

# Spinning-out a fuel cell company from a UK University—2 years of progress at Ceres Power

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## Abstract

Ceres Power Ltd (Ceres Power) has been spun-out from Imperial College London (Imperial) after more than 10 years fundamental research. The studies have shown that it is possible to combine ceramic materials, based around doped cerium oxide, with stainless-steel to produce a robust intermediate temperature solid oxide fuel cell (IT-SOFC) capable of operating at 500–600 °C. Ceres Power has been formed to exploit this technology commercially. This paper first briefly reviews the process of forming the Company and raising finance. It then discusses the unique technology platform that is being developed by Ceres Power and summarises some of the technical highlights to date.

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## 1. Company formation and growth

Promising results on a novel metal-supported, intermediate temperature solid oxide fuel cell (IT-SOFC), which arose from more than 10 years fundamental research at Imperial College in London, ultimately led to a decision to create a company to commercialise the technology. The associated business plan won the European Business Plan of the Year competition at the IESE in Barcelona in June 2001, and culminated in the formation of Ceres Power Ltd in July 2001.

During the summer and early autumn of 2001, investor interest in the company was high. In part, this was being driven by the almost daily reports in the financial press of electrical supply problems and costly consumer power in the USA and other developed countries. At that time, there high market values and expectations were being placed on all types of fuel cells, with polymer electrolyte membrane fuel cells (PEMFCs) dominating commercial plans of large automotive manufacturers for fuel cell vehicles. In common with other embryonic, technology-based, spin-out companies, the early fund-raising strategy of Ceres Power focused on knowledgeable individual investors, and was then fol-

lowed by institutional investment. The strength of the business plan and Ceres Power team allowed fund raising to proceed through the events of 11 September 2001, and the company officially began operating after first-round financing in October 2001. The first two Ceres Power employees occupied a room on the ground floor of the Royal School of Mines at Imperial College, opposite the remnants of the laboratory where Professor Brian Steele started his work on solid-state ionics over 35 years before.

The move, in October 2002, to purpose-designed premises in Crawley (adjacent to Gatwick Airport) was a key step in the company’s evolution. Not only did a single, customised facility enable large operational efficiencies, but the geographic independence from Imperial College reinforced the fact that Ceres Power was a commercially-driven entity. Since the move, market and industry reports and developments have shown that Ceres Power has a technology and the potential to exploit a unique space within fuel cell and distributed-power generation markets.

## 2. Ceres Power technology platform

Ceres Power is developing a platform technology for applications in the 1–25 kWe range. To set this technology in context, it is first necessary to consider briefly the present state-of-the-art in solid oxide fuel cell and polymer elec-

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trolyte membrane fuel cell technology, considered by many to be the two leading fuel cell types.

Polymer fuel cells are widely seen as the preferred technology for battery-replacement applications and for fuel-cell vehicles. This is because they are fast to start-up, lightweight and deliver a high power density. Nevertheless, PEMFCs have the major disadvantage that they require hydrogen of very high purity as a fuel (which is expensive to produce and difficult to store). Furthermore, they do not produce high-grade waste heat, which inhibits their application in the important combined heat and power (CHP) market.

By contrast, the main benefits driving the development of SOFCs are as follows:

- The elevated operating temperature of SOFCs means that carbon monoxide, always produced during the reforming of hydrocarbon fuels, is a fuel to the electrodes used within the stack, rather than a poison. This considerably simplifies the fuel-processing regime and reduces cost.
- The high-grade waste heat produced by the SOFC is of value in CHP applications, and can be used to drive the endothermic fuel-processing reactions via an integrated heat exchanger. This increases efficiency and simplifies the balance of plant requirements, saving space, weight and cost.
- Pure hydrogen fuel is not required, although hydrogen can, of course, still be used.

These benefits mean that SOFCs are widely seen as the leading technology for application on the present available fuels of natural gas, LPG, gasoline, diesel and alcohols.

