

International Energy Agency (IEA) Advanced Fuel Cells Implementing Agreement

ANNUAL REPORT 2010

June 2011



This Annual Report has been prepared by the Operating Agents and the Secretariat of the Executive Committee, who also acted as Editor.

Copies can be obtained from the programme's web site at www.ieafuelcell.com or from:

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1. Introduction

1.1 GENERAL

The Implementing Agreement for a programme of research, development and demonstration on advanced fuel cells was signed by seven countries in Paris on April 2nd, 1990. Since that time, a further thirteen countries have signed the Implementing Agreement and three countries (New Zealand, Spain and the UK) have left the Agreement. The current participants are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Japan, Korea, Mexico, Netherlands, Norway, Sweden, Switzerland, Turkey and USA, although Norway decided to leave at the end of 2010.

The aim of the International Energy Agency (IEA) Advanced Fuel Cells programme is to advance the state of understanding of all Contracting Parties in the field of advanced fuel cells. It achieves this through a co-ordinated programme of research, technology development and system analysis on Molten Carbonate (MCFC), Solid Oxide (SOFC) and Polymer Electrolyte Fuel Cell (PEFC) systems. There is a strong emphasis on information exchange through Annex meetings, workshops and reports. The work is undertaken on a task-sharing basis with each participating country providing an agreed level of effort over the period of the Annex.

The IEA's Committee on Energy Research and Technology (CERT) approved a five-year extension to the Advanced Fuel Cells Implementing Agreement in February 2009. The extension is underway and will run until February 2014. The Implementing Agreement covers fuel cell technology and its potential applications in stationary power generation, portable power applications and transport.

This report gives an overview of the status, progress and future plans of the programme, summarising the activities and decisions of the Executive Committee, as well as of each of the Annexes.

1.2 Participants

The following eighteen IEA-member countries participated in this Implementing Agreement during 2010.

Denmark

Signatory Party: Riso National Laboratory
Date of Signature: September 2004

Belgium

Signatory Party: Vlaamse Instelling voor
Technologisch Onderzoek (VITO)
Date of Signature: November 2002

Netherlands

Signatory Party: Netherlands Energy
Research Foundation (ECN) (from October
1999, previously Netherlands Agency for
Energy and the Environment (NOVEM)
Date of Signature: April 1990

Canada

Signatory Party: Delegation to the OECD
Date of Signature: November 1991

United States

Signatory Party: Department of Energy
Date of Signature: May 1995

Mexico

Signatory Party: Electrical
Research Institute
Date of Signature: June 2006

France

Signatory Party: Commissariat à l'Energie
Atomique (CEA)
Date of Signature: May 2005

Italy

Signatory Party: Ente per le Nuove
Tecnologie, l'Energia e l'Ambiente (ENEA)
Date of Signature: April 1990





The Executive Committee meets twice a year under the Chairmanship of Professor Lars Sjunnesson (E.ON Sverige, Sweden). The Vice-Chairs are Professor Detlef Stolten (Forschungszentrum Jülich, Germany) and Dr Nancy Garland (Department of Energy USA), and the Secretary is Mrs Heather Haydock (AEA, UK). The IEA/OECD representative during 2010 was François Cuenot.

The following table lists all the Executive Committee Members, their Alternates and the Operating Agents of the different Annexes at the end of 2010. Addresses and contact numbers are given in Appendix 1 to this report.

Country	Ex Co Member	Ex Co Alternative	Operating Agent	Annex Number
Australia	K Foger			
Austria	G Simader	V Hacker		
Belgium	Y Alvarez-Gallego			
Canada	V Scepanovic	E Andrukaitis		
Denmark	I Pihl Byriel	A Nielsen		
Finland	H Kotila	R Rosenberg	J Kiviaho	24
France	T Priem			
Germany	D Stolten	R Samsun	M Müller	27
Italy	A Moreno			
Japan	T Itomi			
Korea	H-C Lim	T-H Lim	T-H Lim	23
Mexico	J Huacuz	U Cano Castillo		
Netherlands	F de Bruijn			
Norway	T Tronstad			
Sweden	L Sjunnesson	B Gustafsson	B Ridell	25
Switzerland	S Oberholzer			
Turkey	G Behmenyar	B Erdor		
USA	N Garland	W Surdoval	X Wang	22
			R Ahluwalia	26

1.3 CURRENT AND FUTURE ANNEXES

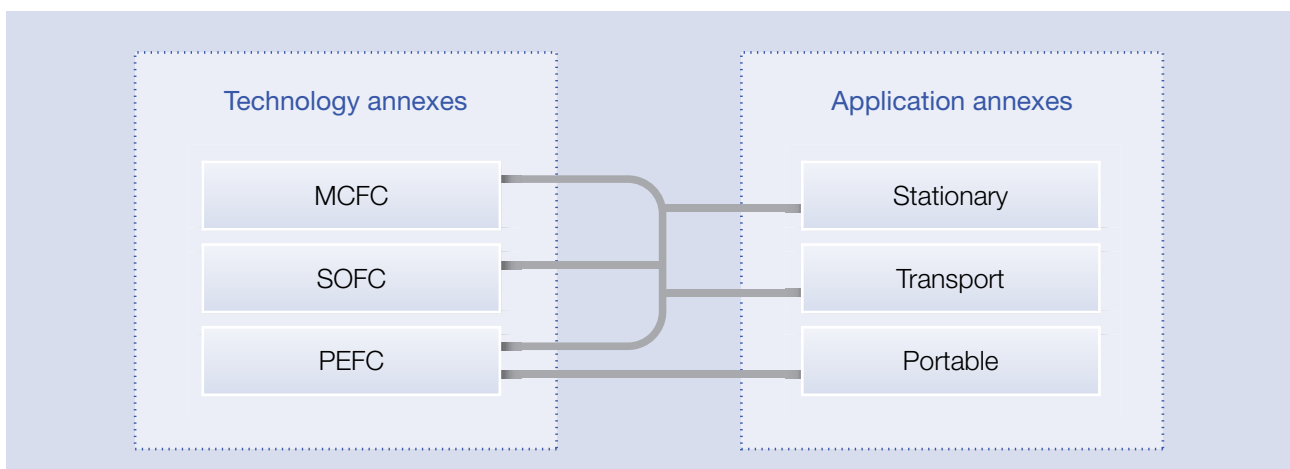
Six Annexes were active in 2010:

Annex	Title
Annex 22	Polymer Electrolyte Fuel Cells
Annex 23	Molten Carbonate Fuel Cells
Annex 24	Solid Oxide Fuel Cells
Annex 25	Fuel Cells Fuel Cells for Stationary Applications
Annex 26	Fuel Cells for Transportation
Annex 27	Fuel Cells for Portable Applications

In addition one new task was proposed in October 2010, a Systems Analysis Task.

Together these six annexes form an integrated programme of work for February 2009 to February 2014, comprising three technology-based annexes (MCFC, SOFC and PEFC) and three application-based annexes (stationary, transportation and portable applications), as shown in Figure 1 below.

Figure 1 Diagram illustrating the relationship between the three technology-based annexes and the three application-based annexes



The programme places a greater emphasis on application and market-orientated issues than it has previously, whilst continuing to address technology development and information management. The scope and timing of the programme are shown in Table 1 and Table 2 below.

Table 1 Scope of the programme for 2009-2014

Information Management Internal and external network	Implementation and Application Issues Reduction of barriers	Technology Development Stationary, Mobile, Portable
		MCFC, SOFC, PEFC
Co-ordination within the Implementing Agreement	Market issues	Cell and stack
Co-ordination with other Implementing Agreements	Environmental issues	<ul style="list-style-type: none"> • cost and performance • endurance • materials • modelling • test procedures • minimise size of stack
Public awareness and education	Non-technical barriers (e.g. standards, regulations)	
	User requirements and evaluation of demonstrations	Balance of Plant
		<ul style="list-style-type: none"> • tools • availability • data base
		Fuel processing
		Power conditioning
		Safety analysis

Table 2 Timescales of the current programme 2009-2014

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
MCFC	Annex VI			Annex XIV				Annex XVII				Annex 22						
SOFC	Annex VII			Annex XIII				Annex XVIII				Annex 23						
PEFC	Annex VIII			Annex XI				Annex XVI				Annex 24						
Stationary	Annex IX			Annex XII				Annex XIX				Annex 25						
Transport		Annex X				Annex XV			Annex XX				Annex 26					
Portable									Annex XXI				Annex 27					

A new Annex was proposed in October 2010: Annex 28: Systems Analysis Annex. Further development of the purpose and aims of this proposed Annex will take place in 2011.



2. Executive Committee Report

2.1 MEMBERSHIP AND PARTICIPATION

Norway considered whether to leave the Implementing Agreement, and ultimately decided to do so at the end of 2010. No new member countries joined in 2010.

There were changes in the Executive Committee membership in 2010 for Turkey with Ms. Gamze Behmenyar taking over from Dr Evren Gunen, and Anne Nielsen taking over from S. Linderoth for Denmark.

Paul van den Oosterkamp resigned as Operating Agent for the Transportation Annex, Annex 26 in 2009, and was replaced by Rajesh Ahluwalia as the new Operating Agent towards the end of 2010. As a result activities within Annex 26 did not recommence again until the end of 2010.

The other five Operating Agents continued to run the Annexes as they transitioned into the new phase of work: Dr Xiaoping Wang for the PEFC activities under the Annex 22; Dr Tae Hoon Lim for Annex 23; Dr Jari Kiviaho for the SOFCs activities under Annex 24; Bengt Ridell for stationary fuel cell systems under Annex 26 and Martin Müller for fuel cells for portable applications as Annex 27.

François Cuenot remained as the IEA Desk Officer.

2.2 ACTIVITIES AND DECISIONS

2.2.1 Activities

Two Executive Committee meetings were held; the 40th meeting was held in Essen, Germany in May 2010, and the 41st was held at the IEA in Paris, France in October 2010.

The Executive Committee continued to co-ordinate its activities with other relevant IEA Implementing Agreements. This has included cross-representation on the Executive Committees of the Hydrogen Implementing Agreement and a joint ExCo meeting was held in May 2010 in conjunction with the WHEC.

The web site of the Implementing Agreement (www.ieafuelcell.com) was maintained.

2.2.2 Financing and Procedures

All activities under the Annexes of the Implementing Agreement are task shared. The only cost shared activity is the Common Fund, which provides funding for the Executive Committee Secretariat.

There were no changes to the procedural guidelines for the programme during this year.



2.2.3 Future Plans

Information exchange with other Implementing Agreements will continue to be encouraged, building on links already in place with the Hydrogen and Hybrid Electric Vehicle Implementing Agreements.

Two Executive Committee meetings will be held in 2011. The 42nd meeting will be held in Rome, Italy on May 21-22, 2011. The 43rd meeting will be held in Cuernavaca, Mexico in October/November 2011.

Continued implementation of the approved work programme for the six current Annexes is planned, and refinement of the concept of the proposed Systems Analysis Annex. There may also be additional cross-cutting workshops and other activities. The six current Annexes comprise three technology-specific annexes on PEFC, SOFC and MCFC, and three application-specific annexes on stationary, transportation and portable applications.



3. Key Achievements

This section of the Annual Report summarises the key achievements of the programme during the year. Further details are given in Section 4.

3.1 ACHIEVEMENTS OF ANNEX 22 POLYMER ELECTROLYTE FUEL CELLS

- Manufacturing technologies, such as coating and assembling technologies for Direct Methanol Fuel Cells (DMFCs), were developed with better reproducibility and productivity. Such developments significantly improve DMFC system performance, durability, and cost.
- Better autothermal reforming catalysts with improved diesel conversion and hydrogen yield were developed for heavy truck APU applications.
- Advanced characterisation tools, such as electron tomography and X-ray computed tomography, X-ray absorption spectroscopy, and anomalous small angle X-ray scattering, have enabled not only ex situ 3D images of fuel cell components, such as electrode catalysts, Gas Diffusion Layers (GDL), and Membrane Electrode Assembly (MEA) showing structural changes in used MEAs, but also in situ catalyst degradation, including both oxidation state and catalyst particle size changes.
- Low cost microbial fuel cell (MFC) materials enabled the development of a MFC for simultaneous wastewater purification and energy recovery from industrial wastewater.
- Alternative cathode catalyst supports, such as doped tin oxide SnO₂, carbon nanotubes and nanofibers, and their composites were developed as improved supports over traditional carbon black, as they render the catalyst with either better stability or/and better mass transport properties, while allowing low loadings of Pt to maintain the same high oxygen reduction reaction (ORR) activity.
- A study of the performance of MEAs with different non-woven carbon GDLs under dry operating conditions helped to identify the desired properties or parameters of GDLs for high temperature Polymer Electrolyte Fuel Cells (PEFCs).
- Investigations of the effects of operating conditions, composition, morphology, and particle sizes of the cathode and anode catalysts on the PEFC membrane or cell performance degradation provided insight into membrane and catalyst degradation mechanisms.
- Modelling and simulation were developed for determining fuel cell polarisation curves, hydrogen depletion along the gas channel and GDL transport properties to enable visualization of the motion of water droplets in the gas channel and to evaluate the transport properties of the cathode layer.
- A novel anion-conducting pore-filling membrane was developed for solid alkaline fuel cells with improved stability and hydroxyl ion conductivity over the commercially available product.
- Active non-platinum (Pt) electrocatalysts are under development for the electro-oxidation of ethanol in a basic media for direct ethanol fuel cells with an alkaline membrane as the electrolyte.
- Non-platinum group metals (PGM) oxygen reduction electrocatalysts have been developed using novel precursors including metal organic frameworks and porous organic polymers, and exhibit promising results.
- It has been identified that inert gas build-up has a profound effect on cell voltages, and its formation strongly correlates to the quality of the cells. The accumulation of inert gas in the anode stream strongly depends on the current load and the quality of the hydrogen, with higher current load and lower quality hydrogen leading to a greater build-up of inert gas or other impurity.
- A testing protocol was developed as a quality control measure for bipolar plates (BPPs) and MEAs, by measuring hydrogen crossover through BPPs and MEAs prior to fuel cell assembly.
- It has been identified that electro-oxidation of ethanol for direct fuel PEFC on a model catalyst (Pt) depends on the ethanol concentration, the presence of carbonate, and the acidity of the electrolyte; with a higher CO₂ conversion at higher carbonate concentration and lower acidity.
- Investigation of palladium (Pd)-based bulk alloy systems as ORR catalysts provided better understanding of the relationship between electronic structure, composition, morphology, and activity of the catalysts.

3.2 ACHIEVEMENTS OF ANNEX 23 MOLTEN CARBONATE FUEL CELLS

Highlights from 2010 include results from two different demonstrations;

- 1) 330 kW MCFC system for ship application by MTU in Germany;
- 2) 125 kW external reforming type MCFC system by KEPRI in Korea.

Over 100 MW of MCFC systems are installed, or on order, worldwide, with 69 MW installed in Korea and 24 MW in California and the west coast of the United States of America.

Grid support is the main application, accounting for 71 MW of the total. POSCO Power built up 50 MW/yr stack and system manufacturing facility in Pohang, Korea.

3.3 ACHIEVEMENTS OF ANNEX 24 SOLID OXIDE FUEL CELLS

There is a strong solid oxide fuel cells (SOFC) demonstration programme in Japan. During the programme, 27 residential units were installed in 2007 and 36 further residential units were installed in 2008. All units were operating during 2010 without serious problems arising. National SOFC Projects in Japan consist of two key projects;

- The Demonstration Programme operated by NEDO/NEF (New Energy Foundation).
- The R&D project on SOFC systems looking at durability and reliability, cost reductions and improvement of stack/module technologies.

The SOFC system demonstration programme started in 2008 and ends this year, 2010. In 2007-2008, 0.7kW of SOFC systems were tested by Kyocera, Nippon Oil and TOTO, with further 2kW/8kW systems operated by

TOTO. In 2009-2010 the 0.7 kW system was switched to Toyota/Aishin and new systems, built by Tokyo Gas and NGK Spark Plugs, joined the demonstration programme. Improvements in the durability of the Kyocera/Toyota Aishin systems were achieved during 2010. Durability and reliability improvements have been seen during the project, made possible through cooperation amongst the industrial groups, universities and national laboratories. The main causes of degradation in the stacks being studied are identified as relating to the fabrication process/sequence.

Figure 2: Nippon Oil SOFC, 0.7kW fuel cell unit on the left hand side, hot water tank unit on the right hand side.



Figure 3: Toto SOFC, 0.7kW fuel cell unit on the left hand side, hot water tank unit on the right hand side.



The Natural Sciences and Engineering Research Council of Canada (NSERC) has funded a consortium of organizations to research solid oxide fuel cells since January, 2008. The “NSERC Solid Oxide Fuel Cells Canada (SOFC) Strategic Research Network” is an association of 21 research groups from universities and government partnered with Canadian industries. The 5 year technical goals of the Network are focused on improving the lifetime, performance, and fuel flexibility of two next-generation SOFC technologies: a metal-supported planar system and an anode-supported tubular SOFC platform. To date the main progress has been made in developing planar type ASC SOFC. The best example of this is Versa Power Systems (VPS) who have developed large-scale stacks.

VPS is a developer of SOFCs and has been working with its development partner FuelCell Energy within the U.S. Department of Energy (DOE) Office of Fossil Energy’s (FE) Solid State Energy Conversion Alliance (SECA) Programme to apply SOFC technology to large-scale power plant systems. As a result, initiatives such as scale-up of the cell and stack are being actively pursued for these applications. Single stacks operate at a nominal power rating of 20 kW. Recently, VPS has collaborated with VTT Technical Research Centre of Finland to produce a 10 kW fully integrated SOFC system. VPS supplied the stack and stack module, while VTT was responsible for system design & BoP (Balance of Plant) module. System testing of the VTT 10 kW demonstration unit shows performance that compares favourably with laboratory condition testing.

