ANL-94/46

EUROPEAN FUEL CELLS R&D REVIEW

Final Report
Purchase Order No. 062014

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September 1994

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Operated by The University of Chicago
under Contract W-31-109-Eng-38
for the U.S. Department of Energy

FUEL CELLS IN TRANSPORTATION

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FOREWORD

This report documents work performed by ETSU (now known as AEA Technology) for Argonne National Laboratory under Purchase Order No. 062014, European Fuel Cells R&D Review. The objective of this work was to determine the status of fuel cell development in Europe by 1) reviewing the research, development, and demonstration activities underway, 2) identifying the key European organizations active in the development of fuel cells, and 3) detailing their future plans.

The alkaline, phosphoric acid, proton-exchange-membrane (polymer), direct methanol, solid oxide, and molten carbonate fuel cell technologies were reviewed in each country in which development is underway. Activities in the 12 Member States of the European Community, Switzerland, and Austria were scrutinized most closely; less detail is provided on the Scandinavian countries of Finland, Norway, and Sweden.

This work was undertaken in support of the U.S. Department of Energy, Energy Efficiency and Renewable Energy, Office of Transportation Technologies, which is developing fuel cell technologies for transportation applications. Walter F. Podolski of the Chemical Technology Division was the project manager at Argonne National Laboratory. Philip Michael was the project manager at ETSU.

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EUROPEAN FUEL CELLS R&D REVIEW

FINAL REPORT

SUMMARY

This Report presents the results from a European Fuel Cells R&D Review, undertaken by ETSU on behalf of the US Department of Energy (DOE). The principal aim of the Review is to present the DOE with a statement on the status of fuel cell development in Europe; addressing the research, development and demonstration (RD&D) and commercialisation activities being undertaken, identifying the key European organisations active in the development and commercialisation of fuel cells and detailing their future plans. The principal conclusions from the Review are as follows.

- Many organisations and countries in Europe are demonstrating phosphoric acid fuel cell (PAFC) systems, largely for cogeneration applications. There is one PAFC system being demonstrated in a bus. The stacks for these demonstrators are supplied by US and Japanese companies.
- The main European solid oxide fuel cell (SOFC) programmes are those of Siemens and Dornier in Germany. Sulzer (Switzerland) and Statoil (Norway) have both made rapid initial progress using US cell technology.
- On molten carbonate fuel cells (MCFCs), BCN/ECN of the Netherlands have an ambitious programme, aimed at 250kW systems by 1995, leading to field trials of complete systems by 1998. Other European MCFC programmes mainly rely on imported stack technology.
- For polymer electrolyte fuel cells (PEFC), there has been a significant growth in R&D activity in recent years. There is particular emphasis on transport applications, and growing interest in PEFCs for small-scale cogeneration. Many European organisations are gearing their programmes towards satisfying the Californian Zero Emission Vehicle (ZEV) markets from 1998. The collaboration between Daimler-Benz and Ballard (of Canada) is likely to make a significant contribution to the development of PEFC systems for transport. Johnson Matthey (UK) is also working with Ballard, to develop improved stack components. Stacks are being developed by Siemens (of Germany) and De Nora (of Italy).
- Siemens is making significant progress on the direct methanol fuel cell (DMFC).
- The only significant activity on alkaline fuel cells (AFCs) is that led by Elenco. Its AFC bus will be operating on the streets of Brussels and Amsterdam during 1994.
- The overall expenditure in Europe on fuel cells RD&D is estimated to be in the region of \$64million/year.

- A number of American organisations have been identified as active in Europe, either through supplying fuel cell components and systems, or collaborating with European organisations on research and development.

1. INTRODUCTION

ETSU has been commissioned by the US Department of Energy (DOE) to undertake a European Fuel Cells R&D Review (Argonne National Laboratory Purchase Order 062014). The principal aim of the Review is to present the DOE with a statement on the status of fuel cell development in Europe, addressing the research, development and demonstration (RD&D) and commercialisation activities being undertaken, identifying the key European organisations active in the development and commercialisation of fuel cells and detailing their future plans.

This document presents the Final Report from the Review. It describes the RD&D activities in Europe on Alkaline, Phosphoric Acid, Polymer Electrolyte, Direct Methanol, Solid Oxide and Molten Carbonate Fuel Cell types. The information has been drawn from the public domain, from ETSU's in-house database and supplemented by information gathered by personal contacts throughout the countries being studied.

It gives a description of the European Commission's (EC's) activities, its role in the European development of fuel cells, and its interaction with the national programmes. It then presents a country-by-country breakdown of the RD&D and commercialisation activities being undertaken in all 12 Member States of the European Community, Switzerland and Austria. For each country, an overview is given followed by a detailed description of its activities, presented by fuel cell type. The Scandinavian countries of Finland, Norway and Sweden are also addressed, but in less detail. All powers quoted are "kW_e" and, for simplicity, all estimates of funding are provided in US dollars. The Report also identifies a number of American organisations that are active in Europe, either through supplying fuel cell components and systems, or in collaborating with European organisations on research and development and commercialisation of fuel cells.

Two appendices are attached to this Report. The first presents, in a tabular form, a summary of the European fuel cell activities by fuel cell type. The second appendix provides a brief description of the main fuel cell types.

2. THE EUROPEAN COMMISSION

The European Community funds fuel cell R&D and demonstration activities in Europe through the European Commission (EC) in Brussels.

The European Community co-ordinates research through its "Framework" programmes, implemented by the EC's Directorate General XII for Science, Research and Development (DGXII). The Framework programmes in the field of Technological Development and Research sets aims and priorities and outlines budgets for EC research support over 5 year periods. The Third Framework programme is currently in place but is due to finish in 1994.

EC support to fuel cell R&D activities forms part of a much larger EC research programme on "Non-nuclear energies and the rational use of energy". The EC is a key player in European fuel cell R&D activities at present and it is likely that it will play an increasingly important role in the future, as a growing amount of European RD&D is being funded by the EC.

The EC's DGXII has supported R&D into all the main types of fuel cells for many years, with a significant growth in its activities since 1985. Between 1985 and 1989, emphasis was placed on the research and development of MCFC and SOFC technology and on encouraging the development of AFC. Between 1989 and 1992, the DGXII's JOULE programme supported the industry-led development of SOFC and MCFC and basic R&D on DMFC, undertaken at universities. From 1992 to 1995, the JOULE-II programme has continued with the development of SOFC and MCFC and the basic research into DMFC. PEFC systems are also being addressed through stack development, systems integration and reformer development.

In 1993, the EC extended its JOULE-II programme through a "top-up" to its JOULE-II budget; these additional projects are due to start early in 1994. Full information on the projects being supported under the JOULE-II top-up is still confidential as not all the contracts have yet been finalised.

In addition to the specific fuel cell activities supported under the JOULE programmes, the EC's DGXII BRITE-EURAM (Industrial and Materials Technologies) programmes also support R&D on fuel cells, through basic materials research.

Table 1, below, presents estimates of the total cost of EC DGXII supported fuel cell R&D over the period from 1985 to the present.

The expenditure estimates presented in Table 1 give the total cost of the EC supported fuel cell R&D activities. In general, the EC provides up to 50% of the costs of an individual R&D project supported under its programmes. The remaining costs are provided by the industrial participants and/or their national Governments. The EC does provide up to 100% funding for research carried out at universities.

Table 1
EC DGXII Funded Fuel Cell R&D Programmes - Estimated Total Expenditure

	1985-89	1989-92	1992-95	1994-97
DGXII PROGRAMMES				
R&D	\$10million			
JOULE		\$16million		
JOULE-II			\$30million	
JOULE-II "top-up"				\$16million
BRITE-EURAM	\$16million			

The EC also supports the demonstration of fuel cell systems that are nearer the market through its Directorate General for Energy (DGXVII), responsible for the THERMIE

energy technology demonstration programme. The THERMIE programme has supported PAFC and MCFC demonstrations, using stacks purchased from the USA and Japan. EC demonstration activities have been at a lower level of effort than R&D on advanced fuel cell systems. Between 1986 and 1992, the EC DGXVII supported 6 demonstrations, with a total cost estimated to be in excess of \$14million; 50% of this funding was from the EC. It is likely that further development work to advance the status of fuel cell technologies will be required before DGXVII can justify further demonstration.

Table 2
EC DGXVII Funded Demonstration Programmes - Estimated Total Expenditure

	1985-89	1989-92	1992-95	1994-97
DGXVII PROGRAMMES				
THERMIE	\$14million			

Clearly, there is much fuel cell R&D being undertaken in Europe that does not involve the EC directly. At the International Fuel Cell Conference in Japan, 1992, the EC estimated that the overall spending on fuel cells in Europe was \$64million/year. This is the total funding from all sources for all applications; it includes the contributions from the EC programmes, from national Governments and from European industry. It is considered that the level of overall European fuel cell activity and funding has increased since the EC made these estimates in 1992.

The EC is currently developing its Fourth Framework programme, which is expected to commence in 1995. Much closer co-operation and co-ordination between the R&D activities of DGXII and the demonstration activities of DGXVII is expected in this programme. Throughout 1994, European industry and national programme representatives are contributing to the development of the EC's strategy for fuel cells RD&D and commercialisation, through consultation and workshops with DGXII and DGXVII staff. ETSU is actively participating in this exercise.

No firm information on the EC's future plans is yet available. However, the EC has indicated its intention to increase its expenditure on fuel cells for transportation, particularly PEFC systems, with emphasis on PEFC stack cost reduction, methanol reforming and the integration of PEFC systems into vehicles. It is therefore expected that the EC will attach a higher priority to PEFC systems than it has have previously, particularly for transportation, but also for cogeneration applications. The EC is also expected to continue to support fundamental research on the DMFC. For SOFC, the EC's future target is the development of a 100-200kW prototype system by 1997. For MCFC, its goal is to produce a 100-200kW internal reforming prototype by 1996.

The EC is also considering an "urban fuel cell network", which would include a large scale central reformer supplying hydrogen to a number of distributed stacks for cogeneration, possibly integrated with an urban transport system; however, there are no firm proposals at present.

Overall, the EC's budget for the Fourth Framework programme is to be \$12.3billion. This is an increase by a factor of two since the Third Framework programme. Of this overall budget, the EC's budget for non-nuclear energy RD&D, including work on renewable energy and improved energy conversion, is to be \$1billion. Fuel cells and electric vehicle RD&D will be supported from within this non-nuclear energy budget.

No detailed information on the specific fuel cells budget is available. However, on the basis that the EC's overall budget has doubled between the Third and Fourth Framework, it is estimated that the EC's budget for fuel cells RD&D will be in the region of \$60million over the five year period of the Fourth Framework programme. As stated above, the EC's contribution to RD&D generally has to be matched by funding from industry or national governments. Thus it is estimated that the total cost of fuel cells RD&D to be supported by the EC under the Fourth Framework programme will be approximately \$120million. The EC will finalise its budgets towards the end of 1994.

The programmes of the EC require collaboration between its Member States. Many of the national programmes described in this report interact with each other and with the EC programmes; the participants in the national programmes frequently receive funding from Brussels as part of its JOULE and THERMIE programmes. The activities of the individual countries are described below; where EC funding has been provided to the national activities described, this is identified.

Finally, in addition to the specific fuel cell activities of DGXII and DGXVII, the EC has other programmes that involve the development and demonstration of fuel cell systems.

The EC is supporting the Euro Quebec Hydrogen Hydro Pilot Project (EQHHPP). The EQHHPP is evaluating the feasibility of a "hydrogen economy". As part of this project, two hydrogen fuelled buses (one powered by PEFC and one by PAFC) and a PEFC powered boat are being developed. The total cost of the EQHHPP is \$45million over 8 years-this expenditure is in addition to that stated for fuel cells, above. The EC's Joint Research Centre at Ispra (in Italy) is leading this project.

Table 3
EC Euro Quebec Hydrogen Hydro Pilot Project - Estimated Total Expenditure

	1992-97
EQHHPP	\$45million

Fuel cell systems are also being developed in the EC's EUREKA programme. In this programme, the EC acts as a stimulus for promoting collaboration between European industry, which provides its own funding. The Elenco AFC bus demonstration project is an example of a collaboration undertaken within the framework of the EUREKA programme. The EC does not provide funding to this project.

3. EUROPEAN FUEL CELL RD&D AND COMMERCIALISATION ACTIVITIES BY COUNTRY

In this section, the fuel cell RD&D activities throughout Europe are described for each country being studied. The information provided on expenditure and budgets is estimated.

The information given in this Section is also summarised, in a tabular form, in Appendix A. The tables presented in Appendix A provide a useful summary of European fuel cell activities, presented by fuel cell type.

3.1 United Kingdom

The focus of the UK's fuel cell work is the Department of Trade and Industry's (DTI's) Advanced Fuel Cells Programme, managed by ETSU. This programme started in April 1992, although UK industry and researchers had been active for some time prior to this. The DTI's programme is currently focused on PEFC and SOFC technologies, aiming to contribute to the world-wide development of these technologies. The programme is industrially focused and UK industry is strongly involved, participating actively in the research. R&D is funded jointly with industry and the programme also participates in the programmes of the EC and the International Energy Agency (IEA).

In addition to the DTI, the Government's Engineering and Physical Sciences Research Council (EPSRC), formerly known as the Science and Engineering Research Council (SERC), funds fundamental research at UK universities. The DTI and the SERC are co-ordinating their fuel cell research programmes.

3.1.1 PAFC

Although the DTI's programme is not at this stage specifically addressing PAFC, a number of UK organisations see PAFC as an important technology. Its demonstration in the UK could increase awareness of fuel cell technology in the UK energy markets, and help develop UK systems expertise. PAFCs are not seen as a strong candidate for transport applications in the UK.

The principal UK activity is that of EA Technology which is collaborating on a 3 year programme with Imatran Voima Oy (IVO) of Finland on the demonstration of a 200kW ONSI PAFC in a cogeneration application; this facility was commissioned in 1993 at the Vanaja Power Station near Hameenlinna in Finland, and has been successfully operating since then. A number of the UK Regional Electricity Companies and electricity utilities are contributing to funding this work, through EA Technology.

