



Project no. 019739

# LARGE-SOFC

## Towards a Large SOFC Power Plant

*Instrument: Integrated Project*  
*Thematic Priority: 6.1 Sustainable Energy Systems*

### **Publishable Final Activity Report**

*Authors:* Rolf Rosenberg, Jari Kiviaho, Jaakko Saarinen, Matias Halinen, Markus Rautanen, Anja Oasmaa, Päivi Aakko-Saksa – VTT  
Kim Eklund, Jukka Göös, Peik Jansson – Wärtsilä  
Peter Dixon, John Vedy – RRFCS  
Joachim Jacobsen – TOFC  
Ludger Blum, Robert Steinberger-Wilckens – FZJ  
Aristide Massardo, Renzo Di Felice, Loredana Magistri, Adriana del Borghi, Carlo Strazza – UNIGE  
Yves De Vos, Jean-Paul Janssens – Bosal  
Stephan Jegust, Moritz Von Witzleben – Inmatec  
Olli Kämäri – The Switch

*Period covered:* from 1.1.2007 to 31.12.2009  
*Start date of project:* 1.1.2007

*Date of preparation:* 24 May 2010  
*Duration:* 36 months

*Project coordinator:*  
Mr. Rolf ROSENBERG  
VTT Technical Research Centre of Finland

Revision 2

## Preface

The proposal for the Large-SOFC project was originally prepared during October–December 2004 and submitted to the Commission on 8<sup>th</sup> December 2004. The hearing of the project was on 17<sup>th</sup> of February 2005. The coordinator was contacted in July 2006 by the Commission offering a strongly reduced grant. The prerequisite was that the contract could be signed during that autumn. Taking into account that the offered grant was about half of the originally requested one, and the long delay, during which some of the proposed task had been performed, several changes to the original proposal had to be done. The number of participants was reduced and a part of the work re-planned. Even so, the contract was signed on 28<sup>th</sup> November 2006 and the project started on 1<sup>st</sup> January 2007. The project duration was three years ending 31<sup>st</sup> December 2009. The report was finalised in the end of March 2010. The total budget was 11 M€ including the Commission grant 5.8 M€

The participants are indicated in the Table below.

| Participant                              | Participant short name | Country |
|--|------------------------|---------|
| VTT Technical Research Centre of Finland | VTT                    | FI      |
| Wärtsilä Finland <sup>*)</sup>           | Wärtsilä               | FI      |
| Rolls-Royce Fuel Cell Systems Ltd        | RRFCS                  | UK      |
| Topsoe Fuel Cell A/S                     | TOFC                   | DK      |
| Forschungszentrum Jülich GmbH            | FZJ                    | DE      |
| University of Genoa                      | UNIGE                  | IT      |
| BOSAL RESEARCH nv                        | Bosal                  | BE      |
| The Switch <sup>**)</sup>                | Switch                 | FI      |
| Inmatec Technologies GmbH                | Inmatec                | DE      |

<sup>\*)</sup> Former Wärtsilä Corporation

<sup>\*\*)</sup> Former Verteco Oy

### *Coordinator contact information:*

VTT Technical Research Centre of Finland

Rolf Rosenberg, Chief Research Scientist

Tel. +358 20 722 6342

E-mail: rolf.rosenberg@vtt.fi



*European Commission 6<sup>th</sup> Framework Programme*

*Project no. 019739*

*Towards a Large SOFC Power Plant*

*Abbreviation: LARGE-SOFC*

*www.largesofc.com*

# Contents

|  |    |
|--|----|
| Preface  |    |
| List of symbols  | 2  |
| 1 Executive summary  | 6  |
| 1.1 Introduction   | 6  |
| 1.2 Work performed and results                                   | 7  |
| 1.2.1 System analysis, component modelling and validation        | 7  |
| 1.2.2 System concept and integration                             | 7  |
| 1.2.3 Components and sub-systems                                 | 11 |
| 1.2.4 Industrial stack   | 14 |
| 1.2.5 Verification of system concepts and sub-systems            | 15 |
| 1.2.6 Fuel quality, gas cleaning and reforming                   | 17 |
| 1.2.7 Grid connection, safety and standards, life-cycle analysis | 17 |
| 1.2.8 Training, dissemination and public activities              | 18 |
| 1.3 Discussion   | 18 |
| 1.3.1 Status of achievements                                     | 18 |
| 1.3.2 Intentions for use and impact                              | 22 |
| 1.3.3 Final remarks  | 24 |
| 2 Background   | 25 |
| 3 Objectives and structure                                       | 28 |
| 4 System analysis, component modelling and validation (WP1)      | 39 |
| 4.1 System analysis  | 39 |
| 4.2 Component models for dynamic simulation                      | 43 |
| 4.3 System Component Validation                                  | 46 |
| 4.4 Dynamic component and system simulation                      | 47 |
| 5 System concepts and integration (WP2)                          | 52 |
| 5.1 Atmospheric system   | 52 |
| 5.2 Pressurized system   | 58 |
| 6 Components and sub-systems (WP3)                               | 67 |
| 6.1 Turbomachinery and Gas and Air recirculation                 | 67 |
| 6.1.1 Blower testing   | 67 |
| 6.1.2 Blower development   | 67 |
| 6.1.3 GT-SOFC emulator   | 69 |
| 6.2 Heat exchangers and recuperators suitable for fuel cell use  | 78 |
| 6.2.1 Pressurised SOFC system                                    | 78 |
| 6.2.2 Combined heat and power (CHP)                              | 81 |
| 6.2.3 Heat exchanger testing                                     | 82 |
| 6.2.4 Steels for heat exchangers                                 | 87 |

|       |  |     |
|-------|--|-----|
| 6.3   | Fuel Processing Equipment  | 99  |
| 6.3.1 | Reforming and anode recycle  | 99  |
| 6.4   | Power electronics and controls   | 102 |
| 6.4.1 | Control system for pressurised operation                                     | 102 |
| 6.4.2 | Power electronics for atmospheric SOFC system                                | 105 |
| 6.5   | Insulation   | 106 |
| 6.5.1 | Insulation for pressurised system  | 106 |
| 6.5.2 | Insulation for 50 kW unit  | 108 |
| 7     | Industrial stack (WP4)   | 109 |
| 7.1   | 50 kW planar SOFC stack assembly   | 109 |
| 7.2   | Potential options for stack ceramic material                                 | 113 |
| 8     | Verification of system concepts and sub-systems (WP5)                        | 118 |
| 8.1   | Verification of atmospheric SOFC systems                                     | 118 |
| 8.1.1 | Concept verification unit site planning and preparation                      | 118 |
| 8.1.2 | Concept verification unit procurement and construction                       | 118 |
| 8.1.3 | Concept verification unit installation and verification                      | 118 |
| 8.2   | Review of current test equipment and capability for pressurised SOFC hybrid  | 119 |
| 8.3   | Component testing of 50 kW atmospheric SOFC unit                             | 122 |
| 9     | Fuel flexibility (WP6)   | 126 |
| 9.1   | Potential biofuels for SOFC  | 126 |
| 9.2   | Gas impurities – tolerance of SOFC   | 131 |
| 9.3   | Gas cleaning for SOFC  | 135 |
| 9.4   | Costs of biofuels  | 137 |
| 10    | Grid connection, safety and LCA  | 139 |
| 10.1  | Grid connection  | 139 |
| 10.2  | Safety and standards   | 140 |
| 10.3  | Life-cycle analysis  | 140 |
| 11    | Training, dissemination and public activities (WP7)                          | 144 |
| 11.1  | Technology workshops   | 144 |
| 11.2  | Summer schools   | 144 |
| 11.3  | Exhibitions in industrial and education context / Interaction with the press | 145 |
| 12    | Acknowledgments  | 146 |

APPENDIX 1: Publications of Large-SOFC project

## List of symbols

|                 |                                      |
|-----------------|--------------------------------------|
| BoP             | Balance of Plant                     |
| C               | compressor                           |
| CC              | Combustion Chamber                   |
| CHP             | Combined heat and power              |
| EX              | Heat EXchanger                       |
| GC              | Grid-Connected                       |
| GT              | Gas Turbine                          |
| HS              | Hybrid System                        |
| IP              | Internet Protocol                    |
| MCFC            | Molten carbonate fuel cells          |
| mGT             | Micro Gas Turbine                    |
| MMA             | Magnesia stabilised Magnesia Alumina |
| NO <sub>x</sub> | Nitrogen oxides                      |
| PAFC            | Phosphoric Acid Fuel Cells           |
| PEMFC           | Proton exchange membrane fuel cells  |
| REC             | Recuperator                          |
| RRFCS           | Rolls-Royce Fuel Cell Systems        |
| SOFC            | Solid Oxide Fuel Cell                |
| SO <sub>x</sub> | Sulphur oxides                       |
| THD             | Total harmonic distortion            |
| THT             | Tetrahydrothiophene                  |
| TPG             | Thermochemical Power Group           |
| T               | Turbine                              |
| UPS             | Uninterruptible Power Supply         |
| WHEx            | Water Heat Exchanger                 |

### *Variables*

|         |                                  |
|---------|----------------------------------|
| CIT     | Compressor Inlet Temperature [K] |
| F       | Recirculation ratio              |
| N       | Rotational speed [rpm]           |
| p       | Pressure [Pa]                    |
| ROT.SP. | Rotational speed (sensor) [rpm]  |
| T       | Temperature [K]                  |
| TIT     | Turbine Inlet Temperature [K]    |
| TOT     | Turbine Outlet Temperature [K]   |

### *Greek symbols*

|               |                           |
|---------------|---------------------------|
| $\beta$       | Pressure ratio            |
| $\varepsilon$ | Recuperator effectiveness |

### *Subscripts*

|   |           |
|---|-----------|
| 0 | On design |
|---|-----------|

# 1 Executive summary

## 1.1 Introduction

The main task of the Large-SOFC project has been the development and verification of concepts, components and sub-systems for SOFC power plants with a potential for hundreds of kW to several MW. Thus the aim of the project was to address the basic problems when moving from kW to MW size SOFC power plants. The focus will be on technologies with long term potential for:

- Unit output hundreds kW to several MW
- Cost below 1000 €/kW at production scale
- 50,000 hours durability
- Efficiencies exceeding 60% electrical and 80% for CHP.

In practice the project deliverables include, in addition to concepts and components, the development and construction of computer programmes for system and component simulation as well as improvement in existing testing devices and construction of new ones needed for component development. The computer programmes and testing devices are available after this project for new project and development faces.

The work was divided into work packages which dealt with 1. system analysis and modelling, 2. system concepts and integration, 3. component and sub-system development, 4. stack and stack component development and 5. system and sub-system verification. This technical development work was supported by work dealing with biofuels, fuel cleaning and reforming, grid connection issues, safety issues and life cycle assessment of SOFC systems. Finally dissemination of information through workshops, summer schools and presentations in international conferences were undertaken.

It was interesting to note that contrary to the original intention, it appeared that the problems encountered with the pressurised and non-pressurised systems were so different that the project quite clearly was divided into those two lines. In addition to this the two development lines were quite different in character. The development of the non-pressurised 50 kW unit comprised a continuous development path starting from basic concept analysis, followed by system development and integration, choice and development as well as testing of the required components and was ending in the construction and verification of the 50 kW unit. The pressurised case was different in character. In this case separate problematic issues were dealt with, involving modelling of different concepts to look at system efficiencies, different materials development and analysis, some component development, control system development and analysis of control regimes of hybrid systems. Quite a lot of work was dedicated to constructing testing equipment at several of the partner's premises.

## 1.2 Work performed and results

### 1.2.1 System analysis, component modelling and validation

In case of the atmospheric system, different system configurations have been designed and characterised by steady state simulations. Wärtsilä has carried out system calculations of five alternative system layouts for a 50 kW SOFC system fuelled with natural gas and FZJ has performed parameter variations on three different system concepts. These studies served as a basis for the work carried out in the work packages “System concepts and integration” and “Components and subsystems”. Any additional design calculations required for the continuing work on integration were carried out in system concept and integration part. The BoP components available in “Apros” have been found suitable for SOFC system simulations.

The simulation platforms for dynamic system simulations have been agreed on and the suitability of the BoP components available in the platform “Apros” simulation software have been checked. The 1-D SOFC stack model was further optimised and adapted to the requirements of VTT and Wärtsilä for the integration in “Apros”. The 1D component models based on the 1D-SOFC stack model for heat exchanger and pre-reformer were developed and validated and integrated into the dynamic system software platforms “Apros” and Simulink.

The “Apros” and Simulink component models were validated by various measured data.

Dynamic system simulations based on the chosen concept of Wärtsilä were performed for different operation modes with both dynamic models. A good agreement of the results could be achieved providing a good basis for further collaborations.

### 1.2.2 System concept and integration

#### **Atmospheric system**

The work has been divided into 3 selected phases: Phase 1. Conceptual creation and identification of sub-systems to integrate both mechanically and thermally. Phase 2. Determination of the requirements for the selected sub-systems to integrate and thermal optimization of fuel cell layout. Phase 3. Finalizing detailed design and documentation.

During the first phase a huge effort was put on identifying the selected sub-systems to integrate. This was highly connected to the modelling work where the different flow schemes were developed and analyzed. Several concepts were developed in workshops together with parties from the consortium. Finally a number of sub-systems were selected for further investigation.

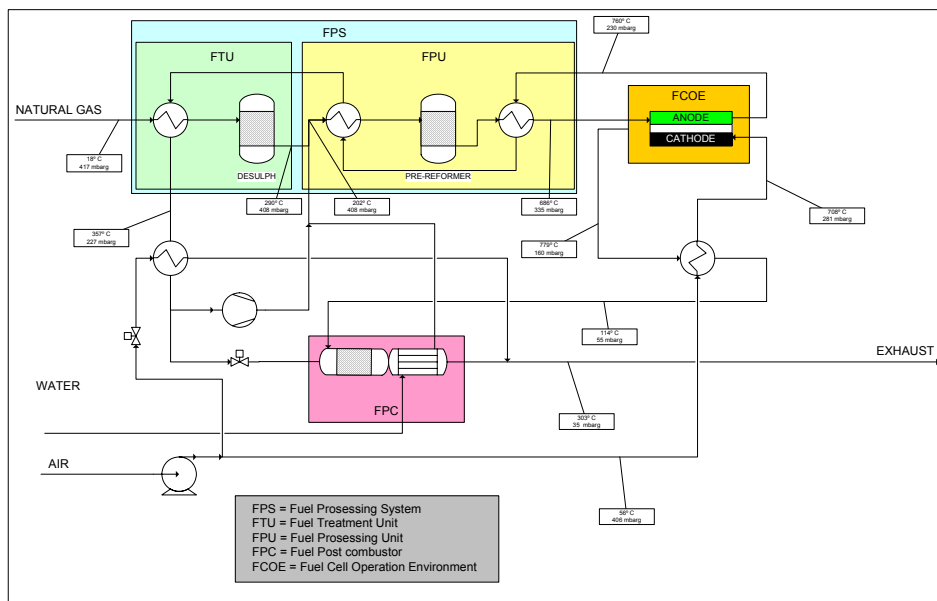


Figure 1.1. The selected sub systems for further development

During the second phase of this task the previously selected sub-systems were developed further. The requirements and specifications for each sub-system were drafted.

The unit lay-out and the modular division were also created during this time. The main reasons for modularization are to improve manufacturability, maintainability, quality and change management. The unit was split into 7 modules with different interfaces and operational temperatures.

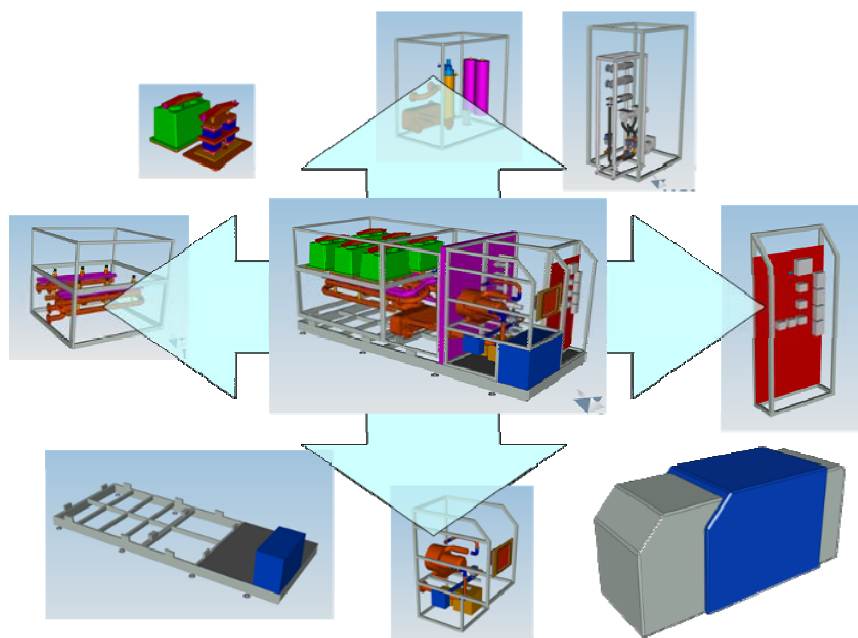


Figure 1.2. The modular division of the WFC50kW fuel cell unit.

During the last phase of the task the detailed design and engineering of the WFC50kW fuel cell unit was completed. All the required documentation for manufacturing and installation such as installation, assembly and manufacturing drawings and quality related documentation

such as factory acceptance test reports, leakage test reports and transportation and installation instructions for the construction and verification were created. The fuel cell unit consist of over 2000 different articles, and near as many related drawing and documents. All these documents and drawings where needed for a successful manufacturing and installation to the testing facilities.

### Pressurized system

The work performed by the University of Genoa has been aimed to investigate potential options for a highly efficient SOFC hybrid system. To do this, different models of pressurised SOFC hybrids systems have been developed. The tool used for this analysis, WTEMP software developed by the University of Genoa, is able to carry out a detailed thermodynamic and thermo-economic analysis.



Figure 1.3. The WFC50kW unit successfully installed in the testing facilities.

Thermo-economic analysis of the most promising plants has been carried out, taking into account variable and capital costs of the systems as provided by RRFCS and Wärtsilä.

The plant layouts have been analysed in order to compare several plant solutions in terms of operating parameters and thermodynamic performances starting from the current RRFCS Hybrid System (Figure 1.4).

Different options have been included, in order to improve the plant efficiency, in particular considering the integration of a recuperated micro gas turbine and the introduction of a blower instead of the ejector at the cathode side (Figure 1.5).

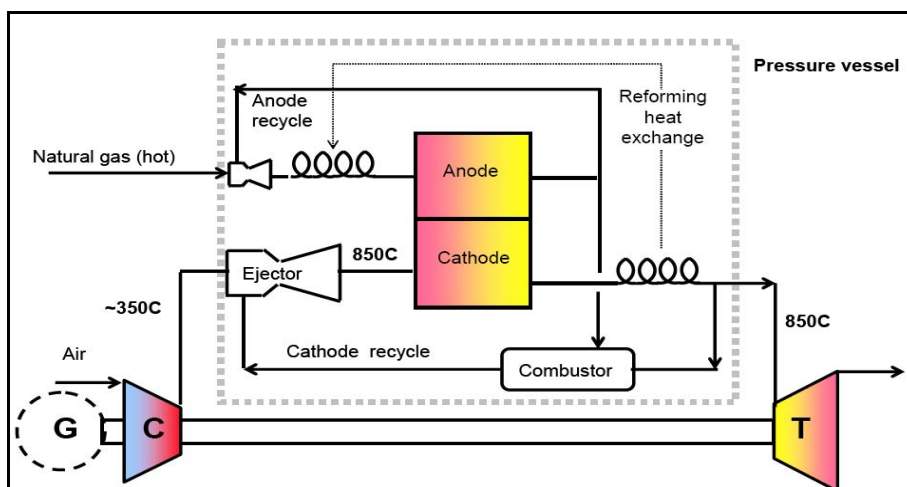


Figure 1.4. Current RRFCS Hybrid Plant

Moreover the sustainability of SOFC hybrid systems in the frame of the large size power generation has been analyzed. Different options to separate carbon dioxide have been deeply investigated and the WTEMP codes representing the systems have been created. A thermodynamic comparison among such systems and a thermo-economic comparison with the worldwide most used technologies in the field of the distributed generation (small micro gas turbines, reciprocating engines) have also been carried out.

In Table 1.1. the main characteristics for each plant proposed are described.

Table 1.1. Main characteristics of the systems proposed

| System No. | Fuel                | CO <sub>2</sub> separation and compression | Main features   |
|------------|---------------------|--|---|
| SYS 1      | NG                  | NO   | RRFCS current system [1]  |
| SYS 2      | NG                  | NO   | RRFCS current system with cathode blower instead of ejector                   |
| SYS 3      | NG                  | NO   | RRFCS stack integrated with 100 kW commercial MGT (blower at cathode inlet)   |
| SYS 4      | NG                  | NO   | RRFCS stack integrated with 100 kW commercial MGT (blower in cathode recycle) |
| SYS 5      | NG                  | NO   | Generic recuperated HS  |
| SYS 6      | NG                  | YES  | HS with Pre-combustion CO <sub>2</sub> separation                             |
| SYS 7      | NG                  | YES  | HS with CO <sub>2</sub> separation inside the generator module                |
| SYS 8      | Pure H <sub>2</sub> | -  | HS feed by pure hydrogen  |

The analysis has been conducted for systems able to produce about 1 MW<sub>e</sub> in order to have a significant comparison with other technologies used in the field of distributed generation with and without the CO<sub>2</sub> separation and compression section.

The results showed that by replacing the cathode ejector with a blower and the bespocen micro turbine with a commercial 100 kW unit, the efficiency could be increased from 56% to almost 60%. Secondly it was shown that an IG-FC with CO<sub>2</sub> capture had clearly better efficiency than an IGCC with CO<sub>2</sub> capture.

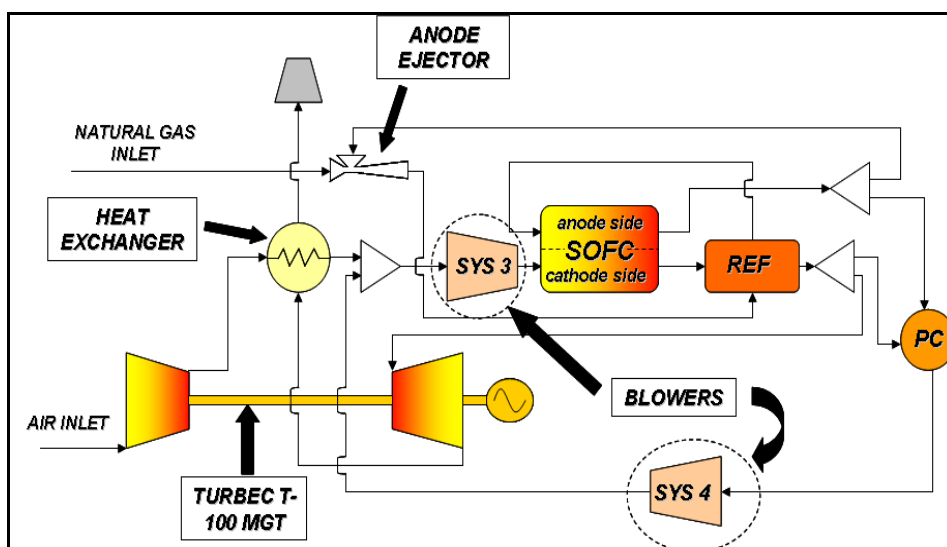


Figure 1.5. SYS 3 and SYS 4 layout (The different blower positions are shown)

### 1.2.3 Components and sub-systems

#### *Reforming and recycle blowers for non-pressurised systems*

For the 50 kWe atmospheric SOFC application being developed at Wärtsilä the selection of air blower was based on matching available technical solutions with the performance requirements of the system. Various alternatives were investigated including a centrifugal high speed blower and a Roots type supercharger. Testing and characterisation of these blowers within this project are more fully reported in Chapters 1.2.5 and 8.

For the Anode blower, it was recognised that an alternative design was required in order to achieve reliability and pressure boost capacity targets at the scale required for a 50kWe system. A blower incorporating a synchronous, high speed permanent magnet motor and an integrated active magnet bearing system was developed and manufactured. Testing of this blower was again transferred to “Verification” part of this project.

An alternative Anode blower was also investigated. This was based on more conventional technology using a mid speed motor and conventional bearings. This blower was tested by VTT where experiments were conducted using a modified test stand and air to characterise the performance of the blower at various temperatures and flow rates up to the operating temperature of 300°C.

#### *Sub-systems for pressurised operation*

The following sub systems were designed manufactured and tested as part of the RRFCS development programme:

1. Anode and Cathode ejectors
2. High temperature heat exchanger
3. Control (functional and safety) systems
4. Insulation system

Testing of these sub systems was demonstrated during the commissioning and performance test programme of a 15kWe Stack Block rig. This rig integrates these sub systems with the fuel cell stack and provides a demonstration and validation of the key features of the RRFCS system cycle. To date this rig has completed 6 thermal cycles and over 520 hours of operation. During this time the rig has performed as expected with no significant loss in performance. Furthermore the rig has been operated unmanned demonstrating the robustness of the control system and this rig will continue to be used in the ongoing development of the RRFCS 1MW product.

#### *Turbomachinery, gas and air circulation*

Work on pressurised SOFC systems focused on the steady-state and transient analysis of high temperature fuel cell hybrid systems and components and the validation of simulation models. This work was carried out at UNIGE and used the micro gas turbine (Turbec T100) based test rig facility developed at the University of Genoa with the support of a former European Integrated project (FELICITAS) and improved for the experimental tests carried out in this Large-SOFC project.

An initial activity was carried out with the facility layout coming from the FELICITAS project. In fact, after the development of an apt valve control system the cathodic side vessel was used to emulate the start-up and shutdown phases of for hybrid system technology development.

An important activity regarded a wide experimental campaign on the machine recuperator. Several tests were carried out on this component when it operates inside the T100 machine in both electrical grid-connected and stand-alone modes. For this activity a new system (air/water heat exchangers, water pipes, control valves, and control software) was developed to control the compressor inlet temperature. Furthermore, in the section devoted to the recuperator tests the attention is focused on transient phases during the machine start-up procedure.

Other experimental activities are related to the comparison of two different machine control systems for possible applications in mGT-SOFC hybrid systems. The attention is focused on experimental results obtained with both constant rotational speed and constant turbine outlet temperature (TOT) control systems operating with the machine in its standard recuperated cycle or connected to the fuel cell volume emulator (the modular cathodic vessel).

A great attention is devoted to validate time-dependent simulation models at both component (the recuperator) and system levels (the hybrid system emulator test rig). Then, this report shows the development of a real-time model to be coupled with the rig for full hybrid system emulation. This hardware/software approach is essential to generate at turbine inlet level the same effect of a SOFC outlet flow, and to complete the emulation study of the turbine/cell coupling. Another hardware/software based activity is devoted to the presentation of a diagnostic tool for this micro gas turbine (the T100 machine). It was developed, with the objective of monitoring the operating parameters of the turbomachine, the performance of the heat exchanger and, in general, the good operation of the plant.

The layout of the hybrid system emulator facility (T100 turbine coupled with a modular vessel) was enhanced to include an anodic recirculation system. This experimental facility layout was used to analyze the anodic circuit performance and the cathodic/anodic side interaction from fluid dynamic and thermal point of view showing new operational limits to be considered for hybrid system development activities.

Furthermore, the experimental facility was equipped with a steam generator system to produce super-heated steam to be injected in the turbine. This is essential to emulate the effect of SOFC outlet composition on the machine performance. Several tests are presented to show the operational limits of the machine with different steam injected mass flow rate values.

All these experimental data are used in this report for a control system strategy assessment for hybrid system applications. This work completes the previous control system considerations considering the results obtained with both the anodic recirculation and the steam generator systems. Work on this project also devoted to the additional activities carried out on the experimental facility to enhance its capabilities and its emulation performance.

#### *Heat exchangers and recuperators suitable for fuel cell use*

Heat exchangers, which exchange heat between cathode and anode flows, need to be leak tight. Various manufacturing processes, including welding and brazing, have been

investigated to achieve this requirement. Further work has looked at balancing conflicting requirements of compact size and low pressure drop whilst at the same time maintaining acceptable heat transfer.

For use in the 50kWe atmospheric SOFC system two types of heat exchanger were evaluated. The heat exchangers were of the plate-fin type, manufactured by Steward Warner South Wind Corp. and a plate heat exchanger from FZJ. Evaluation of these components was carried out at FZJ using a new heat exchanger test bench and as part of the system evaluation testing reported.

#### *Evaluation of heat exchanger materials*

Work on developing a heat exchanger for pressurised applications has focused on understanding the materials durability under the aggressive environments encountered in the RRFCS SOFC system. The main concerns with alloy selection are corrosion and creep and these phenomena have been investigated by Bosal N.V.

Testing of a heat exchanger in a representative pressurised system environment was completed at RRFCS as part of a test programme using a 15kWe Stack Block Rig. This rig fully simulates the RRFCS system cycle and to date has been operated for ~380 hours at temperatures > 900°C with no discernible loss of heat exchanger performance.

As part of the rig design, activity stress modelling of the heat exchanger and other components was also completed. This activity used creep data produced by Bosal N.V. and successfully predicted creep deformation in a 'Flame tube' assembly.

#### *Fuel processing equipment*

A lab-scale experimental setup at VTT was used to perform test runs with a catalyst to assess the affinity to carbon formation and hydrocarbon conversion. A gas composition corresponding varying recirculation ratio in a SOFC system was fed into the reformer. Synthetic anode exhaust gas (CO, CO<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O) and desulphurised natural gas were used. The operating temperature of the catalyst, the recycle fraction of the anode exhaust gas and the space velocity of the catalyst were varied during the test run to solve the limiting operating conditions. It was concluded that no significant carbon formation occurs if the reactor inlet temperature is maintained above 500°C and recycle fraction above 0.4.

#### *Power electronics and controls*

During the Large-SOFC project, a control system has been developed to manage thermal and electrical loads, and to control the various external sub-systems which make up the RRFCS system. The core of the control system consists of a Comano controller, which is capable of supporting a range of communication interfaces and hence integrating with a wide selection of Fieldbus input/output (IO) devices and other intelligent systems. The Comano controller has been developed by OSys (formerly DS&S) and is used widely within Rolls-Royce plc for the control of other power generation systems and is the preferred Rolls-Royce Common Controls platform.

The control system was developed for the 1MW product, but the controls philosophies, hardware and software are also appropriate for the control of pressurised test rigs. A version

of the control system was applied to the 15kWe Stack Block rig and various automated control functions were demonstrated during the commissioning and test programme on this rig, including a 250 hour test, the majority of which was operated unmanned with the control system responsible for rig operation and management of safety issues.

For the 50kWe atmospheric SOFC system, work at The Switch focused on the selection of power electronics and control solutions. Prototype systems were designed, assembled and tested before being incorporated into the atmospheric SOFC system.

### *Insulation*

For SOFC applications an efficient insulation system is required. The insulation materials need to be stable throughout prolonged operation in order to minimise thermal losses and hence maintain system efficiency. During the Large SOFC project, work was completed on insulation material selection and design of insulation assemblies. Testing was also carried out to understand mechanical performance and to verify the accuracy of manufacturers' data for SOFC applications.

The insulation design concept for a pressurised SOFC application was demonstrated at RRFCS on a 15 kWe Stack Block Rig. During the commissioning and test programmes of this rig the insulation was found to work well and pressure vessel metal temperatures were maintained within safe limits.

## 1.2.4 Industrial stack

### *50 kW planar SOFC stack assembly*

Based on a large stack prototype developed in the National Danish SOFC programme, the stack/system interface was analysed jointly by Wärtsilä and TOFC. This resulted in a detailed definition of this interface in 2007.

In January 2008 a unit consisting of two stacks was tested by TOFC and Wärtsilä at Wärtsilä's laboratories in Espoo, Finland under various operating conditions relevant for the upcoming 50 kW demonstration unit. The test served as a verification of the stack/system interface definition as well as the stack performance prediction model. The models were used to predict overall system performance as a function of the number of stacks in the system, and the total number of cells and stacks in the 50kW demonstration unit was decided on.

In the second half of 2008, the production of stacks with the design used in the 50 kW demonstration unit was initiated by TOFC. In close cooperation with Wärtsilä, an ongoing analysis of selected key mechanical and electrical quality assurance parameters was carried out in the initial production phase to ensure optimum quality of the stacks throughout the later production phase.

As the production proceeded in 2009, the quality assurance parameters were closely monitored, and reviewed by TOFC and Wärtsilä. 24 stacks meeting the agreed quality specification were produced and shipped to Wärtsilä. A full set of stack documentation has been developed and provided to Wärtsilä to support the development of system operation procedures ensuring stack performance throughout the life-time. The objective of this task was

fully met, ultimately by the delivery of 24 stacks of high quality and homogeneity and the associated necessary documentation.

#### *Options for stack ceramic material*

Work at RRFCS Ltd and Inmatec focused on investigating the manufacturing route for fuel cell substrates. The entire manufacturing route was assessed, with particular attention being paid to the production of the Magnesia stabilised Magnesia Alumina (MMA) powders, ie the substrate material. Three processing routes for the production of ceramic powder were investigated, these were:

1. Mixtures of fine Alumina and Spinel powders with pore formers
2. Mixtures of coarse Alumina and Spinel powders without pore formers
3. Scaled up 'Large' fused MMA ingot

The use of fine powder mixtures proved to be impractical due to their high sinter activity. Resulting substrates proved to be excessively dense and unusable in a fuel cell application as it proved impossible to adequately control porosity using the currently available pore forming technology.

Work using mixtures of coarse powders proved more successful and good results were obtained, both in terms of substrate properties and fuel cell performance. Furthermore this process demonstrated benefits in terms of better control of composition, particle size distribution and lower cost.

Work on 'Large' fused ingot was also successful with good substrate properties and excellent fuel cell performance being achieved. This process is a scale up of the original powder production process and significant cost reductions were demonstrated. Furthermore this process was qualified as being 'fit for 'production' for substrate manufacture.

Overall it was concluded that the objectives of the task were met and scaled up methods for the production of fuel cell substrates were developed.

## 1.2.5 Verification of system concepts and sub-systems

### *Verification of atmospheric SOFC systems*

A laboratory facility for the atmospheric SOFC unit was designed and constructed. Most of the site planning and preparation work concentrated on safety issues, such as installing the emergency ventilation blower, gas alarm system and fire extinguishing systems.

Manufacturing of the 50 kWe SOFC unit was an essential part of the project to develop and further learn manufacturing and assembly technology for the future units

The validation of the atmospheric Wärtsilä FC50 unit (WFC50) was completed. The operation period for the unit has been approximately four months including two weeks operation with stacks. As a part of the validation testing, VTT has conducted performance measurements for the unit according to IEC 62282-3-2.

Wärtsilä has made an initial performance validation of the Wärtsilä FC50 unit designed and constructed in this project. The unit was operated with natural gas and the electricity produced was fed to the local 3-phase 400 VAC power grid. During the initial test runs, unit efficiency was determined to be  $37.5\pm 1.9\%$  at 52% power level.  $\text{SO}_2$  content in exhaust gas was measured to be below detection limit,  $\text{NO}_x$  content below detection limit, particles below  $1 \mu\text{g}/\text{m}^3$ ,  $\text{CH}_4$  content below 5 ppm, CO content below 100 ppm, and  $\text{H}_2$  content below 200 ppm. Total harmonic distortion (THD) was measured to be below maximum acceptable limit, i.e. 10%. Sound pressure level measured from 1 m distance was below 67 dB(A), and sound power level below 85 dB. The rated power level (50 kW) of WFC50 could not be achieved during the first performance validation test due to problems with stack module temperature control.

#### *Component testing of 50 kW atmospheric SOFC unit*

Two air blower designs and one blower for hot anode gas re-circulation were developed and validated. One existing anode gas blower was acquired for testing. Tests were carried out in simulated process conditions and characteristic performance maps were produced.

The heat exchanger tests were successful and they gave valuable feedback for heat exchanger design, dimensioning, optimization and further testing. Fuel reforming was tested with an integrated reformer unit. As a result, the integrated reformer performance and start-up period were found acceptable, and its performance met the requirements of SOFC system to a satisfactory extent.

Anode circulation effect on reforming was studied in laboratory scale to provide some background for system optimisation. Steam generation, to provide water needed in reforming reactions, was tested in four different solutions. Five different adsorbents were tested for tetrahydrothiophene (THT) sulphur removal from natural gas.

