A promising power source for the future

The CSIRO has signed a $30 million research contract with Australian business and energy authorities to develop an advanced ceramic fuel cell for electricity generation. If successful, the technology will dramatically cut noxious emissions from the power plants of the future and could lead to the development of a new manufacturing industry in Australia.

Ceramic fuel cells can run on natural gas, coal gas or hydrogen, and convert the chemical energy in the fuel directly into electricity. Unlike conventional power plants, they don't first have to burn the fuel to create heat; instead, it combines electro-chemically with oxygen ions to form water, electrical energy and, when natural or coal gas is used, carbon dioxide.

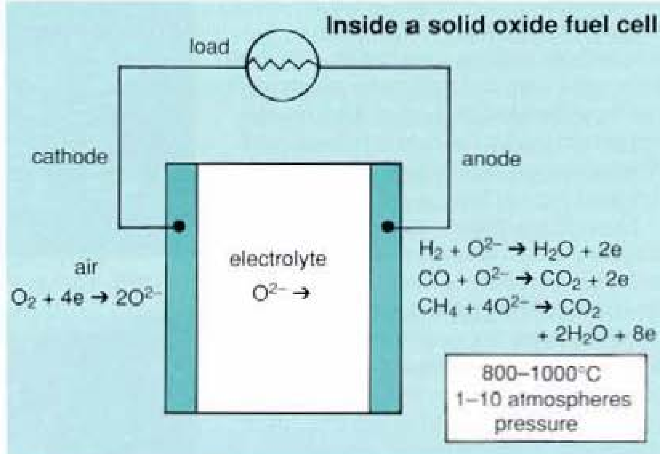
Researchers at CSIRO's Division of Materials Science and Technology believe an advanced-design solid oxide fuel cell (SOFC) can be built to generate electricity at a competitive price for use initially in commercial and remote-area power generation, and later in heavy industry and central station generation. A conservative economic analysis by a consultancy firm, McLennan Magasanik Associates, values the potential market value of SOFC technology in South-East Asia alone at nearly $13 billion. The export value of an Australian development is estimated to be several hundred million dollars a year.

An all-Australian-owned company, Ceramic Fuel Cells Ltd, has been established to commercially develop the technology. The initial shareholders are CSIRO (with about one-third ownership), BHP, Pacific Power Corporation (formerly the Electricity Commission of New South Wales), the Victorian government's Strategic Research Foundation and the Energy Research and Development Corporation. The Melbourne-based company plans to spend $6 million a year for the first 5 years and employ 25–30 scientists and engineers, about half of them CSIRO staff. As the company's prime contractor, CSIRO will contribute $2 million a year in salaries and equipment.

Fuel cells have been in use for years (the scientific principle was demonstrated last century), but their high cost has limited their applications mainly to space and satellite equipment and military hardware. In recent times, however, greater concern about pollution and energy conservation has heightened interest in them as an alternative source of clean energy for civil applications.

The most-developed type is the phosphoric acid fuel cell. It is built like a battery, with platinum-impregnated graphite electrodes and hot phosphoric acid as electrolyte or ionic conductor. The fuel, purified hydrogen gas, is oxidised at the positive electrode or anode into hydrogen ions. These migrate through the acidic electrolyte and react with oxygen at the negative electrode or cathode to produce water and excess electrons, creating an electric current. Unlike a battery, however, the cell does not run down, provided it is continuously fed with hydrogen and oxygen. The essential feature of this cell (and of all fuel cells) is the ionic conductor, which allows the oxygen to react with the fuel without the two substances coming in direct contact with each other (if they did, the cell would probably explode).

The advantage over a thermal power generator such as a coal, oil or gas burner is two-fold. Fuel cells are much cleaner, producing significantly less nitrogen oxides and — when they use methane and other carbon fuels — less carbon dioxide per unit of energy generated. They are also potentially much more efficient.



Oxygen ions react with the fuel at the anode, producing carbon dioxide, water and energy.

The theoretical efficiency of the thermal conversion process is limited by Carnot's principle, which states that the efficiency of an engine depends on the difference between the initial temperature of the system and its final working temperature. In practice, the loss of energy through waste heat and friction lowers the efficiency of the thermal plant; much of the energy in a coal-fired power plant, for example, is used to heat water to make steam that in turn drives a turbine, resulting in an efficiency rating of below 35%.

Fuel cells are not restricted by Carnot, and potential system efficiency ratings are as high as 80%. However, for a phosphoric acid cell the electrical efficiency is typically only 40%, better than a coal-fired plant but still below that of an advanced natural-gas plant (up to 50% efficiency).

Commercial cells

Phosphoric acid fuel cells are produced overseas for commercial use by several major manufacturers, including Westinghouse, IFC/United Technologies and Fuji Electric. Most units are small, usually in the 40- to 200-kilowatt range for use in office blocks, hospitals, supermarkets, mining operations and military bases. The biggest yet is an 11-megawatt cell recently installed in Tokyo Bay. The cells have a number of serious disadvantages, however, including high cost, a limited life and the inability to run on fuels such as natural gas or gasified coal without prior conversion to high-purity hydrogen.

A 'second-generation' type still largely at the developmental stage is the molten carbonate fuel cell. Operating at a temperature of about 650°C, its electrolyte is a mixture of molten alkali carbonates, usually of lithium and potassium, while the electrodes are made from nickel and nickel oxide 'doped' or laced with lithium. Carbon dioxide and oxygen are consumed at the cathode to make carbonate ions; these migrate through the electrolyte to oxidise the fuel at the anode, forming carbon dioxide (which is recycled), water and excess electrons. The cell has an efficiency of 50 to 55%, but the extremely corrosive nature of the liquid electrolyte gives rise to problems associated with preventing leakage or corrosion of the electrodes.