Many other organisations are developing supporting systems, which, although largely for PEFC, could also be utilised in PAFC systems. These are described further in the section giving the UK's activities on PEFC.

The only other UK organisation that is presently involved with PAFC systems is Johnson Matthey, who is the world's leading supplier of catalysts for PAFCs.

3.1.2 SOFC

Imperial College is a leading SOFC materials development group. It is currently focusing on identifying and developing new materials to reduce the operating temperature of the SOFC.

Imperial College participates in an EC project led by Siemens (Germany). Its role in this project is to investigate materials that will operate on methane in the temperature range 700-800°C; the current operating temperature of Siemens technology is 900-1000°C. Imperial College is investigating cells based on duplex electrolytes comprising a self-supporting ceria gadolinia layer and a thin (10µm) layer of yttria-stabilised zirconia. Ceria exhibits significant electronic conductivity at these temperatures and it cannot therefore be used alone in the electrolyte. New cathodes based on lanthanum iron cobaltite are also being developed.

Imperial College also has a significant new programme on intermediate temperature SOFCs for transport applications. This is a three year project supported by the UK EPSRC. The cells are based on thick film ceria electrolytes, lanthanum cobaltite cathodes; a number of oxide materials are still being evaluated for the anode. The cells operate directly on methanol at about 400-500°C. The current performance of these cells is 150-200mAcm⁻² (compared with an ultimate target of 500mAcm⁻²). The performance is currently limited by the anodes; work is underway to develop new mixed-conductor oxide anodes. Imperial College has estimated that these low temperature SOFC stacks could be manufactured for less than \$130/kW. However, this technology is still in its early stages of development and much work is still needed to develop the concept and improve its performance towards that required for commercial application.

The Rolls-Royce Applied Science Laboratory is leading a project to evaluate a novel stack design with an integrated heat exchanger, the Integral Planar SOFC (IP-SOFC). Rolls-Royce collaborates with British Ceramic Research Ltd, Imperial College and the Universities of Birmingham and Keele in this work, which started in 1993. The IP-SOFC has potential advantages over existing stack designs in terms of ease of scale-up, thermal integration and sealing. The stack is capable of incorporating either supported or self-supported cells. Thick-film supported electrolyte cells are also being developed under this project.

British Gas is leading a stack development project, supported by the EC JOULE-II programme; it also involves Tioxide Specialties and BNFL (UK), Risø (Denmark) and TNO (the Netherlands). This project aims to establish the feasibility of a novel SOFC design based on a composite cell comprising an electrolyte plate with interconnect

inlays. The composite plate design is expected to offer advantages in terms of increased cell voltage, reduced materials requirements and, therefore, reduced cost. The target for July 1994 is to demonstrate a power density of over 1kWm^{-2} at 0.6V with a degradation of less than 5% over 100 hours. There is some doubt as to whether this target will be met as the project has encountered problems in making the zirconia/lanthanum chromite plates. It has proved very difficult to produce a gas-tight plate because of the difference in thermal expansion of the two materials. British Gas' main role is cell testing; Tioxide is working on composite plate fabrication and BNFL is using computer modelling to optimise the cell design.

Keele University is to investigate an alternative tubular design as part of an EC BRITE-EURAM project starting in May 1994. This design is based on extruded narrow-bore tubes that are thought to offer increased resistance to thermal shock. Partners in this project include Sapco (France) and Viking Chemicals (Denmark). In a separate project, Keele is investigating a composite interconnect plate comprising a zirconia sheet with lanthanum chromite "rivets". This may be a lower cost option than the conventional ceramic interconnect, also offering the prospect of increased strength.

In addition, GEC Alsthom and Cookson work on the EC JOULE II programme led by Siemens and Dornier respectively. Both are currently focusing on the development of sealing and bonding materials. GEC Alsthom has considerable expertise in this area and has successfully developed high resistance glass-ceramic bonds for both ceramic-ceramic and ceramic-metal bonding.

British Gas is also addressing the SOFC balance of plant requirements. British Gas and Eniricerche (Italy) are now starting a three year programme, part funded by the UK DTI (through ETSU) and the EC, to build a balance of plant test rig. They will design, build, commission and operate a pilot scale "SOFC" system using a simulated SOFC stack. The aim is to investigate system engineering issues and control strategies, including start-up and shut down, transient response and failure mechanisms. This project will also provide a test bed for 1-5 kW SOFC stacks at the end of the project in 1997. British Gas sees small-scale cogeneration as the primary market for SOFCs, with particular interest in industrial applications where steam is required.

British Gas is also researching internal reforming. This is expected to be a major advantage of the SOFC but the mechanisms associated with the process are still poorly understood. British Gas is seeking to identify the important parameters, to investigate reaction kinetics and to collect data that would subsequently be used for stack design.

EA Technology is evaluating microwave-assisted firing as a potential process for improving SOFC stack manufacture. The main features of the process are speed and low thermal gradients. This may allow SOFC components to be produced more cheaply, with fewer process steps, and with improved quality.

3.1.3 MCFC

British Gas has the only significant MCFC programme in the UK. British Gas has been working on MCFC since 1987, when it established good links with IGT (US) and ECN/BCN (Netherlands). The current programme includes system studies, catalyst development and evaluation and internal-reforming testing. A new programme with ECN on heat management will start shortly. British Gas has demonstrated 5,000 hours operation using one of its catalysts.

3.1.4 PEFC

The UK has a significant and growing PEFC programme. As stated above, PEFC is being addressed by the UK DTI's Programme, which started in April 1992. However, a number of organisations in the UK were active prior to this. The UK participates in the programmes of the EC and the IEA, and a number of bilateral agreements are in place.

Major activities are focused on the fuel processing system and the membrane electrode assembly (MEA).

Significant improvements in the performance of the MEA have been reported. Johnson Matthey is developing electrodes that achieve high platinum (Pt) utilisation at very low loading. Its targets for the MEA performance are to achieve 20% Pt utilisation at a loading of 0.5 mg cm^{-2} and to identify improved anode catalysts that can tolerate 100 ppm carbon monoxide (CO) in the fuel stream. This work is still in progress. Promising results have been achieved to date. Pt utilisations of 25% have already been demonstrated in half cell measurements; if these results are translated into the stack performance, they can be expected to have a significant impact on materials costs and power density. Furthermore, a number of Pt/base metal alloy catalysts, including Pt/ruthenium and Pt/nickel, have indicated an improved intrinsic tolerance to CO poisoning; this has been achieved through the alloying modifying the platinum's properties to give a reduced CO chemisorptive bond-strength. Work to quantify the effect of this increased intrinsic tolerance is ongoing; further information will be available by mid-1994. Johnson Matthey is also evaluating a range of Pt based catalysts for improved oxygen reduction performance; if successful, this could lead to the development of cells with higher efficiencies and higher power densities. These catalysts are largely based upon those previously developed by Johnson Matthey for PAFC systems. Results from this work should be available during 1994.

Johnson Matthey has recently signed an agreement with Ballard Power Systems of Vancouver, Canada, to jointly develop catalysts and manufacturing processes for the PEFC. The agreement, which is the result of a long-standing relationship between Ballard and Johnson Matthey, provides for cross-licensing of specific technologies developed under the joint programme.. It will bring together the two companies expertise in the field of platinum catalysts and PEFC stacks, aiming to advance the commercialisation of the Ballard PEFC stack. The principal goals of this partnership are cost reduction and performance improvement of the PEFC cell, and the

development of low cost catalysts. As part of this work, a 75% reduction in the amount of catalyst used in developmental cells has already been achieved.

Johnson Matthey is also participating in the International Energy Agency's (IEA) PEFC Annex IV. Loughborough University and Rolls Royce and Associates also participate in this IEA programme, as do a number of American organisations; these include Argonne National Laboratory, General Motors and Los Alamos National Laboratory, contributing the results of their work to model PEFC systems and components.

Loughborough University and AEA Technology at Harwell Laboratory are also researching methods of improving MEA performance. This work forms part of a much larger project with Siemens of Germany, described in more detail in the section on the German programme, below. The focus of Loughborough's contribution to this project is the improvement of electrode design and novel MEA fabrication processes. AEA Technology is evaluating and developing families of membrane electrolytes as possible replacements/alternatives to NAFION and the Dow membrane.

Loughborough University is also developing a small PEFC stack for transport applications and evaluating alternative transport configurations and system trade-offs. This work started in January 1992 and is expected to complete in late 1994. Loughborough is receiving funding from the UK's EPSRC for this work.

Fuel processing for PEFC is an area where a significant amount of work is being undertaken in the UK. Much of this work is aimed at improving the start-up times and load following capabilities of reformers and on reducing the levels of CO provided from the fuel processor to the stack. The work is addressing both methanol and natural gas.

British Gas, is a key player and is involved in a number of areas. With Newcastle University, it is developing a compact steam reformer for natural gas, based on coating compact heat exchangers with combustion and reforming catalysts. It is also developing a reformer based upon ceramic membrane technology; the membrane reduces CO output levels and, as a result of altering the position of chemical equilibrium, reduces the temperature required to achieve a given level of hydrogen generation. British Gas is also developing "clean-up" methanation as a means of reducing CO levels to those currently required by PEFC stacks. The methanation process is based upon catalysts developed for the ammonia production industry.

CJB Developments has been developing methanol reformers and CO selective oxidation systems for PEFC since 1989. This work has been undertaken within its collaborative programme with VSEL (and Ballard of Canada), described below. In parallel with their systems development work, CJB is researching methods of reducing the mass and volume of methanol reformers and of improving heat transfer between the combustion and reforming sections; CJB's current methanol reformer, which has been integrated with Ballard stacks, requires 15-20 minutes to start-up. This new project, which has only recently started, will aim to make significant improvements on

this start-up time. The project includes ECN of the Netherlands, which is researching, developing and supplying improved methanol reforming catalysts.

The collaboration between CJB, VSEL and Ballard aims to demonstrate an integrated PEFC system at 10kW scale, incorporating a methanol fuel processor, Ballard 5kW stacks and power conditioning unit (obtaining a power conditioning unit that met the requirements of this project has proved difficult). These current activities constitute a technology demonstration; it is believed that this will provide the platform for VSEL and CJB to address the full range of potential PEFC markets. Significant progress has been made by VSEL and CJB in this project. The system is fully integrated, producing 10 kW net AC output (240 volts AC, 50 Hz, 1-phase). Many important development issues have been identified as a result of the integrated system approach adopted by VSEL and CJB.

As part of this work VSEL, recently presented single cell results that indicate a considerable drop in cell voltage over 300 minutes in the presence of 5ppm NO₂ at the cathode, identifying an important issue for the potential use of the PEFC in the urban environment.

VSEL has also recently announced a collaborative project between VSEL, CJB Development, Lucas Advanced Engineering and Rover Cars. The project, which started in 1993, brings together many of the partners that will be required to commercialise fuel cell systems in transportation. The project has been described by VSEL as a fuel cell hybrid vehicle "study". It includes market studies, system studies, including modelling, and the specification, design, construction and, in 1997, the demonstration of a fuel cell/hybrid vehicle.

Rolls Royce and Associates (RRA) is currently developing the autothermal reformer concept. This incorporates both partial oxidation and steam reforming stages, and aims to operate adiabatically. The partial oxidation reaction generates the heat required by the steam reforming reaction. It allows a more rapid start-up and a more compact system than the traditional steam reforming approach. The yield of hydrogen, however, is lower than in steam reforming, and higher CO levels are obtained. Natural gas reforming is currently the focus of their work. However, the system offers potential for application in transport using methanol and other hydrocarbon fuels. RRA has also undertaken economic and market studies for PEFC, and has conducted systems assessments and the evaluation of key components, including PEFC stacks. RRA has previously undertaken a study for the Southern California Air Quality Management District (SCAQMD), addressing the "Technical and Commercial Feasibility for a Residential Energy System Utilising PEFC". As part of this work, RRA worked with Johnson Matthey on the evaluation of partial oxidation reformers.

The Johnson Matthey "hot-spot" partial oxidation reformer has successfully demonstrated the reforming of methanol. This concept has a particularly simple and compact design, offering rapid start-up and excellent load following characteristics. The hot-spot operates exothermically and it generates a lower yield of hydrogen than steam reforming. It is a potentially attractive option in transport applications where space considerations are important and where responsive systems are required. This

work is ongoing, concentrating on understanding the gas-phase catalysis, reaction mechanisms and thermodynamics. Progress is now being made in scaling-up the technology.

Johnson Matthey is also developing palladium membrane technology as a means of providing pure hydrogen. The objective of its current programme on palladium is to evaluate the technical and economic feasibility of developing ultra-thin (5 μ m) palladium membranes supported on ceramic substrates. Such a system offers a number of potential benefits.

- Its cost is expected to be significantly lower than traditional palladium diffusers.
- An improved rate of hydrogen diffusion for a given pressure differential is expected.
- It is the only reformat clean-up system that offers the potential of pure hydrogen, allowing the PEFC stack to be operated "dead-ended".
- It is a very compact system that would increase PEFC stack integrity when using reformers, as it removes CO poisoning.

Three UK companies are also participating in a major EC BRITE-EURAM project to develop a novel compact steam reformer for fuel cell applications. This project involves AEA Technology, EA Technology and PowerGen (UK), GasTec and BCN (the Netherlands), Degussa (Germany), IST (Portugal) and TGI (Spain). The aim of the project is to develop a compact reformer, with improved heat transfer between combustion and reforming catalysts and with induction heating to further improve start-up times and improve reaction control. The project started on 1 May 1994, and is scheduled for completion in 1997.

3.1.5 DMFC

DMFC research continues to be funded at UK universities, both by the UK EPSRC and by the EC. There is limited industrial involvement at present, as it is perceived as a longer term option for transportation applications. Johnson Matthey has previously participated in the programmes of the EC, through the supply of precious metal catalysts, but it is no longer active on DMFC.