#### *Verification of pressurised SOFC sub-systems*

Sub systems developed as part of the Large-SOFC project were tested using a 15kWe Stack Block scale rig. This rig was built as part of a TSB (UK) funded programme and is a scaled version of the RRFCS system cycle. Heat Exchangers, Anode and Cathode Ejectors, Control and Safety systems developed under the Large-SOFC project were tested alongside a 15kWe Fuel Cell stack and the successful operation of this rig provided a good verification of the design and manufacture of components and of the integrated system cycle. The rig was run for ~520 hours including a 250 hour continuous test at 95% power.

Performance and durability testing of smaller scale fuel cell components was also completed using a dedicated pressurised fuel cell test rig. Various improvements were made to this rig as part of the Large-SOFC project including improvements to temperature control, air distribution, maximum operating temperature and modifications to allow testing at varying Oxygen partial pressures. Whilst not fully replicating system operating conditions these rigs have been used to characterise fuel cell behaviour over a range of operating conditions and provide important data which has been used to validate performance models of fuel cell behaviour.

## 1.2.6 Fuel quality, gas cleaning and reforming

The project compiled a report on biofuels, availability and cost, as well as all aspects dealing with the use of biofuels as fuel for SOFC. This is a public report available from the public web-site (public report, see Appendix 1). This also includes information on the composition and impurity levels of the different fuels and gasification products. The report contains information on SOFC requirements for fuel quality: composition, allowed variations and impurity contents. Sources for this information was both the open literature, and results from SOFCNet and Real-SOFC as well as experience of the participants, e.g. VTT's considerable experience of gasification of coal, waste and biomass. Experimental work by cell testing by FZJ and analytical work was performed in order to fill the identified gaps in information.

FZJ performed tests on anode substrate type single cells for up to three selected impurities, toluene, hydrogen cyanide and hydrogen chloride, in order to determine maximum allowed level of contamination. The impurities were fed into the hydrogen fuel stream. Tests included recording of I-V curves and constant load operation up to 2000 hours. The conclusion was that cells stand well these impurities in the low concentrations as usually found in biofuels.

Alongside the work undertaken by VTT, UNIGE investigated in more detail the potential behaviour of fuels in SOFC systems from a generic perspective. This work was based on work undertaken by VTT and UNIGE's own computer models. Due to sulphur sensitivity of the fuel cell anode and the reforming catalyst, sulphur removal will be an important clean-up step. Typically sulphur tolerance of the fuel cell anode is in the order of parts per million (ppm). These sulphur atoms are contained in organic compounds. Light fuels contain simple organo-sulphur compounds such as thiophenes, while heavier feeds may contain large methyl-substituted dibenzothiophenes. Additionally these latter feeds may contain considerable amounts of organonitrogen compounds and particulate matter. Depending on the type of fuel several clean-up routes were considered by UNIGE. In general, reducing the sulphur content from several hundred ppm down to 1 ppm involves a catalytic step, whereas sulphur removal from ppm levels to ppb levels can be achieved by (reactive) absorption technology.

A study on reformer options for different fuels and fuel composition was made by UNIGE: biogas from biomass gasification, bioethanol and biodiesel will be considered as priority alternative fuels; also conventional fuels, such as natural gas and diesel, are included as comparisons.

## 1.2.7 Grid connection, safety and standards, life-cycle analysis

### *Grid connection*

The work on grid connection focused on analysis of grid connection rules and standards applicable to Large SOFC fuel cell. The work covered electrical grid regulations in a wide range of European countries, as well as regulations relating to heat- and gas grid connectivity. Discussions with local grid operators were undertaken and permission obtained to connect the demonstration unit to respective grids.

### *Safety and standards*

A review of safety issues around the operation of pressurised test rigs has been collated for UK by RRFCS.

The safety documentation package for the 50 kW CHP unit was focused on following points: fuel cell standardization, safety management and reliability and maintainability aspects.

### *Life-cycle analysis*

A review of the state of the art, concerning the environmental aspects of the system, has been carried out. Firstly the fuel production has been considered. It was possible to find useful information about methanol production, particularly for the renewable origin, which is in a development stage. Then, the further fuel options were considered. Successively, the focus has been moved on fuel cell unit manufacturing. Some studies have been presented, showing which can be the level of the approach in dealing with such a delicate part of the process. Finally, the whole life of the system has been considered, summarizing the recent evaluations of the environmental impact related to the fuel cells. In this case, the alternative options in respect to SOFCs will be accounted not as a direct comparison, as done for fuels, but as a useful tool for a comparison and/or transfer of methodology of the analysis criteria. At last, a specific overview about the Life Cycle Assessments of Solid Oxide Fuel Cells, which have been developed has been carried out.

The life cycle analysis performed shows favourable environmental performances for a Solid Oxide Fuel Cell system in comparison with a conventional power plant. Fuel production phase strongly influences the environmental impacts of the electricity generation via SOFC. It is clear that bio-fuels can significantly reduce the environmental burdens associated with the up-stream processes. Besides, it results that, if there are not significant changes for the environmental profile of the manufacturing stage, the pressurization of the fuel cell unit entails lower impacts than the atmospheric units, as effect of a higher efficiency. In particular, focusing on global warming, the bio-methanol solution seems highly attractive from the life cycle point of view.

## 1.2.8 Training, dissemination and public activities

Several internal workshops as well as two public workshops have been carried out. Two summer schools took place in 2008 and 2009. Press releases were issued and a project website ([www.largesofc.com](http://www.largesofc.com)) was created. Publications and public activities of project are shown in Appendix 1.

## 1.3 Discussion

### 1.3.1 Status of achievements

In this section some of the results are highlighted and compared with the previous state of the art.

## **System analysis, component modelling and validation**

Component and system modelling is always an important issue to assist fuel cell development. Especially in the case of dynamic modelling of systems not so many tools are available, especially involving validated stack models. So the achieved status of having two dynamic models based on different modelling concepts represents the most advanced status of SOFC system modelling.

## **System concepts and integration**

The completed design of the WFC50kW fuel cell unit represent an industry leading planar SOFC system and brings Wärtsilä fuel cells closer commercialization in terms of product cost, performance, manufacturability, assembly, lifetime and availability.

For a pressurized fuel cell system, the analysis represents an innovative study. It is quite common in open literature to find the comparison of different plant performance only from the thermodynamic point of view. The results achieved in the framework of this project allows a complete assessment of the systems simultaneously considering the thermodynamic operating parameters and performance, the system capital cost and revenue and the off design behaviour.

## **Components and sub-systems**

### *Reforming and recycle blowers for non-pressurised systems*

The experimental evaluation of the fuel processing system with anode recycle gas provided necessary results on the operability and safe operating conditions of a SOFC system. It was realized that a pre-reformer could be used at relatively low recycle fraction i.e. 0.4 without degrading the hydrocarbon conversion or inducing carbon formation in the reformer. This can potentially lead to lower recycle flow rates in a SOFC system, which can decrease the size and cost of the BoP-components in the anode recycle loop.

### *Sub-systems for pressurised operation*

Integration of anode and cathode ejectors, off gas burner and power electronics with the Fuel Cell Stack at system representative conditions were demonstrated for the first time in a test rig. Unmanned running of a system scale rig was achieved. This represents a major step forward in the rig capabilities and verification of the system cycle. In particular all the new facilities designed for the emulator test rig were installed and used to perform wide experimental campaigns. On the other hand, the real-time simulation models, developed in this project, were successfully validated as planned in this workpackage.

All these activities shown have a high impact factor in comparison with the state-of-the-art in large SOFC hybrid system development, especially considering that several activities are under development with SOFC system emulators (NETL-DOE and DLR emulator plants). In fact, all the experimental emulation activities (start-up and shutdown phases, control strategy comparison, anodic side recirculation, composition emulation) furnish a lot of experimental data essential for solving the main problems related to the SOFC/mGT coupling. Furthermore,

an important discussion developed to assess the constant Turbine Outlet Temperature (TOT) control system for hybrid system applications will be extremely useful for future large SOFC power plant design based on commercial machine technology. On the theoretical side, the real-time model development and validation activity improves the state-of-the-art scenario for the wide experimental data used to validate these models.

## **Industrial stack**

### *Planar stacks for the 50 kW SOFC unit*

The delivery of a 50kW stack assembly consisting of 24 anode supported planar SOFC stacks of high quality and homogeneity is the up to date largest stack delivery to a single system and hence it constitutes new world wide benchmark for the scale up of cost-efficient SOFC technology. 50kW has previously been obtained by electrolyte supported planar SOFC cells operating above 850°C. The fact that 50kW is now achieved with anode supported planar cells is of key importance to the objective of achieving a cost-effective, reliable technology with sufficient life time because this technology opens up the necessary possibilities for lower operating temperatures, meaning longer life times for less expensive materials, and for efficient production methods, meaning lower cell costs.

### *Ceramic support materials for the RRFCS cells*

Various alternative methods for the production of Magnesia stabilised Magnesia Alumina (MMA) powders and fuel cell substrates were investigated. The use of fine powder was found to be impractical at this time due to the state of the art of pore forming technology, but the benefits of using mixed coarse powders were demonstrated. Furthermore, scale up of the baseline powder manufacturing process, with consequent reduction in manufacturing costs, was demonstrated.

The use of fine powders and pore former offers the best potential in terms of reducing costs and improving properties of all the manufacturing routes investigated. However, this requires better pore formers than the ones available in this work. Overall improvements and scale up of ceramic substrate manufacture allowed RRFCS to increase fuel cell fabrication and achieve a weekly output of 20kW of fuel cell stack.

## **Verification of system concepts and sub-systems**

### *Verification of atmospheric SOFC systems*

The main achievement is that a non-pressurized solid oxide fuel cell concept verification unit by Wärtsilä (Wärtsilä FC50) was successfully validated in the LARGE-SOFC project. The validated state-of-the-art net efficiency level in power range of 50 kW for solid oxide systems is in a range of 40 – 50 % based on the LHV of NG. Due to problems with stack module temperature control the rated power level from WFC50 could not be obtained. However, the unit design should enable the target efficiency for the unit at rated power.

### *Component testing of 50 kW atmospheric SOFC unit*

Validations of the components for 50 kW atmospheric SOFC system were successfully carried out as well as other component and sub-system testing, and they have given valuable

feedback. Validated components and principles were widely used in the concept verification unit such as the anode gas blower and the integrated reformer. In this task Wärtsilä has constructed two test rigs, which creates useful base for further component and sub-system testing. Tested and developed components, e.g. anode gas blower and evaporator, are representing top level competences and having potential for further development for commercialization.

### *Verification of pressurised SOFC sub-systems*

Significant improvements were made to the pressurised test rigs and it is considered that the objectives of the project have been met. There is however still work to do to achieve full system conditions and this will be the subject of a separate rig upgrade.

Overall the project was successful in improving the test facility and this has improved the capability of RRFCS to develop and validate fuel cell technology. The rigs are used in the performance and durability development programmes and will be of great benefit in the future development of fuel cell components. The most significant result was the improvement in temperature variation within the test box where temperature variation was improved from  $>300^{\circ}\text{C}$  to  $\sim 65^{\circ}\text{C}$ .

The RRFCS SOFC system is a high temperature, pressurised system and the system design relies on significant integration of fuel cell, turbo machinery, fuel reforming and gas recirculation technologies. The rigs required to simulate these conditions fully are therefore very complex machines. The small scale pressurised rigs available at RRFCS whilst not fully capable of simulating system conditions are unique in being able to test under a wide range of temperatures and pressure and Cathode gas compositions.

### **Fuel quality, gas cleaning and reforming**

In this project was very well clarified what are the most potential fuels which can be efficiently used for power production with high temperature fuel cells. The study also included such basic issues as requirements for fuel purity and composition, how to clean the gases to the required composition, the availability of fuels of suitable composition and the required reforming technologies needed for reforming the different fuels. All the objectives set for this task have been achieved.

Results show which state-of-the-art technologies should be selected for optimal impurities removal when using biogas as a fuel for a SOFC. The work on fuels provides a detailed overview about the fuel clean up challenges that should be addressed when using biogas for power generation by means of a SOFC. Results also provide the criteria to industry for selection of the optimal clean up technology and further processing of biogas for an internal reforming SOFC (250 kW).

### **Grid Connection**

The large SOFC power units will mostly be integrated with the different energy related grids. One of the achievements of this project was to analyse grid connection rules and standards applicable to Large SOFC fuel cells. Required permissions to connect the demonstration units to various grids were received

## **Safety and standards**

One achievement was the higher understanding of installing SOFC systems, and the issues arising from their operation from the safety viewpoint. This work provided a safety analysis and also reliability and maintenance planning.

The task has generated an improved understanding of the scope of regulations within Europe as well as in the United States, which is of paramount importance for fuel cell system and power converter developers to be able to design products that safely and reliably interface to the existing infrastructure. Also, the review provided deepened insight to issues still widely unresolved in terms of regulations, and related discussions helped in forming a common understanding of the industry standpoint in respect to these issues.

## **Life-cycle analysis**

One of the achievements was the LCA report where was concluded how future environmental requirements may affect SOFC systems, and how these systems can contribute to environmental improvements in the regions and markets in which they will operate. The meaning of this is that specific overview about the Life Cycle Assessments of Solid Oxide Fuel Cells has been carried out. In the study performed, it has been demonstrated that, in order to evaluate the environmental impact related to the energy production by the use of a fuel cell, it is imperative to consider all the processes related to the fuel cell operation, and not only the FC operation itself. Life cycle assessment provides the cumulative impact resulting from all the stages of the product life. The results are compared to a benchmark conventional technology, i.e. natural gas power plant. Despite the scaling issues, owing to different power capabilities, however FC system appears environmentally preferable.

## **Summer schools and workshops**

Based on the positive feedback both workshops and summer schools did receive, it has been decided to continue those activities on independent basis in 2010 and the following years.

### **1.3.2 Intentions for use and impact**

As part of the discussion the various participants in the project highlight how they intend to use the main results achieved.

## **Wärtsilä**

The LARGE-SOFC project has enabled the development, manufacturing and testing of 50kW solid oxide fuel cell unit in Wärtsilä. This has been essential for Wärtsilä in the way to commercialize SOFC products. Wärtsilä will continue the development of its SOFC power plants in order to commersilaise both APU units for ships and power units for distributed power. During the 2010:s both 20 kW and 50 kW units will be commercialised although the long term goal is to move to 250 kW basic units from which MW class units will be assembled later on.

Wärtsilä will use developed and validated component models for dynamic system simulations. These models support development of control principle and testing of automation safety issues. Wärtsilä will continue further development in EC funded projects.

This project has taken fuel cell technology further in Wärtsilä especially in balance of plant components and contributed substantially in co-operation with research institutions, e.g. VTT Technical Research Centre of Finland and LTY Lappeenranta University of Technology.

## **RRFCS**

RRFCS is continuing to develop a 1MW GT-SOFC hybrid system. Work over the next 2 years will focus on demonstration of system performance and reliability at 15kWe Stack Block level. Understanding degradation mechanisms of the fuel cell and system components will form an important part of this work and this will build directly on the understanding of ceramic substrate materials and heat exchanger materials behaviour gained during the Large-SOFC project.

Product Development activities will continue to develop sub-system design and component integration. This work will involve modelling and validation testing at system level in order to understand how a 1MW product will behave at steady state and transient conditions. Further work will also be required to develop the control and safety systems and to incorporate diagnostic capabilities. This work will use the controls platform and methodologies developed to date and as demonstrated on the 15kWe Stack Block Rig.

The ongoing development programme will require continued collaboration with European Universities and Companies and further funded collaborative programmes are being considered in the UK, EU and US.

## **TOFC**

It will have an impact to the SOFC industry that the scale of demonstration projects is continuously increased, and the Large SOFC project is setting a new benchmark for the anode supported planar SOFC technology. In addition to the 50kW planar SOFC stack delivery, Large-SOFC project has made very significant impact to TOFC in terms of maturing the company from a SOFC development company towards an industrial partner and supplier of SOFC technology. The key contribution from the Large-SOFC project to this development is what comes along with a large stack delivery: the required knowledge, information and documentation to handle interface definitions, performance prediction validation, quality assurance and stack operation manuals.

## **Rerearch organisations**

The modelling and system know how and experience is going to be utilized for example in further EC-funded projects (like proposal "ASSENT") and national projects. It is also intended to further improve the system technology to assist industry in their development.

The test equipment and experience for testing high temperature heat exchangers will be used in further national and international projects by FZJ.

The test rig facilities at UNIGE were developed on the basis of a real hybrid system prototype of RRFCs. The experimental data obtained with the rig will be useful for a real large hybrid system development at industrial level. This experimental approach demonstrated how it is possible to investigate high risk situations on these hybrid systems without the expensive fuel cell stacks. So, the results obtained will be essential at industrial level to develop new SOFC-mGT systems without serious and expensive consequences coming from SOFC-mGT coupling problems. Both experimental data and validated softwares will be extremely useful for control system development activities. For the research sector there are good chances that the test rig facilities will also be proposed to establish case studies for the international mGT model community. In fact, such is difficult to obtain in industrial plants, where details about equipment are often missing or confidential. Furthermore, the experimental data measured with the rig were considered significant for research development at both component and system levels. These public data are essential for the scientific community especially considering that industrial prototype results are often confidential or incomplete.

UNIGE intend to conclude the process for the publication of the PCR document for electricity generation through SOFC systems in the international EPD<sup>®</sup> system through Consultation phase and Approval and publication phase.

UNIGE intend to validate the results from modelling the biofuels clean up by means of adsorption experimental tests on selected adsorbents. A laboratory scale adsorption rig has been developed and set up and. In 2010, some preliminary results on the passive adsorption of trace sulphur compounds by means of typical commercial adsorbents (Molecular Sieves, Activated Carbons) are going to be presented.

### 1.3.3 Final remarks

The main goal of the project was to further the development of large SOFC power plants towards better performance, life time and cost coming closer to commercialisation. There is no doubt that both Wärtsilä and RRFCs concepts and many components as well as some materials have been developed in the right direction. How close to commercialisation, is not easy to estimate, but certainly there is still a way to go. But there is another aspect of it all. We have also worked on secondary issues, which are important when looking at the future development towards the final goals. It was clear from the beginning that this project would not yet produce the commercial units. Therefore new development work is needed. In the Large-SOFC project important know-how and infrastructure has been developed and constructed. Know-how and infrastructure which will be used in the future work and projects. Completely new and advanced computer models, a number of new and/or improved testing equipment have been constructed at several of the participating organisations. New knowledge has been created in the participating organisations, but not only there. The public summer schools have advanced knowledge on SOFC fuel cell systems in many universities and companies outside the project participants. Details of the main achievements and impacts are summarised in the following.

## 2 Background

To date the main emphasis on SOFC research and development has been on the stack, especially cells, interconnects and sealing materials. These subjects have been the focus of the 6<sup>th</sup> Framework IP-project Real-SOFC, and SOFC600. However, the construction of SOFC-power plants requires more than materials; the needs of the entire system, including BoP components and sub-systems must be addressed. Where two thirds of a system costs plus reliability and durability issues are dependent upon balance of plant components and sub-systems the challenges of high cost, performance and durability can only be resolved by developing the system as a whole rather than simply addressing only stack issues.

At present most SOFC research programs in Japan and the USA are targeting the development of stacks and systems in the 1-5 kW scale. These are suitable for APU and residential applications, but not industrial scale power generation. A substantial step in BoP capabilities is required to construct power plants of MW size. However, capability development and technology acquisition must take place simultaneously with materials technologies if MW sized power plants are to be constructed over the medium to long term. The SECA project in the USA aims in long term for very large systems but until now the technology development has focused on small systems.

Therefore, this project aims to address the specific problems that might hinder the development of hundreds of kW to 1-5 MW SOFC power plants. The technical problems relate to both cost and technical performance of large power plants. The issues can be divided into two parts. First how large power plants should be constructed? How is a system integrated and what implication does this have for the components? How are large stacks constructed? What sources exist for different BoP components? How are components integrated into large systems? This includes packaging, especially taking into account heat management, and automation and control systems. Secondly what factors will affect the operational introduction of SOFC units: this includes connection to a fuel supply and the utilisation of the power and heat i.e. connection to the electricity grid and to either the heat or cooling grids, as well as safety and environmental issues.

Two parallel concepts are addressed throughout the project: pressurized system and atmospheric SOFC systems. However, it is anticipated that there will be some commonality between the two systems in terms of basic understanding.

The main objective of the project is to develop a concept of how to construct and manufacture a 0.5-5 MW SOFC power plant. Concepts for both pressurised and atmospheric plants will be elaborated. It is agreed that one of the attractions of fuel cells is their potential modularity, and that fuel cells can be built as small units of kW which can then be added together to create large units of 50 kW to 100 kW which can then be placed in a sub-system and systems added together to create the 1 MW unit.

Fuel cell power plants are complex machines. In order to understand the whole, one has to understand the behaviour of components, their interrelationships and influence on the total system. This is only possible by using system and component specific models, which are combined to form a dynamic system model. Therefore, dynamic component and system

models for layout, operation and control are to be developed. All models need to be verified by testing to make sure that they really represent “real life”.

The hardware needed includes: industrial standard stack technology suitable for large units, fuel processing and gas handling components and BoP components, all of which need to be defined, developed and tested. Moreover, significant hardware modifications need to be addressed for adapting fuel cell systems to biofuels, such as biogas, bio-ethanol and bio-diesel.

The concepts and the system models developed in the project need to be verified. Several approaches will be used for verification, including the construction of a 50 kW class atmospheric SOFC CHP unit, which is connected to the electrical and heat grids, as well as the verification of components and sub-systems for pressurized SOFC units. These represent concepts of the larger modules, from which MW-size power plants can be constructed in medium to long term. A test program will be executed in order to verify the models and the overall concept. Requirements, technology and cost for grid connection will be investigated.

One of the main benefits of SOFC power systems is their potential to use a number of different fuels, mainly hydrogen and both gaseous and liquid hydrocarbon fuels. Although natural gas will be the main fuel for the foreseeable future, SOFC enables the transition to renewable fuels. Those are biogas, biomass gasification gas, ethanol, biodiesel and renewable hydrogen. For this reason the availability and technical consequences of using biofuels will be investigated in the project.

Stationary power generation systems include base load, standby (UPS) and peak saving applications. Typical base load units may serve residential and industrial CHP, commercial HVAC and base load and premium power applications. It is envisaged that stationary fuel cell applications will have significant role in the future distributed electricity generation network.

To 2009 it is estimated that close to 900 stationary demonstration and pre-commercial fuel cell plants larger than 10 kW had been installed worldwide with a total electricity generation capacity of about 170 MW. The principal increase in stationary fuel cells units has been in the USA and Asia, and more recently in Europe. In both the USA and Japan the numbers in service are associated with major demonstration programmes supported by the USA and Japanese government.

Four fuel cell types, namely PAFC, MCFC, PEMFC and SOFC, are used in stationary applications, of which SOFC is divided further into tubular and planar sub-technologies. Compared to PAFC, MCFC and PEM technologies, SOFC technology is immature, but is seen as having more potential than these other fuel cell technologies in terms of applications, efficiencies and costs. Based on lower cost ceramic materials SOFC technologies are believed to have the greatest potential in becoming cost competitive with incumbent technologies. Thus SOFC technologies with net electrical efficiencies of 50% plus are being developed and units of 60% plus are believed possible for the medium to longer term. High electrical and CHP efficiencies will directly impact fuel supplies, whilst low or negligible NO<sub>x</sub> and SO<sub>x</sub> emissions and no particulate matter will contribute to improved air quality. SOFC units can therefore improve both fuel security, through efficiency and flexibility, and lower carbon emissions that will contribute to meeting Kyoto commitments. Looking into the future the fuel flexibility of SOFC systems will allow units to transition from the common hydro-carbon fuels of today, notably natural gas, through to future potential fuels such as bio-

fuels. Thus overall SOFC technologies have the potential to contribute to the European Commission's 2020 targets to some degree but mainly to 2050 targets.

There is widespread interest in SOFC technology in Europe, the USA and Japan. There are a number of developers in all three regions working on SOFC technology suitable for a range of uses from portable for equipment such as computers, through use for transportation to stationary power generation and heat. Developers in the USA, for example GE, Fuel Cell Energy and Siemens and Japan, for example Mitsubishi have advanced SOFC technology programmes. In Europe Rolls-Royce, Wärtsilä and Topsoe Fuel Cells Cell are amongst the leading SOFC developers, along with Hexis, HT Ceramix, Ceres Power, CFCL, Staxera and Prototech. All these businesses are seeking ways to utilize SOFC technology for a range of applications; most notably stationary power and heat generation.

To date the application of fuel cell technologies of all types to a range of applications have been widely studied and discussed, but the fuel cell units actually developed for operation have tended to be at the small and very small scales, hundreds of watts to several kW, primarily for portable and mobile use, cars and busses, and for stationary power and heat for residential purposes. Fuel cell units of hundreds of kW to MW are not common although there is a clear trend, especially in the USA for going into larger units. Recently several MG size MCFC plants have been constructed.

Where large scale fuel cell units have been constructed, they are in the hundreds of kW range primarily produced by US and Japanese developers. Thus several hundred PAFC units of 200kW have been developed and produced by the UTC company of the USA since the early 1990s, with further units produced in Japan. At present UTC fuel cells is coming to the market with a 400 kW PAFC unit. 80 000 h life time and low cost have been promised for this unit. MCFC units are currently available from several hundred kW through to the MW size, with larger units planned. These are produced by Fuel Cell Energy of the USA and MTU-CFC Solutions and Ansaldo of Europe. Of note is that CFC Solutions utilises imported stack from the USA.

In the field of SOFC technology large scale power units have been limited to a handful produced by Siemens based in Pennsylvania, USA (this SOFC development unit has been put up for sale by its parent) and businesses in Japan, notably Mitsubishi (supported by the Japanese government). To date these units have not met performance expectations and demonstration of large scale SOFC units has been slowed. No large scale units have been developed by European developers, yet they are as well placed to produce these units as developers in the USA and Japan.

The Large-SOFC European consortium is developing the technologies necessary for Large Solid Oxide Fuel Cell-based (SOFC) power plants. The project "Towards a Large SOFC Power Plant" has a three year life, and started on January 1, 2007. The total project budget is 11 Million Euros. The research consortium coordinated by VTT Technical Research Centre of Finland comprises collaborators from several European countries: Wärtsilä Finland Oy (Finland), Rolls-Royce Fuel Cell Systems Ltd (UK), Topsoe Fuel Cell A/S (Denmark), Forschungszentrum Jülich GmbH (Germany), University of Genoa (Italy), BOSAL RESEARCH nv (Belgium), The Switch Oy (Finland) and Inmatec Technologies GmbH (Germany).

### 3 Objectives and structure

The objective is to develop innovative concepts for systems, components and sub-systems and verify their suitability for use in both pressurized and atmospheric SOFC units for large-scale power plants for the medium to long term and to undertake verification of components and sub-systems for these power plants. The focus is on technologies with the potential for SOFC units, the characteristics of which are:

- Hundreds of kW to MW
- Cost of Euro1000/kW
- 50,000 hours durability
- 60% electrical efficiency
- 90% efficiency in CHP mode

The project's primary aim is to address the basic problems of moving from existing kW size SOFC units to units of several hundred kW to MW size SOFC power plants.

The work is divided into two parts:

The first and largest part of the project targets the systems, components and sub-system challenges of large scale SOFC units in the following work packages:

- System analysis, Balance of Plant (BoP) modelling and validation
- System layout and integration
- Components and sub-systems
- Development of industrial scale stack
- Verification of the systems and sub-systems

The interrelation and organisation of the system and component development and verification work is shown in Figure. The WP structure is maintained in this description for a means to easy reference to different parts of the report.

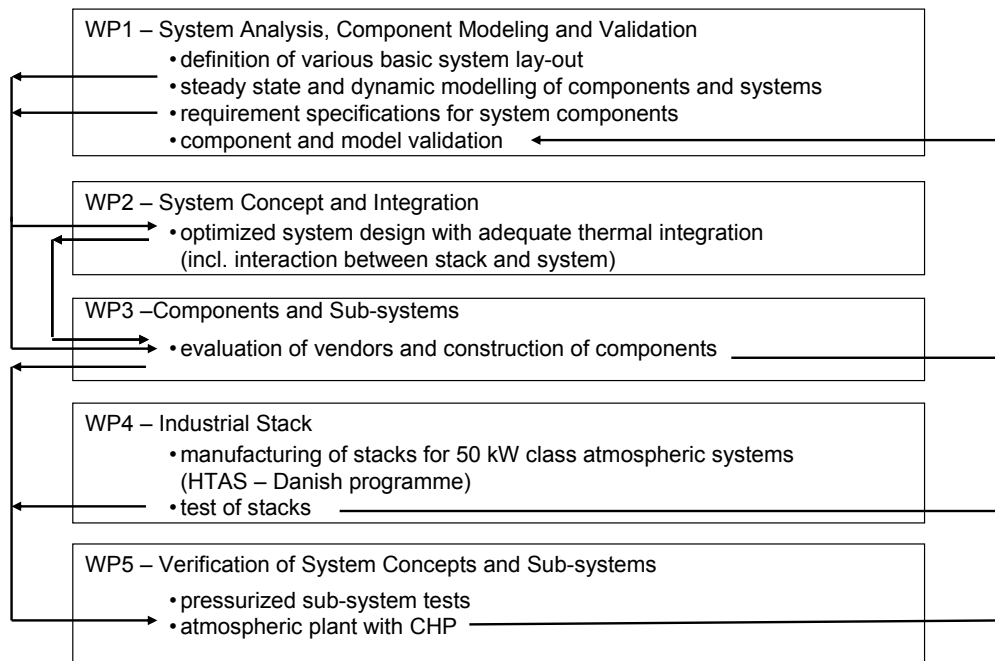


Figure 3.1. Structure of the work on systems, components and sub-system (Work Packages 1-5).

This system development and verification work was supported by a second part (WP6 and WP7), which are packages of work examining the required infrastructure and socio economic issues that will affect installation and operation of SOFC systems. Thus these packages involve:

- Fuels
- Connection to grid
- Safety and Life Cycle Assessment (LCA)
- Training and dissemination of information

### **System analysis, component modelling and validation (WP1)**

The objective of WP1 “System analysis, component modelling and validation” is to develop modelling tools, which are required for plant component layout and design. WP1 is divided in three tasks to obtain this objective: 1) Steady state system analysis of several system layout alternatives 2) component models for dynamic simulation and to further develop and optimize the 1-dimensional dynamic SOFC model to be integrated in the “Apros” platform for 1-dimensional dynamic plant modelling and 3) dynamic component and system simulation.

*System analysis* - Based on the experience of the different partners concerning system layout and test a best suited system concept (atmospheric and pressurised) will be defined. This concept will be calculated in steady state to check its suitability concerning efficiency and complexity and to elaborate the requirements for the different components, necessary in WP 3 for layout and design and to deliver inputs for the plant layout and control done in WP 2.

*Component models for dynamic simulation* - First of all an agreement will be made on the software platform and modelling approach to be used for the dynamic component models and for the system modelling. Based on the 1-dimensional dynamic stack model available at FZJ (programmed in C, to be used under Matlab/Simulink) optimised or additional models will be

established. These models will describe the dynamic behaviour of the components in a simplified way; however, they will be programmed in a way, so that the special properties of the concrete components can be taken into account. The stack model will be validated by the partners using TOFC test results (confidential). Heat exchanger and reformer models available in “Apros” (VTT) and in Simulink (Jülich) will be validated using results of different experiments (steady state and dynamic).

*Dynamic component and system simulation* - Having established the single component models, they will be integrated into the dynamic 1-dimensional system model using the agreed platforms, “Apros” and Simulink. The operational behaviour of the system concepts will be simulated taking into account the optimised plant design (thermal integration) elaborated in “System concepts and integration (WP 2)”. The modelling results will be used to further optimise the system design and the design of the BoP components (developed in WP 3).

## **System concepts and integration (WP2)**

The work is divided into two different work tasks based on the system properties. These are atmospheric systems for planar SOFC technology in single cycle, and pressurised systems in combination with gas turbine as a hybrid system:

### *Atmospheric system*

The objectives of the work performed in this task is to develop, design and optimise a 50 kW fuel cell unit including sub-systems. To achieve high electrical and overall system efficiency together with system cost are the main objectives in the development of fuel cell products for power stationary production. Aspects in sub-system integration and thermal management are critical development areas to achieve these objectives.

Following properties are emphasised:

- To study and improve SOFC system integration in order to increase system efficiency, reliability and cost.
- To minimise overall system cost by reducing the component count or specification.
- To study possibilities for increased sub-system integration such as fuel cell stack, fuel processing, balance of plant components
- Improving overall system performance.
- Improving reliability, maintainability, manufacturability and availability by a improved product structure, where modularization is utilized.

### *Pressurized system*

The objectives have been the thermodynamic and economic investigation of pressurised SOFC Hybrid Systems. Different plant lay-outs and sizes have been analysed in order to understand pro and cons of each system configuration and to compare costs and performance also considering off design and part load behaviour.

### Components and sub-systems (WP3)

The aim was to develop components and sub-systems suitable for atmospheric and pressurised SOFC applications. This work supports the development of a 50kW atmospheric SOFC demonstration unit at Wärtsilä and the ongoing project at RRFCS to develop a 1MW SOFC product. The work on components and sub-systems was organised into 5 tasks with the following objectives.

#### *Turbomachinery and Gas and Air recirculation*

- Development and evaluation of Air (Cathode) and Gas (Anode) blower technologies, including the characterisation of an Anode recirculation blower.
- Steady-state and transient analysis of high temperature fuel cell hybrid systems (and components) and the validation of simulation models.

Objectives were:

To screen available air and gas circulation technologies to match specific requirements set by large SOFC systems in terms of performance and properties and to identify or to develop optimized designs for the purpose. Wärtsilä's activities in the task divided into two separate parts, air blower development and evaluation and anode recirculation blower development and evaluation in view of a full scale system demonstration in WP5.

To characterise anode recycle blower supplied by Wärtsilä to VTT. The operating temperature of the recirculation blower was designed to be  $\sim 300^{\circ}\text{C}$ , twice as high than previously used blowers. The design of the anode recycle loop can be simplified and heat exchanger size decreased as the operating temperature of the recycle blower is increased.

The aim is the steady-state and transient analysis of high temperature fuel cell hybrid systems (and components) and the validation of simulation models. All these activities are carried out with an apt emulator test rig based on a recuperated micro gas turbine (Turbec T100). For the tests performed in this project this facility, developed at the University of Genoa with the support of a former European Integrated Project (FELICITAS), was enhanced with the installation of several additional components. The following points shows the additional equipment installed in the test rig as main objectives of the workpackage.

- Electrical grid connection devices: necessary to operate the machine at electrical grid-connected mode;
- Compressor inlet temperature control system: essential facilities (heat exchangers and control devices) to operate at same inlet temperature conditions for test comparisons;
- Anodic recirculation system based on a single stage ejector: necessary to better study the anodic side performance and the cathode/anode interaction effects;
- Steam injection system: necessary to emulate the turbine inlet  $c_p$  of an hybrid system.

The objective of all these additional facilities was the technology development to obtain the experimental data shown in this report. Particular attention is devoted to the comparison of two different machine control systems for possible applications in mGT-SOFC hybrid systems. The attention is focused on experimental results obtained with both constant rotational speed and constant TOT control systems operating with the machine in its standard recuperated cycle or connected to the fuel cell volume emulator (the modular cathodic vessel).

### *Heat exchangers and recuperators suitable for fuel cell use*

- Development and testing of heat exchangers suitable for use in SOFC applications where temperatures are generally higher than conventional heat exchanger designs.
- Materials property assessment of candidate SOFC heat exchanger materials.

The objective of this work was to develop a heat exchanger for use in the RRFCS system. The RRFCS system operates at temperatures up to 950°C and at pressure. The conditions to which the heat exchanger is subjected are therefore aggressive. To achieve the required corrosion life a FeCrAlY type alloy was selected for a large part of the heat exchanger. This material forms an Alumina surface scale which is exceptionally stable in humidified gas streams, unfortunately it has rather poor mechanical properties and can be difficult to fabricate. Furthermore mechanical property data for this alloy is not widely available.

Key aims of this work therefore, were to:

1. Measure creep properties for the alloy
2. Verify corrosion resistance
3. Design and manufacture a heat exchanger
4. Test a Heat Exchanger under representative conditions.