Historically, SOFC development focused solely on high-temperature (900–1000 °C) operation, with the intention of integrating SOFCs into large-scale stationary power plant. This aspect of SOFC development continues today, driven by developers such as Siemens and Westinghouse [1] and Rolls-Royce [2], who seek to couple the SOFC with a gas turbine for stationary power generation at high efficiency. It is increasingly recognised by the SOFC community, however, that for smaller SOFC stacks not requiring integration with gas turbines, the operating temperature should be lowered as far as possible without compromising the electrode kinetics and internal resistance of the fuel cell. The lower operating temperature increases the range of materials that can be used to construct the device (including metals), increases material durability and overall product robustness, and crucially lowers cost. This has driven increasing interest in IT-SOFCs which operate at temperatures below 800 °C.

Selection of the solid electrolyte for these IT-SOFCs depends on the chosen temperature of operation. To help this selection process, it is useful to consider the following. Assuming that the electrolyte component should not contribute more than  $0.15 \Omega \text{ cm}^2$  to the specific resistance (ASR) of the total cell area, then for an electrolyte film thickness ( $L$ ) of  $15 \mu\text{m}$  the associated specific ionic conductivity ( $\sigma$ ) value of the electrolyte should exceed  $10^{-2} \text{ S cm}^{-1}$  ( $\sigma = L/\text{ASR} = 0.0015/0.15$ ). The ionic conductivity of the most

commonly used SOFC electrolyte, yttria-stabilized zirconia (YSZ), attains this target value above 700 °C, whilst the electrolyte used by Ceres Power, ceria gadolinia oxide (CGO), attains this conductivity at temperatures above 500 °C [3], given that the electrolyte is manufactured in the form of a film of some 10–30  $\mu\text{m}$  in thickness. Therefore, the use of a CGO electrolyte allows the cell operating temperature to be lowered to around 500 °C, i.e., a temperature at which standard stainless-steel can be used for many of the balance-of-plant components. This operating condition therefore enables a significant reduction in the cost of both the stack and the balance-of-plant. A concern often expressed with regards to the use of CGO electrolytes in SOFCs is that, at elevated (>600 °C) temperatures,  $\text{Ce}^{4+}$  ions can be reduced to  $\text{Ce}^{3+}$  under the fuel rich conditions prevailing in the anode compartment. The resulting electronic conductivity (and deleterious lattice expansion) produces an internal short-circuit that can significantly degrade the efficiency and performance of cells incorporating ceria-based electrolytes. Nevertheless, Steele [4] and Goodenough [5] have shown that at temperatures < 600 °C the reduction of  $\text{Ce}^{4+}$  ions to  $\text{Ce}^{3+}$  in the anode compartment is minimised, and can be neglected under typical cell operating conditions. This therefore defines an operating temperature window of 500–600 °C for SOFCs based on CGO.

The use of thick-film electrolytes requires the electrolyte to be supported on an appropriate substrate. As the substrate is the principal structural component in these cells, it is necessary to optimise the conflicting requirements of mechanical strength and gaseous permeability. Most development work on planar IT-SOFC systems has involved thick films of YSZ electrolyte supported on anode (Ni-YSZ) substrates in which electrolyte powder is densified at temperatures of around 1400 °C. The resultant cells and stacks operate with satisfactory power densities ( $0.3\text{--}0.5 \text{ W cm}^{-2}$ ) in the temperature range 700–800 °C using a ferritic, stainless-steel, bi-polar plate material. The relatively thick porous composite anode support ( $1.0 \pm 0.5 \text{ mm}$ ) does, however, introduce problems in the operation of such stacks as this structural component is relatively weak mechanically, and can have difficulty withstanding the thermal and mechanical stresses that are generated by rapid temperature fluctuations, or the severe vibrations experienced when the stack is used for transport applications. Moreover, Ni/NiO redox cycling, which is induced by air diffusing into the anode compartment during loss of fuel supply and other operational excursions, can disrupt the anode microstructure and produce a severe degradation in performance.