Newcastle University has been undertaking R&D in this area for a number of years. Current activities include the development of improved electrocatalysts for both the oxygen reduction and methanol oxidation, largely based upon Pt and Pt/Ruthenium, and on the development of improved anode designs.

Cambridge University is developing a methanol/air fuel cell for potential transport applications. The focus of its work is the development of improved catalysts (higher activity and reduced poisoning), improved electrode structures and low cost materials. This work is based upon the use of a sulphuric acid electrolyte, on the grounds that it allows simpler engineering solutions.

3.2 Germany

Germany is playing a key role in the development of fuel cell systems. It is active on many fuel cell types, from fundamental R&D on the DMFC to the demonstration of PAFC systems developed in the USA and Japan. The German companies Siemens and Daimler-Benz are likely to be particularly important European organisations in the world-wide development and commercialisation of fuel cells. Siemens is very active on SOFC for heat and power generation and is developing PEFC and DMFC stacks for transport applications. Daimler-Benz has recently announced a collaborative programme with Ballard of Canada to develop PEFC stacks for transportation. The German Government has also recently announced new programmes on the development of PEFC, involving both Siemens and Daimler-Benz, and on SOFC.

3.2.1 PAFC

German activities on PAFC are limited to demonstrating stack technology developed by others; in particular there are a number of 200kW PC25 systems being demonstrated, supplied by ONSI of the USA.

Ruhrgas is operating a plant on natural gas for cogeneration applications. The plant was commissioned in September 1992 and is currently based at Dorsten. During the first 6 months of operation, a 90% plant availability was achieved. At the end of the first year of operation, the plant was scheduled to be field tested at a public utility. Work will include evaluating the performance of the PC25 with different anode gas compositions, and assessing the availability of heat as a function of electrical load. Ruhrgas sees the PAFC as a strong potential competitor in the cogeneration market, at scales of less than 10MW, particularly if the cost projections of the manufacturers are achieved.

Thyssengas is also operating a PC25, and has agreed to co-operate with Ruhrgas on the field testing of their systems. Both organisations are jointly pursuing the objective of supporting the introduction of fuel cell technology to the cogeneration market.

The German utility HEAG is also evaluating an ONSI PC25 system.

3.2.2 SOFC

Siemens and Dornier lead two major SOFC development programmes in Germany. The German Research Ministry, BMFT, provides support for both of these programmes and has also recently announced a new national programme on SOFC involving a number of German industrial groups (including Siemens and Dornier) and managed by the KFA Jülich Research Centre. This programme will be directed towards power generation with an ultimate aim of developing SOFC systems suitable for operation on lignite.

Siemens works with ECN (Netherlands), Imperial College and GEC Alsthom (both UK) in an EC JOULE-II project aimed at developing a planar SOFC stack with metallic interconnect plates.

The overall Siemens SOFC programme plan is as follows:

1988-1990	Preparation phase;
1991-1993	Basic Research (to 1kW scale);
1993-1995	Technology development (leading to the development of a 20kW system);
1995-1999	Demonstration (initially proposed to be a 300kW system).

The current development phase has the main objective of demonstrating a 20kW SOFC system by the end of 1995. Siemens also hope to improve the long term stability of its stacks and to evaluate the likely costs of SOFC systems.

A major milestone was met in April 1994 when Siemens demonstrated a 1.8kW stack generating approximately 600mAcm^{-2} at 0.7V. These results are achieved on H_2/O_2 - the corresponding values with H_2/air are approximately 200mAcm^{-2} lower. Nevertheless, this performance is very impressive and gives confidence that Siemens can meet or exceed the design specifications of 200mAcm^{-2} at 0.7V for a commercial scale stack operating on natural gas and air. The recent improvements in performance can be attributed to the introduction of a new conducting layer placed between the electrode and the interconnect to improve interfacial contact.

The 1.8kW stack comprises 14 plates; each plate contains sixteen 5x5cm cells in a 'window frame' arrangement. Each cell produces approximately 10W. The cells were a conventional planar design made from screen printing electrodes on to a tape cast electrolyte sheet. The support plates, interconnects and stack housings are all made of an Yttria/Chromium/Iron alloy manufactured by Plansee (Austria). The window-frame concept and the use of metallic components are the key features of the Siemens stack design, offering potential advantages in uniformity of temperature through the stack and improved potential for scale-up.

Dornier continues to make steady progress with an all-ceramic planar SOFC. This is a conventional planar design with a thick ribbed lanthanum chromite interconnect plate. This work is done in collaboration with Cookson (UK) and the University of Patras (Greece) under the EC JOULE-II programme. The overall aim of the current programme is to produce a 3-5 kW stack by 1995. Dornier's role is to develop stacking techniques suitable for scale-up, to develop manifolding and joining methods, and to manufacture and test stacks. Single cells have now been scaled-up to 10x10cm and ten cell stacks have been operated successfully for over 1000 hours. The performance is now about 200mAcm^{-2} at 0.7V. Dornier believes that this can be improved upon in the future by optimising the cell geometry.

ABB had a significant SOFC programme until 1992, but this has now been discontinued.

KFA Jülich is undertaking basic research and modelling activities to underpin the German programme. These include investigations of anode reaction kinetics, the development of new cathode materials, finite-element stack modelling and the development of high temperature auxiliary equipment (heat exchangers etc.) for SOFC systems. An estimated 20 staff are now working on SOFC development at Jülich, but up to now this work has not been closely linked to the industrial programmes.

3.2.3 MCFC

Daimler Benz, through MTU, leads a consortium of Danish and German firms which aims to develop MCFC systems using stack technology licensed from ERC (USA). Partners in this programme include Ruhrgas, Elkraft and Haldor Topsøe. The development programme has three phases. The first phase, to 1994, focuses on cell technology, stack cost reduction and system design. The second phase, from 1994 to 1997, will aim to improve cell current density and lifetime (to 40,000 hours), to reduce system costs and to demonstrate a 200-300 kW prototype system for operation on gas or gasified coal. Finally, the third phase, from 1997 to 1999, will involve field trials of 300kW units at 'early application' customer sites. MTU believes that the first market will be industrial cogeneration, a rapidly growing market in Germany, and that the first product will be a pressurised, skid mounted plant.

3.2.4 PEFC

There are a significant number of PEFC activities in Germany. The level of activity is expected to grow in the future following the German Government's recent announcement of a programme to develop PEFC for transportation. The cost of this Government programme over the next 4 years is \$19million, with 50% of the costs to be provided by German industry. This new programme involves Siemens (stacks), Daimler-Benz (systems), Hoechst, Degussa and BASF.

A key German organisation in the development of PEFC stacks and systems is Siemens. Following on from the successful demonstration of a 100kW AFC for air independent propulsion systems (described below), Siemens began a major effort on the development of PEFC. Initially, Siemens licensed the original General Electric technology through Hamilton Standard, with the licence applying to military applications only. After acquisition of the technology, Siemens began developing a 34kW PEFC stack for an air-independent propulsion system for submarine applications.

Its performance targets were 540mAcm^{-2} at a cell voltage of approximately 700mV (active cell area 1160cm^2). A current density of 700mAcm^{-2} at 700mV was reported in 1991, based upon hydrogen-oxygen operation at 2 bar pressure. In 1993, Siemens reported that its PEFC stack, comprising 70 cells, was operational, generating 34kW of power at a stack voltage of 52V and with an efficiency of 59% at full load (69% at part-load). This performance was achieved with operation on hydrogen and oxygen at 80°C and approximately 2 bara (slightly greater on the cathode side) with Du Pont's NAFION 117 membrane as the electrolyte. A peak stack power of 55kW has been achieved. The stack has been operated for in excess of 1000 hours, with individual

cells having demonstrated lifetimes in excess of 7000 hours. Siemens has indicated that the price of this technology is between 1000-10000\$/kW.

At the single cell level, Siemens has reported higher power densities with the use of both the NAFION 115 and the Dow membrane electrolytes. The following single-cell performances have been demonstrated:

- 750A at 0.7V with NAFION 117;
- 1100A at 0.7 V with NAFION 115;
- 1500A at 0.7V with the Dow XUS electrolyte.

Building upon this experience, Siemens, with support from the EC, is now developing PEFC stacks for transport applications. Siemens sees the PEFC as a strong candidate for transport application, and the thrust of its PEFC programme is the development of high power density, low cost stacks. The project's goal is to develop PEFC stacks, operating on air, at low over-pressure, and a price of <100\$/kW.

Centre d'Etudes Nucleaire (CEA) of Grenoble (France), AEA Technology of Harwell (UK), Loughborough University (UK) and the Paul Scherrer Institute (Switzerland) are participating in this programme. They are addressing a number of technical areas, aiming to do much of the ground work from which Siemens and its partners could commercially develop PEFC stacks. These include CO-tolerant anode catalysts, new membrane electrolytes, new cell designs with improved electrode structures, an improved air electrode design to reduce mass transport losses, novel and improved bipolar plates, cheaper materials, heat exchangers and system modelling studies of fuel cell powered cars.

At the single cell level, 330mAcm^{-2} has been generated at 0.6V, with hydrogen fuel at 2 bara, air at 1.5 bara and twice the required stoichiometry, and a temperature of 80°C. Siemens has also noted significant poisoning of the anode with 10ppm CO, but that this has been diminished through the use of Platinum/Ruthenium catalysts.

It is expected that the results from this ongoing project, which is due to complete in 1996, will be a major factor in determining the future role of Siemens in the development and provision of PEFC stacks for transport applications.

Daimler Benz has maintained an interest in hydrogen powered vehicles for a number of years. In 1990, it was already evaluating a Ballard 2kW stack, and it has carried out extensive trials of hydrogen powered internal combustion engine vehicles, with hydrogen stored in the metal hydride form.

Daimler-Benz has recently announced a collaborative development programme with Ballard Power Systems of Vancouver, with the aim of developing fuel cell technology for electric vehicles. As part of this joint programme, both partners will contribute their respective background technology. Daimler-Benz has agreed to contribute \$15million to the continuing PEFC stack development at Ballard. Furthermore, each partner has agreed to fund the development of components for the stack; each partner is to provide a further \$10million for this. The aim is to develop jointly, over a period

of 4 years, compact, high power density PEFC stacks that more closely meet the requirements of commercial vehicles, in particular Daimler-Benz vehicles. The work will include the development of appropriate manufacturing processes for component production and they shall be working towards a further substantial reduction in stack and system size, weight and cost. Their eventual target is to produce a stack at a cost of \$30-50/kW. Clearly, the time scale of this development programme is geared towards the initial Californian requirement for ZEV commencing in 1998.

Daimler-Benz has already applied Ballard technology to power a Mercedes Benz MB180 van. The NECAR (New Electric Car), as it is called, is a prototype fuel cell vehicle; it was commissioned in December 1993. The NECAR is powered by twelve 5kW Ballard PEFC stacks, generating 130-230volts, with a single cell voltage of 0.6volts. The vehicle uses a 30kW asynchronous electric motor. Compressed hydrogen gas is used as the fuel, with air as the oxidant. The NECAR has a top speed of 90km/h and it can accelerate from 0-50km/h in 18 seconds and from 0-80km/h in 47 seconds. The vehicle, which has an overall weight of 3500kg, has a range of 100km. The fuel cell system currently takes up the vehicles entire payload space.

Daimler-Benz sees the following as the principal development issues, all being addressed in its R&D programme.

- Increased stack power density.
- System optimisation for specific applications.
- System dynamics, particularly the on-board methanol reformer.

Daimler-Benz sees methanol as the eventual preferred fuel, on the ground of energy density and range. However, Daimler-Benz also envisages that hydrogen could be used for buses and fleet vehicles. The time scale for commercialisation is also likely to be different in different applications. Daimler-Benz expect it to be 20 years before fuel cells achieve full commercialisation in private cars, but fuel cell buses may be commercial before this.

In addition to the technical barriers to the commercialisation of PEFC in vehicles, Daimler-Benz identifies a range of further factors as relevant to the commercialisation of fuel cell systems. These include improved emission standards/legislation, the creation of a fuel infrastructure, suitability for mass production and price in comparison with competing technologies (Daimler-Benz believes that fuel cell systems must be cheaper than battery powered vehicles, but only "competitive" with internal combustion engines).

Daimler-Benz do not expect on-board battery storage systems to be required, eventually. Daimler-Benz, however, continues to work on battery powered vehicles which it sees as being required to bridge the gap to full commercialisation of fuel cells in vehicles.

To date, Daimler-Benz has invested approximately \$60million in fuel cell developments. Its current expenditure is approximately \$20million per year on fuel cells.

KFA Jülich is participating in a EC funded project, led by Haldor Topsøe of Denmark. The aim of this project is to develop a compact methanol reformer for transportation applications. This project is described in more detail in the section describing the Danish national programme.

The Fraunhofer Institute is collaborating with TNO (the Netherlands) and Hotzenblitz Mobile GmbH (Germany) on the development of a hydrogen generation system for a small battery/PEFC hybrid car (total power 12kW), with the PEFC (1kW) being used to charge the battery only. The hydrogen generator is based upon the steam reforming of compressed natural gas, with heat generation by catalytic combustion, followed by electrically heated high and low temperature shift reactors. Systems studies are being undertaken to optimise the system design, and this is to be followed by the construction of a laboratory system, to test the concept of the integrated system.

There are some additional activities in Germany related to the "hydrogen economy" which are also reported in this section.

BMW has been working on hydrogen powered cars for over 10 years. As part of this work, BMW is collaborating with Siemens, DASA and Linde, who are co-funding work at Solar-Wasserstoff-Bayern (SWB), to gain experience of all the components in a hydrogen energy chain. The companies are aiming to demonstrate progress towards the "hydrogen economy". The first phase of the work, between 1987 and 1991, cost a total of approximately \$40million. A further \$47million has been approved for the second phase of the work up to 1996. 50% of this funding is provided from the German Government. As part of this project, SWB is operating a demonstration power plant in Bavaria, using hydrogen generated by the photovoltaic electrolysis of water to fuel a Siemens 6kW AFC stack and a Fuji 80kW PAFC stack. As part of this project, BMW is also evaluating PEFC stacks provided by Siemens. BMW is also developing hydrogen powered internal combustion engines (ICE) vehicles. BMW reported at a recent Alternative Motor Fuels conference in Belgium that it believed that hydrogen powered ICE would find commercial application before fuel cells; BMW intends to introduce a range of cars powered by liquid hydrogen ICE early in the next century. In parallel with these activities, the Fraunhofer Institute for Solar Energy Systems is developing an integrated photovoltaic/PEFC system. Fraunhofer is also developing small scale single PEFC cells.