For heat exchangers the goal was to find heat exchanger alternatives suitable for fuel cell use. The motivation of the task is that there are no dedicated heat exchangers on the market that would be designed for fuel cell use. The challenge in the heat exchanger section is the high operating temperature of the SOFC as well as the demand for gas flows without any particles or impurities. These requirements force to build the heat exchangers out of high temperature steels and thus the manufacturing technologies have to be suited for these materials.

The objective of the work at Jülich was to test heat exchangers suitable for heating air or fuel to the required inlet temperature of the planar stack. The tests should be performed under realistic conditions using hot air which simulates the outlet conditions of the stack. Because the mass flow necessary for a 20 kW system was too high for the existing test benches a new test equipment had to be designed and manufactured.

### *Fuel Processing Equipment*

- Experimental evaluation of the feasibility of using a commercially available catalyst for the reforming of Natural Gas.

Objective in this work task was mainly to assess the effect of the anode recycle to the operation of the fuel processing system. An experimental evaluation of the technical feasibility of a commercially available catalyst for reforming of natural gas with recycled anode exhaust gas was performed. Critical parameters to assess the feasibility were the affinity of the catalyst to carbon formation and the activity of the hydrocarbon conversion with recycled gas. The effects of the anode recycle to the SOFC system was analysed numerically to identify relevant operating conditions for fuel processing system.

### *Power electronics and controls*

- Development of control systems to integrate SOFC system operations
- Development of power electronics for SOFC applications
- Investigation into Grid Connection issues.

The RRFCS SOFC system is a high temperature integrated gas turbine- solid oxide fuel cell (GT-SOFC) system designed to operate on natural gas (NG). It is a hybrid of a fuel cell stack and a micro gas turbine. The integrated-planar solid oxide fuel cell (IP-SOFC) stack operates at a temperature up to 950°C and elevated pressure. The waste heat from the stack is used to drive turbo machinery (TM) that pressurises the system which raises the overall efficiency. The micro turbine contributes some power and also provides the system's air management by maintenance and control of cathode pressure and air flow rate.

This is a complex machine and has to operate reliably and safely if it is to be commercially successful. The objective of this work is to develop a robust control system which integrates all sub-systems and controls both electrical generation and safety functions.

The Switch has concentrated on power electronics. Because of the essential role of power electronics in the matter of grid connection, The Switch has also a minor role in the work on grid connection issues. Main focus is at the performance and safety of the power electronics prototype.

The Switch has built an air cooled 50kW DC/AC converter for atmospheric SOFC system's grid connection that is to be used with the DC/DC converter. The task of VTT in this task was to support the power electronics development by providing expert input on SOFC system design and control issues.

### *Insulation*

- Develop high efficiency insulation systems for pressurised SOFC applications
- Assessment of insulation materials for use in atmospheric SOFC applications.

A significant component of the RRFCS programme is thermal management of the system. The very high efficiency of the RRFCS-SOFC system is in part owing to maintenance of high internal temperatures. An effective insulation system is therefore required. The objective of this work was to review the commercially available insulating materials and determine an acceptable solution for use in the RRFCS system.

Insulation for high temperature fuel cell systems is at this stage of development a niche product. Manufacturers try to promote more or less conventional insulation materials. These materials generate significantly large heat losses as the insulation industry is mainly interested in surface temperature instead of the heat flux. Objectives of this task in the Large SOFC project was to further study and test insulation materials and their suitability for SOFC systems.

## **Industrial stack (WP4)**

The work is divided into two different work tasks: 50 kW planar SOFC Stack Assembly and potential options for stack ceramic material. The objective of the first task has been to (1) identify a suitable stack/system interface, which defines a suitable and well-defined handover-point between stack manufacturer and system integrator while still facilitating integration between the parties and (2) to verify the stack design developed by manufacture of one 50 kWe class stack assembly. The objective for the second task was to investigate and develop scaled up manufacturing processes for the production of fuel cell substrates for use in the pressurised fuel cell system.

### *50 kW planar SOFC Stack Assembly*

Large size SOFC systems present significant challenges for stack technology and design. With increasing size of the system more design features become available like cell size, stack height, stack module coupling and stack/system integration.

The relevant strategies for large scale cost effective industrial atmospheric SOFC stacks are pursued in a national Danish programme, which in 2007 has resulted in a new design for a 3kW stack based on 18x18cm<sup>2</sup> foot print cells. This timing has ensured that state-of-the-art large scale atmospheric stack technology could be utilised for the present project.

The objective of the present Work Package has been to (1) identify a stack/system interface, which defines a suitable and well-defined handover-point between stack manufacturer and system integrator while still facilitating integration between the parties and (2) to verify the stack design developed by manufacture of one 50 kWe class stack assembly. The manufactured stack assembly should serve as a proof-of-concept for large scale atmospheric SOFC stack technology, which later can be extrapolated towards MW class atmospheric SOFC units.

The stack/system interface which was decided early in the project should be tested under laboratory conditions in order to allow for the following scaling up to system level in the 50 kW demonstration unit. Also the performance of the stack itself in this situation under various stack operating conditions was essential to allow for estimates of total system performance. Documented procedures for start-up and normal operation as well as during hot idle stand-by and emergency shut-down were also needed.

Later in the project as stack production proceeded, it was the objective of this work package to monitor preliminary quality assurance parameters and to agree upon final acceptance criteria for individual stacks together with Wärtsilä, balancing the need for homogeneity with the production efficiency.

### *Potential options for stack ceramic material*

Rolls-Royce Fuel Cell Systems Limited is developing a 1MW Solid Oxide Fuel Cell (SOFC) system for applications in stationary power generation. The SOFC stack within this system is based on a series-connected, thick film array of cells deposited on a fuel-carrying porous support substrate. The inert porous support substrate is a structural component and does not provide electrochemical functionality. It does, however, have to fulfil important criteria in order to meet the long-term targets of durability, chemical stability and cost.

As well as low cost a key feature of the substrate is that it has a coefficient of thermal expansion (CTE) which is matched to that of the active fuel cell layers being fabricated on it. A substrate based on Magnesia stabilised Magnesia Alumina (MMA) spinel was therefore chosen, as by controlling the ratio of Magnesia to Alumina the CTE of the substrate can be matched to that of the active fuel cell layers.

The objective of this task was to investigate alternative ceramic precursor powders and processing route for the production of fuel cell substrates. Options considered include:

4. Fine powders
5. Coarse powders
6. Large ingot

## **Verification of system concepts and sub-systems (WP5)**

### *Verification of atmospheric SOFC system*

Wärtsilä has in this project developed, constructed and validated a 50kW solid oxide fuel cell unit. The unit utilizes natural gas at near ambient pressure level enabling high electrical efficiency. The unit is installed into VTT premises with all necessary safety and measurement features in close collaboration with VTT. The main objective of the verification work in the project was to conduct initial verification of the system enabling increased understanding of required process improvements. Verification tests were conducted by VTT according to IEC 62282-3-2 “Stationary fuel cell power systems – Performance test methods”.

Objectives were further detailed in three sub-tasks:

Concept verification unit site planning and preparation - The aims of this subtask were to design and construct a suitable and safe lab facility for the unit.

Concept verification unit procurement and construction - An essential part of the project was to develop and construct 50 kWe SOFC unit. The main objectives of this subtask have been sourcing, procurement and construction related to the concept verification unit. During the design process, described in work package 3, the unit was decided to be designed and manufactured from modules. Module design and manufacturing schedules were established to optimize unit main assembly and furthermore to enable installation and verification in time.

Concept verification unit installation and verification - The aim of the installation and commissioning tasks was to place the unit to the test site, to verify that the unit is safe in terms of personnel and process point of views, to validate the overall functionality of individual components as a part of the overall system, to repair possible defects, and to complete the unit manufacturing in terms of stack module installations. The commissioning tests include inspections of the electrical, mechanical and software systems and their interfaces.

### *Component testing of 50 kW atmospheric SOFC unit*

Through the experience gained in fuel cell development, it has been noticed that many of the used components and sub-systems are not performing as wished. To ensure component

compliance with the requirements, and to verify new concepts, two test rigs for BoP components and sub-systems were planned to construct. These test rigs were used widely to meet objectives of this task described below:

- To validate the air and anode gas blowers developed in task 3.1.
- To verify reformer operation with varying gas qualities, and to try out effects of abnormal conditions on gas quality, catalyst life time, coking tendencies and catalyst behaviour, to have a better understanding on the boundary phenomena and find out the safe operation limits for different conditions.
- To validate integrated reformer in a real SOFC unit.
- To validate the properties, capacity and the life time of the sulphur adsorbents.
- To test and evaluate steam generation methods
- To test heat exchanger focusing in the ratio between heat transfer performance and the pressure losses.

The work was divided in the following subtasks:

Tested and validated working examples of gas and air re-circulation equipment – Objective was to screen available air and gas circulation technologies to match specific requirements set by large SOFC systems in terms of performance and properties and to identify or to develop optimized designs for the purpose. Wärtsilä's activities were divided into two separate parts, air blower evaluation and anode recirculation blower evaluation in view of a full scale system demonstration in WP5.

Tested and validated working examples of heat exchangers – The starting point for the work was a cathode side heat exchanger for atmospheric SOFC system. The objective is to test two individual heat exchangers for atmospheric SOFC system. In testing attention was to be paid on ratio between heat transfer performance and the pressure losses. Another important factor to be tested is the applicability of the manufacturing technology in the high operating temperatures. Part load testing will produce information for start up phase.

Tested and validated working examples of pre-processing and internal fuel processing equipment – The objects for laboratory scale reforming tests were to verify reformer operation with varying gas qualities, and to try out effects of abnormal conditions on gas quality, catalyst life time, coking tendencies and catalyst behaviour, to have a better understanding on the boundary phenomena and find out the safe operation limits for different conditions. These conditions include absence or reduced anode recycling flow, differing O/C –ratio and variations in the inlet gas composition.

Other objects in this subtask were:

- To test integrated reformer in a 20 kW size SOFC unit for realistic results on performance
- To validate the properties, capacity and the life time of the sulphur adsorbent
- To evaluate and test different steam generation methods to find a good, accurate and reliable method with good controllability of producing steam.

## *Review of current test equipment and capability for pressurised SOFC hybrid*

The RRFCFS SOFC is designed to operate over a range of temperatures and pressures and so to characterise fuel cell performance and durability test facilities are required which can mimic these conditions. RRFCFS has developed a series of small scale pressurised test rigs which partially simulate system conditions but they are not capable of replicating all temperatures, pressures and gas compositions. Furthermore the rigs were initially designed to test single fuel cell tubes. As more has been learnt about the interaction between system and fuel cell performance it has become clear that a more representative test environment is required in order to understand all the subtleties of fuel cell performance throughout the operating envelope.

The objectives of this work can be summarised as follows:

1. Increasing the air mass flow to the rig to allow testing of larger fuel cell sub assemblies
2. Increasing the maximum operating temperature of the rig
3. Improving the temperature variation within the test box
4. Devising a means of operating the rigs at reduced partial pressure of oxygen

## **Fuel flexibility, grid connection, safety and LCA (WP6)**

Objective is to ensure that the most relevant issues of using a SOFC power plant are clarified. The objectives are:

- Investigate issues related to the use of different fuels.
- Make the analysis of grid connection rules and standards applicable to large SOFC FC as well as sort out their grid supporting capabilities.
- Provide an understanding of the safety requirements, legal regulations and standardization context in which SOFC systems will be required to operate it.
- Understand how future environmental requirements may affect SOFC systems, and how these systems can contribute to environmental improvements in the regions and markets in which they will operate. With the growing emphasis upon reducing emissions and raising fuel efficiencies, SOFC systems can potentially provide significant benefits for society as a whole.

## *Fuel quality, gas cleaning and reforming*

SOFC is a power source with one of the main benefits being its multi-fuel potential. Therefore issues related to the use of different fuels are investigated. Special emphasis is on renewable fuels. The study include such basic issues as requirements for fuel purity and composition, how to clean the gases to the required composition, the availability of fuels of suitable composition and the required reforming technologies needed for reforming the different fuels.

## *Grid connection*

The large SOFC power units will mostly be integrated with the different energy related grids. The objective is to analyse grid connection rules and standards applicable to Large SOFC fuel cells. Grids under consideration are natural gas grid, power grid and heat grid. The objective of the task was to review the relevant codes and regulations relevant for connecting DG to

electricity, heat and gas grids and to obtain all required permissions to operate a demonstration unit. In addition to the work related to the demonstration unit, codes and regulations were to be reviewed for a selection of countries on a general level. The focus was on the electrical grid connection issues, gas and heat grid connectivity were to be covered less extensively as these are considered less complicated and more site-dependent.

#### *Safety and standards*

The objective is to understand the challenges of installing and operating SOFC systems. This work task will provide a safety analysis and report of that, using 50 kW<sub>e</sub> unit of Wärtsilä Finland as a case. The fuel cell standardization study was included in this WT already at the beginning, but product supportability issues (reliability and maintainability) were increased later on and standardization objectives got less intension than was planned.

#### *Life-cycle analysis*

The objective is to evaluate the potential environmental impact of a SOFC unit that can be developed for large-scale power plants from a life cycle point of view. The LCA study considers a 50kW class atmospheric SOFC CHP unit. This unit is compared, using a life cycle approach, with a pressurized SOFC unit and with conventional power plants. The Task also provides specific rules for the product group to ensure comparability among LCA results within the same product system in the framework of Type III Environmental Declarations (ISO 14025).

#### **Training, dissemination and public activities (WP7)**

The main objective in “Training, dissemination and public activities” was to communicate SOFC concepts, development plans, progress and results to consortium partners, the professional fuel cell community and to government agencies and the general public in the form of (i) technology workshops; (ii) summer schools and introductory courses; (iii) exhibitions in industrial and educational context, interaction with the press; and (iv) creation of a website.

## 4 System analysis, component modelling and validation (WP1)

### 4.1 System analysis

Using the experience with system modelling and layout of its 20 kW system FZJ has elaborated some basic concepts, comparing a concept with catalytic after-burner and air pre-heating via cathode off-gas with concepts using a thermal after-burner and air pre-heating via burner off-gas. For this comparison parameter studies were performed, varying cell voltage and air compressor efficiency.

Criteria for the comparison are system efficiency, size of the air pre-heater and inlet temperature of the anode recycling blower.

Three different plant concepts were investigated, all using anode recycling to avoid steam production.

The first concept (comparable to the original Wärtsilä concept, see Figure 4.1) uses a catalytic burner and heats up the cold air by the cathode off-gas. This leads to a relatively big air pre-heater, because the mass flow is a bit lower on the hot side and the hot inlet temperature is relatively low (about 700°C). The anode off-gas is cooled by the anode inlet gas, which restricts the cooling to about 500°C. After mixing with anode fuel gas the operating temperature for the recycling blower is in the range of 400 to 450°C. Also the pre-reformer operates at a quite low temperature of about 450°C. So nearly no methane is reformed.

The FZJ-hot concept (see Figure 4.2) uses the after-burner off-gas with about 840°C to heat the cold air. This results in a reduction of the air pre-heater size to about 30%. Cancelling the anode gas pre-heater (or anode off-gas cooler) increases the blower operating temperature by about 100 K to about 550°C. The pre-reformer temperature increases to about 500°C, which results in a reforming rate of about 10%. This concept has the lowest number of components.

In the FZJ-cold concept (see Figure 4.3) the recycled anode gas is cooled by the incoming air to about 200°C before it is mixed with the anode fuel gas, which results in a blower operating temperature of 170°C. This requires a heating of the pre-reformer. This concept has the same number of components as the Wärtsilä concept, except for the necessity of a heated pre-reformer. But it has the lowest temperature for the recycling blower. The size of the air pre-heater is reduced to 40% and the fuel cooler also helps reducing the size of the air pre-heater.

To identify the potential of these concepts cell voltage and blower efficiency were varied. These calculations show that there exists the possibility to increase the electric net efficiency from 46% (base case with 750 mV cell voltage and air compressor efficiency of 30%) up to 56% (800 mV cell voltage and air compressor efficiency of 60%).

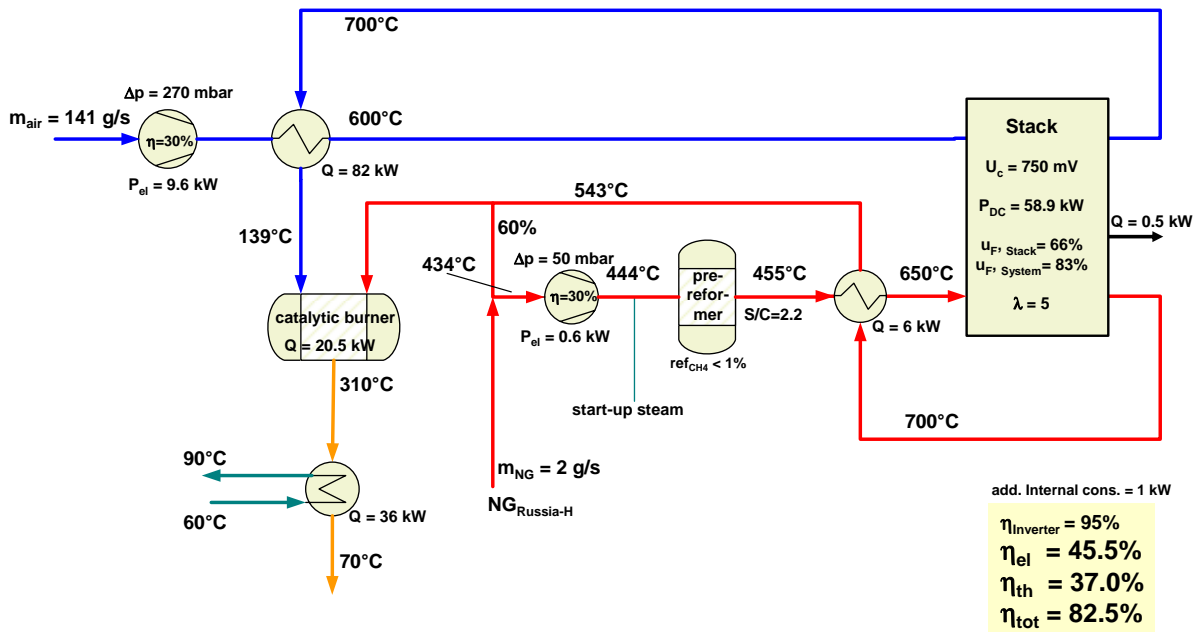


Figure 4.1. Layout of first concept "Wärtsilä old" (hot recycling of anode gas): 750 mV and  $\eta_{\text{compressor}} = 30\%$

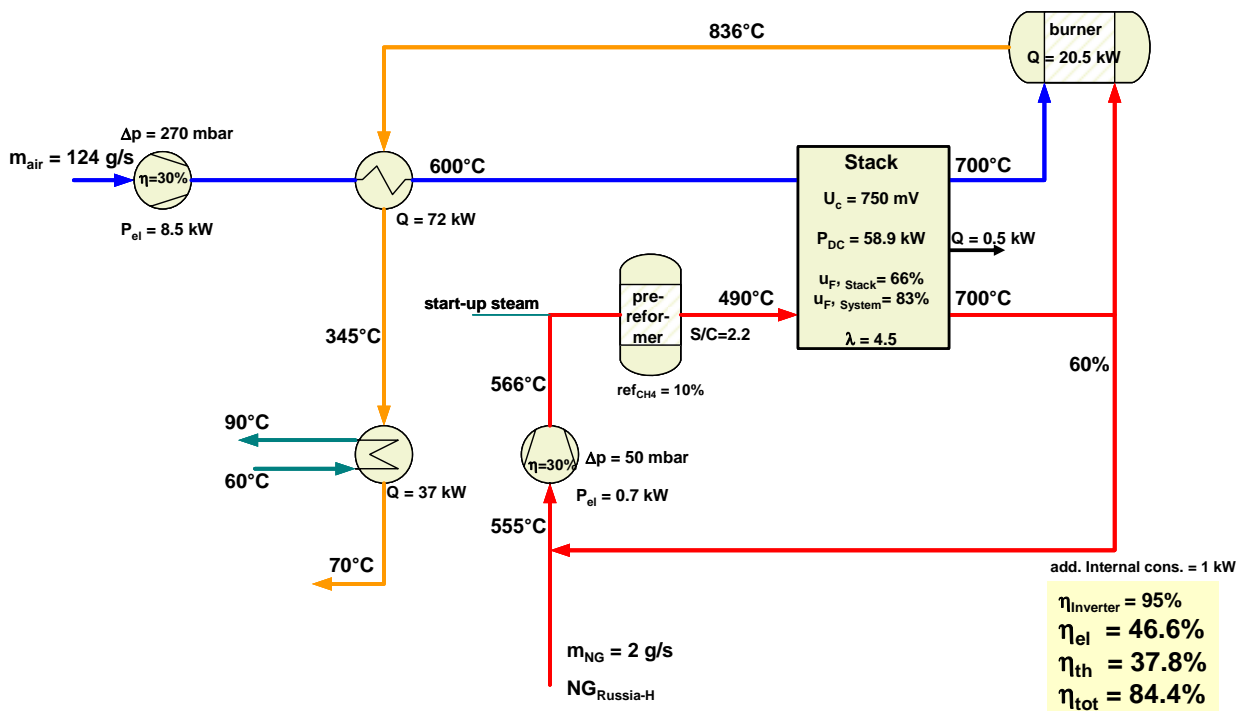


Figure 4.2. Layout of "FZJ hot concept": 750 mV and  $\eta_{\text{compressor}} = 30\%$



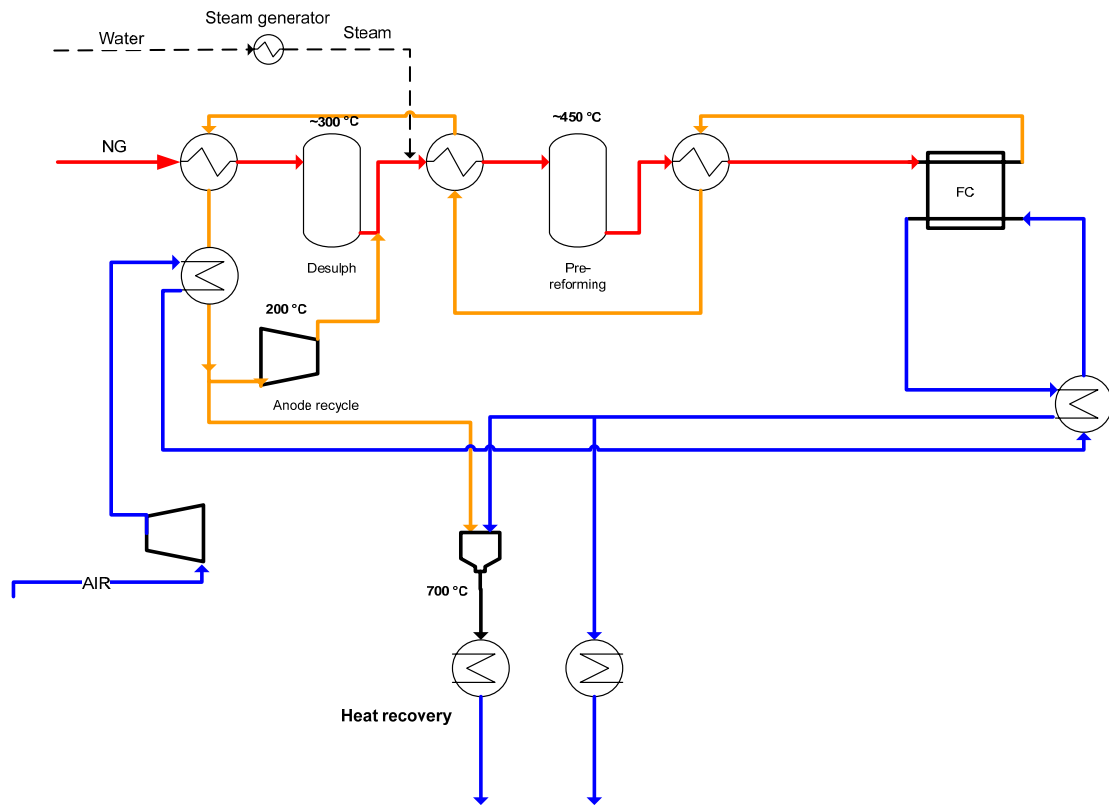


Figure 4.4. Layout of the “Base case” (parallel reactant feed to all stacks) for evaluation (cases 1 and 2)

These studies serve as a basis for the work carried out in WP 2 - System concepts and integration and WP3 - Components and subsystems. Any additional design calculations required for the continuing work on integration were carried out within WP 2.

In Task 1.1 RRFCS has had a supportive role to Genoa University by providing data on the existing RRFCS pressurised fuel cell system, of which the basic lay-out is shown in Figure 4.5. A basic steady state cycle analysis has been carried out using the PRO/II software. PRO/II is a commercially available steady state process analysis package commonly used in the process/chemical industry. The following table gives a performance summary of the system at steady state conditions.

|  |           |
|--|-----------|
| Stack DC nominal power output                              | 272 kW    |
| Stack power conditioning losses                            | 15 kW     |
| Stack fuel utilisation                                     | 75%       |
| System maximum power output (including auxiliaries losses) | 262 kW    |
| System net efficiency                                      | 53.5%     |
| HP Turbine entry temperature                               | 860 C     |
| Stack operating pressure                                   | 7 bara    |
| Stack operating temperature                                | 800-970 C |

The detailed work is done outside LargeSOFC.



Finally all additional features like heat loss extension were validated by VTT as well as the speed up of the model by a factor of 4 which resulted in a speed of about 20 times faster than real-time.

The same 1-D SOFC model was then implemented with the GenFC Interface and was made available for the use in a dynamic system model at FZJ in 4.1.3. The advantages of using the GenFC Interface are the following:

- 1 It was possible to use an existing coupling interface. This piece of software can be used to couple any dynamic component model in the field of fuel cell simulation to the system simulation software Simulink. With this action the project LargeSOFC was coupled to the results of the EC project GenFC.
- 2 The generality of the coupling interface makes it suitable for the other dynamic component models to be developed in 4.1.2.

The developed features and applicability of the 1D SOFC model have been tested by VTT in the “Apros” environment. The robustness of the model in rapid load changes and the effect of varying time steps on simulation results have been tested. Additionally, model tests under various operation conditions outside normal operation under load, such as zero load and fuel or oxidant exhaustion have been reported.

The geometry and operation parameters needed to run the TOFC large stack in system modelling applications using the 1D SOFC model have been evaluated by VTT. Two deliverable reports prepared by TOFC and Wärtsilä were used as basis for the analysis. The eligibility of the obtained results was verified by TOFC. The results were used by Wärtsilä and FZJ in the dynamic benchmark modelling on system level.

### **1D HEAT EXCHANGER model**

The 1D HEAT EXCHANGER model is a spin-off of the 1D SOFC model which already contains heat transfer features. Advantage was taken by using the same programming interface as the SOFC model internally.

Features of the heat exchanger model:

- 1 Differential equations for fuel, air and solid body temperature implemented
- 2 Co and Counter flow
- 3 Heat loss of the model by convection and radiation at the two tips (0 and 1) of the model. Temperatures of the environment and the furnace can be specified.
- 4 Switch implemented which allows non-rectangular channels specified by hydraulic diameter.

For validation of the simulated heat exchanger the modelling results were compared to real measurements performed at Forschungszentrum Jülich. A steady state characteristic of an air pre-heater was considered as well as dynamic simulation.

The results of the dynamic behaviour of the temperatures comparing measurement and simulation are shown in Figure 4.6. The time for the first simulation step is 3600 s and then every sampling interval is 10 s.

The figure shows that the simulated temperatures increase in the beginning and decrease in the end of the dynamic simulation similar to the measurement. Only in the middle area there are differences, which can be explained by the fact that the simulation is adiabatic but in the measurement there is insulation. The reason for the differences between the highest temperatures is that the measurements were taken outside the device whereas the simulation calculated the temperature inside the device (also known from steady state calculations).

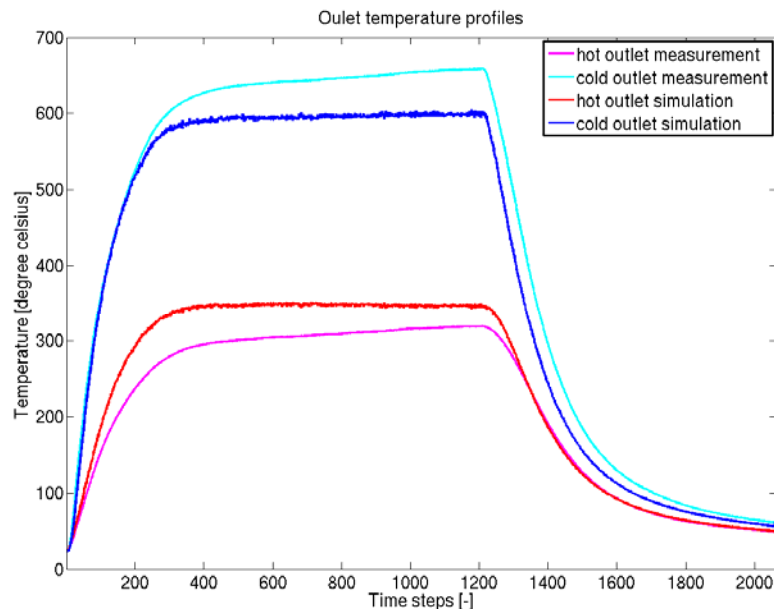


Figure 4.6. Results for the outlet temperatures for measurement and simulation.

## 1D REFORMER model

The 1D REFORMER model is also a spin-off of the 1D SOFC model which already contains heat transfer and reforming features. Advantage was taken by using the same programming interface as the SOFC model internally.

Features of the reformer model:

- 1 Differential equations for fuel temperature, air temperature, solid body temperature and reforming/ shift reaction implemented.
- 2 Co and Counter flow
- 3 Heat loss of the model by convection and radiation at the two tips (0 and 1) of the model. Temperatures of the environment and the furnace can be specified.
- 4 Switch implemented which allows non-rectangular channels specified by hydraulic diameter.
- 5 Switch for number of flows (2 and 1).

For validation of the simulated heat exchanger the modelling results were compared to real measurements performed at Forschungszentrum Jülich. A steady state characteristic of an air pre-heater was considered as well as dynamic simulation.

Based on the 1D SOFC model all three sub-models (SOFC used above 580°C, Reformer used between 350 and 580°C and Heat Exchanger used up to 350°C) were developed and successfully tested under the platforms Linux and Windows XP. After coupling of the three sub-models to the SOFC 1D model (according to Figure 4.7) for heat up with Simulink and “Apros”, using results of EC project GenFC, the models were successfully tested both at VTT using “Apros” and at Jülich using Simulink. Finally the temperature at which the models shift from reformer to stack was changed to an input parameter which can be changed by the user within a certain range.

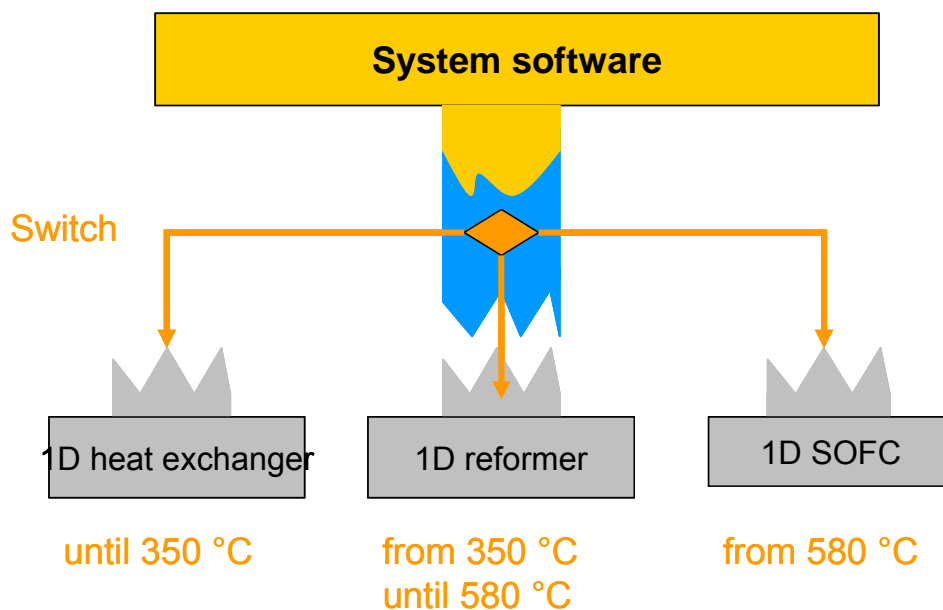


Figure 4.7. Coupling of the three sub-models to system software

### 4.3 System Component Validation

Beside the validation of the 1D Stack model by comparison with TOFC stack data, VTT and Jülich did validation of the “Apros” respectively Matlab-Simulink models by comparison with measured data of heat exchangers (Jülich type, company Raucell) and reformers (Jülich type at FZJ and TOFC type at VTT). Both components were compared with steady state and dynamic measurements. Additionally, VTT used fan models available in “Apros” to model a recycling fan tested in WP3 of the project. The fan model was validated in steady-state operation.

#### 1D SOFC model

The three stack test cases reported by TOFC and Wärtsilä have been simulated with the 1D SOFC model. A good agreement was found.

Also the simulations with 1D SOFC in Simulink at FZJ showed little discrepancies in the outlet gas composition and in the operational parameters (less than 2% in galvanostatic mode respectively 3% in potentiostatic mode).

## **Reformer**

Using the reformer model of “Apros” and comparing the results to chemical equilibrium values the outlet temperatures and molar fractions calculated by “Apros” seem to be reasonable. The correspondence to the single experimental result for the reformer outlet temperature in once-through fuel operation seems to be satisfactory.

The calculations with the FZJ model in comparison to measurement results with a special designed planar reformer (using nickel cermet as catalyst) show, that at lower reforming temperatures the relative deviation between real composition and equilibrium composition strongly increases. The used kinetics describes this behaviour with a very good conformity. Also the calculated outlet temperatures of fuel and heating air agree quite well with the measurements. Calculations of steady state behaviour show that the cascade model is working properly. The differences in temperature are smaller than 30 K and for the gas composition less than 10%. Also the calculation for the dynamic behaviour shows good agreement with measured values of outlet temperatures.

## **Heat Exchanger**

The somewhat complicated design of plate type heat exchanger from company Raucell can be modelled by VTT as well as by FZJ in good agreement in steady state cases. In the FZJ calculations a deviation was found on the hot outlet side of +12% at higher flow rate and +11% at lower flow rate and on the cold outlet side of -5% at higher flow rate and +6% at lower flow rate, which both can be seen as an acceptable deviation.

The results of the dynamic simulation of the heat exchanger including its heat up and cool down phase in case of load steps compared to the measured values fit quite well using counter flow configuration.

Calculations of the FZJ-design plate type heat exchanger show deviations in steady state on the hot outlet side of 12% at high flow rate and 3% at low flow rate and on the cold outlet side of 3% at high flow rate and -10% at low flow rate, which both can be seen as an acceptable deviation. The results of the dynamic simulation of the heat exchanger including its heat up and cool down phase compared to the measured values are in very good agreement in the heating and cooling phase and an acceptable deviation is found in the steady state phase.

## **Recycling fan**

A recycling fan manufactured by CAP, Japan, was tested at VTT.

The operational behaviour was analysed using “Apros” and proposals for improvements could be elaborated.

Based on these findings it can be stated that all relevant components are available for the system calculation to be performed in Task 1.3.

## **4.4 Dynamic component and system simulation**

Based on the system lay-out work performed in the first year a simplified concept (“Wärtsilä Catalytic Simplified Concept” WCSC – see Figure. 4.8) was defined at full load and 50% part

load to start system simulation. Based on first steady state calculations, parameters for the various components of the FZJ model were provided. The cases and parameters for stack and component validation were agreed on in a meeting in Jülich. All these data were also used for component validation in 4.1.2. The elementary balance and the system parameters such as: fuel utilisation degree, system utilisation degree, current density, plant power, number of stacks, and number of cells in a stack were used for first steady-state calculation of the stack. The model was also checked for the calculation of several stacks connected in parallel.