Denmark presented some recent durability test results on cell, stack and system level¹. Single solid oxide fuel cells with different compositions of the active layers and support have been tested at steady state conditions up to, typically, a few thousand hours. Cell generations based on ceramic anode supports, have been further optimized to fulfil durability specifications demanded for expected SOFC applications. By introduction of scandium (Sc) doped YSZ (Yttria stabilized zirconia) into the anode and electrolyte, for example, it was possible to increase the long-term sulphur tolerance of state-of-the-art anode supported cells significantly. LSC (lanthanum strontium chromite) and LSCF (lanthanum strontium cobalt iron oxide) based cathode compositions, which have greater activity at the lower operating temperatures of ~700°C, have been shown to possess excellent steady state durability over periods of a few thousand hours operation under relevant operating conditions, for example under humid air.

¹ The presentation was given by Anke Hagen (Fuel Cells and Solid State Chemistry Division Risø DTU). The results presented are the outcomes of projects within the consortium between Risø DTU and Topsoe Fuel Cell A/S and collaborations with Wärtsilä.

Denmark produced further results showing that the durability of metal supported cells has been significantly improved were given in 2010; degradation values of <1% over a testing period of 3000 h were achieved². Cells with more active LSCF/CGO cathodes (composite cathode containing La, Sr Co, Fe and Ce, Gd oxides) were implemented in the production line and integrated into stacks. Promising durability behaviour over testing periods of 14,000 h, including thermal cycling events, was demonstrated. The whole stack resistance increased by only 35 mOhm cm²/kh and a further reduction of degradation is expected from new stacks containing new improved cells. Robustness behaviour on stack level, specifically the effect of system failures or loss of stack compression, was tested successfully.

Department of Energy (DOE) Office of Fossil Energy (FE), through the National Energy Technology Laboratory (NETL), conducts leading research and development of advanced solid oxide fuel cells (SOFC) as a key enabling technology. This work is being performed in partnership with private industry, academia, and national laboratories. The Fossil Energy Fuel Cell Programme, embodied in the Solid State Energy Conversion Alliance (SECA), has three parts:

- Cost Reduction
- Coal-Based Systems
- Core Technology.

The Cost Reduction effort is aimed at reducing the manufactured cost of SOFC stacks and associated complete power blocks to \$175 per kilowatt and \$700 per kilowatt (2007 basis), respectively. The Coal-Based Systems goal is the development of large (>100 MW) integrated gasification fuel cell (IGFC) power systems based upon the aforementioned low-cost fuel cell

technology for the production of near-zero-emission electric power from coal. Meeting this latter objective will require a power system that operates with high electric efficiency, captures carbon and limits to specified levels the emission of other pollutants such as mercury, NO_x, and SO_x. Programme efforts in the Core Technology area involve research and development on rigorously-prioritized technical hurdles, focusing on materials set, processing and design optimisation.

In Finland VTT Technical Research Centre has designed, manufactured and tested a 10 kWe SOFC demonstration unit. The 10 kW power class SOFC stack and stack module were designed and manufactured by VPS. A successful commissioning test of the unit was conducted in 2010, with long term testing of the unit starting in November 2010. The unit has been operated with natural gas for over 1500 hours supplying electricity to the local grid. The unit has shown robust and uninterrupted performance. Stack DC efficiency of 60% and system net AC efficiency of 43% has been measured during the operation.

The R&D programme of Wärtsilä includes the development of the WFC20 and WFC50 units; 20 kW and 50 kW SOFC units. Wärtsilä has continued the operation of the first demonstration unit in Vaasa, where the fuel cell is driven by biogas collected from a landfill site. A methanol based unit has been demonstrated within the METHAPU project, which was successfully concluded in 2010. Development of larger units has progressed through the manufacturing of two 50 kW units within the frames of Demo SOFC and Large SOFC projects, both of which are partially funded by the EU. Commercialisation of fuel cell units for onshore and offshore power plant applications is proceeding in parallel with the development programme.

² These results were given in a presentation by Anke Hagen of the Fuel Cells and Solid State Chemistry Division

3.4 ACHIEVEMENTS OF ANNEX 25 STATIONARY FUEL CELLS

Key achievements of Annex 25 included:

- The impressive update from the stationary fuel cells programme in Japan, see 3.3.
- The new European building directive (Energy Performance of Buildings Directive, EPBD) and the influence of higher electricity prices on the use of fuel cells in buildings.
- The use of large scale PEFC fuel cells for electricity production using surplus hydrogen from chemical industries.
- The significant influence of different natural gas qualities on the performance of fuel cells.

3.5 ACHIEVEMENTS OF ANNEX 26 FUEL CELLS FOR TRANSPORTATION

Annex 26 was dormant during the 2010 reporting period in the absence of an Operating Agent.

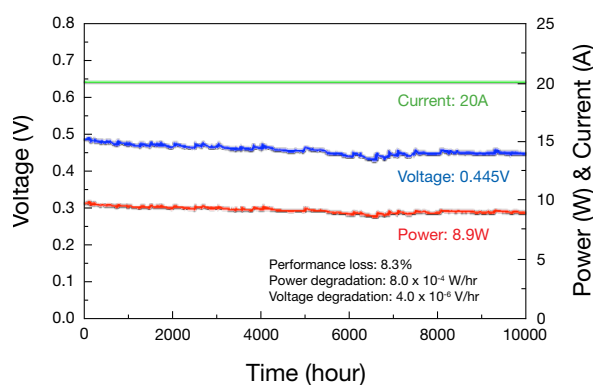
3.6 ACHIEVEMENTS OF ANNEX 27 FUEL CELLS FOR PORTABLE APPLICATIONS & LIGHT TRACTION

Key achievements of Annex 27 were:

- Detailed description of Toshiba's Dynario system (Japan). It's the first commercial available DMFC micro system with a power output of 2W. The system was available for €220 and is sold out now. Cartridge, DMFC and Fuel Connector Design comply with IEC PAS 62282-6-1, IEC 62282-6-100 FDIS and IEC 62282-6-300.
- Demonstration of cheap methanol sensor from FWB (Germany). In limited lot production it is available for €600 but the cost reduction potential is very high so that it should be possible to produce such a sensor for less than €30 in large lot numbers.

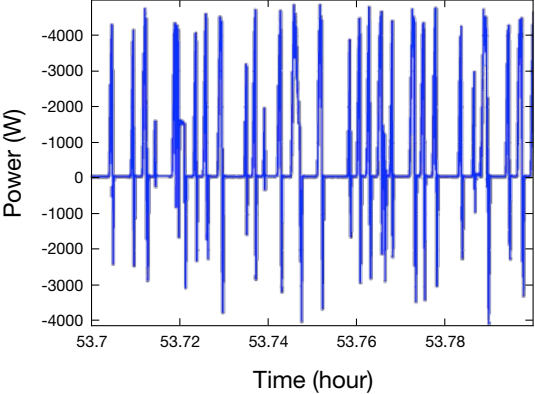
- 10,000 hour durability test of DMFC MEA in single cell (Korea). The degradation rate was $4 \mu\text{V/h}$ @ $0,133 \text{ A/cm}^2$. This is shown in Figure 1 below.

Figure 4 Results of the 10,000 hour durability test, 150 cm² MEA for DMFC. Stable operation over 10,000 hrs, still on going.



- Operation of ~1 kW DMFC system for 3,000 hour under real load profile (Germany). The system was operated in a test facility with a load profile that is recorded in a fork lift truck that is operated in a depository warehouse. This is the first time a durability of 3,000 h was achieved in such a power full DMFC system.

Figure 5 Example load profile (below) and testing facility for DMFC system designed to operate a fork lift truck (lower picture).





ANNEX
22

The objective of this annex is to contribute to the development of techniques to reduce the cost and improve the performance and durability of polymer electrolyte fuel cells, direct fuel polymer electrolyte fuel cells, and corresponding fuel cell systems.

4. Annex Reports

4.1 ANNEX 22 REPORT

POLYMER ELECTROLYTE FUEL CELLS

4.1.1 Duration

February 2009 until February 2014 (five years).

4.1.2 Operating Agent

Argonne National Laboratory, Contractor, for the United States Department of Energy

4.1.3 Participants

Agencies from thirteen countries and regions were involved in this Annex during the year 2010:

Austria	Graz University of Technology
Belgium	VITO
Canada	Ballard Power Systems
Finland	VTT
France	CEA
Germany	Jülich and ICT Fraunhofer
Japan	Kyushu University
Korea	KIER
Mexico	Instituto de Electricas
The Netherlands	ECN
The European Commission	Joint Research Centre
Sweden	KTH - Royal Institute of Technology
USA	ANL

4.1.4 Objective

The objective of Annex 22 is to contribute to the identification and development of techniques to reduce the cost and improve the performance and durability of polymer electrolyte fuel cells (PEFCs), direct fuel polymer electrolyte fuel cells, and corresponding fuel cell systems. Major applications are in the automotive, portable power, auxiliary power, and stationary power (residential, commercial), and combined heat and power (CHP) sectors.

Specifically

Subtask 1. New Stack Materials

Research in this subtask aims to develop improved, lower-cost membranes, electrode catalysts and structures, membrane-electrode assemblies (MEAs), bipolar plates, and other stack materials and designs. The effort includes:

- > composite and high-temperature membranes
- > membranes that conduct protons without external humidification
- > reduced precious metal loadings in electrodes
- > non-precious metal cathode and anode catalysts
- > anode catalysts and electrode layer configurations with enhanced tolerance to carbon monoxide
- > higher-activity cathodes
- > lower-cost bipolar plates and other stack materials
- > lower-cost, continuous fabrication techniques for MEAs
- > stack materials for stacks operating at higher temperatures (>100°C)

Subtask 2. System and Balance-of-Plant Issues

This subtask addresses system-level and balance-of-plant issues in PEFC systems. This subtask involves development, engineering, modelling, testing, and standardization of test procedures involving:

- > fuel processors, fuel processing catalysts, and supports

- > gas purification membranes
- > compact fuel reformers and micro-structured reactors
- > effects of contaminants, operating environments, duty cycles, and operating temperatures, including temperatures below 0°C
- > system designs offering high efficiency and dynamic response while maintaining costs, weights, and volumes within target values
- > reliability, durability, rapid-start, and dynamic behaviour of PEFC systems

Subtask 3. Direct Fuel Polymer Electrolyte Fuel Cells

The objective of this subtask is to improve the performance and lifetime of direct fuel polymer electrolyte fuel cells, including direct methanol, direct ethanol, and direct sodium borohydride fuel cells. This subtask involves identification and development of improved:

- > anode and cathode catalysts
- > electrode/electrolyte structures
- > fuel-impermeable membrane electrolytes
- > anion-conducting membranes
- > concepts in stack materials and designs

4.1.5 Task Description

The following gives the topics that were presented at the two Annex 22 workshops in 2010 (the second one was delayed to January 2011).

Subtask 1 Stack Materials

- Low cost microbial fuel cell for energy recovery from industrial wastewater (Belgium).
- Electrospun carbon nanofibers and carbon nanofiber/nanotube composites as catalyst supports, and graphite-PPS (polyphenylene sulfide) composite materials for bipolar plates for high-temperature PEFCs (Finland).
- Novel anion-conducting pore-filling membrane for solid alkaline fuel cells (Korea).
- Alternative catalyst supports, including carbon-free supports (e.g., SnO₂ and doped SnO₂) and stable carbon supports (e.g., graphite carbon and carbon nanofibers with different structures) (Japan).
- Different non-woven carbon gas diffusion layers (GDLs) in defining MEA performance under dry operating conditions (Netherlands).
- Pd-based bulk alloy systems as ORR catalysts to identify best systems and understand the relationship between electronic structure, composition, morphology, and activity of the catalysts (USA).
- Non-PGM electrocatalysts for the oxygen reduction reaction (USA).

Subtask 2 System, Component, and Balance-of-Plant

- PTFE-reinforced PFSA membrane degradation behaviour in fuel cells at various operating conditions (Austria).
- Addressing durability, performance, and cost of PEFCs via both cathode and anode optimization to achieve increased commercialization (Canada).
- Effect of inert gas enrichment in PEFC system operation (Finland).
- Hydrogen crossover through bipolar plates (BPPs) and MEAs as a quality control measure for BPP and MEA defects (Mexico).
- Reconstruction of a PEM fuel cell cathode layer using a scaling method to determine effective transport coefficients (Mexico).
- Micro- and nano-structure analysis of PEM fuel cell components using TEM, electron tomography, and X-ray computed tomography (The European Commission).

- Modelling of PEFCs for determining cell polarization curves and hydrogen depletion along the gas channel, GDL transport properties, and the motion of water droplets in the gas channel (The European Commission).
- Zoned monolith catalysts for autothermal reforming of diesel for heavy truck APUs (Sweden).
- Role of Pt-based electrocatalyst degradation (USA).

Subtask 3 Direct Fuel Polymer Electrolyte Fuel Cells

- Non-Pt group electrocatalysts for the ethanol oxidation reaction (Austria).
- Influence of electrolyte composition and acidity on the electrochemical oxidation of ethanol at a model electrocatalyst surface (polycrystalline Pt) (Germany).
- Manufacturing technologies for DMFCs to improve the performance, durability, and cost of DMFC systems for light traction (Germany).

4.1.6 Progress Summary

4.1.6.1 Background

This Annex continues the work previously conducted under Annex XVI with the same participating countries, except UK who withdrew from the Implementing Agreement in early 2009.

4.1.6.2 Activities

For the 2010 calendar year, two meetings of this Annex were held, one on May 27–28, 2010, at ECN, Petten, the Netherlands, and the other (delayed) on January 26–27, in the form of a web-based teleconference. The participants decided to continue the various Subtasks of the Annex during the new phase of the Implementing Agreement. Potential host sites for the 2011 Annex meetings were discussed.

4.1.7 Technical Accomplishments

Subtask 1: Stack Materials for Improved Performance and Reduced Costs

- Research at VITO has developed a low-cost microbial fuel cell (MFC) for wastewater treatment without using external energy, or for simultaneous wastewater treatment and energy production. The new air cathode contains no platinum; it is based on a porous carbon layer integrated with a PTFE layer and a metal grid current collector. It works well at pH 7 in the presence of microbial inoculum and produces only slightly less power than a Pt-containing electrode in a low salinity medium, but better than Pt in a saline environment. The developed ion-permeable membrane (Zirfon®) consisting of 85 wt% ZrO₂ and 15 wt% polysulfone (PSF) binder was found to be stable for use in acetate MFC, and it is expected to be a good

replacement for Nafion® membrane in MFCs. The MFC works with both acetate and real wastewater. The operation of MFCs on industrial wastewaters is currently being tested. The industrial wastewaters used include wastewater from a chemical company, a milk production unit, a soy-based food and drink company, and a laundry, all located in Flanders, Belgium. The maximum electrochemical activity recorded in 14 days of operation of MFCs was shown by the wastewater from the milk company, with a maximum power density of 128 mW/cm² at a current density of 241 mA/cm² and a COD reduction by 70%. During the 14-day operation of MFC with the milk company wastewater, the milky, turbid wastewater became crystal clear. This demonstrates the benefit of using the MFC in treating wastewater without consuming power. However, to simultaneously produce power effectively along with treating wastewater, the power density of MFC needs to be improved, probably by developing high performance materials. (Álvarez Gallego, Belgium)

- Researchers at VTT have developed a fabrication method for carbon nanofiber-based catalyst supports by electrospinning of polyacrylonitrile (PAN) and subsequent heat treatment in air and nitrogen for stabilization and carbonization, respectively. Three types of supports or support composites were prepared by electrospinning PAN alone, PAN/CNT (carbon nanotubes), and PAN/Pt salt, respectively. The resulting fibres had diameters between 100 and 1,000 nm. The PAN/CNT composite support formed by electro-spinning exhibited high surface area and it was easy to handle. Carbonization of the electrospun PAN/Pt salt resulted in a large increase in the Pt particle sizes. Deposition of Pt on the formed carbon fibre

support using Atomic Layer Deposition (ALD) or Laminar Flow Deposition (LFS) is underway in an effort to reduce the Pt particle sizes.

