FUEL CELL TODAY

Opening doors to fuel cell commercialisation

Solid Oxide Fuel Cells (SOFC)

Gemma Crawley
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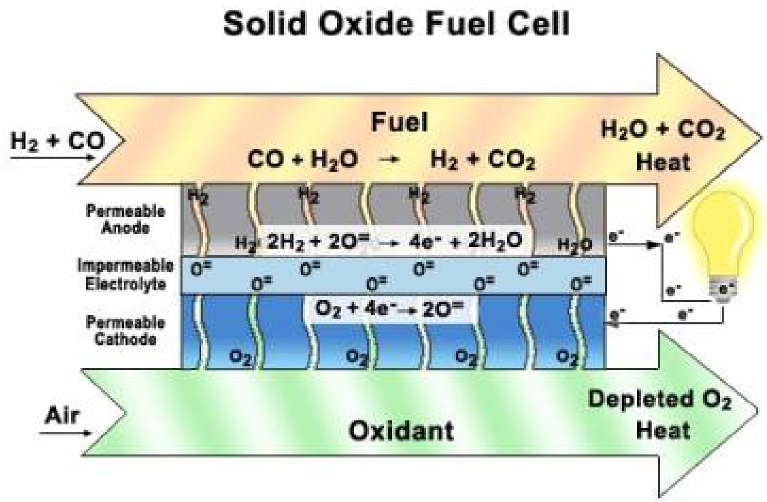
Introduction

This is the third of six articles designed to focus on each of the fuel cell technology types in turn. The reviews will provide a brief overview of the technical aspects of each system, the developmental milestones achieved, an estimate of the number of units currently in operation and a review of the key companies involved in the development, manufacture and commercialisation of each fuel cell type. Looking forward, the reports will also aim to provide details of any goals set by fuel cell companies for each system.

Previous articles have examined PEM and AFC technology and this instalment will take an in-depth look at SOFC. The final three reports will cover MCFC, DMFC, and PAFC and will be published over the course of the next twelve months.

Technological Overview

Solid oxide fuel cells are high temperature fuel cells which operate in the range of 800-1,000^{0}C. The SOFC is based around the same central design as many other fuel cell technologies and is composed of an anode and a cathode separated by an electrolyte. In the case of the SOFC unit, this electrolyte is a solid ceramic, such as zirconium oxide stabilised with yttrium oxide. During operation of the cell, oxygen (in the form of air) is supplied at the cathode. The ceramic electrolyte conducts oxygen ions from the cathode to the anode whilst electrons are pushed round an external circuit in order to produce electricity. At the anode, the oxygen ions combine with hydrogen to produce water. Heat and carbon dioxide are also generated at the anode.



In–depth SOFC Schematic (Courtesy of Solid State Energy Conversion Alliance, SECA)

There are two basic designs of SOFC units. In the planar design, components are assembled in flat stacks where the air and hydrogen traditionally flow though the unit via channels built in to the anode and cathode. In the tubular design, air is supplied to the inside of an extended solid oxide tube (which is sealed at one end) whilst fuel flows round the outside of the tube. The tube itself forms the cathode and the cell components are constructed in layers around the tube.

SOFC systems are generally thought to be best suited to the generation of electricity and heat in industrial applications although they are also used to provide auxiliary power to some selected vehicles. Currently, some organisations are branching out to newer applications of SOFC units and in doing so are beginning to produce smaller units than previously manufactured. SOFC units are also used by the military in selected applications.

SOFC units have achieved high efficiencies of over 60% and the high operating temperatures allow direct internal processing of fuels such as natural gas. A further advantage of the high operating temperature is that the reaction kinetics are improved in the SOFC unit thus removing the need for a metal catalyst. However, high temperature corrosion can sometimes be a problem and requires the use of expensive materials and protective layers within the cell. In the past, there have also been some problems related to sealing.