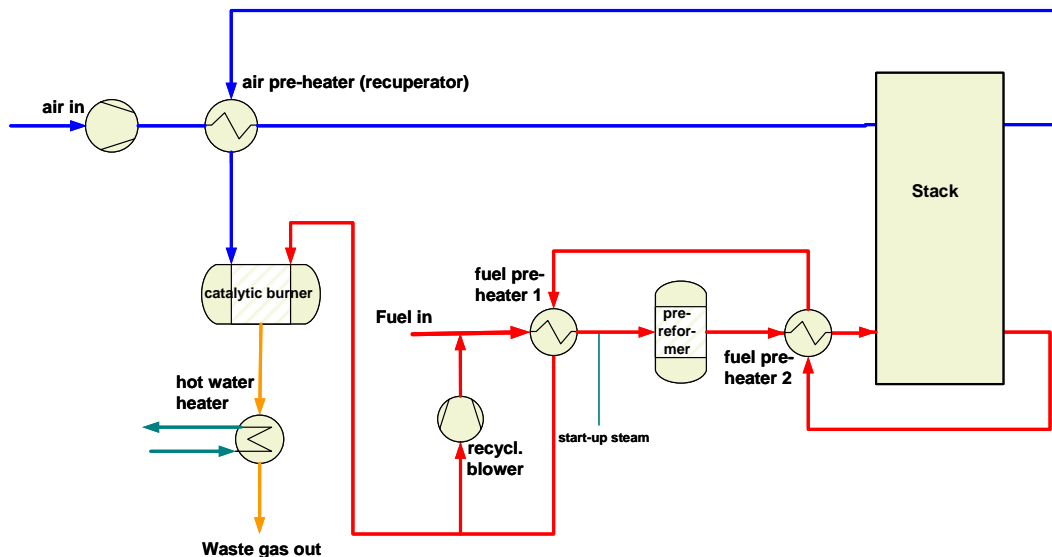


Figure 4.8. Wärtsilä Catalytic Simplified Concept

Wärtsilä and VTT use the commercial environment “Apros” (Advanced Process Simulation Software) for SOFC component and system simulations. Forschungszentrum Jülich uses the commercial package Simulink for the system simulations implementing special developed component models. Apros 5.09 version created on 29.05.2009 was used for the modelling and simulation of the system. The solid oxide fuel cell stacks were modelled with the 1-dimensional SOFC model prepared by FZJ. The SOFC1D model version was v2.6.

The system does not contain any active controllers. The purpose is to study the interactive behaviour of the main components and to compare the behaviour of the VTT/Wärtsilä system model and the FZJ system model.

The components, i.e. the heat exchangers, reformer and SOFC stack, are modelled with the validated component models.

To study the system behaviour and to compare the FZJ and VTT/Wärtsilä models two dynamic simulations were performed.

Case 1: 100 % to 50 % to 100 % load.

Here the fuel and air flow rates are ramped along the current output. The ramp rate is such that the step is performed in 15 minutes to both directions. The fuel recycle ratio is maintained at 60 %.

Case 2: current density from 100 % to 50 % and back to 100 %.

The current ramping rate is as in Case 1. Recycling ratio and fuel and air flow are maintained constant. This simulation is intended for the studying and comparing of the cool down and heat up behaviour of the models. It is not intended to be a realistic simulation.

Case 1 showed good results with respect to system behaviour. The system temperatures maintained mostly in the same region before and after the load transition. Also the performance with respect to power output and efficiency of the system was good throughout the simulation.

For the nominal load (100% fuel flow) the temperatures calculated by the two models do not differ more than 20...30 °C, besides two temperatures of the fuel gas at the cold inlet and hot outlet of the first heat exchanger in the fuel gas line. This could be shown to depend strongly on the size of the heat exchanger HEX1 (in front of the pre-reformer, which determines the actual amount of heat transferred. The temperatures at the hot side in (which is equal to hot side out of fuel HEX2, which is located between pre-reformer and stack) and at the cold side out, which is the temperature of the fuel gas entering the pre-reformer, are always almost the same for both models.

Similar differences in the temperatures of the fuel gas occur at the fuel HEX1 for partial load. Here, however, larger differences in temperatures occur also at the air pre-heater and the fuel HEX2, mainly affecting the temperatures of the air and fuel entering and leaving the stack. Stack and system parameters are, however, still consistent between the two models.

In Case 1 the transition from 100% load to 50% and back appears to be quite smooth according to the simulations. The stack and system fuel utilization factors remain constant and thus the reformer operation does not vary much; the degree of reforming changes 2–3% which inflicts a small change in the reformer outlet methane content (see Figure 4.9) and causes the reformer outlet temperature to stay nearly constant. Also the flow rates change smoothly as they are implemented with boundary conditions. Stack temperatures recover relatively fast after the load change back to nominal load (see Figure 4.10).

The efficiency of the system is high; at 100 % load it is close to 55% (LHV) and at 50% load it is slightly over 62% mostly due to the increased cell voltage.

Case 2 also showed quite good agreement between the two models.

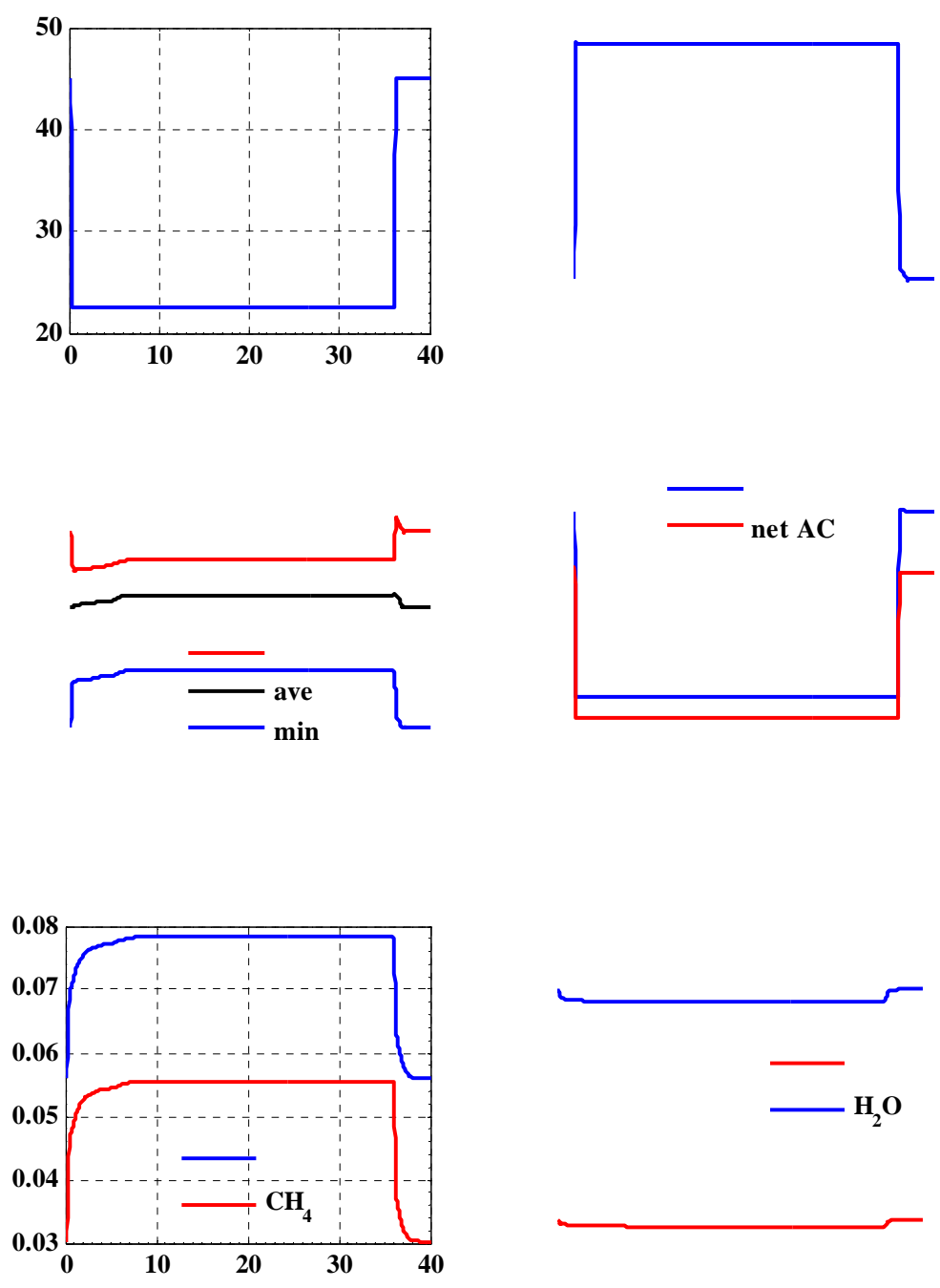


Figure 4.9. Case 1: results from "Apros"/VTT – Stack and Reformer data

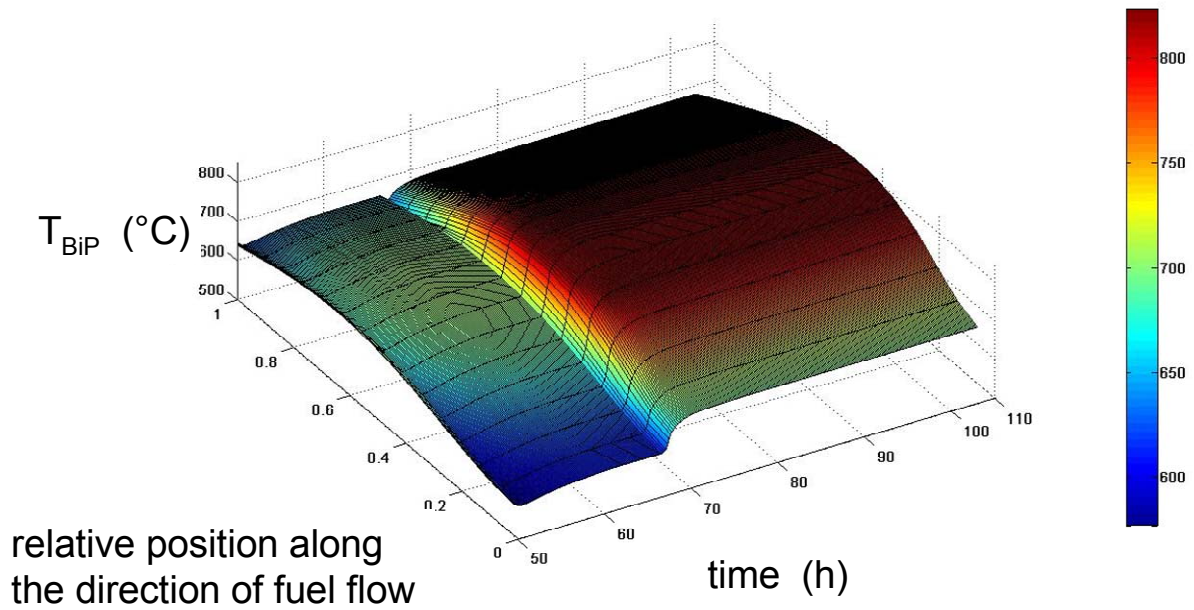


Figure 4.10. Temperature distribution in the SOFC stack as function of time and relative position along the direction of the fuel gas flow during the load change from partial (50% fuel flow) to nominal (100% fuel flow). (Simulink model)

## 5 System concepts and integration (WP2)

### 5.1 Atmospheric system

During the whole project the work has been highly focused on to complete a functional highly integrated, but still manufacturability and maintainable fuel cell unit. This has been a challenging task.

In the start-up of work a huge effort was put on to transfer information and knowledge between work package task partners, in this case FZJ, VTT and Wärtsilä. All partners had previously to this projects some own understanding of how to integrate and design a fuel cell system. By keeping this information sharing sessions important knowledge were transferred between partners and this was a base for a productive cooperation.

During the first parts of the project the collaboration with WP1 where the different process alternatives were developed, analyzed and finally selected. The different process layout concepts had very much impact on the selection of sub-systems and process components to be integrated. WP2 was also involved in analyzing the different process layouts and commenting the benefits in the different alternatives from design and integration point of view.

In the workshops where the different integration concepts where created based on the selected process layout. The different alternatives were analyzed and finally selected. Other findings were discovered during the analysis of the different process layout concepts. The thermal integration of the different process components that have different operational temperatures, have impact on each other and therefore the fuel cell unit needs to be split into selected heat zones. The optimization of these was selected as a supporting function for the functional integration of the selected sub-system. The different heat zones in the fuel cell system can be seen in 5.1.

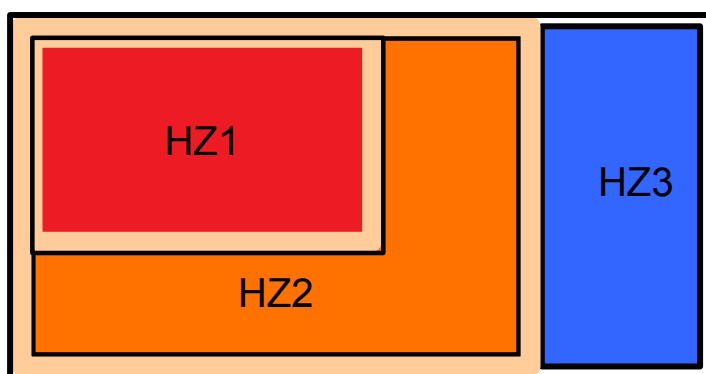


Figure 5.1. Tthe different heat zones in the fuel cell system

The first main achievement in this task was to select the different sub systems to integrate. The following sub-systems, and other parts of the fuel cell unit that have huge impact on the efficiency cost and performance, were decided to integrate:

- Fuel cell stack operation environment

- Fuel processing system
  - Fuel processing unit
  - Fuel treatment unit
- Fuel post combustion
- Heat zone optimization

The selected subsystems which were selected for further investigation and finally integrated can be seen in 5.2.

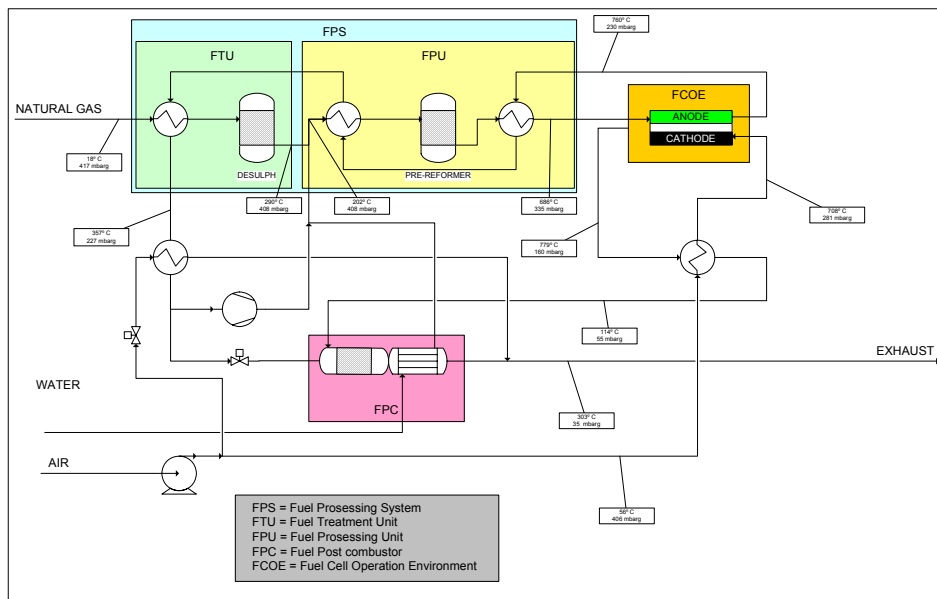


Figure 5.2. Subsystems selected for further investigation

When the different sub-systems and heat zones were selected for further investigation and development, the requirements and specifications for the selected areas needed to be gathered. The flow values for the selected process layout were calculated in WP1. The requirements and safety regulations was studied and feedback was given to process development in WP2 so that the unit is under the limitation of classification as pressure vessel. The maximum allowed pressure made it possible to select almost any type of heat exchanger and reactor vessel for the integration of the fuel processing components to integrate.

### Fuel cell stack operation environment

The fuel cell stack operation environment is the most complex and therefore also the subsystem generating the biggest cost of the different sub systems. The complexity is generated by the entire requirement for the proper and safe operation of the fuel cell stacks.

The different components requiring the complex operation environment are:

- Operation temperature 750 C°
- Operating pressure max 500 mbar
- Spooling of possible fuel leakages required
- Compression force for fuel cell stacks 6-12 kN
- Even flow distribution for the fuel and air feed
- Electrical connections and isolations

The complexity is generated by the combination of the different requirements, e.g. electrical connection and isolation in combination to high temperature makes solutions easily expensive and complex.

A strong focus on requirement engineering was the first stepping stone in the development process of the fuel cell operation environment.

These all requirements have been analyzed and the integration concepts have been analyzed according to this. The basic idea from which the concepts was created from is viewed in Figure 5.3

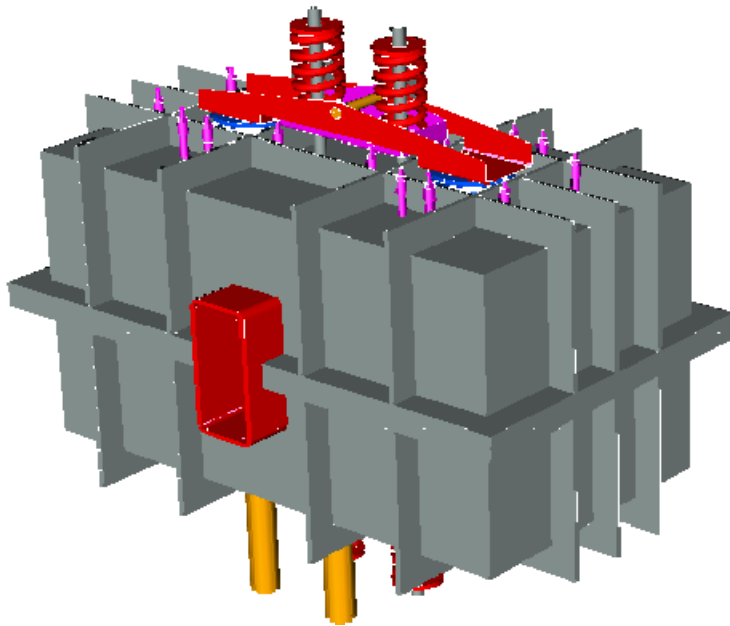


Figure 5.3. The concept that was selected for the further development

### **Fuel processing system**

The fuel processing system was divided into two integrated units. The fuel treatment unit, where sulphur, which is poisonous for the fuel cells and reforming catalyst is removed, and the fuel processing unit where the fuel gas is reformed to suite the fuel cells. A detailed description of the requirement functionalities, operating temperatures is reported in the deliverable D2.2. The units of the integrated sub-systems in the fuel processing system are visualized in a schematic figure (5.4).

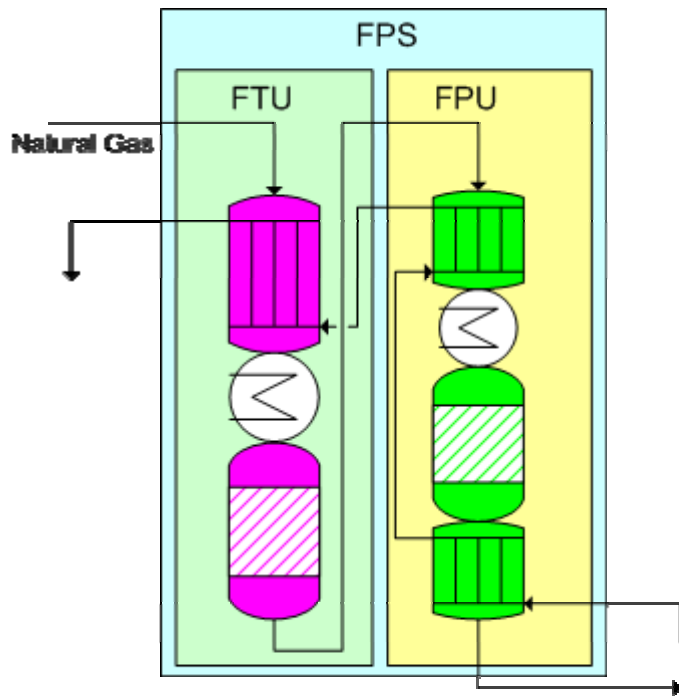


Figure 5.4. The integrated units of the fuel processing unit.

### Fuel post combustion

The fuel post combustor FPC requirements are to combust the non re circulated off gas, using the air exhaust from the fuel cells as oxidant. The combustion produces heat and the heat is used for evaporating water into steam. The fuel cell and reformer requires steam to operate and this will be used when the steam in the re circulated gas is not sufficient. The heat from the exhaust gas produced in the post oxidation is recovered outside the fuel cell unit, and can be used for several purposes based on the different applications

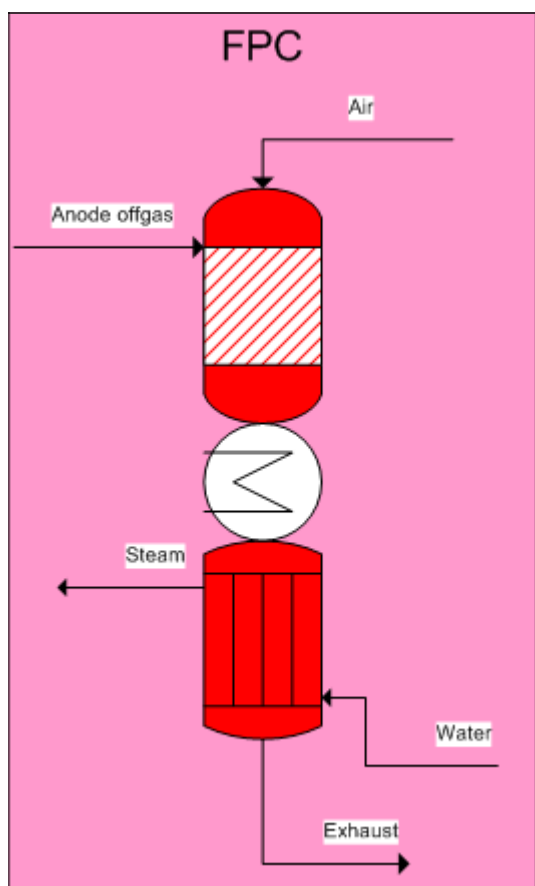


Figure 5.5. The integrated process components of the fuel post combustor

The main achievement during this phase of the project was the thorough requirement engineering which set a solid base for the detailed engineering and design. The selected concepts still has several features and functionalities that needed to be fixed and evaluated in terms of manufacturing, cost effectiveness, lifetime maintenance etc.

During the last phase of the task the design and engineering of the complete fuel cell unit was executed. All the selected sub-systems to integrate was engineered and manufactured with various manufacturing methods.

The modularization of the unit was done during the finalization phase of the layout engineering, and the layout was split into 8 different modules based on functionalities and operational temperature. The modules are;

1. Platform module
2. Stack support module
3. Stack sub-module
4. Thermal components module
5. Middle module
6. Cold air module
7. Instrument panel module
8. Cover and insulation

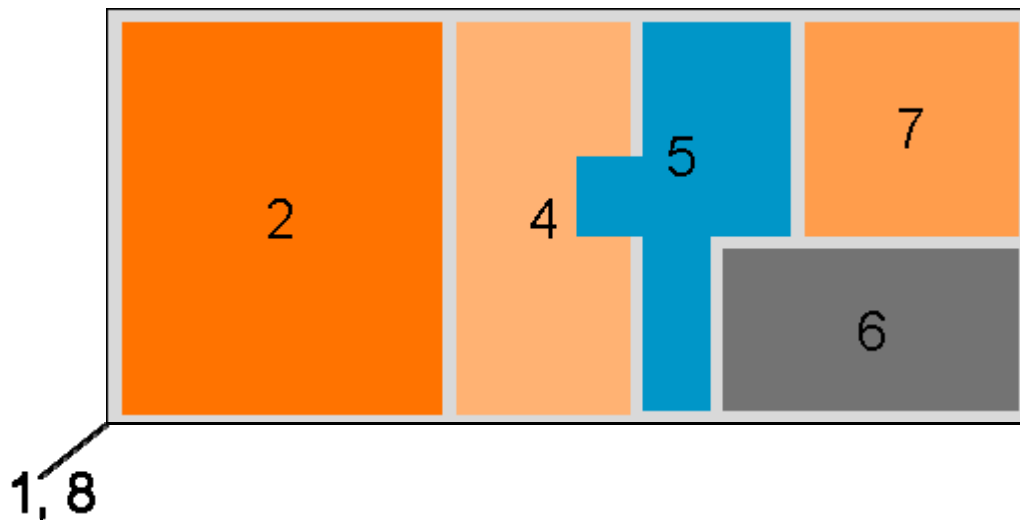


Figure 5.6. Schematic layout and modular division from a bird's perspective

The modularization opens several possibilities for future development project, where only a selected module / subsystem is redesigned. The modular division has improved change management, quality management and control, cost follow up and lead time in production dramatically compared to our previous experiences from the WFC20kW units.

Time vice the detail design and finalization was probably the most underestimated task of this work package. The large amount of drawings and articles to be documented and managed in an effective and controlled manner needs effective tools and systems.

The completed design consisting of a modularized product hierarchy, with selected integrated subsystems is a huge achievement and a result of a massive effort from all partners in this project. The successful installation and production of the completed unit is a good indicator of the design.

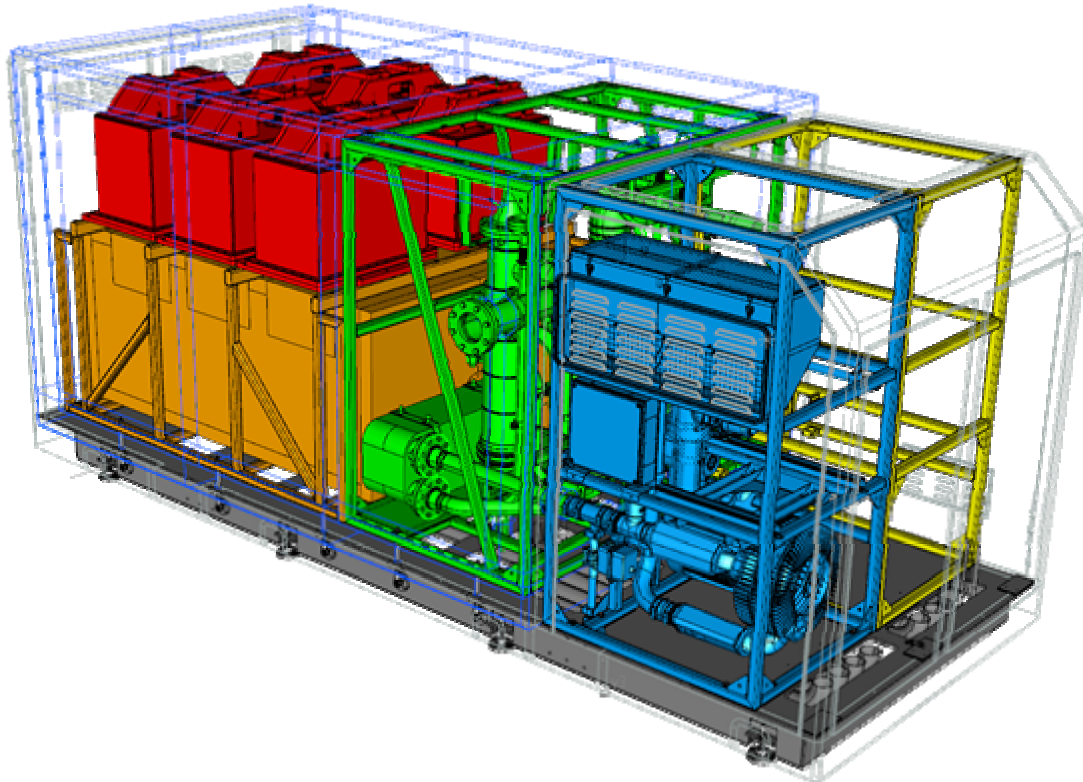


Figure 5.7. The completed design of the wfc50kW unit.

## 5.2 Pressurized system

### RRFCS Stack based Hybrid Systems Study

The thermodynamic and economic models representing the system configurations considered have been realised and the complete comparison has been carried out.

A short overview of the results is depicted in Figure 5.8 and Figure 5.9.

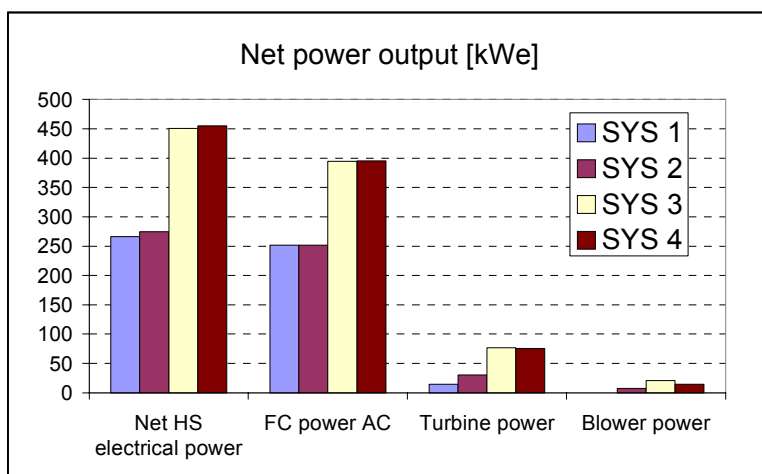


Figure 5.8. Net power output distribution for SYS 1, SYS 2, SYS 3 and SYS 4

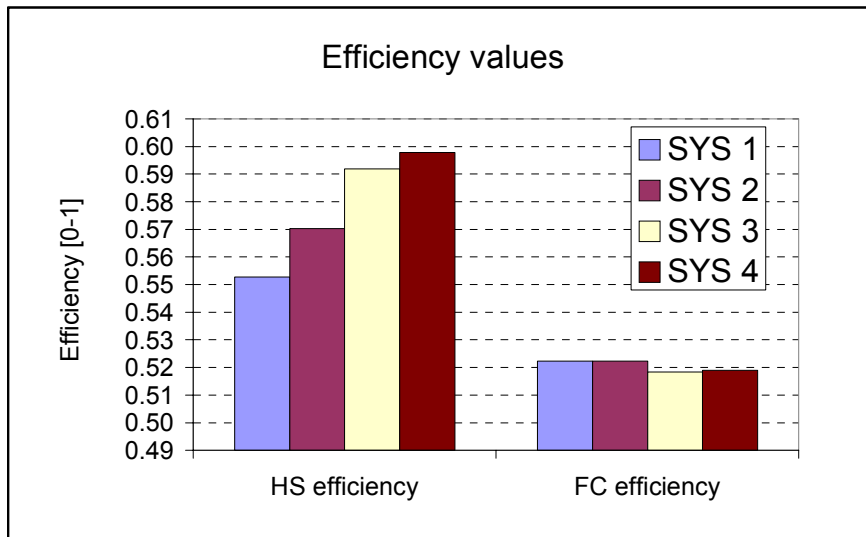


Figure 5.9. Efficiency values for SYS 1, SYS 2, SYS 3 and SYS 4

The main difference between SYS 1 and SYS 2 is represented by the turbine power outlet that in SYS 2 can achieve 30 kW<sub>e</sub> with respect to 14.6 kW<sub>e</sub> of SYS 1.

Taking into account that the turbine inlet temperatures and the turbo machinery adiabatic efficiencies are constant for both cases, the turbine power outlet improvement is given by the lower air compression work in SYS 2. The power generated by the fuel cell results constant for both cases in accordance with the main assumptions considered (operative temperatures and pressures, recycle factor, fuel cell size). The power requirement for the blower in SYS 2 is 7.23 kW<sub>e</sub>. This parameter is strongly affected by the operating conditions such as the flow temperature, the recirculation factor and other assumptions (pressure losses and adiabatic efficiency). Despite of the blower power requirement, the net overall power outlet of SYS 2 is 274.8 kW<sub>e</sub>, almost 10 kW<sub>e</sub> higher than SYS 1.

The air mass flow rate worked out by the commercial micro gas turbine considered here, leads to scale up the system at about 450 kW<sub>e</sub> that is almost double with respect to SYS 1. More precisely SYS 3 can generate 450.7 kW<sub>e</sub>, while SYS 4 455.2 kW<sub>e</sub>; considering that the power produced by the fuel cell and gas turbine is the same for both the systems, the total power difference is mainly due to blowers requirement.

The operative conditions of the blower in SYS 3 are more expensive in terms of energy requirement (20.6 kW<sub>e</sub>) with respect to the blower positioned as in SYS 4 (14.6 kW<sub>e</sub>). On the other hand it is important to remark that blower is working at very high temperature, near to 970 °C in the system SYS 4 and to 850 °C in plant called SYS3 so, in both cases, the thermal stresses can affect the reliability and the cost of the component.

Systems with recuperated MGT (SYS 3, SYS 4) show an higher percentage of turbo machinery power production (16.5% of total power production) with respect to SYS 1 (5.5%): this difference is due basically to two reasons:

- The high mechanical work avoided for the air compression
- The lower anodic recirculation factor that allows a higher flowrate.

SYS 2 can reach 57.0 percentage points in terms of efficiency with respect to SYS 1 that achieves 55.2 percentage points. The present investigation shows that the use of a cathode ejector reduces SYS 1 global efficiency of 1.8 percentage points.

The introduction of a recuperated MGT can increase the global efficiency of the reference case up to almost 60%. It is important to mention that the efficiency increase is feasible only growing the entire size of the system moving from around 266 kW<sub>e</sub> to 452 kW<sub>e</sub> (due to the size of the microturbine considered).

The installation of the blower in the cathode recycle can generate an efficiency increase of 0.59 percentage points moving from 59.2% for SYS 3 to 59.8% for SYS 4.

It is very interesting to note how the reduction of total pressure on the SOFC cathode side does not generate a huge reduction of the fuel cell efficiency. The reduction of the recycle factor increases the partial pressure of the oxygen at cathode inlet reducing at least the expected SOFC performance losses. The reduction in terms of efficiency is estimated at around 0.4 percentage points moving from 52.2% of SYS 1 to 51.8% for SYS 3 and SYS 4.

The recuperated system can increase, as demonstrated, the global efficiency of about 4 percentage points. Moreover the heat exchanger can help the start-up and the shut-down procedures. On the other hand the implementation of a heat exchanger increases costs, volumes and the complexity of control strategy for the whole system.

In parallel to the thermodynamic analysis, the global costs of the hybrid systems have been compared to the most worldwide used technologies in the field of the distributed generation: a small simple cycle gas turbine and a reciprocating engine. The results show that high natural gas price can strongly favour systems with high efficiency such as SOFC hybrid systems as shown in Figure 5.10.

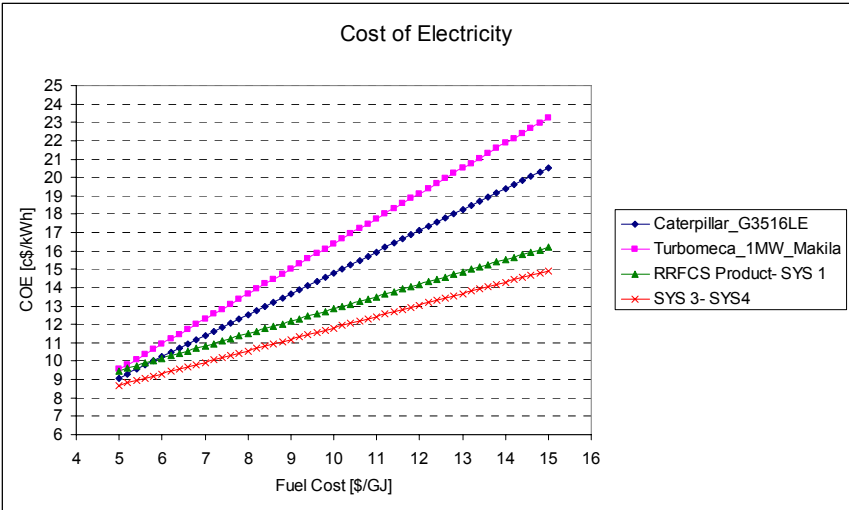


Figure 5.10. Cost of Electricity in the first operating year vs. natural gas cost

To have a consistent economic comparison between different systems for the power production in the field of the distributed generation, a reciprocating engine (Caterpillar G3516LE) and a small gas turbine (Turbomeca Makila) have been analysed.

In Table 5.1 the main thermoeconomic assumptions for the power units considered are reported.

