TOPSOE FUEL CELL

Final Report

Manufacturing of cells and stacks for SOFC development, test and demonstration projects and SOFC hotbox design development, phase 2

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Lotte Gottschalck Egeberg
Peter Koch Larsen
Magnus W. Larsson
Morten Lüthje
Uffe Rahbek

Project responsible:

Topsoe Fuel Cell A/S
Nymøllevej 66
2800 Lyngby

CVR No. 28308523

Project partners:

Risø DTU
DONG Energy

Summary (UK)

This project is one of the core projects in the implementation of the Danish national SOFC strategy. The project, which was performed in a co-operation between Topsoe Fuel Cell (TOFC) and Risø DTU and DONG energy, encompassed three important subjects for the implementation of the long term goals in the SOFC road map: 1) Optimization of fuel cell production; 2) Development of stack production and 3) Integration of stacks into systems.

A number of cells were manufactured during the project period. The cell production contributed to increased production experience, and at the same time the produced cells were used in stacks for development purposes and in stacks for test and demonstration purposes together with TOFC partners. The project milestones on cost reduction in cell production were met. A number of achievements have contributed to the cost reductions. A more efficient stacking of half cells in the sintering furnace has been developed to reduce the power consumption for production. Screen printing of contact layers has been developed to reduce the waste of raw materials compared to the traditional spraying technique. Also machines with more automation has been built and set up for production to minimize man power in production.

The project milestones on bringing two new and more efficient stack designs into standard stack production were met. Also a series of stacks were manufactured for test and demonstration purposes in the project.

A first batch of stacks was installed at the SOFC test unit on the H.C. Ørsted Power Plant (H.C. Ørstedsværket or HCV) and the first electrical power was delivered to the Danish grid in March 2009 using natural gas as a fuel. The system was tested and debugged using the first batch of stacks. Later in May 2009 a second batch of improved stacks were mounted. The system has been characterized and procedures for starting, running and closing the system have been specified. Tackling the difficulties resulted in the gain of valuable experience and know-how. Particularly, Topsoe Fuel Cell greatly widened its expertise in the details of system design and process control, deepened the know how on its core technologies, and increased the knowledge on fuel cell system technologies outside the TOFC core area and on how the surroundings will affect a fuel cell system. This broader knowledge is at present accelerating the development in TOFC particularly within PowerCore (hotbox) development and in joint development with system integrators such as Wärtsilä.

The project activities on PowerCore development was focused on a design suitable for running on diesel. All project milestones on the design and testing of a diesel PowerCore were met. The electrochemical state has been simulated and the PowerCore has been build from these calculations. The single components have been tested and the PowerCore has run successfully. The complete system has been tested at TOFC and has delivered power.

Resumé (DK)

Projektet er en del af den danske nationale SOFC-strategi. Projektet er udført som et samarbejde mellem Topsoe Fuel Cell (TOFC) og Risø, DTU, og der er blevet arbejdet med følgende tre vigtige mål indenfor SOFC road map: 1) Optimering af brændselscelleproduktion; 2) Udvikling af stakproduktion; 3) Integration af stakke i anlæg.

Der er produceret en mængde brændselsceller i forbindelse med projektet. Dette har bidraget til en bedre forståelse af brændselscelle-produktionen, og samtidig er de producerede celler anvendt i stakke til udvikling, test og demonstration i samarbejde med TOFC partnere. Der er lagt et stort arbejde i at udvikle metoder til at fremstille cellerne billigere og med mindre materialespild. I den forbindelse er der indført en metode til at fylde sintringsovnen mere, således at der spares elektricitet i produktionen. Desuden er der indført silketryksteknik til kontaktlagene og derved spares en del råvarer i forhold til den traditionelle sprayteknik. Endelig er nye og mere automatiserede maskiner taget i brug i forbindelse med nybygningen af pilotfaciliteterne i Ravnholm. Milepælen vedrørende reduktion af omkostningerne ved cellefremstilling blev opfyldt.

Før projektets start var der kun et stakdesign i produktionen. Udviklingen indenfor stakproduktion har været koncentreret om at indføre nye og mere effektive design af stakke. To nye design er blevet indarbejdet som rutineproduktion i projektperioden, og dermed er milepælen opfyldt indenfor dette område. Desuden er der samlet en række stakke, der er anvendt til forsøg med drift af systemer.

Et batch af alfa-stakke er blevet installeret i den 10 kW SOFC test stand, der står på H.C. Ørstedsværket (HCV). Den første strøm fra anlægget blev leveret til det danske el-net i marts 2009 med naturgas som brændsel. Senere blev et nyt batch stakke installeret, og systemet blev karakteriseret. Flere forhindringer måtte løses undervejs, og det store arbejde har båret frugt, ved at TOFC har fået stor viden om systemdesign og proceskontrol. Denne viden har udvidet TOFCs indsigt på områder, der ellers har ligget udenfor TOFC kernekompetencer. Disse erfaringer bliver benyttet til at drive andre udviklingsprojekter endnu hurtigere frem, f.eks. i arbejdet med PowerCore (hotbox) og i samarbejdet med systemintegratorer.

Et fuel cell system (PowerCore) med diesel som brændstof er også udviklet i projektperioden. Arbejdet har omfattet et koncept-design af diesel hotboxen (PowerCore), hvor den elektrokemiske drift er simuleret. Ud fra dette arbejde er PowerCoren blevet bygget, og delkomponenterne er prøvet af. Tre forskellige slags dieselolie er blevet testet i reformeren. PowerCoren har kørt vellykket, og der er leveret strøm fra opstillingen. Alle milepæle i denne del af projekt blev opfyldt.

1 Introduction

1.1 Project objectives

The aim of the project was to develop cell production, stack manufacturing and solve technical challenges on integrated systems. The efforts on improving production in cost and quality required the possibility of making a larger number of cells.

