STATUS OF THE EUROPEAN SOFC PROGRAMME

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ABSTRACT

This paper will provide a summary of the Fuel Cell (FC) program in Europe and particularly the state of the art of the European development of Solid Oxide fuel cell (SOFC) technology.

FUEL CELL ACTIVITIES WITHIN THE EUROPEAN COMMISSION

Although the European Commission (EC) funding for fuel cell R,D&D in Europe forms only a relatively small share of the overall fuel cell funding due to some very important industrial support especially in transport, EC programs play an important role in bringing about a collaboration and information exchange between most of the fuel cell activities in Europe. Each European project co-financed by the EC is subject to the participation of several partners from different European Union (EU) member states. Each EC project on the average consists of three to four partners and in the 40 ongoing or starting EC fuel cell projects, around 60-80 different organisations participate which are also involved in national and industrial fuel cell activities. Regular EC fuel cell contractors’ meetings and cluster meetings assure a continuous contact and information exchange between major fuel cell groups in Europe. EC Funding is generally limited to about 35% - 50 % of total project costs, which means that additional financing must be provided by national and/or industrial sources.

In the Fourth Framework Program (FP4) of the EC for Research and Technological Development (1994-1998), fuel cell R,D&D was carried out in the JOULE, THERMIE and BRITE-EURAM programs. Fuel cell activities in these three programs were complementary in nature mainly focusing on stationary fuel cells for heat and/or power generation and mobile fuel cells for transportation. JOULE focussed on basic research and on stack and system development with the aim to demonstrate their technical feasibility. BRITE-EURAM dealt with the development of production processes for systems and materials. THERMIE allocated funds to the demonstration of the economic feasibility of innovative fuel cell technologies. The overall EC contribution to fuel cell R,D&D amounted to around 58 MEUR in the period 1994 to 1998, the total cost of this research being around 120 MEUR.

In JOULE (Energy research), during the period 1994-1998, around 48 MEUR were allocated
to 30 projects. A substantial focus was put on MCFC and SOFC (~40% of total EC funding) where basic research was carried out to improve the lifetime (corrosion problems) and reduce the cost. In addition, a series of projects aiming at scaling up MCFC and SOFC stacks were also supported. This research led to projects that develop ER-MCFC stacks of 100 kW, IR-MCFC of 10 kW and IR-SOFC of 20 kW (ER: External Reforming; IR: Internal Reforming). Much emphasis was also put on prototype and systems development, with projects dealing with Balance of Plant (BOP) of SOFC and MCFC systems.

In THERMIE (Energy demonstration), during the period 1994-1998, around 10,4 MEUR were allocated to 12 projects (including three accompanying measure) mainly dealing with stationary applications for decentralised heat and power generation (62% of total THERMIE funding) but also with transport applications. THERMIE focussed especially on MCFC and PEMFC systems to demonstrate the technical feasibility and economical potential of these innovative technologies. MCFC projects mainly concerned the demonstration of IR-MCFC cogeneration plants from 90 kWe up to 300 kWe, focusing especially on the optimisation and integration of the Balance of Plant. The demonstration of small to medium scale PEMFC systems was also supported for decentralised heat and power generation in buildings or houses but also for niche applications on industrial sites where waste or by-product fuels (e.g. waste hydrogen) are available. Two projects also aim to demonstrate the use of PEMFC in buses and light vehicles fuelled with hydrogen. There was no demonstration SOFC project in this period.

Since the Fifth Framework Program (FP5) (1999-2002) started, the EC support for the development of FC systems already exceeds 59 MEUR (for a total cost of 185 MEUR) distributed to 17 projects (an additional same order of magnitude could be expected for the two remaining years of this program). 20.5% of this budget was allocated to SOFC (research and demonstration). The support to MCFC concentrated on the development and field testing of biomass process and MCFC integrated system and on a demonstration of a 500 kWe MCFC power plant in Spain representing 11% of the fuel cell budget. A large amount close to 43% was devoted to support PEMFC for distributed heat and power generation and transportation (including large demonstration of clean urban transport) as well as on advanced hydrogen storage systems based on PEMFC and portable devices. The remaining budget was allocated to development of on board fuel reformers for gasoline and bio-ethanol (13%), DMFC (5%) and transversal (socio-economic, standards,) projects.

