Final report

Solide Oxide Fuel Cells towards Real Life Applications

EUDP Project J. No. 64009-0035

Period 01.07.2009-31.07.2010

Project responsible:
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Project partner:
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PROJEKT STØTTET AF:

EUDP

Summary (UK)

Solid Oxide Fuel Cells offer a clean and efficient way of producing electricity and heat from a wide selection of fuels. The project addressed three major challenges to be overcome by the technology to make commercialisation possible. (1) At the cell level, increased efficiency combined with production cost reduction has been achieved through an optimization of the manufacturing processes, b) by using alternative raw materials with a lower purchase price and c) by introducing a new generation of fuel cells with reduced loss and higher efficiency. (2) At the stack level, production cost reduction is reduced and manufacturing capacity is increased through an optimization of the stack production. (3) At the system level, development of integrated hotbox concepts for the market segments distributed generation (DG), micro combined heat and power (mCHP), and auxiliary power units (APU) have been developed. In the mCHP segment, two concepts have been developed and validated with regards to market requirements and scalability. In the APU-segment, different types of reformers have been tested and it has been proven that diesel can be reformed through appropriate reformers. Finally, operation experience and feedback has been gained by deployment of stacks in the test facility at the H.C. Ørsted Power Plant (HCV). This demonstration has been carried out in collaboration between TOFC and DONG Energy Power A/S (DONG), who has participated as a subcontractor to TOFC. The demonstration has given valuable knowledge and experience with design, start-up and operation of small power units connected to the grid and future development within especially the mCHP segment will benefit from this. In this report, the project results are described for each of the work packages in the project.

Resumé (DK)

Fastoxid brændselsceller giver mulighed for en både ren og effektiv produktion af elektricitet og varme med en meget bred vifte af forskellige brændselstyper. Dette projekt har adresseret tre af de største udfordringer frem mod en kommende kommercialisering af teknologien. (1) På brændsels-celleniveau er effektiviteten af cellen forøget samtidigt med at omkostningen ved fremstilling er nedbragt. Dette er sket a) ved at optimere fremstillingsprocesserne, så der er mindre spild og frafald, b) ved at benytte alternative og mindre rene råmaterialer og hjælpematerialer, der kan indkøbes til en lavere pris, c) ved at indføre en ny generation af brændselsceller, der har mindre tab og dermed giver en højere effektivitet. (2) På brændselscellestakniveau er omkostningen ved fremstilling nedbragt og produktionskapaciteten er forøget. Dette er sket ved effektivisering i stakproduktion hvorved overflødige og/eller meget omstændelige arbejdsrutiner er fjernet eller optimeret.

(3) På brændselscellesystemniveau er der udviklet koncepter for integrerede hotbox koncepter i markedssegmenterne mikro-kraftvarme (mCHP) og mobile hjælpekraftanlæg til tunge køretøjer (APU). I markedssegmentet mikro-kraftvarme (mCHP) er der udviklet to systemintegrations-koncepter og de er begge valideret i forhold til markedskrav og skalerbarhed med tilfredsstillende resultat. I markedssegmentet mikro-kraftvarme (APU) er forskellige typer af reformerings-løsninger afprøvet, og det er eftervist, at der er muligt at reformere diesel vha passende reformere, der kan indbygges i et delsystem. Et delsystem er derefter designet mhb at få en fremtidig udviklingsplatform. Endelig har der været arbejdet med et forsøgsanlæg på H.C. Ørstedsværket (HCV). Dette arbejde er gennemført som et samarbejde mellem TOFC og DONG Energy Power A/S (DONG) og har givet værdifuld erfaring med design, opstart og drift af små kraftanlæg koblet direkte til el-nettet, og fremtidigt udviklingsarbejde med produkter til især mikro-kraftvarme (mCHP) vil drage stor nytte af de opnåede erfaringer.

Abbreviations

Technical

APU:	Auxiliary power unit
ASR:	Area specific resistance
CGO:	Cerium gadolinium oxide
CPO:	Catalytic partial oxidation
DG	Distributed generation
EAP:	Electrical anode protection
HHC:	Higher hydro carbon
IC:	Interconnect
LPG:	Liquefied petroleum gas
LSCF:	Lathan strontium cobalt ferrit
LSM:	Lantan-strontium-manganat
mCHP:	Micro combined heat and power
MTC:	Multilayer tape casting
NiO:	Nickel Oxide
SAT:	Site acceptance test
SEM:	Scanning electron microscope
SOFC:	Solid oxide fuel cell
ULSD:	Ultra-low sulphur diesel
YSZ:	Yttria-stabilised zirconia

Organisations

DONG:	Dansk Olie og Naturgas
DTU:	Danmarks Tekniske Universitet
EUDP	Energiteknologisk Udviklings- og Demonstrationsprogram
HCV:	H.C. Ørstedsværket
PCI:	Precision Combustion Inc.
TOFC:	Topsoe Fuel Cell A/S

Introduction and project outline

The EUDP project 64009-0035 was a project with a duration of thirteen months from 01-July-2009 to 31-July-2010. The project was organised in three Work Packages (WP), which addressed the overall objective at three levels: the cell level, the stack level and the system level. As a part of the project documentation, a midterm progress report on milestones was submitted in January 2010, and quarterly status reports have been submitted after the end of the first and third quarter of the project.