VTT has also developed composite materials consisting of graphite and polyphenylene sulphide (PPS) for bipolar plates for high temperature PEFCs, by using injection moulding to reduce manufacturing cost. To simultaneously achieve high electrical conductivity and low melt viscosity for the composite, different additives, including inorganic materials, liquids, and polymers, and various graphitic carbon fillers such as synthetic graphite, purified natural graphite, exfoliated graphite, carbon black, carbon nanofibers, and CNT, were investigated. The optimal composition, containing 77 wt% graphite filler and 0.75 wt% inorganic additive, was made into composite bipolar plates by injection moulding, which exhibited a through-plane resistivity of about 0.1 Ω cm when a polymer-rich skin did not form. A single fuel cell test of the composite bipolar plate at 200°C indicated that the composite bipolar plate possessed a better stability but higher resistance, compared to the BASF standard graphite bipolar plates. The results also indicated that PPS could possibly protect graphite from attack by H₃PO₄ vapour. The melt viscosity will need to be reduced further, however, to mould plates of larger sizes with built-in manifolds. (Kauranen, Finland)

- Researchers at Kyushu University have developed durable electrocatalyst supports, including more stable carbon supports than traditional carbon black (e.g., graphitized carbon and carbon nanofiber (CNF)) and non-carbon supports (e.g., doped SnO₂ and doped TiO₂). Pt nanoparticles supported on two different CNF structures

(tubular and platelet) showed that the Pt catalyst dispersion and performance depended on the type of carbon support and on the strength of the CNFs. Corrosion of CNFs still remained, however. The non-carbon supports, including SnO₂ alone and SnO₂ doped with up to 5 wt% Al (acceptor-doping) and Nb (donor-doping), were synthesized and their electrical conductivities were determined. The electrical conductivity of the SnO₂ based materials at 80°C was about two orders of magnitude smaller than that of carbon black, and increased in the order Al-SnO₂ < SnO₂ < Nb-SnO₂. The conductivity of Nb-SnO₂ depended on the Nb dopant concentration and exhibited a maximum at 2 wt% Nb. The Pt catalyst supported on the 2 wt% Nb-doped SnO₂ exhibited the largest ECSA, while Pt supported on the 5 wt% Nb-doped SnO₂ showed the highest ORR activity (specific activity). Although this activity was still smaller than that of Pt supported on carbon black (Pt/C), the durability of these non-carbon-supported Pt catalysts is much better than that of the Pt/C, as indicated by the smaller decrease in ECSA after 10,000 cycles between 0.6 and 1.3 V in aqueous electrolyte. The test of the Pt/SnO₂ as a cathode catalyst in single cells exhibited a performance comparable to that of the Pt/C cathode catalyst. Microstructural analyses showed that the Pt/SnO₂ cathode was not as porous as the Pt/C cathode, indicating room for activity improvement by controlling and optimizing the structure. (Sasaki, Japan)

- Researchers at KIER have developed an anion-conducting membrane for SAFC. The anionic membrane uses a porous substrate (high density polyethylene with mean pore size of 100 nm, porosity of 40–50%, and thickness of 25 μm), with its pores filled with a highly cross-linked quaternary-

aminated hydrocarbon electrolyte, to enhance the mechanical, thermal and dimensional stability of the membrane. The membrane was prepared by filling the pores of the substrate with a mixture of an electrolyte (such as divinyl 1-trimethylammonium ion, divinyl 2-dimethylammonium ion, and divinyl 3-trimethylammonium ion) and crosslinking agents (bi-functional amides), and then carrying out the crosslinking (polymerization) reaction. The prepared membranes were then characterized by FT-IR, TGA, Fenton Test, and other techniques to determine membrane structure, the hydroxyl ion (OH⁻) conductivity, water content, oxidative stability, and KOH permeability. The prepared anion-conducting pore-filled membranes showed thermal stability up to 150°C and a very wide range of hydroxide ion conductivity (0.01–0.45 S/cm), depending on the composition ratio of the electrolytes. In most cases, the hydroxide ion conductivity of the membranes was higher than that of commercial products, such as Tokuyama membranes. The prepared membranes were then used for making SAFCs. The testing of the prepared SAFCs with Pt/C electrodes at a Pt loading of 0.5 mg_{Pt}/cm² showed a maximum power density of 210 mW/cm² at a current density of 450 mA/cm² when the SAFC was operated on pure hydrogen and oxygen at 50°C (Choi, Korea)

- Researchers at ECN are investigating the effect of GDL on MEA performance, which includes 1) sourcing and qualification of new GDL materials for high temperature (HT) and/or low relative humidity (RH) operating conditions, 2) understanding the role of GDL by carrying out systematic in situ investigations of MEA performance, and 3) in-depth analyses of performance losses at the cathode and MEA under low RH conditions for designing HT MEA. At high operating temperatures,

insufficient water is a common problem at low current densities. It is critical to match the GDL with the catalytic layer to properly manage water. A good GDL should effectively retain water, while not compromising gas permeability. Six types of GDLs, including the commonly used H2313 C2 and SGL 35BC, and GDLs made from non-woven carbon materials, were used in various combinations with either the same GDL materials on both sides of the MEA, or keeping the anode side GDL the same while varying the cathode side GDL materials. The performance of the MEAs with Nafion 212CS membrane, Pt/C (60wt%, JM) anode and cathode of the same Pt loading (0.4 mg/cm²), and the various GDL materials, was evaluated by determining polarization curves and using impedance spectrometry to determine performance losses at the cathode as a function of temperature, RH, and current density. It was found that properties of the GDL had a prominent effect on MEA performance. This effect largely depended on the operating conditions, such as temperature, humidity, and current density. It also depended on the MEA components and design. For example, for a given MEA design, components, and operating conditions, some of the GDLs studied previously that were recommended for dry operation did not show superior performance to the commonly used GDLs in this study, as indicated by high ohmic resistance and high protonic resistance at a low RH of 30%. Good gas and water permeability remained the important factors for GDL designs for low RH and HT operations. (Rosca, the Netherlands)

- Researchers at Argonne have investigated Pd-based bulk alloy model systems as ORR catalysts to understand the relationship between electronic structure, composition, morphology, and activity of the catalysts, and to identify the best candidate catalysts for ORR. Several candidate Pd bimetallic systems (Pd-W, Pd-Mo, Pd-Ta, and Pd-Re with various proportions of the two metals) selected based on modeling predictions from Caltech were investigated for their ORR activity and valence band structure. These model systems were prepared using an arc melting process to form the alloys. Heat treatments at various temperatures and under various atmospheres were conducted to promote the formation of the desired catalytic surfaces in these model systems. Optimal heat treatment conditions for generating the best electrocatalyst for the ORR for each of these bulk systems were identified. The Pd³Mo system exhibited the greatest ORR activity enhancement (2.1 times over Pd only). (Wang, USA)
- Researchers at ANL have developed non-PGM oxygen reduction electrocatalysts for PEFCs to address the cost issue of the Pt-based cathode used in PEFC. Three methods are being used to prepare non-PGM catalysts: 1) utilizing iron and nitrogen decorated aligned carbon nanotubes (ACNT) as integrated electrode catalyst; 2) using metal organic frameworks (MOFs) as precursors for catalyst preparation; and 3) using a porous organic polymer as a precursor for catalyst preparation. The preparation and investigation of the Fe- and N-decorated ACNT catalysts showed that the catalysts have good activity towards the oxygen reduction reaction (ORR), with an onset potential of 0.8 V vs. RHE, and excellent stability. The active site structure was proved by X-ray

absorption spectroscopy to be the Fe-N₄ moiety in the catalysts. The use of MOFs as precursors for preparation of non-PGM catalysts has the following benefits: 1) MOFs have the highest precursor density for active site conversion; 2) they have well-defined coordination between metal and ligand; 3) their porous 3-D structure provides high specific surface area and uniform micropores; and 4) there is a large selection of existing MOF compositions and motifs. Co-ZIF (zeolitic imidazole framework) represents one type of MOF, where the Co is coordinated to four nitrogen atoms in imidazole; it was synthesized and investigated. It became active towards the ORR after thermal activation in inert gas at in the temperature range of 600 ~ 800°C, with 750°C being the optimal thermal activation temperature leading to an ORR onset potential of 0.86 V vs. RHE and a Faradaic efficiency of ORR to water formation of 85%. Various X-ray spectroscopic studies of the thermally activated catalysts indicated that organic to graphitic carbon conversion occurs at ~700°C, and that pyridinic nitrogen represents the dominant feature in the most active catalyst. Substantial conversion from Co²⁺ to Co⁰ occurs during the thermal activation. The size of the cobalt crystallites increases at higher activation temperatures. Further improvement of the non-PGM catalysts' performance is expected to be achieved by selecting different ligands, transition metals, and 3-D architectures through rational design. (Liu, USA)

Subtask 2: System, Component, and Balance-of-Plant Issues

- Researchers at Graz University of Technology carry out in situ investigation of the degradation of PEFC membranes under different operating conditions by using short, 4 or 6-cell, fuel cell stacks. Commercial MEAs of 25 cm² active area were used in the stacks, which consisted of a Pt anode (0.4 mg_{Pt}/cm²), a Pt cathode (0.6 mg_{Pt}/cm²), and a 35-μm-thick composite perfluorinated membrane containing two layers of PFSA with a layer of PTFE-reinforced PFSA in between.

The stacks were operated at a constant temperature (70°C) but with varied humidity (30, 60, 90% RH), gas overpressure (0.1 and 0.5 bar), and current density (45 and 90 mA/cm²). The variations of the individual fuel cells' open circuit voltage, membrane resistance and thickness, fluoride emission rate, and pinhole formation with operating time under different operating conditions were monitored or determined. Some results from the study are given below,

1. Pinhole formation can be detected by measuring the diffusion-limited hydrogen oxidation current as a function of potential when the cathode side has nitrogen flowing through it. A diffusion-limited current greater than 5 mA/cm² that increased with increasing potential indicated that there was pinhole formation.
2. The OCV of the cells decreased non-linearly with operating time. Both an increased gas overpressure and a decreased current density yielded a greater OCV drop, whereas the lower humidity case exhibited the smallest OCV drop. The drop in OCV was attributed mainly to membrane degradation resulting from membrane thinning and pinhole formation.

3. The fluoride emission rate (FER) was membrane-specific and it was not influenced by electrode or catalyst degradation. The value of the FER correlated with the OCV of the cell, with a lower FER corresponding to a low OCV drop.
4. Membrane thinning occurred in all cases and increased with operating time, with the lowered humidity case showing the smallest degree of thinning.
5. Damage to MEA also occurred, as indicated by the delamination and cracking of electrode layers, accumulation of Pt in the membrane, and structural changes in the membrane.
6. The measurement of membrane resistance did not indicate any correlation between cell performances and the varied operating conditions.

It was noted that the lower humidity case showed no pinhole formation even after 8 weeks of operation, indicating smaller membrane degradation under these operating conditions. This finding is opposite to the results from previous studies by others, where a lower humidity caused greater membrane degradation. This shows the importance of careful water management in PEFCs. (Stadlhofer, Austria)

- Durability, performance, and cost are the major technical challenges to increased fuel cell commercialization. Quantitative analysis of the interactions of operating conditions, design, and material properties is required to ensure best overall system options and performance. Part of the research activities at Ballard are addressing the key technical challenges on both cathode and anode catalysts.

For the cathode, it is the investigation of the performance requirements and trade-off with durability. It was found that significant improvement of the cathode ORR activity was realized by using Pt alloy or alloy-coreshell catalysts instead of Pt catalyst and different carbon support for catalyst and optimizing catalyst-support interaction and cathode layer composition. Higher carbon support surface area increases active surface area of the catalyst, leading to increased activity. However, accelerated dissolution test (square wave cycling from 0.6 V for 30 s to 1.2 V for 30 s) showed that high surface area carbon supported catalysts had the highest performance degradation rates. However, heat treated catalysts showed reduced performance degradation rates. Graphitized carbon supported Pt catalyst had the lowest performance degradation rates. Graphitized carbon supported Pt catalyst also showed the lowest cumulative carbon loss during corrosion tests at 1.2 and 1.4 V. The investigation of the effect of upper potential limit (UPL) ranging from 0.8 to 1.5 V during the square wave potential cycling indicated that both ECSA and cell voltage at 1 A/cm² losses increase with exposure to higher upper potentials. The primary degradation mechanism changes from kinetic to mass transport losses with increasing UPL. At UPLs <1.2 V, the dominant degradation mechanism is kinetic loss due to Pt agglomeration, Pt in the membrane, and Pt washout. At UPLs >1.3 V, the dominant degradation mechanism becomes mass transport control due to carbon oxidation/corrosion.

Currently, Ballard is leading a US DOE-funded project (2010~2013) on the “Development of Micro-Structural Mitigation Strategies for PEM FCs”,

with Georgia Institute of Technology, Los Alamos National Laboratory, Michigan Technological University, Queen's University, and University of New Mexico as partners. The objectives of the project are to identify/verify catalyst degradation mechanisms, correlate catalyst performance & structural changes, develop kinetic and material models for aging, and develop durability windows. The anode durability investigations focused on PtRu catalysts for reformate. Metallic Ru is thermodynamically unstable at potentials higher than $\sim 0.4\text{V}$ in an acidic medium, where it oxidizes to ionic Ru forms and migrates to the cathode side, where it can deposit onto the cathode catalyst. When the fuel cell is shut down, air gradually diffuses into the anode channel and raises the anode potential to above 0.9 V , which oxidizes the metallic Ru. An anode accelerated stress test with potential cycling from 0 to 0.9 V vs. DHE at 65°C was employed in a fuel cell to simulate potential spikes that occur during fuel cell start-ups and shutdowns to induce Ru dissolution and crossover. The air/air start-up/shut-down process leads to Ru corrosion from the PtRu anode, and migration to the cathode. This failure mode negatively impacts the cathode ORR activity and anode CO tolerance. However, cycling in 40% hydrogen exhibits a lower extent of Ru crossover to the cathode than cycling in 70% hydrogen. Also, drier conditions can significantly reduce the Ru crossover and improve fuel cell durability. (Knights, Canada)

- One JRC effort is focusing on the characterization of catalyst materials and GDLs/MEAs using high resolution TEM including electron tomography, SEM, XRD, and X-ray computed tomography. In addition to utilizing TEM in the classical way

and other techniques to get images of catalysts showing catalyst phase, composition, and size changes before and after catalyst usage, 3D images of various catalysts were acquired using TEM electron tomography, in which several TEM images were taken by rotating sample catalysts to various angles and then reconstructing the sample structure. Example shown was the carbon supported PtRu catalyst, a 3D image of which showed the distribution or fraction of metals and support in the catalyst. The X-ray computed tomography was used to obtain 3D images of the GDLs, with a resolution sufficiently high to resolve individual fibers and to discriminate between fibers, PTFE, and the microporous layers. The obtained 3D structures of GDLs were very useful for modeling the properties of GDLs, such as thermal conductivity, and gas and water permeability and transport within GDLs. The 3D structure of a used MEA was also determined using X-ray computed tomography, showing the degradation of electrode layers in the MEA (e.g., formation of cracks). (Pfrang, the European Commission)

- JRC's modeling activities on PEFCs include modeling of electrochemistry at the centimeter scale, determination of GDL transport properties at the micrometer scale, and simulation of water droplets in gas channels at the millimeter scale. The electrochemical modeling considered fluid flow, heat transfer, and mass transport in porous media, multiphase flow with phase change, and electrochemical reactions with gas channels of serpentine configuration. The modeling results for the polarization curve and H_2 depletion along the gas channels were presented. The modeling work on GDL was focused on the thermal conductivity and permeability of GDLs that were made of

carbon paper or cloth. The effect of geometry (e.g., anisotropy), porosity, and content of the binder (PTFE) on GDL's thermal conductivity was investigated for different GDLs using carbon paper (Sigracet), Toray paper, and carbon cloth (Electrochem) with nanotom[®] X-ray computed tomography combined with the numerical method of harmonic averaging and explicit jumps for solving the energy equation. The modeling results indicated that thermal conductivity of GDLs decreases with increasing porosity and with increasing PTFE content. Permeability was computed using Darcy's law and by solving the Stokes equation at low Reynolds numbers by the lattice Boltzmann method. For the simulation of water droplets in gas channels, water transport in the gas channels was described and the influence of local wetting angle, geometry, and flow operating conditions was studied. (Veyret, the European Commission)

- The research in VTT is investigating the inert gas problem in hydrogen fuel cell systems. In these systems, there is a mass transfer problem on the anode side due to the combined effect of both water and inert gas accumulation. On the one hand, inert gas (nitrogen) is transported through the membrane from the cathode. On the other hand, for the hydrogen fuel cell systems operated at less than 100% fuel utilization per pass, the anode exit gas is normally recycled to the anode inlet. Any inert gases present in the anode gas then increase in concentration as the hydrogen is consumed. To prevent excessive buildup of the inert gases, a portion of the recirculating anode gas is purged. However, what is the optimal level of purge is not clear. Inert gas enrichment was studied by experimental work conducted on an 8-kWe PEFC system, which is being developed for a hybrid

power pack consisting of two 8 kW PEFC systems, lead-acid battery packs, and ultra-capacitor modules for forklift application. The 8-kW PEFC stack system was rebuilt with incorporation of an online hydrogen sensor. The build-up of nitrogen in the recirculated anode stream was monitored using the hydrogen sensor to determine the partial pressure of hydrogen. The rate of nitrogen build-up was measured by varying the current load and the rate of nitrogen feed. Higher current load and lower quality hydrogen resulted in a greater build-up of inert gas or impurity. The effect of nitrogen build-up on cell voltages was also studied. The build-up of nitrogen in the anode channels had a profound effect on cell voltages, depending strongly, however, on the quality of the cells, with weak cells exhibiting a stronger effect. Thus, the optimal purge interval depends not only on the recirculation rate and on the inert build-up rate, but also on the condition of the cells. (Ihonen, Finland)

- In 1998, the Japanese government prioritized twenty one technologies to be advanced further, which included fuel cell vehicles, stationary FC, and H₂ production, transportation, and storage as three important technologies. In the overall PEFC R&D area, one of its major efforts is in the commercialization of fuel cell vehicles and hydrogen stations. The commercialization of FCVs consists of four phases. The first phase was technology demonstration in 2010, and the second will be technology and market demonstration from 2011 to 2015. During these two phases, approximately one thousand hydrogen stations and two million FCVs are to be constructed and demonstrated to resolve technical issues, promote regulation review, and verify utility of hydrogen stations and FCVs from a social-economic viewpoint. The year 2015 is the

target year for beginning commercialization of FCVs to the general public. Phase Three, from 2016 to 2025, will be the time for early commercialization and expansion. Phase Four is the full commercialization starting in 2026, where profitable business is expected. For stationary power application, the Fukuoka Hydrogen Town is being developed to be the world's largest hydrogen town through community-based installation of residential combined heat and power fuel cell systems, as a showcase of a society based on hydrogen energy. About 150 units were installed in residential areas of Minakazedai and Misakigaoka in Itoshima City, Fukuoka, during October 2008 to February 2009, with a planned operating time of about seven years. (Sasaki, Japan)