Figures 1 and 2, present the dynamic of the EC support to fuel cell technologies since 1995.
SOFC ACTIVITY WITHIN THE EUROPEAN COMMISSION

In FP4 (1995-1998), the EC budget allocated to SOFC amounted to 11.9 MEUR (28% of total EC funding by JOULE program). JOULE financed five research projects led respectively by RISOE National Laboratory (DK), CERAM Research (UK), Siemens (DE), GASTEC (NL), and Bertin Technologies (FR); BRITE-EURAM financed a project led by RISOE National Laboratory (DK). One of the main objectives of these projects is to reduce the cost of SOFC by improving the durability or/and by reducing the operational temperature (the so-called intermediate temperature SOFC technology). A concerted action gathering 13 co-ordinators of EC, national and industrial projects on SOFC and MCFC is also being implemented by the JOULE program (co-ordinator: Bertin Technologies) in view to identify the barriers to the implementation of high temperature fuel cells on the market. All these projects were/are carried out in very close synergy with national and industrial activities at European level.

Until now, in the current FP5 (1999-2002), the EU support to SOFC already amounts to 12.1 MEUR (for a total cost of 30.2 MEUR) distributed respectively to 8.2 MEUR in research and 3.9 MEUR in demonstration, both financed by the energy component “ENERGIE” of the Energy, Environment and Sustainable development program. Since 1999, European research focuses on the development of experimental planar stacks from 5 to 20 kWe and to define and design a new SOFC product i.e. a power system between 200 to 500 kWe, as well as specify the quality control for continuous manufacturing. Cost reduction still remains the driving force for the progress of these projects and for future field trial demonstrations in stationary applications to be implemented in a 2003-2005 time frame. Basic research concentrates to improve the reliability of SOFC systems using ferritic steels as interconnects for cost competitive reasons, and in general, to demonstrate a loss in performance of less than 0.75% per 1000 hours of operation during long-lasting experiments under realistic operating conditions. Another very recent project aims at developing an integrated model of SOFC/gas turbine hybrid systems with the objective to explore a wider range of system configurations i.e. from sub-MWe distributed CHP generations to 20-30 MWe systems, contributing to define specifications of components and sub-components and to improve the potential for finding lower costs solutions. A key large project started in 2000 with the objective to demonstrate the feasibility of a SOFC/gas turbine system of the MW class, based on the existing tubular SOFC technology. A pressurised hybrid system will be tested using available turbine(s) adapted to the requirements of the SOFC module reaching an electrical efficiency above 55%. This project is the first one in co-operation with US (co-funded by DoE) in this field.
Table 1 shows all Solid Oxide Fuel Cell RTD projects supported by the EC since 1995.

| Program   | Status    | Title of Contract                                                                 | Coordinator                        |
|-----------|-----------|-----------------------------------------------------------------------------------|------------------------------------|
| JOULE     | ended in '99 | Improving durability of SOFC Stacks (IDUSOFC)                                     | RISOE National Laboratory          |
| JOULE     | ended in '99 | Evaluation and Scale -up of Intermediate Temperature (700 °C) SOFC Technology (ITSOFC) | British ceramic Research Ltd       |
| JOULE     | ended in '99 | Development of 50kW Class SOFC System and Components                              | Siemens AG                         |
| JOULE     | ended in '99 | Development of a Novel Partial Oxidation Reactor for Natural Gas and Integration into a Micro-CHP SOFC System | Gastec NV                          |
| BRITE-EURAM | ended in '99 | Low cost Fabrication and Improved Performance of SOFC stack Components (LOCO-SOFC) | RISOE National Laboratory          |
| JOULE     | ended in '00 | Feasibility Study of an Urban Fuel Cell Network with Coal Gasifier (BARAKA)        | Bertin                             |
| JOULE     | ended in '00 | High Temperature Fuel Cells Use for the Next Ten Years (FUNTY)                     | Bertin                             |
| ENERGIE   | on-going   | Decentralized Power Generation Plants based on Planar SOFC Technology : Proof of Concept (PROCON) | ALSTOM                             |
| ENERGIE   | on-going   | Demonstration of a MWe Class Power System using (SOFC) combined with micro-turbines (1MWSOFC) | EnBW                               |
| ENERGIE   | on-going   | Scale-up of a multi-functional SOFC to multi-tens of kW levels (MF-SOFC)           | ROLLS-ROYCE                       |
| ENERGIE   | starting   | Integrated Modeling Study Of Fuel Cell/gas Turbine Hybrids (IM-SOFC-GT)           | ROLLS-ROYCE                       |
| ENERGIE   | starting   | Component Reliability Of Solid Oxide Fuel Cell Systems for Commercial Operation (CORE-SOFC) | FZ-JUELICH                        |