Cell manufacturing (WP1)
Objectives for WP1 as stated in the original project description.
"*This work package covers cost reduction of cell manufacturing at TOFC's facility in Lyngby and increasing the efficiency of the cell. Efficiency of the cell is addressed in the so-called 2.5G work*[1]*, featuring e.g. Scandium in the electrolyte and improvements of the cathode formulation. The lower production cost will be achieved by larger scale production, development of more cost efficient production techniques and introduction of new, cheaper raw materials of lower grade. As part of the project, cell production capacity will be increased to 100 kW per month by the end of 2009."*

Stack manufacturing, test & demonstration (WP2)
Objectives for WP2 as stated in the original project description.
"As part of this work package, numerous stacks of various designs will be manufactured, the production time will be reduced and the yield increased.
Test run at the HCV unit will provide stack performance data, which will be used for evaluation of the alpha stack design and for development of computer tools for evaluation of system level data. A 10kW module, which will be developed in another project, will be demonstrated using the HCV unit and its performance compared to that of the alpha stack design. In addition, two new 20kW systems built by TOFC's strategic partner Wärtsilä will be taken into operation in 2009. Evaluation of performance data from these units will also provide feedback on the alpha stack design."

Integrated hotbox development (WP3)
Objectives for WP3 as stated in the original project description.

[1] 2.5G work refers to a further development of the cathode and electrolyte of the current ceramic supported cell design (2G). 3G refers to metal supported cells.

"Voice-of-the-customer analyses have shown that customers require an extended scope of supply covering an integrated hotbox (by TOFC referred to as PowerCore. Customers require systems, which are able to run on natural gas or diesel. This necessitates development of dedicated PowerCores. Based on work in the Danish m-CHP project and the EUDP project 63011-0029, a natural gas based PowerCore for CHP applications and a diesel based PowerCore for APU applications will be developed. An integral part of the PowerCore and a key component is the fuel reformer. In order to test and evaluate reformers and PowerCores, two test facilities will be acquired. These will also be used for development of computer models of the PowerCores making simulation of dynamic performance possible. This is required for modelling start-up, shut down and other transient operation."

Cell manufacturing (WP1)

The transfer of standard cells production has been finalized. The production of standard cells has been moved from Risø facilities to TOFC facilities in Lyngby, Denmark. The last standard cells were produced at Risø in September 2009. Up to September 2009 Risø was used as backup production due to quality issues at the TOFC facility. The TOFC facility in Lyngby is now fully operational with high quality cells and reproducible cell performance results.

One of TOFC's overall goal's is to reduce cell cost and in the project period, the cell cost has been reduced by more than 50% due to capacity scale-up, partial automation, reduction of cost of raw materials and general optimisation.

WP 1.1 Cell manufacturing

The overall goal is to reduce labour time consumption for each cell by 50% compared to February 2009. In the project period, the time consumption has been reduced by 64% for a standard 12x12 cell. The reduction of labour time consumption has been reached by "economies of scale", automation of the core processes, significant work with general optimisation, and the following specific activities:

- Production data is recorded on batch level instead of on cell level. This has provided a significant part of the 64% time consumption reduction for a standard 12x12 cell.
- Introduction of large scale batches in production. There is still an unused potential of cost reduction from increasing batch sizes more and this reduction will be achieved after the end of the project period.

WP1.2 Cost reduction

Reduced use of materials through recycling and thinner anode supports and use of lower grade materials have been investigated in the project period.

Reduced use of materials

To test and verify cells with recycled anode support, rejected tape was mixed into a standard anode support slurry. Slurries with up to 100 % rejected tape were successfully made and the resulting standard recipe is designed for 10 % recycled material. Cells were made for cell testing and stack testing. In the table below, performance of the cells with recycled material is compared to standard cells, and comparable performance is seen.

Cell type	OCV @800°C (V)	ASR @800°C (ohm*cm²)	ASR @750°C (ohm*cm²)	ASR @700°C (ohm*cm²)
Standard	1,08	0,511	0,509	0,721
10 % recycled material	1,08	0,521	0,542	0,777

Material consumption can be reduced if the support layer is made thinner, but the rejection of half cells can increase as the cells become more fragile and thus more difficult to handle. Two types of tapes were made, with the first having 90 % standard thickness and the second 80 % standard thickness. The rejection rates in cell production based on these supports were no different from standard cells. A series of thin cells were tested in a stack and the result is shown below. It is noticed that cells with a thinner support have the same performance as standard cells.

Cell type	OCV @800°C (V)	ASR @800°C (ohm*cm²)	ASR @750°C (ohm*cm²)	ASR @700°C (ohm*cm²)
Standard	1,08	0,511	0,509	0,721
Thin anode support	1,09	0,490	0,509	0,738

Alternative materials

In the previous work on fuel cells, attention has been given to stability, efficiency and success rate in manufacturing. To achieve this, manufacturing processes were based on high grade materials, but in order to reduce production costs, materials with lower grade or lower cost must be tested and for this purpose a procedure for validation of new raw materials is needed.

NiO, LSM and YSZ are responsible for approximately 90% of the raw material cost for cells and were selected as a primary targets for substitution. Alternative vendors for all three chemicals were contacted and samples of alternative raw materials were provided. The cost for these alternative chemicals are approximately 50% compared to the standard chemicals that are used in production.

NiO was provided with similar specification as the material used today. The presently used material in the anode support and the anode was substituted with the alternative NiO and cells were produced with all other materials and process conditions as standard cells. The cells were tested in a stack with 5 standard cells combined with 5 cells with the alternative NiO and the results are shown in the table below:

	OCV @ 750°C (V) - end	ASR @750°C, 20A (Ω*cm^2)
Standard NiO	1,117	0,657
New NiO	1,124	0,602

It is noticed that the cells with the new material have a slightly higher OCV, lower ASR and leak current, but the overall conclusion was that cells with the new NiO have a performance similar to standard cells and the new material was accepted for production.