SOFC Developmental Milestones

The SOFC was first developed in 1937 by Baur and Preis. Initially basing their research on a solid compound that had been developed by Wilhelm Nernst in 1899, Baur and Preis went on to manufacture and test a series of ceramic materials for use as the electrolyte. The two scientists finally decided that a combination of 30% lithium zirconate, 10% clay and 60% 'Nernst-Mass' (85% ZrO_2 and 15% Y_2O_3 named after the original material developed by Nernst) was the most effective electrolyte. However, the components required to manufacture this material meant that it was too expensive for practical use. Despite this fact, Bauer and Preis concluded that practical solid electrolytes could be manufactured if less expensive materials were used in place of zirconia and yttria.

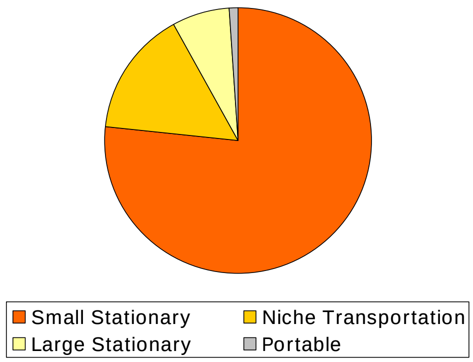
In 1962, Weissbart and Ruka at the Westinghouse Electric Corporation developed a fuel cell system that used 85% ZrO_2 and 15% CaO as the electrolyte, a variation on the Nernst-Mass material. In the system, porous platinum was used as the electrodes. The cell was cased in a tube (sealed at one end) made from the same materials as the electrolyte. The cell was put through rigorous tests first with pure oxygen and hydrogen or methane as fuels and later with a mixture of 3.8% methane, 2.1% water and 94.1% nitrogen provided as a fuel at the anode. Testing took place at temperatures between 800 and 1,100^{o}C.

Westinghouse continued to develop SOFC systems and in 1998 joined with Siemens to found the Siemens-Westinghouse Power Corporation. The newly founded company focussed on the tubular SOFC concept and its formation marked the discontinuation of Siemens' in-house development of planar fuel cell technology. Siemens Westinghouse continues to develop and commercialise tubular systems whilst the former Siemens planar SOFC was developed further by Entwicklungsgesellschaft Brennstoffzelle GmbH and Fraunhofer-IKTS in Germany.

In the current SOFC market, interest in the technology from the military sector is one of the key drivers for development. In addition, several of the large automotive manufacturers are working on the use of SOFC systems for auxiliary power and government sponsored programmes (such as the Solid State Energy Conversion Alliance, or SECA, scheme in the USA) help to ensure that industry, academia and governments continue to achieve new milestones for the development of SOFC technology.

The Current SOFC Market

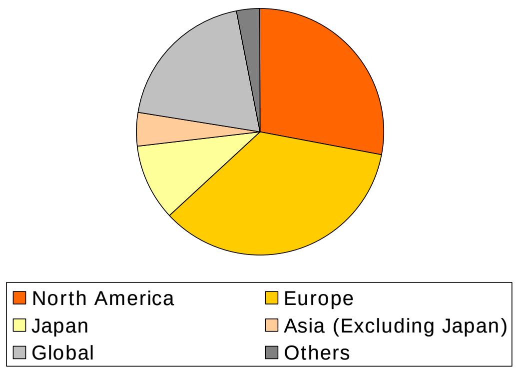
The end-uses of SOFC systems may be classified in to three main groups: stationary applications (large stationary power generation of over 10 KW and small stationary power generation of under 10 KW), niche transportation applications and portable applications.



Total Number of SOFC Units Installed Globally by Application

It is clear to see from the graph that the majority of SOFC units installed across the globe are being used for small stationary applications. This classification includes stationary units used for domestic power supply, industrial applications requiring uninterrupted power supply (UPS) (for example banks) and military applications. As previously mentioned, high efficiencies and operating temperatures make SOFC technology well suited to these types of application. It may be somewhat surprising to see that the use of SOFC in the niche transport sector is higher than that in the large stationary category. However, companies working on SOFC for large stationary applications tend to be working on the development of hybrid technologies and use SOFC systems as part of a combination solution to power supply. In the niche transport sector the SOFC units can be used as standalone systems used as APUs to supply auxiliary power to selected vehicles.