3.2.5 DMFC

A number of universities are active in this area. In particular the University of Bonn is participating in the programmes of the EC, with the University of Poitiers (France) and Innovision (of Denmark), aiming to developing improved electrolytes that reduce methanol cross over (inorganic, proton selective electrolytes), yet maintain their ionic conductivity, and electrolytes that operate at higher temperatures. The work has also been evaluating the potential for an oxygen selective cathode catalyst that does not oxidise any methanol that has diffused through the membrane. Finally, the research has explored methods of controlling the methanol concentration at the anode to reduce its concentration at the membrane surface, and hence the extent of methanol diffusion

through to the cathode. Good progress has been reported; current densities of 100mAcm^{-2} have been achieved at cell voltages of 400mV. The research target has now been advanced to a single cell current density of 500mAcm^{-2} at 600mV. These are ambitious targets, that, if achieved, would justify the production of a 1kW demonstration stack.

In addition to its work on PEFC and SOFC, Siemens is also working on a polymer electrolyte DMFC, with support from the EC. Innovision, of Denmark, is collaborating with this research. The initial goal of this ongoing work was to develop a small (100W) stack. Single cells using Pt/Ruthenium electrodes with a loading of 4mgcm^{-2} were developed with a cell area of 25cm^2 ; these cells were reported in 1992 as generating 150mAcm^{-2} at 450mV. Based on these results, electrodes of active area 250cm^2 were developed and incorporated into a 12 cell stack. This stack developed 5.4V at 100mAcm^{-2} , with a peak power of 150W at a current density of 130mAcm^{-2} .

Methanol diffusion through the NAFION electrolyte continues to be a major development problem for DMFC; fuel is lost (approximately 10% methanol loss at a current density of 200mAcm^{-2}) and Faradaic efficiency is also reduced due to methanol oxidation at the cathode. Siemens recent approach to tackling this development issue is based upon the fine control of the amount methanol supplied, to ensure complete oxidation at the anode. Recent progress has been made by Siemens and single cell current densities of 400mAcm^{-2} at 500mV are now being reported. The aim is to develop a 1kW DMFC stack within the next 2 years. This work could lead to a significant improvement in the prospects for the DMFC.

3.2.6 AFC

Siemens has been involved in the development of the AFC for many years, supplying a 100kW system to a German Federal Navy submarine in 1988. Despite the successful operation of this system, Siemens discontinued its work on AFC for this application, re-focusing its efforts on the PEFC, as described above. Siemens has, however, continued with the development of the AFC for the European Space Agency's HERMES space shuttle.

Hoechst is developing an Alkaline Falling Film Fuel Cell (AFFFC) for transportation. This technology was originally developed by Hoechst for the chlor-alkali industry. The principal difference between the AFFFC and a traditional AFC is that the electrolyte flows from top-to-bottom through the cell. This technique allows gravity to compensate for hydrostatic pressure drop at the gas diffusion electrode, allowing cell designs with low internal resistance, thereby increasing power density and improving the economics (in comparison with AFC). Hoechst has calculated that the material requirements amount to less than \$8/kW for the AFFFC. Hoechst is therefore confident that target costs of \$50-200/kW for transportation can be achieved. Hoechst

has developed a schematic AFFFC powered car. They expect such a vehicle would have the following characteristics.

- 400 km range, requiring 108 litres of liquid hydrogen (62kg of H₂).
- 110 kW fuel cell stack (volume 20 litres).
- 42kg of oxygen stored on-board as the liquid, requiring a 45 litre storage tank.
- 25 litre of KOH electrolyte.
- An overall vehicle weight of 1.1 tonne.

Hoechst envisage centralised production of H₂ and O₂, potentially allowing CO₂ recovery and disposal/enhanced oil recovery.

3.3 France

France is not very active in the development of fuel cells. Most of the French work reported in the literature is based in universities, receiving funding from the EC. More recently, the EC announced its support to the French car manufacturer Renault to participate in a collaborative project with Volvo and De Nora Permelec (Italy) on the integration of PEFC systems into cars. However, the agreements between the partners have not yet been signed for this project. Furthermore, France has recently announced a programme to develop PEFC for transportation based on hydrogen/air.

On DMFC, a number of French universities have participated in the programmes of the EC. The University of Poitiers is collaborating with the University of Bonn, as described earlier in the German programme.

On SOFC, Sapco is to work with Keele University (UK) on a new EC project aimed at investigating a new tubular SOFC design. Sapco currently makes burner elements and other high-volume ceramic components. Rhone Poulenc also develops ceramic powders for SOFCs.

Recently, France has described its programme to develop PEFC for transportation. This programme is divided into four principal activities: fuel cell development; on-board hydrogen storage; systems studies; databases.

The fuel cell development element of the programme includes CEA's work to develop and evaluate a range of potential alternative proton exchange membranes. Results from this work are being contributed to an EC project with Siemens. This has already been described in the German programme. CEA's role in this project is on the development and testing of membrane electrolytes. CEA is also working on alternative PEFC cathode catalysts, contributing this information to the IEA's PEFC Annex. Composite membranes are also being developed by the Institut National Polytechnique de Grenoble, using a grafting technique.

The goal of the work on on-board hydrogen storage systems is to develop a system capable of providing a range of 400-500km, but weighing less than 150kg and with a volume of less than 150litres.

Liquefied hydrogen has been ruled out due to the energy required for liquefaction. Metal hydrides have been examined but also ruled out due to their weight. Compressed hydrogen is considered a feasible option, but safety and economics have not yet been resolved. Encouraging results have been achieved with various carbons for the cryoadsorption of hydrogen, with the best results being a system weighing 46.3kg with a volume of 125litres, providing 5kg of hydrogen. Hydrogen storage in glass microspheres (20µm diameter, 2-4µm wall thickness) is also being assessed, based upon the high permeability of hydrogen through glass at temperatures greater than 300°C.

The PEFC systems work includes gas, water and thermal management systems, being explored through theoretical and experimental work. As part of this work, a Ballard 5kW stack has been purchased.

On AFC, SAFT is participating in the Elenco (Belgium) AFC bus project through the development and provision of nickel cadmium batteries.

More generally, Advanced Carbon Materials (ACM) of Paris is developing improved carbon electrodes for fuel cells and École des Mines in Paris is investigating ammonia as a hydrogen carrier for fuel cell systems.

3.4 Italy

A significant level of fuel cell activity is underway in Italy on most fuel cell types. In particular, there are a number of PAFC system demonstrations, including the largest in Europe (the 1.3MW system in Milan). There is a small programme on SOFC and major programmes on MCFC and PEFC. Italian companies are strongly involved with the programmes of the EC and Ansaldo and De Nora Permelec (particularly for transport) are expected to be major players in the commercialisation of fuel cell systems in Europe. ENEA, the Italian agency for New Technologies, Energy and the Environment, a public RD&D organisation, is the Italian national agency responsible for the Italian fuel cells R&D programme. ENEA undertakes much basic research "in-house", particularly on MCFC, and to a lesser extent on PEFC. ENEA also acts as a source of government funding to Italian Industry and Universities for fuel cells research, development and demonstration.

Over the next 3 years, the Italian Government, through ENEA, is to spend approximately \$9million on fuel cells (this budget excludes Italy's work on PEFC). Approximately 90% of this will be on MCFC. The goal is for Italian industry and other sources (such as the EC) to match this level of funding, giving a total programme value of \$18million.

In addition, and again over the next 3 years, the Italian Government (Ministry of Industry) is to spend approximately \$19million on "transportation". It is expected that industry (and other sources) will provide a further \$20million towards this programme, giving a total programme value of \$39million. Of this, a total of \$20million is for R&D on PEFC for transportation. As part of this transportation programme a total of \$7million is budgeted for the development of improved lithium-polymer batteries for applications in vehicles.

3.4.1 PAFC

The Italian programme officially started in 1985. Prior to this, market assessments and technology status work had been undertaken, in 1984. On the basis of the results from these studies and discussions held with Italian industry and the Department of Defence, ENEA commissioned two 5kW PAFC demonstration units.

The decision to demonstrate PAFC was made on the basis of the state of development of this technology at that time, the contribution Italian industry could make to the further development of PAFC technology, and the potential the technology has in the distributed generation market. The PAFC demonstrations were also to be a tool for learning about the system engineering, which has subsequently proved valuable to the Italian MCFC programme.

Since then, a number of PAFC demonstration plants have been established in Italy, over a large range of system scales.

- Eniricerche is operating a 50kW Fuji stack.
- ACOSER, the public gas utility in Bologna, owns and operates a 200kW PAFC system. The PAFC stack for this project, a PC25, was provided by ONSI through CLC. The aim of this project, which started in 1991 with funding support from the EC's DGXVII THERMIE programme, is to undertake the technical, economic and environmental evaluation of PAFC systems, in order to promote the more widespread application of the technology. It is a cogeneration system that operates on natural gas with hydrogen generated by steam reforming followed by the shift reaction; it has been operational since April 1993.
- The largest PAFC demonstration system in Europe is located in Italy. The system is to be operated by AEM (the municipal energy utility in Milan), at a site in Milan. It comprises two IFC 670kW PAFC stacks, operating at 8.3 bar and 207°C, with European manufacturers providing the balance of plant. The stacks are series connected, generating 1900A at 700V DC. The project results from a collaborative agreement between ENEA, AEM and Ansaldo. ENEA is providing the majority of the funding required for this project and is also managing the project. The aim of the project is to identify engineering solutions and to evaluate the interfaces between the stack and other components and between the system and its "environment", thereby generating experience on the operation of this large scale PAFC system in a real application. The system is designed to operate on natural gas. It has a target electrical efficiency of 40%. Two water streams are

produced at different temperatures; one for district heating application, one for warm water, with a total efficiency target of 84%. The fuel processor is designed and supplied by Haldor Topsøe of Denmark. It comprises a steam reforming system with high and low temperature shift reactions. The system can operate either in grid connected or stand alone modes, with power conditioning technology developed by Ansaldo. The project started in 1988 and was scheduled to be operational in 1992. The construction of the system has been completed and it is now under test. The revised goal is to connect the system to the electricity grid in June 1994. There will then follow a 2 year "field trial" of the system. During this period, AEM will fund normal operation and maintenance costs, whereas ENEA will fund work to rectify any faults related to the fuel cell system.

ENEA has spent approximately \$16million on this project since 1990.

AEM will eventually own and operate the facility, with continued advice and assistance from Ansaldo and ENEA.

As part of this project, ANSALDO has developed an advanced gate-turn-off inverter. The decision to develop improved inverter technology was made principally on the basis that there was a lack of suitable technology available; the development of improved power conditioning equipment would also help to put Ansaldo in a good position regarding the provision of power-conditioning equipment to other fuel cell systems.

There has not yet been a decision on the future of Italian PAFC activities beyond the 2 year field trial of the 1.3MW Milan system. This will be a decision that Italian industry will need to take. PAFC is unlikely to feature strongly in future Italian Government activities. However, if advanced PAFC stacks are developed by IFC, they may be installed in the Milan system. Future Italian Government expenditure on PAFC (over the next 3 years) will be modest in comparison with its PEFC and MCFC programmes. At most, 10% of the Italian effort over the next 3 years will be devoted to PAFC, giving an estimated maximum expenditure of \$2million. As stated above, this expenditure will be devoted to the Milan 1.3MW project, for work to rectify any faults found within the fuel cell system.

Finally, CLC, a company established and owned by ONSI/IFC and Ansaldo, manufactures 200kW PAFC units (PC25s) under licence; it also services all PAFC stacks delivered by ONSI to Europe. At present, however, certain components of the PC25 still have to be imported from the USA; in particular, the graphite bipolar plates required in the PC25 cannot be manufactured in Italy. CLC is, however, presently having discussions with a company in Germany who can potentially supply the graphite plates.

3.4.2 SOFC

There is a small SOFC programme at Eniricerche which focuses on powder production, component fabrication and cell testing. Eniricerche is also participating in the British Gas balance of plant test rig project, described in the section on the UK

programme, where its role is to provide stack data, to assist with system modelling and to provide support for plant operation.

Of relevance to the Italian SOFC work is the decision to privatise ENI, due to the restructuring of the Italian energy supply industry. This will have implications to Eniricerche, which is part of the ENI group. ENEA is now encouraging Eniricerche to define industrial goals for its SOFC development work, which could lead to a greater involvement of Italian industry in the programme..

ENEA see much greater uncertainties in SOFC technology in comparison with MCFC technology. However, ENEA believe that MCFC could act to open the market for SOFC to follow.

Future Italian expenditure on SOFC (over the next 3 years) is modest in comparison with its PEFC and MCFC programmes. At most, 10% of the Italian effort over the next 3 years is devoted to SOFC, giving an estimated expenditure of \$2million.

3.4.3 MCFC

There is a significant Italian programme on MCFC systems, building upon the experience gained under its PAFC programme. ENEA and Ansaldo are the key players in the programme, which also involves CISE, CNR and a number of universities.

ENEA is responsible for the overall management of the Italian MCFC programme; it also undertakes much of the basic MCFC research. ENEA believes that if the problems with cell corrosion can be successfully tackled, MCFC costs would be significantly less than current PAFC systems. Ansaldo provides stack and system engineering expertise to the programme. Ansaldo has also undertaken basic research on MCFC cathodes, anodes and corrosion-resistant bi-polar plates under the EC programme. It has also signed an agreement with IFC (USA) to develop MCFC systems. This has led to a new project to develop 100kW MCFC by 1995 (part funded by the EC).