LSM is used in the cathode and the cathode contact layer. Previously it has been shown that a commercially available LSM-powder can substitute TOFC's in-house manufactured LSM-powder in the contact layers and during this project it was proven that LSM for cathodes can be substituted as well. The new material has a lower specific surface area compared to the TOFC LSM and the calcination temperatures are therefore decreased in order to match the surface area. It was not possible to get a full match of the particle size distribution for the two materials, but the acceptance limits for the viscosity of the cathode spray could be met anyway. Cells with cathode with the alternative LSM were tested and accepted in the cell test unit at TOFC and the new LSM powder was therefore accepted for production.

YSZ is used in both the anode support, the anode, the electrolyte and the cathode and verification of an alternative material is thus far more difficult and far more time consuming. An alternative YSZ was provided and half cells with electrolyte from the new YSZ were made. It was verified that dense half cells can be made with this powder, as illustrated in the pictures.

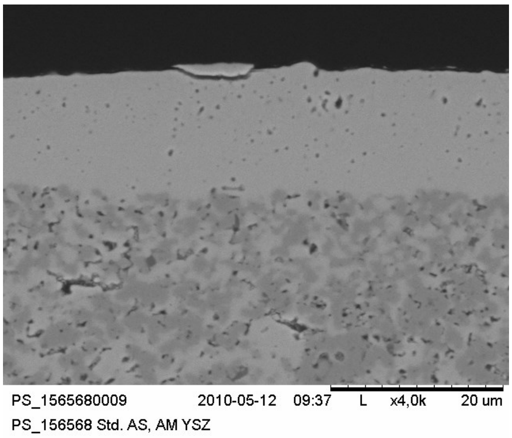

Figure: *Anode and electrolyte with 8 % YSZ from a new supplier in the standard recipe. Some cavities are seen in the electrolyte and this is likely due to the manufacturing process and not material-related.*

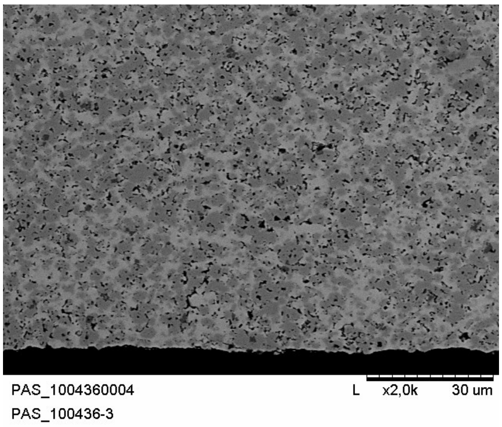

Figure: *Anode support with new 3% YSZ in the standard recipe*.

Half cells have been submitted to cathode and contact layers and will be electrically tested, and later a verification similar to what was used to approve the alternative NiO will be used, but these activates have not been completed at the end of the project and the milestone is therefore not fully completed with regards to YSZ.

Reduction of raw material expenses

This activity was based on a more efficient use of raw materials and a reduction in cost from larger scale of production. A reduction of 36 % was achieved.

WP 1.3 Cell Improvements

In addition to improvements in the production of the current standard 2G cells, challenges with coming cell generations have been addressed. Water-based slurries are preferred from work-health and environmental considerations and investigations of water based slurries were therefore included in the project. Also transfer of the production technology for 2.5 G cells from Risø to TOFC was included.

Water based slurries

A number of new challenges must be addressed when the solvent is substituted with water. Organic growth, pH regulation, foam and wetting are all problems which must be addressed when defining the process parameters for milling, casting and drying. An efficient dispergent and softener is necessary in the slurry and a commercial product was recommended for water based system and worked fine in this application. It was possible to mill the ceramic powder to the necessary particle size. A screening of a list of candidates was made and a combination of two commercially available products was selected for the further work. The screening was made by adding the candidates to a mixture of ceramic powder and water. The mix was filled in a casting mould in a thin layer and allowed to dry and the dried material was evaluated for drying cracks, foam and shrinkage. Also other dispergents showed the same positive effect. The chemicals proved to give a water based slurry with particle size, viscosity and solid load similar to the existing slurry for anode support and a recipe for water based slurries was formed. Based on this, a single piece of tape was made. The tape was casted on a piece of foil without degassing the slurry. After casting and drying, squares were cut and sintered using the standard sintering process from production. SEM pictures of two different sintered elements are shown below.