In terms of where SOFC units are installed across the globe, Europe accounts for nearly 35% of the geographical split. Perhaps unsurprisingly, North America accounts for the second largest share of the geographical split thus indicating that the majority of SOFC research, development and commercialisation is occurring in these two regions. Interestingly, as can be seen from the graph on the following page, approximately 19% of the companies sampled believe their business to be a ‘global’ business indicating a significant proportion of companies with activity in more than one country. This could reflect international agreements between academic institutions, business and academia or a company with offices established in more than one country.



SOFC Activity by Geographical Split. Data is based on a discrete sample of companies listed in the FCT Industry Directory.

Nearly one third of all the companies sampled are operating as research and development entities and 42% are operating as commercial organisations. This indicates that the SOFC industry is not as far forward in terms of the commercialisation process as the PEM sector where 75% of companies describe themselves as being commercial entities.

Chart I) All SOFC activity

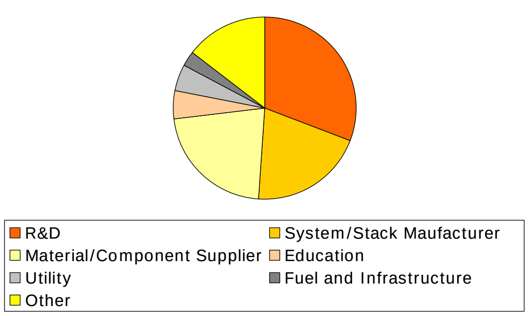
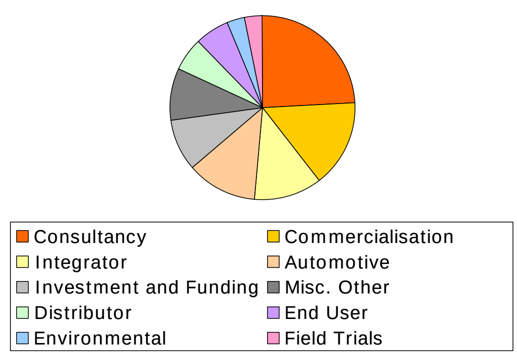


Chart II) SOFC activity termed as 'other' in Chart I)



SOFC Activity Across the Globe Split by Application. Data is based on a discrete sample of companies listed in the FCT Industry Directory.

Of particular interest however, is the 'other' sector shown in chart I. Further analysis of this group shows that it is composed of at least ten sub-groups (as illustrated in chart II). In comparison to the previous technology articles, this level of diversification found within the SOFC industry is quite unique from anything found whilst analysing the PEM and alkaline markets. We believe that many of the categories shown in Chart II reflect an association with research programmes and academic activity thus confirming the view that the SOFC industry is still more research focussed than commercialised. This is not to say that the SOFC sector lacks a commercial focus, indeed many major players within the sector (such as Rolls Royce) have consistently cited timeframes as close as 2008 for product commercialisation. However, there is still a great deal of developmental work occurring in the SOFC sector which is at present, accounting for the focus of more companies than commercial activities are.

In terms of current government involvement in the development of SOFC technology, most regions have been supported to some extent. However, Japan is of particular interest as this region has seen several recent developments in terms of SOFC government support.

In Japan, the past 12 months have seen some encouraging developments for SOFC government supported activity. For the first time ever, SOFC technology has been included in Japanese funding documents. This move may indicate to some that until this point the Japanese government could not justify investment in SOFC technology however, as a result of extensive research and development work the technology has since become a more attractive investment. In addition, the Japanese government has recently published its revised, highly detailed, roadmap with well defined targets for PEM, DMFC, SOFC and hydrogen development up to 2025. Although the focus for SOFC remains heavily on research and development activities rather than commercial targets, it is anticipated that the document will strengthen future fuel cell development and commercialisation in Japan and promote similar strategic planning across the globe.

Key Company Review

As previously shown, SOFC technology finds a range of end-use applications across several different sectors. This section of the report is designed to give a brief overview of some of the key companies working within the SOFC industry and is by no means a complete list of all organisations operating in this space.

Acumentrics is developing a number of products for both UPS and CHP systems using its tubular SOFC technology. As well as a 10 kW unit specifically targeted at the Japanese market, it is also developing CHP units for the European and US markets.