SYS 1 and SYS 3-SYS 4 size assumed for this analysis is about 1 MW<sub>e</sub>: SYS 1 package is composed by four 266 kW<sub>e</sub> modules, SYS 3-SYS 4 package is composed by two 452.5 kW<sub>e</sub> modules. SYS 3 –SYS 4 efficiency is assumed as an average between both systems.

SYS 1 capital cost has been directly provided by RRFCS [14]. SYS 3-SYS 4 includes the cost of the stack and BOP provided by RRFCS and the cost of the recuperated MGT Turbec T-100 provided by the manufacturer. Caterpillar G3516LE and Turbomeca Makila capital costs are taken respectively from [11, 12] and [13]. O&M costs have been estimated from [15]. The variable costs as the natural gas price and the electrical revenue are referred to [10].

In Figure 5.10 the cost of electricity for the systems considered varying the natural gas cost is reported. It is evident how the increase of the natural gas cost favours drastically the hybrid systems that are supported by a higher thermodynamic efficiency. SYS 3-SYS 4 cost of electricity reduction is justified by the turbo machinery lower capital cost: this is due by the large scale production that reduces consistently the cost production.

Table 5.1. Main thermoeconomic assumptions for distributed generation power systems.

|   | CAT<br>G3516LE | Turbomeca<br>Makila | RRFCS-<br>SYS 1 | SYS3 –<br>SYS4 |
|---|----------------|---------------------|-----------------|----------------|
| Power [kW <sub>e</sub> ]                          | 1020           | 1050                | 1064            | 905            |
| Efficiency [%]                                    | 32.4           | 27.1                | 55.2            | 59.4           |
| Inflation [%]                                     |                |                     |                 | 3.0            |
| Nominal escalation rate of PEC [%]                |                |                     |                 | 3.0            |
| Nominal escalation of Fuel and other supplies [%] |                |                     |                 | 3.0            |
| Book life [y]                                     |                |                     |                 | 15             |
| Hours per year [h/y]                              |                |                     |                 | 8000           |
| Construction time [y]                             |                |                     |                 | 1              |
| Sale Price of Electric Power [\$/GJ] [10]         |                |                     |                 | 47.55          |

### Generic fuel Cell stack Hybrid Systems Study

The thermoeconomic models of four generic pressurised SOFC hybrid systems (SYS5, SYS6, SYS7 and SYS8 in Table 5.1) with and without fuel decarbonisation and carbon dioxide sequestration have been successfully constructed and used. The CO<sub>2</sub> separation section, based on the use of an aqueous solution of blended amines detailed model has been investigated in order to evaluate its operational behaviour (e.g.: auxiliary and steam consumptions) and capital cost.

It is important to underline that the installation of fuel decarbonisation and carbon sequestration systems is responsible for a considerable increase in plant complexity, affecting overall efficiency, capital cost and cost of electricity. In Figure 5.11 and Figure 5.12 the SYS6 and SYS7 are depicted respectively.

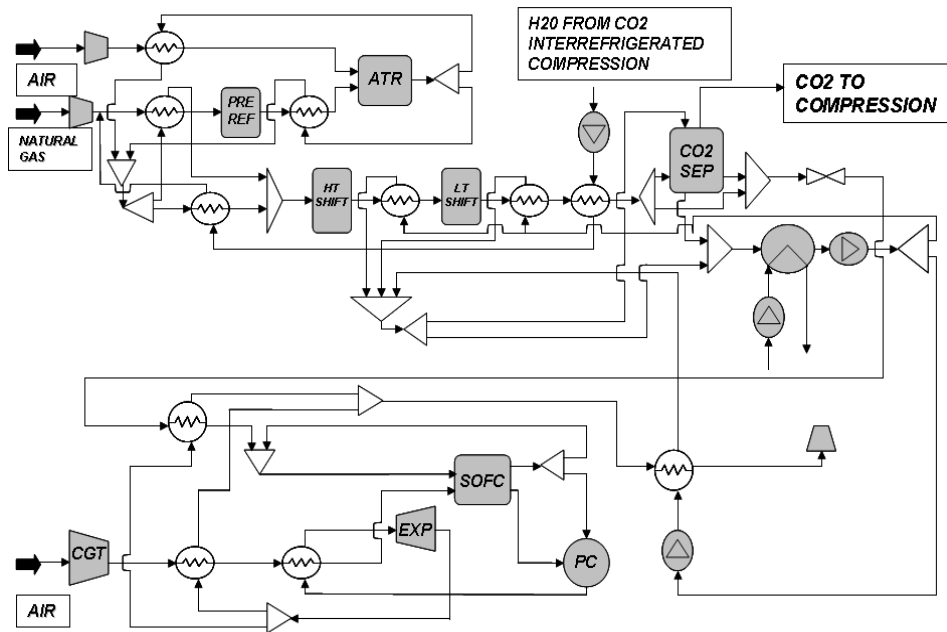


Figure 5.11. Pressurised SOFC hybrid system fed by decarbonised syngas layout (SYS6)

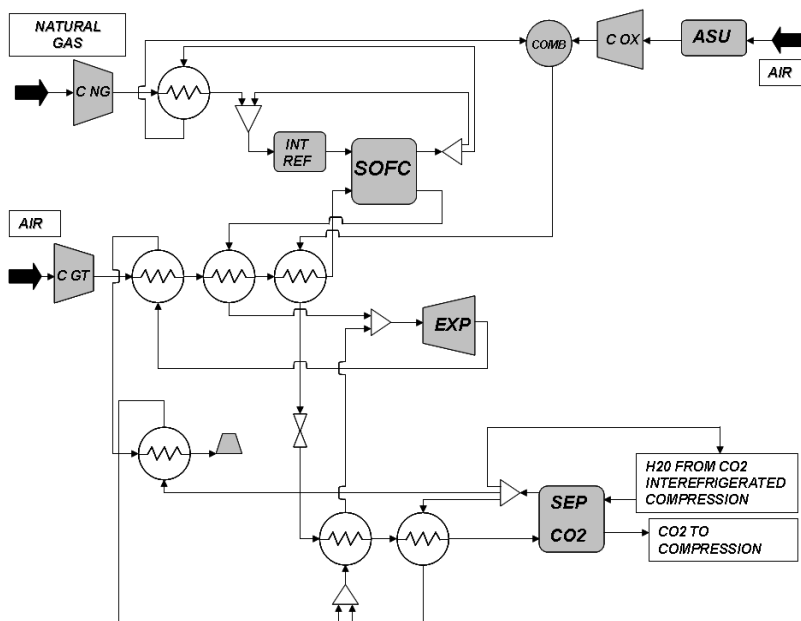


Figure 5.12. Layout of pressurised SOFC hybrid system with CO<sub>2</sub> separation obtained separating anode and cathode sides (SYS7)

The thermodynamic analysis shows that a significant efficiency loss is caused by the fuel pre-treatment and CO<sub>2</sub> separation and compression. This is the reason why the hybrid system with CO<sub>2</sub> separation plant for steam condensation has been investigated and developed; the results have been encouraging from the efficiency point of view.

The results of the thermoeconomic analysis show that the considerable increase in the total investment cost for the amine separation plant is accompanied by a significant net efficiency decrease, causing the COE to reach very high values.

The implementation of the carbon dioxide separation by condensation of the exhaust streams of the system appears to be really attractive in terms of efficiency and costs. Assuming the same COE at the first operating year, the carbon tax applied to SYS 5 to get to SYS 6 is equal to 159.6 \$/tonCO<sub>2</sub>: this value is very far from the actual values of CO<sub>2</sub> emissions quotes (at present the price of CO<sub>2</sub> quote is at around 15 €/ton CO<sub>2</sub>).

### **Off-design Performance Study**

The last part of the work has regarded the study of the operating envelop of the hybrid systems. To this aim a model, already realised by the University of Genoa, has been enhanced to represent the systems in study.

The system performance model was developed in Matlab-Simulink<sup>®</sup> environment and comprises different sub-models that were designed from scratch or upgraded from previous ones and tested or validated were possible; in particular it comprises: ejector steady state models for both cathode and anode loop, cathodic and anodic loop circuit characteristic models, detailed reformer model, detailed stack model, compressor models, turbine models, off-gas burner model; non negligible heat exchanges between certain components or with the ambient are also modelled. The model calculates all main parameters such as pressure, temperature, mass flow and composition at inlet and outlet of all the components. Together with this information, the model provides also a complete distribution of the operating parameters inside stack and reformer.

In order to characterise the system behaviour, its operating envelope was calculated taking into account the effect of ambient temperature and load. Given the complexity of the system, various constraints have to be considered in order to obtain a safe operating condition not only for the system as a whole but also for each of its part; in particular each point calculated had to comply with limits on stack temperature distribution, maximum and minimum temperatures, limits on high and low pressure spool rotational speed and at least at the beginning limits on the depressurisation of the system. The system model used for the calculations integrated the detailed stack model since only in this way hot or cold point or unfeasible temperature distributions inside the stack could be detected as a result of the system operating condition. A drawback of this approach was an increase in calculation time given the detail of the stack model but it was deemed acceptable in view of the information required. The design point of the system was an input data.

Considering the current RRFCS plant (SYS1), system performance is mainly determined by the stack since the main function of the turbogenerator is to pressurise the system and its contribution to power output is very limited: hence each operating point is mainly determined by reducing or increasing the current drawn hence reducing or increasing the power output of the stack. The first operating envelopes were calculated with the aim of understanding the behaviour of the system and its response to changes in control parameters; a final one was later calculated drawing from the experience of the first ones with the aim of optimising system performance also in view of the definition of a possible control system.

All operating points were calculated reducing the current from the design value down to 50% and varying fuel and air flow at the same time to comply with the following constraints for a safe system operation:

- Stack temperature cannot exceed maximum and, to a lesser degree, minimum temperature limits; maximum temperature is far below usual operating temperature for SOFC found in literature (1000-1100 °C) since operating life decreases with the increase in temperature and a reduced operating life cannot be accepted in a base load power generation system.
- Surge condition for the compressor must be avoided: hence a minimum safe limit of 1.1 in kp was always maintained.

On a general basis, ambient parameters that can affect performance of SOFC hybrid systems are temperature, pressure and air humidity. Ambient temperature and pressure are by far the most important since they greatly affect turbo machinery performance and hence indirectly affect the performance of pressurised hybrid systems relying on them.

Various operating curves for different ambient temperature have been simulated; the load has been reduced from 100% to 50% nominal load by reducing the operating current of the fuel cell itself. A reduction in operating current causes a reduction in the heat released by the operation of the stack, causing as a consequence a cooling of the stack itself if no action were to be taken. In order to ensure a proper thermal management of the system and consequently avoid any relevant changes in stack temperature, two parameters, fuel and air mass-flow, can be effectively controlled:

- Rotational speed of the turbine: air flow is primarily reduced by reducing the rotational speed of the machine through the alternator (alternator control).
- Bleed valve: a reduction in fresh air flow to the cathodic primary can be obtained by blowing off part of the air flow at the outlet of compressor through the bleed valve (bleed control).
- Fuel flow: reducing or increasing the fuel flow, hence increasing or reducing the fuel utilisation factor ( $U_f$ ), varies the fraction of unspent fuel in the anodic off-gas burning in the off-gas burner with part of the cathodic flow thus increasing the overall system temperature through the cathodic recirculation ( $U_f$  control).

A reduction in air flow is primarily obtained by reducing the rotational speed of the turbo machinery that also causes a decrease in system operating pressure; blowing-off part of the air at the compressor outlet through the bleed valve yields the same result and although being helpful in avoiding surge conditions of the compressor itself is obviously less efficient since part of the air is discharged to the ambient without doing any useful work. Also in this case system operative pressure decreases although comparatively less than the previous case due to the change in the turbo machinery operating condition. Obviously in case of an increase in the operating current, both parameters could be effectively controlled in the opposite way to avoid an increase in system temperature. From these preliminary considerations, the effect of ambient temperature could be considered, at least in principle, similar to an increase or reduction in current since an increase or reduction in ambient temperature from the standard reference temperature of 288.15 K should cause a corresponding increase or reduction in stack temperature by means of the cathodic recirculation.

The effects of ambient temperature can be summarised as follow:

1. Part-load performance increases with ambient temperature since a high temperature helps in keeping the system in temperature.

2. Full-load performance is favoured by lower ambient temperatures, at least in the range  $+30^{\circ}\text{C} \div -20^{\circ}\text{C}$  where system performance is deeply affected by turbo machinery behaviour.
3. Issues on thermal management of the system may arise in conditions such as very hot day and full-load when the system might over-heat due to the reduced air-flow delivered by the compressor.

Further calculations were done with the aim of optimizing the operating envelope in terms of efficiency in order to provide useful information for the definition of a optimum control system with the following assumption:

1. Fuel utilisation factor has been kept constant since this control strategy was previously highlighted as the optimum in terms of overall system performance.
2. Air flow is solely controlled through compressor rotational speed.
3. Use of bleed valve is limited to avoid surge of the compressor: all the operating points are calculated at minimum surge margin (i.e.  $k_p 1.1$  ca).

With a proper control strategy, the efficiency of the system is kept at very high value during the part load operation despite a strong reduction of the requested power (at least 95% of the nominal efficiency value at less 50% of power) and with different ambient conditions.

Moreover all the system components can be kept in safe condition avoiding the hot spot temperatures, thermal gradients and arising of surge problem for the compressor.

The general behaviour of the plant is similar considering an ejector or a blower for the cathodic recirculation, in both cases the recirculation factor is a key point for the thermal management of the stack in each operating condition.

If the cathodic recycle is lead by the ejector the recirculation factor is a result of the matching point of the components of the cathodic circuit (compressor, fuel cell stack, expander) and it is not a free variable.

If a blower is the responsible of the cathodic recirculation, compatibly with the component features, it is possible to consider the recirculation factor as a free control parameter. This option adds an additional degree of freedom in the control strategy facilitating the thermal management in some critical operating conditions.

Similar conclusions can be drawn for a generic plant with a commercial recuperated gas turbine like the system performance of a 100 kW hybrid system.

Also in this case the possibility of varying the machine rotational speed is a key point in order to keep the system in safe and efficient operating condition in a wide power range. The surge margin must be controlled as well in this plant in particular at reduced rotational speed.

The study of the off-design performance is very significant in the choice of the system features as well as the economic investigation and the system reliability analysis.

In particular for distributed generation plants with high capital cost, such as hybrid systems, it is essential that the system efficiency is not appreciably affected by the ambient conditions

and load required, remaining very near to the design point reference value in a wide operative range.

For the systems considered, with an appropriate control strategy, this goal may be completely achieved.

## 6 Components and sub-systems (WP3)

### 6.1 Turbomachinery and Gas and Air recirculation

#### 6.1.1 Blower testing

Modifications to the existing VTT test stand were carried out to enable characterization of the anode recycle blower supplied by Wärtsilä. Air was used in the characterization of the blower instead of anode exhaust mixture ( $H_2$ -CO-CO<sub>2</sub>-H<sub>2</sub>O) due to construction of the existing test stand and gas supply facilities, and due to safety reasons.

The anode recycle blower was characterized at room temperature and at actual operating temperature (300°C) with varying air flow and pressure rise. The blower was able to deliver close to 800 l<sub>n</sub>/min with 80 mbar pressure increase between inlet and outlet at 300 °C (Figure 6.1). At room temperature the blower was able to deliver flows in excess of the measurement capabilities (1000 l<sub>n</sub>/min) at pressures over 120 mbar. The blower could meet the specified operating temperature and performed reliably during the testing.

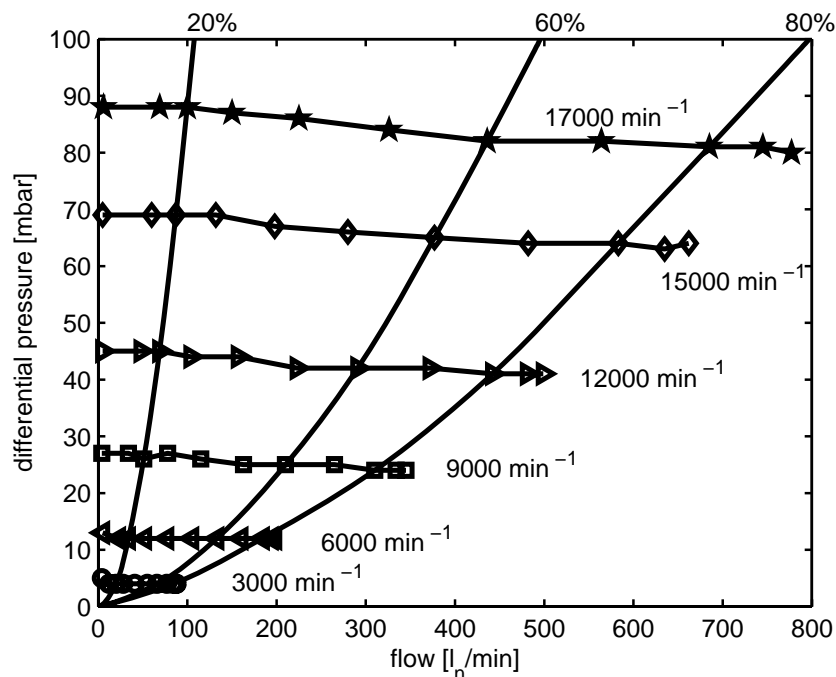


Figure 6.1. Differential pressure between blower inlet and outlet as a function of flow at different revolution speeds at 300 °C. The three upward sloping curves connect the measurement points obtained with the control valve open at 20%, 60% and 80%, respectively

#### 6.1.2 Blower development

While the challenge with air blowers was correct matching of performance requirements with available technical solutions, taking into account efficiency, lifetime, reliability and cost

criteria, development of hot anode gas re-circulator focused on requirements engineering at a very early stage and an entirely new design in order to overcome problems of reliability and inadequate pressure boost capacity which Wärtsilä Fuel Cell Group had earlier identified as central issues of known designs.

### **Air blower development**

Available components and potential manufacturers were screened and an experimental approach was taken to address certain essential issues of commercially available off-the-shelf air blower products, namely efficiency, life cycle cost and compact size. A vertically standing radial blower with a high-speed motor and magnetic axial bearings was developed by a firm specializing in high speed technology to match with requirement specifications defined by Wärtsilä for a 50 kWe SOFC system. A centrifugal high speed blower design was chosen to facilitate high efficiency and high power density and magnetic bearings for long life. The design has potential for up-scaling in the future.

As an alternative approach, a commercially available off-the-shelf, small scale roots type positive displacement automotive supercharger was mated directly to a customized axial flux AC motor without transmission gears or belts. Integration of electric motor and supercharger resulted to a working proof of concept piece of machinery offering a potentially compact, reasonably efficient air supply system at low initial cost, scaling for small systems and can be considered an alternative to regenerative blowers which also increase pressure quite well at low flows but with modest efficiencies.

Since both of the blowers were intended for use in a near ambient pressure SOFC system, operational validation and performance characterization was decided to be carried according to an adapted standard fan performance set-up and procedure ("ISO 5801: 2007. Industrial fans – Performance testing using standardized airways"). Experience with the two experimental designs underlined the importance of matching capacity requirements with correctly sized blower hardware in order to minimize the parasitic load on the system.

### **Anode re-cycle blower development**

As a starting point, basic requirements in terms of mass flow, pressure increase capacity and operating temperature for anodic tail gas re-circulation were established. It was also decided that a motor blower would best address the system requirements for controllability and flexibility for the system function of water recovery by anode gas re-cycling in a near atmospheric 50kWe SOFC system, thus excluding other possibilities such as ejectors.

Basic requirements of an anode off-gas blower are unlike those of existing, commercially available gas circulation equipment. In addition to harsh operational environment, for a SOFC system with electrical output in tens of kilowatts, the required mass flow in anodic re-circulation loop is relatively small compared to typical industrial compressor equipment available, which means it is not necessarily easy to find similar or close equivalent designs, from which purpose built blower design could be derived from. Therefore screening phase of the task concentrated on screening for technological solutions available, suitable and feasible in the scale concerned. With the special requirements in mind and knowledge of reliability issues of prior designs, and entirely new blower concept and design were created together with an external research partner.

A blower incorporating a synchronous, high speed permanent magnet motor and an integrated active magnetic bearing system was developed and manufactured. The unit can meet mass flow and pressure increase demands of a 50kWe fuel cell system anode gas re-circulation. The first generation of the blower design was designed to operate in a vertical rotor orientation but the design approach has a potential to be adapted to horizontal or intermediate orientation or even to dynamic environment.

In the process of concept development and design of the blower, understanding of process impacts on equipment and possible trade-offs relating to different technical solutions became clear. A high speed design was chosen to make it possible to achieve high pressure rise even at a relatively high temperature and yet relatively small mass flow. On the other hand, magnetic bearings made it possible to come up with a design with minimized number of wearing parts and thus a high life expectancy. The design has also potential for up-scaling in the future. The first built working prototype made it possible to validate the technical concept and provided important feed back of issues regarding manufacturing, assembly, thermal insulation and control for further optimization and productization of the blower .

Due to tight project schedule for a Large SOFC 50kWe system design and manufacturing delays, validation of the blower in simulated process conditions and its performance characterized with cold and hot air was postponed and transferred to task 5.1 in 2008-2009.

As a base line for comparisons, a commercially available, yet experimental anode gas re-circulation blower was acquired. The blower incorporated a mid speed induction motor and a set of conventional bearings. Simpler design and a more conventional motor and bearings bring along potential for low cost. On the other hand, lower operational speed also means lower pressure increase capacity at the specified operational point and larger size of equipment. Testing of the commercial anode gas blower was carried out by VTT in 2007 (8.3.1.1).

### 6.1.3 GT-SOFC emulator

#### **FELICITAS Facility Layout**

The “GT-SOFC Emulator” test rig (Figure 6.2), with the configuration supported by a former European Integrated Project (FELICITAS), is based on the coupling of a modified commercial 100 kW recuperated micro gas turbine with a special modular volume designed for the experimental analysis of the interaction between different dimension fuel cell stacks and turbomachines [1,2,3]. The rig, originally developed with the support of the European Integrated Project “FELICITAS”, was used and improved in the framework of this project.

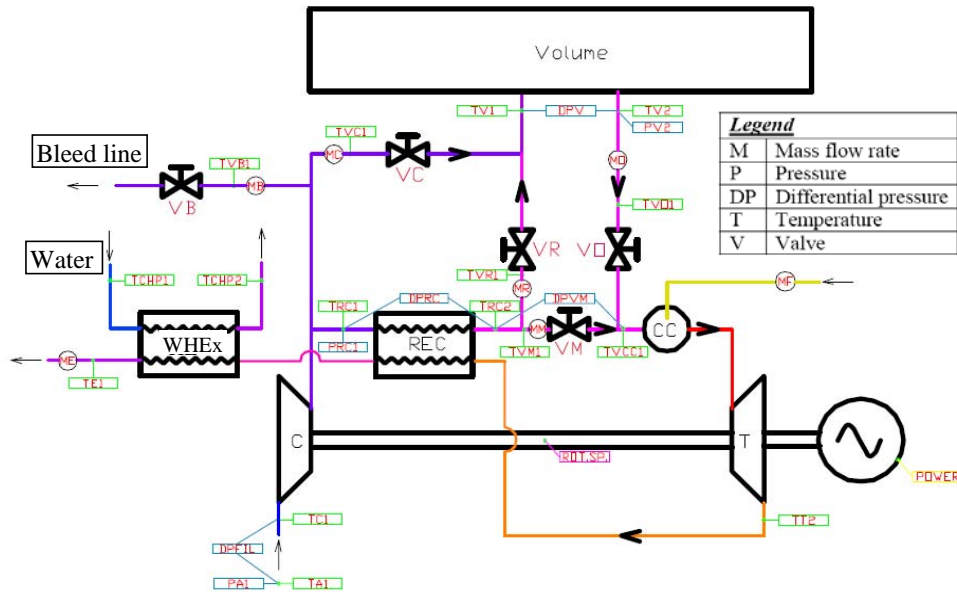


Figure 6.2. Initial Plant layout (FELICITAS project configuration).

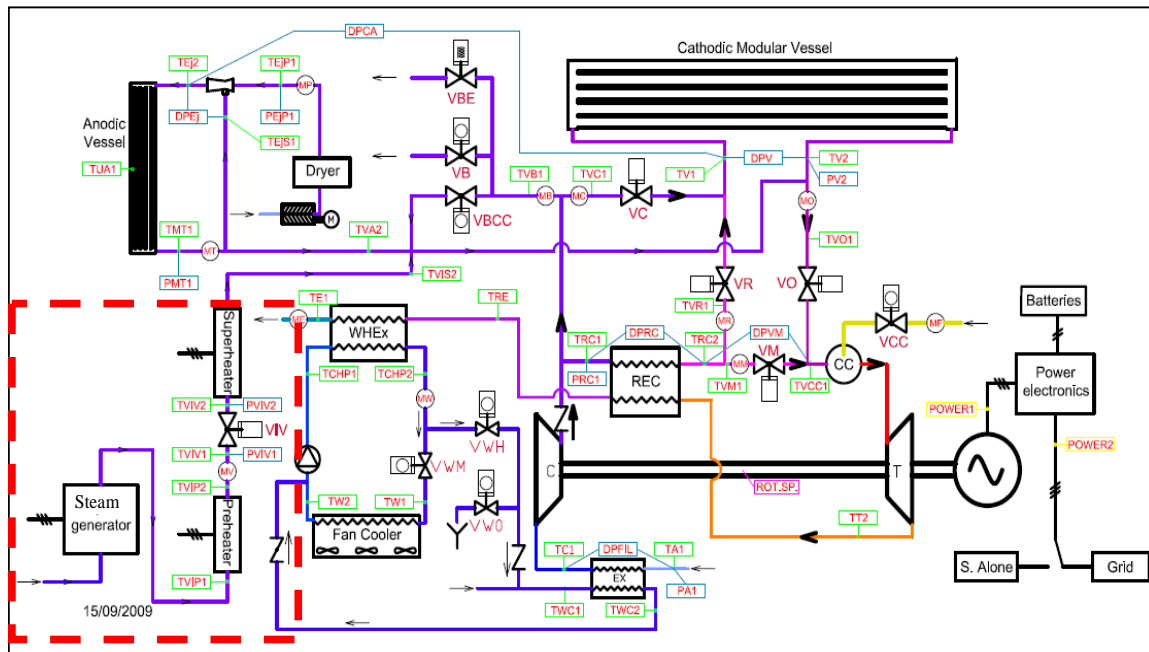


Figure 6.3. Final Plant layout (LARGE SOFC Project configuration)

Figure 6.3 depicts the final plant layout realised in the framework of this project, all the modifications are described in details hereinafter.

### Grid Connection of the GT-SOFC Emulator

The “GT-SOFC Emulator” was already used for stand-alone configuration tests, carried out in the FELICITAS project, while in the framework of this project it is required to simulate the behaviour of a real big fuel cell plant. The purpose of this type of hybrid plant (1-2 MW power) is base power generation; then, the emulator must be connected to the grid of the campus (and to the national electrical grid).

In this case the control system of the microturbine uses a control strategy that is based on a constant TOT and variable rotational speed, to maximize the efficiency of the machine, instead of the strategy at constant rotational speed and variable TOT used in stand-alone configuration that is used for maximizing the stability of the machine at suddenly load variations.

To use constant TOT and variable rotational speed, it is mandatory that the machine is connected to the grid, because if the grid is not present or in a well defined field of voltage and current, the control system performs an emergency shutdown, if the machine is running, or prevent the start-up of the machine, if the start-up command is lighted on. This control logic cannot be modified because it is implemented into the PLC of the machine and the control program can be modified only by the manufacturer.

The variable rotational speed controller allows the study of the behaviour of the machine at different pressure and air mass flow rate. This capability coupled with the cathodic volume connection can highlight conditions or plant working points that may be dangerous for the fuel cell or the microturbine. With this control strategy the tests are performed at constant temperature and variable produced power, because of the constant TOT for all the electrical loads.

To connect the machine to the national grid several electrical works were carried out starting from an apt adaptation of the line already in use (from the laboratory general electrical panel to the step-up transformer of the campus). These works were mandatory for the actual regulation of the electrical supplier, for safety and legal reasons.

Beside, also the laboratory general electrical panel was modified in order to obtain this goal, with the installation of a security and measurement interface, that executes the current measures, and open the main switch if the grid is out of the nominal current and voltage values (mandatory for the Italian security standard). Another work that was done is the installation of a controlled switch to have an easy commutation capability from stand-alone to grid connected modes. This switch is under the control of the security and measurement interface that inhibits the grid connected configuration if some parameter is wrong. Another thing is the adaptation of the line from the turbine to the step-up transformer of the campus to meet the standard security performance requested for an electric generator connected to a grid.

### **Facility Layout for Recuperator Tests**

The test rig was improved with the installation of a water fan cooler located outside of the laboratory. It is based on three 0.7 kW electrical fans used to cool the water (coming from the WHEx of Figure 6.3), and to operate in closed circuit conditions (a 1.5 kW pump was installed). Furthermore, a new water system was designed and installed to control the machine compressor inlet temperature. This is composed of three air/water heat exchangers, installed at the machine air intakes and connected to the water system; moreover it was equipped with three controlled electrical valves (VWM, VWH, and VWO). The compressor inlet air can be cooled (opening VWO) by means of cold water from the supply system, and heated (by closing VWM, and opening VWH) by means of the hot water coming from the machine co-generation system (WHEx). Currently the maximum cooling performance depends on the supply water temperature (about 22°C in summer, that is 295.15 K), while the only constraint

on heating performance is the maximum compressor inlet air temperature for the machine cooling system, that is 40°C (313.15 K). In comparison to the layout reported in [2,5,6], here additional thermocouples and a water mass flow meter were installed [2,4,7). While the thermocouples have the same accuracy as the previous ones (see [2] for details), the new mass flow meter has an accuracy of  $\pm 4\%$ . It is important to highlight the installation of a new thermocouple at the compressor inlet (TC1) used for the control system, and a second one at the recuperator outlet (TRE), for temperature measurement at the hot side outlet of this heat exchanger

### Recuperator Performance in Steady-State Conditions

These steady-state tests were carried out with the machine in stand-alone mode or connected to the electrical grid to measure recuperator performance at different mass flow rate values.

$$\varepsilon = \frac{TRC\ 2 - TRC\ 1}{TT\ 2 - TRC\ 1} \quad (1)$$

Figure 6.4 shows the recuperator effectiveness (defined as in Eq. 1 because in the tests reported in this paper the cold flow is always the recuperator lowest capacitance flow) performed at different loads. Since the effectiveness values are calculated by using temperature measurements with a  $\pm 2.5$  K accuracy, it is possible to exploit the error theory [8] to calculate an accuracy ranging from  $\pm 6\%$  (at low load and temperature values) to  $\pm 2\%$  (at high load and temperature values) in stand-alone mode, and an accuracy around  $\pm 2\%$  during the tests performed in grid-connected mode (at maximum TOT, i.e. 918.15 K). While, in stand-alone mode, the recuperator effectiveness is high (between 0.935 and 0.945) in low temperature conditions (idle conditions), an almost decreasing behaviour is produced increasing the load and temperatures. This is essentially due to an increase in the maximum temperature difference (TT2-TRC1) on the recuperator, which generates an increase in the temperature difference along the whole thermal exchange surface. In grid-connected mode, as shown in previous theoretical works [9,10], starting from the maximum flow (and maximum load) it is possible to see an effectiveness increase with the mass flow rate and load decrease, and an effectiveness peak followed by a decrease. However this final decrease is not as evident as it is in [10]. In fact, the substantial effectiveness decrease at low mass flow rates is not measured by these tests because, to avoid unstable condition risks, the machine control system does not enable steady-state tests at less than 20 kW. A CIT increase generates a general recuperator effectiveness decrease for the effect on the recuperator coming from the compressor outlet temperature increase. Furthermore, Figure 6.3 shows a recuperator effectiveness increase when the machine operates connected to the cathodic volume. This is mainly due to the lower air mass flow rate of these tests (see [11] for further details).

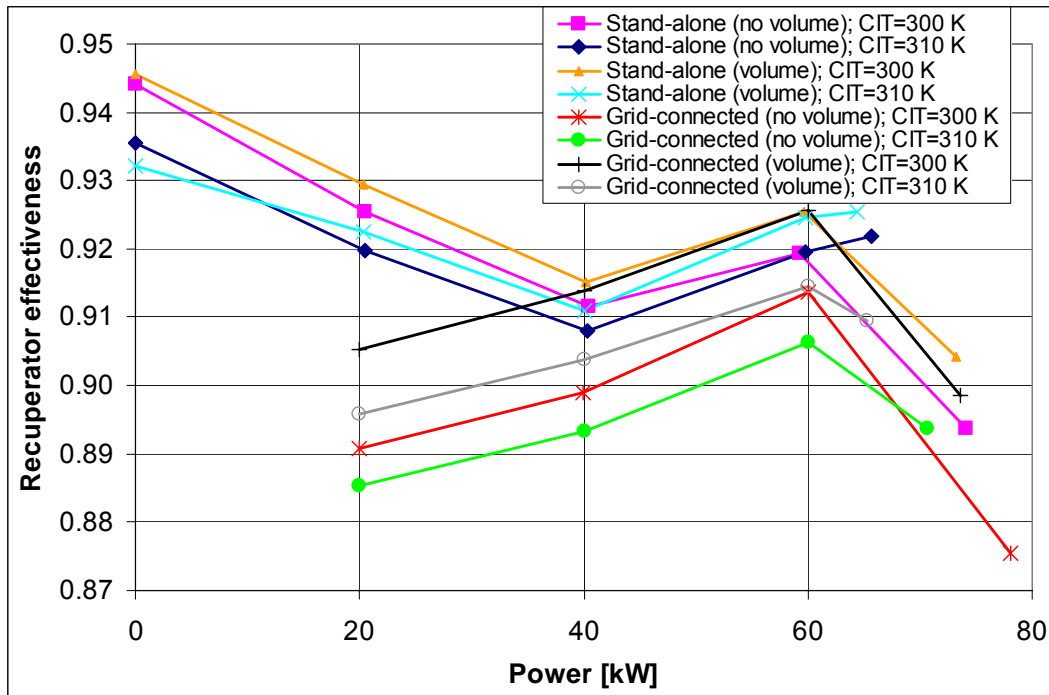


Figure 6.4. Reciprocator effectiveness in stand-alone and grid-connected modes.

### Control System Performance Comparison

A wide experimental campaign was carried out at TPG laboratory to compare the machine performance with the two different control systems. This approach is necessary to test the machine with two typical different control strategies: constant rotational speed (stand-alone machine) and constant turbine outlet temperature (grid-connected tests). The machine operates in its standard recuperated cycle (VM fully opened and VR, VO fully closed), or connected to the cathodic volume (VM fully closed and VR, VO fully opened). All the tests were carried out at two different operative compressor inlet temperatures (300 K and 310 K) to show this temperature effects on machine performance. After the machine start-up (in stand-alone or grid-connected mode) and the reaching of steady-state condition (idle in stand-alone mode, or 20 kW load in grid-connected condition) with the volume included or not in the flow line (working with the compressor inlet temperature control system), each test was carried out at different load values (20 kW, 40 kW, 60 kW, and maximum load value).

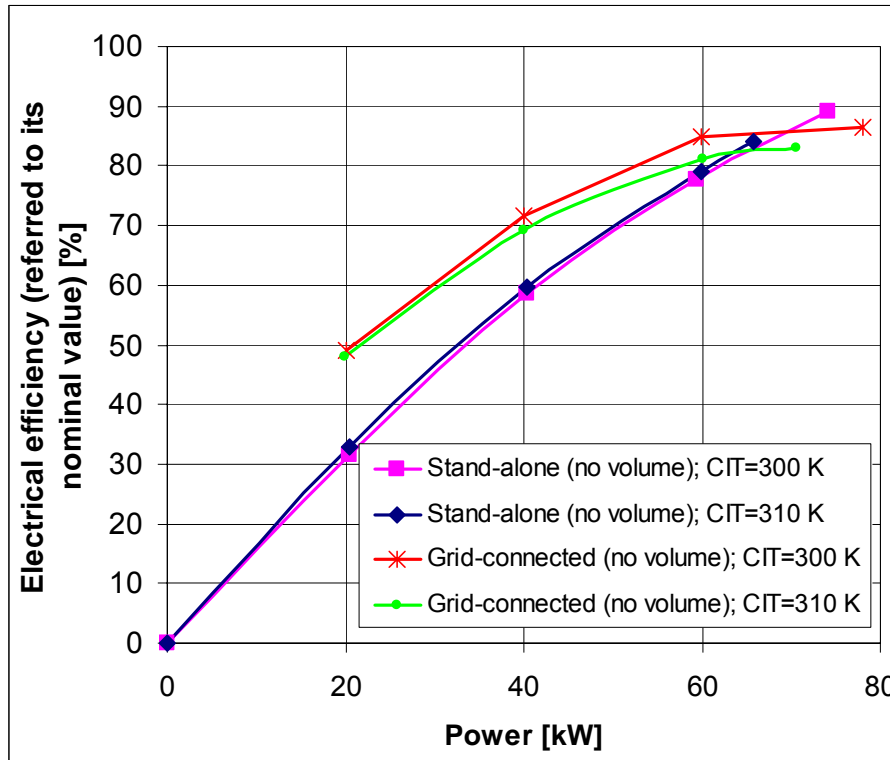


Figure 6.5. Electrical efficiency in standard recuperated configuration (100% refers the nominal efficiency of the commercial machine [1]).