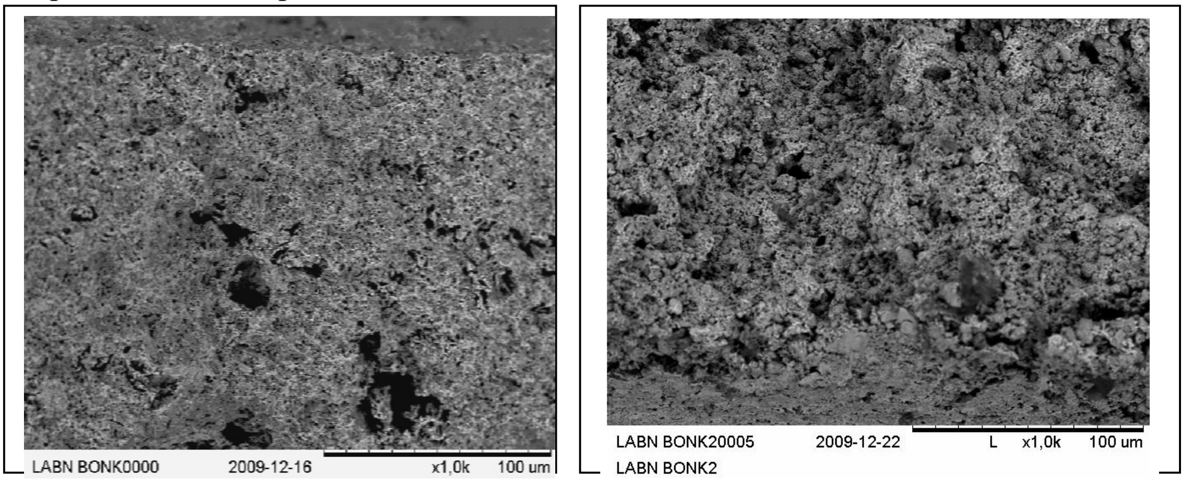

Figure: *Anode support from water based system.*

2.5 G cell technology produced at the TOFC production facility

2.5G cells consist of 2G half cells with screenprinted CGO barrier layer and LSCF/CGO cathode, where both the barrier layer and the cathode ink is produced with environmental friendly solvents and plasticizers. For optimal performance the barrier layer has to be thin, dense and uniform. A formulation with acceptable density and levelling was developed and this formulation was used for the first production runs. The barrier layer was produced in an attrition mill and one batch is sufficient for approximately 1000 cells.

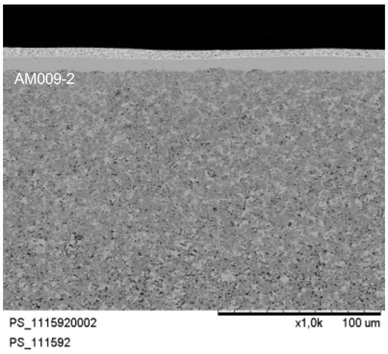

Figure: *SEM picture of barrier layer printed on a 2G half cell.*

Cells with approved barrier layers were printed with LSCF/CGO cathode. Production of these cathodes was very time consuming and during the project period it became clear that an improved production method for cathode ink processing was necessary.

Single cell test was performed on a production cell, showing much lower ASR than 2G cells and an ASR on the same level as 2.5G cells from the development phase.

Cell type	2G, screen printed cathode	2.5G, development	2.5G, production
ASR @750°C (ohm*cm²)	0,33	0,21	0,23

Stack test showed similar good results. Below is shown ASR for 2G and 2.5G cells.

Cell type	OCV (V)	ASR @800°C (ohm*cm²)	ASR @750°C (ohm*cm²)	ASR @700°C (ohm*cm²)	ASR @670°C (ohm*cm²)
Standard	1,08 @800°C	0,511		0,721	
2.5G	1,10 @750°C		0,440	0,515	0,609

Cells from the first production run shows a degradation rate of 20 mohm cm^2/1000 hr, which is lower than for 2G cells.

Stack manufacturing, test & demonstration (WP2)

The main objectives have been to improve stack production efficiency and capacity, to develop efficient evaluation tools and to evaluate stack performance in the Wärtsilä and HCV systems.

WP 2.1 Stack manufacturing

A number of proposals to cost reduction in stack manufacturing has been evaluated and after a period of further investigations, the list was reduced to ensure focus on activities with potential for cost reduction within a reasonable timeframe.

WP 2.2 HCV operation

The project of building and demonstrating a 10 kW natural gas based solid oxide fuel cell system at H.C. Ørstedsværket (HCV) successfully demonstrated the target of a 10 kW power output, but only for shorter periods. The reason was problems with system stability and was therefore more related to the system design than to solid oxide fuel cell technology. Despite the problems with the system, it was proven that the principal design of the unit is viable and the system has been operated for several hours at an electrical power output ranging from 2 to 4.3 kW AC and for shorter periods at 9.6-9.9 kW AC (pictures of AC output display show below) corresponding to 10.0-10.4 kW DC. This proves that SOFC technology can be used for power generation in industrial plants, and with a more mature system, longer periods can be achieved.

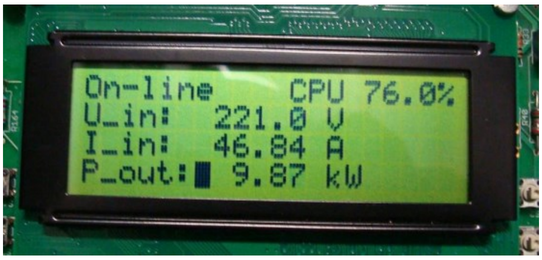

Figure: Display pictures from the HCV-unit showing 9.9 kW AC output.

The extended phase with troubleshooting and problem solving has given know-how and experience on SOFC-system design and operation, and this know-how is utilized in the PowerCore™ projects and has in general strengthened the PowerCore™ development, as some of the system problems have been of a more general nature and the solutions were therefore also generally applicable.

WP 2.3 Demonstration data evaluation tools

Tools for data analysis suited to the amount and type of data and to projects requirements has been developed and tested. The tools are mainly based on Haldor Topsøe A/S' proprietary process simulations software and a part of the tools were available in the form of subroutines to be implemented in the code used for simulating a process. Those tools where adapted to the SOFC systems by implementing them in the code describing the process of a natural gas based PowerCore™, and steady state experimental data recorded at TOFC premises with such a PowerCore™ were used to validate the technique. The result has been satisfying as inconsistent experimental data were recognized, which eventually helped in identifying heat losses and leaks.

A reformer evaluation tool has been developed, tested and used in several of the activities in this project. A reformer for any gaseous or liquid fuels (natural gas, LPG, logistic fuel, diesel, gasoline) is evaluated on the following factors, i.e., (i) efficiency which depends on reformer type which can be either steam reforming, auto thermal reforming or catalytic partial oxidation, (ii) size and volume per kW of electricity produced which depends on the reactor type which can be micro reactors with coated catalyst or tube reactors with pellet catalyst, (iii) start up time which depends on thermal mass, (iv) operation time between planned service i.e., regeneration of catalyst, change the batch of catalyst etc., (v) transient response, (vi) gas composition of the products, (vii) lifetime of the reformer, (viii) mobile or stationary focus and (ix) ability of sulphur handling. The ultimate requirement would be the composition of gaseous products where higher hydro carbon (HHC) concentration which constitutes total concentration of C2, C3…C7, should be less than 100 ppm. A value more than 100 ppm can deteriorate the performance of the stack significantly. An example of a reformer evaluation is shown below.