Table 1, European Commission financing of SOFC RTD shared-cost projects since 1995
SOFC NATIONAL PROGRAMMES IN EUROPE

Germany

In Germany, the national fuel cell program is an important subject of the “Programme for Energy Research and Energy Technologies”, with a yearly budget of around 8 MEUR. It supports investigation, development and demonstration of three different fuel cell technologies (SOFC, MCFC, PEMFC). A four year program focussing on PEMFC mainly for mobile applications has been started in 1998. For the decentralised co-generation of electricity and heat, the SOFC and MCFC technologies are supported with roughly 4 MEUR (3 MEUR for SOFC) on an annual basis (government money). The programme is co financed by industry that brings an additional 4 MEUR amount per year. The federal government has recently approved additional funds within the mentioned energy programme for a period of three years (2001 – 2003) supporting new energy technologies i.e. fuel cells, geothermal energy, offshore wind energy. 60 MEUR (three year basis) of the anticipated budget will be reserved for the development and the demonstration of fuel cell technologies.

France

In France, the Fuel Cell technological research and innovation network (“PACo”) was created by the French government in June 1999 with the objectives to contribute to the governmental orientations for the development of new energy technologies devoted first to the development of fuel cells including the problems linked to the fuels for fuel cells, to stimulate technological innovation and finally to contribute to the creation of new employment and innovative enterprises.

At the end of November 2000, the PACo network labelled 28 projects distributed as follows:

- 13 projects on fuel cells and fuel cell systems for a total budget of 28 MEUR including a public grant of 11,4 MEUR. 3 projects are dealing with the development of SOFC for a total budget of 5,7 MEUR including the public grant of 2,3 MEUR. Research on SOFC concentrates on low cost and/or low temperature ceramic components with direct reforming of methane.
- 7 projects on hydrogen and other fuels related technologies (hydrogen storage and production, reforming, etc.) for a total amount of 14 MEUR including 6,5 MEUR of grant.
- Cross-cutting actions on safety, technical and economic analysis, technological watch and large test facilities

The total amount of selected projects reaches 56,1 MEUR including 22 MEUR of requested public support (i.e. 7,4 MEUR from the Ministry of Research, 8,8 MEUR from the Ministry for Economic Affairs, Finance and Industry and 5,8 MEUR from ADEME).
The Netherlands

Since 1986, fuel cell efforts in the Netherlands have focussed predominantly on the development of ER- and IR-MCFC; the available budget for a period of 5 years (1992-1996) amounted to 40 MEUR. In 1990, R,D&D on SOFC and PEMFC has been initiated with an average annual budget of 5 MEUR. In addition, a group of Dutch utilities (EDB) and a Danish utility (Elsam) have performed a field test of a 100 kWe tubular SOFC system from Siemens Westinghouse Power Corporation in Westervoort (NL). The total cost of this project is in the order of 10 MEUR and has received public support (0.7 MEUR). The specific public governmental support has been stopped in 1999, so there is no more a National fuel cell program as such, however support is given from different generic programs. Effectively, activities on SOFC and PEMFC are continued at a higher funding level, mainly at the research organisation ECN. Furthermore, start-up firms have been initiated on SOFC components (‘InDECO) and SPFC stacks and systems (‘NedStack). Also field tests are being performed or initiated of SOFC and SPFC systems.

Spain

In Spain, a 15 MEUR over 5 year program is carried out by Spanish utilities for the development of MCFC. Support to fuel cells is part of the Spanish RTD&I National Plan for 2000 – 2003. Fuel Cells appears as a transversal priority through the programme of Energy (fuel cell components/tests/control/simulation/design, electric propulsion with fuel cells) and the programme of motor vehicles (electric-gas-, hybrid-cars).

