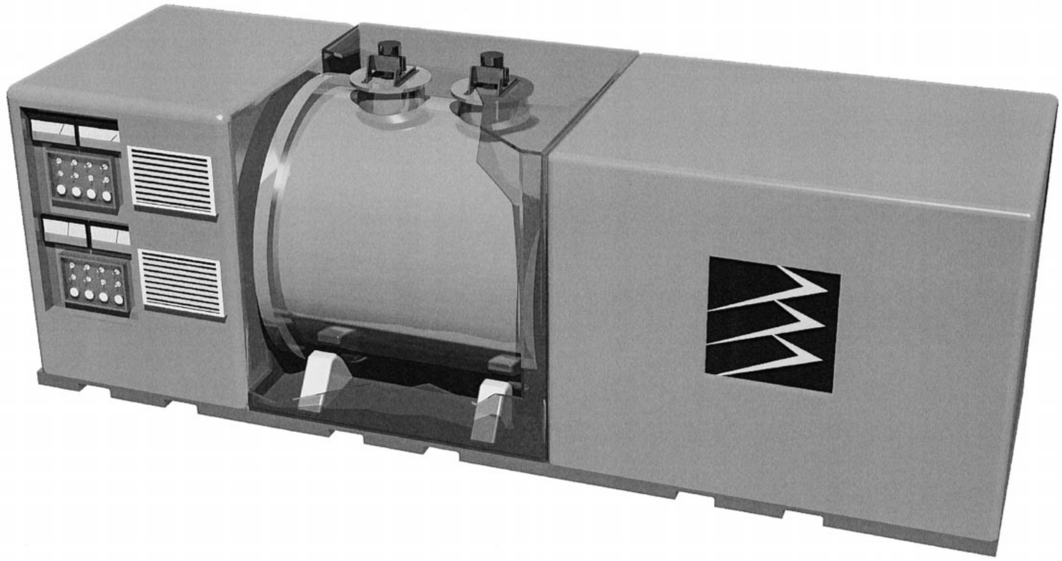

Fig. 9. MTU 250-kW class power plant.

Fig. 10. Direct Fuel Cell™ powering FCE (March 1999).

In summary, the 19th century saw the birth of the fuel cell right here in Great Britain. In the first half of the 20th century, Mr. Bacon nurtured the fuel cell, again, here in England. The second half of the century saw the rest of the world get on board and an explosion in fuel cell development began. I believe in the first decade of the 21st century, we will see the widespread commercialization of the efficient and environmentally benign fuel cell.

Again, I want to thank the Grove committee for selecting me for this prestigious award.

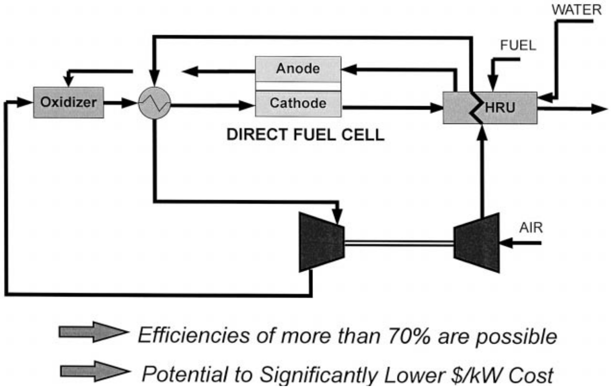

Fig. 11. High efficiency hybrid DFC™/turbine power plant.

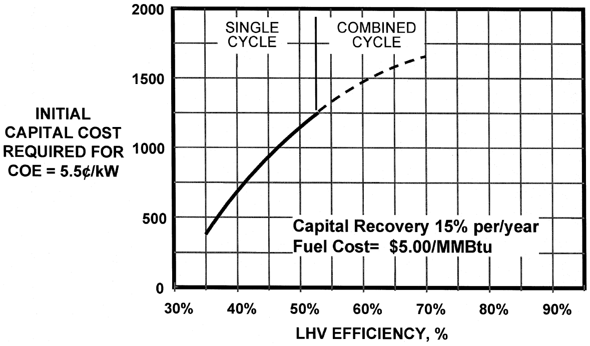

Fig. 12. Fuel cell capital cost vs. efficiency.