The table shows the gaseous products with HHC concentration less than 20 ppm for a 5 kWth feed for ULSD road diesel over a period of 6.5 hours. This fuel is an ideal feed for a solid oxide fuel cell stack with no propensity for carbon formation. The O/C ratio of reformed products is in the vicinity of 1.8-2.

Time (min)	H_2	N_2	CH_4	CO	CO_2	Ethane (ppm)	Ethylene (ppm)	Propane(ppm)	Propylene (ppm)
0	31.4	45.5	0.1	16.7	8.27	12.3	0	0	0
116	31.07	45.13	0.085	16.7	8.16	9.5	0	0	0
162	30.74	45.4	0.22	14.87	9.96	0	0	0	0
402	31.24	45.7	0.081	16.6	8.61	0	0	0	0

Also, a simple but effective tool allowing the evaluation of the stack performance was developed. The tool needs as input a few selected experimental data readily available both during tests at TOFC and customer/partners premises, and as output it delivers single stack (or stacks' group) fuel utilization and performance factors. The tool was optimized for analyzing data measured in the various Wärtsilä demonstrations. This partner is highly committed in providing the relevant data and thus a regular monitoring of the stacks' performance in the ongoing demonstrations is effectively done, resulting in a fast determination of the performance vs. time curve. Adaptation of the tool to other demonstration project is easily achievable.

WP 2.4 Evaluation of 20 kW Wärtsilä Systems

Two Wärtsilä 20 kW demonstration systems each with 24 Alpha stacks have been in operation within the given period. The Methapu system is based on methanol as fuel and is located on a vessel sailing between Europe, USA and Asia. The New Energy system is based on landfill gas from a location near Vaasa in Finland. Evaluating the system performance over time has proven important to understand which issues are related entirely to the overall mechanical design of the system, process regulation of the system, stack/system interface design and stack quality in order to improve the overall understanding of how to eliminate various failure modes and ensure that degradation is kept at a minimum for long term trouble free operation.

Integrated hotbox development (WP3)

The PowerCore™ is the central unit in a SOFC system integrating all the hot components in a design which ensures that high system efficiencies can be obtained. The PowerCore™ is a tight thermal and mechanical integration of functional components including the fuel processing equipment, heat exchangers, burners and the fuel cell stack. TOFC is pursuing two individual lines of PowerCore™ development

- Natural gas fuelled PowerCore™s for micro Combined Heat and Power (mCHP) systems
- Diesel fuelled PowerCore™s for Auxiliary Power Units (APUs)

WP 3.1 Natural Gas PowerCore™ Development

A competitive design concept which combines all the hot balance of plant components in a linear configuration has been developed. In this system it has been necessary to design tailored components due to the extent of mechanical integration.

The first PowerCore™ prototype was assembled in February and the basic functionality was tested in March.

The purpose of the first design was to investigate integration advantages in a linear design concept and as such the design was not optimized for a high electrical efficiency. Also, during testing, focus was on integration issues, so the optimum operational point for the electrical efficiency was not reached. The corresponding flowsheet gave a target electrical efficiency of 57%, which is low compared to state-of-the-art. The results from testing are summarized below. Most notably is the low electrical efficiency. The test was without anode recycling and the unit suffered from high leaks and this accounts for the difference between the calculated value (57%) and the measured value (41%).

- First test round completed (No Anode recycle, Natural gas combustion in burner)
- The temperatures in the pre-reformer showed an expected behaviour.
- The performance of the heat exchangers was as expected.
- The performance of the burner is as expected.
- Startup time from ambient: 2 hours

Voltage, [V]	62.5
Current, [A]	15
$Power_{DC}$, [W_{DC}]	937.5
NG flow, [Nl/min]	3.5
LHV NG, [J/s]	2287
$Efficiency_{DC}$, [%]	41
Fuel utilization, [%]	75
Reformate flow, [Nl/min]	12.07
T stack, [C]	750 - 792
T inlet reformer, [C]	460

Table 1. RALCore performance data.

The conceptual design work and system modelling efforts showed that a linear design concept scalable to 10kW would be far from optimum with regards to performance and cost. To address this and to mitigate risk, an alternative second mCHP integration concept based on a spherical integration concept was pursued. In the spherical integration concept, the hot components are kept in the centre and the cooler components are kept at the periphery. This gives an advantage on heat management and permits a simpler insulation. Also, this second concept is well suited for upscalling, as the fuel cell stacks and the components can be scaled according to the requirements to output power.

WP 3.2 Diesel APU PowerCore™ Development

The main goal of the diesel PowerCore™ activities is to develop a PowerCore™ with an electricity efficiency of 25-30% and which is able to start up independently of external heat sources and protection gasses. A flow sheet for such a PowerCore™ was developed and the calculations for this PowerCore™ gave an efficiency of 27% in good agreement with the target specification. Compared to an earlier diesel PowerCore™, this design has the following additional features:

- Anode recycle
- An additional catalytic heat exchanger-burner CatHex which is used to create warm protection gas from the reformed diesel during start-up
- A post reactor which can be used for de-sulphurization of the reformate and for increasing the system efficiency by catalytic conversion of some of the CO (+H_2O) in the reformate to CH4 (+ CO_2)

Catalytic Partial Oxidation CPO has previously been selected as the preferred diesel reforming technology, however suitable suppliers for such reformers still had to be qualified. In the beginning of 2010 reformers were tested from two suppliers. Both reformers could operate with sulphur rich fuels (up to 400 ppm) and this is considered important as it will allow systems to be deployed not only in EU and the US but also in third world countries where sulphur rich fuels are common.