Alstom's SOFC activities are mainly based in the UK and in conjunction with Forschungszentrum Julich it has developed an anode-supported planar SOFC stack. Although work has been downscaled in this area the company continues to participate in a number of European Union projects.

BMW, together with **Delphi Automotive Systems** developed a SOFC unit as an auxiliary power unit for light duty vehicles. The SOFC was made by **Global Thermoelectric** and the first vehicle using the system was demonstrated in spring 2001.

Ceramic Fuel Cells develops planar SOFC and fuel cell components. The company specialises in anode and electrolyte supported fuel cells and produce 1 KW modular stacks. Ceramic Fuel Cells has been developing SOFC technology for over 14 years and claims to have one of the world's largest SOFC testing resources with 50 test stations operating on natural gas.

Ceres Power was formed in 2001 to develop intermediate temperature SOFC systems based on technology from **Imperial College** of which it is a spin off.

The **Japanese Central Research Institute of the Electric Power Industry (CRIEPI)** promotes research and development in to various power generation, environmental and energy topics. The Institute has dedicated significant time to the development of SOFC systems and in April 2004 presented a SOFC made of entirely ceramic materials. The operating temperature of this system was between 700^{0}C and 800^{0}C.

As part of the **SECA** programme, **Cummins Power Generation** and **SOFCo** have developed a 10 kW SOFC for stationary and mobile applications.

Also under the **SECA** programme, **Delphi and Battelle** continue to develop a common SOFC design for automotive and truck APUs, distributed generation and niche applications within the military sector. Delphi has plans to demonstrate a 5 kW unit that costs only US$400/kW.

ENrG is a solid oxide fuel cell component engineering and manufacturing company that designs and produces ceramic components for SOFC units.

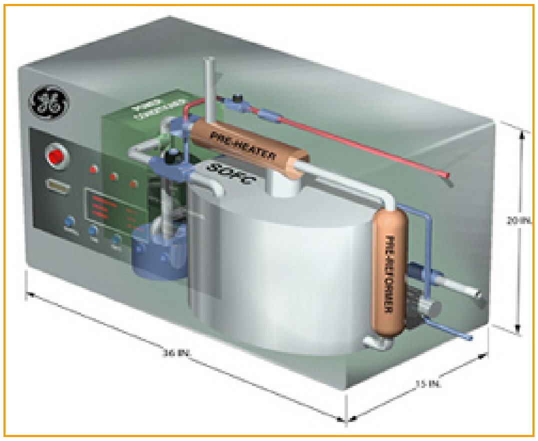
Franklin Fuel Cells was founded in 2001 to commercialise direct oxidation solid oxide fuel cell technology which was originally developed at the University of Pennsylvania. The company has had a specific focus on the design and development of high performance stacks.

FuelCell Energy is an Industry Partner in the **SECA** programme and as part of this scheme undertakes development of SOFC for small stationary applications and portable power systems for use in the military sector.

Fuel Cell Technologies developed a modular 5KW SOFC for distributed power generation. The system used a **Siemens Westinghouse** stack and is designed to provide electricity in residential, small commercial and remote facility applications.

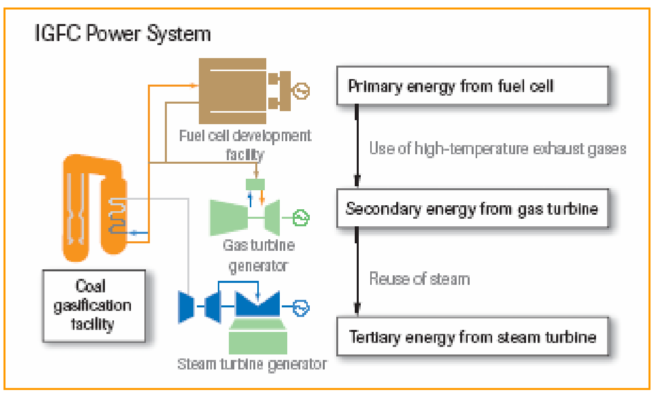
General Electric is working on the US Department of Energy Clean Coal Initiative, which aims by 2013 to have an efficient Multi-MW SOFC in combination with coal-gasification. It has recently announced that as part of the project is has delivered a 49% efficient 6kW prototype to the **National Energy Technology Laboratory** for testing. Further to this GE claims to have also demonstrated a low cost, high volume manufacturing method for the ceramic and electrolyte materials which could allow a US$800/kW system cost. GE is also heavily involved in the **SECA** programme.