- Research at IIE is developing a test protocol to inspect bipolar plates and membrane electrode assemblies for permeability manufacturing defects by determining the hydrogen crossover through the BPPs or MEAs before fuel cell assembly. Possible gas crossover can be result from PEFC seal leaks, or high permeability of MEAs and BPPs due to manufacturing or design defects. For testing the permeability defects of MEAs, a single PEFC is used, with the anode chamber filled with hydrogen at 5 psig and the cathode chamber filled with nitrogen at 2 psig. The cell is held at a constant potential ranging from 0 to 0.8 V and the hydrogen oxidation current at the cathode is monitored. Twenty five newly made MEAs were tested, and it was found that twenty-four MEAs exhibited acceptable hydrogen crossover (2×10^{-3} ml/min). One MEA was unacceptable, with a hydrogen crossover of 4.3×10^{-3} ml/min. For testing the permeability defects in BPPs, a BPP and a gas diffusion layer were added to the

MEA testing setup, with the BPP being placed next to the cathode and the gas diffusion layer in between the BPP and the cathode end plate. The chamber between the BPP and the cathode end plate was filled with hydrogen at 12 psig, while the anode and the cathode chambers were filled with hydrogen and nitrogen, respectively, each at the same pressure of 2 psig. Again, the hydrogen oxidation current at the cathode was measured at various applied voltages. The permeability defects of BPPs can be determined by comparing the measured current at various voltages for the setups with and without a BPP. The increased current with the presence of a BPP can be attributed to the permeability of the BPP. Of twenty new BPPs tested, only one showed an unacceptable H_2 crossover rate (6×10^{-3} ml/min) while all the others showed acceptable H_2 crossover rates (2×10^{-3} ml/min). However, the downside of this protocol is the time needed to inspect each sample (1.5 h). Future activities will focus on optimization of the testing hardware for a faster assembly and testing, and further investigation to determine the source of failure in the samples that show high crossover rates. (Tatiana Romero, Mexico)

- Researchers at IIE are investigating transport properties of the cathode layer of PEFC through modelling work. A 3D cathode layer structure was reconstructed by using a reconstruction algorithm, in which a domain is divided into finite control volumes (FCVs). Each FCV is defined by an index number that is randomly distributed and computer-generated by a random number generator. The construction method considers three formation stages: (1) the centres of the representative elements at each scale (i.e., primary elements, agglomerates, mesoporous, isles,

etc.) are stochastically distributed, (2) around such centres and in one single step, a previously configured specific three-dimensional geometry is generated (i.e., amorphous sphere structures, ellipses, tubes, etc.), and (3) surroundings are filled in a random manner until the required volume fraction is fulfilled. The reconstructed cathode layer contains Pt, carbon, ionomer, and pores, with their respective fractions being in the typical ranges used in manufacturing. Charge continuity was employed to calculate the effective electronic and protonic conductivities of the reconstructed cathode layer, which are functions of ionomer content and porosity of the electrode. The model results still need experimental validation. (Cano-Castillo, Mexico)

- Overall R&D activities at the ECN cover the areas of solar energy, biomass, wind energy, efficiency and infrastructure, H₂ and fossil fuels, and policy studies. The PEFC R&D, together with Hydrogen Production and CO₂ Capture, Hydrogen Transitions and Infrastructure, is under the programme called “Unit H₂ and Clean Fossil Fuels”, the goal of which is to develop these technologies into products for application in fuel cell vehicles and stationary power plants with zero emissions.

There are 17 people in the PEFC group. Annual funding level is about €2.2 million. The projects undertaken by the group included R&D of MEA, stack, and water electrolysis, with MEA being the main focus. For the MEA, ECN focused on the improvement of performance and durability, cost reduction, and high temperature PEFC operation at low relative humidity (<50%). These were being done by lowering the transport losses and improving the Pt utilization via better control of electrode morphology and the use of thinner

electrode layers (1–3 μm), in combination with the development and use of stable and active support materials, and with thorough understanding of the electrochemical processes, for which good characterization is essential. The development or exploration of non-supported Pt catalysts and Pt on stable supports and other new materials for catalysts, GDL, and membrane materials for high temperature PEFCs are being carried out. Accelerated stress tests for various components in varied conditions were being performed for MEA lifetime determinations. The stack research includes metal flow plates for low temperature PEFCs (up to 80°C) and composite flow plates for high temperature PEFCs (up to 120°C), with the aim of improving their performance and reducing their costs. A 5-kW stack consisting of 30 cells of 400-cm² active area and composite plates for atmospheric pressure operation on H₂ and reformat has been built. For water electrolysis using reversible PEFCs, ECN has developed MEAs with catalyst composition of Pt:Ir 1:2 and a method for making Ti-GDL partially hydrophobic, and validated stack designs at the 20-cell level. ECN is also active in a commercial activity addressing systems for transportation applications. (Mallant, the Netherlands)

- The ECN developmental plan for the PEFC MEA projects for the period 2010 to 2015 has technical objectives that are consistent with the US DOE 2015 targets. The objective of the MEA projects is to produce high power, robust MEAs that will have high efficiency at part load (0.25 W/cm² at 0.8 V) and high power at rated load (1 W/cm² at 0.68 V), a good durability (5000 h with <10% loss in automotive application), and cost

competitiveness (MEA $< \$5/kW_e$ with $0.2 \text{ mg}_{Pt}/\text{cm}^2$). The on-going projects cover the following topics, 1) developing supported Pt catalyst with superior stability, 2) developing Pt nano-structured catalyst with high mass activity, 3) identifying better membrane materials from commercially available or developmental electrolyte membranes, 4) defining/selecting stationary and automotive protocols for determining MEA lifetimes, and 5) identifying better GDL materials and optimizing their properties. (Bouwman, the Netherlands)

- KTH is developing autothermal reformers (ATR) for the production of hydrogen rich-gas from diesel for APU applications, with various industrial partners such as Volvo Technology, Alfa Laval, Thermogen, etc. The role of KTH in this collaboration is in catalyst development and evaluation. Zoned catalysts consisting of a cordierite monolith with two different coatings in the axial direction, were developed to improve the performance and lifetime of the catalysts. The zoned monolith comprised two zones with the first one being an oxidizing catalyst containing Rh and Pt, and the second one being a steam reforming catalyst containing only Rh. An ATR of 5 kW_e using diesel as feed was built, which used a catalyst bed consisting of two zones, a mixing zone containing no catalyst and a catalytic zone consisting of the zoned monolith and the monolith steam reforming catalyst. Better performance in terms of diesel conversion and hydrogen production was obtained, compared to the uniformly coated monolith catalyst, as indicated by complete fuel conversion (99.9%), increased hydrogen concentration (31%, dry basis), and very low concentrations of olefins and other light hydrocarbons in the reformat. (Pettersson, Sweden)
- Hydrogen production research, development, and demonstration have been quite active in Sweden. Big investments for demonstration of gasification technologies are in progress or planned, with emphasis on the next generation biofuels for vehicles. Some demonstration projects were given as examples in the presentation, including the Chrisgas project for hydrogen production from biomass (2004–2009) and the VVBGC project for an 18-MW pressurized CFB gasifier demonstration plant for production of hydrogen- and methane-rich gases (2010–2013). A new demonstration project based on the technologies and knowledge developed from the Chrisgas project is in the planning stage and it will be started in 2010. (Pettersson, Sweden)
- Research at ANL is investigating the Pt-based cathode degradation to identify the important degradation modes and factors that contribute to the degradation, and to determine operating conditions and catalyst types/structures that can mitigate performance loss and allow PEFC systems to achieve the DOE lifetime targets. This US DOE funded project has various collaborators from industry and academia, including Johnson Matthey Fuel Cells (JMFC), United Technologies Research Center (UTRC), Massachusetts Institute of Technology (MIT), University of Texas at Austin (UT), and University of Wisconsin-Madison. Various methods and techniques are being used in the investigation, including systematic cell degradation tests, in situ and ex situ structural characterization of the catalysts, fundamental out-of-cell studies, and theoretical modeling. To establish the background for studies of advanced classes of catalysts (e.g., Pt alloy nanocatalysts),

the initial studies focused on determining the effects of cell operating parameters and initial Pt particle size on cell performance and performance degradation. Ketjen carbon black-supported Pt nanoparticle catalysts with four initial Pt mean particle sizes (1.9, 3.2, 7.1, and 12.7 nm) were prepared and studied in an aqueous electrochemical environment (0.1 M HClO₄ electrolyte) using anomalous small angle X-ray scattering to determine the evolution of Pt particle size and particle size distribution as a function of potential cycling using the DOE cycling protocol (0.6 V to 1.0 V triangle wave 50 mV/s). These catalysts were also incorporated into the cathodes of MEAs and subjected to the DOE cycling protocol in a fuel cell environment. Cell diagnostics of cathode catalyst ECA, ORR mass activity, and air and oxygen polarization curves were performed after 1,000, 3,000, 5,000, and 10,000 voltage cycles. Studies were also performed on the effects of various fuel cell operating parameters (relative humidity (RH), temperature, cycling profile, and upper potential limit) on the degradation of the cathode electrocatalyst performance in MEAs containing the 3.2-nm Pt/C as the cathode catalyst.

Initial fuel cell performance increased with decreasing cathode electrocatalyst mean Pt particle size; however, performance degradation with potential cycling increased with decreasing particle size. Potential cycling caused Pt catalysts of <~4 nm initial mean diameter to evolve to specific surface areas comparable to those of 7–12-nm particles (20–30 m²/g). Cell performance degradation with potential cycling can be attributed to increased rates and extents of ECA loss with decreasing Pt particle size for electrocatalysts

with mean Pt particle sizes <~4 nm. Extent of loss of ~3-nm Pt nanoparticle cathode electrocatalyst performance, caused by loss of ECA, increased with increasing cell temperature, increasing RH, and increasing upper limit of potential cycling. (Wang, USA)

Subtask 3 Direct Fuel Polymer Electrolyte Fuel Cells

- Researchers at Fraunhofer ICT (Germany) have investigated the electrochemical oxidation of ethanol and ethylene glycol in both acidic and alkaline solutions. Both fuels were identified to be more suitable fuels than methanol for direct fuel polymer electrolyte fuel cells. The investigation of the effect of electrolyte pH on the electro-oxidation of ethanol indicates that the oxidation of ethanol depends on both the electrolyte pH and ethanol concentration. The pH of 12.5 yielded a maximal ethanol oxidation current density. However, a higher pH value (>12.5) yielded a lower onset potential. This pH effect became less pronounced when the concentration of ethanol was lowered from 1 M. The study of the carbonate concentration effect indicated that the initial oxidation current increased with increasing carbonate concentration. This indicated that the presence of carbonate increased CO₂ current efficiency, leading to higher ethanol conversions. (Cremers, Germany)
- FZ-Jülich's R&D focuses in the fuel cell area include development of DMFC systems for light-duty traction (forklifts), high-temperature PEFC systems for reformat utilization, fuel processing systems for hydrogen production from diesel or kerosene for on-board supply (APU) with fuel cells, and SOFC systems such as CHP and APU for efficient power generation and on-board supply.

One of the Jülich's current efforts is to develop manufacturing technologies for DMFCs, aiming to improve power density, lifetime, and cost of DMFC systems. Manufacturing processes can greatly affect performance of the DMFC systems. For example, variation in a parameter in the manufacturing process can change component properties and, thus, affect fuel cell performance. In addition, a reproducible manufacturing process is required to study fine differences in fuel cell performance that is affected by new materials or new designs. In the development of manufacturing technologies, Jülich was mainly concentrating on improving coating and assembling techniques for DMFCs. Coating technology was developed for making fuel cell electrodes and highly conductive contacts, and assembling techniques were developed for larger components such as MEAs and bipolar units consisting of flow fields and separator plates, as well as entire stacks. Jülich has achieved manufacturing of gas diffusion electrodes (GDEs) in square-meter size and MEA production using hot-pressing in a fully automated process. Also, via pre-assembling, the number of parts that had to be assembled in a stack was reduced by a factor of 10. These achievements make DMFC manufacturing more reproducible, less error-prone, and more efficient, which will be helpful in reaching the technical targets for performance, durability, and cost. (Kimiaie, Germany)

- Researchers at Graz University of Technology are developing less expensive non-PGM electrocatalysts for ethanol oxidation for direct ethanol fuel cells that use an alkaline membrane as electrolyte. Various families of materials including metals (Au, Co, Ag, and Ni) or alloys (Ni-Co) supported on carbon, carbon nanofibers (CNF),

metal carbide (WC), and mixed oxides (La_2NiO_4) were prepared and investigated as catalysts for ethanol electro-oxidation in a basic aqueous electrolyte using thin-film RDE with Nafion as binder. The testing results indicated that the Co-based and silver catalysts are inactive. However, Ni-based and gold catalysts are active for the electro-oxidation of ethanol. The Au catalyst exhibited a lower oxidation onset potential than all active Ni-based catalysts (e.g., 0.91 V for Au/C vs. 1.2 ~ 1.35 V for the Ni catalysts), but the Ni catalysts showed a much higher peak oxidation current than Au catalysts (e.g., 244 mA at 1.64 V for Ni/C vs. 36 mA at 1.10 V for Au/C). In addition, for Ni-based catalysts, the ethanol oxidation onset potential varied with the type of the support, in the decreasing order of $\text{C} > \text{CNF} > \text{WC} > \text{La}_2\text{NiO}_4$. Future activities include continued investigation of product composition, characterization of the catalyst systems, and development of ethanol-compatible catalysts for oxygen reduction. (Stadlhofer, Austria)

4.1.8 Work Plan for Next Year

During 2010, the areas of active R&D within the Annex addressed many of the critical technical barriers that have prevented PEFC technologies from achieving widespread commercialization. For both hydrogen PEFCs and direct fuel PEFCs, the R&D included cell and stack materials and components, improved MEAs, reduced catalyst costs, improved catalyst and support durability, and enhanced system design and analyses. Although significant progress has been made in many areas, there is still a need for further advancement. Thus, it is expected that these topic areas will continue to be active for R&D in future years. Recently, there has also been increased activity in fuel processor development for small-scale PEFC power plants, and in residential PEFC system development and demonstrations. Participants in this Annex are expected to contribute significantly to these developments.



ANNEX
23

The objective of this annex is to provide for further international collaboration in the research and development of certain aspects of Molten Carbonate Fuel Cells technology, in order to realise commercialisation of the system.

4.2 ANNEX 23 REPORT

MOLTEN CARBONATE FUEL CELLS AT THE BEGINNING OF MARKET PENETRATION

4.2.1 Duration

February 2009 until February 2014 (five years).

4.2.2 Operating Agent

Korea Institute of Science and Technology (KIST) of Korea.

4.2.3 Participants

Germany	Forschungszentrum Jülich GmbH (KFA) through Motoren und Turbinen Union Friedrichshafen GmbH (MTU)
Italy	Ente Nazionale per le Nuove Tecnologie l'Energia e l'Ambiente (ENEA)
Japan	New Energy and Industrial Technology Development Organization (NEDO)
Korea	Ministry of Commerce, Industry and Energy (MOCIE) through Korea Institute of Science and Technology (KIST)
United States	US Department of Energy (DOE) through Fuel Cell Energy (FCE)
Turkey	Marmara Research Centre of Scientific and Technological Research Council of Turkey [from June 2007]
Sweden	KTH Royal Institute of Technology
Japan	Central Research Institute of Electric Power Industry (CRIEPI; Observer)

4.2.4 Objective

The objective of the Task is to provide for further international collaboration in the research and development of certain aspects of MCFC technology, in order to realise commercialization of the MCFC system. These aspects include:

- Improvement of performance, endurance, and cost effectiveness, for stacks and BOP.
- Development and standardisation of effective test-procedures for materials, cells and stacks.
- Identification of present and envisaged problems to be solved for commercialisation.

4.2.5 Task Description

There are three subtasks in Annex 23:

- | | |
|-------------------|---|
| Subtask A: | R&D Issues for Longer Life, Higher Performance and Lower Cost |
| Subtask B: | Lessons Learned from Demos and Early Products |
| Subtask C: | Standardisation of stack and balance of plant (BoP) |

4.2.6 Progress Summary

4.2.6.1 Background

This Annex continues work undertaken under Annex I “MCFC Balance of Plant Analysis”, Annex III “MCFC Materials and Electrochemistry”, Annex XIV “MCFC under Real Operating Conditions” and Annex XVII “MCFC towards Commercialisation”.

4.2.6.2 Activities

The first meeting was held on November 16, 2009 and was hosted by DoE at The Courtyard by Marriott Palm Springs Hotel - CA, USA. There were six presentations at the meeting.

The second meeting was held on July 09-10, 2010 and was hosted by University of Perugia (UNIPEG) and ENEA at UNIPEG, Italy. There were six presentations at the meeting.

The MCFC booklet 2011 is in preparation and ENEA (Italy), KIST (Korea) and FCE (USA) are the main contributors. The booklet will include global overview of MCFC status and special features of MCFC such as MCFC for CO₂ separation, MCFC in the gas grid and for production of hydrogen, and MCFC in the waste-to-energy chain.