Italy

In Italy, fuel cell R,D&D is carried out since 1987, with a yearly budget of around 5 MEUR; both government and industry contributed to this programme. Until now, the main effort was directed towards the development of MCFC, for the decentralised co-generation, and PEMFC, mainly for transport applications. Minor R&D activities were carried out in the field of materials and components for SOFC. A new research programme with a budget of 7 MEUR over the next 3 years was decided by the Italian government in November 2000 to support the fuel cell effort. This new programme will go on to focus on PEMFC and MCFC reinforcing the development of PEMFC for stationary applications taking into account the re-oriented objectives of the new company Nuvera (result of the Epyx and De Nora alliance) and of SOFC in support to Enitecnologie.

Denmark

Danish national program aims at establishing technologies to make planar SOFC stacks for decentralised co-generation of electricity and heat. 27 MEUR were spent during the 1990-1999 period with a decline towards the end of the decennium. A new 5 years continuation was recently agreed upon with a combined public and industrial funding for 2000-2002 of 7 MEUR. This includes the establishment of a pilot plant for up-scaling of fabrication technologies. Other
activities related to the actual SOFC-development amount to 2 MEUR.

**United Kingdom**

Since 1992, the United Kingdom government started a fuel cell program which focussed on SOFC and SPFC. Public funding amounted to around 2 MEUR per year. To the end of July 2000, the programme extended to SOFCs, SPFCs, PAFCs, MCFCs and AFCs including generic studies representing in total 138 projects with a total value of about 130 MEUR. The aims of the future programme are under preparation and would most probably permit to support also field trials and demonstrators of complete fuel cell systems.

**Sweden**

The Swedish national fuel cell program runs for the period 1998-2001. The Swedish government has divided the program into two parts: one with funding exclusively devoted to universities and the other jointly funded by the government and the industry. The total budget for the program over the four years is 3 MEUR. The university program is concentrated on the development of MCFC (modelling, alternative cathode material, heat transfer analysis, BoP) and SOFC(heat transfer analysis, BoP, integration with gas turbine) and generic studies while the other program also involves PEMFC (material studies, assessment of fuel cell vehicles).

**Switzerland**

Apart from the fuel cell activities in the European Union, research is also carried out on SOFC in Switzerland supported by the Federal Office of Energy. This programme is led by Sulzer Hexis. Switzerland also supports since many years research activities on PEMFC at Paul Scherrer Institute (PSI). In 2000, the research activity has been enhanced by two new contracts co-financed by the Federal Office of Energy. Thus the total annual expenditures were almost doubled from about 0.5 MEUR per year to 1 MEUR for the year 2000. The PEMFC activity will increase in 2001 in direction industrial fabrication of the PSI-PEM. It is foreseen to equip a Volkswagen automobile as well as boats with these cells.

**DEVELOPMENT OF SOFC IN EUROPE – INDUSTRIAL PROGRAMMES**

Today, the European industries devoting substantial resources on SOFC development and manufacturing are Rolls-Royce (UK) and ALSTOM (UK) inside the Union and Sulzer Hexis(CH).

In United Kingdom **Rolls-Royce plc** has been developing an innovative SOFC concept over the past eight years. The technology, known as the Integrated Planar SOFC, combines attractive features from both planar and tubular stacks to optimise the balance between performance, manufacturability and cost. Rolls-Royce has achieved very competitive cell current densities and has designed and demonstrated a 1 kW stack through a number of iterative design steps.
Rolls-Royce is leading the “MF-SOFC” framework five programme, the main aims of which are to design and develop a 20kW atmospheric modular stack which meets commercial cost, durability and reliability targets. In addition design and manufacturing specifications will be developed in conjunction with a cost model to determine the production volume required to achieve short and long term cost targets. MF-SOFC is a three year Euro 9 million programme, involving a number of European partners, namely RISOE National Laboratory (DK), Gas de France, Imperial College (GB) and Advanced Ceramics Ltd (GB).

Rolls-Royce will also be leading the “IM-SOFC-GT” framework five programme. The project will aim at developing the capability to assess the performance of Fuel Cell/Gas Turbine hybrids using a novel approach of close integration of system and stack models. It will also aim at obtaining specifications of the fuel cell stack, turbo-machinery and other key balance of plant components by combining market understanding and integrated modelling capabilities. IM-SOFC-GT is a 2 and half year Euro 2.9 million programme, involving 9 other European partners, namely Turbec (S), ABB Turbo Systems (CH), Turbomeca (F), Sydkraft (S), University of Genoa (I), Lund University (S), Alstom Power Sweden (S), ENEL (I) and PA Consulting France (F).