The work on the test facility at HC Ørstedsværket (HCV) was continued in this project. The aim was to demonstrate a suitable start-up procedure and a characterization of the unit.

For hotbox design development, the aim was to design, construct and test a PowerCore designed for diesel, and to come up with recommendations for further work.

The project work was structured around three work packages:

- WP1 Cell manufacturing
- WP2 Stack manufacturing, test & demo (including the system test at HC Ørstedsværket)
- WP3 Hotbox design development (with focus on a diesel PowerCore)

1.2 Project history

This project was originally applied for in the EFP programme in September 2007. Due to the change from the EFP programme to the EUDP programme, it was decided that phase 1 of the project was funded by the EFP programme (EFP 2007 33033-0235), and a new application should be made for phase 2 to the EUDP programme. The application for phase 2 was sent to the EUDP programme in April 2008 and ended with the present project, which started in September 2008 (EUDP 2008 63011-0029).

The present project builds upon the results of the phase 1 project. Table 1 gives an overview of the objectives and activities in the two projects.

WP	Description	Phase 1 (EFP 2007 33033-0235)	Phase 2 (EUDP 2008 63011-0029) (present project)
1.1	Cell manufacturing technology optimisation	Mature screen printing of contact layers	Debottle-necking towards 2.000 units/mon
1.2	Production of cells	produce 3.000 units	produce 9.000 units
2.1	Stack test unit		Obtain & Install teststand
2.2	Stack Manufacturing	produce 25kW of stacks	produce 75kW of stacks
3.1	HCV operation		operation of system established
3.2	Methanol Hotbox design development	concept design, construction and test	
3.3	Diesel Hotbox design development		concept design & preparation for test

Table 1: Overview of the project and use of results from earlier project EFP 2007 33033-0235

2 WP 1 Cell manufacturing

Both the amount of cells and stacks produced has grown, as well as equipment and facilities for these activities have improved. Stack assembly, burn-in and test have left the laboratory and entered a pre-pilot scale level at Ravnholm. A large part of these activities have enjoyed funding from various projects under PSO, EFP as well as the EC-Life programme.

2.1 Production of cells and stacks

From September 3rd 2008 to June 30th 2009 EUDP 63011-0029 has been funding part of the production. Manufacturing statistics is shown in the table below.

Period	Stacks (in kW)
Sept 2008	27
Oct 2008 – Dec 2008	21
Jan 2009 – March 2009	49
Apr 2009 – June 2009	53

Table 1: EUDP 63011-0029 supported production.

The first milestone in WP1 was manufacturing of 2.500 cell equivalents before end of October. The production reached 3.344 equivalents and the milestone was reached.

Second milestone was production of further 6.000 equivalents before end of March. 1.000 equivalents should be made with a cost reduction on 25 %. In the period from November till end of March was made 9.129 cell equivalents but less than 6.000 of these were used directly for EUDP purposes. Even though the production capacity was present we were not able to make enough cells to store cells for EUDP. The purpose on meeting the capacity and getting familiar to manufactory of fuel cells in larger amount was, however, meet.

2.2 Sintering cycle and number of half cells in a furnace

Half cell sintering is a long and relatively costly process. The green bodies are stacked individually on ceramic plates and placed in a furnace. This furnace slowly heats up the green elements to burn off binder and other organics and later to actual sintering the half cells. Then half cells are cooled down slowly to avoid thermal stress. The furnace is heated by electricity. Therefore was a study on faster sintering cycle and more cells in the furnace was initiated.

2.2.1 Sintering cycle time

The sintering cycle is based on a thorough studies made on Risø in the start of the fuel cell project. Many other parameters and procedures have been altered since the sintering profile was made and it was therefore not certain that the existing profile still is optimal and a revision of the profile was initiated.

Three different profiles were tested.

A fast profile was made by keeping the original temperatures and doubling the heating rates. This profile is 25 % faster than the original standard profile.

A "new standard" profile was made by keeping the heating rates as they were and stop the binder burn off at a lower temperature

Experiments with fast heating resulted in significantly more broken cell after sintering. Therefore the fast sintering profile was not a possible new procedure in the production.

The profile called "new standard" ends the relatively slow binder burn of at a lower. Experiments with this profile showed no differences in rejection rates at this stage. Therefore was this lower temperature for binder burn off made a new standard in production and approximately 7 % was saved on the. It has not been possible to precisely determine the amount of energy saved in this process but it is estimated to be some 50 kWh.

2.2.2 Load in furnace

Other savings in energy could be made if more half cells are placed in the furnace in each batch.

Traditionally is a sandwich of a half cell placed in between two Repton plates put on a SiC plate. Then another layer with a new SiC plate and a sandwich is made and put on the stack.

An alternative set up was made were one or two other sandwich was placed directly on top of the cell as shown in the Figure.

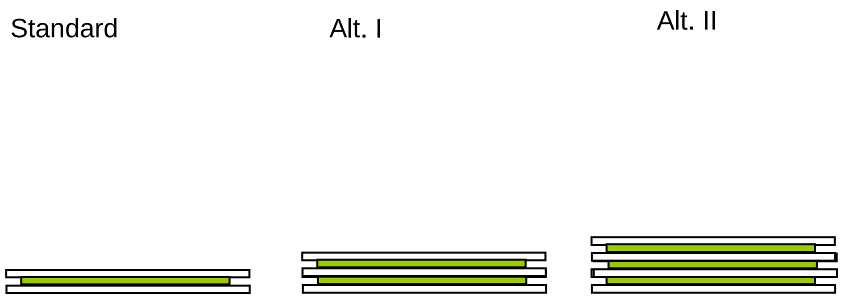

Figure 1: Drawing of alternative furnace filling.

The standard setup and the two alternatives were sintered using the standard sintering profile and the cells were visually inspected and the leak rate of the electrolyte was measured. Some 16 samples using the two alternatives were made.

The results showed that the cells using Alternative I were all acceptable were as the alternative II had a tendency to give broken or deform cells for these placed in the bottom with the larger mass on.