4.2.6.3 Technical Accomplishments

Germany

- MTU developed 200kW HotModule system with its own EuroCell.
- MTU continue demonstration with various fuels and for various application fields.
- MTU demonstrated MCFC system (330kW) for ship application onshore and offshore. Please see Figure 6 above right.

Figure 6 Demonstration of MCFC system for ship application



Italy

- ENEA develop MCFC system for stationary application.
- ENEA develop integrated system based on “waste to energy system” and biomass.
- ENEA also studies on feasibility of CO₂ separation with MCFC.
- Ansaldo is developing 500kW MCFC-GT system and demonstrating 500 kW system using various fuels.

Korea

- KEPRI demonstrated 125kW external reforming type MCFC system.
- DHI developed and operated 25kW stack for 1,200 hours.
- POSCO Power disseminated 28.4MW MCFC.
- POSCO Power built up 50MW/yr stack and system facility.

Figure 7 POSCO Power's stack manufacturing facility in Pohang, Korea



USA

- FCE installed/backlog 100MW over the world for various applications.
- FCE sells 1.2MW, 2.8MW and 5.6MW MCFC systems.
- FCE keeps working to reduce the cost.

Figure 8 FCE's 2.8MW DFC3000 installed in Korea



Japan

- No government programme for MCFC in Japan.
- CREIPI has in house project for MCFC and they achieved 66,000 hour-operation of MCFC single cell.

4.2.7 Future Plans

The third meeting of Annex XXIII Working Group will be held on December 13, 2011 in Rome, Italy. The meeting will be hosted by ENEA. Discussion topics will include:

- Presentations concerning the sub tasks
- Preparation of the new version of MCFC status of the art.



The objective of this annex is to organise a series of annual workshops to discuss selected Solid Oxide Fuel Cells topics.



4.3 ANNEX 24 REPORT

SOLID OXIDE FUEL CELLS

4.3.1 Duration

Period is from February 2009 until February 2014 (five years).

4.3.2 Operating Agent

The overall Operating Agent of Annex 24 is Dr. Jari Kiviaho from VTT Technical Research Centre of Finland. The Overall Operating Agent is responsible person for arranging annual meeting and reporting to the Executive Committee.

4.3.3 Participants

Australia	Ceramic Fuel Cells Ltd
Canada	Natural Resources Canada and Versa Power Systems
Denmark	Risø National Laboratory
Finland	VTT Technical Research Centre of Finland and Wärtsilä Corporation
France	ADEME and CEA
Germany	Forschungszentrum Jülich
Japan	The New Energy and Industrial Technology Development Organisation, NEDO
Korea	Korea Institute for Energy Research, KIER
Netherlands	TU Delft
Sweden	Swedish National Energy Administration
Switzerland	Swiss Federal Office of Energy and HTCeramik
United States	US DOE

4.3.4 Objective

The overall objective of Annex 24 is to organise a series of annual workshops, each to be organised by and in a different country. Each workshop will be organised over one or two days, with discussions on general progress and/or selected SOFC topics. Where possible, these workshops will be linked to other relevant conferences, in order to minimise travelling costs. The workshops should lead to open discussions relating to common problems and should have realizable and achievable aims.

4.3.5 Task Description

Annex 24 comprises a series of workshops, each to be organised by and in a different country. The list of workshops is as follows:

Table 3 Workshops held for Annex 24

Year	Location	Workshop in connection with:
2009	Vienna, Austria	SOFC XI Conference
2010	Lucerne, Switzerland	European Fuel Cell Forum
2011	Montreal, Canada	SOFC XII conference
2012	Lucerne, Switzerland	European Fuel Cell Forum
2013	Okinawa, Japan	SOFC XIII Conference

4.3.6 Progress Summary

4.3.6.1 Overview

This Annex will build on the successful collaboration engendered during Annex XVIII and earlier SOFC annexes. The aim of this new annex, Annex 24, is the continuation and intensification of the open information exchange to accelerate the development of SOFC towards commercialization. The mechanism proposed to reach this aim is via annual workshops, each year organized by an Interim Operating Agent, where representatives from the participating countries present the status of SOFC Research, Development and Demonstration in their respective countries, in addition to discussing a selected topic.

4.3.6.2 Administration

The Operating Agent (Jari Kiviaho) prepared status reports on Annex 24 for the ExCo meetings.

4.3.6.3 Activities

The last meeting of Annex 24 was held in Montreal on May 1st 2011. There were 16 participants from 13 countries. Topics discussed included:

- Overview for the Annex 24 work
- Status of the participating countries: Canada, Korea, Italy, German, Sweden, Japan, USA and Finland.
- Durability and degradation of SOFCs
- Accelerating testing for SOFC
- BlueGen™ development by CFCL
- New EU initiatives on Fuel Cell and Hydrogen
- How to continue work in Annex 24

Decisions were taken on the locations and timing of future workshops – see above for full list.

In addition Annex 24 is helping in arrangements couple of workshops like “International workshop on degradation issues in fuel cells – Greece, September 2011” and “SOFC for next generation power plants – Netherland, June 2011”.

Also the “Future Aspect Report” is under preparation and responsible person for that is Stephen McPhail from ENEA.

4.3.6.4 Technical Accomplishments

During the workshop, 13 presentations were made by experts from participating countries dealing with SOFC research, development and demonstration.

The presentations showed that in the recent years a real progress has been made toward manufacturing and commercialisation of SOFCs.

4.3.6.5 Conclusion

The system of an Overall Operating Agent and annual Interim Operating Agents and the organisation by these Interim Operating Agents of workshops linked to other large, international SOFC conferences has so far turned out to be a successful concept. The openness of discussions, the open exchange of technical know-how and the intimate atmosphere of such workshops, are highly appreciated by the participants of the workshops.

4.3.6.6 Future Plans

In future, the main focus will be on the annual meetings. It was agreed that partners’ motivation is necessary to move Annex 24 in the right direction and that support is needed from the ExCo Committee. Specifically, there must be orders based on needs, good instructions and templates and sufficient time to react.



ANNEX
25

The objective of this annex is to understand better how stationary fuel cell systems may be deployed in energy systems.

4.4 ANNEX 25 REPORT

FUEL CELL SYSTEMS FOR STATIONARY APPLICATIONS

4.4.1 Duration

February 2009 until February 2014 (five years).

4.4.2 Operating Agent

The Swedish Energy Agency acting through Grontmij AB, Sweden.

4.4.3 Participants

The Contracting Parties, which are the Participants in Annex 25 are:

Austria	Austrian Energy Agency
Belgium	Waterstofnet, under discussion
Denmark	Haldor Topsoe
Finland	Technical Research Centre of Finland, VTT
Germany	FZJ, Jülich
Italy	Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, ENEA
Japan	NEDO
The Netherlands	Under discussion
Sweden	The Swedish Energy Agency
Switzerland	Thoma & Renz
USA	The Department of Energy

A full list of participating experts is provided in Appendix 7 to this report.

4.4.4 Objective

The objective of Annex 25 is to understand better how stationary fuel cell systems may be deployed in energy systems. The work will focus the requirement from the market on fuel cells for stationary applications; both opportunities and obstacles that must be overcome will be investigated and discussed. The market development will be followed closely with a special focus on fuels, environment and competitiveness.

4.4.5 Task Description

Subtask 1 Residential Fuel Cells

Subtask leader: Ulf Birnbaum, FZJ, Germany

Co-leader: Yamanashi University, Japan

The main focus of this subtask is to evaluate conditions for the commercialisation of small residential fuel cells and examine fuel cells for use in larger residential buildings.

Subtask 2 Fuels for Fuel Cells

Subtask leader: Viviana Cigolotti and Angelo Moreno, ENEA Italy.

Hydrogen: Adwin Martens, Waterstofnet Belgium

The new subtask fuel for fuel cells will focus on the use of waste to energy by the use of fuel cells, mainly biofuels from waste and biofuels not directly competing with food production.

This subtask will also study the possibilities to use industrial surplus hydrogen as fuel for fuel cells.

Subtask 3 Fuel Cell Plants Components

Subtask leader: Jari Kiviaho, VTT, Finland

This subtask will identify projects in which BoP components are developed and look at their approaches to what and how is developed and which the targets are. CHP and hybrid systems will be investigated. The technical requirements defined earlier in the task will be used as a basis. Component developers will be approached to get their views on how realistic the cost estimates are

and SOFC, MCFC and high temperature PEFC- systems will be addressed.

Subtask 4 Analysing design, operating and control strategies

Subtask leader: Whitney Collela, Sandia NL, USA

This subtask aims to identify optimal design, operating and control strategies for fuel cells systems, CHP and trigeneration and hydrogen production. Annex 25 will follow the modelling work at PNNL and give feed-back.

Subtask 5 Follow up of demonstration projects

Subtask leader: Stephan Renz, Switzerland

This subtask will analyze demonstrations projects with the aim to study the real status of the technology. It will also analyse the different definitions of efficiency for energy conversion systems. Data and information about efficiencies of existing plants or systems (fuel cells, demonstration plants, competing technologies, the grid etc.) will be collected. The main differences will be explored and conclusions will be elaborated. Finally a common questionnaire will be developed for the analysis.

Subtask 6 Market status

Subtask leader: Bengt Ridell, Grontmij, Sweden

The aim of this subtask is to present and discuss the latest development in the area of stationary fuel cells for instance new technology break-through, major programmes, market development etc.

4.4.6 Progress Summary

4.4.6.1 Activities

Two Annex meetings were held 2010. The spring meeting was held 27-28 April 2010 in Winterthur, Switzerland and the autumn meeting was held 13-14 October 2010 in Lyngby, Denmark. Part of this meeting was held together with IEA Hydrogen Task 23 on Small Scale Reformers.

4.4.7 Task Results

Subtask 1 Residential Fuel Cells

- The discussions about the new European Building Directive and its influence on the fuel cell market. The heat demand will decrease significantly but the electricity demand will increase. Also the electricity will most probably increase worldwide. That will enhance the focus on higher electric efficiency for microCHP.
- The Callux project in Germany is going and followed up in the Annex; the total number of fuel cells expected to be 800 units.
- The vision is that the full commercial market in 2020 will have a volume of 72,000 units per year in Germany. In Annex 25 the conditions for that vision will be investigated and analysed.
- The outstanding expansion of the ENE-FARM stationary fuel cell programme in Japan with close too 14000 fuel cells installed in buildings in Japan in January 2011.
- The experience in Denmark from Dantherm Power and there delivery of fuel cells systems for MicroCHP both PEFC and SOFC.
- The interesting cooperation in France between GDF Suez and CFCL and De Dietrich on small stationary fuel cells.

Table 4 Model house information

Single family house with 121 qm living area*		
	Constructed 1990	Renovated 2010
Specific heat demand	170 kWh/m ²	80 kWh/m ²
Operation hours	1,800 h/a	1,800 h/a
Heat capacity	12 kW	6 kW
Boiler capacity (12kW/0.77η)	15,5 kW	6.5 kW (6 kW/0.92η)

* 121m² is the medium living space of the single family houses in Germany, DeStatis

Subtask 2 Fuels for Fuel Cells

Current activities within Subtask 2 focus on:

- Renewable fuels.
- Fuel that do not compete with food production.
- Anaerobic digester plants.
- Waste from agriculture or food industry.
- Waste fuels other industries.

Figure 9 A fuel cell system in the brewery industry



Some highlights and findings during 2010

- The presentation of the 1 MWe PEFC project from Nedstack and the future use of the fuel cell at Solway-Solvic in Lillo.
- The influence of nitrogen content in natural gas a significant has been observed in Denmark between natural gas from the North Sea and natural gas coming from Germany.

Subtask 3 Fuel Cell Plants Components

The following findings were discussed during the Annex meeting:

- Balance of Plant (BOP) represents 50-67% of total cost and most failures occur in BOP components.
- There is a lack of dedicated components and few component developers.
- Components are too expensive and there is no incentive for lowering cost.
- Information about component requirements and the potential developers is needed.

Figure 10 Breakdown of costs of principal components and sub-systems for SOFC

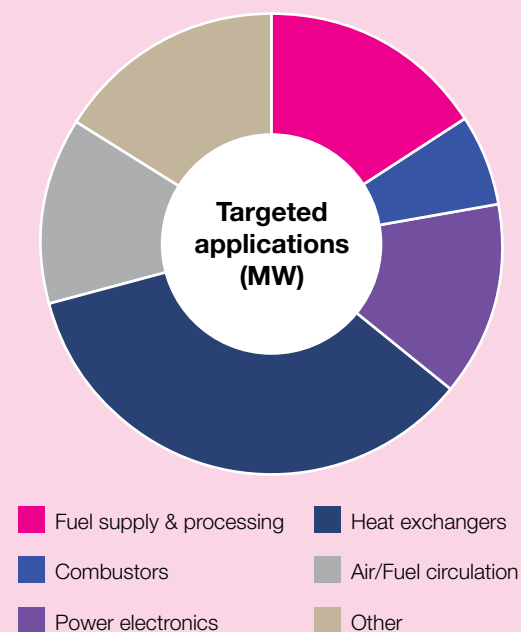
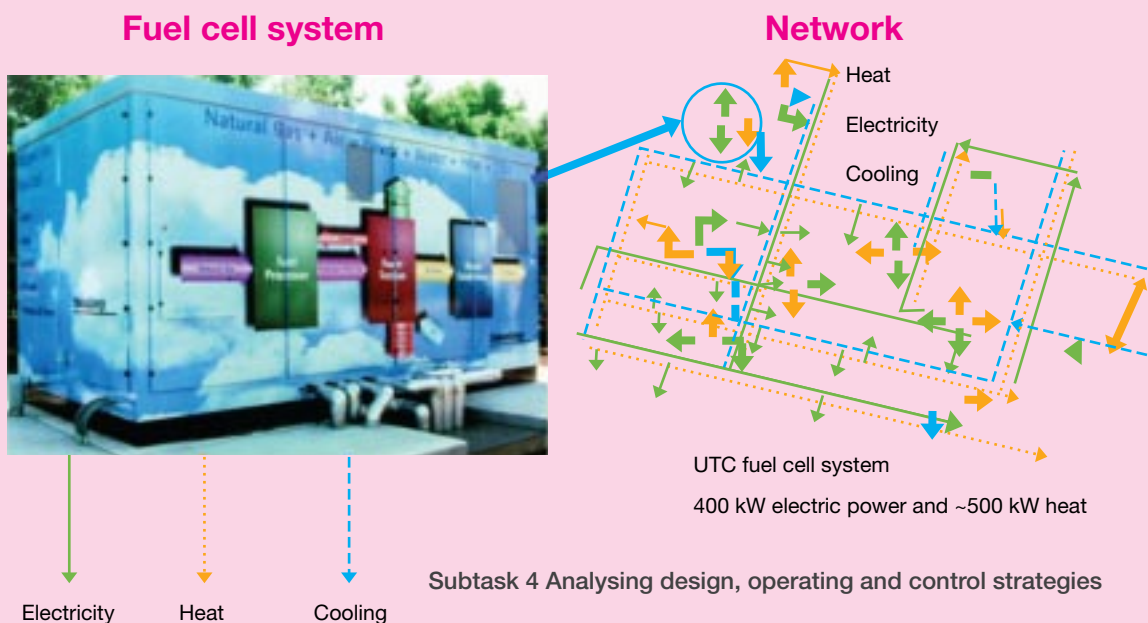


Table 5 SOFC system component cost (Euros)

System cost	1500 €/kW	2000 €/kW	2500 €/kW	4000 €/kW
Fuel system	276	368	461	737
Air system	207	276	345	552
Automation & control	161	215	269	430
Structural	151	202	252	404
Power conversion	120	159	199	319
Exhaust system	26	35	44	71
Purge system	22	29	36	57
Safety system	12	16	20	32
Start-up system	10	13	16	25
Assembly & testing	65	87	108	173
Stack	450	600	750	1200
Total	1500	2000	2500	4000

Figure 11 Tri-generative fuel cell system



Subtask 4 Analysing design, operating and control strategies

Combined cooling, heating and power (CHP) or tri-generative fuel cell systems (FCS) can convey electricity, recoverable heat, and chilled water and hydrogen as transport fuel to multiple buildings via networks, as shown in the figure above.

Subtask 5 Follow up of demonstration projects

Several large MCFC projects especially has been followed and discussed for example the EWZ 240 kWe MCFC project in Zürich, Switzerland.

The new structure of the suppliers of large fuel cells plants has been discussed and followed up in details. Some developers are expanding and others have to close down.

The influence of different type's subsidies on the development of the demonstration market has been presented and followed up. The conditions are very different in for instance USA and Japan compared to several European countries.

Subtask 6 Market status

Examples of highlights and topics discussed 2010 in Subtask 6 include:

- H2Energia presented MCFC projects in Spain with the existing feed in tariffs in Spain a MCFC running on biogas connected to pulp and paper mill can be profitable today.
- VTT Finland presented their SOFC programme. A special topic was the commissioning of a Versa Power 10 kWe power unit.
- IEA in Paris has started to consider hydrogen and fuel cells in their scenarios for the ETP, Energy technology perspective. In two of five scenarios is hydrogen considered as a fuel the Blue Map and the Blue-map-shift. Hydrogen will then be taken into account both in the transport sector and as fuel for CHP in the building sector

4.4.7 Work Plan

The spring meeting 2011 will be held in 10-11 May in Lillo-Antwerp in Belgium and hosted by Solway and Waterstofnet.