The figure shows the stack performance over 24 hours when supplied with reformate from a CPO. The stack performance is stable even though the CPO emitted roughly 700 ppm of higher hydro carbons which potentially can create carbon formation problems. However, no carbon formation was detected during the test.

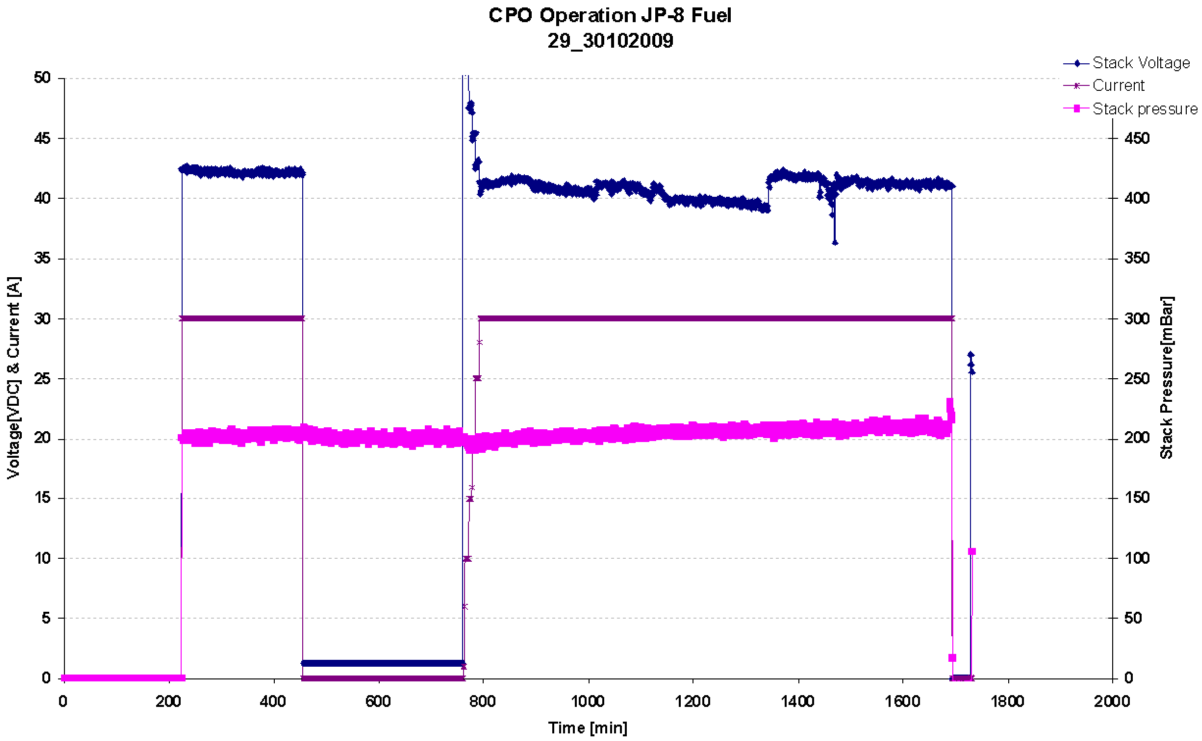

Figure: *Testing a CPO in a TOFC PowerCore™ with a heavy diesel type (JP-8) containing 280 ppm sulphur*

The other CPO was tested with a heavy diesel type (JP-8) with about 300 ppm sulphur. The performance was stable and the levels of critical higher hydrocarbons such as ethylene were well below 200 ppm for the entire test.

All in all it was found that both reformers are good candidates for a future PowerCore™ .

One of the key components in the diesel PowerCore™ is the catalytic heat exchange burner which is a TOFC designed component specifically developed for PowerCore™ applications. The following figure shows a measurement of the performance of this component when operating in the heat exchanger combustion mode, proving that the CatHex can provide the desired heating temperature and that combustion is possible without damaging the catalytic burner.