ALSTOM has recently expanded its programme on the development of SOFC systems for the distributed generation market. The focus of the activity is on the development of low cost technology with a high level of system integration. In order to reduce costs, ALSTOM is basing its programme on planar SOFC stacks that will operate at temperatures less than 800 °C. Systems designed for operation at these temperatures have significant cost advantages compared to those operating at higher temperatures as the stack and other high temperature components, such as heat exchangers and ejectors, can be constructed from low cost stainless steels. As part of this programme ALSTOM is leading a collaboration with Forschungszentrum Juelich (D) and Prototech (No) which has the aims of testing a 5 kW stack and of developing a low cost concept for a 20 kW system. ALSTOM also co-operates closely with Forschungszentrum Juelich (D) and ECN (NL) on the development of stack technology based on the anode-supported-cells concept.

In Switzerland, Sulzer Hexit Ltd. is developing and manufacturing micro scale SOFC systems for decentralised electricity and heat generation in single households. Sulzer started their program in 1991, and in 1997 the first 1 kWe field test system was realised. In 1998, a second generation field test system was launched. Since the end of 1998, four field test systems are running at the sites of different partners. The partners are city utilities -AET Basel (CH) and EWE Oldenburg (D)- and large gas suppliers -ThyssenGas (D) and Tokyo Gas (J). All systems are running with natural gas and are connected to the electrical grid. The maximum power output is 1-1.5 kWe at an electrical efficiency of 30-35%. The exhaust heat is used for heating and warm water supply. In 1999, three more systems will be installed. The field tests will be discontinued in December 2001. In parallel, Sulzer has started focusing on system integration, cost reduction and compatibility with industrial production. Sulzer wants to launch a first commercial 1 kWe system in 2001 together with two additional field test partners i.e. Gas de Euskadi from Spain and Gasunie from the Netherlands. The system has an additional gas heater if the exhaust heat (1-2 kW) is not sufficient. In 1999, Sulzer has started a program together.
with the Swiss oil industry to develop a comparable system running on heating oil. The main task is the development of the fuel processor. At the end of 1999, a first 1 kWel field test system running on heating oil was in operation. Research on SOFC is being carried out in cooperation with the Swiss Federal Institute of Technology (EPFL) of Lausanne (interface reactions and exchange phenomena), as well as with the Federal Institute of Technology of Zurich (ETZH).

World wide, Siemens (Germany) is one of the largest key player in fuel cell technology. Through its subsidiaries KWU (Germany) and Siemens Westinghouse (U.S), the company has centered its capabilities on development of the SOFC and PEMFC for power generation purposes. Up to 1998, Siemens (Germany) also devoted substantial resources to the development of a planar SOFC concept. The first international collaboration dates from 1990, when an EC project involving Siemens (D); ECN (NL), Imperial College (UK) and Alstom (UK), aimed at developing a flat plate SOFC with metallic bipolar plates and with a multiple cell array. A SOFC stack with multiple array cells giving an output of 10 kW was successfully tested. This work was continued in FP4 with the addition of new partners: BG (UK), Enitechnologie (IT) and Electricité de France (FR) (EC funding of 4.8 MEUR). The goal of this activity was to demonstrate a 50 kW class SOFC system based on the planar array concept, along with the development of other auxiliaries including the pre-reformer and the power conditioning and control. After the successful demonstration of the increase of the bipolar plate size, the doubling of the power density at reduced operating temperature and the improvement of the sealing technology, this project was terminated (in February 1999) before the demonstration of the final goal. Siemens indeed decided to discontinue the work on planar SOFC technology and to concentrate only on tubular SOFC technology developed by Westinghouse (now Siemens Westinghouse Power Corporation). This decision was based on the fact that the tubular design was at a more advanced development stage. The Siemens Westinghouse SOFC is based upon the seal-less tubular design operating over a range of 800-1000 °C. This technology has already been demonstrated successfully (~ 13,000 hours without detectable degradation) in a 100 kW plant Westervoort, the Netherlands. In California, Siemens Westinghouse announced the demonstration of a 220 kWc SOFC/gas turbine hybrid power system to be delivered to Southern California Edison. In February 2000, Siemens Westinghouse and Norske Shell announced the first demonstration of a 250 kWc SOFC plant in Norway with CO2 capture and sequestration into depleted oil and gas reservoirs. In Europe, two 320 kWc demonstration SOFC/GT hybrids should be put into operation in 2002 by RWE Energie AG (Germany) and Edison (Italy). These projects will be followed by a 1 MW SOFC/gas turbine hybrid system at 3 bara which will be operated in 2003 by Energie Baden-Wurttemberg AG, Electricité de France, Gaz de France and Austria’s TIWAG. This project co-funded by the EC (3.9 MEUR) under the Fifth Framework Programme and the DoE implements for the first time in the field of fuel cell the co-operation between US and EU. Today, the accumulated know-how by Siemens KWU on planar SOFC especially on material research and process development is also used to improve the tubular technology. This effort is also co-funded by the federal German government.