In January 2007, fuel cell manufacturer **GTI** announced that it would be focussing its US$10.5 million research programme on developing SOFCs. The company, working together with **FuelCell Energy** is hoping to target markets for smaller devices as well as reducing the cost of SOFC units.



A schematic of the future GE SOFC hybrid (picture courtesy of GE)

The Electric Power Development company, more commonly known as **J-Power** (Japan), is looking at various areas of work linked with coal and power generation. Since 1989, in collaboration with **Mitsubishi Heavy Industries**, it has been developing increasingly larger stationary SOFCs. The initial unit was an atmospheric 1kW test unit, with the most recent successful test being concluded on a 25kW unit, in May 2006. The next stage in the development plan is for a 150kW co-gen unit with a 10,000 hour durability. The longer term aim of J-Power is the development of a Coal Gasification Fuel Cell Combined Cycle unit (IGFC).



A schematic of the IGFC under development at J-Power (picture courtesy of J-Power)

Kansai Electric Power is involved in the development of low temperature SOFC systems which utilises nanotechnology.

In Japan, **Kyocera** is developing 1 kW SOFC fuel cells for residential use and larger units for businesses. The 1 kW system is being developed in collaboration with **Osaka Gas**, whilst the larger fuel cell is being developed with **Tokyo Gas** and is anticipated to be commercialised in the spring of 2007.

Lilliputian Systems develops SOFC technology for portable electronic applications. The company was developing an integrated micro SOFC and micro reformer based on technology from **MIT** and **Lawrence Livermore National Labs**.

Mitsubishi Heavy Industries (Japan) is working on two designs for SOFC units. The first is known as MOLB (Mono-block Layer Built) co-gen unit, in cooperation with **Chubu Electric Power**. In 2005 the company ran one of these units at the Aichi World Fair. It is not known if this unit will now be re-commissioned at another site. For the MOLB design the aim is to now build larger units, in terms of higher output, and more efficient units for cogeneration. The second design is a tubular SOFC with Gas Turbine (MGT). The hybrid system is being developed under a NEDO project, in collaboration with **Electric Power Development (EPDC)**. To date 36.5kW of electrical power was obtained from a 40kW unit. Mitsubishi Heavy Industries planned to manufacture a 200kW SOFC-MGT during 2006 and undertake verification tests in 2007. As to the SOFC unit, EPDC plans to install a 150kW atmospheric co-gen system in FY2006 for further verification.

The MHI SOFC hybrid unit and its co-gen unit
(picture courtesy of MHI)

Mitsubishi Materials (Japan) is working with **Kansai Electric (KEPCO)** (Japan) and **Kyushu University** on planar SOFCs. The target is to develop a range of sizes from <1kW to several tens of kW for on-site power generation. The project, which started in 2004, is supported by NEDO. During 2005 a 10kW test unit was built and achieved an electrical efficiency of 50%HHV, using town gas as a fuel. The unit is based on a lanthanum gallate cell to be operated at temperatures below 800°C, allowing the unit to be therefore classed as an Intermediate Temperature SOFC. In January 2005 the companies announced that their 1kW prototype system achieved continuous operation for more than 1,000 hours with efficiency of 57.6% at 800°C. The plan is to commercialise several tens of kilowatt systems by March 2007.

Nippon Steel (Japan) will jointly develop a power generation system with **Sumitomo**, using SOFC stacks developed by **Acumentrics** (US).

US firm **NanoDynamic** won US$2 million in federal funding for work on its portable solid oxide fuel cell (SOFC). Passed as part of the Defence Appropriations conference report for 2007, the funding agreement will see the company continue its work on the portable power packs which are designed for use by soldiers in the field. An additional US$729,000 was awarded to the company in the form of a Phase II Small Business Innovation Research grant from the US Army for carbon nanotube production technology. The company also gained a patent on SOFC structures.