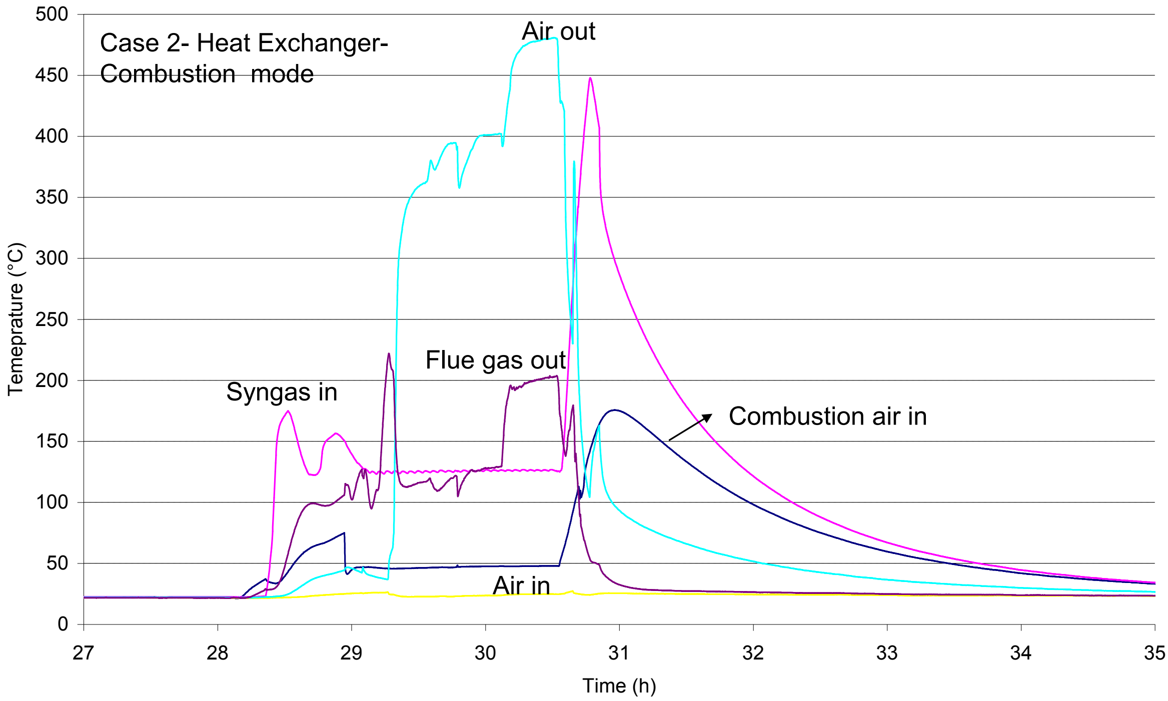

***Figure**: Example of catalytic burner heat exchanger operating in combustion mode. Diesel reformate starts to combust at 29.2 hours and a sudden increase in the temperature of air (out) to 350 °C is seen. The CatHex air (in) flow rates were then adjusted to get the flue gas temperature to about 200 °C. At this temperature of flue gas outlet, the air (out) was 460 °C.*

The mechanical design of the PowerCore™ is shown in the following figure. Rather than making a very compact PowerCore™, it was chosen to mount the components in a fairly large frame which would allow space for component replacements and for a large amount of temperature and pressure probes. This would allow this PowerCore™ to serve as a development platform for optimising performance and selecting components and thereby leading to a more mature next generation PowerCore™ which could then be designed mechanically compact.

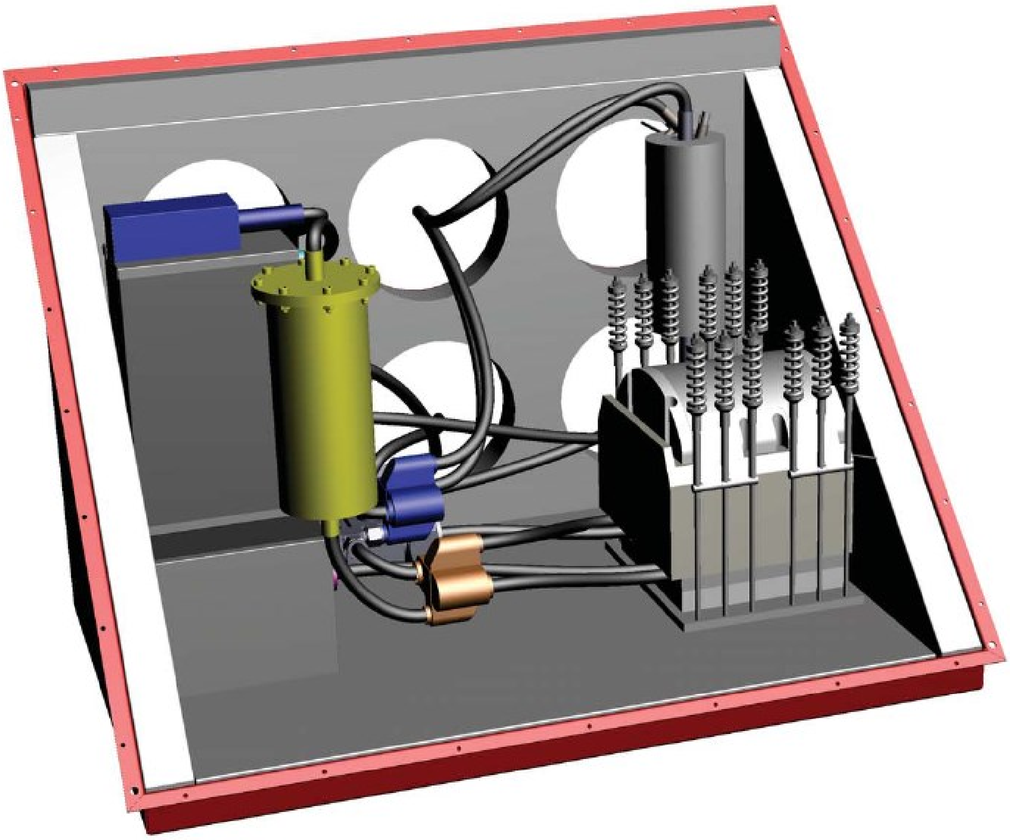

Figure: *The mechanical design of the diesel PowerCore™. The stack is seen to the right with compression springs, the CPO is the cylinder to the left and the two CatHex are placed in the left corner.*

WP 3.3 Test facilities

In the project plan, two large test facilities were planned. The first test facility was a fuel processing test facility, and this was specified and commissioned according to plan. The test facility was installed at TOFC in November 2009 and Site Acceptance Test, SAT, was conducted and approved in December 2009. The unit was brought into operation in the first quarter of 2010.