The R&D activities in Forschungszentrum Juelich (FZJ-Germany) on SOFC are part of the
Research Center’s research priority of energy technology. The project involving several institutes is primarily intended to advance the further development of Juelich’s substrate concept, a planar fuel cell technology with 5-10 μm thin electrolyte and a strength-carrying anode substrate. This advanced SOFC variant provides an extraordinary development potential in terms of higher power density at reduced operating temperature, which has been demonstrated on laboratory units in the past few years. On this basis, the next development phase (3-5 years) will involve the realisation of a cell, stack and system technology to be mass produced as the R&D goal with a unit power size of approx. 10-20 kW. In order to achieve this goal, the SOFC activities at FZJ are embedded in an international development consortium receiving additional financial support under national (German Federal Ministry of Economics, BMWi) and European (EU) support programs. In addition to this largely technology-oriented effort, the above activities are supported and validated by materials scientific investigations and theory-oriented work to derive new SOFC basic data.

**Fraunhofer-IKTS (Germany)** develops SOFC stacks up to an output of 25 kW_{el} in cooperation with the company “Developing Society Fuel Cell“ (Entwicklungsgesellschaft Brennstoffzelle (EBZ) – GmbH) on the basis of the former planar SOFC technology of Siemens for decentralised household applications.

The national Danish program on Solid Oxide Fuel Cells with 27 MEUR between 1990-1999 develops fundamental knowledge of materials and processes in parallel to the development of design, performance models and fabrication technologies for cells and other bipolar flat plate SOFC stack elements. The project participants include universities, industries, power companies and Riso National Laboratory. The first development campaign (1990-96) demonstrated a 0.5kW_{el} stack with electrolyte supported cells over 2000h at 1000°C. Interactive economic modelling was used to reduce the projected overall stack mass production cost below 3000 Euro/kW_{el} by modification of design details and materials composition. However, the high operation temperature implies the use of high-cost constructional materials for at least part of the balance-of-plant. Reduced temperatures are required to minimize cost of complete plants. Consequently a new cell type for operation in the temperature range 750-850°C became a main target for a second development campaign (1997-99). The resulting anode supported cell has a thickness of 250μm and current densities up to 2 A/cm² have been measured at 0.5V. High strength and flexibility during handling removes the size limitations imposed on previous electrolyte supported cells by their brittleness. The present maximum cell size of 22x22 cm² seems limited solely by the size of the ceramic shaping equipment. The performance improvement allows operation below 800°C and enables the use of cheap ferritic steel interconnects. The projected stack mass production cost is below 300 Euro/kW_{el} and due to the temperature impact on BOP materials a total plant cost well below 2000 Euro/kW_{el} is anticipated.

In the European project IDUSOFC ended in 1999 (EU support : 2,5 MEUR), led by Risø National Laboratory (DK), cells developed showed low performance losses during thermal cycling (0.01%/cycle) and the degradation rate was below 1% per 1,000 hours up to 0.3A/cm². It was shown that operation temperature was not a main parameter in controlling the
degradation rate. Most important was the current density, which grossly affected the durability of both the anode and the cathode. Also the fuel utilisation proved to be of significant importance for the anode durability. The contacts between cell and metallic interconnect were improved, but further investigation is necessary. Future challenge is to reach similar durability for anode supported cells with thin electrolytes allowing current densities of about 1A/cm². High performance anode-supported cells have already been developed in several European national projects in Denmark (Risø), Germany (FZ-Juelich), The Netherlands (ECN) and the UK (Rolls-Royce). This will be a major step towards meeting the economic demand necessary for commercialisation.