NanoDynamic's portable fuel cell unit on display at the 2006 Fuel Cell Seminar (Source: Fuel Cell Today)

Nippon Telegraph and Telephone's (NTT) (Japan) Energy and Environment Systems Laboratories is actively involved in fuel cell development. After an initial foray into SOFC technology for stationary fuel cells, with a timeline of commercialisation in 2007, it appears now to have jumped ship to miniature portable fuel cells.

Mesoscopic Devices is a developer of portable fuel cell systems and components for military and commercial applications. The company has a dedicated line of SOFC portable generators known as the MesoGen series.

QinetiQ develops reduced temperature SOFCs with proton conducting ceramic electrolytes.

Rolls-Royce is developing solid oxide fuel cell technology for stationary power generation and is currently testing a 80kW unit, with plans to have a demonstration product in 2008. A turbo generator for the system is being developed in-house. The company planned to install an automated pilot production facility by 2006 with a fully automated cell production process.

The **Solid State Energy Conversion Alliance (SECA)** was established in the USA in 1999 with the aim of bringing together US government, industry and the scientific community to promote the development of SOFC technology in the 3 kW to 10 kW for use in stationary, transportation and military applications.

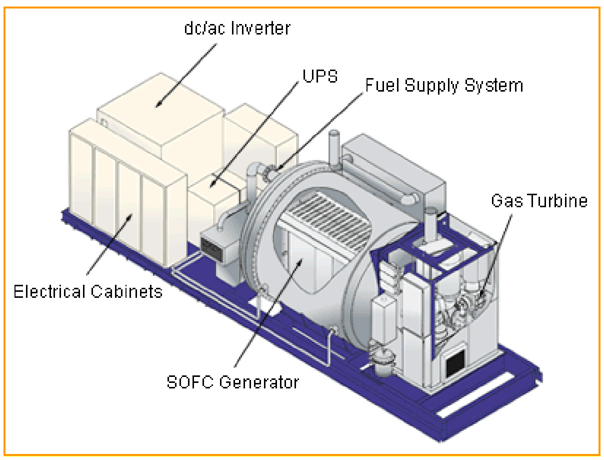
There are several SECA projects operating in various locations throughout the United States. Overall, the SECA programme involves six 'Industry Teams' (**Acumentrics**, **Cummins Power Generation**, **Delphi Automotive Systems**, **FuelCell Energy**, **General Electric Power Systems** and **Siemens Westinghouse Power Corporation**) and numerous participants in the Core Technology Programme. The Industry Teams work with the Core Technology Programme partners to develop SOFC technology. As the teams identify R&D gaps in SOFC development, they pass these areas on to the Core Technology Partners to investigate. The third party involved with the project is federal government management which facilitates interaction between the Industry Teams and the Core Technology Programme participants as well as establishing technical priorities and approaches.

SECA is coordinated by the US Energy Department through the **National Energy Technology Laboratory** and **Pacific Northwest National Laboratory**. Phase I SECA targets include:

- Dramatic reductions in the cost of SOFC technology (the target is currently to achieve a cost of US$400/kW by the end of 2010).

- A minimum of 50,000 units by 2010.
- The development of a modular, solid state fuel cell that can be mass produced for different uses.
- An availability of 80%.
- An efficiency of 35% in a 5.4 kW system.

Siemens Power Generation (USA) (part of the **Siemens** group, formerly known as **Siemens Westinghouse**) is working on SOFC/turbine technology. The company's first pre-commercial product is the SFC-200, which is now being tested in a number of locations. The SFC-200 is a 125 kW SOFC cogeneration system, operating on natural gas at atmospheric pressure, with electrical efficiency of 44-47% at full load. An overall system energy efficiency is expected at >80% assuming steam/hot water or other cogeneration. In the longer term the SFC-200 is going to be a building block for systems up to 500 kW. Siemens claims that to date it has been the only company to successfully demonstrate its pressurised SOFC/GT hybrid system and has two units, a 220kW at the University of California, Irvine and a 300kW unit in Pittsburgh, as proof-of-concept.