The autumn meeting in 2011 will be hosted by USA DOE and held in connection with the Fuel cell Seminar 2011 in Orlando, Florida.



ANNEX
26

The overall objective of this annex is to develop understanding of fuel cells with their particular properties, applications, and fuel requirements.

4.5 ANNEX 26 REPORT

FUEL CELL SYSTEMS FOR TRANSPORTATION

4.5.1 Duration

February 2009 until February 2014 (five years).

4.5.2 Operating Agent

Argonne National Laboratory, USA, took on the role in late 2010.

4.5.3 Participants

Agencies from nine countries participate in this Annex:

Austria	Austrian Energy Agency
Denmark	Danish Energy Agency
Finland	Finnish Agency for Technology & Innovation (TEKES)
Germany	Forschungszentrum-Jülich GmbH
Italy	Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, ENEA
Korea	Korea Institute of Science and Technology (KIST)
Netherlands	Netherlands Energy Research Foundation (ECN)
Sweden	Swedish Energy Agency (STEM)
United States	US Department of Energy (DOE)

A full list of participating experts is provided in Appendix 7 to this report. These include several representatives of the automotive industry.

4.5.4 Objective

The overall objective of Annex 26 is to develop the understanding of fuel cells with their particular properties, applications, and fuel requirements. The specific objectives are to:

- Improve the common understanding of state of the art fuel cell systems, on board fuel storage systems, technology development directions, cost reduction approaches.
- Improve the concepts for alternative fuels by discussing manufacturing technologies, required infrastructure for storage and distribution, efficiencies and emissions during fuel production
- Leverage the emissions work being carried out in Participants' organisations
- Jointly review the ongoing work on practices and procedures relevant to alternative fuels and fuel cell vehicles, and help identify their niche applications
- Accelerate the market entry of advanced fuel cell systems by identifying open development issues of common interest, but also contradictory views and recommendations on private and government strategies.

4.5.5 Task Description

This Task consists of four subtasks:

Subtask A Advanced Fuel Cell Systems for Transportation

This subtask will focus on the fuel cell module (fuel cell, peripherals and reformer, if applicable). It will prepare an inventory of markets and a summary of gaps and barriers.

Subtask B On-board Hydrogen Storage Systems

This subtask will focus on the market readiness of storage materials for different market segments, including the definition of efficiency targets.

Subtask C Hydrogen infrastructure

This subtask will evaluate hydrogen production methods, considering production efficiency and hydrogen purity features. It will also examine the status of hydrogen network activities.

Subtask D Technology Validation and Economics

This subtask will exchange and compare cost models and assess the economic gap of fuel cells in transport.

4.5.6 Progress Summary

4.5.6.1 Background

This Annex is the successor to Annex XV that ran from May 1, 2001 and ended on December 31, 2003 and Annex XX that ran from 2004 to 2008.

4.5.6.2 Activities

No meetings were held during 2010.

4.5.6.3 Technical Accomplishments

No technical advances were recorded during 2010.

4.5.7 Work Plan for Next Year

To be decided. Now that a new Operating Agent is in place, work with recommence.



ANNEX
27

This annex is concerned with fuel cells and fuel cell systems for portable applications and light traction. Promising techniques for these applications are polymer electrolyte fuel cells operated with methanol or hydrogen.

4.6 ANNEX 27 REPORT

PORTABLE FUEL CELLS

4.6.1 Duration

February 2009 until February 2014 (five years).

4.6.2 Operating Agent

Forschungszentrum Jülich GmbH, Germany

4.6.3 Participants

Agencies from nine countries participate in this Annex:

Austria	Technische Universität Graz
Canada	NRC
Germany	Fraunhofer Institut Chemische Technologien
Germany	Forschungszentrum Jülich GmbH
Germany	FWB
Italy	CNR-ITAE
Japan	AIST
Korea	KIER
Sweden	Intertek Semko

A full list of participating experts is provided in Appendix 7 to this report.

4.6.4 Objective

Annex 27 is concerned with fuel cells and fuel cell systems for portable applications and light traction. Promising techniques for these applications are polymer electrolyte fuel cells operated with methanol or hydrogen.

4.6.5 Task Description

Compared to batteries fuel cells offer advantages in powering portable and small mobile applications. The main advantage is the high power density of the fuel and the longer operating time of the device. Also the time that is necessary for recharging batteries is may be a problem that can be avoided by using fuel cells.

The direct methanol fuel cell (DMFC) that is often used in portable and small mobile devices offers the advantage of using a fuel with a volumetric energy density that is four times higher than the energy density of hydrogen at 350 bars. Yet the DMFC itself provides a much lower power density than the polymer fuel cell operated with hydrogen.

In most applications it is necessary to couple the fuel cell with a hybridization battery to cope with load peaks or energy recovery.

Key issues in developing MEAs are improving durability and performance. Also the operation at low air stoichiometry is necessary to achieve high operating temperatures and to close the water loop.

Subtask 1: System analysis and hybridization

Subtask 2: System, stack and cell development

Subtask 3: Codes and standards, safety, fuels and fuels packaging

Subtask 4: Lifetime enhancement

4.6.6 Progress Summary

4.6.6.1 Background

This annex follows on from Annex XXI on portable applications, which entered into force on April 1, 2004. As the market for portable applications is expected to be the first market for fuel cells this annex focuses on the specific research demands and technical conditions for portable fuel cells.

4.6.6.2 Activities

The Annex 27 meeting was held on October the 4th, 2010 in Jülich, Germany.

At the meeting, the following topics were discussed:

- System, stack and cell development
- Lifetime enhancement
- System analysis and hybridization

The highlights of the meeting were as follows:

- Detailed description of Toshiba's Dynario system (Japan)
- Demonstration of cheap methanol sensor from FWB (Germany)
- Durability of DMFC MEA in single cell 10,000 h (Korea)
- Operation of ~1 kW DMFC system for 3,000 h under real load profile (Germany)

No decisions were taken at the meeting.

4.6.6.3 Technical Accomplishments

Stacks and systems for light traction

In this section, the activities in developing fuel cell systems in the range from 250 W up to several kW are shown. These systems are suitable for small mobile application respectively light traction.

DESIGN, MANUFACTURING AND TESTING OF A 3 KWE PEFC STACK OPERATING AT 120 °C AND BASED ON HOME MADE COMPOSITE MEA AND FLOW FIELD (ITAE; ITALY)

Max. power Output: 2 x 1.5 W

Operating Temperature: 120 °C

Cell number: 40 cells (150 cm² active area)

100% RH Fuel – 100% RH Air

Working current 150 A

Stack Voltage at 120°C with H₂ 28 V

Stack Voltage at 120°C with H₂ + CO₂ 26 V

Rated Power - 120°C / H₂ 4200 W

Rated Power - 120°C / H₂+CO₂ 3900 W

95% RH Fuel – 49% RH Air

Working current 150 A

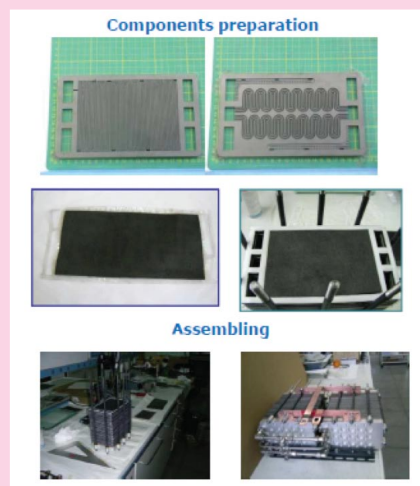
Stack Voltage at 120°C with H₂ 22 V

Stack Voltage at 120°C with H₂ + CO₂ 21 V

Rated Power - 120°C / H₂ 3300 W

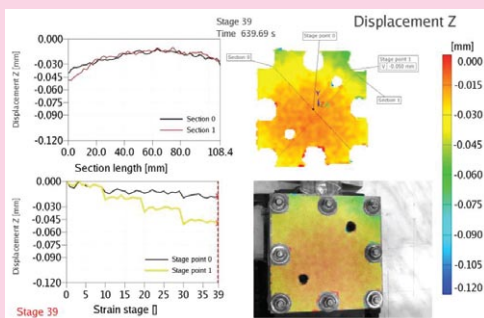
Rated Power - 120°C / H₂+CO₂ 3150 W

Optimization of membrane production: 15%wt Nafion dispersion was used to reduce production time and a new deposition device was used to increase thickness precision and homogeneity



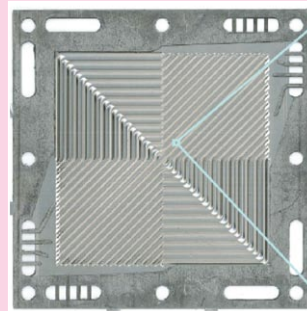
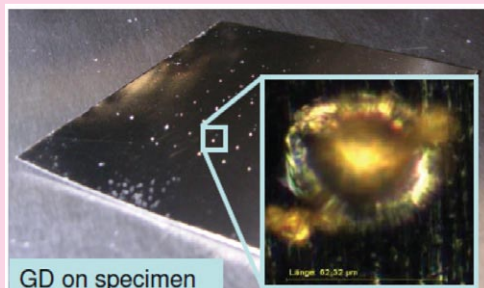
MEASUREMENT OF CONTACT PRESSURE DISTRIBUTION (ITAE; ITALY)

Measurement of contact pressure distribution in end plates or bipolar plates (collaboration with UNI-ME)



METAL DMFC BIPOLAR PLATE DEVELOPMENT (FORSCHUNGSZENTRUM JÜLICH, GERMANY)

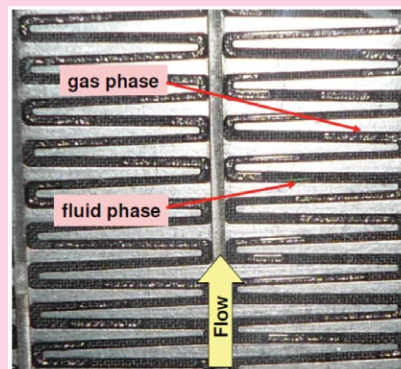
- Development of a new bipolar plate and stack concept: saving of weight >30 % & saving of volume >45% compared with graphite bipolar plates
- Stable material in DMFC environment: nickel-base alloy
- Novel technique for reduction of contact resistance: segmented laser coating with gold dots
- Investigation of the influence of dissolved metal ions on DMFC performance: relation of ionic contamination and DMFC lifetime



TRANSPARENT DMFC (FORSCHUNGSZENTRUM JÜLICH; GERMANY)

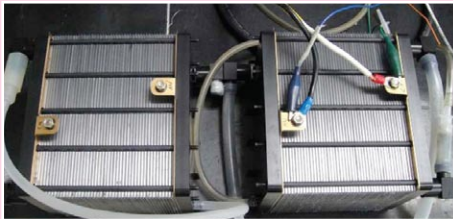
DMFC cell with 315 cm² active area:

- It is possible to actuate a cell in the transparent construction
- Visualization of the anodic and cathodic water/gas transport
- Measurement of the local current distribution
- Correlation of flow distribution and bubble formation with the current distribution
- Equal distribution of partial currents is problematic due to contact resistance



DEVELOPMENT OF DMFC 800 W STACK FOR SCOOTERS (KIER; KOREA)

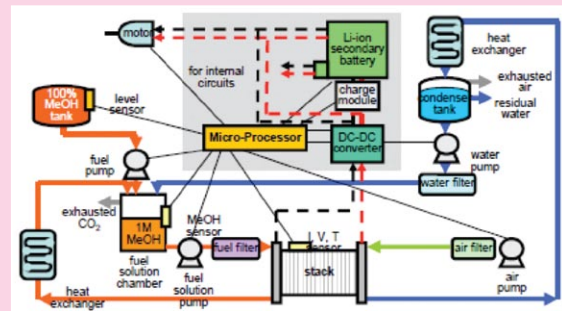
Specification:	2 sub-stacks (45 cells/sub-stack)
Active area:	102 X 151 mm ²
Cell pitch:	2.94 mm
Peak power:	~700 W/sub-stack
Normal power:	~500 W/sub-stack @ 18V
Dimensions:	120 X 190 X 175 mm ³ (4 l/sub stack)
Power density:	175 W/l



DEVELOPMENT OF DMFC SCOOTER (PROPOWER, KIER, KIST, S&T MOTORS, HYUPJIN INC., KAIST, JBTP;KOREA)

Specification:

- Hybridization DMFC 800 W + Battery 1.6 kW
- Fuel 0.7 M methanol solution (Stack)
- Fuel tank 4.5 L (pure methanol)
- Li polymer battery
- Max speed 35 km/h



Stacks and systems for portables and handhelds

In this section, the activities in developing fuel cell systems and stacks with a power output up to several Watt are shown. These systems are suitable as a power supply or recharge unit for electronic devices. All the systems are fed with methanol as a fuel.

TOSHIBA DYNARIO (TOSHIBA; JAPAN)

Toshiba's first micro fuel cell device which was released in October 2009 and sold out now.

- USB power source (DC 5 V, max. 400 mA)
- Internet sales via Toshiba web site in Japan price fuel cell: 29,800 yen (~220 EUR) five cartridges: 3,150 yen (~23 EUR)
- 50 ml fuel cartridge for charging cell phone battery around 7 times.
- Fuel: Methanol 98% + pure water 2%
- Methanol consumption: about 60 µl/min.
- Oxygen consumption: 60 ml/min.cf. oxygen consumption by human at rest ~ 1 l/min.
- CO₂ emission: 50 ml/min. CO₂ from a human 1 l/min.
- Water evaporation: 60 µl/min cf. water drop from hypodermic needle: 20 µl
- No emission of CO, formaldehyde, methanol or any other toxic substance.

Figure 12 Component parts of Dynario



Dynario construction:

- Two fuel cells, fuel volume is 14 ml
- Small Li-ion battery for start-up
- Anode side valve and pump for safety reasons

Cartridge, DMFC and Fuel Connector Design
Comply with IEC PAS 62282-6-1, IEC 62282-6-100
FDIS and IEC 62282-6-300

- 1) No leakage when the cartridge is squeezed with 100 kgf.
- 2) Fuel discharge pressure from the cartridge must not exceed the gauge pressure of 0.1 MPa (1 atm) even if it pressed with 100 kgf.
- 3) Fuel connector between cartridge and MFC and every part inside MFC must withstand a pressure twice higher (0.2 MPa). Toshiba designs every part including connectors to withstand a pressure of up to 0.6 MPa.

4) Disconnection of cartridge without damaging MFC or cartridge. No fuel leakage must occur under any compression, tension, torsion, bending, dropping or vibration while cartridge is connected.

5) This results in no fuel leakage under normal or, misuse condition and no over fill during refilling operation.

Figure 13 Built-in type DMFC prototype for a smart-phone



EMISSION FROM MICRO FUEL CELLS (AIST JAPAN)

Remained problem in test procedure on emission from micro fuel cells specified by IEC 62282-6-100
Need of investigations for more reasonable local effect test

Figure 14 Concentration limits of emission from micro fuel cells

Gaseous chemical compound	Concentration limit (based on 10m ³ · (air changes per hour)) / mg·m ⁻³
Methanol	260
Formaldehyde	0.1
Carbon monoxide	29
Carbon dioxide	9000
Formic acid	9
Methyl formate	245

24 W CLASS PORTABLE FUEL CELL POWER PACK (KIER, CHUNGNAM NAT'L UNIV., KAIST; KOREA)

24 W class portable fuel cell power pack

Targets:

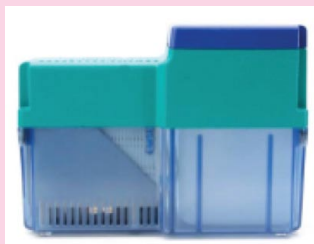
- Weight: <1.2 kg
- System normal power/voltage: 24 W (peak 30 W), 12 V
- Operating temperature: -32 - 65 °C, 500 h
- Specific energy: 0.72kWh/kg

DIRECT METHANOL FUEL CELLS FOR SMALL INDUSTRIAL APPLICATIONS (FWB; GERMANY)

Direct methanol fuel cells for small industrial applications

- Enhanced runtime in hybrid technology
- Higher usability in competition to accumulators by stable voltage and less self discharge
- Cost and customer advantage e.g. by reduced maintenance cycles
- Target costs < 300 € / system as an acceptable start into a niche market

Advantage of the FWB cell concept: Flat and self breathing technology with planar connection to requested voltage levels allows high efficiency and low system complexity to achieve low cost targets.



PASSIVE VAPOR FED DMFC SYSTEMS (FWB; GERMANY)

Passive vapor fed DMFC systems

- Gaseous methanol for improved diffusive reaction kinetics
- Neat methanol for highest energy density
- Improved mass transport without 2-phase-problem
- Avoiding peripherals (BoP) higher efficiency
- Injection moulding technology for series production
- Flat planar construction for device integration



MEA-development

In this section, the different developments in MEA and electrode or catalyst development are shown.

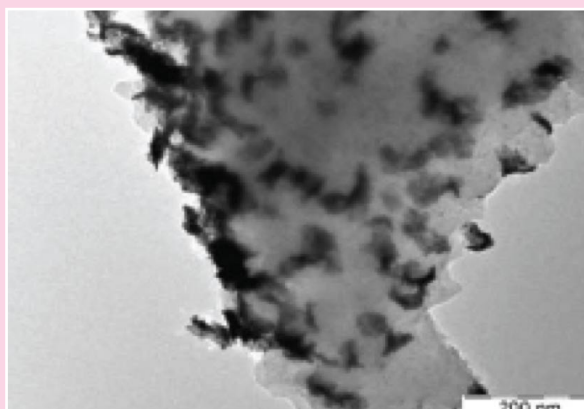
The focus is on carbon-free supported catalysts, on membranes for HT-PEFC and on catalysts for alternative fuels like ethanol or glucose.