The conclusion was that alternative I could be used along with the standard sintering.

2.3 More efficient production methods

An important task in this project was to optimize the production procedures in order to reduce the cost. This was achieved by using the new production facilities in Ravnholm were the production equipment is better and the layout of the shop is designed only for production of fuel cell and not as the case on Risø were existing facilities had to be adjusted to the production.

The cell manufacturing in Ravnholm was slightly delayed so measures on the cost reduction were also postponed. Costs have been divided into costs used for manpower, materials and external services respectably. Manpower cost was reduced by 32 % in the first quarter of 2009. The milestone on this project was a 25 % reduction on the manpower which was reached with 32 %.

2.4 Screen printing

In order to reduce the use of raw materials was screen printing applied to the contact layers. Traditionally are the contact layers sprayed on and it is necessary to spray wider than the cells to get an even layer of slurry on the cells. This overspray is waste material and can comprise as much as 50 % of the slurry. With screen printing is the waste much lower because the slurry/paste only is applied on the cells where it should be located.

The task of making a screen printed, useful contact layer is, however, not simple. A paste with the correct electrochemical properties and right microstructure in the stack after birth should be made. At the same time the paste most be printable and should preferably not contain hazardous solvents nor phthatalates. When the pasta has been formulated right then is the printer adjusted to give the right thickness of the layer and the automatic handling of the cells should be so gentle that the do not break during the printing process.

During 2008 new printing pasta formulations were developed. Contact layer pastas free of phthalate and terpineol were successfully produced and tested. Cathode pasta was also made with success but so far it has not been possible to find a formulation without phthalate.

Manufacturing of the screen printing pasta is made routinely by the operators in the pilot.

Both rheology and printing method of the pastas have been modified to reduce cracks on the printed anode contact layer during firing of the fuel cell stacks. Studies have been carried out to elucidate the nature of these cracks in the printed layers. It was showed that the particle size and the thickness of the anode contact layer were strongly confounded with these cracks and adhesion problems.

We have improved the reproducibility of the printed layer thickness compared to the sprayed layers. We are able to reproduce print thickness to within approximately ±1 µm

The number of cells that breaks during the printing is approximately 5 % .

3 WP 2 Stack manufacturing

3.1 Stack test unit

A milestone on specifying, ordering and test a new stack test unit was not meet.

The existing stack test unit at TOFC has been used for stack testing and a new test unit was not necessary to reach the goals in the project. The existing unit has been troublesome to use as a production equipment and questions on the relevance of more equipment from the same vendor has been raised. Therefore it has not been possible to make a decision on which equipment should be purchased. A new stack test unit has, however, been specified and contacts to different vendors of test equipment have been made.

3.2 Stack production

The production of stacks has been scaled up in the project period. The first two milestones in this part were to manufacture 25 kW accepted stacks and introduce one new design in the production line.

In Q3 of 2008 was 27 kW standard stacks manufactured. The milestone was reached.

The new design was the Generation 2 stack with a 2.5 kW effect. One advantage of this design is a more compact design because the stack not is 2.5 times larger or heavier than the 1 kW alpha stack.

In Q4 were produced 21 kW stacks and further one more new design called 6H was introduced in production. The 6H is also a compact 1 kW stack. Production routines for the 6H stacks have been established during the project.

Table 1 shows the production of stacks in the project.

The next three milestones in the project were that 1) at least 25 % of the produced stack should be larger than 2.5 kW, 2) an additional stack design introduced in production and 3) a production of 50 kW stacks.

In Q1 2009 more than 80 % of the produced stacks were made with 2.5 kW capacity. This means that the first of the three milestones was reached.

6H stack and Generation 2 have been produced in project, and the second milestone with one new design in 2008 and one new design in 2009 was reached.

In Q2 was the overall production larger than 50 kW and also the third milestone was reached.

4 WP 2.3 HCV operation

4.1 Introduction

The project was initiated by Topsoe Fuel Cell A/S in 2006 with the objective to build and evaluate a 10 kW demonstration unit based on solid oxide fuel cell (SOFC) technology at the power plant H.C. Ørstedværket (HCV) in Copenhagen. The aim of the project is to demonstrate the feasibility of small to medium sized combined heat and power (CHP) units based on the SOFC technology. CHP plays an important part in the distributed generation (DG) sector and can yield considerable savings of primary energy.

The system is the first complete fuel cell system designed by Topsoe Fuel Cell A/S (TOFC), including a complete fuel processing line and all other auxiliary equipment required in order to make a SOFC-system work in practise. Operation of the test unit results in a lot of valuable practical experience regarding SOFC system operation and control. Moreover, it provides experimental data for validation of system models. Once the unit is fully operational it will act as a test platform for new hotbox and stack designs.

4.2 Project history

The original plan was to design and construct a 10 kW natural gas based SOFC stack test facility at DONG Energy's (at that time ENERGI E2) power plant at Kyndby. The location was later changed to H. C. Ørsted-værket for practical reasons. The kick off meeting took place in April 2006 and a number of project meetings were held over the next months. The partners were TOFC, E2 and Dantherm. In November 2006, Dantherm had come to the conclusion that the project was too complex for their competencies and resources and with-drew from the consortium.

TOFC informed energinet.dk and DONG Energy about this unfortunate development, which inevitably lead to delays in the project as the next work packages concerning instrumentation, detailed mechanical design, procurement and fabrication were the responsibility of Dantherm. Instead, TOFC collaborated with the Tech-nology Division of Haldor Topsøe A/S to establish and complete a basic engineering package. The package included:

- Battery Limit Definition
- Process Flow Diagrams
- P&I Diagrams
- Process Specifications
- Equipment Specifications

TOFC initiated the selection of an alternative supplier of these work packages by requesting offers based on the finalised basic engineering package from pre-qualified vendors. In March 2007, a contract was signed with EBZ, Dresden, as a sub-supplier for the test unit. After several meetings the detailed project design was agreed upon in collaboration between TOFC, EBZ and DONG Energy and the unit was constructed at EBZ's premises except for the inverter, which was delivered by Wärtsilä.