In the European LOCO-SOFC project ended in 1999 (EU support : 1,9 MEUR) also led by Risø (DK), low-cost fabrication of SOFC components is being achieved by the use of screen printing, spray deposition and tape casting techniques, and by aiming at the use of more environmentally friendly inks and slurries. Improved performance, including durability, is obtained by the fabrication of thin electrolyte and electrodes with enhanced performance at low temperatures (down to about 800°C). A lanthanum-chromite with good conductivity has been notably developed.

An approved continuation of the program for 2000-2004 expands previous project targets by including the up-scaling of fabrication techniques to enable continuous operation. The up-scaling element has been started with intensive participation of industry, part of the project being the build-up of a pre-pilot plant for cell production. The plant is expected ready for standard production of anode supported cells from 2002. Development of methods for non-destructive characterisation of cells are also planned as well as intensified stacking activities with cells, produced by the plant. Public demonstration of Danish cell- and stacking technologies are planned for 2002-2003 in units with a few kWₑ output. The continuation of the European co-operation is judged important by the Danish program for pre-competitive development topics such as establishment of knowledge on generic lifetime limiting factors, the development of Ni-free, rugged anodes, and for the adaptation of SOFC techniques to high temperature electrolysis as a means for energy storage.

In the Netherlands, the SOFC efforts are mainly being implemented by the Netherlands Energy Research Foundation ECN. The budget for the year 2000 was 3 MEUR. The SOFC programme focuses on the development of planar cell specifications and manufacturing procedures. R&D goals are dictated by the requirements from the stack and system developing parties ECN co-operates with: i.e. cost reduction, performance improvement, mechanical integrity of the cells, internal reforming, sulphur tolerance and the extension of the range of operating temperature. Both, the electrolyte and the anode supported cell types are under development or optimisation.

In September 1999 a small company called InDEC pilot productions has been established as a full subsidiary of ECN. InDEC manufactures cells according to protocols developed by ECN and sells them non-exclusively to third parties.

Within the electrolyte supported cell development line the major collaboration is with Sulzer Hexis (CH). In 2000 a successful Sulzer Hexis field test, equipped with cells that were developed by ECN and manufactured by InDEC, has been performed at Gasunie in the Netherlands. The cells in the stack were optimised for resistance against oxidation-reduction.
cycles.
The anode supported cell development is related to the commercialisation of SOFC-CHP systems (over 40 kW_e) within the consortium consisting of Alstom (United Kingdom), Forschungszentrum Juelich (Germany), Prototech (Norway) and ECN. Recently collaboration with Fuel Cell Technologies Ltd. (Canada) aiming for the commercialisation of domestic CHP systems has been started.

In Norway, two major projects have focussed on the development of flat plate SOFC. A project from Statoil (1991-1997), with an average annual budget of 2 MEUR, led to the demonstration of a 10 kW class planar natural gas fuelled SOFC system in 1997. This unit was equipped with an integrated Balance of Plant, i.e. pre-reformer, high temperature heat exchangers and afterburner. Prototech (main contractor to Statoil for the SOFC development) continues this development. Prototech is focussing on BOP components and systems (yearly budget ~0.6 MEUR, EC, national, private) and has a co-operation with Alstom and Forschungszentrum Juelich supported by the EC. Two Norwegian companies and one research organisation (SINTEF) also co-operated in another 3 year collaborative project (yearly budget around 1.6 MEUR) which terminated in 1994.

Gaz de France (GdF) created a small Fuel Cell team in 1993 with the major objective to promote the use of natural gas fuel cells. A first project aimed at developing low cost deposition techniques such as screen-printing, tape casting and spray painting, for the manufacture of high performance, intermediate temperature SOFC. A second project (1998-2000) aims at integrating a catalytic partial oxidation reactor into a SOFC system from Sulzer Hexis in order to replace the existing steam reformer which requires a costly water purification unit. In the future, work on SOFC at Gaz de France will continue with a higher emphasis on the compatibility of SOFC anode materials with the complex composition of natural gas. This includes the study of the effects of sulfur compounds and those of the variation of natural gas composition both in space and time. Gaz de France also contributes to the 1 MWe SOFC/gas turbine demonstration project supported by the EC.