A schematic of the SFC-200 system being developed by Siemens (picture courtesy of Siemens)

Internal analysis at Siemens indicates that efficiencies up to 70% are possible at 2-3MW capacity units. For 1MW units ~60% efficiency is thought possible and this is only reduced to 55% at 250kW scale.

Siemens was working on flattened tubular SOFCs but last year announced that is was also working on a new design, High Power Density (HPD) 'Delta 9'. This new design provides higher power density by about 30-40 per cent as well as still avoiding the sealing problems of planar fuel cells.

A proof-of-concept HPD Delta 9 stack
(picture courtesy of Siemens)

One point to note is that Siemens has been working with the now defunct **Fuel Cell Technologies** for balance-of-plant for a number of units. It is unclear as it what route the development will now follow.

Siemens Westinghouse Power Corporation continues to develop a 7-10 kW SOFC combined heat and power system for residential use and a 3-10 kW APU for automotive markets as part of the **SECA** programme.

Versa Power Systems (USA/Canada) is a joint venture between **Gas Technology Institute**, **Electric Power Research Institute**, **FuelCell Energy** (FuelCell Energy transferred its SOFC R&D to Versa Power Systems), **Materials and Systems Research** and the **University of Utah**. Its stack is currently under development within two **SECA** programme projects, one for FuelCell Energy and the second for **Cummins**. As well as developing its stack technology it is also developing end-use systems in the 2-10kW range and has a number of pre-commercial units in field trails.

Ztek (USA) develops planar SOFC systems with the focus on larger applications. The company demonstrated a 1 kW fuel cell stack with over 15,000 hours in operation. A

25kW system with multiple fuel cell stacks and natural gas internal reforming has been developed and is currently in operation to test its durability. The longer term plan is to develop half megawatt and a megawatt version for the distributed electricity market, based on the 200 kW SOFC/Gas Turbine system which is still under construction.

Future Prospects for SOFC Systems

The future for SOFC technology is promising. There are numerous companies working towards the commercialisation of this technology and a significant number of research programmes designed to further the understanding of and enable future technological developments for SOFC systems. In terms of future goals, several organisations are focused on lowering operating temperatures and developing intermediate temperature SOFC systems. Size reduction of the fuel cell unit is also an issue which needs to be addressed to enable future commercialisation.

Many key developers are currently examining the possibility of using SOFC technology as a hybrid technology, combining the fuel cell units with gas turbines in order to provide power generation. If successful, this could open up many possibilities for new applications and markets that were previously unobtainable when considering SOFC technology as a stand alone power solution.

Interest in SOFC technology remains high with programmes such as SECA encouraging industry, academia and government to work hand in hand to develop SOFC solutions. The high level of support received from the military sector also drives SOFC research and provides funding for many projects.

In the future, target markets for end use of SOFC technology remain likely to be stationary power generation, niche transportation and portable applications. If the market continues to develop according to early predictions, small stationary power will be the largest sector for SOFC systems. Currently, there is SOFC activity occurring across the globe and as the fuel cell industry expands this is likely to remain the case.

It is expected that as the SOFC market moves towards becoming more commercialised there will be a streamlining of the activity currently found within the sector. The level of diversification found within the SOFC industry is extremely high indicating that it is still heavily researched focussed. As the sector begins to reach commercial goals and targets, key players will emerge and some of the more diverse activities may fall out of the market.

Barriers to entry for the SOFC market remain high. Components and materials are expensive, production costs are high and there is still development work to be undertaken before the technology is fully commercialised. However, there remains a high level of interest in SOFC units and robust support from various research programmes, in addition to government funding schemes, will enable future development. Interest from sectors such as the military will continue to drive demand for SOFC technology and help to achieve full commercialisation of this market. It remains to be seen if 2008 will be the success story that many SOFC developers are claiming for stationary power applications but there are positive signs from the sector that commercialisation remains the top priority and will ultimately be achieved.

About the Author

Gemma Crawley works as a Senior Market Analyst for Fuel Cell Today. Her area of interest is the adoption of fuel cell technology in developing countries. Gemma can be contacted via gemmacrawley@fuelcelltoday.com