TOFC and EBZ hired KIWA Gastec to assist in the safety concept evaluation and CE marking process. To-gether with DONG Energy a pre assessment was carried out and it was concluded that the unit will be able to meet the requirements for CE approval without any problems (CE test report signed 12 February 2008).

The demonstration unit was installed at H.C. Ørstedværket in December 2007, see Figure . At this point the system contained no actual fuel cell stacks. The so-called "hotbox", i.e. the compartment which contains the fuel cell stacks, contained only "dummy stacks", such that the system functionality could be verified without risk of damaging the expensive fuel cell stacks.

Figure 2: The 10 kW SOFC demonstration unit in place at H.C. Ørstedværket.

4.3 Project progress

During the year following the unit installation at H.C. Ørstedværket, the functionality and the dynamic behaviour of the main system components have been thoroughly tested and the personnel operating the unit were extensively trained (cf. *EFP 2007 – Final report*). However, during these tests the system was equipped with "dummy stacks", which did not allow a complete test of the system, but only of selected parts. In December 2008, the first hotbox containing real stacks was implemented to the unit, and within the project period from December 2008 to June 2009 extensive testing of the entire unit was performed. The work, carried out by Topsoe Fuel Cell A/S in close collaboration with EBZ and Wärtsilä, led to a few modifications of the system hardware itself and especially to a continuous development of the control system and of the graphical user interface, and not least to the removal of quite a few software bugs. Moreover, the TOFC personnel familiarized it self also with the components that previously could not be tested (like the prereformer, the hotbox, and the inverter) and gained valuable knowledge of the chemical process and of the thermal behaviour of the entire system.

The following subsections include the progress of the project, descriptions of the start-ups with first batch and improved stacks, and some delaying factors and challenges, which caused a part of the milestones to not be achieved yet.

4.4 Milestones and project status

4.4.1 Successes

Below some of the main of successes are listed:

- Numerous hardware and software problems solved and basic system functionality and controllability achieved.
- Catalyst reduction procedures successfully performed.
- Optimized start-up procedure using protection gas developed

- Inverter problem solved
- Power produced to the grid
- Fast unit restart after a trip (the same operation point at 10 A was reached again in only 15 minutes after trip)
- Installation of second batch of improved stacks
- A new burner is manufactured and installed only 1½ week after the burner meltdown
- The TOFC know-how on SOFC system design and operation is significantly strengthened and the level of competency of TOFC personnel employed in 2007 and 2008 regarding SOFC system design and operation has increased very significantly.

4.4.2 Delaying factors

As discussed in section 3 the project has suffered a number of significant delaying factors. These can be summarized as follows:

- Numerous design corrections, software bug fixes and hardware changes were dealt with from October 2008 until February 2009 before the site acceptance test could be completed and the first start-up with real stacks could take place in March 2009.
- During the first real start-up an unexpected erroneous inverter behaviour damaged some of the first batch stacks. The necessary electronic hardware corrections were completed in May 2009.
- A burner meltdown in June caused a further delay. More severely however, the replacement burner did not support the developed start-up procedures.

Despite the fact that TOFC have put in significantly increased resources in the project to deal with these factors, together they result in a status where major milestones have not been met within the time frame of this project.

4.4.3 System functionality

System functionality verified:	Status	Comment
o System controllability and control strategies tested (complete system)	OK	
o Thermal balance characterized and thermal losses measured	Partially completed	Will be completed with improved stacks
o System efficiencies (El. & total) with first batch stacks characterized	Cancelled	Replaced by similar milestone with improved stacks
o Start-up procedure with steam generation optimized	OK	
o System dynamics and operation at partial load characterized	Partially completed	Will be completed with improved stacks

System controllability and control strategies tested (complete system)

The system controllability has been widely verified under both steady state and transient conditions. A large number of software bugs have been eliminated. Different control strategies and control parameters were tested for the main components of the unit, and those warranting smooth operation of the system as a whole were finally adopted. Despite no longer run has been so far performed, there are indications that, once in steady state, the unit can be run in a fully automatic fashion without continuous personnel presence. Operator supervision will instead be necessary during start-up and during transition from two different steady state conditions (e.g. part and full load operation). Major external disturbances that cannot be handled by the control system will result in an emergency trip of the unit. However, also the trip diagram has been thoroughly investigated and constantly improved in order to warrant no damage of any component of the unit and especially no hazard for the operators.

Thermal balance characterized and thermal losses measured

The characterization of the thermal balance of the unit is still not finalized. However, some of the components have been extensively tested, and a deep knowledge of their thermal management is acquired. Particularly, the behaviour of heat exchangers E1 and E4, regulating the temperature at the inlet of the desulphurizer and of the prereformer, is well understood. Their correct thermal balance implies the choice of the proper gas flow at the system inlet (for E1) and the proper recycle flow (for E4), together with a correct burner operation (optimized by regulating both fuel and air flow entering and bypassing the burner).

A quantitative determination of the thermal losses has not been performed yet. However, a critical analysis of the unit has been done identifying the major sources of heat losses. In some cases, actions were taken in order to minimize such losses, for example by improving the insulation of tubing and components. Heat “wasted” with the vented gasses can instead be reduced by optimized burner operation, which is strictly connected the E1 and E4 thermal balance previously discussed.

System efficiencies (El. & total) with first batch stacks characterized

The characterization of the electrical efficiency with the first batch stack was interrupted. In fact, during the first start-up two stacks were damaged, and in order to proceed the set of stacks (four in total) containing the damaged stacks was disconnected from the unit. It was decided to use the remaining eight stacks only to show the possibility of producing electrical power with the unit, but not to plan an extended test for characterizing the efficiency, as with only eight stacks the design figures could not be reached. The objective behind this milestone will be met by meeting the milestones relating to the improved stacks below.