At Electricité de France (EDF), an extensive numerical modelling activity on SOFC was performed with the aim of simulating the static and dynamic behaviour of SOFC cells, stack and system under various operating conditions and their interactions with the grid. A numerical model of electronic power converter has also been developed to simulate the interface between the fuel cell and the grid. EDF is also leading a national project on the development of low temperature SOFC materials and low cost manufacturing techniques of planar cells in collaboration with Rhodia, the CEA, and the universities of Toulouse, Bordeaux, Grenoble and Dijon. EDF also participates to the 1 MWe SOFC/gas turbine project supported by the EC.

The SOFC activities in Sweden are theoretical and carried out by two groups at Lund University and Royal Institute of Technology in Stockholm. The focus is on stack and system modelling including hybrid SOFC/gas turbine systems. Swedish Energy administration sponsors the work under a Stationary Fuel Cell Research Program".

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Table 2, shows the results of the latest SOFC developments carried out by the main developers in Europe.

| Tubular | Planar | Many cells (matrix or series) per planar surface |
|---------|--------|--------------------------------------------------|
| One cell per tube | One cell per planar surface | Ceramic inter-connectors |
| Metallic inter-connectors | Ceramic inter-connectors | Metallic inter-connectors |
| Thick electrolyte | Thin electrolyte | Thick electrolyte |
| Siemens Westinghouse | Sulzer Hexis | Forshungszentrum Juelich |
| (100 kW, 1998, 1152 cells 200-250 mA/cm² 1000°C, 83% NG) | (1 kW, 2000, 70 cells, 270 mA/cm² 0.175 W/cm² 900°C, x% NG) | (1.6 kW, 2000, 10 cells, 610 mA/cm², 800°C, 44% H₂) |
| ECN | (0.09 kW, 2000, 5 cells, 250 mA/cm², 950°C, steam ref. NG at SCR=2.5) | ECN | (0.054 kW, 2000, 3 cells, 250 mA/cm², 800°C, 4g/hr/cell ref CH₄) |
| Riso | (0.5 kW, 1995, 50 cells, 300 mA/cm², 1000°C, 40% H₂) | Riso | (0.47 W/cm², 1999, 1 cell, 560 mA/cm², 0.7 V 850°C, 97% H₂) |
| Siemens (stopped) | (7.2 kW, 1998, 2 stacks of 50x4x4 cells, 400 mA/cm², 900°C, 30% H₂) | Rolls Royce | (1 kW, 2000, 27x20 cells 385 mA/cm², 970°C, x% H₂) |
CONCLUSIONS

Europe expects that FC applications will play an important role in our future energy economy and could in the longer term replace a major part of the conventional energy systems in all targeted end user sectors. With natural gas, fuel cells have in the medium term a great potential for energy saving with a significant reduction of CO₂ and other pollutants. In the long term, FC should form an integral part of a Renewable Energy Sources based energy supply with hydrogen as a very promising energy vector that can be produced from several primary energy sources including fossil, renewable and nuclear. The penetration of FC into the energy market should lead this future hydrogen based economy.

The potential market for FC is huge and its emergence comes at an opportune time. The growth of the information economy, the potential impact of the Kyoto Protocol along with an increasing public environmental awareness, market liberalisation, a forecast of an unprecedented demand for electricity, and the growing trend for distributed generation and clean vehicles are all pushing FC towards centre stage. In many ways the transition that is taking place in the power and car businesses is similar to what happened in the computer industry not that many years ago.

The public support to SOFC at European level continues. In the non-nuclear energy program of the EC, a last call was launched for the two remaining years (2001–2002) of FP5 actively stimulating RTD effort for the short and medium/long terms on fuel cells and hydrogen technologies for stationary, mobile and portable applications also including socio-economic, pre-normative research to develop standards, safety norms, and training.

In addition, the EC is exploring the establishment of a network structure supporting a EU FC and H₂ Advisory Group. It aims at assisting the Commission in promoting the establishment of a European Research Area including, inter alia, support in identifying and developing opportunities for co-ordination and collaboration between EU and national RTD programmes, or other relevant actions, such as international co-operation.

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