Fabricazzioni Nuclear, based on its experience of ceramic fuels for the nuclear industry, is also developing ceramic electrodes for the MCFC programme, contributing to tackling a key development issue, the cell corrosion problem.

As stated above, the Italian MCFC programme is to continue to receive Italian Government support. Over the next 3 years, the Italian Government, through ENEA, is to spend approximately \$8million on MCFC. The goal is for Italian industry and other sources (such as the EC) to match this level of funding, giving a total programme size of \$16million over the next 3 years.

3.4.4 PEFC

There is a significant level of activity in Italy on the development of PEFC systems for stationary and mobile applications. This activity is presently focused on the methanol reformer development of Tecnars and the PEFC stack development of De Nora Permelec. More recently, Fiat has announced its plans to research and develop PEFC systems for transportation.

Tecnars, from Bari, is participating on the EC funded project led by ECN of the Netherlands, to undertake a "Brass-board integration of a reformer/fuel cell/battery/electric motor system for electric traction". "Brass-board" refers to the laboratory demonstration of a complete, integrated system, that includes all the system components required for a methanol fuelled PEFC system for transportation. The overall project is described in more detail below, under the Dutch programme. Tecnars is providing its present state of the art methanol steam reforming technology to this project

In parallel, Tecnars is collaborating with Ansaldo, the Stazione Sperimentale per i Combustibili (SSC) and the University of Barcelona (UB) on another EC funded project. The aim of the project is to develop and construct an improved methanol reformer for transportation with a high efficiency of conversion to hydrogen, suitable for integration with 50kW PEFC stacks. Ansaldo is undertaking the systems studies to define the operational parameters of the reformer. SSC and Tecnars will evaluate and select catalysts for the reforming and combustion reaction and for a CO clean-up system. UB is developing hydrogen permeable membranes for hydrogen enrichment. The complete fuel processing system will be constructed and tested by Ansaldo. It is expected that this project will be completed in 1995. The approach being adopted by Tecnars in this project includes the partial oxidation of methanol, similar to the "hot-spot" reformer developed by Johnson Matthey in the UK. As such, the work is focused on the development of compact, responsive methanol reformer systems, at low cost. The partial oxidation route generates significant levels of CO; hence the requirement for CO clean-up systems utilising hydrogen permeable membranes. Tecnars receives some financial support from ENEA for this project.

De Nora continues to be active in developing PEFC stacks. De Nora has received Italian Government funding since 1989, through ENEA, though this has been at a modest level. Much of the work has been funded by De Nora from its own resources. However, it is envisaged that De Nora will receive a greater level of funding from ENEA as part of the new 3 year Italian programme, as the emphasis of Italian fuel cell activities changes from the PAFC demonstration activities to PEFC development for transportation.

The De Nora 5kW PEFC stack technology has been described as using a "simple" cell/electrode design. This compares with the Ballard Mk V technology which is considered to be very well engineered. However, it is claimed that De Nora's 5kW PEFC stack is available at a third of the cost of the Ballard technology. De Nora's

simpler design has a reduced lifetime target, in comparison with Ballard. The lifetime target for the De Nora 5kW stack is just 5000 hours.

The De Nora 5kW PEFC stack has a power density that is comparable with the Ballard 5kW stack ("slightly lower power density"). The platinum loading in the current De Nora stack is 0.35 mg cm^{-2} per electrode; 0.7 mg cm^{-2} per cell. The De Nora stack currently uses NAFION 117 as the electrolyte; there seem to have been difficulties in obtaining supplies of the Dow membrane electrolyte. However, De Nora is currently in discussion with a German subsidiary of Siemens who can manufacture and supply membrane electrolytes.

De Nora is currently working on a 10kW PEFC stack, which will be supplied to ENEA in 1994. The 10kW stack will have the same power density as the De Nora 5kW stack. Future work to be tackled by De Nora includes:

- improved electrode design, leading to higher power densities;
- improved stack water management

As stated in Section 2 of this report, De Nora aims to start a collaborative project with Volvo and Renault on the integration of De Nora stacks into cars, under the EC JOULE II programme. However, the contracts between the partners for this proposed project have not yet been agreed and the start of the project has been delayed.

It is possible to estimate the value of the funding currently required for the De Nora PEFC stack development work. De Nora has 12 people working full time on PEFC, plus shared technician support. On this basis, it is estimated that De Nora's fuel cells programme is presently funded to the level of approximately \$2million per year.

Fiat, a major European car manufacturer, is now becoming more involved with the development of fuel cell and hybrid vehicles.

Following Fiat's decision to close its Alfa Romeo plant, the Italian Government is to provide support to Fiat to convert the plant to a new electric/hybrid vehicle production facility. The new production line will be capable of manufacturing 1000 vehicles per year, using existing lead acid battery/diesel technology systems.

In parallel, Fiat is to establish an R&D facility, to develop PEFC systems for transportation. ENEA will be involved in defining the R&D programme. The goal is to establish links between R&D and production, eventually converting the proposed electric/diesel production facility to a future PEFC powered vehicle production facility.

Fiat has received proposals from industry for polymer stacks that would form the basis of its R&D programme. So far, proposals have been received from H-Power in the USA and Ansaldo/De Nora from Italy. Fiat's budget for PEFC research and development over the next 3 years is in the region of \$30million; this is three times larger than the Italian Government's funding for PEFC development.

Fiat is also involved in the development of Li-polymer batteries for transport applications.

Finally, as part of the Euro Quebec Hydrogen Hydro Pilot Project (EQHHPP), described earlier, a fuel cell/battery hybrid power system for a bus demonstration project is being developed with support from the EC. The project involves collaboration between Ansaldo, De Nora, Messer Grisheim (of Germany) and the municipality of Brescia. A 10kW PEFC stack, fuelled by hydrogen (liquid hydrogen stored at -250°C) is being developed by De Nora. Ansaldo is providing its systems expertise and is developing a similar drive train to that being supplied by it to the Elenco AFC bus project. The design phase started in 1991, and the bus is expected to be on the road for testing during 1994. Preliminary tests are to be performed in Germany, with extensive road tests taking place during 1994 in the Italian city of Brescia. The feasibility of PEFC powered boat for Venice is also being undertaken as part of the EQHHPP.

3.4.5 AFC

Ansaldo is participating in the Elenco AFC bus demonstration project, through the provision of the electric drive system. This is described below, in the description of the Belgian programme.

3.5 Belgium

Belgian activities are dominated by the work of Elenco (Europe's foremost AFC stack developer) on AFC for transport applications. No work is reported on PAFC, SOFC, MCFC and DMFC. VITO, the Flemish Institute for Technological Research, is undertaking some research into PEFC.

3.5.1 AFC

The most significant European activity on AFC is that being undertaken by Elenco in Belgium. Elenco has been developing AFC's for transport applications for many years. Between 1976 and 1984, Elenco spent approximately \$18million on basic research.

Since 1985, Elenco has been developing prototype (technological demonstrations) AFC systems, including a 14kW AFC stack incorporated in a Volkswagen van. In 1991, Elenco started collaborating with Italian (Ansaldo), French (SAFT) and Dutch (Air Products) partners on the development of a full sized electric bus, powered by a 200kW battery/AFC hybrid system. The bus, which is articulated, was originally constructed by van Hool, but it has been modified to meet the requirements of this project. The bus can carry 56 passengers. The Elenco bus project is being developed within the European industrial collaboration framework of the EUREKA programme.

The bus will use an Elenco AFC stack operating on hydrogen and air (scrubbed to remove CO_2), and using circulating KOH as electrolyte and coolant. It operates at a nominal temperature of between $60-70^{\circ}\text{C}$ and virtually ambient pressure. The stack

uses nickel based catalysts and generates approximately 78kW at 180-200V. Ansaldo has developed the electric drive system and SAFT has developed the nickel cadmium (STH 800 Ni-Cd) batteries which provides a significant fraction of the systems power requirements, particularly during start-up and acceleration. The batteries generate 120kW of power at a discharge voltage of 510-940 volts. They contain 80Amp.hours of charge and the bus can operate for up to 1 hour on its batteries alone. The Ni-Cd batteries are located at 3 different positions in the bus, for weight distribution. Even so, the weight distribution is very close to the bus axle limit (the overall bus weight is 25 tonnes). The AC motor generates 180kW of power and it weighs 250kg. Air Products has developed the on-board liquid hydrogen storage system, considered to be the best available option in terms of system weight, gas purity and refuelling logistics. The on-board hydrogen storage system, estimated to weigh 1 tonne, is designed for 45kg/700 litres of liquid hydrogen, providing a daily range of 250-300km (12-15 hours of city driving). Gaseous hydrogen is vented from the system when the vapour pressure exceeds 8 bar. The liquid hydrogen is generated in a central plant, at the rate of 5.5tonnes/day. It is transported by truck to the bus garage/filling station, which has 860 kg/12700 litres of liquid H₂ storage capacity available.

The bus has already operated on the streets, but on battery power only. The bus is expected to be operating in Brussels during 1994, and subsequently in Amsterdam. Elenco consider this project as a technical demonstration, rather than a pre-production prototype. If successful, Elenco hopes to initiate the development of a number of prototype bus systems to be operated in cities throughout the world. It is intended that prototype bus production will commence next year. Elenco believes that the AFC stack can be easily transferred to mass production and that its cost in mass production would be lower than PEFC stacks. Elenco has estimated that the total relative operating cost of AFC is 30% more expensive than diesel powered buses.

3.6 The Netherlands

The Netherlands is active in the development and commercialisation of most fuel cell types. Activities include PAFC demonstrations, fundamental research into SOFC, and systems integration work for PEFC in transport applications. No work is reported on DMFC and AFC. The most significant Dutch effort is on the development and commercialisation of MCFC, through the programmes of ECN and BCN. The Dutch MCFC work is strongly integrated with the EC's programmes.

3.6.1 PAFC

Kinetics Technology International (KTI) has demonstrated 25kW PAFC systems, with Fuji stacks and KTI reformer and systems technology, with support from the EC's DGXVII programme between 1988 and 1992. KTI has also developed and supplied a PAFC system of 80kW scale to Solar-Wasserstoff-Bayern, the German demonstration of the hydrogen economy, described under the German programme. KTI also has plans in place to increase the capacity of its PAFC systems to 300kW.

3.6.2 SOFC

There is a national SOFC programme involving ECN, TNO and the universities of Delft and Twente. This programme aims to fabricate thin layer SOFC components using tape casting and electrochemical vapour deposition (ECVD) techniques.

ECN also works with Siemens in developing planar SOFC components for the EC-funded stack development programme. The work at ECN is primarily concerned with optimising SOFC materials and fabrication processes, especially tape casting. Single cells have been made with much reduced polarisation losses to give power densities of 1500 mA cm^{-2} at 0.7V (on H_2/O_2). Endurance tests have shown that cells decay by about $30 \mu\text{V/h}$ over 1000 hours, due mainly to degradation of the anode. ECN's target is to reduce this decay to below $10 \mu\text{V/h}$ - roughly equivalent to 15% per year.

TNO works on an EC JOULE project led by British Gas. TNO's role is to improve the conductivity of the cathode and to reduce the interfacial resistance between anode and interconnect. TNO has developed a new multi-layer cathode containing lanthanum chromite, lanthanum manganite and zirconia. This makes use of a new technique for producing thin porous ceramic layers which has been developed by another Dutch company, DSM. The anode/interconnect interface resistance has been reduced by a factor of 100 by improving the contact area between the reactive nickel and the lanthanum chromite.

3.6.3 MCFC

It is estimated that about \$30million was spent on MCFC research in the Netherlands from 1986 to 1991.

ECN acquired MCFC technology from IGT (USA) in a technology transfer programme in 1987. Since then ECN has focused on materials development, component fabrication and stack technology. ECN has been involved in a number of EC-funded programmes and by 1993, a 10kW external reforming stack had developed. Work has now begun on a similar 50kW stack. The 50kW project is also supported by the EC, under its JOULE-II programme; the project involves IBERDROLA and TGI (both Spain). ECN is also developing internal reforming MCFC technology with British Gas (UK) and CNR-TAE (Italy).

In another EC JOULE-II project, ECN and the Technical University of Delft are working on new cathode materials aimed at overcoming the dissolution of nickel oxide in the electrolyte. Recent developments have included a new cathode material, lithium cobaltate, which has an estimated lifetime of over 40000 hours.

In 1991, two Dutch industrial companies, Stork and Royal Schelde, formed a joint venture company with ECN. The objective of this new corporation, Brandstofcel Nederland BV (BCN), is to exploit ECN's MCFC technology. BCN provides the project management team and assigns: research to ECN, engineering design and scale up to Stork and stack and system production to Schelde.

The next development stage in the Dutch MCFC programme is not yet clear - BCN has designed a 250kW demonstration plant but may instead opt to demonstrate a 50kW system in a real application.

3.6.4 PEFC

ECN has recently commenced work on PEFC. The focus of its work is methanol reforming, hydrogen storage, cell performance and cost reduction, and systems studies. It is participating in the IEA PEFC Annex IV, building upon its MCFC expertise and contributing novel stack concepts to the IEA programme. With financial support from the Dutch Government agency NOVEM and the EC, it is also currently leading a major EC funded project on the development of a laboratory based "brass-board" PEFC system for vehicular applications. The brass-board system is based upon four Ballard 5kW PEFC stacks. ECN will design and construct the system around the stacks and systems modelling studies, based upon an IVECO 3 tonne (unladen) van, have been undertaken by ECN. A methanol reformer is being supplied by Tecnars from Italy. Loughborough University (UK) is providing a reformat clean-up system, based on an oxygen bleed to the anode. The system will be a hybrid, incorporating batteries. The choice of battery has not yet been made, but is likely to be nickel/cadmium technology, probably supplied by SAFT of France. The principal goals of this project, which is due to complete in 1995, is to develop the technology needed to integrate the key components for a fuel cell/battery hybrid vehicle with an on-board methanol reformer, to integrate these components and to assess the system's performance using realistic drive patterns. TNO, from Delft in the Netherlands, is also participating in this project, assisting ECN with the specification and selection of the battery system.