Start-up procedure with steam generation optimized

By wrapping up results and experience gained over extensive system testing and knowledge deriving from system modelling, a start-up procedure has been developed. The procedure also covers the use of an external steam generator for providing steam to the system during the start-up phase and reports detailed information on how switching the steam generator off and tuning the fuel utilization and recycle flow to achieve the correct steam to carbon ratio at stack inlet. The start-up procedure also contains the conditions (look-up tables for flow, temperatures, current, etc.) that have to be established to achieve steady state part or full load operations.

System dynamics and operation at partial load characterized

As already mentioned, no extensive testing has been performed with the first batch of stacks due to the damage of some stacks. However, the characterization of the system dynamics at part load operation was initiated. Particularly, valuable knowledge on the prereformer-stack-recycle loop behaviour was already gained: The temperatures in the prereformer catalytic bed could be effectively tuned by slight changes in the recycle flow and in the current withdraw.

Moreover, it was observed that the burner runs in a much smoother way with anode off gasses rather than external natural gas, dramatically reducing the majority of the instabilities and oscillations observed during the start-up phase, and thus eliminating many potential trip causes.

4.4.4 Performance with improved stacks

Performance with improved stacks verified:	**Status**	**Comment**
o Installation of second batch of improved stacks	OK	
o System efficiencies (El. & total) characterized in a 50-100% load range	Started by 30.06.2009	Expected to be completed during August-September 2009
o Achieve stack electrical efficiency of 60% (dc) at 10kW DC output	Not achieved by 30.06.2009	Expected to be achieved during August-September 2009
o Performance stability and degradation test initiated with 500h of stable operation at 10kW DC output.	Not achieved by 30.06.2009	Expected to be completed during September 2009
o Report with conclusions on system controllability and dynamics, efficiencies with second batch stacks and preliminary results on performance stability and degradation.	This Report	The remaining results relating to the milestones above will be reported as part of the reporting under the new EUDP 2009-I project in which the HCV efforts are continued.

Installation of second batch of improved stacks

The second batch of improved stacks was successfully installed to the unit. Knowledge acquired during the first hotbox replacement, resulted in a faster and smoother installation, thus reducing the down time.

System efficiencies (EL & total) characterized in a 50-100% load range

The characterization of the system efficiencies with the batch of improved stacks was initiated, and will be completed during August-September 2009.

Achieve stack electrical efficiency of 60% (DC) at 10kW DC output

A stack electrical efficiency of 60% has not been achieved yet. However, the stacks voltage observed at open circuit with the second batch stacks is a clear indication of a very good stack performance, thus rendering the target of 60% efficiency reachable in the near future.

Performance stability and degradation test initiated with 500h of stable operation at 10kW DC output

Degradation tests were not initiated yet. However, once the 10 kW DC stable output will be established and demonstrated, the optimized automatic control strategy is expected to allow performing such tests.

Report with conclusions on system controllability and dynamics, efficiencies with second batch stacks and preliminary results on performance stability and degradation

The present document is already part of that report. However, when the milestone at present only partly achieved will be completed, the results will be included in the reporting of the subsequent EUDP 2009-I project.

4.4.5 General Progress

The innovative nature and the high technological level of this project unavoidably gave rise to different problems and difficulties as mentioned above. The problems which relates to technologies outside the fuel cell stack obviously delayed the HCV SOFC activity. On the other side, tackling the difficulties resulted in the gain of valuable experience and know-how. Particularly, Topsoe Fuel Cell greatly widened its expertise in the details of system design and process control, deepened the know how on its core technologies, and increased the knowledge on fuel cell system technologies outside the TOFC core area and on how the surroundings will affect a fuel cell system. This broader knowledge is at present accelerating the development in TOFC particularly within PowerCore development and in joint development with system integrators such as Wärtsilä.

5 WP3 Hotbox design development (diesel PowerCore)

5.1 Introduction

The experience gained so far with regards to the interface between stack and the system has shown that - with a few exceptions - the system integrators do not have sufficient experience in dealing with the high temperatures of SOFC stacks. This has led TOFC to conclude that it is essential to start more extensive work on a hotbox design development, referred to as a “PowerCore”. The package includes the hot stack surroundings such as load frame, reformer, cathode side heat exchanger and off-gas burner.

WP3 focuses primarily on hotbox designs for liquid fuel (diesel), which is relevant for APU. At the initiation of the project, it was planned to have two development tracks, such that both methanol and diesel PowerCores would be developed. Market research has shown that the market desires that APUs should operate on diesel. The availability of a diesel hotbox will represent a very important progress for APU applications. It was thus determined to put the activities in WP 3.1.1 on hold, and focus on executing WP 3.1.2.

5.2 WP 3.1.2 Concept design for diesel hotbox

The concept design phase has encompassed process development and system development, which includes the following work packages:

1. Process conceptual design
2. Simulation and modelling
3. Process Risk Analysis
4. Process Operating Procedures

5.2.1 Process conceptual design

The process conceptual design was initiated by setting up a specification for a representative APU: A specific application was identified together with a major player in the APU field, based on the following considerations:

- Large market share - needs to be defended by the partner company.
- On-board water source - could be available for the APU, if the technology would require fresh water.
- Low cost-sensitivity – is necessary as cost will initially be higher than state-of-the art diesel APUs.
- Ultra-low Sulphur diesel operation – because a readily available fuel is required by the end customer.

The basic system lay-out was already designed and demonstrated in the Methanol project during 2007 and 2008. Using this lay-out, a generic Diesel system was generated, in order to start a survey of Diesel fuel reformer technology providers.