An innovative approach to overcome these challenges, and thereby enhance the robustness of SOFCs, is replacement of the Ni-YSZ anode support by a metal (normally stainless-steel). This improves thermal shock resistance, reduces temperature gradients due to the greater thermal conductivity of the metal, and enables conventional metal joining (e.g., welding) and forming techniques to be used. The concept of using a stainless-steel support for SOFC

PEN assemblies was first patented in 1966 [6], but little attention was paid to this configuration until some 30 years later when DLR in Germany fabricated metal-supported SOFC structures using (expensive) vacuum plasma spray techniques [7]. By contrast, work at Imperial [8] and Ceres Power [9,10] is focused on the integration of low-cost, ‘wet’, ceramic routes with metallic materials.

Three suitable grades of ferritic stainless-steel have so far been identified for use within the Ceres Power SOFC. At present, the preferred substrate is a Ti–Nb stabilised 17% Cr ferritic stainless-steel (European designation: 1.4509). It is important to note that operating at 600 °C imposes far less severe corrosion constraints on the steel than sustained operation at 750–800 °C, as is the case for a typical anode-supported cell stack. Also importantly, the thermal expansion of CGO10 and the selected ferritic stainless-steel are comparable, with values in the range  $(12.5\text{--}12.8) \times 10^{-6} \text{ K}^{-1}$  for both materials.

The ceramic components of the cell are deposited as thick films by conventional ceramic deposition technology. The electrodes are deposited by wet spraying or screen-printing. The electrolyte is deposited using an electrophoretic deposition (EPD) process [11]. All these processes are low-cost and scaleable, and are used for mass manufacturing in industry today. The cell, shown in cross-section in Fig. 1, consists of a steel foil substrate, which is impermeable around the edges, and porous in the centre. The edges facilitate sealing, as the cell can be laser-welded to the metallic interconnect. The anode layer is deposited over the porous section of the substrate. The anode is a nickel cermet, with a ceramic phase of cerium gadolinium oxide (CGO).

The electrolyte layer is deposited over the anode as a thick film (10–30  $\mu\text{m}$ ) of CGO. Ceres Power is able to fabricate fully-dense CGO electrolyte films, fired at only 1000 °C. This is a major technological breakthrough, as this temperature is unusually low for ceramics processing. The low firing temperature is crucial to protect the steel substrate from excessive oxidation.

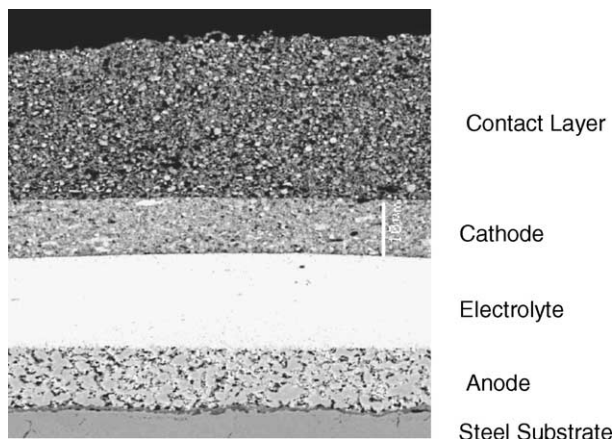


Fig. 1. Polished cross-section through a metal supported IT-SOFC, after testing on moist hydrogen/air at temperatures up to 600 °C.

The cathode layer is deposited over the fired anode and electrolyte. Various cathode materials are being investigated. At present, a doped lanthanum ferrite (LSCF)/CGO composite is the material of choice, which has been shown to have good performance at temperatures around 550 °C [12,13].

So to summarise, by comparison with other SOFCs, the Ceres Power approach has the following advantages.

- Uses a thick-film cell supported on a cheap stainless-steel substrate.
- Substrate foil can easily be brazed/welded to a stainless-steel bi-polar plate to allow flexible power scale-up via a simple array design.
- Low-cost manufacturing techniques which lend themselves to mass production and thus a low-cost product.
- Robust manifold gaskets simplify construction and increase stack durability.
- Lower operating temperature than current SOFC designs (550 °C versus >750 °C).
- Rapid start-up times compared with competing high-temperature fuel cells due to materials used in construction and compliant stack seals.
- Simple, scaleable and cost-effective modular design.
- Rugged and simple construction providing reliability and long operating life.