TNO is also participating in an EC funded project, in collaboration with the Fraunhofer Institute for Solar Energy Systems and Hotzenblitz Mobile GmbH. This project is described in the section presenting the German programme.

3.7 **Denmark**

Denmark has demonstrated a number of PAFC systems and has a significant programme on SOFC. A key organisation is Haldor Topsøe, a major developer of reformers for all types of fuel cells systems; it is likely to be a key European organisation in the commercialisation of fuel cells, particularly for cogeneration applications. Haldor Topsøe is also now developing smaller methanol reforming systems for transportation.

3.7.1 PAFC

In commons with many European countries, Danish PAFC activities are largely based upon demonstrating technology developed by others. Danish gas and electricity utilities (Naturgas Syd and Sonderjyllands) are collaborating on the evaluation of a 200kW ONSI system.

However, Haldor Topsøe is developing and supplying large scale (up to 5MW) fuel processing systems based upon its Heat Exchange Reformer (HER) concept to PAFC demonstrators throughout Europe, the USA and Japan. The concept could also find application in externally reformed SOFC and MCFC systems and has already been demonstrated at an MCFC plant in Japan. Haldor Topsøe sets a lower limit of the applicability of its technology as 50kW; thus small-scale cogeneration and transport applications (with on-board reformers) are likely to require alternative systems. The HER has demonstrated a start-up from ambient conditions to 25% full-load in 3 hours. It responds to a change in load from 100% to 25% in less than a minute. The HER has been demonstrated on both natural gas and kerosene.

3.7.2 SOFC

The first phase of the Danish SOFC programme ran from 1991 to 1993 with a total budget of approximately \$7million. It was financed by the Ministry of Energy, the energy companies ELKRAFT and Elsam, and the project participants - Risø, Innovision A/S, Odense University, Haldor Topsøe and the Technical University of Denmark. Risø manufactured cell components and tested small cells, Topsøe manufactured ceramic powders and tape-casts components and Innovision worked on the extrusion of ceramic materials and on the screen printing of electrodes.

A new 4-year programme has now been agreed with similar cost sharing and a total budget of approximately \$15million. This will include stack development at the kW scale as well as further fundamental research.

Risø works on two projects within the EC JOULE-II programme: a stack development project run by British Gas and a new programme on lower temperature SOFCs. Its main tasks within the British Gas project are to develop sintering aids for lanthanum chromite and to identify and optimise electrode deposition techniques. The programme on lower temperature SOFCs involves many European research groups: Haldor Topsøe, KFA Jülich (Germany), NTH and SINTEF (Norway), TNO (Netherlands), the University of Patras (Greece) and, from 1994, the University of Ljubljana (Slovenia), the Institute for Inorganic Chemistry (Latvia) and the Institute of Physical Chemistry (Romania). The main targets for this project are to reduce cell resistance to at least $0.5\Omega\text{cm}^2$ at 850°C and to at least $2\Omega\text{cm}^2$ at about 600°C .

3.7.3 MCFC

Elkraft installed and operated a 7kW MCFC supplied by ERC (USA). The plant was only run for six months, from October 1990 to March 1991, and was then shipped back to ERC. This trial was largely unsuccessful due to problems with the control of the plant and overheating in the stack. Elkraft have now joined the MTU-led German/Danish group which plans to demonstrate a 100kW ERC stack.

3.7.4 PEFC

Haldor Topsøe is currently collaborating with KFA Jülich (Germany) in the development of a compact methanol reformer for transport applications. This project is supported by the EC's JOULE-II programme. The project aims to achieve a high yield of 2-3m³ of hydrogen (STP) hour⁻¹litre⁻¹ of catalyst and emissions of NO_x, CO and hydrocarbons considerably lower than the Californian ULEV standards. The approach adopted utilises catalytic combustion, using a platinum based catalyst supported on an aluminium oxide carrier. The project is also developing nickel catalysts for methanation to reduce the levels of CO fed to the stack. It is believed that the intention is to control the equilibrium conditions accurately to encourage the methanation of CO, without methanating the CO₂ present. This project is due to complete in 1996.

3.7.5 DMFC

Innovision is active in the development of DMFC. It has participated in an EC project with the University of Bonn, developing improved electrolytes with reduced methanol cross-over. It is presently collaborating with Siemens on another EC funded project on DMFC, which has been described earlier.

3.8 Greece

Very little work is reported for Greece. The University of Patras is involved in several SOFC projects supported by the EC. One of these projects focuses on the possibility of using the SOFC as a chemical reactor for oxidation processes. Researchers have shown that the addition of small quantities of oxygen at the fuel electrode can strongly influence the selectivity and yield of such processes. This is known as the NEMCA effect (Non-Faradaic Enhancement of Catalytic Activity). Other research activities include an investigation of internal reforming anode kinetics.

3.9 Spain

Spain has a number of fuel cell activities underway and Enagas has been operating 50kW Fuji PAFC system since 1992.

The Institute of Ceramics and Glass undertakes basic research into ceramic materials, although there is no national SOFC programme.

TGI and IBERDROLA (formerly HIDROLA) formed the Spanish National MCFC programme in 1992 with the aim of developing both stack technology and systems. The programme budget is approximately \$10million over 4 years. The partners have since agreed to collaborate with overseas partners in three major projects, supported under EC programmes.

The first of these projects, a JOULE-II project led by BCN (Netherlands), aims to demonstrate a 50kW external reforming MCFC stack operating at 4-6 bar pressure with an active cell area of about 1m². The second project, also under the JOULE-II programme, involves the design, manufacture, assembly and testing of a 100kW stack with integral reformer operating at 3-4 bar. This project is a collaboration with Ansaldo, ENEA and CISE (all Italy) and will use MCFC stacks supplied by IFC (USA). The third project comes under the THERMIE programme and involves the demonstration of a full 100kW MCFC cogeneration plant in Milan. This project again involves Ansaldo and CISE and also uses IFC stack technology.

The University of Barcelona is participating in the Ansaldo (Italy) led project to develop a methanol reformer for transport applications. Barcelona is developing hydrogen selective membrane technology for this project.

TGI is also participating in an EC BRITE EURAM project on the development of a compact steam reformer, developing and evaluating improved reforming catalysts and catalyst support materials.

3.10 Portugal

Very few activities are reported for Portugal. Although there is no national SOFC programme, the Instituto Superior Technico (IST) carries out basic research on ceramic materials as part of an EC JOULE-II project. IST is also participating in an EC BRITE EURAM project on the development of a compact steam reformer. IST is undertaking fluid flow, heat transfer and combustion modelling activities in this project.

3.11 Ireland

Very little fuel cell work is carried out in Ireland. The University College at Cork has undertaken some basic research on the development of an improved air cathode for the DMFC, but good oxygen reduction performance was not demonstrated. This work, undertaken in co-operation with the University of Bonn in Germany, was funded by EC DGXII and was completed in 1989. More recently, the University of Cork has reported improved DMFC cathode performance following the deposition of the Pt catalyst using a thermal reduction technique, as opposed to the more traditional wet chemical process.

3.12 Luxembourg

There are no fuel cell activities reported in the literature for Luxembourg.

3.13 Austria and Switzerland

Very little activity is reported for Austria although Switzerland is more active, particularly on SOFC through the programmes of Sulzer.

3.13.1 PAFC

There are two demonstrations of the ONSI 200kW PAFC system; one is operated by Ferngas in Austria, the other by SIG in Switzerland.

3.13.2 SOFC

Sulzer is developing a novel SOFC design called the HEXIS (Heat Exchanger Integrated Stack). This design is based on circular planar cells inter-spaced with heat exchanger units. These cells are each effectively a combined electrochemical cell, air pre-heater and afterburner. Metallic or ceramic interconnects can be used and the design is, in principle, suitable for a range of cell materials and stack sizes. Sulzer has made rapid progress since starting its SOFC programme in 1992 and is currently building a 1kW stack. This is being done in co-operation with Ceramtec (USA), who provides the cell components. It is planned to start field trials of small prototype systems (~ 30-40kW) by 1997. Sulzer believes that the first market for this technology will be small-scale cogeneration in the range 50-500kW. Preliminary cost calculations show that a cost target of 1000\$/kW could be achieved for a 50kW stack. Sulzer currently employs 4 man-years/year on SOFC development with additional resources at participating universities. A total budget for this programme is estimated at \$1million/year, with significant funding from the Swiss Government Department of Energy (OFEN).

The Swiss Government is also funding complementary basic SOFC research at universities in Lausanne and Zurich. This is aimed at investigating lower temperature ($\approx 750^{\circ}\text{C}$) cells based on ceria which could be used in conjunction with the HEXIS design.

3.13.3 PEFC

The Paul Scherrer Institute of Switzerland is developing improved polymer electrolytes for PEFC. It is participating in an EC funded project, led by Siemens and described in the German programme, and is also participating in the IEA's PEFC Annex IV.

3.14 Finland, Norway and Sweden

All three countries are demonstrating PAFC systems with Japanese and American stacks. No activities are reported on PEFC, DMFC and AFC. Norway is active in the development of internally reformed SOFC stacks.

3.14.1 PAFC

Sydskraft in Sweden is demonstrating two PAFC systems; these are a Fuji Electric 50kW system, in operation since December 1991, and an ONSI 200kW system which has been in operation since June 1992. Sydkraft's future plans include further PAFC systems, possibly requiring between 5 and 30MW of PAFC capacity. Vattenfall of Sweden is demonstrating a 50kW Fuji system.

In Finland, as described in the UK programme, IVO is demonstrating a 200kW ONSI system in collaboration with EA Technology.

In Norway, Norsk Hydro agreed in June 1990 to install and demonstrate a 400kW PAFC, provided by Westinghouse, at its chlorine plant in Rafnes, southern Norway. The stack was to be fuelled with by-product hydrogen from a chlorine production facility. No information has since been published on the progress of this project.

3.14.2 SOFC

An SOFC development programme called NORCELL was launched in 1988. It is funded by the Norwegian Government, oil companies and utilities and contributors include Elkem, Norsk Hydro and Saga Petroleum. The current phase of this programme, 1991-1994, has a budget of about \$7million. Elkem owns Ceramatec (USA) and Ceramatec plays an important role in the NORCELL programme - providing cells and stacks. The main goals for the programme are to build and test planar SOFC prototypes in the 2-5kW range with internal reforming capability, and to develop a suitable design for scale-up to commercial application.

Statoil was originally involved in the NORCELL programme but has now decided to work separately. Its programme aims to demonstrate a 10kW stack by 1995. The partners in this programme are Prototech, a small company specialising in the scale-up of laboratory technologies, the Norwegian Institute of Technology (NTH) and SINTEF, an independent research organisation. Prototech is supplying the SOFC cells and NTH and SINTEF provide modelling support. Good results have been obtained with a 345W stack operating on methane. Statoil is the major Norwegian (state-owned) oil and gas company. Its primary interest in SOFC is to increase the use of natural gas. It is unlikely to produce stacks on a commercial basis, but may instead licence its technology to a Third Party.

Finland and Sweden have no SOFC programmes.

3.14.3 MCFC

Swedish utilities Sydkraft and Vattenfall are both conducting system studies and are considering future demonstration activities.

The Royal Institute of Technology, Stockholm is working on basic MCFC research in a programme funded by NUTEK, the Swedish National Board for Industrial and Technical Development. This includes research on catalysts for internal reforming MCFCs and new cathode materials based on lithium cobaltate.

Norway and Finland have no MCFC programmes.

4. AMERICAN ORGANISATIONS INVOLVED IN EUROPEAN FUEL CELL ACTIVITIES

A number of American organisations have been identified as active in Europe, either through supplying fuel cell components and systems, or collaborating with European organisations on research and development. The involvement of these organisations is briefly summarised in this section of the Report.

IFC/ONSI provide PAFC stacks and systems to many demonstration projects throughout Europe, including the 1.3MW system in Milan. ONSI also part owns the Italian company CLC, established to manufacture and market the PC25 200kW system throughout Europe.

IFC also has an arrangement to provide MCFC stacks to the Italian programme.

Ceramatec plays an important role in the Norwegian SOFC (NORCELL) programme, providing cells and stacks. The current phase of this programme, 1991-1994, has the goals of building and evaluating planar SOFC prototype stacks in the 2-5kW range with internal reforming capability, and to develop a suitable design for scale-up to commercial application.

Argonne National Laboratory, General Motors and Los Alamos National Laboratory have all participated in the IEA's PEFC programme, contributing simulation models of PEFC components and systems. A number of European organisations collaborate with these American organisations in this programme, which is led by CANMET of Canada.

Dow Chemicals supply samples of its PEFC electrolyte to selected laboratories and fuel cell developers throughout Europe. Dow-Europe is also raising its profile on fuel cells, but little information on its work is available.

Du Pont supply its product NAFION on a commercial basis throughout Europe.

H-Power is in discussion with Fiat regarding the provision of PEFC stacks to Fiat's proposed new hybrid electric vehicle programme.

Finally, ERC licences its MCFC technology to a consortium of Danish and German companies, including Daimler-Benz.

5. CONCLUSIONS

The principal conclusions from the Review are as follows.