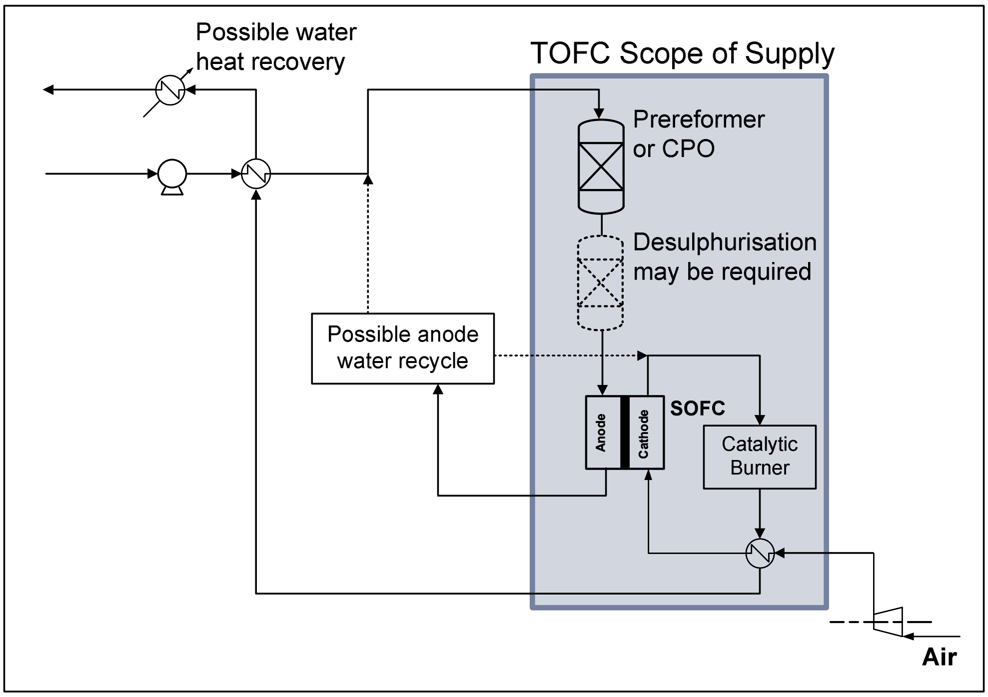

Figure 3: Generic system lay-out

5.2.2 Full System Simulation and Modelling

The most critical component of the new system is the fuel reformer, which is a unit that must be carefully specified as the fuel composition out of the reformer is determining the operating performance of the system (e.g. net. efficiency, start-up time) and the feasibility of operating the system in a stable manner (e.g. avoiding soot formation in the anode line or on the anode side of the stack.

The in-house modelling tool simulates mass and heat balance in a chemical processing system, by considering thermodynamic equilibrium after each unit process (fuel reforming, combustion), as well as simulating the reactions in the SOFC stack. The latter simulations are based on a mathematical model of the TOFC stack, which is calibrated using data obtained in actual stack-level performance tests.

It is concluded that the most critical aspects of the design are:

1. Establish the appropriate conditions of the fluids and gases supplied to the fuel reformer
2. Design the anode supply line between the fuel reformer and the stack such that Boudouard reaction carbon formation is avoided.
3. Investigate which water quantity is needed for stable operation
4. Evaluate the level of higher hydrocarbons that the stack can tolerate
5. Evaluate the quality of desulphurisation needed.

The system model was set up in TOFC's simulation system in order to simulate a base configuration, as described in the generic configuration shown in figure 5, which was used for further conceptual evaluation.

The approach taken in this project was to evaluate the operating conditions of the fuel processor, while keeping the remainder of the system constant in order to identify the trade-off between the technical challenge of the fuel reformer, and the stack operating point. The stack operating point determines the required configuration of the stack, the number of cells required, and thus the basic cost of the system.

It should be noted that the analysis was performed, using the performance of currently available stack technology.

The analysis showed that a number of CPO based system configurations show promising performance, and that >31% system electrical efficiency is expected to be possible with the current stack generation. Thus the absolute value for system electrical efficiency is expected to increase over time, as lower pressure-drop stack, and lower ASR (area specific resistance) technology is incorporated into the design.

The most important realisation of the conceptual study was that pure steam reforming of diesel, i.e. that diesel is reformed using anode recycle gas or water only, potentially gives a very efficient system and/or a significantly smaller stack than a system, which includes an element of partial oxidation.

Our survey has uncovered only very few development activities and no available technology for diesel steam reforming, so a strategy of operating with pure steam reforming is not possible at present.

However, TOFC is pursuing, under the remainder of this project, a parallel development of steam reforming technology, in the hope that the high electrical efficiencies and/or small stack sizes can be realized.

5.2.2.1 Partial System Simulation and Modelling

Given the identification of the critical system components described in the beginning of the previous section, and that available fuel reformers are CPO-based, it was decided that the demonstrator should be capable of using multiple fuel reformers, and be reconfigurable, such that multiple desulphurisation strategies can be evaluated.

The configuration of the base case was then used to design the process lay-out of the demonstration unit. The demonstration unit contains three compartments; one for fuel reformer, one for intermediate reactors, and one for the stack/manifold/compression system. Each compartment is individually temperature-controlled, such that investigations relevant to the upcoming integration efforts can be performed.

The lay-out is shown in figure 4.