In addition, the technology retains the operational advantages common to all SOFCs, namely:

- high fuel efficiency and low emissions compared with heat engines, including internal combustion engine (ICE) generators (operating system efficiency  $\approx$  40% SOFC versus 25% ICE);
- near silent operation;
- fuel type flexibility, notably the ability to run on fuels other than pure hydrogen, e.g., natural gas, LPG, methanol and gasoline.

### 3. Recent technical highlights

Recent successes in the Ceres Power technical programme have included the following:

- Cell-level (16 cm<sup>2</sup> active area) power density 310 mW cm<sup>-2</sup> at 600 °C on moist hydrogen/air and 210 mW cm<sup>-2</sup> on emulated reformat (a gas mixture of CO, H<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O representative of that produced by the steam reforming of natural gas) at the same temperature.
- Cell-level (16 cm<sup>2</sup> active area) power density of 240 mW cm<sup>-2</sup> at 550 °C on moist hydrogen/air and 180 mW cm<sup>-2</sup> on emulated reformat at the same temperature.
- Rapid cell start-up from cold (<13 min), which is presently limited by the test rig design.
- No degradation after >2000 h lifetime testing to date.
- Short (three layer) stacks of twelve cells (total active area 192 cm<sup>2</sup>) tested, giving >80% maximum power.

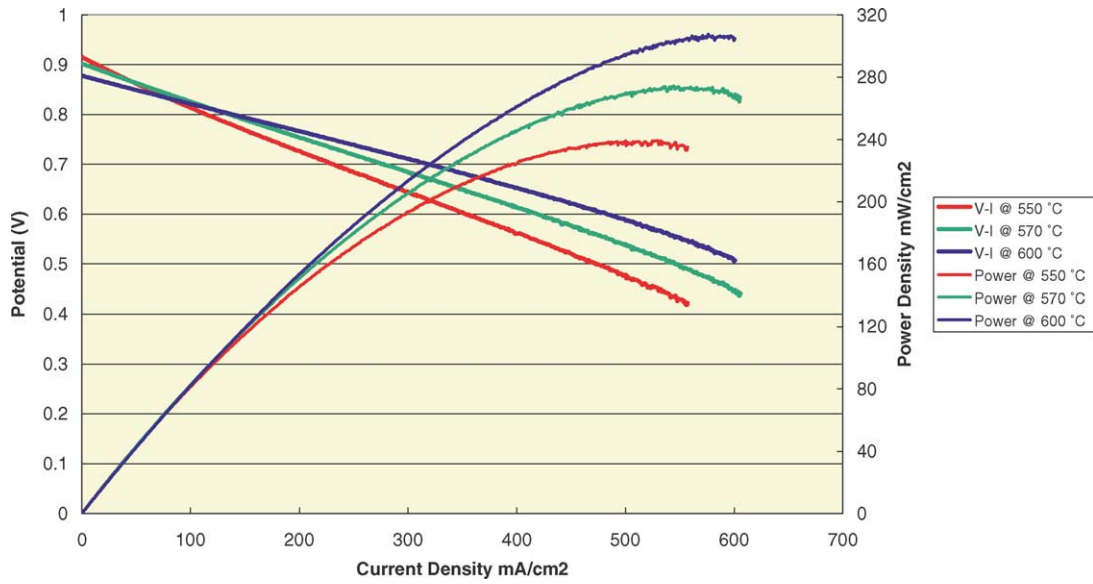


Fig. 2. Current–voltage and power curves for a 16 cm<sup>2</sup> cell, tested at temperatures of 550, 570 and 600 °C using moist hydrogen (3% H<sub>2</sub>O)/air.

- Gas-tight stack seal demonstrated using conventional compression gaskets surviving repeated thermal cycling.
- Laser welding of cells to metallic interconnect demonstrated to give gas-tight seal.
- Promising results from redox and thermal cycling trials, with <3% degradation evident after 25 thermal cycles and seven redox cycles to date.