Figure 6.5 shows the machine electrical efficiency (referred to its nominal value) obtained in standard recuperated configuration (machine not connected to the cathodic volume) in both stand-alone and grid-connected modes. This graphic is essential to show that in grid-connected mode it is possible to obtain a higher efficiency value at part-load conditions. This is possible operating the machine at the highest TIT and TOT values in every load conditions. In fact, this approach allows to obtain higher expander efficiency values, while in stand-alone mode the power generation carried out at low load values and temperatures is affected by low efficiency values. Furthermore, while in stand-alone mode the compressor inlet temperature increase does not affect significantly the machine efficiency (the CIT increase generates a compressor outlet temperature increase: this means a compressor consumed power increase, but, at the mean time, a fuel consumption decrease), in grid-connected condition Figure 6.5 shows a significant efficiency decrease (the CIT increase generate a rotational speed and fuel mass flow rate increase). However, in both cases the CIT increase generate a maximum power decrease and, as a consequence, a decrease of the maximum efficiency value.

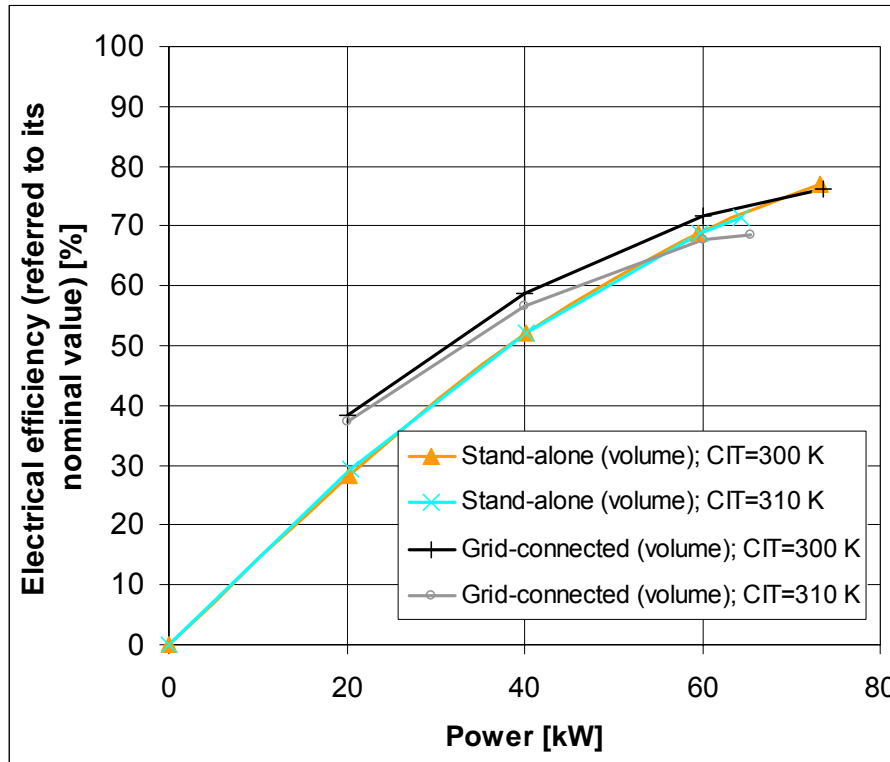


Figure 6.6. Electrical efficiency in cathodic volume-connected configuration (100% refers the nominal efficiency of the commercial machine [1]).

The same discussion can be carried out for Figure 6.6, showing the electrical efficiency values (referred to its nominal value) obtained during tests with the machine connected to the cathodic volume in both stand-alone and grid-connected modes. Also in this case, for the same reason discussed in the previous paragraph, in grid-connected mode it is possible to obtain a higher efficiency value at part-load conditions. Furthermore, it is important to highlight the general efficiency decrease at volume-connected configuration, in comparison with the corresponding values during the standard recuperated tests. This is due to the significant thermal losses through the volume external surface.

### Model Validation Activities

A great attention is devoted to this activity to validated time-dependent simulation models at both component (recuperator) and system (the hybrid system emulator test rig) levels. In particular:

- A recuperator real-time transient model was validated against the experimental data produced with the facility located at Savona laboratory of TPG. Several data comparison are shown in this report in both steady-state and transient conditions.
- A second validation activity on a real-time model of the whole emulator test rig was carried out at transient conditions. This report shows the calculated results successfully compared to experimental data for both heating-up and cooling-down phases (essential phases for the hybrid system operations).
- To complete the emulation of a SOFC hybrid system, a real-time model was developed in Matlab<sup>®</sup>-Simulink<sup>®</sup> to be coupled to the experimental test rig developed by TPG at

Savona laboratory. This report shows a brief model description of the whole hardware/software emulation approach.

- The final part devoted to model activities shows the development of a monitoring system for the mGT incorporated in this test rig. In this work attention is focused on estimating the efficiency of the most important components of the mGT, during an experimental test carried out with the machine in stand-alone configuration, without having the volume coupled with the mGT and varying the load on the machine, in order to have a clear picture of the machine behaviour in the largest number of operating conditions.

### **Design and Installation of an Anodic Recirculation System, and Related Tests**

The purpose of this work was the test rig enhancement with the integration of the anodic loop into the system. This part of the plant represents the recirculation device and anodic side of the fuel cell stack and, in this case, it is composed by an ejector, a heat exchanger (anodic loop inside cathodic vessel) and a volume to emulate the anodic side of the fuel cell as depicted in Figure 6.3.

The aim of this experimental study is the assessment of the cathode-anode pressure difference during different operating conditions and load transients, and the assessment of the anodic ejector behaviour during hybrid system (HS) operation. The HS emulator with the anodic loop will be also used to run compressor surge margin tests in order to define a control strategy apt to avoid surge. In fact, when a fuel cell is connected to gas turbine, the expander mass flow rate is higher than the mass flow rate of the standard configuration turbine. The results of this study are significant for similar gas turbine hybrid systems and will lead to a development of a safe control strategy for a real hybrid system plant.

To design the anodic loop, and in particular the ejector and volume, it was necessary to define the hybrid system and fuel cell size to be consistent with the micro gas turbine mass flow rate. The Rolls-Royce Fuel Cell Systems Ltd (RRFCS) fuel cell stack and plant was considered as initial reference system [13]. Starting from the RRFCS plant lay-out, reported [12], some calculations were carried out taking into account the different system layouts and operating parameters obtained combining the fuel cell with the commercial gas turbine. With a proper simulation model, the size and performance of the fuel cell stack coupled with the T100 micro gas turbine was defined, and the anodic and cathodic volume and mass flows were calculated [14,15].

The experimental results were produced on both cathodic and anodic emulation systems of the TPG test rig, with the machine working connected to the fuel cell system emulator as in a typical pressurized hybrid system (VM, VC, VBCC, VB fully closed, and VR, VO fully open).

### **Design and Installation of a Steam Generator System, and Related Tests**

To implement the steam injection system different layout modifications were designed and installed. With the reference to the 450 kW hybrid system already presented in paragraph 8.2.2 (natural gas mass flow rate of about 18.8 g/s), this operation requires the design and installation of a steam generator capable of at least 27 g/s, a super-heater to increase the steam temperature from the steam generator outlet condition to a temperature compatible for the turbine combustor inlet (around 515°C), and a controlled valve for the mass flow rate management. The measuring of the steam flow rate requires a completely mono-phase steam.

So upstream the mass flow probe, an additional electrical heater was installed. Furthermore, several thermocouples were added for control purposes. The final layout is shown in Figure 6.3 where the modifications are highlighted by the red dotted box.

Figure 6.7 shows the whole steam injection system coupled with the hybrid system emulator rig and ready for tests.

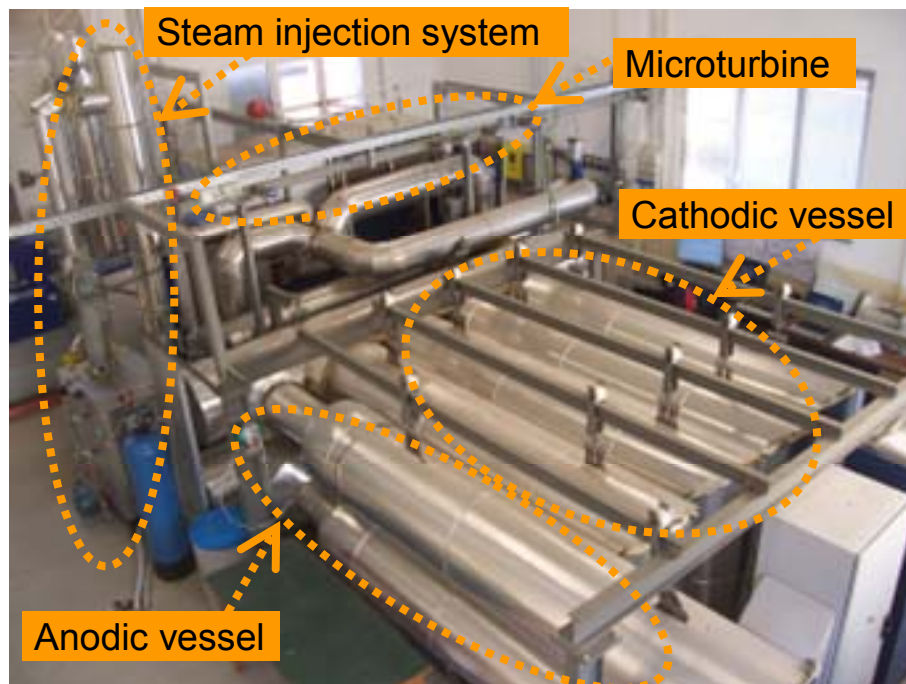


Figure 6.7. The whole steam injection system coupled with the hybrid system emulator rig.

## Control System Strategy Comparison and Discussion

As already discussed in [11], it is necessary to reduce the air mass flow rate in SOFC cathodic ducts at part-load conditions. This is essential to maintain constant the SOFC temperatures to avoid performance decrease and thermal stress at each operative conditions. As already stated the constant TOT control system seems to be the best solution to control the SOFC temperatures and to avoid high efficiency decrease at part-load conditions.

Furthermore, the results reported in this report show another reason to justify the necessity to use a variable speed control system. In fact, the DPCA increase with MP increase needs to be carefully considered when operating a hybrid system at part-load conditions, to avoid excessive mechanical stress on the cell materials. It is essential to develop an operative control strategy to couple the fuel mass flow rate decrease with the machine rotational speed decrease (at part-load conditions) avoiding excessive cathode/anode differential pressure values. It is possible to reduce the DPCA value decreasing mass flow rate with a machine rotational speed decrease at part-load conditions. So, it is necessary to use (for a hybrid system) a variable speed control system not only for SOFC temperature control or for high performance reasons, but also to avoid excessive cathode/anode differential pressure values. On the other hand, even if the bleed solution can solve the differential pressure problem

reducing the air mass flow rate value, this approach is extremely negative from the plant efficiency point of view as already discussed.

The tests carried out on the anodic side showed that the machine accepts, with no surge problems, the additional mass flow rate from the anodic loop (in a real hybrid system is the fuel mass flow rate). This is due to an enough surge margin for these operations, typical of the T100 machine (see [3] for manufacturer compressor map). So, no further recommendations are necessary for control system development activities.

The tests carried out with the steam mass flow rate injection showed further machine details to be considered for a hybrid plant control system. In high load conditions the grid-connected tests showed that it is possible to obtain maximum electrical power of 78.2 kW (obtaining an additional 5.2 kW load in comparison with the low injected steam conditions), and in low load conditions it is not possible to operate below 23.2 kW load for the low rotational speed limit (to prevent surge conditions). This operative limit (52500 rpm) has to be carefully taken into account not only for load operations, but also during the start-up and shutdown phases. For instance, turbine outlet temperature needs to be slowly increased not only to avoid excessive thermal gradient in the cell [5], but also to avoid surge conditions at compressor level.

As already stated for the tests carried out on the anodic side, the tests operated with the steam mass flow rate injection showed that the machine accepts, with no surge problems, the additional steam mass flow rate used to operate in  $c_p$  similitude condition at the expander inlet. This is due to an enough surge margin for these operations, typical of the T100 machine. So, no further recommendations (coming from steam injection tests) are necessary for control system development activities.

### **Additional Activities With the Test Rig**

Further activities were carried out on the experimental facility to enhance its capabilities and its emulation performance. These works were essential to solve many problems (extraordinary maintenance included) related to the experimental test rig and to assess calculation performance of simulation models. They are summarized in the following points: 1) vessel insulation improvement, 2) microturbine electrical board maintenance, 3) high temperature valve maintenance, 4) mass flow rate measurement improvement, 5) remote control system development.

## **6.2 Heat exchangers and recuperators suitable for fuel cell use**

### **6.2.1 Pressurised SOFC system**

#### **Testing of high temperature heat exchange in a SOFC rig**

During the Large SOFC project RRFCs has developed a high temperature heat exchanger for use in a pressurised hybrid GT-SOFC system. This work forms an integral part of the larger

project to develop a 1MW SOFC product. A modular scaleable design has been developed which can be used in a range of Pressurised rigs with only minor modification.

In order to achieve component life and cost targets material selection and detail design have been important considerations. The high temperatures encountered in the RRFCs system cycle rule out the use of conventional heat exchangers which are typically designed to operate at 600 – 700°C and use conventional 18/8 stainless steels. For this SOFC application an alumina forming ferritic steel has been selected. This material has excellent corrosion and oxidation properties but has very limited creep strength.

This material is not usually used in this application and so creep data is not widely available. Furthermore fabrication processes have not been widely developed. Considerable effort has therefore been expended in generating creep data and developing manufacturing techniques. This work has been completed by Bosal N.V and is summarised later in this report.

Development work on the heat exchanger culminated with the development of a 15kWe Stack Block demonstration rig. This rig incorporates the various sub-systems required for the RRFCs system cycle and the heat exchanger tested during the commissioning and test programme for this rig.



Figure 6.8. 15kWe Stack Block Rig Heat Exchanger assembly.

A 250 hour steady state test was completed as part of this activity during which the heat exchanger was found to be working in line with system design predictions. In total the heat exchanger was at temperatures >900°C for 520h and endured a total of six thermal cycles.

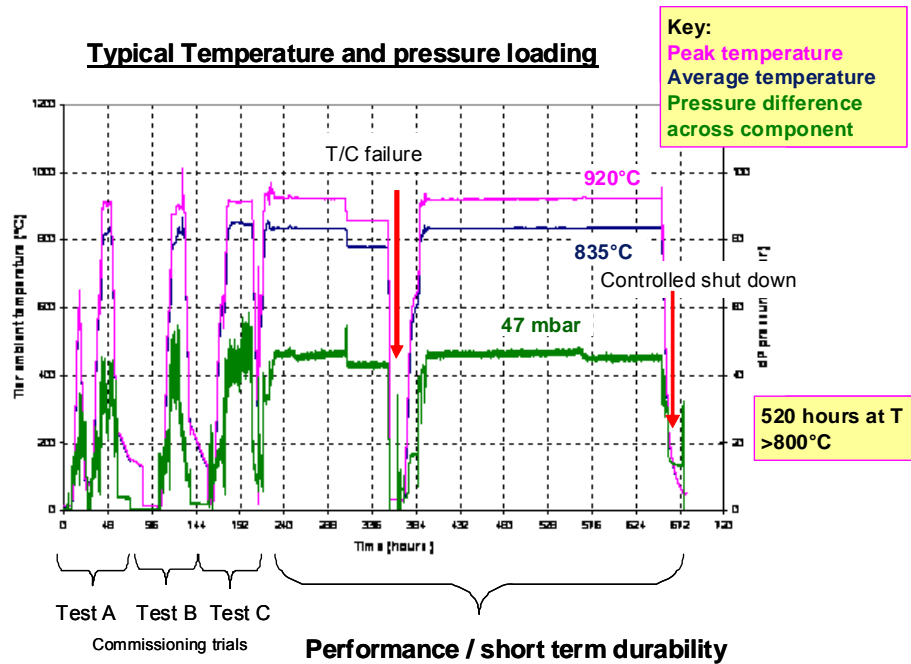


Figure 6.9. 15kWe Stack Block Rig – Commissioning and 250h Short term durability test.

Following the test the heat exchanger was removed for inspection and it was found to be in excellent condition with only minor distortion of a pressure drop plate being evident. Leakage measurements also indicated that no damage to the internal structure had occurred. The ‘Flame Tube’ from this test was also assessed. This component was subjected to the highest temperatures in the system and previous modelling work had highlighted this part as one which could be prone to distortion.

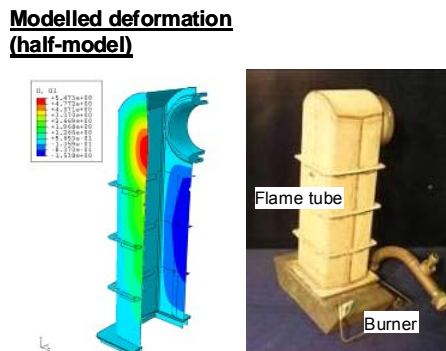


Figure 6.10. Flame tube and prediction of area of deformation.

Post test inspection did reveal a level of distortion with the rear face of the flame tube and when compared to the modelled predictions good agreement was gained.

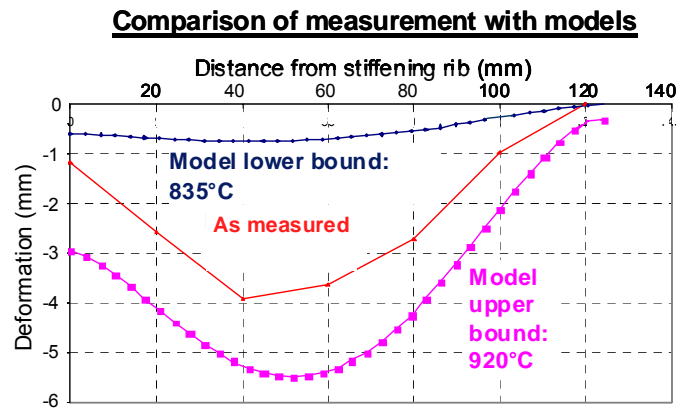


Figure 6.11. Comparison of modelled and actual distortions

The stress modelling of the Flame Tube utilised the creep data generated by Bosal.

Overall, these tests have shown that the design, manufacture and materials selection for the Heat Exchanger have been satisfactory and the performance and short term durability of the unit have been demonstrated. Furthermore the stress modelling and creep data have been validated against an experimental result.

## 6.2.2 Combined heat and power (CHP)

The hydrogen content in the SOFC fuel side does not allow any leakage in the heat exchangers. Due to this fact the commonly used manufacturing technologies for high temperature heat exchangers are welding and brazing. In high temperature heat exchangers the material should be as thin as possible in order to ensure effective heat transfer. The most suitable manufacturing technology for these kind of structures is laser welding. In laser welding the heat of the weld is significantly smaller than in other welding technologies and thus there will be little warping. In brazing technology the key finding was the unsuitability of copper brazing. Generally the brazing parameter determination is essential factor for final brazing quality. New manufacturing methods will be discussed with heat exchanger manufacturers also after Large SOFC project.



Figure 6.12. An example of brazed heat exchanger

Another issue is the will to build compact SOFC units with little pressure loss. A compact heat exchanger generates inevitably larger pressure loss. The ratio between heat transfer

performance and pressure loss is especially challenging in high temperatures as the gas flow has very low density. In low density and high temperature gas the effective pressure increase in the blower or a compressor is difficult. These questions had been widely discussed with various heat exchanger manufacturers in the beginning of the project. The heat exchanger manufacturers have some methods to balance between heat transfer and pressure loss. The customer has to choose which of the two should be emphasized. In the Large SOFC project two atmospheric heat exchangers have been tested, one with design emphasis on heat transfer and compactness and the other with design emphasis on small pressure loss. From point of view of a SOFC system, testing concluded that better results will be obtained by emphasizing the heat transfer. In this way compact units may be built and pressure losses may be prevented in piping design etc. In the future the ratio between heat transfer and pressure loss should be designed in co-operation with the manufacturer. Also shared testing is a feasible method to increase the design knowledge.

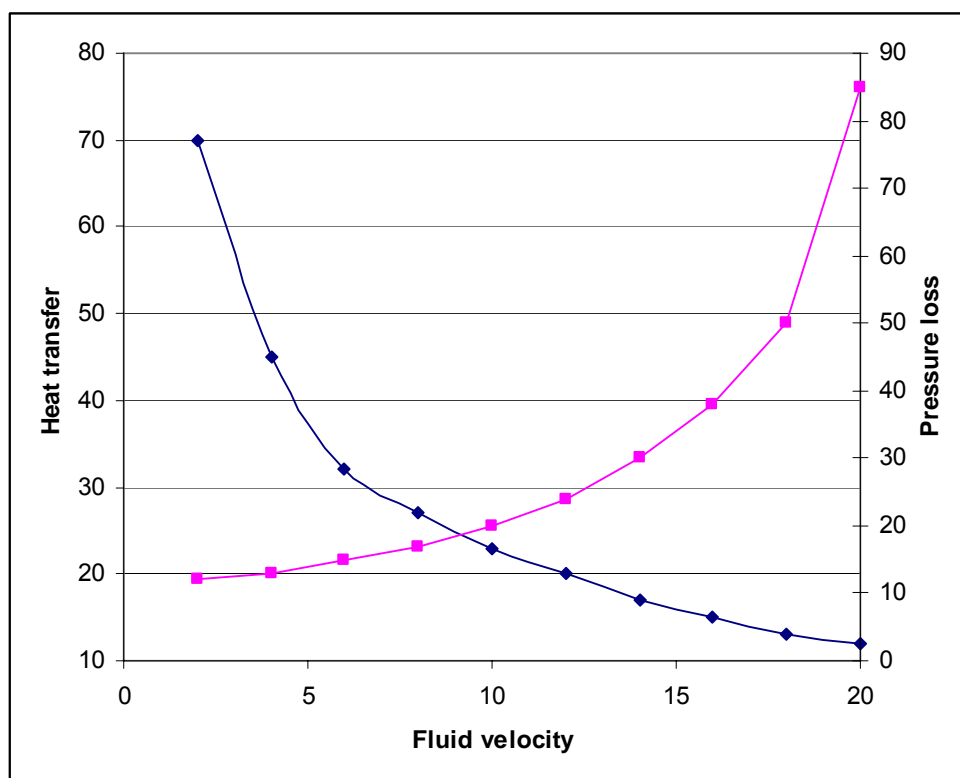


Figure 6.13. Example of heat transfer and pressure loss relationship.

The heat exchanger testing was performed by Forschungszentrum Jülich and some of the testing was moved to WP5 within this same project.

### 6.2.3 Heat exchanger testing

#### Test Bench

For the Large SOFC project Forschungszentrum Jülich has designed and constructed a new heat exchanger test bench (see Figure 6.14).

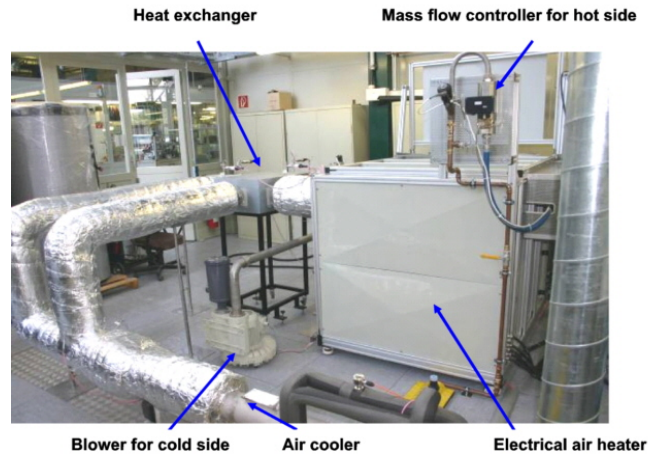


Figure 6.14. Heat Exchanger Test Bench at Forschungszentrum Jülich.

The electrical air heater has a heating power of 40 kW. The maximum mass flow rate at hot and cold side is 200 Nm<sup>3</sup>/h. The maximum outlet temperature at hot side is 900°C. The test bench is controlled by a LabVIEW program, which is also used for data recording.

In total two heat exchangers were tested within the LargeSOFC project. The first one was a plate-fin heat exchanger from the Steward Warner South Wind Corp. and the second one was a plate heat exchanger from Jülich.

### **Test of plate-fin heat exchanger from Steward Warner South Wind Corp.**

#### *Test Program Plate-Fin Heat Exchanger*

The first test phase starts with the characterization of the heat exchanger performance. The test procedure includes five tests under stationary conditions and four dynamic tests. The performance tests shall determine the heat transfer and part load behaviour (e.g. k-value, temperature distribution) of the heat exchanger. The dynamic tests are made to check the transient behaviour of the heat exchanger. These data are used for modelling purposes to evaluate the temperature behaviour over time (e.g. start up, load change). In a second phase, an endurance test of 1000 hours is planned. The test is divided into four sections of 250 hours. After each section a leak test will be done. This test shall evaluate the long term behaviour (e.g. leak rate, fouling) of the heat exchanger.

#### *Test Results Plate-Fin Heat Exchanger*

The heat transfer coefficient calculated from the measured results as function of volume flow is shown in Figure 6.15

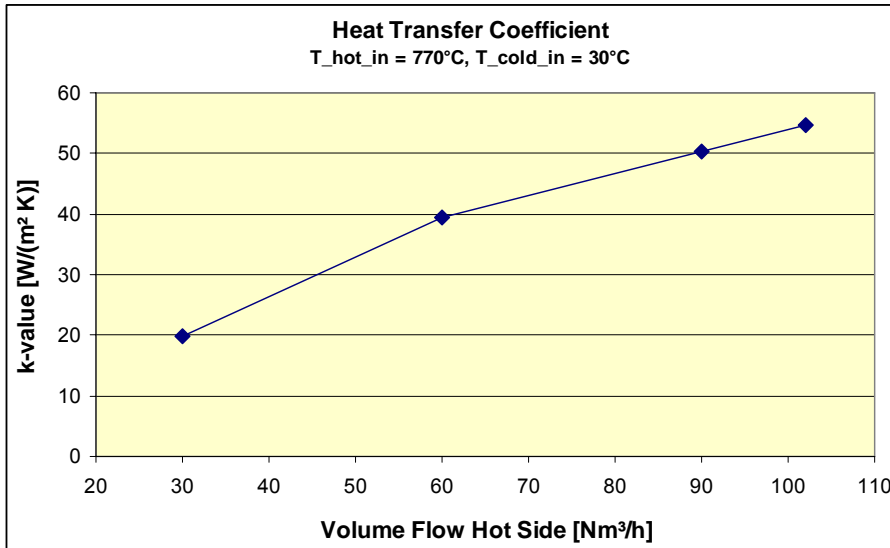


Figure 6.15. Heat transfer coefficient as function of volume flow from 25 to 85% of nominal flow

The temperatures of hot gasout and cold gasout at part load operation are depicted in Figure 6.16. It shows that at part load the cold outlet temperature (in the system this would be the stack inlet temperature) slightly increases, which is normally favourable for system part load operation.

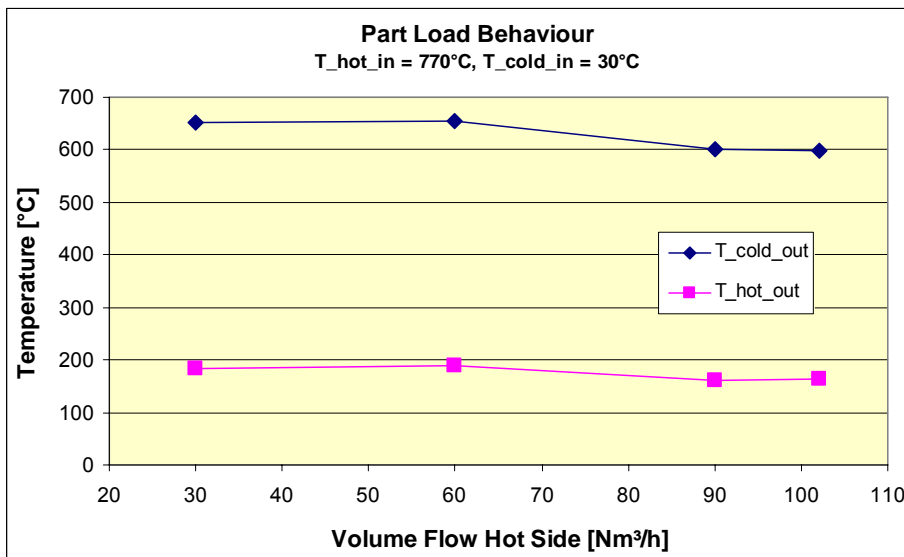


Figure 6.16. Temperature distribution at part load operation.

The endurance test evaluated the long term behaviour of the heat exchanger. It lasts 1000 hours divided into four sections of 250 hours. After each section the heat exchanger was dismantled from the test bench and a leak test was performed.

The results of the endurance test are shown in Figure 6.17

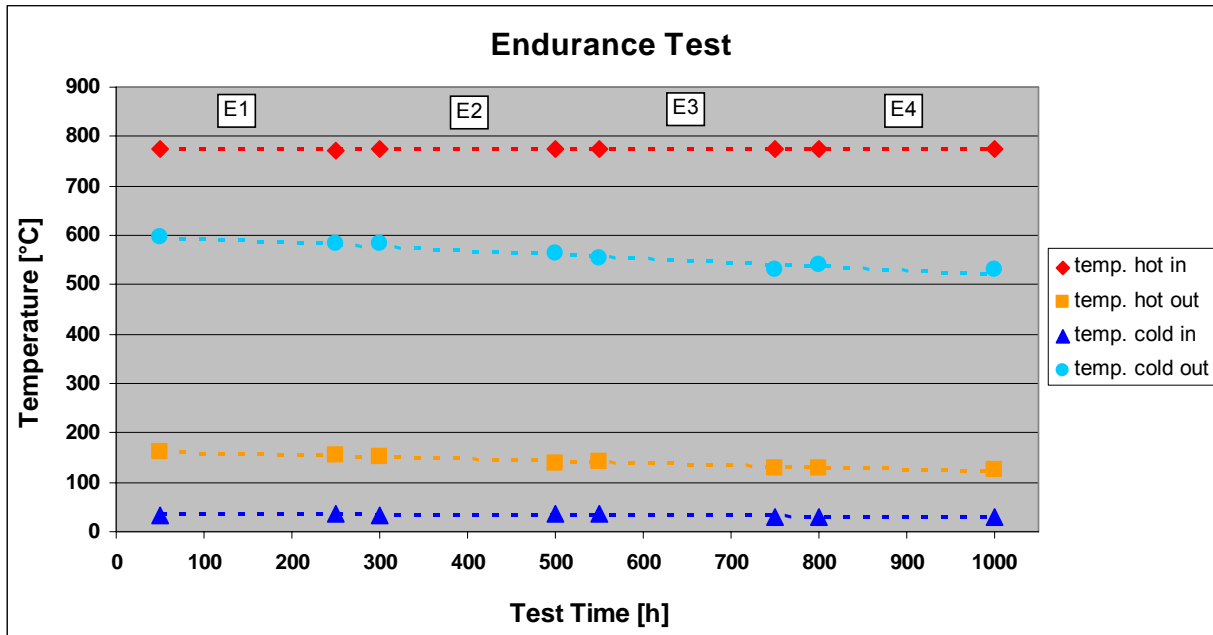


Figure 6.17. Temperature development at endurance test.

The Temperatures of hot- and cold-inlet are stable over a test time of 1000 hours, but hot- and cold-outlet temperatures are slightly decreasing. A check of the mass flow controller at the hot side shows no deviation from the calibrated values.

The test of the mass flow meter at the cold side showed a certain deviation from its original calibration. The set point flow rate was 108 Nm<sup>3</sup>/h and the real flow rate at the end of test E4 was 120 Nm<sup>3</sup>/h. An explanation for this behaviour is an internal sensor failure. However, the deviation of the mass flow rate at the cold-side hasn't had a significant influence on the result of the endurance test; in since of leak rate, fouling and reliability.

### Test of plate heat exchanger

#### *Test Program Plate Heat Exchanger*

This test starts also with the characterization of the heat exchanger performance. The test procedure includes four tests under stationary conditions and two dynamic tests.

#### *Test Results Plate Heat Exchanger*

The heat transfer coefficient calculated from the measured results as function of volume flow is shown in Figure 6.18

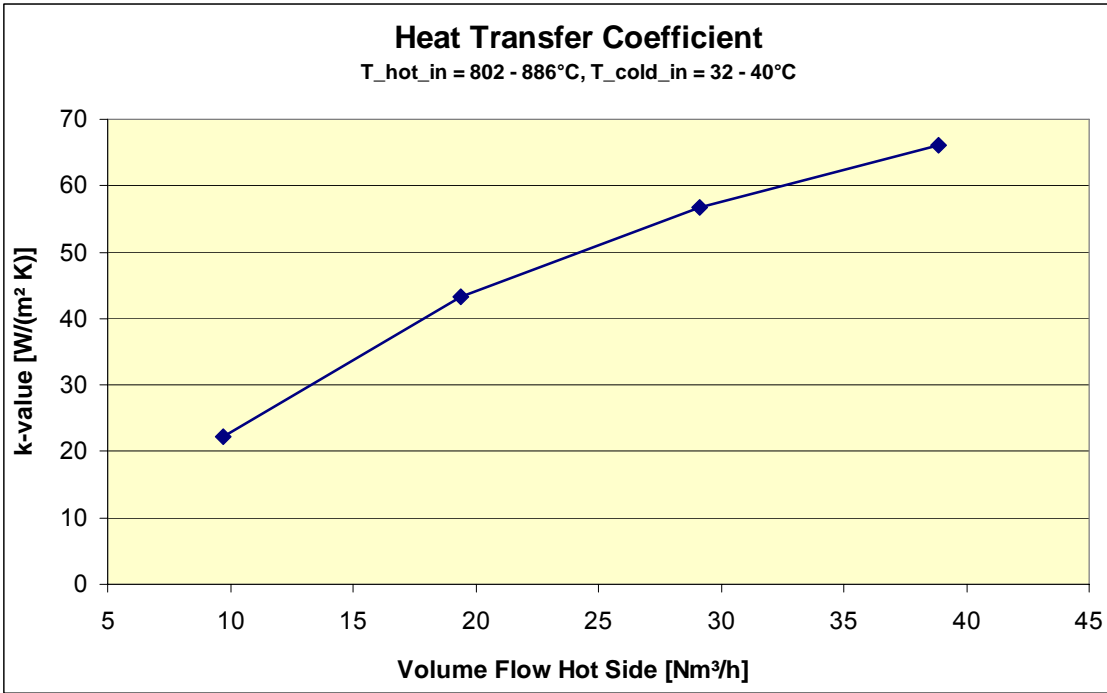


Figure 6.18. Heat transfer coefficient as function of volume flow from 25 to 100% of nominal flow.

The temperatures of hot gas and cold gas in- and outlets at part load operation are shown in Figure 6.19. It shows that at part load the cold outlet temperature slightly increases. Below a volume flow of 29 Nm³/h at the hot side the inlet temperature cools down due to the heat loss of the inlet pipe. That also causes a decrease of the cold outlet temperature. Remarkable is the temperature difference between the two hot outlet temperatures. This is caused by a non-uniform flow distribution in the planes of the heat exchanger.