- Many organisations and countries are demonstrating phosphoric acid fuel cell (PAFC) systems, largely for cogeneration applications. There is one PAFC system being demonstrated in a bus, as part of Euro Quebec Hydrogen Hydro Pilot Project. The PAFC stacks for these demonstrators are supplied by US and Japanese companies.
- European solid oxide fuel cell (SOFC) R&D activities focus on planar stack designs with the potential for internal reforming. The main SOFC programmes are those of Siemens and Dornier in Germany. Siemens has recently made good progress in improving stack performance. There is a growing level of interest in other European countries, notably the UK, Switzerland and Norway. The Sulzer (Switzerland) and Statoil (Norway) programmes have both made rapid initial progress using US cell technology. Fundamental R&D is still needed in many areas and commercialisation is considered unlikely before 2005. The initial market in Europe is expected to be small-scale cogeneration.
- On molten carbonate fuel cells (MCFCs), the Netherlands has an ambitious programme of work and it has received significant levels of support from the Dutch Government and the European Commission. If successful, BCN expect to be operating 250kW systems by 1995, leading to field trials of complete systems by 1998. These time scales are not far behind those anticipated by leading US and Japanese developers. Other European MCFC programmes mainly rely on imported stack technology and are aimed at systems development and, to a lesser extent, integration with coal gasifiers. Haldor Topsøe of Denmark is a leading European supplier of reformers for MCFC (and other) systems.
- For polymer electrolyte fuel cell (PEFC) systems, there has been a significant growth in R&D activity in recent years and this is expected to continue. There is particular emphasis on transport applications, and growing interest in the technology for small-scale cogeneration. PEFC stacks are being developed by Siemens and De Nora, with individual stack components being developed in the UK (Johnson Matthey) and the Netherlands (ECN). Johnson Matthey has recently signed a collaborative agreement with Ballard Power Systems to develop improved components for PEFC stacks. De Nora stacks are being supplied to transport "technology demonstration" projects. These include a bus being developed as part of the Euro Quebec Hydro Hydrogen Pilot Project and the recently announced

proposed collaboration with Volvo and Renault. There is a significant level of activity on the development of fuel processing technology for PEFC transport and cogeneration applications, notably in the UK, but also in Denmark and Italy. There is a growing belief amongst European fuel cell developers that PEFC shows significant potential for widespread application in transport and small-scale cogeneration markets. Many European organisations are gearing their programmes towards the Californian ZEV markets for 1998. The recent collaboration between Daimler-Benz and Ballard is likely to make a significant contribution to the development of PEFC for transport applications prior to 1998. Fiat is to establish a significant R&D programme on hybrid vehicles. VSEL and CJB Developments, in the UK, have recently announced their collaboration with Rover Cars and Lucas Advanced Engineering.

- Direct methanol fuel cell (DMFC) systems are generally considered to be a longer term option than PEFC for transport applications. Fundamental research continues, mostly at universities, frequently with support from the EC. Siemens, also with support from the EC, is developing cells and stacks and is making significant progress with this technology.
- The only significant activity on alkaline fuel cells (AFCs) is that led by Elenco. Its AFC bus will be operating on the streets of Brussels and Amsterdam during 1994. Elenco aims to establish a number of prototype AFC buses and is looking for opportunities to demonstrate its technology at different cities throughout the world. More recently, Hoechst of Germany has announced its work to develop Alkaline Falling Film Fuel Cells (AFFFC), which it sees as having potential applications in vehicles.
- In 1992, the EC estimated that the total expenditure on fuel cells was \$64million/year. This is the total funding from all sources for all potential fuel cell applications; it includes the contributions from national Governments, the EC and industry. It is difficult to accurately estimate the overall level of expenditure on fuel cells RD&D and commercialisation activities in Europe. However, it is considered that the overall level of European fuel cell activity and expenditure has increased since the EC made this estimate in 1992.
- A number of American organisations have been identified as active in Europe, either through supplying fuel cell components and systems, or collaborating with European organisations on research and development. These include ONSI/IFC, Ceramatec, ERC, Dow, Du Pont, and through the IEA PEFC programme, Argonne National Laboratory, General Motors and Los Alamos National Laboratory.

Appendix A
Tables Summarising European Fuel Cell Activities, by Fuel Cell Type

Table A-1	Summary of PAFC Programmes
Table A-2	Summary of SOFC Programmes
Table A-3	Summary of MCFC Programmes
Table A-4	Summary of PEFC Programmes
Table A-5	Summary of DMFC Programmes
Table A-6	Summary of AFC Programmes

Table A-1
Summary of PAFC Programmes

Country	Participants	Activity	Timescale	Current Scale/ Type	Future Targets	Expenditure in Timescale
United Kingdom	EA Technology/ IVO (Finland)	Demo. Nat gas/Cogen	93-95	200kW ONSI	-	Unknown
	Johnson Matthey	Provision of catalysts	Ongoing	N/A	-	Unknown
Germany	Ruhrgas	Demo. Nat gas/Cogen	Since 93	200kW ONSI	Further field trials	Unknown
	Thyssengas	Demo. Nat gas/Cogen	-	200kW ONSI	Further field trials	Unknown
	HEAG	Demo. Nat gas/Cogen	-	200kW ONSI	-	Unknown
	KTI/Solar-Wasserstoff-Bayern	Demo. Hydrogen	-	80kW KTI/Fuji	-	Unknown
France	None					
Italy	Eniricerche	Demo. Nat gas	-	50kW Fuji	-	Unknown
	ACOSER	Demo. Nat gas	91-94	200kW ONSI	-	Unknown*
	CLC	Stack Manufacture	ongoing	200 kW ONSI under licence	-	Unknown
	AEM/ENEA/Ansaldo	Demo.	91-94	1.3MW with IFC stack.	Further 2 years operation	\$16M from ENEA*
Belgium	None					

* = funding also received from the EC

Table A-1 Continued

Country	Participants	Activity	Timescale	Current Scale/ Type	Future Targets	Expenditure in Timescale
The Netherlands	KTI	Demo.	88-92	25kW with Fuji stack	300kW systems	\$0.45M*
	KTI/Solar-Wasserstoff-Bayern (see above)	System supply	Ongoing	80kW	300kW	Unknown
Denmark	Naturgas Syd/Sonderjyllands	Demo.	-	200kW ONSI	-	Unknown
	Haldor Topsoe	Reformer Development	-	up to 5MW	PAFC and others > 50kW	Unknown
Greece	None					
Spain	Enagas	Demo. on Nat gas	Since 92	50kW Fuji	-	Unknown
Portugal	None					
Ireland	None					
Luxembourg	None					
Austria and Switzerland	Ferngas (Austria)	Demo. on Nat gas	-	200kW ONSI	-	Unknown
	SIG (Switzerland)	Demo. on Nat gas	-	200kW ONSI	-	Unknown
Finland, Norway and Sweden	Sydkraft (Sweden)	Demos on Nat gas	Since 91 Since 92	50kW Fuji 200kW ONSI	Further demos - 5-30MW	Unknown
	Vattenfall (Sweden)	Demo on Nat gas	-	50kW Fuji	-	Unknown
	IVO (Finland) with EA Technology (UK)	Demo Nat gas/cogen	93-95	200kW ONSI	-	Unknown

* = 50% funding from EC

Table A-2
Summary of SOFC Programmes

Country	Participants	Activity	Timescale	Current Scale	Future Targets	Expenditure in Timescale
United Kingdom	Rolls-Royce/Birmingham Univ./ Keele Univ./ CERAM Research	Evaluation of Integral Planar IP-SOFC stack design/ thin-layer cell fabrication	93-94	Lab scale	1kW by 95/96	\$0.5M (60% from UK Gov)
	British Gas/ Tioxide/ BNFL/ Riso (Denmark)/ TNO (Netherlands)/ IST (Portugal)	Development of novel composite plate cells	93-94	Lab scale	-	\$1.4M* (~5% from UK Gov)
	Keele University/ CPSL/ Sapco (France)/ Viking Chemicals (Denmark)	Stack development based on narrow tubular cells	94-97	-	-	\$2M*
	Imperial College	Research on low temperature cells ($\approx 500^{\circ}\text{C}$) for direct operation on methanol	93-96	Lab scale	10W, 500mAcm^{-2} by 96 Development for transport applications	\$0.7M (100% from UK Govt)
	British Gas/ Eniricerche	Balance of Plant test rig with simulated SOFC stack	94-96	-	1-5kW test rig by 96	\$1.5M* (25% from UK Govt)

* = 50% funding from the EC

Table A-2 Continued

Country	Participants	Activity	Timescale	Current Scale	Future Targets	Expenditure in Timescale
Germany	Siemens/ GEC (UK)/ ECN (Netherlands)/ Imperial College (UK)	Stack development - Planar with metal interconnect.	93-95	1.8kW 600mAcm ⁻² 5cmx5cm cells	20kW by 95 300kW by 99	~\$8M*
	Dornier/ Cookson (UK)	Planar all-ceramic stack development	93-95	25W	3-5kW by 95	~\$3M*
France	Sapco/ Keele Univ etc - see above					
Italy	Eniricerche/ British Gas - see above					
The Netherlands	ECN/TNO/Univ of Delft/Univ of Twente	Novel fabrication techniques for thin layer cells	-	Lab scale	-	Unknown
	ECN/Siemens etc - see above					
Denmark	Riso/ Innovation/ Odense Univ/ Haldor Topsoe/Technical Univ of Denmark		91-93 93-97	Lab scale Scale-up	~1kW by 95	\$22M total from Danish Gov and Utilities
	Riso/British Gas etc - see above					

* = 50% funding from the EC

Table A-2 Continued

Country	Participants	Activity	Timescale	Current Scale	Future Targets	Expenditure in Timescale
Greece	Univ of Patras	Basic research on cogeneration of chemicals and electricity	Since 91	Lab scale	-	Unknown*
Spain	None					
Portugal	IST/ British Gas etc - see above					
Ireland	None					
Luxembourg	None					
Austria and Switzerland	Sulzer (Switzerland)	Development of new stack design with integral heat exchangers (HEXIS)	92-97	1kW	Prototype system by 97	~\$1M/yr (~60% from Swiss Govt.)
Finland, Norway and Sweden	Statoil (Norway)/ Prototech/ NTH/ SINTEF	Stack development using Ceramtec (US) cells	93-95	300W	10kW by 95	Unknown
	Elkem/ Norsk Hydro/ Saga Petroleum (NORCELL programme)	Stack development using Ceramtec (US) cells	91-94	-	2-5kW by 94	\$7M (from Norwegian Govt., utilities)

* = 50% funding from EC

Table A-3
Summary of MCFC Programmes

Country	Participants	Activity	Timescale	Current Scale	Future Targets	Expenditure in Timescale
United Kingdom	British Gas/ ECN (Netherlands) /CNR-TAE (Italy)	Internal reforming stack development	93-95	1kW	10kW by 95	\$3M*
Germany	MTU/ Ruhrgas/ Haldor Topsoe (Denmark)/ Elkraft (Denmark)	System development and demo. using US stacks (ERC)	91-95	Design stage	100kW systems by 95 Commercial launch by 99	~\$20M
France	None					
Italy	Ansaldo/ CISE/ ENEA/ TGI (Spain)/ Iberdrola (Spain)/ AEA Technology (UK)	System development and demo. using US stacks (IFC)	93-96	Design stage	100kW system by 96	Unknown*
Belgium	None					
The Netherlands	BCN/ECN	Development and demo. of systems using ECN stacks	Since 93	10kW	50kW by 94 250kW (nat gas) by 95; 250kW (coal gas) by 96	Unknown. Part funded by EC, Stork, Royal Schelde
	ECN (Netherlands)/ British Gas (UK) /CNR-TAE (Italy) - see above					

* = 50% funding from the EC

Table A-3 Continued

Country	Participants	Activity	Timescale	Current Scale	Future Targets	Expenditure in Timescale
Denmark	Haldor Topsoe/ Elkraft/ Deutsche Aerospace Germany)/ Ruhrgas (Germany) - see above					
	Elkraft	Demo. of US stack (ERC)	90-91	7kW	-	Unknown*
Greece	None					
Spain	TGI/ Iberdrola/ Ansaldo (Italy) etc - see above					
Portugal	None					
Ireland	None					
Austria and Switzerland	None					
Finland, Norway and Sweden	Sydskraft (Sweden)	System studies	-	-	Future demos?	Unknown
	Vattenfall (Sweden)	System studies	-	-	Future demos?	Unknown
	Royal Institute of Technology (Sweden)	Basic research	-	-	-	Unknown - funded by Swedish Gov

* = 50% funding from EC

Table A-4
Summary of PEFC Programmes

Country	Participants	Activity	Timescales	Current Scale	Future Targets	Expenditure in Timescale
United Kingdom	VSEL and CJB Developments (with Ballard Power Systems)	System demonstration and reformer development	Pre-1990	10kW system with methanol reformer	20kW methanol reformer	~\$1M
	CJB and ECN (Netherlands)	Reformer development	1994-1996	10 kW	Improved dynamic characteristics	~\$0.5M
	VSEL, CJB, Rover and Lucas	Vehicle demonstration	1993-1997	-	Demo by 1997	Unknown
	Johnson Matthey	Electrode and catalyst development	Since 1992 (with Ballard since 93)	Single cell	Pt utilisation-20% at 0.5mgcm ⁻² by 1994	Unknown.)
		Palladium membrane	Since 1993	Lab evaluation	100% hydrogen selectivity	\$0.75M (30% from Govt.)
	British Gas	Natural gas reformer development for cogeneration	Since 1992	Laboratory evaluation	Compact reformer <50kW	\$0.4M (50% from Govt.)
		CO clean-up	Since 1992	Laboratory evaluation	<10ppm CO	\$0.3M (50% from Govt.)
	Rolls Royce and Associates	Autothermal reformer development	Since 1992	5kW lab demonstration	10kW system by 1995	\$0.4M (30% from Govt.)