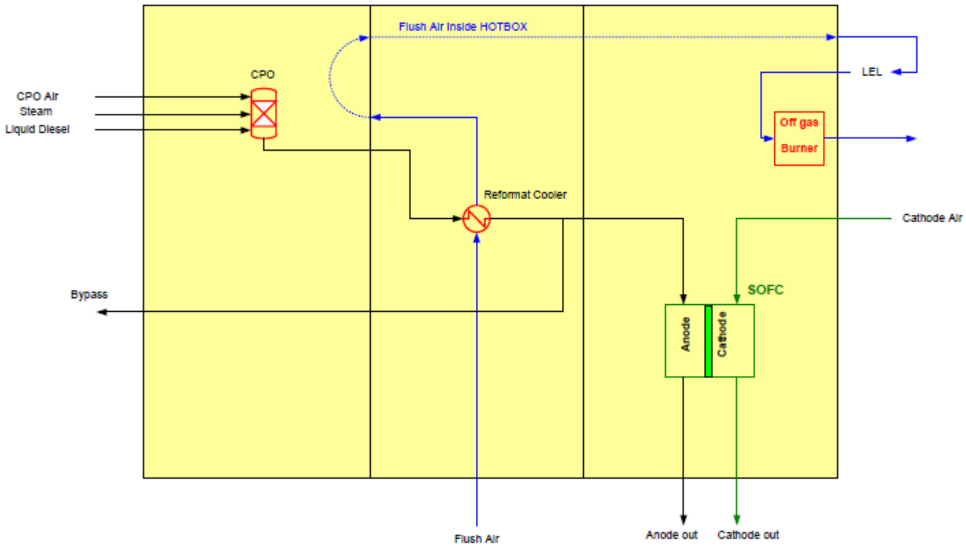

Figure 4: Initial process lay-out of the demonstration unit.

5.2.2.2 Fuel reformer development

TOFC has worked with a partner company on a concurrent engineering effort, where the fuel reformer design could be adopted to meet TOFC's specification, as the system development progressed.

It was identified at an early stage that "real-world" fuels would be needed to insure that the results obtained in this project are applicable for later demonstration unit development.

Thus, three fuels were purchased;

1. Danish diesel fuel – corresponding to the spec which is in effect in most of Europe.
2. Swedish diesel fuel – with < 5% aromatic content, and <10 ppm Sulphurs representing a "best case" fuel.
3. Two samples of U.S. Ultra-low Sulphur (ULSD) diesel were procured in Houston, Texas, U.S.A. One sample was out of spec in terms of Sulphur content (34 ppm S). Both had approx. 38% Aromatic content.

All three fuels were tested in the fuel reformer

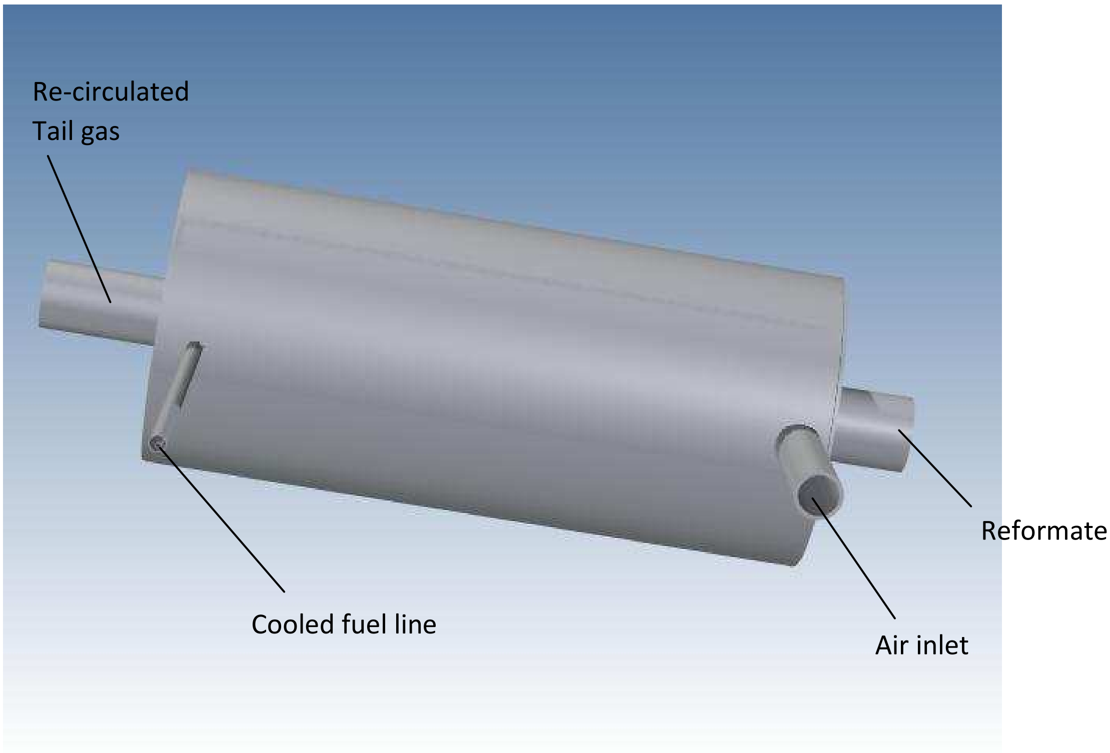

Figure 5: Initial fuel reformer

The fuel reformer gave unsaturated hydrocarbon emissions, which were satisfactory with Danish and Swedish fuels. Emissions were deemed too high when operating on U.S. spec fuels, as the level of unsaturated compounds could theoretically produce carbon deposition in the anode line.

It was thus decided that an internal redesign of the fuel reformer was needed in order to ensure stable long-term operation.