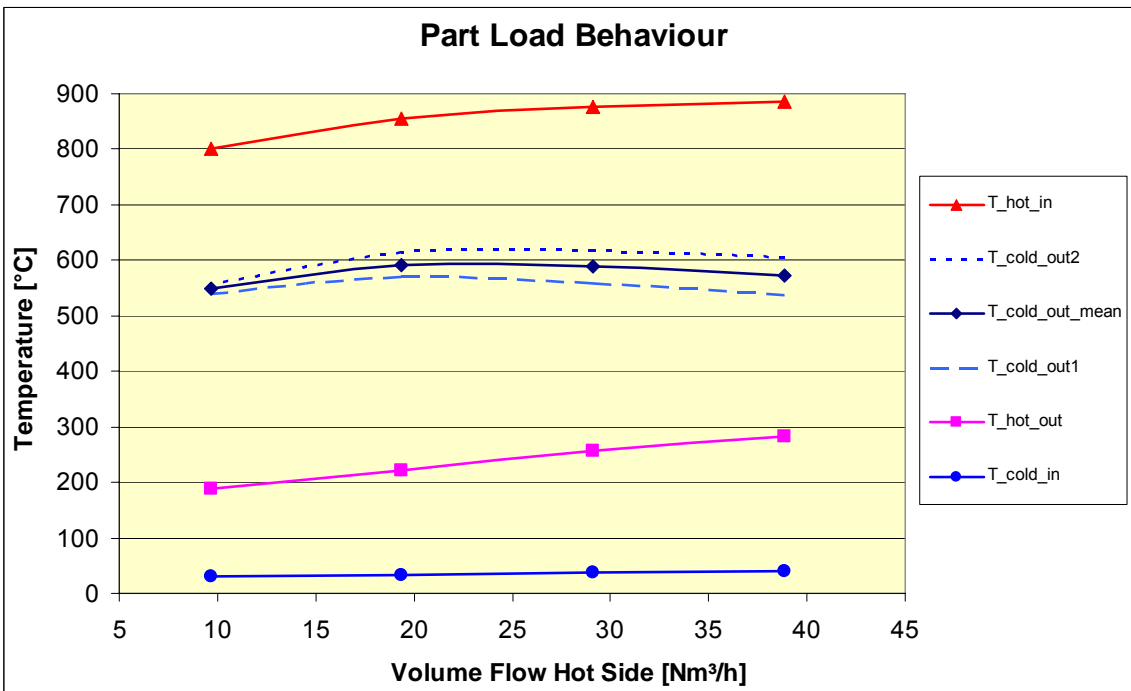


Figure 6.19. Temperature distribution at part load operation.

## 6.2.4 Steels for heat exchangers

The global efficiency of a SOFC (power plant / system) is increased by a heat exchanger. The device transfers heat from one fluid to another, without exchanging mass (between the fluids). In a SOFC the heat is extracted from the exhaust gas flow or the SOFC core. This heat is used for heating inbound gas flows.

This research focuses on three axes: specific design considerations for high temperature heat exchangers, dedicated manufacturing techniques and materials selection.

Designing a heat exchanger starts with the choice of an architecture, the calculation of the main dimension, and the determination of compliance constraints. The design of high temperature heat exchangers is constrained by specific requirements on pressure, temperature difference, flow uniformity and differential thermal expansion.

The manufacturing techniques put additional constraints on the design: Some high temperature alloys cannot withstand the strain that is introduced during the forming process. This limits the design options and the material choice.

This section of this report describes the work done at Bosal and RRFCS covering the following topics:

1. Design and manufacture of heat exchangers
2. Mechanical properties - creep behaviour
3. Chemical stability and corrosion behaviour of alloys under real SOFC atmospheres and temperatures.
4. The stability of the welds and the effect of leakage under exposure to real conditions: high temperatures and SOFC atmospheres.
5. Testing of heat exchangers in a SOFC test rig at RRFCS.

A workshop on high temperature heat exchangers was organised, bringing together specialists from the consortium members.

### **1. Design and manufacturing heat exchangers for SOFC applications**

#### **Architecture**

Two architectures are considered for the HE:

- Tube heat exchangers, composed of a series of tubes.
- Plate heat exchangers, consisting of a series of multiple thin plates.

Plate and tube heat exchangers are used extensively for low and medium temperature applications. The choice between both architectures is mainly determined by

- the pressure and temperature difference between the two mass flows
- the required surface area
- the available volume for the HE

The pressure and temperature difference are the driving parameters for a high temperature HE.

## **Dimensions**

The main dimensions of the HE are calculated before the start of the design phase (CAD):

- the typical optimal hydraulic diameter
- the total surface area
- the wall thickness

These dimensions are calculated from the operational parameters:

- the performance requirements at rated or partial load
- the total pressure drop budget
- the required exchanged heat
- the mass flows
- the required flow uniformity

## **Compliance**

The compliance puts constraints on the design of the HE. Compliance requirements are derived from

- the interfacing
- the differential thermal expansion

the interaction of the parts over lifetime.

## **High temperature design considerations**

The only proven technology for joining materials for high-temperature applications (850-950 °C) is welding. Welding requires the use of compatible alloys; the welds must remain stable at high temperature under typical SOFC gas compositions; the weld must not emit excessive quantities of oxidation products (either in the gas- or solid-phase) that are detrimental to the SOFC.

Trials are executed on a number of the welding technologies that are to be studied in this project: laser; TIG; switch welding; capacity discharge welding (CDW); brazing.

Welding techniques are crucial for realizing the main function of a heat exchanger: exchanging heat between two or more fluid flows, without exchanging mass. This means that the metal separating the flows must be thin walled and welded gas tight at the edges.

The work has mainly focussed on leakage free TIG welds. The tests involve the welding of two or three thin walled sheets of high temperature alloys. The samples are subsequently tested on leakage, before and after thermal cycling.

Leakage occurs either due to porosity of the welds, or crack initiation in the heat affected zone of the metal sheets.

## **Manufacturability**

### *Forming*

Forming techniques are required for the manufacture of components, and the production of subassemblies. Some high temperature alloys cannot withstand the strain that is introduced during the forming process. This limits the design options and the material choice. Furthermore, it can require the use of highly specialised, expensive forming techniques, which are difficult to integrate in a mass production process.

### *Joining*

Components are connected by joints, designed for

- Exchanging forces between connected parts
- Keeping the gas flows separated. Small gas leakage between the mass flows reduces the global efficiency. Major gas leaks can lead to mixture of hydrogen containing gas and oxygen, causing failure of the complete system.

Joining materials at high temperatures (850 – 950°C) is done by welds, the only proven technology.

- This requires the use of compatible alloys.
- The welds must remain stable at high temperatures in the SOFC typical gas compositions. The grain structure of the weld can change during the lifetime of the product, causing loss of mechanical properties and.
- The weld can emit oxidation products (gas or solid flakes). This can impair the SOFC operation

We will investigate five weld technologies for the high temperatures application:

- Laser
- TIG
- Stitch welding
- Capacity discharge welding (CDW)
- Brazing

## **2. Creep measurements**

The mechanical properties of steel are influenced by temperature: The modulus of elasticity and the tensile strength of steel alloys drop with increasing temperature. Some creep data are published for high temperature alloys. However the data are incomplete. Therefore, creep data are measured on a temperature/stress matrix in the 850 – 950°C range.

Creep (plastic deformation by prolonged stress) occurs at temperatures above 60% of the melting point of an alloy. Creep is a complex process, depending on the stress, the temperature and the atmosphere surrounding the alloy. It occurs in three phases (phase 1 is not relevant for our application):

- Phase II creep: linear progression of the strain over time (at constant stress). This can cause deformations in the heat exchanger, and can adversely affect the flow uniformity.
- Phase III creep: accelerating strain at constant stress, until failure of the part. This can cause leakage between the gas flows in the heat exchanger.

## Medium precision creep measurements

The medium-precision creep test equipment has been designed to determine phase II creep, and the onset of phase-III creep.

The test equipment consists of the following components: a dedicated test furnace; a creep resistant chassis; a contact less position measurement system; a data acquisition system. The creep-resistant chassis was designed and fabricated in house; the other test components were purchased specifically for this project. The box furnace (Figure 6.20) was supplied by Nabertherm. It has a maximum operating temperature of 1280 °C. Commissioning tests showed that at 950 °C there was a temperature variation of no more than 2.0 °C within the zone of the furnace where tests will be carried out. The furnace is large enough to allow measurements to be made on 50 samples simultaneously.



Figure 6.20. Furnace for medium-precision creep measurements.



Figure 6.21. Creep-resistant chassis for medium-precision creep measurements.

The creep resistant chassis is designed to hold up to 50 samples in the test furnace. The chassis is fabricated from 253 MA, 2 mm; information from the material data sheets and in-house testing has shown that this material is creep resistant under the conditions to be used in this study. The creep resistant chassis is shown in Figure 6.21. The position measurement equipment (Figure 6.23), is an LED digital micrometer system. There are a total of 10 detector systems each capable of measuring up to 5 samples, giving a total measuring capacity of up to 50 samples.

Testing started after commissioning of the medium-precision creep test equipment. The medium precision creep tests are executed in a modified box furnace. 28 samples are tested in parallel.

15 tests were executed. A test run lasted for 450 – 800 h, depending on the temperature and load of the samples.



Figure 6.22. Data acquisition system for medium precision creep measurements.



Figure 6.23. Array of 28 samples and optical micrometers, under the furnace.

The creep graphs showed typical phase II creep, but - depending on the material definition – non linear creep behaviour was observed during prolonged testing.

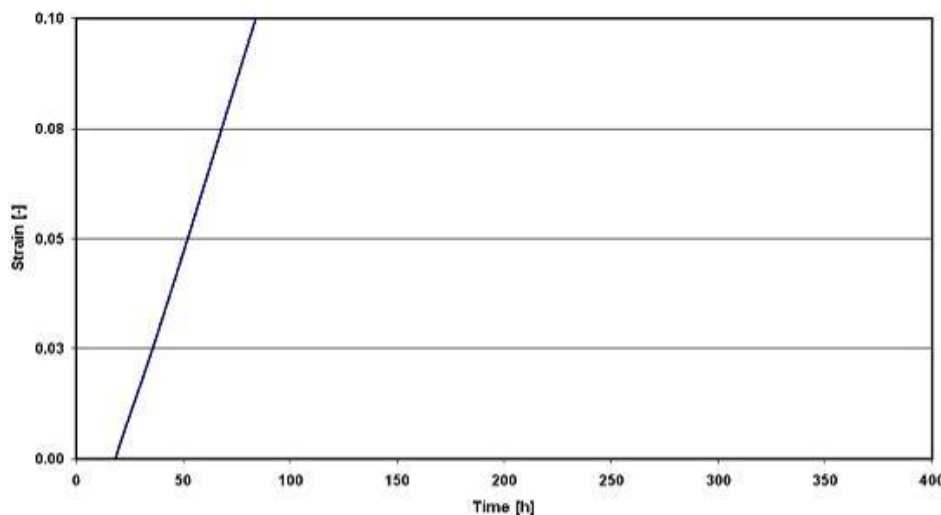


Figure 6.24. Pure type II creep.

### High precision creep measurements

The high-precision creep test equipment has been designed to more accurately determine the rate of phase-II creep. The furnace, supplied by Nabertherm has been installed in a specially built test facility. The test facility has been equipped with air-conditioned climate control (Mitsubishi Electric) to minimise variations in temperature around the test equipment that would lead to changes in the measured creep rate. The furnace, shown in Figures 6.25 and 3.26, is a vertical split tube furnace to allow easy access. The furnace has a maximum operating temperature of 1100 °C and has a temperature variation of less than 1.5 °C along the length of the furnace hot zone.



Figure 6.25. High-precision creep furnace



Figure 6.26. High-precision creep furnace

The position measurement equipment is supplied by Keyence and is a CCD Laser Displacement Sensor (type LK-G32) system. The data acquisition system consists of a voltage and temperature acquisition unit, capable of logging 32 channels (IMC Spartan T-32). Furthermore, the measurements of the digital micrometers are acquired by a DaysyLab programme, communicating with the Keyence controllers over a 4 port serial server (VLink ESP-904).

183 high precision measurements were executed, on 5 sample definitions. A typical high precision test ran for 20 – 60 h. The temperatures and material choice was the same as for the medium precision test. The results are in line with the medium precision measurements. However, the test is not suited for determining delayed phase II creep, due to the short test duration.

### Creep data reduction

According to literature, the strain rate depends on temperature and stress, by an Arrhenius-type relation:

$$\dot{\epsilon} = A \sigma^n e^{-\frac{E}{RT}}$$

The relation is only valid if the creep is determined by one underlying creep mechanism. This limits the creep relation to a stress and temperature range. The goal of the data reduction is:

- To establish the parameters of the relation E (activation energy), n (stress power coefficient) and A (pre-exponential factor).
- To check if the relation is valid in the stress and temperature range where the materials will be applied.

The power coefficient and the activation energy are determined for three out of five tested materials. The results for medium and high precision creep tests are in good agreement, therefore high precision creep tests are chosen to fill the gaps in the data, and to repeat those single creep measurements, that cause the highest spread.

## Creep Data

### Medium precision data.

The creep rate for three alloy definitions was mapped as a function of the load ( $\sigma$ ) and the temperature. The load ranged between 1 and 15 MPa, while the temperature varied between 750 and 950°C.

### High precision data

High precision tests focussed on high loads (10 – 25 MPa). Furthermore, MP tests were repeated if the data showed too much scatter, or if these data were not in line with other measurements.

The creep data are now available for FEM calculations.

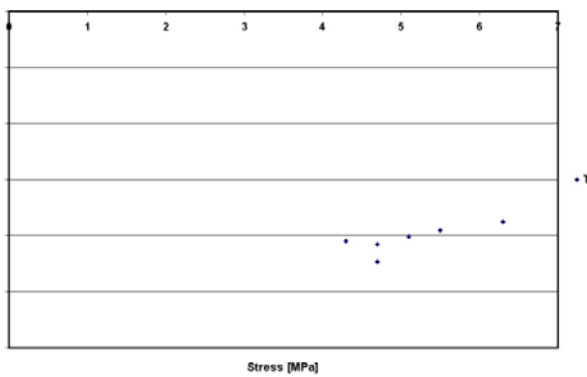


Figure 6.27. Creep rate at 875°C, plotted vs stress (4 – 9 MPa).

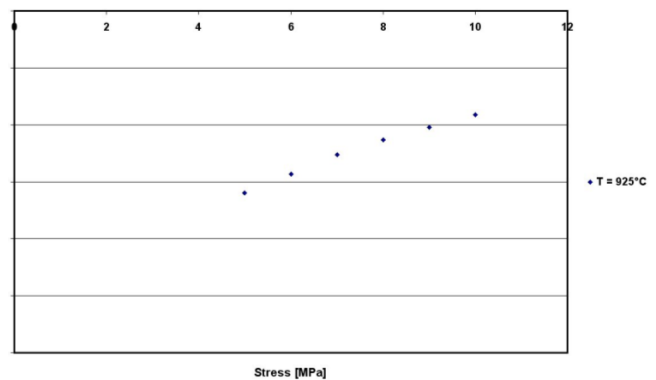


Figure 6.28. Creep rate at 950°C, plotted vs stress (4 – 10 MPa).

## SEM / EDX analysis

SEM / EDX analysis was carried out on 4 creep samples, before and after creep. The results showed that recrystallisation occurred during creep:

The grain size of the material was 10-25 microns before testing and 20-50 microns after 500 h creep test (900°C, 8 MPa). The analysis on a ferritic alloy showed concentrations of Hafnium before the test. The Hf was diffused after the test. Hf is added to this alloy to pin the dislocations, and to improve creep behaviour. The uneven Hf distribution can adversely affect creep properties during the first use of the material.

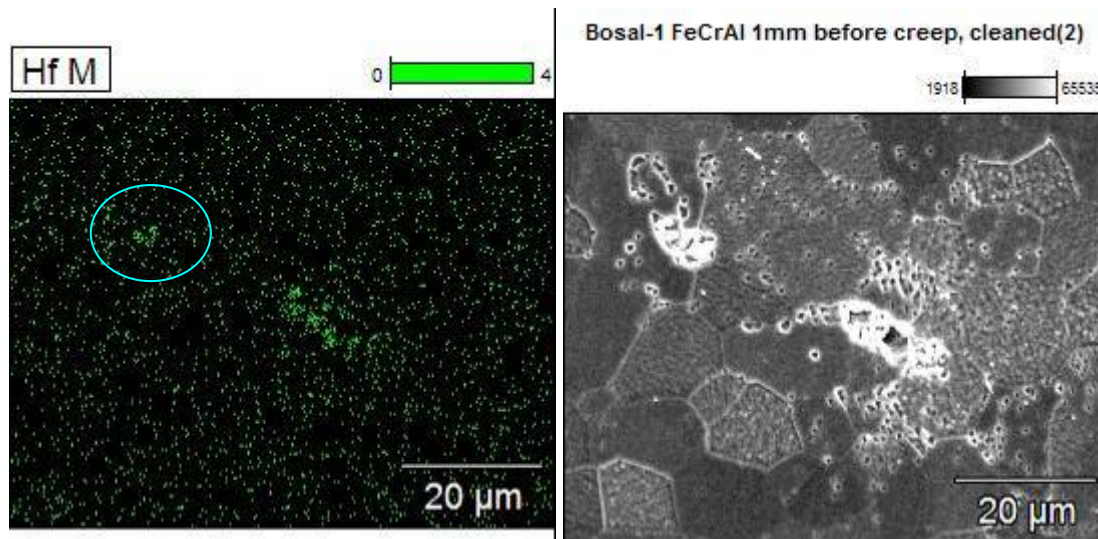


Figure 6.29. Hafnium M-line distribution on as-received surface.

### 3. Chemical stability

The materials test programme at Bosal Research focused on the material properties of high temperature alloys. These alloys contain a substantial chromium fraction, needed for their increased tensile strength, creep resistance and corrosion resistance. However, trace amounts of the chromium fraction is oxidised to gaseous hexavalent chromium compounds. Hexavalent chromium in the gas flow reduces the power output of the SOFC stack.

Chemical interactions between the HE components and the atmosphere can lead to degradation of the mechanical properties. Furthermore, the parts can contaminate the atmosphere by releasing corrosion products (gas or solid flakes). This can affect the operation of the SOFC system:

- The gas flow downstream of the HE can be blocked by flakes.
- SOFC stack can be poisoned by corrosion products

The chemical interactions are determined by the composition of the atmosphere, and the temperature. Chemical stability data are not available for the atmosphere in a SOFC, therefore the following data was measured during this research project.

- the mass loss or gain of the steel
- the changes in grain structure
- the changes of mechanical properties
- the release of corrosion products

### Test Facility

The materials' test facility at Bosal Research N.V. has been designed to test the chemical stability heat exchanger materials under SOFC operating conditions. These include: high temperature; elevated pressure; oxidising atmospheres that represent the SOFC cathode conditions; atmospheres that represent the SOFC anode conditions. Tests were carried out in dedicated test rigs. Each test rig consists of a horizontal tube furnace that can be fitted with

one of two types of reactor: one to perform tests under atmospheric conditions; and one to form tests at elevated pressure. Each test rig is fed from a dedicated gas facility through which gas compositions that are representative of both the SOFC anode and SOFC cathode can be generated.

The gas stream to each rig is humidified through a steam-generator system. A condenser system is fitted downstream of each test rig to enable the collection of condensate that can be analysed in order to determine loss of volatile compounds such as chromium-containing materials from each sample under test. Due to the flammable nature of some of the gas mixtures to be used in these tests the test facility will be fitted with gas- and fire-detection equipment (Dräger) that is fully integrated with the gas supply system; all flammable gases will be automatically turned off in the event of a significant gas leak or fire. The test facility has fully air-conditioned climate control that was already described earlier.

The horizontal tube furnaces (Figure 6.30), have been installed in the test facility, each on a custom-built test bench. Figure 6.31 shows the test rig setup for an atmospheric test. The figure shows the water / vapour mixing pipe that allows the introduction of humidified gas mixtures to the reactor.

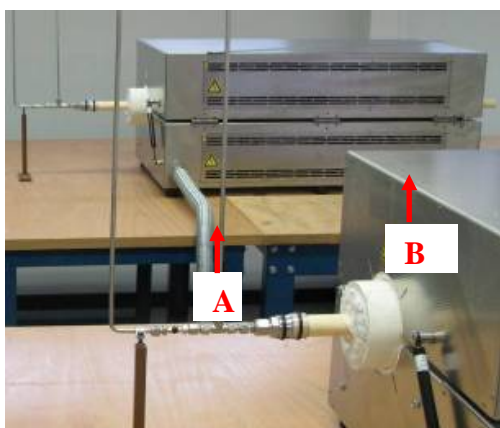


Figure 6.30. Horizontal tube furnaces for materials' chemical stability tests.



Figure 6.31. Reactor inlet, showing A: press. water feed; B: reactor for atmospheric tests.

All gas flows to the test rigs are controlled through mass-flow controllers (Figure 6.32). The controllers have been installed in a custom-built ventilated cabinet to reduce the risk of gas leaks into the rest of the test facility. Water is fed to each test rig through a Bronkhorst liquid-flow controller, which is in turn fed from a custom-built pressurised water system.



Figure 6.32. Mass-flow controllers and ventilated cabinet.

### Test upgrade – pressurised testing

The tests were upgraded after completion of the cathode/atmospheric testing programme.

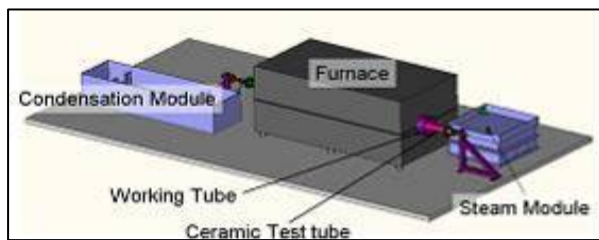


Figure 6.33. Drawing of the set-up, showing the main components.



Figure 6.34. Tube furnaces, holding a single atmospheric reactor.

Six test rigs were built, capable of handling both cathode and anode gas, at pressurised conditions (7 bar). Under cathode gas the test duration was extended to 500 h.

The main components of the upgraded rigs are:

- Double walled Ti/Steel reactor
- Gas and water tubing, applying a constant gas and water flow to the reactor
- Internal water boiler, integrated in the reactor
- Gas cooler, condensate trap and pressure controller



Figure 6.35. Tube furnace, showing the inlet tubing for gas and water flows.

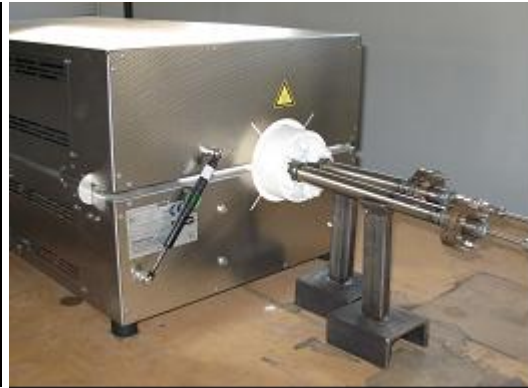


Figure 6.36. Tube furnace, holding two pressurised set-ups.

### Chromium Evaporation test results

116 tests were executed during M25-M36:

- 84 at 150 h, atmospheric, cathode gas
- 11 at 500 h, pressurised, cathode gas
- 13 at 500 h, pressurised, cathode gas
- at 150 h, atmospheric, anode gas
- at 150 h, pressurised, anode gas

The Chromium evaporation was mapped, depending on the temperature and the alloy definition. This was correlated to the output of a 3D numerical model, taking into account the flow conditions, atmosphere, and literature based surface reaction kinetics of Cr VI evaporation.

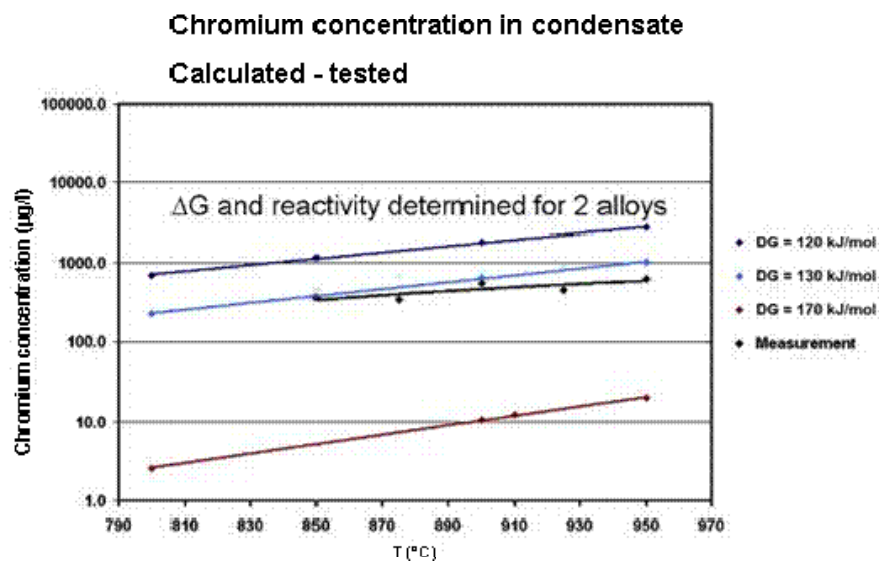


Figure 6.37. Chromium evaporation, measured and calculated values are shown.

## SEM / EDX Analysis

SEM (Scanning Electron Microscope) imaging was carried out on cross-sections of the tested samples. A mapping of the elements was carried out by EDX (energy-dispersive X-ray spectroscopy).

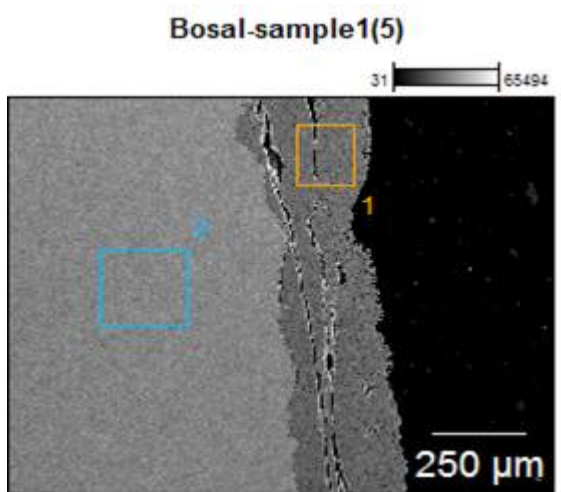


Figure 6.38. Oxide layer on an austenitic high temperature alloy (pressurised test).

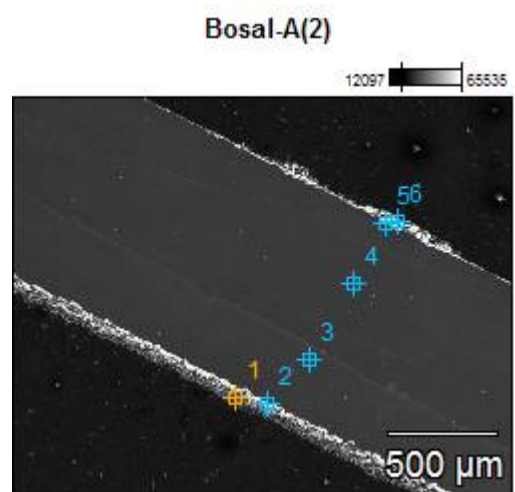


Figure 6.39. Oxide layer on a ferritic, alumina forming alloy (pressurised test).

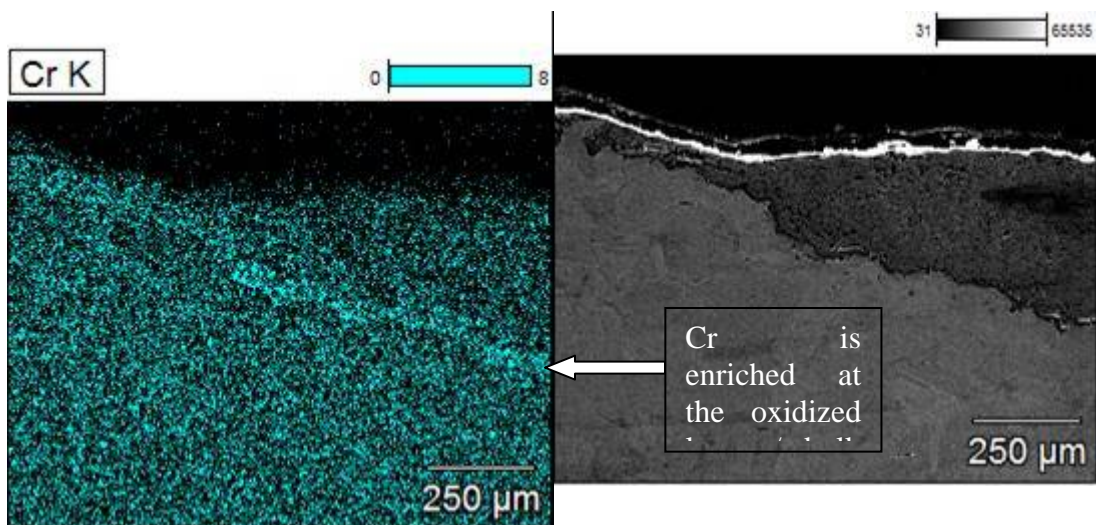


Figure 6.40. Chromium distribution of an austenitic high temperature alloy (pressurised test).

The measurements have led to guidelines, allowing for the selection of materials in Heat Exchangers and high temperature BoP components.

## 4. Weld Stability and Leakage propagation

4 welded samples (2 alloy definitions) were subjected to cathode gas (2 pressurised and 2 atmospheric tests). The samples were analysed by SEM / EDX.

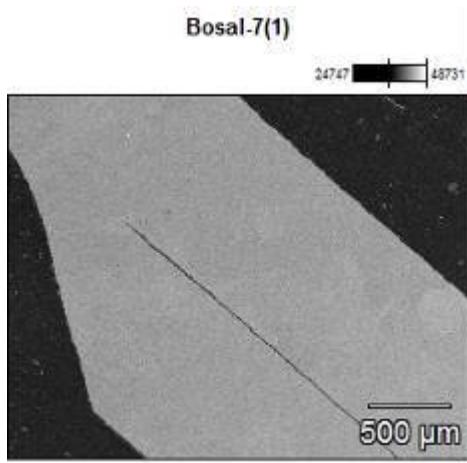


Figure 6.41. SEM image of one side of the weld.

## Leakage Propagation

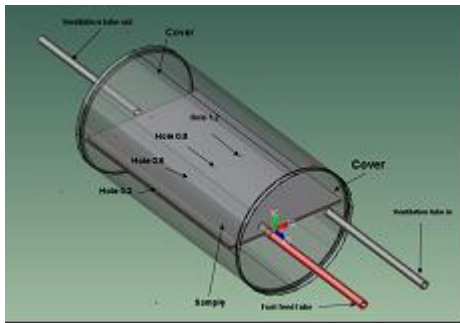


Figure 6.42. Test sample, showing the single cell (centre), gas inlet and outlet tubing, and the canister.

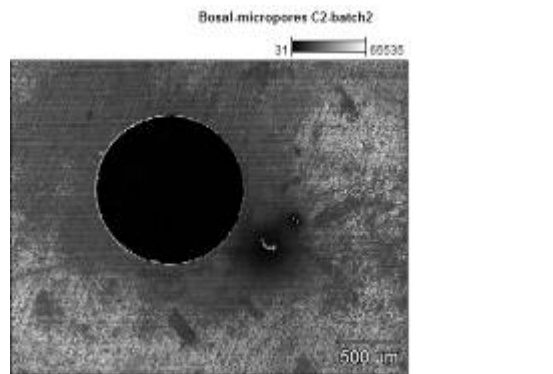


Figure 6.43. Calibrated hole (800 μm) after 150 h leakage test

Four samples were tested. Each sample consisted of a single cell of a heat exchanger. The diameter of the holes ranged between 0.20 and 1.25 mm. The exterior of the cells was subjected to cathode gas, while anode gas entered the cells, and leaked through the holes. The tests were executed at 900°C, atmospheric.

The samples were analysed by SEM / EDX. Local hot spots are seen to be formed around the diameter of the holes and are seen to contain a higher proportion of Al and O, compensated by lower amounts of Fe and Cr.

## 6.3 Fuel Processing Equipment

### 6.3.1 Reforming and anode recycle

The numerical analysis was conducted on the basis of thermodynamic equilibrium of the reformer unit and the SOFC with varying recycle fractions and reformer inlet temperatures.

According to the numerical analysis the critical parameter in viable anode recycle system for planar internal reforming SOFCs is the affinity for carbon formation in the reformer unit. According to this equilibrium analysis, high (> 60%) recycle fraction is needed to impede the carbon formation in the reformer reactor. High recycle fraction lowers the cell voltage and increases the size and cost of the recycle blower. However, carbon formation in the reformer can not be solved through equilibrium analysis alone as the kinetic properties of the catalyst may inhibit carbon formation. Therefore experimental analysis of the limiting operating conditions for carbon formation were needed to realize safe operating conditions of the fuel processing system.

A lab-scale experimental setup was used to perform test runs with the catalyst to assess the affinity to carbon formation and hydrocarbon conversion. A gas composition corresponding varying recirculation ratio in a SOFC system was fed into the reformer. Synthetic anode exhaust gas (CO,CO<sub>2</sub>,H<sub>2</sub>,H<sub>2</sub>O) and desulphurized natural gas were used. The operating temperature of the catalyst, the recycle fraction of the anode exhaust gas and the space velocity of the catalyst were varied during the test run to solve the limiting operating conditions.

The experimental results were compared to the calculated equilibrium values to identify any limiting operating conditions. The experimental result for the conversion of methane was comparable with corresponding equilibrium values when synthetic recycle gas was used (Figure 6.44). When no recycle gas was used, the thermodynamic equilibrium of methane conversion was not reached. Furthermore, the inlet temperature of the reformer should be 600°C or more to achieve above 95% conversion of C<sub>2+</sub> hydrocarbons in the natural gas under adiabatic operating conditions. Increasing the GHSV from 20 000 to 35 000 h<sup>-1</sup> did not cause significant changes in the conversion of methane as equilibrium was again reached.

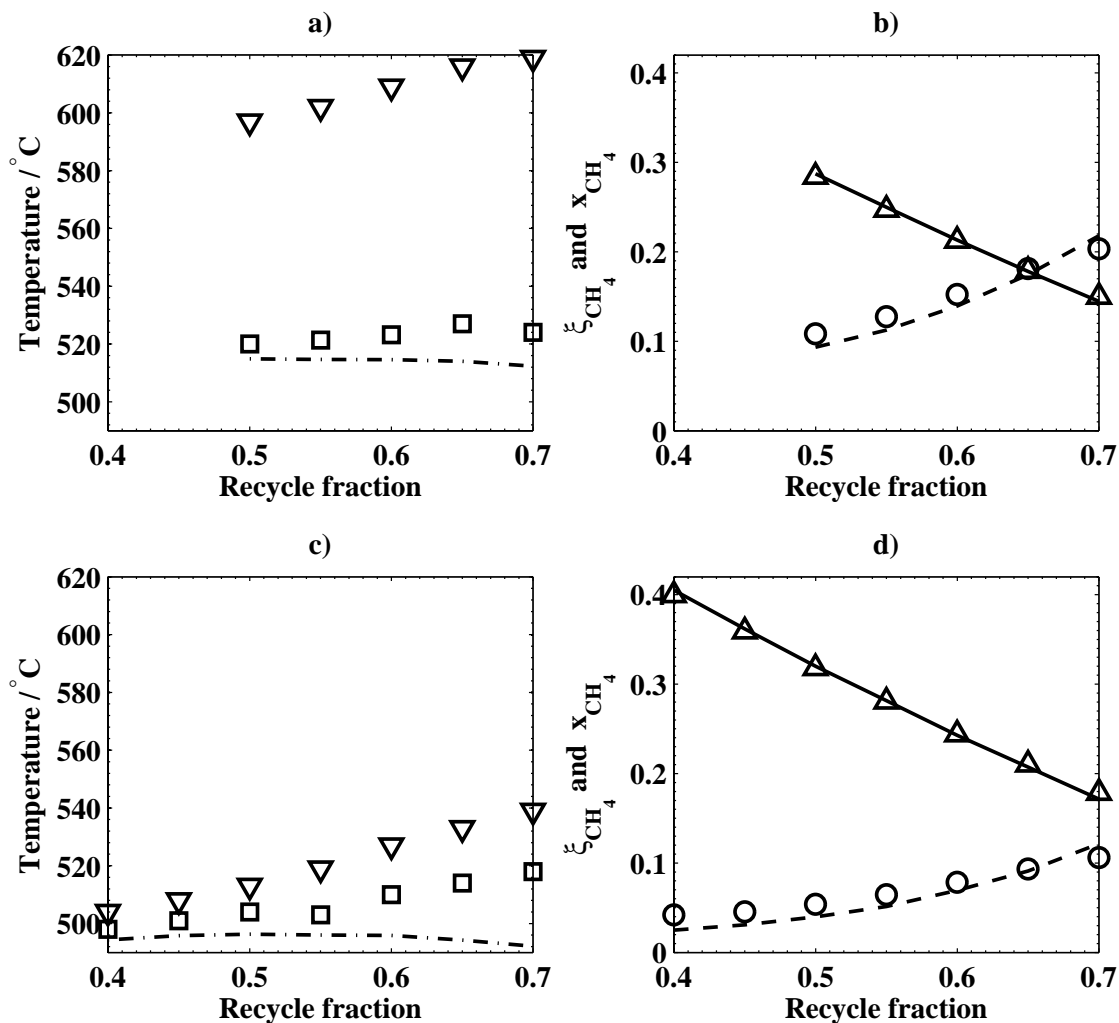


Figure 6.44. Temperature at the reactor inlet and at the trailing edge of the catalyst, mole fraction of methane in the dry reformat gas and conversion of methane versus the recycle fraction. a), b) inlet temperature =  $610 \pm 12^\circ\text{C}$  and c), d) inlet temperature =  $520 \pm 20^\circ\text{C}$ . Markers represent measured values and lines calculated equilibrium values. ( $\square$ , dash-dot line) = temperature at the trailing edge of the catalyst, ( $\circ$ , dashed line) = conversion of methane and ( $\Delta$ , solid line) = mole fraction of methane.