CATALYST DEVELOPMENT (ITAE; ITALY)

Catalyst development

Table 6 Carbon-free supported catalysts with low corrosion, Pt/Pani Catalyst

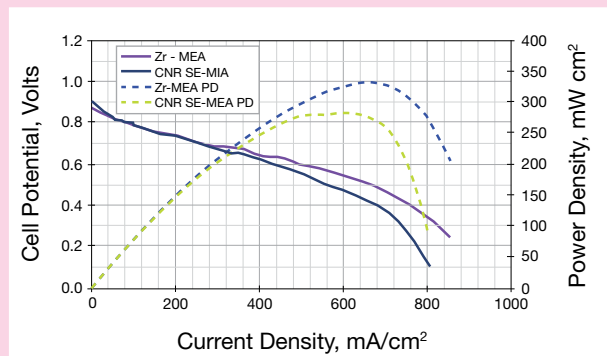
Catalyst	Support	Rapporto Pt/Pani, mg	%, Pt	Cristalite size, nm
Pt-PANI-6	PANI salt	620/690	37	4.4
Pt-PANI-7	PANI salt	310/690	22	4.2
Pt-PANI-8	PANI salt/HCl treated	620/690	30	5.9
Pt-PANI-9	PANI base	620/690	30	5.7



HT-PEFC DEVELOPMENT (ITAE; ITALY)

HT-PEFC development

- Nafion /ZrO₂ - Y₂O₃ doped composite membranes
- S-PEEK-SiONH₂ membranes
- Membranes reinforcement by electrospinning (collaboration with UNI-RC)
- Composite membranes with inorganic oxides (collaboration with CITEDEQ)
- Composite membranes containing TPSS-4 (collaboration with CNR-ISMN)



DIRECT GLUCOSE FUEL CELLS (AIST JAPAN)

Anode: PtRu 3 mg/cm²

0.5 M glucose aqueous solution or 0.5 M glucose / 0.5 M KOH 4 ml/min

Cathode: Pt 3 mg/cm², O₂ 100 ml/min

Membrane: CEM or AEM

At room temperature and atmospheric pressure

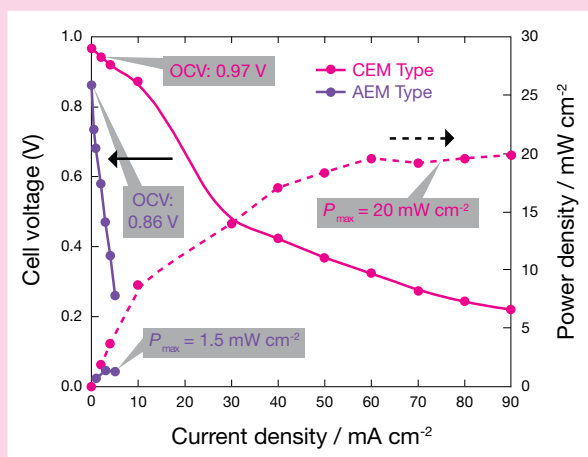
Anode: $C_6H_{12}O_6 + 2OH^- \rightarrow C_6H_{12}O_7 + H_2O + 2e^-$
 $E^\circ = -0.853V$ vs. SHE

Cathode: $\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$
 $E^\circ = 0.403V$ vs. SHE

Total: $C_6H_{12}O_6 + \frac{1}{2}O_2 \rightarrow C_6H_{12}O_7$
 $E^\circ_{cell} = 1.256V$

N. Fujiwara, S. Yamazaki, Z. Siroma, T. Ioroi, H. Senoh, K. Yasuda, *Electrochem. Commun.*, 11, 390 (2009).

Figure 15 Cell voltage & power density plots



DMFC-MEAS PT-RU ELECTROCHEMICAL ACTIVATION/DEACTIVATION (NRC; CANADA)

Pt-Ru FC anode catalysts: Electrochemical activation/deactivation

K. Ramanujam, C. Bock, B. MacDougall (National Research Council of Canada)

Pt_xRu_y alloy catalysts are generally viewed as being the most active for the CH₃OH electro-oxidation reaction in DMFCs; This is largely related to a bi-functional mechanism [1,2] (see on the right side)

However, Pt-Ru catalysts suffer of Ru dissolution problems; This is experimentally seen in cross-over of Ru to the cathode, subsequent deposition of Ru onto the Pt catalyst sites on the cathode, and lowering of the FC performance [3,4]

Results of the investigations

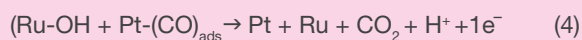
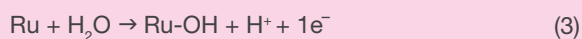
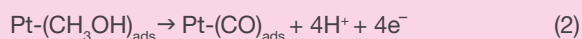
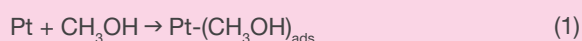
No loose Ru phase observed:

- XRD and EDX analysis suggest that an unsupported Pt₇₅Ru₂₅ alloy catalyst powder is made that has the same bulk alloy composition, i.e., without the presence of an excessive amount of a separate Ru/Ru-oxide component;
- Excess Ru/Ru-oxide phase of Pt₇₅Ru₂₅ alloy catalysts not completely removable by acid leaching (in boiling 0.5 M H₂SO₄);

Activity of Pt₇₅Ru₂₅ remains same before and after acid leaching;

- background CVs, CH₃OH oxidation characteristics seen in CV scans and CO_{ads} stripping CVs are essentially the same for the as-prepared and acid leached catalyst;

- Cycling to high anodic potential (0.6 to 0.8 V) is necessary to activate Pt₇₅Ru₂₅ catalysts;
- Small amount of Ru phase can remain on as-prepared catalyst's surface reducing the CO_{ads} stripping and CH₃OH oxidation kinetics;
- The Ru-oxide can be removed by electrochemical leaching either by E-cycling between E⁺ of 0.6 and 0.8 V. Potential holding within these E⁺ limits also removes the excess Ru-oxide phase, however, needs to be applied for a longer time period;
- 35% increase in CH₃OH oxidation activity observed after cycling up to 0.8 V;



Literature:

[1] M. Watanabe and S. Motoo, J. Electroanal. Chem., 1975, 60, p. 267

[2] H. Gasteiger, N. Markovic, P. Ross and E. Cairns, J. Electrochem. Soc., 1994, 141, p. 1795

[3] P. Piela, C. Eickes, E. Brosha, F. Garzon and P. Zelenay, J. Electrochem. Soc., 2004, 151, p. A2053

[4] T. I. Valdez, S. Firdosy, B. E. Koel and S. R. Narayanan, ECS Transactions, 2006, 1, p. 293

DIRECT ETHANOL FUEL CELL (DEFC) DEVELOPMENT (ICT FRAUNHOFER, GERMANY)

Table 7 Comparison of different fuels

Property	Hydrogen 700bar	Sodium borohydride	Methanol	Ethanol	Diesel
Energy storage density	--*	+	O	+	++
Mass of storage reduces with fuel consumption	(no)*	no	yes	yes	yes
Gaseous products	no	no	yes	yes	yes
Availability	-	--	O	++	++
Simplicity of handling	O	O	O (++)	++	++
Potential risks					
toxic	no	no	yes	no	low
explosive	yes(*)	no	no	no	no
flammable	highly	highly	highly	highly	yes
Use in direct converting fuel cells	commercial	under development	commercial	under development	under development
Use as hydrogen source		commercial	commercial	under development	under development

* Because of tank

Acidic versus alkaline direct alcohol fuel cells →
Alkaline anion exchange membrane fuel cell (AEMFC)

Advantages

- Reaction kinetics
- Non noble metal catalysts
- Less expensive membrane materials

Disadvantages

- Membrane technology is less mature
- Membrane electrode connection is difficult
- Catalyst may require activation before start

Potential Application

- Portable power source 50 W to 0.5 kW potential up to 5 kW
- Battery charger

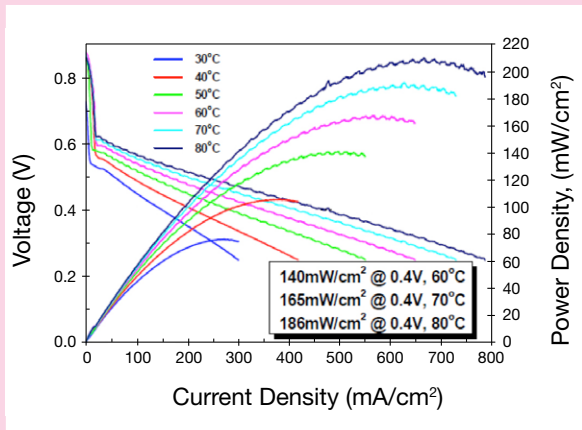
Experimental Investigations:

Choice of for Fuel Cell suitable denaturing agents

→ A mixture of ETBE and BITREX is a viable denaturing agent for DEFC

DMFC-MEA DEVELOPMENT (KIER, KOREA)

Anode: -1 M, 3 cc/min
Cathode: Air, 350 cc/min
Catalyst: Tanaka 73wt%PtRu/C 2mg/cm² & 67wt%Pt/C 2mg/cm²
Membrane: Nafion 115
Cell temp: 30-80 °C



DMFC WATER AUTONOMOUS MEA FOR HIGH CONCENTRATION METHANOL FEED DEVELOPMENT (KIER, KOREA)

Water-autonomous MEA development for high concentration methanol feed

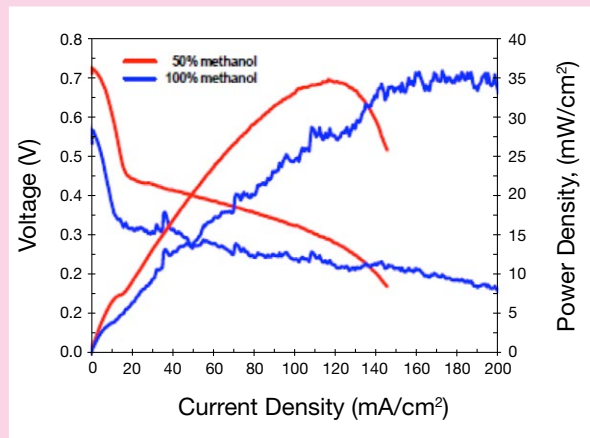
Targets:

- Power density: >30 mW/cm² (passive) >70 mW/cm² (semi-passive) (0.4 V, 60 °C, >6 M methanol)
- Volumetric power density (20 W stack): >90 W/l, 500 hs – operation

Development of polymer electrolyte membrane and catalyst for water autonomous MEA

Targets:

- Methanol permeability < 1x10⁻⁷ cm²/s, conductivity 0.05S/cm
- IEC > 2.0 mequiv/g, weight average molecular mass (Mw) > 105 g/mol
- MOR resistance catalyst for cathode



RADIATION GRAFTED POLYMER ELECTROLYTE FOR LOW METHANOL CROSSOVER (KIER, KOREA)

Long-term stability test of DMFC MEAs with radiation-grafted PEM > 5 M of methanol concentration

- Operation time 2000 hrs
- MEA fabrication process optimization
- Operation condition optimization

Development of 60 W class DMFC stack with radiation-grafted PEM

- Fabrication of 60 W class DMFC stack
- Long-term stability test of the stack (>2000 hrs)
- Diagnosis of performance degradation

Figure 16 Conductivity

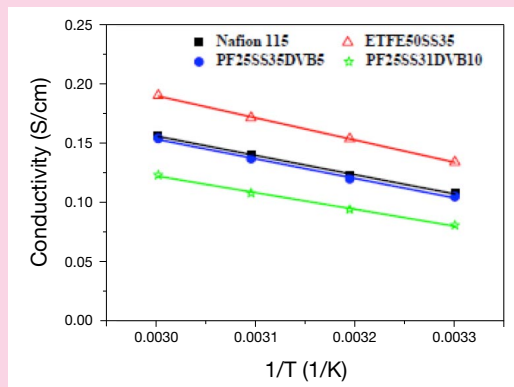
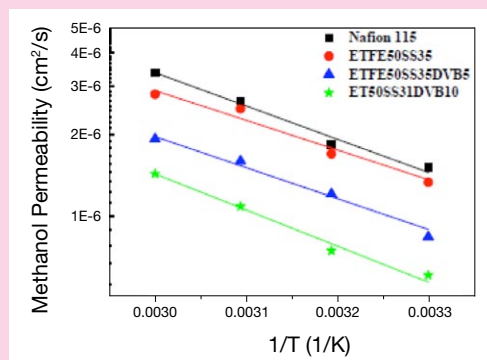


Figure 17 Methanol Permeability

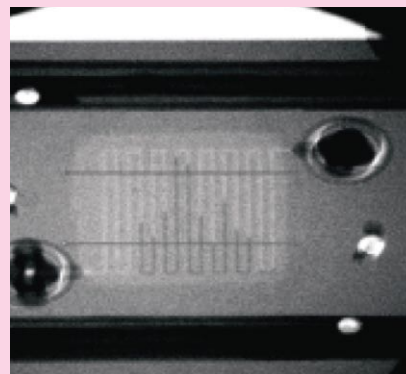


WATER-MANAGEMENT PEFC (TU-GRAZ; AUSTRIA)

Water-management PEFC, Project INNO PEM

Understanding of water transport phenomena within a PEFC for validation of a 3D-CFD-fuel cell model

- Visualization of water-transport by neutron radiography
- Development of a “gradient-free” fuel cell, to be able to measure an one-dimensional system of cathode (gas channel – GDL) – MEA – anode (GDL – gas channel)



Durability of MEAs

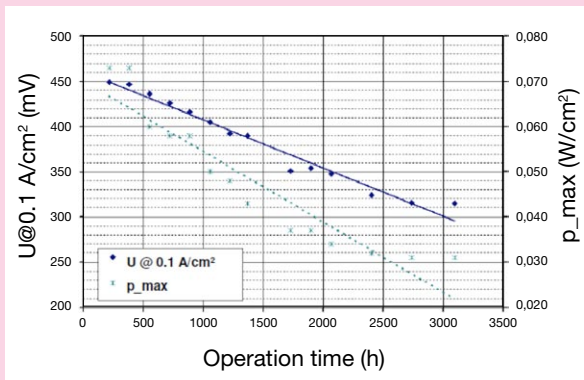
In this section, results of the durability tests of MEAs integrated into stacks and single cells are shown.

STACK OPERATION (NINETY CELLS WITH 315 CM² EACH) (FORSCHUNGSZENTRUM JÜLICH; GERMANY)

Lifetime: 3000 h at realistic load schemes

Degradation rate: -53 $\mu\text{V/h}$ @ 100 mA/cm²

Degradation is affected by cation contaminated media in anode loop.



LONG OPERATION OF 150 CM² - SINGLE CELL (KIER; KOREA)

Constant current of 20 A (133 mA/cm²)

Load, fuel, and air on-off mode (30 min-10sec)

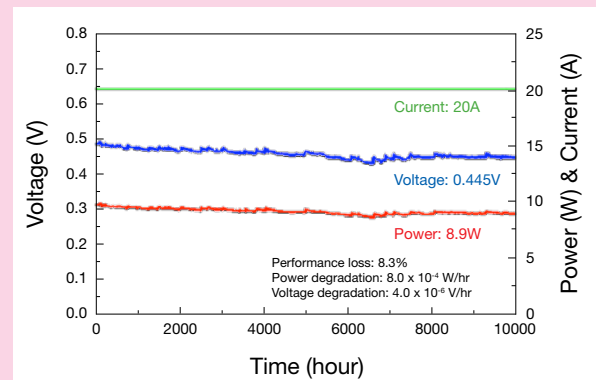
After 4000 h

- 5.6% performance loss
- power degradation rate: -1.29×10^{-4} W/h
- voltage degradation rate: $-6.46 \mu\text{V/h}$

After 10,000 hr

- 8.3% performance loss
- power degradation rate: 8.0×10^{-4} W/hr
- voltage degradation rate: $4.0 \mu\text{V/hr}$

Figure 16 Results of the 10,000 hour durability test, 150 cm² MEA for DMFC. Stable operation over 10,000 hrs, still on going.



FUEL CELL SYSTEM COMPONENTS ETHANOL-REFORMING (TU-GRAZ; AUSTRIA)

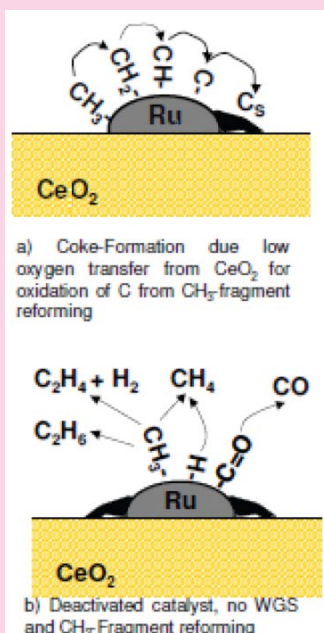
Ethanol-Reforming

- Reforming of renewable Hydrocarbons
- Ethanol as Source for renewable Hydrogen

Catalysts for ethanol steam reforming: Co/CeO₂ und Ru/CeO₂

- 10%Co/CeO₂ and 10%Ru/CeO₂
- Similar activity and selectivity
- No deactivation at T=500 °C in long time tests
- Stronger coking on Co/CeO₂-Katalysator
- Co and Ru/CeO₂ are promising catalysts
- Co/CeO₂ and Ru/CeO₂ are almost equal
- Differences in raw material costs is factor 100

Influence of Catalyst Preparation of 10% Co/CeO₂ on catalytic activity and coke-formation, reaction mechanism, coke formation and deactivation.