Table A-4 continued

Country	Participants	Activity	Timescales	Current scale	Future Targets	Expenditure in Timescale
United Kingdom	AEA Technology, EAT and PowerGen (with GasTec and others)	Reformer development	Since 1994	Lab evaluation	Compact, responsive system by 1997	\$3M (50% from Govt and EC)
	Loughborough University	Stack development	Since 1992	~100W	1kW stack by 1994	\$0.3M (from Govt.)
Germany	Siemens	Stack development (naval)	Pre 1990	34kW stack, 700mAcm ⁻² , 60% efficiency		Unknown
	Siemens (with AEA Technology, CEA, PSI)	Stack development for transport	Since 1992	Hydrogen/air 300mAcm ⁻²	<100\$/kW	\$3.5M (50% from EC)
	Daimler-Benz (with Ballard Power Systems)	Stack evaluation	Since 1990	2kW stack		\$60M
		Vehicle demonstration	Since 1993	Operational		
France		Stack development	Since 1993		Compact stack at 50\$/kW by 1998	\$35M (30% from Ballard)
	KFA Julich (with Haldor Topsoe)	Methanol reformer development	Since 1992	-	-	Unknown (50% from EC)
	BMW, with SWB, DASA and Linde	Various activities on H economy	1987-1996	-	-	\$87M
	CEA (with Siemens)	Electrolyte development	Since 1992	-	-	See Siemens, above

Table A-4 continued

Italy	De Nora Permelec	Stack development	Since 1991	10kW 0.7mgcm ⁻² of Pt	Integration into vehicles by 1997	Estimated at \$2M/year at present
	Tecnars (with University of Barcelona)	Methanol reformer development	Since 1993	-	50kW; high efficiency; by 1996	Unknown (50% from EC)
	Fiat	System development	1994-1997	-	Hybrid vehicles	\$30M
	Ansaldo	Systems integration; electronics	Since 1991	-	-	Unknown
Belgium	VITO	Electrode development	Upto 1993	Work stopped	-	Unknown
The Netherlands	ECN (with CJBD,UK)	Systems integration	Since 1993	Brass-board	Evaluation in stacks	~\$2M (50% from EC)
		Bipolar plate development	Since 1992	Lab evaluation		
		Methanol reformer	Since 1994			
	GasTec with BCN, AEA Technology and others	Compact reformer development	Since 1994	Lab evaluation	Compact reformer by 1997	See AEA Technology, above
Denmark	Haldor Topsoe	Methanol reformer development	Since 1992	-	-	See KFA Julich, above

Table A-4 continued

Country	Participants	Activity	Timescales	Current Scale	Future Targets	Expenditure in Timescale
Greece	None					
Spain	University of Barcelona (with Tecnars)	CO clean-up	Since 1993	-	-	See Tecnars, above
	TGI (with GasTec and AEA Technology)	Reforming catalysts	Since 1994	Lab evaluation	Compact reformer by 1997	See AEA Technology, above
Portugal	IST (with GasTec and AEA Technology)	Catalytic combustion	Since 1994	Lab evaluation	Compact reformer by 1997	See AEA Technology, above
Ireland	None					
Luxembourg	None					
Austria and Switzerland	Paul Scherrer Institute (with Siemens)	Electrolyte development	Since 1992	Lab evaluation	Cost reduction by 1995	See Siemens, above
Finland, Norway and Sweden	None					

Table A-5
Summary of DMFC Programmes

Country	Participants	Activity	Timescales	Current Scale	Future Targets	Expenditure in Timescale
United Kingdom	Newcastle University	Electrode and catalyst R&D	1993-1996	Single cell	Small stacks (post-1996)	\$0.3M (from Govt.)
	Cambridge University	Electrode and catalyst R&D	1993-1996	Single cell	-	\$0.3M (from Govt.)
Germany	Siemens (with Innovision)	Stack development	Since 1992	150W; 400mAcm ⁻²	1kW stack by 1996	Unknown (50% from EC)
	University of Bonn (with Innovision and the University of Poitiers)	Inorganic electrolyte R&D	Ongoing	Single cell; 400mV at 100mAcm ⁻²	Single cell; 600mV at 500mAcm ⁻²	Unknown (>50% from EC)
France	University of Poitiers (see above)	-	-	-	-	-
Italy	None					
Belgium	None					
Netherlands	None					
Denmark	Innovision (with Siemens and others)	Improved electrolytes	Since 1992	See above	See above	See Siemens, above
Greece	None					
Spain	None					
Portugal	None					
Ireland	University of Cork	Improved cathode	Since 1985	-	-	Unknown (100% from EC)
Luxembourg	None					
Austria and Switzerland	None					
Finland, Norway and Sweden	None					

Table A-6
Summary of AFC Programmes

Country	Participants	Activity	Timescales	Current Scale	Future Targets	Expenditure in Timescale
United Kingdom	None					
Germany	Siemens	Stack development for military and space	Pre-1988	100kW	Work completed	Unknown
	Hoechst	AFFFC	Unknown	Unknown	-	
France	SAFT	Battery supply to Elenco bus project	Since 1991	-	-	See Elenco, below
Italy	Ansaldo	Electronics and drive train for Elenco	Since 1991	-	-	See Elenco, below
Belgium	Elenco	Research Stack development Bus demonstration	1976-1984 Since 1985 Since 1991	78kW Road testing	Bus operational during 1994. Further buses	\$18M
The Netherlands	None					
Denmark	None					
Greece	None					
Spain	None					
Portugal	None					
Ireland	None					
Luxembourg	None					
Austria and Switzerland	None					
Finland, Norway and Sweden	None					

Appendix B
Description of Fuel Cell Technologies

Description of Fuel Cell Technologies

Fuel cells are electrochemical devices which convert the energy of a chemical reaction directly into electrical energy. They are similar in principle to primary batteries except that the fuel and oxidant are stored externally, enabling them to continue operating as long as reactants are supplied. Fuel cells have a number of potential advantages over conventional heat engine technologies. These include greater generation efficiency, a higher power density, lower noise and vibration characteristics, and lower pollution levels.

Fuel cells are usually classified by their electrolyte. The main types and their principal characteristic are summarised below.

Main fuel cell types and their principal characteristics						
Fuel Cell Type	Short Name	Electrolyte	Operating Temp (°C)	Catalyst	Development Status	Applications
Alkaline	AFC	Potassium Hydroxide	50-200	Ni/Pt	Developed	Space, transport
Phosphoric Acid	PAFC	Phosphoric Acid	190-210	Pt	11 MW (system)	Cogeneration, power generation
Solid Polymer	PEFC, SPFC, PEMFC	Sulphonic Acid	50-80	Pt	40 kW (stack)	Transport, cogeneration
Molten Carbonate	MCFC	Potassium and Lithium Carbonates	630-650	Ni	100 kW (stack)	Power generation
Solid Oxide	SOFC	Yttria Stabilised Zirconia	850-1000	Ni	25 kW tubular 1.8 kW planar (stacks)	Cogeneration, power generation
Direct Methanol	DMFC	Sulphonic Acid/Sulphuric Acid	80-120	Pt or Pt/Ru	0.2 kW (stack)	Transport

An individual fuel cell consists of an electrolyte sandwiched between two electrodes. Fuel is oxidised at the anode, liberating electrons which flow via an external circuit to the cathode. The circuit is completed by a flow of ions across the electrolyte that separates the fuel and oxidant streams. In principle any fuel can be used in a fuel cell. In practice, hydrogen gas is frequently used, due to its high reactivity. Hydrogen can be generated from hydrocarbons by a process known as reforming. The higher temperature fuel cells, such as the SOFC and the MCFC can operate directly on natural gas and on gas from coal gasifiers.

Practical cells typically generate a voltage of around 0.7 volts and power outputs of a few tens or hundreds of Watts. Cells are therefore assembled in modules known as stacks, in which the cells are connected electrically in both series and parallel to

provide a larger voltage and current. For practical applications, the electrical energy from the stack undergoes power conditioning, such as inversion to alternating current, to generate the electrical energy with the required current and voltage characteristics.

The cell efficiency is directly proportional to the voltage generated by the cell, and, unlike heat engine technologies, the cell efficiency is greatest at part-load. No information on efficiency has been provided in the above table, as this would be difficult to achieve concisely in a brief summary such as this. Generally, the higher temperature fuel cells have higher efficiencies.

Fuel cells that can operate at low temperatures, such as the PEFC, are suitable for transport applications and small-scale cogeneration. High temperature fuel cells, such as the SOFC, offer the potential of high-quality exhaust heat and are potentially attractive in cogeneration and in schemes that integrate the fuel cell with steam turbines.

The principal fuel cell types are described further, below.

Alkaline Fuel Cells (AFCs)

The AFC is a relatively simple device and was the first to be developed. An alkaline electrolyte, such as potassium hydroxide, is used with activated nickel or precious metal electrodes. The electrolyte has excellent electrochemical properties but reacts with carbon oxides, which reduces performance. Consequently, the cell is usually limited to operation with pure hydrogen and pure oxygen.

Early systems operated at about 200°C and 20-40 bar pressure. The first fully engineered system was developed in the 1960s and was subsequently used in the Apollo spacecraft. During the 1980s low temperature operation (60-80°C) was greatly improved, enabling more rapid start-up, which is a valuable feature for potential transport applications.

The AFC may have a long-term future in transport and specialist applications. It would likely become a more important technology if hydrogen becomes more widely available.

The AFC operating on pure hydrogen and pure oxygen can have a cell efficiency in the range of 60-70%.

Phosphoric Acid Fuel Cells (PAFCs)

The PAFC employs a phosphoric acid electrolyte and platinum based catalysts on carbon gas diffusion electrodes. The moderate operating temperature (200°C) precludes internal reforming of hydrocarbon fuels and a separate reformer is required. At 200°C, the catalyst is reasonably tolerant to the carbon monoxide from the reformer; this can simplify the fuel processing system to a reformer with a shift reaction, avoiding the need for further gas clean-up systems.

A number of demonstration units for power generation and cogeneration, in the 50kW to 1MW range, have operated for several thousand hours in Japan and the USA. The largest installation to date has an output of 11MW and a total of about 100 installations worldwide is expected by 1995. Overall system electrical efficiency is typically in the 37-43% range, with some further improvement expected.

System costs are currently estimated to be \$3000/kW. If reasonable cost reductions can be achieved through commercial production, PAFC systems would be expected to play a significant role in Japan, where electricity costs are high and dispersed generation is preferred. Opportunities in Europe are expected to be more limited, although a number of trial installations are either being evaluated or under way. In the longer term more, advanced fuel cells, currently at an earlier stage of development, are expected to replace the PAFC in most applications.

Polymer Electrolyte Fuel Cells (PEFCs)

The PEFC uses a sulphonic acid electrolyte which is incorporated into a polymer membrane so that the electrolyte is effectively solid. The PEFC uses gas diffusion electrodes with platinum catalysts on both the anode and cathode. Graphite bipolar plates provides the electrical connection between the cells and acts as an impermeable barrier between the fuel and oxidant flows.

To maintain ionic conductivity, the electrolyte must be kept hydrated at all times; this effectively limits the operating temperature of the cell. PEFC stacks currently operate at a temperature of 80°C, but over 100°C has been achieved in single cells. The cell can be run directly on hydrogen or on reformed methanol or natural gas, but as platinum is poisoned by carbon monoxide this must be removed during fuel processing.

System studies have shown that PEFC systems operating on natural gas would have efficiencies of around 36-40%, and slightly higher than this for operation on methanol. In addition to a system efficiency that is greater than current internal combustion engine technology, the PEFC also has a high power density, is responsive to changing loads and has excellent efficiency at part-load.

Although PEFCs have been used in specialist space and military applications they remain relatively undeveloped and are not, as yet, commercially viable for wider use.

Molten Carbonate Fuel Cells (MCFCs)

The electrolyte in a MCFC is an alkaline mixture of lithium and potassium carbonates, which is liquid at the operating temperature of 650°C, and is supported by a ceramic matrix. Both electrodes are nickel-based.

The operation of an MCFC, involves the net transfer of carbonate ion across the electrolyte. It is tolerant to both carbon monoxide and carbon dioxide, but the latter must be reintroduced to the cell with the oxidant. Hydrocarbon fuels, including coal gas, may be reformed directly at the anode and an external reformer is not necessarily required. Sulphur tolerance remains a problem. The recycling of anode gas to the

cathode places a limit of 5ppm on the sulphur content of the fuel with current technology.

Development programmes in Japan and the USA have produced many small prototype units in the 5-20kW range. Electrical efficiencies of 48-53% have been achieved with natural gas fuel and units have operated on simulated coal gasifier gas and natural gas for several thousand hours. In the USA, ERC has now built a 100kW, 300 cell unit. Materials problems, however, remain an issue and still limit the useful lifetimes of the stacks.

Solid Oxide Fuel Cells (SOFCs)

The SOFC uses a solid zirconia-based electrolyte which conducts over the 850-1000°C temperature range. The anode is a porous cermet (ceramic/metal complex) of nickel oxide and zirconia while the cathode is based on lanthanum manganite doped with strontium. A separate bipolar plate is needed and is usually made from doped lanthanum chromite, but metallic plates have also been suggested. The final components are a current collector and a nickel felt that provides structural flexibility.

Natural gas is the preferred fuel for most applications and may be reformed within the cell, in an external reformer or by using a combination of both. Other fuels, such as coal gas, could be used but, although the SOFC is thought to be more tolerant to sulphur than other types of fuel cell, some clean-up during fuel processing would still be required.

The SOFC is one of the most promising fuel cell systems but is still at an early stage of research and development. Considerable work is needed to improve the structural integrity and power density of the fuel cell stack and to develop fully engineered systems. In the USA, Westinghouse has built and tested a number of 3kW and 25kW stacks using a tubular cell design; work on a 100kW unit is under way. Planar designs are at a much earlier stage of development, with the development of 1kW prototype stacks expected shortly.

Direct Methanol Fuel Cells (DMFCs)

Direct methanol fuel cells are considered as a long term candidate for transportation. The DMFC oxidises methanol directly at its anode, allowing for a simple and potentially efficient system. Furthermore, methanol, as a liquid, would fit easily into existing transport fuel distribution infrastructure.

During the late 1980s liquid acid electrolyte cells were investigated, but were found to have slow methanol oxidation rates. Work has focused on increasing reaction rates through the development of suitable catalysts and solid electrolytes that can operate at higher temperatures. Higher operating temperatures lead to faster reaction rates and lower precious metal catalyst loadings.

Development programmes are still at an early stage, but cell voltages of up to 500mV at 400mAcm^{-2} have recently been reported by Siemens in Germany. At this voltage, cell efficiency (methanol to direct current) is in the region of 40%.