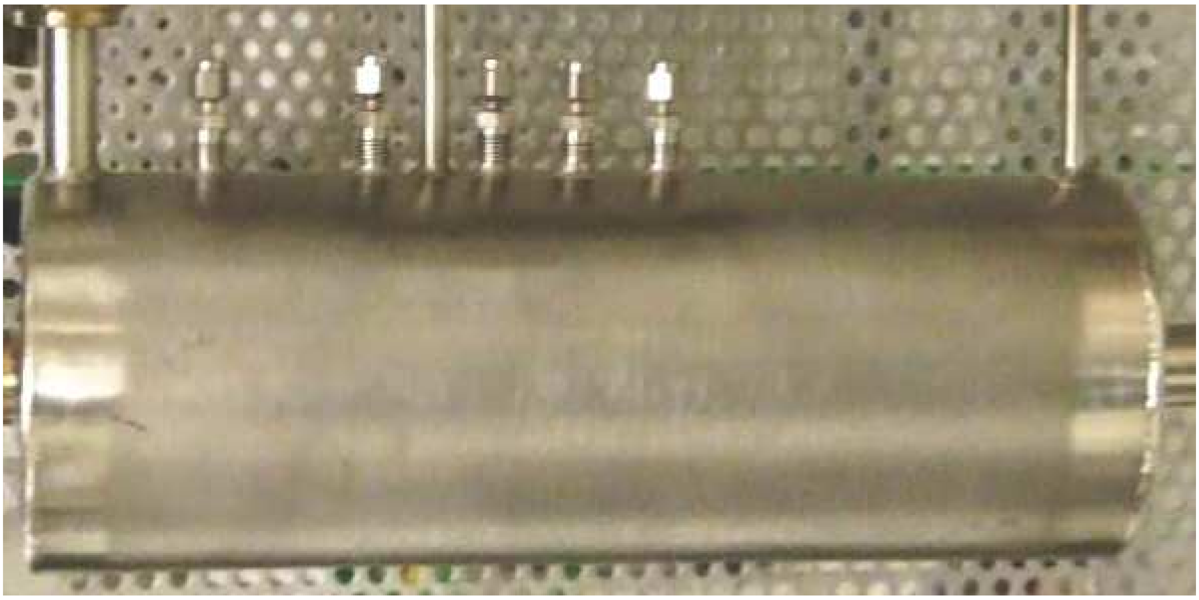

Figure 6: Second fuel reformer

The redesign was successful, as the hydrocarbon emissions were at a level, which is seen as uncritical. Comparison of the first and second fuel reformers is shown in figure 7.

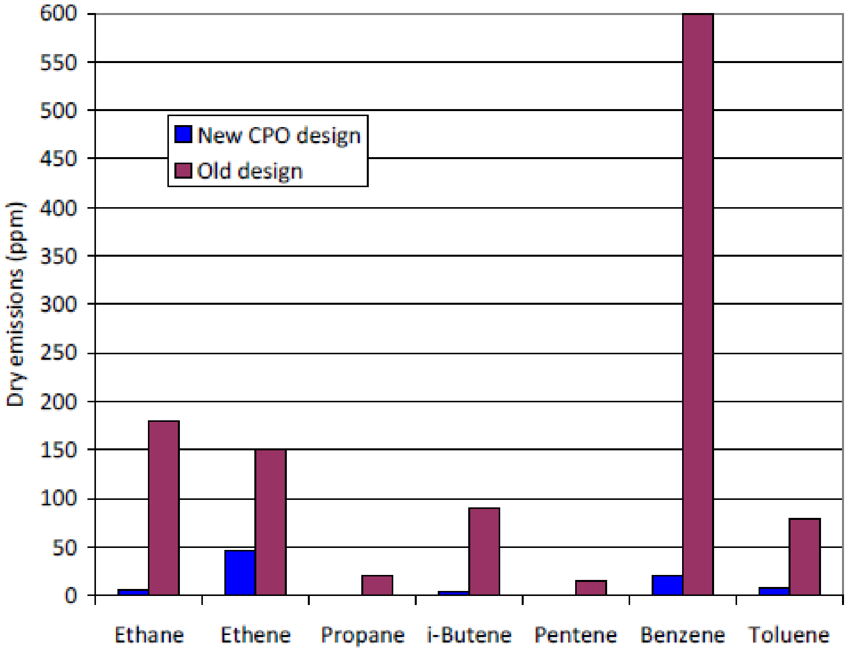

Figure 7: Performance comparison of the two fuel reformers, operating on U.S. diesel

5.2.3 Process Operating Procedures

The operating procedures were developed on the basis of the fuel reformer development experience, the process simulations and the risk analysis.

This work package has been documented as a start-up/operation/shut-down procedure, which in turn has been translated into process states and alarm handling procedures.
Based on the finalised flow sheet simulations, the adaption of the TOFC-Command Centre has commenced.

The technical implementation is done in the TOFC Command Centre, a flexible simplified control system, which has been developed specifically for PowerCore testing.

The Command Centre was adapted to be capable of utilising the transducer signals, and control the test bench according to start-up, operation, shut-down, and emergency stop procedures.

5.2.4 Mechanical design and development

The test unit was designed such that it would be able to support the process conditions described previously. Thus, for instance, minimising heat losses from the test unit were given a lower priority than ensuring exact temperatures in the process.

Each of the three compartments is electrically heated, and contains provision for temperature and pressure sensing, and possibility for taking gas samples at key process points.

The final 3D CAD design is shown in figure 10.

Figure 8: 3D design of test unit

5.2.5 Construction of test unit

All hardware was ordered and delivered by early January. Stacks were manufactured and pre-tested in a separate test stand. The diesel fuel reformer was developed in parallel with the test unit as described previously.

5.3 Diesel hotbox available for testing

A number of modifications were required to the test stand in order to support the desired process conditions. The quality of the test unit was also ensured by performing leak tests and testing that the heaters were capable of establishing the correct process conditions.

Of course, many minor issues were handled during this phase, but no major design issues were found.

All qualification testing was done using a dummy stack such that any system failures would have minimal cost impact.

Figure 9: Test unit being mounted in test stand

5.3.1 Initial operation

Upon completion of the acceptance test, a first operation of the system was done on 5 June 2009.
A total of 5 A current was drawn, which at a stack voltage of 50.5 V corresponds to approx. 250 W.

5.4 Next development steps

Towards the end of the project period, it was found that the diesel inlet line was excessively heated by nearby components, and it was decided that a slight redesign of that section of the unit must be done before further system performance testing should be performed. Once this change has been completed, the next steps are as follows:

- Demonstrating long term operation on the three types of Diesel as such.
- Evaluation of the effect on the stack by having no desulphurisation, by operating for a significant amount of time at steady-state conditions.
- Practical evaluation of the Sulphur-isotherm published by John B. Hansen of Haldor Topsøe A/S.