The 'third-generation' fuel cells, the solid oxide cells, are based on the rare compound zirconia or zirconium oxide

(ZrO_2) and, at this stage, are at an early stage of development. The CSIRO researchers believe these cells, although unproved commercially, are potentially the most flexible and offer the greatest opportunities in the marketplace. And Australia supplies 70% of the world's demand for zircon.

The cell is almost entirely ceramic. Its electrolyte — a solid made from zirconia and yttrium oxide — is an excellent ionic conductor. The yttrium atom readily substitutes for the similarly-sized zirconium in the cubic crystal structure of zirconia. However, each pair of yttrium oxide molecules has one fewer oxygen atoms than each pair of zirconia molecules, thereby creating a vacancy for an oxygen ion. These vacancies make it possible for oxygen ions to pass through the otherwise impermeable electrolyte.

A cermet (a mixture of ceramic and sintered metal) made from nickel and zirconia forms the anode, while the cathode is an alloy of the rare earth element, lanthanum, mixed with manganese oxide. Oxygen from the air is reduced at the cathode into oxygen ions, which migrate through the electrolyte to react with the fuel at the anode, producing carbon dioxide, water and energy.

A model solid oxide fuel cell stack.

An early working prototype in the CSIRO laboratories.

Operating at about 1000°C, the solid oxide cell consumes a wide range of fuels and has a high electrical efficiency — about 55 to 60% (and heat-recovery equipment could lift the total efficiency of a power plant to 80%). It has an exceptionally high power density; a power plant smaller than an office desk could produce more than a megawatt of electricity. However it does require a 20- to 30-minute warm-up period, making the technology unsuitable for light vehicles such as private cars, although possibly applicable in trains, ships and aircraft. Scientists expect the cell to have a long operating life due to the robust ceramic materials in it. But its main attraction is the potential for low emissions of pollutants.

The emissions from natural gas turbines (considered the cleanest of the conventional fossil-fuel technologies) contain nitrogen oxides at a concentration of between 10 and 100 parts per million. The solid oxide fuel cell should lower that level to between 1 and 5 parts per million. Carbon dioxide emissions will also be lower, by a factor of 2 to 4, and sulfur emissions almost negligible. The potential gains in pollution abatement are considerable: in Melbourne, for example, industry (including power generation) emits more than 10 000 tonnes of nitrogen oxide a year, exacerbating the city's photochemical smog problem.

The challenge

Research into SOFC technology is under way in several countries, notably the United States, Japan and Germany. The challenge is to design and build a competitively priced fuel cell. An existing small-scale design (25-kW) being tested in the United States at the moment costs well in excess of $US5000 per kilowatt. By comparison, advanced coal-fired power stations have a capital cost of between $US1200 and $1600 per kilowatt.

Dr Sukhvinder Badwal, the project leader of the SOFC group at CSIRO's Division of Materials Science and Technology, says Australian scientists have world-class expertise in the key research areas of structural ceramics, solid-state electro-chemistry and oxidation catalysis. In particular, they lead the world in zirconia technology and fabrication — thanks largely to the development of partially stabilised zirconia as a substitute for metal components in industrial and automotive equipment.

Ceramic Fuel Cells Ltd, he says, has three main research and development goals: to fabricate a single fuel cell based on zirconia wafers 100 sq. cm in area and about 200 microns thick; to join together two cells with a leak-proof seal; and to build a working stack of fuel cells. The CSIRO team has already conducted laboratory tests on a small tubular fuel cell made from zirconia and a flat cell using a zirconia wafer about 2 sq. cm in area.

A single cell may produce only 3–4 W of power, so the researchers need to develop methods of stacking cells in series, to make — within 3 years, Dr Badwal estimates — a 100-W power plant. Within 5 years, they hope to build a 1- to 5-kW stack. 'If we get that far, then we'll need to start looking at production and for that we'll need hundreds of millions of dollars,' he said.

Dr Badwal explained that CSIRO, if it desired, could have licensed its SOFC technology to overseas manufacturers, but little would have been gained. 'Our ultimate aim is to set up an Australian company manufacturing fuel cells or at least some of the components of fuel cells.'

Fuel cells have an enormous potential world market. Applications range from 1- to 10-kW units for remote-area electricity through engines for ships and submarines up to 100-MW power stations. A study by the Commission of European Communities puts the total market for solid oxide fuel cells over the next 25 years in five European nations at 80 000 MW. The American Public Power Association and Electric Power Research Institute have estimated the market in the United States public sector alone at 1000 MW a year from 1996 to 2015.

An Australian market assessment study commissioned by the consortium partners in 1990 estimated that SOFC technology could compete well with the more than $350 million of existing investment in photovoltaic cells and diesel generators used for communications and residential power supplies in remote areas. The report also identified potential Australian markets in commercial lighting and heating, industrial power and central power generation.

Ceramic Fuel Cells Ltd will be based in the Melbourne suburb of Clayton, near to BHP's research laboratories and the Division of Materials Science and Technology.

Brett Wright

Solid oxide fuel cell technology — market assessment. S.P.S. Badwal, K. Foger and M.J. Murray. *CSIRO Division of Materials Science and Technology Report* No. 91–01, 1991.