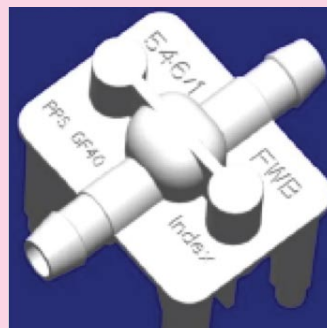
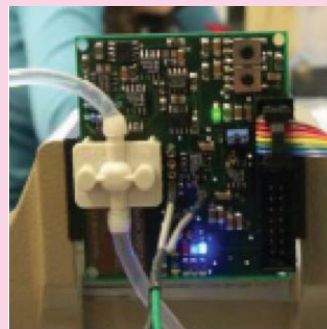


METHANOL SENSOR (FWB; GERMANY)

FWB – methanol sensor approach

Motivation: Currently no low cost methanol sensor is available

- High temperature resistant sensor housing
- Compact sensor system (26 x 15 x 16 mm³)
- Low weight (ca. 22 g)
- Concentration range: 0–100 % (w/w)
- Reliability 0,3 % (w/w)
- Temperature range: 3 – 50 °C for methanol
- Economic injection moulding part
- Cost sensitive sensor components



4.6.7 Work Plan for Next Year

The phase of testing the systems under real operating conditions has now started and the aims for further development of Annex 27 are as follows:

FC STACK / MEA

- Improvement of power density by use of better catalysts
- Employment of new stack materials
- Checkout of alternative fuels (ethanol, glucose)
- Improvement of MEA durability and better quality control to minimize performance variation among cells
- Decrease of the methanol crossover

POWER GENERATION SYSTEM INCLUDING BOP, SECONDARY BATTERIES AND CONTROLS

- Maximization of the system efficiency
- Maintaining of the water balance in the system at elevated environmental temperature
- Detoxification of in the emission gas
- Assurance of reliability

PRODUCT DEVELOPMENT

- Better product concepts and quality assurance to exceed customers expectations / requirement
- Assurance of fuel quality and establishment of fuel-supply network
- Cost reduction



APPENDICES

Appendix 1: Membership of the Executive Committee

Appendix 2: Executive Committee meetings to date

Appendix 3: Task proposals under consideration

Appendix 4: Executive Committee reports and publications

Appendix 5: Workshops and task meetings

Appendix 6: Task Reports and publications

Appendix 7: Task Experts



Appendix 1

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Appendix 2

EXECUTIVE COMMITTEE MEETINGS TO DATE

Meeting	Date	Place
1	April 2, 1990	Paris, France
2	November 25, 1990	Phoenix, Arizona, USA
3	June 27-28, 1991	Petten, The Netherlands
4	February 7, 1992	Makuhari, Japan
5	September 24-25, 1992	Malmö, Sweden
6	March 15, 1993	Rome, Italy
7	September 28, 1993	London, United Kingdom
8	March 15, 1994	Zürich, Switzerland
9	October 11, 1994	Jülich, Germany
10	May 11-12, 1995	Oslo, Norway
11	September 18th, 1995	Loughborough, United Kingdom
12	February 1-2, 1996	Tokyo, Japan
13	September 17-18, 1996	Roskilde, Denmark
14	April 15-16, 1997	Vancouver, Canada
15	September 18-19, 1997	Amsterdam, The Netherlands
16	March 19-20, 1998	Santa Fe, USA
17	October 1-2, 1998	Melbourne, Australia
18	April 13-14, 1999	Jülich, Germany
19	September 20-21	1999, London, UK
20	April 10-11, 2000	Malmö, Sweden
21	November 4, 2000	Portland, Oregon, USA

Meeting	Date	Place
22	May 3-4, 2001	Capri, Italy
23	September 5-6, 2001	Basel, Switzerland
24	May 30-31, 2002	Paris, France
25	November 22-23, 2002	Palm Springs, California, USA
26	May 8	Espoo, Helsinki, Finland
27	October 23-24, 2003	Dusseldorf, Germany
28	April 1-2, 2004	Vienna, Austria
29	October 13-14, 2004	Seoul, Korea
30	April 28-29, 2005	Copenhagen, Denmark
31	November 18, 2005	Palm Springs, California, USA
32	April 20-21, 2006	Mol, Belgium
33	November 2-3, 2006	Oslo, Norway
34	April 19, 2007	Amsterdam, the Netherlands
35	October 19, 2007	San Antonio, Texas, USA
36	February 25-26, 2008	Tokyo, Japan
37	October 27, 2008	Phoenix, Arizona, USA
38	April 15, 2009	Istanbul, Turkey
39	November 26, 2009	Copenhagen, Denmark
40	May 21, 2010	Essen, Germany
41	October 4-5, 2010	IEA, Paris, France

Appendix 3 and 4

APPENDIX 3

TASK PROPOSALS UNDER CONSIDERATION

There is currently one Annex proposal, that of the System Analysis Annex. This was proposed in October 2010. The intention of this Annex would be to assist the development of fuel cells through analysis work to enable a better interpretation of the current status, and the future potential, of the technology. This work will provide a competent and factual information base for technical and economic studies.

APPENDIX 4

EXECUTIVE COMMITTEE REPORTS AND PUBLICATIONS

The following reports have been issued:

- Minutes of 41 Executive Committee Meetings since initiation (1990).
- Annual Reports 1990-2009.
- Draft strategic plan, January 2009.
- End of term report on the phase 2004-2008, October 2008.
- Contribution on the Advanced Fuel Cells Implementing Agreement for the 2003/2006 Implementing Agreement Highlights IEA publication (2006)
- Regular contributions on the Advanced Fuel Cells Implementing Agreement for the EUWP Status Reports on Transport related Implementing Agreements
- Strategy and Procedural Guidelines for the IEA Advanced Fuel Cells Programme, (1992).
- Revised Procedural Guidelines for the IEA Advanced Fuel Cells Programme (1998)
- Updated Implementing Agreement (1998).
- Strategy for the IEA Advanced Fuel Cells Programme 1999-2003 (1998).

- “International Co-operation of Fuel Cell R&D via the International Agency”, K Joon, H Barten, paper presented at the 1994 Fuel Cell Seminar, San Diego, USA.
- “The IEA Advanced Fuel Cells Programme”, K Joon, invited paper presented at the 2nd International Fuel Cell Conference, Kobe, Japan, February 1996.
- End of Term Reports to the IEA in September 1995, September 1998 and October 2003.
- “Progress in Fuel Cell Development through Co-operation in the Framework of the International Energy Agency”, K Joon, L Sjunnesson, invited paper presented at the 3rd International Fuel Cell Conference, Nagoya, Japan, December 1999.
- Summary Final Report of the IEA Advanced Fuel Cells Programme 1996-1999.

In addition, verbal presentations have been given by the Chairman and Secretary to the IEA Working Party on End Use Technologies, the Committee on Energy Research and Technology, the Working Party on Fossil Fuels and the IEA Hydrogen Executive Committee.

Appendix 5

WORKSHOPS AND TASK MEETINGS

This section lists meetings and workshops held in 2010.

5.1 TASK 22:

May 27–28, 2010, ECN, Petten, the Netherlands
January 26-27, 2011, Web Teleconference (delayed
2010 Fall workshop)

5.2 TASK 23: MOLTEN CARBONATE FUEL CELLS

July 9-10, 2010, University of Perugia, Italy

5.3 TASK 24: SOLID OXIDE FUEL CELLS

June 28, 2010, Lucerne, Switzerland

5.4 TASK 25: FUEL CELL SYSTEMS FOR STATIONARY APPLICATIONS

April 27-28, 2010, Winterthur, Switzerland
October 13-14, 2010, Lyngby, Denmark

5.5 TASK 26: FUEL CELLS FOR TRANSPORTATION

No meetings held

5.6 TASK 27: FUEL CELLS FOR PORTABLE APPLICATIONS & LIGHT TRACTION

October 4, 2010, Jülich, Germany

Appendix 6

TASK REPORTS AND PUBLICATIONS

This section lists task reports and publications produced to date for those tasks which were active during the year. These publications are classified according to the following system.

Level	Classification	Report Type	Distribution
1a	Restricted - sub-task participants only	Working papers	Distribution limited to those experts participating in the specific sub-task.
1b	Restricted - annex participants only	Sub-task reports, detailed technical reports	Distribution limited to those experts participating in the annex.
2a	Restricted - annex participants and Ex Co members only	Summary technical reports	As above + Ex Co members from countries participating in annex for personal reference and approvals.
2b	Restricted - countries participating in annex only	Summary technical reports, summary final reports	As above + Ex Co members from countries participating in annex may distribute report to organisations in that country not participating in the annex
2c	Restricted - IA signatory countries only	Summary final reports	Distribution to any organisation in a country participating in the IA
3a	Unrestricted within IEA	Annual reports; summary final reports	Open distribution to all countries in IEA.
3b	Unrestricted	Annual reports; summary final reports	Open distribution including countries not in IEA. To publicise and inform about IEA programme.

Some of the reports are classified according to an earlier system which only used three levels:

1	Experts participating in relevant Sub-task only.		
2	Participating Countries and all Executive Committee Members.		
3	Level 3: Unrestricted.		

6.1 TASK 22: POLYMER ELECTROLYTE FUEL CELLS

Level 3b reports, papers and abstracts:

Mergel, J; Glüsen, A; Wannek, C; Current Status of and Recent Developments in Direct Liquid Fuel Cells, Hydrogen and Fuel Cells, Fundamentals, Technologies and Applications; ed.: D. Stolten, Wiley-VCH, 2010, Weinheim. - 978-3-527-32711-9. - S., 41 – 60

Wannek, C; Nehr, S; Vahlenkamp, M; Mergel, J; Stolten, D; Pseudo-half-cell measurements on symmetrical catalyst-coated membranes and their relevance for optimizing DMFC anodes, Journal of Applied Electrochemistry, 2010, 40, 29-38

Adachi, M; Romero, T; Navessin, T; Xie, Z; Shi, Z; Mérida, W; Holdcroft, S; Water Permeation Through Catalyst-Coated Membrane, Electrochemical and Solid-State Letters, 2010, 13 (6) B51-B54

Kariuki, NN; Wang, XP; Mawdsley, JR; Ferrandon, MS; Niyogi, SG; Vaughey, JT; Myers, DJ; Colloidal Synthesis and Characterization of Carbon-Supported Pd-Cu Nanoparticle Oxygen Reduction Electrocatalysts, Chem. Mat. 2010, 22 (14): 4144-4152.

Reports (Level 2b)

- Status reports to Executive Committee, twice each year.

6.4 TASK 23: MOLTEN CARBONATE FUEL CELLS

6.4.1 Reports Published to Date

- Annual reports
- Book on International Status of MCFC – see http://www.ieafuelcell.com/documents/MCFC_international_status.pdf

6.1 TASK 24: SOLID OXIDE FUEL CELLS

This information is not collected in the Annex 24 level.

6.2 TASK 25: FUEL CELL SYSTEMS FOR STATIONARY APPLICATIONS

- Short report on fuels for fuel cells see http://www.ieafuelcell.com/documents/Adv_Fuel_Cells_Annex_XIX_Summary_rpt.pdf
- Minutes from Expert's meetings, Status Reports, two per year, and Annual Reports for Annex 25 and predecessor annexes.

6.5 TASK 26: FUEL CELL SYSTEMS FOR TRANSPORTATION

- No publications as Annex was dormant

6.6 TASK 27: PORTABLE FUEL CELLS

- Annual and status reports.

Appendix 7

TASK EXPERTS

This section lists the Operating Agents and the other experts who have participated in those tasks that were active during the year. Each organisation is categorised as government or government agency (G), research institution (R), industry (I) or academic (A).

7.1 TASK 22: POLYMER ELECTROLYTE FUEL CELLS

Expert	Organisation	Categorisation	Country
OPERATING AGENT: XIAOPING WANG, ARGONNE NATIONAL LABORATORY, USA (R)			
Viktor Hacker	Graz University of Technology	A	Austria
Gilbert Van Bogaert	Vito - Energy Technology	R	Belgium
Steven Holdcroft	Simon Fraser University	A	Canada
Brant Peppley	Royal Military College of Canada	A	Canada
Jorgen Lundsgaard	IRD Fuel Cells A/S	R	Denmark
Matti Valkiainen	VTT Processes	R	Finland
Jürgen Mergel	Forschungszentrum Juelich GmbH	R	Germany
Torsten Schwarz	ICT Fraunhofer	R	Germany
Marco Brocco	Italian National Agency for New Technologies, Energy and Environment (ENEA)	R	Italy
Tomohiko Ikeya	New Energy and Industrial Technology Development Organization NEDO	G	Japan
Ulises Cano-Castillo	Instituto de Electricas		Mexico
Gaby Janssen	ECN- Fuel Cell Technology	R	Netherlands
Børre Børresen	Norwegian University of Science and Technology (NTNU)	A	Norway
Lars Pettersson	Royal Institute of Technology, KTH	A	Sweden
Xiaoping Wang	Argonne National Laboratory	R	United States
Deborah Myers	Argonne National Laboratory	R	United States
Piotr Zelenay	Los Alamos National Laboratory	R	United States

R = research institution, A = academic institution, G = government

7.2 TASK 23: MOLTEN CARBONATE FUEL CELLS

Expert	Organisation	Categorisation	Country
OPERATING AGENT: TAE-HOON LIM, KIST, KOREA (R))			
M. M. Bischoff	MTU	I	Germany
A. Moreno	ENEA	G	Italy
B. Marcenaro	Ansaldo	I	Italy
Y. Izaki	CRIEPI	R	Japan
Y. Mugikura	CRIEPI	R	Japan
M. Yoshikawa	CRIEPI	R	Japan
M. Tooi	IHI	I	Japan
K. Tanimoto	AIST	R	Japan
T-H. Lim	KIST	R	Korea
J. Han	KIST	R	Korea
S-P. Yoon	KIST	R	Korea
H. C. Lim	KEPRI	R	Korea
J. H. Jun	RIST	I	Korea
H. Maru	FCE	I	USA
M. Farooque	FCE	I	USA
D. Connor	GenCell	I	USA

7.3 TASK 24: SOLID OXIDE FUEL CELLS

Expert	Organisation	Categorisation	Country
OPERATING AGENT: JARI KIVALHO, VTT, FINLAND (R)			
Brian Borglum	Versa Power Systems	R	Canada
Tony Petric	McMaster University	I	Canada
Erkko Fontell	Wartsila Corporation	I	Finland
Jari Kiviaho	VTT Processes	R	Finland
Laurent Antoni	CEA	R	France
Robert Steinberger-Wilckens	Forschungszentrum Jülich	R	Germany
Takashi Ujiie	NEDO	G	Japan
Harumi Yokokawa	AIST	I	Japan
Rak-Hyun Song	KIER	R	Korea
Bert Rietveld	Energie Onderzoekscentrum Nederland	R	Netherlands
Mohsen Assadi	Lund Institute of Technology		Sweden
Olivier Bucheli	HTceramix	R	Switzerland
Subhash Singhal	Pacific Northwest National Laboratory	R	USA

7.4 TASK 25: FUEL CELL SYSTEMS FOR STATIONARY APPLICATIONS

Expert	Organisation	Categorisation	Country
OPERATING AGENT: BENGT RIDELL. GRONTMIJ AB, SWEDEN			
Karl Föger	CFCL	I	Australia
Stéphane HHHody	GDF-Suez	I	France
Ulf Birnbaum	FZJ	R	Germany
John Bøgild Hansen	HTAS	I	Denmark
Per Balslev	Dantherm Power	I	Denmark
Adwin Martens	Waterstofnet	R	Belgium
Jari Kiviaho	VTT	G	Finland
Timo Kivisaari	Wärtsilä	I	Finland
Osamu Tajima	NEDO	G	Japan
Angelo Moreno	ENEA	G	Italy
Bengt Ridell	Grontmij	I	Sweden
Whitney Colella	PNNL	R	USA
Shailesh Vora	DOE	G	USA
Dan Rastler	EPRI	I	USA
Stephan Renz	Thoma & Renz	I	Switzerland
Günther Simader	E.V.A.	G	Austria
Julia Gsellmann	E.V.A.	G	Austria

7.5 TASK 26: FUEL CELL SYSTEMS FOR TRANSPORTATION

No information available

7.6 TASK 27: PORTABLE FUEL CELLS

Expert	Organisation	Categorisation	Country
OPERATING AGENT: MARTIN MÜLLER, JUELICH RESEARCH CENTRE, GERMANY			
Ed Andrukaitis Adamson	Def. Research and Development	-	Canada
Carsten Cremers	Fraunhofer Institut Chemische Technologien	-	Germany
Alexander Dyck	FWB	-	Germany
Viktor Hacker	Technische Universität Graz	-	Austria
Eva Fontes	Intertek Semko	-	Sweden
Sang-Kyung Kim	KIER	-	Korea
Yoshinori Miyazaki	AIST	-	Japan
Gerd Rabenstein	Technische Universität Graz	-	Austria
Andreas Schulze	Forschungszentrum Jülich	-	Germany
Gaetano Squadrito	ITAE	-	Italy