Additional detail is provided in Fig. 2, which illustrates the current–voltage and power density response from a single cell of 4 cm × 4 cm active area, tested on moist hydrogen/air at 550, 570 and 600 °C. A maximum power density of 310 mW cm<sup>-2</sup> is obtained. This is excellent performance for

an SOFC at this temperature range, and meets the power density requirements of first-generation commercial products. Note that the cell voltage of around 0.91 V is in line with that expected from a CGO-based SOFC at this temperature, and with this fuel composition. Modelling work indicates that power densities of 0.4 W cm<sup>-2</sup> can be achieved at 550 °C on hydrogen/air, and 0.3 W cm<sup>-2</sup> on reformed natural gas/LPG with the present system, at a cell efficiency of 40–60% (LHV); the efficiency depends on the actual operating point.

The results of a long-term durability test of an earlier 200 mW cm<sup>-2</sup> class cell, operated under a load of 3 A on moist hydrogen/air at 570 °C are shown in Fig. 3. The cell suffered from loss of fuel on two occasions due to problems

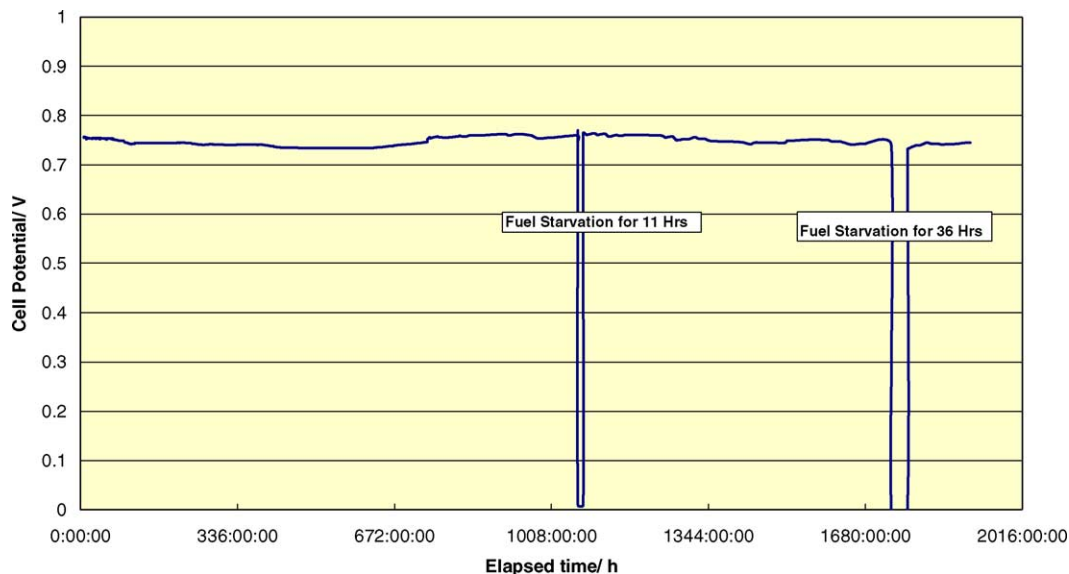


Fig. 3. Durability data for a 16 cm<sup>2</sup> cell, tested at a constant current of 0.2 A cm<sup>-2</sup> at 570 °C on moist hydrogen (3% H<sub>2</sub>O)/air.

with the testing infrastructure. Despite this, the cell has displayed no net loss in performance after more than 2000 h operation to date. This represents a very encouraging level of robustness, and the test is continuing.

#### 4. Applications of Ceres Power technology

Metal-supported IT-SOFC technology is ideally suited to applications where a combination of fuel flexibility, fast start-up, high efficiency and mechanical robustness is important. Thus, products that are being developed include 1–25 kWe units for remote power, auxiliary power units, uninterrupted power supplies and heat and/or electrical load lead micro-CHP applications.

#### 5. Conclusions

Since its formation some 2 years ago, Ceres Power has successfully established itself with a unique metal supported SOFC concept. Work continues to build on this success to meet both the commercial and technical targets necessary to enable a successful product launch.

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