Figure: *The fuel processing test facility after successful installation at TOFC.*

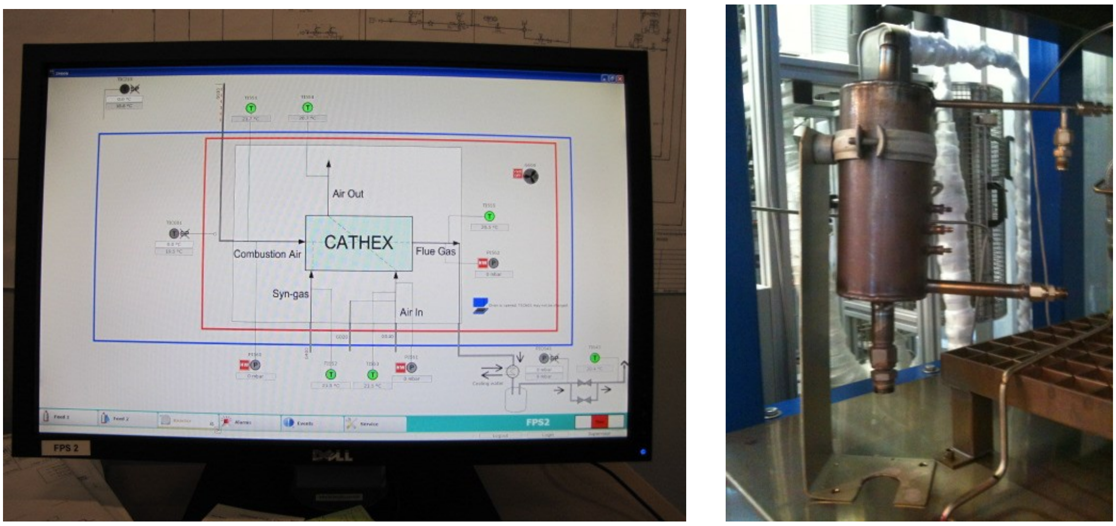

Figure: *Components(CatHex and CPO) installed and tested in the fuel processing test facility.*

The second intended test facility was a PowerCore™ test facility for power ranges up to 20 kW. This facility has been postponed for approximately a year and the current plan is to have the unit commissioned beginning of 2011. The delay has not had any impact on progress in the PowerCore™ development since the existing test capacity at Topsoe Fuel Cell has been sufficient for the planned tasks.

WP 3.4 Development of dynamic models for fuel cell systems

Dynamic subsystem models are important tools in the development of fuel cell systems and their operation algorithms for start-up, load change and shut down.

Modelling work to develop and verify subsystem models which could be used to represent the HCV test unit has resulted in a library of generally useable sub-models for modelling heat integration in fuel cell systems. These sub-models can be used in dynamic flow sheet models representing fuel cell systems in order to account for heat exchange between system components by means of conduction, radiation and convection. The model library also comprises a model of a PowerCore™. This model can exchange heat with all system components individually by means of both convection and radiation. When using the sub-models in a given situation, the subsystem models, e.g. pre-reformer, pipes, burners etc., must be modified in order to allow for heat loss (or heat gain) due to interaction with surrounding equipment.

At the end of the project period, the subsystem models have been developed to the extent that they can be used in development of subsystems in the integrated PowerCore™ units and it has been verified that they can indeed be used for dynamic predictions. As an example, a dynamic model of a plate heat exchanger has been used in order to set up a model that can predict a stack heat-up sequence. Experimental data was used to fit the heat transfer coefficients of the model. The model structure, as represented in the software used (gPROMS) and the resulting prediction compared to measured data is shown in the following figures.

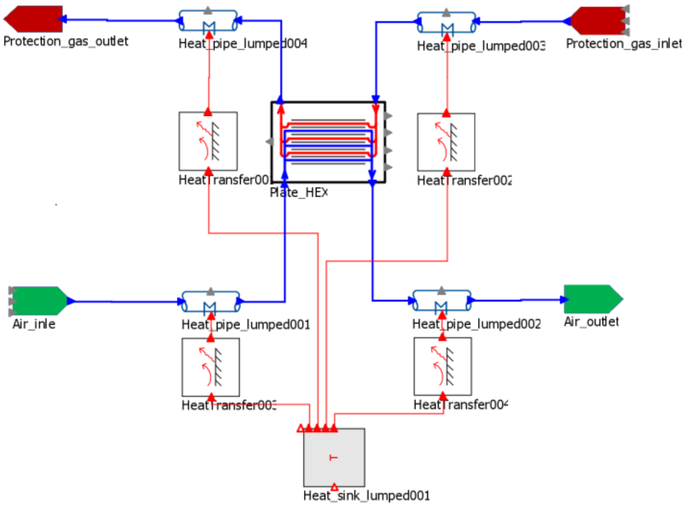

Figure: *gPROMS model of stack heat-up.*

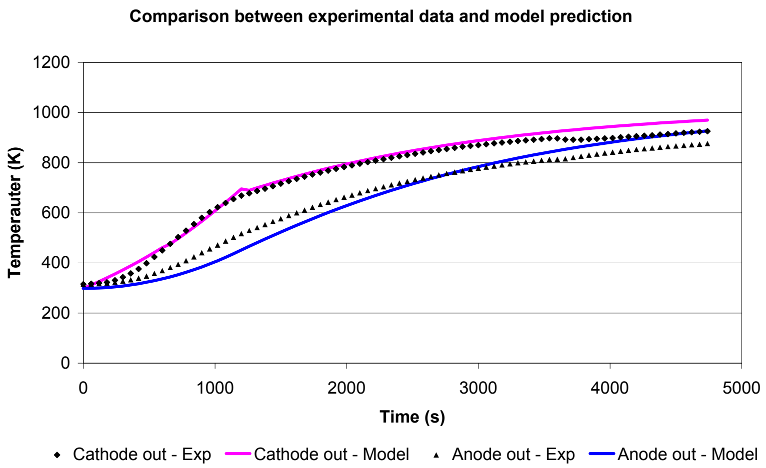

Figure: *Model prediction compared to experimental results.*