A qualitative analysis of carbon formation in the reformer was conducted by observing the evolution of methane conversion and pressure drop of the catalyst over time. No decrease in the methane conversion (Figure 6.45), or increase in the pressure drop could be measured which would indicate accumulation of carbon in the catalyst. Additionally, periodic oxidation tests were made by supplying air to the catalyst to oxidize possible carbon deposits which could be then measured by online gas analysis. Only trace amounts of carbon were detected and the amounts were nearly equal regardless of the whether the carbon formation was thermodynamically possible or not.

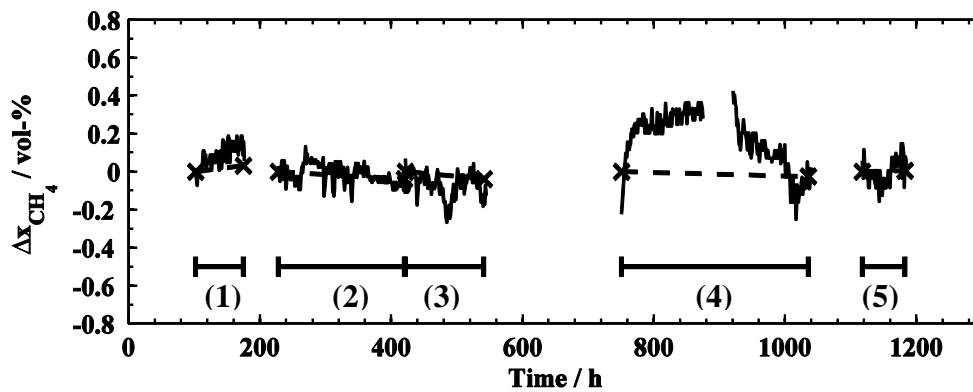


Figure 6.45. Changes in the mole fraction of methane of the reactor outlet gas over time. (solid line) = measured values and (x, dashed line) = equilibrium values. Recycle fraction was (1) 0.7; (2) and (3) 0.6; (4) and (5) 0.5

Based on the experimental analysis, it can be concluded that no significant carbon formation was observed that would compromise safe operation of the reformer with reactor inlet temperature above 500°C and recycle fraction above 0.4. Therefore, the pre-reformer and the catalyst are technically feasible for SOFC systems that utilize anode off-gas recycling.

## 6.4 Power electronics and controls

### 6.4.1 Control system for pressurised operation

The RRFCS SOFC system is a high temperature integrated gas turbine and solid oxide fuel cell system designed to run on natural gas. The system is designed to operate with the RRFCS integrated planar solid oxide fuel cell stack, operating at temperatures between 850°C and 950°C and at high pressures.

The key components of the 1MW product demonstrator are described below.

#### Generator Module (GM)

Four GMs, each capable of producing 250kW and consisting of two tiers containing:

- Off Gas Burner (OGB) – Used for heating or maintaining tier temperature fuelled either externally or from excess fuel from the stack.
- Cathode Loop – Ejector driven air loop used to recycle air provided by the turbo machinery around the fuel cells' cathodes, reformer and OGB. Some of the hot recycled air is diverted to drive the turbo machinery.
- Anode Loop – Ejector driven fuel loop used to recycle externally supplied fuel through the reformer and over the fuel cell anodes. Some of the unused fuel is diverted to fuel the OGB.

Each GM also contains turbo machinery for pressurising the stack; an external fuel processor to process the gases used to fuel the SOFC; and a start combustor used to bring the tiers up to temperature following start-up.

## Package

These four GMs are linked to a package system consisting of four inverters, one for each GM, used to export to the grid; grid connection and load bank facilities; air and gas compression systems; oil supply systems required for the turbo machinery; safe gas generation; and fire protection systems.

A control system has been developed by RRFCS to manage thermal and electrical loads, and to control the various external sub-systems. The core of the control system consists of a Comano controller which is capable of supporting a range of communication interfaces and hence integrating with a wide selection of Fieldbus input/output (IO) devices and other intelligent systems. The Comano controller has been developed by OSys (formerly DS&S) and is used widely within Rolls-Royce for the control of other power generation systems and is the preferred Rolls-Royce Common Controls platform.

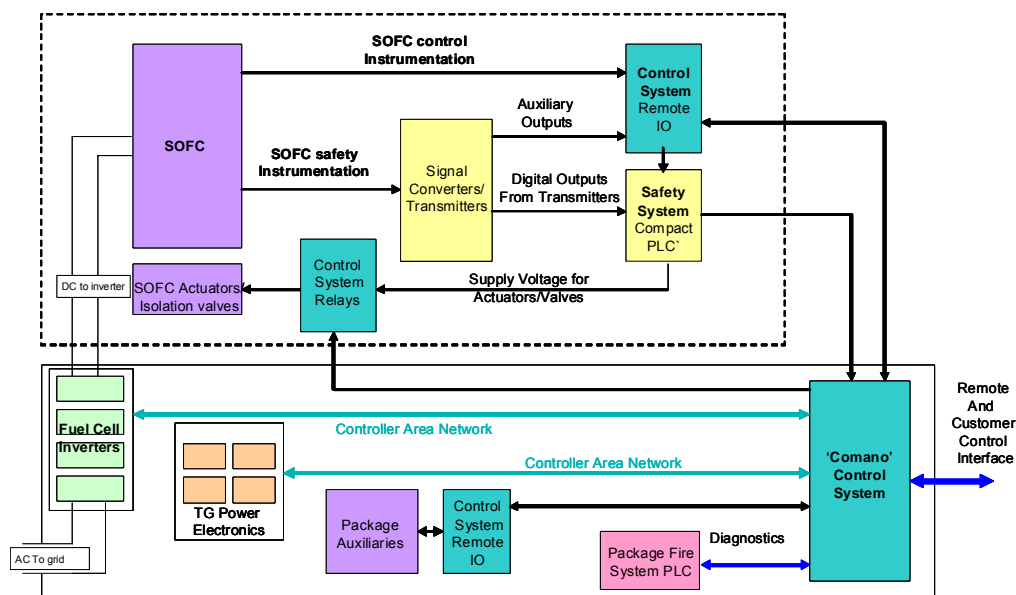


Figure 6.46. Overview of the RRFCS control system.

Due to the flexibility of the Comano controller it is possible to integrate with a wide range of commercial off the shelf (COTS) hardware and software systems. This allows RRFCS to use the latest technologies in validated products at a reduced cost. Comano also offers web based client tools and a high speed pre/post trip logger to enable remote diagnosis and support to operating problems.

A simulated test environment has been created in order to develop the complete integrated control software. This System Test Facility (STF) uses a simulator to model the plant dynamics (plant models developed by UNIGE). This enables the integrated control system to be verified off-line in a laboratory environment using the same configuration as used on a rig or field demonstrator.

The STF also provides an integrated off-line environment for fault finding and problem solving and allows tests to be performed on the control system under simulated system conditions that would otherwise prove hazardous if performed on a real system. Additionally

the STF can also be used as a training simulator allowing operators to become familiar with the controls and the plant.



Figure 6.47. System Test Facility, Loughborough UK.

The control system has been adapted to work with a 15kWe Stack Block Rig. This rig is designed to integrate the operation of the fuel cell stack with; the Anode and Cathode loops, and the OGB, with the power electronics.

A series of tests were completed on the 15kWe rig including a 250 hour test the majority of which was completed unmanned. During this test the following operations were demonstrated:

- Fully automated processes
  - Warm up
  - Off Gas Burner lighting
  - Stack reduction
  - Shut down
- On-Load Temperature Control
- Off Gas Burner Temperature Control
- On-Load Current Control
- Automatic control of gas chromatograph and logging of gas analysis data
- Alarm management system, health monitoring & reversion modes

## 6.4.2 Power electronics for atmospheric SOFC system

The Switch task was to find optimal power electronics (PE) solution for atmospheric SOFC systems, which fulfils both technical and economical requirements and to verify the technology in a 50 kW prototype system. Task was divided into 3 subtasks:

- 1) PE technical requirement analysis,
- 2) Prototype concept design,
- 3) Prototype design and evaluation.

Table 6.1. The project schedule for 2008 and first half of the 2009 (Prototype design & testing part II continues to end of the year 2009).

| 2008                     |   |   |   |   |   |                                |   |   |    |    |    | 2009 |   |   |                                 |   |   |
|--------------------------|---|---|---|---|---|--------------------------------|---|---|----|----|----|------|---|---|---------------------------------|---|---|
| 1                        | 2 | 3 | 4 | 5 | 6 | 7                              | 8 | 9 | 10 | 11 | 12 | 1    | 2 | 3 | 4                               | 5 | 6 |
| Converter concept design |   |   |   |   |   |                                |   |   |    |    |    |      |   |   |                                 |   |   |
|                          |   |   |   |   |   | Prototype design & testing (I) |   |   |    |    |    |      |   |   |                                 |   |   |
|                          |   |   |   |   |   |                                |   |   |    |    |    |      |   |   | Prototype design & testing (II) |   |   |

### Prototype

In this project it is necessary to control individual fuel cell stacks in the prototype system, therefore boost converter with grid inverter was selected in requirement analysis.

#### Advantages

- Use of standard converter and filters, boost circuit to be customized,
- Power from individual fuel cell stacks can be controlled,
- No transformer.

#### Disadvantages

- More complex control - two converters in cascade to be controlled.

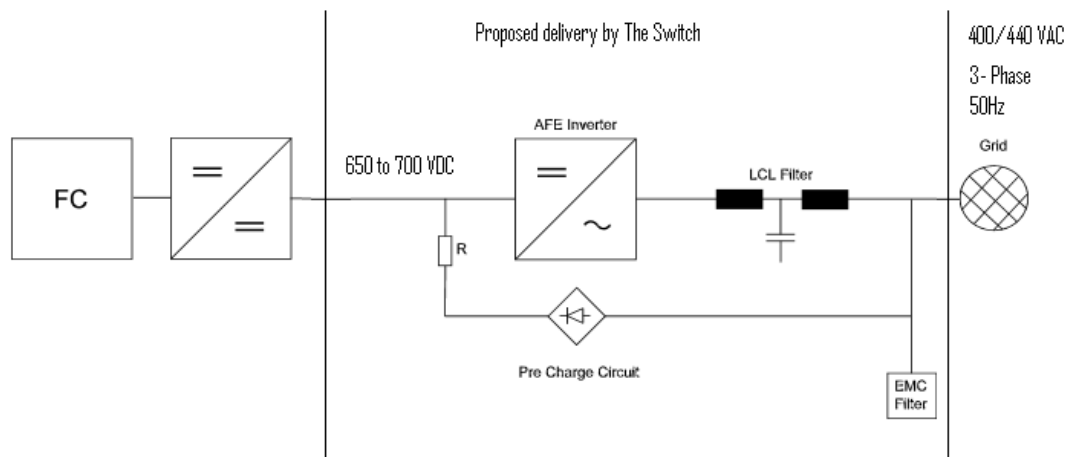


Figure 6.48. Designed concept for grid interface.

The concept was designed and assembled. The Switch performed full power testing of the converter during test phase, after which the unit was given for future use with fuel cells. Prototype converter was designed so that it is ready for production in larger quantities with only minor modifications.

Prototype cost of the 50kW grid cabinet using standard components is around 20k€unit. - For 1MW unit the comparable prototype cost is approximated to be around 50k€unit (+ liquid cooling system). (Including: cabinet and mechanics, cabinet liquid system, logic, fuses, filtering, circuit breaker, pre-charge circuit and grid Inverter). In series production and using cost optimised product structure the price level can be reduced. Further cost reduction can be achieved using system level integration of the power electronics. (Boost converter and grid inverter as a one unit).

## 6.5 Insulation

### 6.5.1 Insulation for pressurised system

A compact high efficiency insulation system is required for the RRFCS product. The insulation must limit thermal losses from the system in order to maintain system efficiency and it should be compact in order to minimise the overall dimensions of the pressure vessel. Furthermore the insulation should be mechanically and chemically stable within the cycle environment. A series of potential candidate materials were reviewed as summarised below:

**Ranges of Thermal Conductivity at Different Temperatures for Types of Insulating Material**

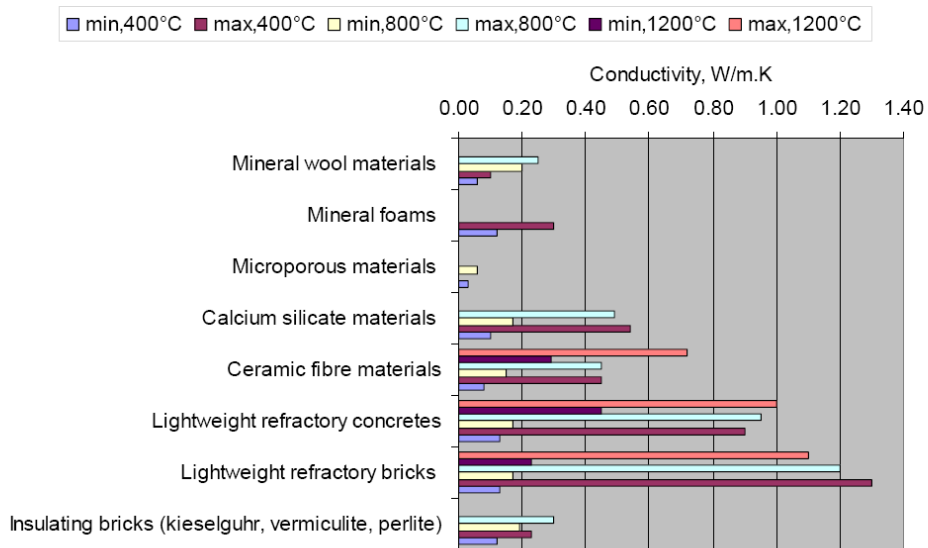


Figure 6.49. Survey of commercially available insulation materials.

Based on these data an insulation system was proposed.

Further work was also carried out on the physical design of the insulation. The insulation was found to be relatively weak and thought to be incapable of surviving thermo-mechanical loads imposed during operation and shock loads induced by transport. It was therefore necessary to support the insulation on a metallic structure.

The support structure had to ensure that the insulation was held in place against the side of the pressure vessel to ensure that air flows to the back of the insulation could be avoided. Care was required with the design of the support structure to ensure that ‘thermal bridging’ between the hot and cold faces could not occur.

A version of the insulation system developed for the 1MW product was used in the 15kWe Stack Block rig. The insulation system was found to work well throughout the 15kWe rig test programme with no signs of degradation. To date the insulation system has operated for 520h at temperatures > 800°C, whilst maintaining an acceptably low pressure vessel metal temperature.



Figure 6.50. 15kWe Stack Block Rig – Insulation.

## 6.5.2 Insulation for 50 kW unit

During Large SOFC project special attention was paid on material shrinkage and the compatibility between different insulation materials. New information was gained on issues related to insulation assembly and the handling. Few insulation assembly companies have experience on high temperature and microporous insulation materials and therefore it is challenging to find suitable assembly subcontractors.

Insulation shrinkage and compression testing was made during the project. Results proved that the information given in the datasheets is often not valid in SOFC operating temperatures which might lead to insulation failures. Shrinkage was also discovered. In figure 6.51 there is a failed sample after the compression in high temperature.



Figure 6.51. *Failed insulation sample after high temperature compression.*

## 7 Industrial stack (WP4)

### 7.1 50 kW planar SOFC stack assembly

#### **Stack/system interface for the 50kW demonstration unit**

Based on a large stack prototype developed in the National Danish SOFC programme, the stack/system interface was analysed jointly by Wärtsilä and TOFC. This has resulted in a detailed definition of this interface. Some of the key findings and definitions are summarized here.

The 18x18cm<sup>2</sup> stack is terminated by top and bottom plates whereas manifold plate and compression system is on the system side of the interface. The gas and air manifolding, the compression system and related subsystems needed to support the stack operation has been identified as a costly part of the system and will be focus areas in design optimization for future large SOFC systems.

The Interface information reported in detail within the project addresses electrical power characteristics, process values, physical measures, mechanical load, and the thermal environment of the stacks. 24 stacks are foreseen to produce a gross electrical power of 57.6kW. A nominal operating point at 48V and 50A per stack is suggested. Model estimates of stack performance data in co-flow mode were reported at a low, nominal and high power operating point.

The Topsoe Fuel Cell Large Stack can be operated either in co- or counter flow mode with respect to air and fuel flow directions. A co-flow configuration can be an advantage because of a close to linear temperature and hence thermal expansion profile through the stack and from a Balance-of-plant thermal management point of view, whereas a counter-flow configuration will in general give rise to a more uniform stack temperature profile because due to cooling by the internal reforming.

#### **Stack testing, interface verification and performance prediction**

Two stacks on a shared manifold plate was tested at Wärtsiläs test-lab under two series of different operating conditions – one with O/C ratio = 1.5 and one with O/C ratio = 2.0. The test stand is a once-through system with desulphurization and prereformer before the stack furnace.

The operation procedure in short was the following:

- Stack installation and cold verification of physical interface including leakage test
- Start-up procedure with stacks inline: heating of desulphurizer, prereformer and furnace in 64 % H<sub>2</sub> in N<sub>2</sub> anode side flow
- Stack voltage checked by increasing current from 0 A to 25 A
- Steam and natural gas added
- Test series with various loads carried out

The data obtained from the test points was compared to stack model predictions to verify the existing stack model which is the basis for system performance calculations. The agreement between observed and calculated values can be seen in Figure 7.1.

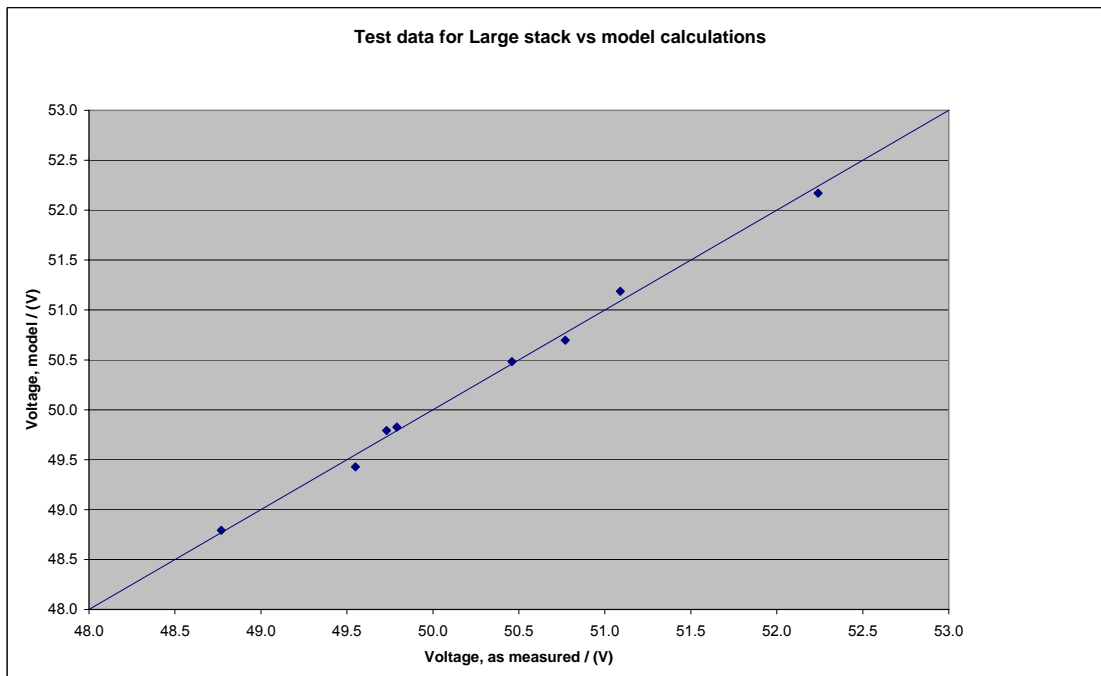


Figure 7.1. Model predictions vs measured voltages at various loads.

This stack model is used in TOFC system level flow sheet calculations and used to assist Wärtsilä in developing the flow sheet for the 50kW demonstration unit. An example of the flowsheet can be found in Figure 7.2. The test data and stack model results was made available to the relevant project partners to further the project progress, in particular VTT and FZ Jülich in their development of dynamic model tools, and Wärtsilä as mentioned above.

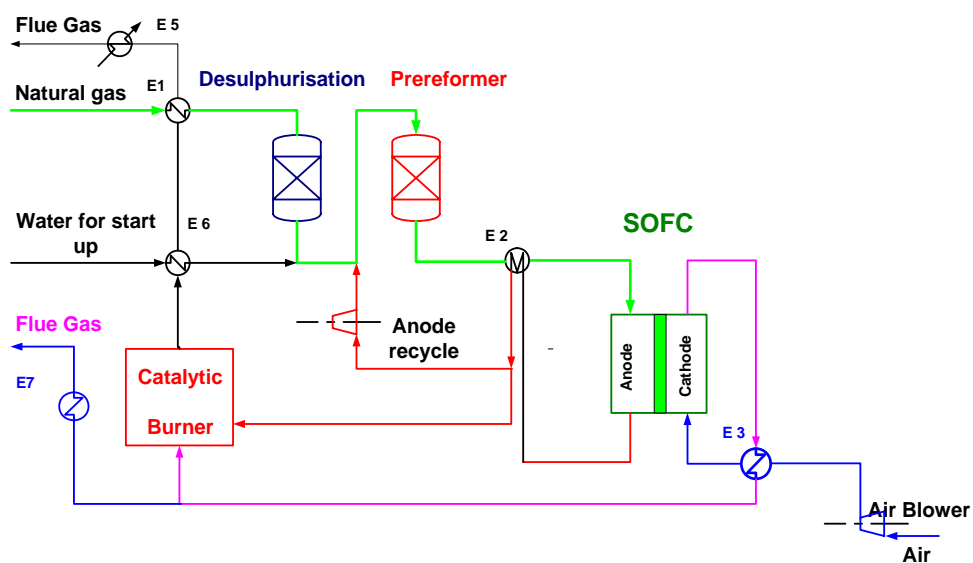


Figure 7.2. Example of flow sheet analysis.

Based on this multiple calculations were carried out to determine the optimum number of stacks and the corresponding system performance to be expected. An example of the results is shown in Figure 7.3.

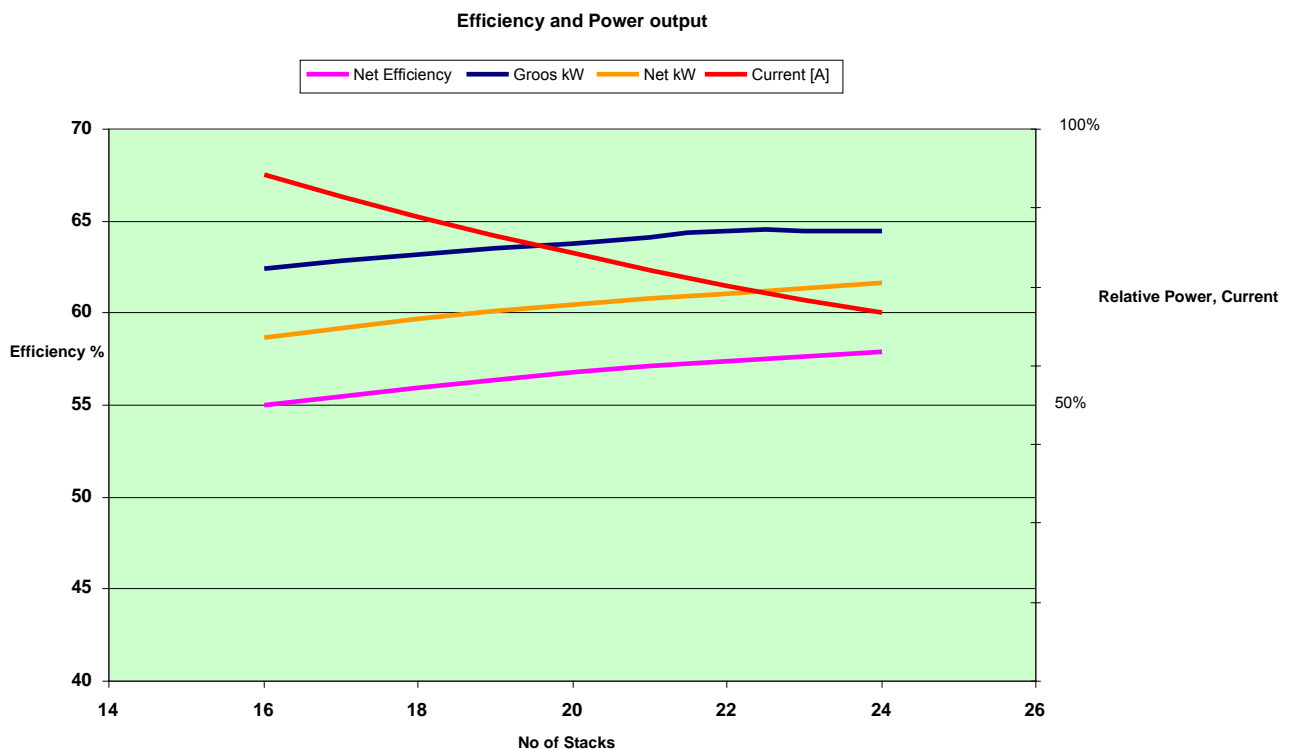


Figure 7.3. Efficiency and power output of stack assembly

Based on system design considerations of the optimal stack connection topology considering mechanical and flow distribution requirements, as well as on having a high electrical efficiency with the present stack technology, the decision was made to carry on with 24 stacks.

### Stack manufacturing and quality assurance parameters

The solid oxide fuel cells are manufactured by TOFC in facilities at the Risoe National Lab. In close cooperation between Wärtsilä and TOFC a list of stack quality assurance parameters has been defined and based on an early production of 6 stacks acceptance criteria were preliminarily determined to ensure a good and homogenous quality of the stacks to be used in the 50 kW demonstration unit.

The quality assurance criterias include but are not limited to:

- overall geometric measures
- mechanical tolerances
- leakage rates
- reference voltages at predefined operating conditions

After production of the first large stacks the criteria were compared to the results achieved from these stacks and it was anticipated to be possible to produce at least 24 stacks of the necessary high quality within the project budget.

During 2009 the remaining stacks were produced to complete the batch of 24 stacks for the 50 kW demonstration unit. By sharing the production data with Wärtsilä on a regular basis it was ensured that Wärtsilä was updated on the development and could keep track of the stack production status.

Final selection was carried out in connection with an inspection by a Wärtsilä representative at TOFC premises in Lyngby, Denmark, September 30 before final shipment to Wärtsilä.

The conclusion from the inspection was that overall quality was excellent with very high homogeneity stacks in between and for many of the most important parameters with quite big margin to the upper and lower boundaries of the acceptance criteria. The stacks were shipped to Wärtsilä on September 14. With this result a main milestone for WP4 was achieved.

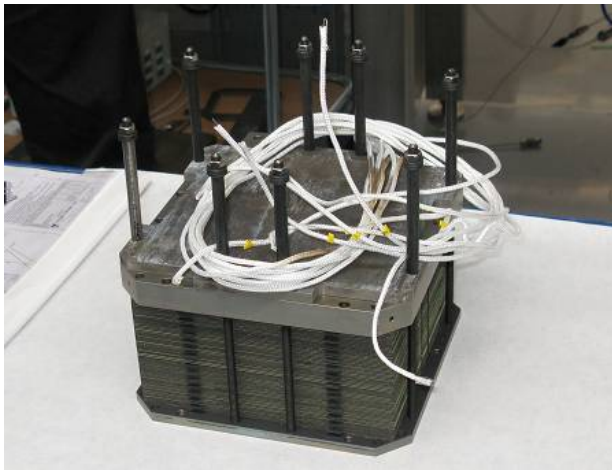


Figure 7.4. Example of stack produced – picture is taken after the stack has passed all quality tests and is now ready for packing to delivery.



Figure 7.4. The 24 stacks meeting the agreed quality specification has been produced, packed and shipped to Wärtsilä in September 2009.

The final verification of the stack assembly was performed as part of the concept verification unit. This verification will be performed in collaboration by TOFC and Wärtsilä, as well as VTT.

## Documentation

In parallel to the stack production, in a separate document all general stack operation specifications were determined and agreed upon. This will include the following information:

- installation and compression details
- start-up and shut-down procedures
- specific recommended operating points
- allowed operating windows for process and power parameters
- number of thermal cycles allowed

Detailed input has been given to Wärtsilä to ensure operating procedures for start-up and shut-down in which keep the temperature differences caused by stress inside the stack to levels well below any critical limit. The regulation implemented into the control system will monitor and regulate based on input from thermo couples placed on stacks in various positions.

For the same reason – i.e. to keep thermal stress well below any critical limit – regulation of current between various normal operating points and maximum current supplied from the stacks during such conditions have been specified in details.

Furthermore situations involving long periods with high temperature have been classified separately with respect to need for reducing gasses supplied from outside or generated from the system itself thus eliminating any risk of excessive oxidation of anode side which could be harmful to stack performance over time.

## 7.2 Potential options for stack ceramic material

The RRFCs fuel cell utilises an electrochemically inert support substrate which is made from Magnesia stabilised Magnesia Alumina spinel (MMA). The manufacturing route for the substrate can be summarised as follows:

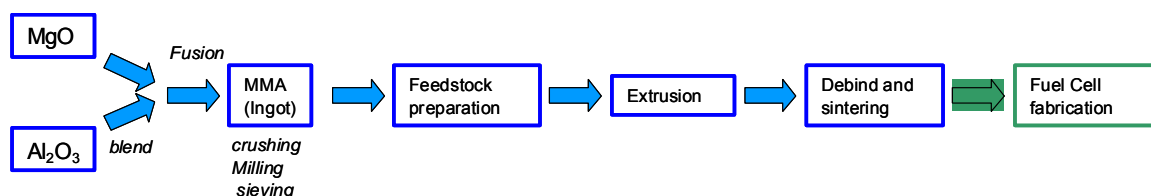


Figure 7.5. Substrate manufacture

The properties of the substrate and hence the performance of the fuel cell are heavily influenced by the properties of the MMA powder.

The initial method used for the production of this powder was based on a fusion process. Magnesia and Alumina powders were fused together to produce a 500kg ingot of MMA. The ratio of Magnesia to Alumina is carefully controlled in order to produce a powder with the desired CTE. The ingot was then crushed and ground to produce an MMA powder suitable for use in the substrate manufacturing process. A coarse powder with a relatively coarse microstructure was produced and this microstructure was retained throughout the substrate and fuel cell fabrication processes. Whilst good and reproducible fuel cell performance was obtained this manufacturing route was too expensive for large scale production. Alternative methods for the production of MMA powder were therefore investigated during this project.

## Fine powders

An alternative method for substrate production was investigated based on the use of fine powders. The process investigated involved mixing powders together and forming the MMA *in situ* during the substrate manufacturing process. The fine powders are more sinter active and so inter diffusion would be expected during the sintering cycle of the substrate manufacturing process. Various starting powders were assessed and these included mixtures of Magnesia and Alumina powders and mixtures of Magnesia and Magnesia Alumina spinel powders.

A mixture of Magnesia and Magnesia Alumina spinel fines powders in conjunction with a calcination pre process was found to give the most promising results and the development work focussed on this system.

To produce a porous tube pore formers were incorporated into the feedstock. These are designed to burn out during the Debinding cycle and so produce a porous substrate.

This process has the potential for lower powder manufacturing costs, a more finely divided microstructure and better control over the porosity in the substrate. This in turn should lead to a more stable fuel cell support with better durability properties. The process can be summarised as follows:

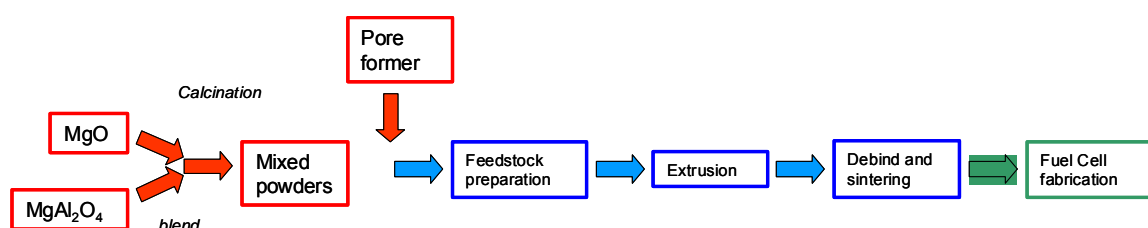


Figure 7.6. Fine powder processing route.

The work completed during the Large SOFC project showed that the MMA phases could be formed *in situ* during the substrate sintering cycle. Unfortunately the pore formers proved to be ineffective in producing the desired level of porosity in the sintered substrate. The pore formers are organic and were excessively degraded during the feedstock and extrusion processes where temperatures can reach 180°C. Various process optimisations were investigated in an attempt to find an acceptable processing route including:

- Calcination of mixed powders

- Powder milling and particle size optimisation
- Tube extrusion parameters
- Pore former / substrate Debinding cycle

The most promising methods were taken forward to fuel cell fabrication and testing but poor electrochemical performance resulted. Poor electrochemical performance was due to poor transport of gaseous species to the Anode of the cell due to a lack of porosity. Typical microstructures obtained during this work are as follows:

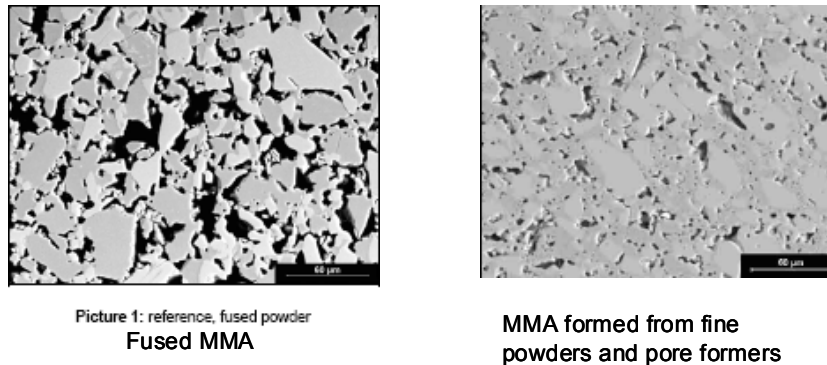


Figure 7.7. MMA microstructures.

After considerable process optimisation trials it was concluded that a the correct level of porosity could not be achieved with the pore formers available and that significant additional work would be required to develop the pore forming technology to allow this manufacturing process to be viable.

### Coarse powders

The work using fine powders demonstrated some useful benefits in terms of control of the chemistry of the MMA but it also highlighted the problem of controlling porosity. It was recognised that coarse powders would not need a pore former to achieve the porosity but the advantages of mixing separately formed Magnesia and Spinel powders could still be retained. The following process was therefore investigated:

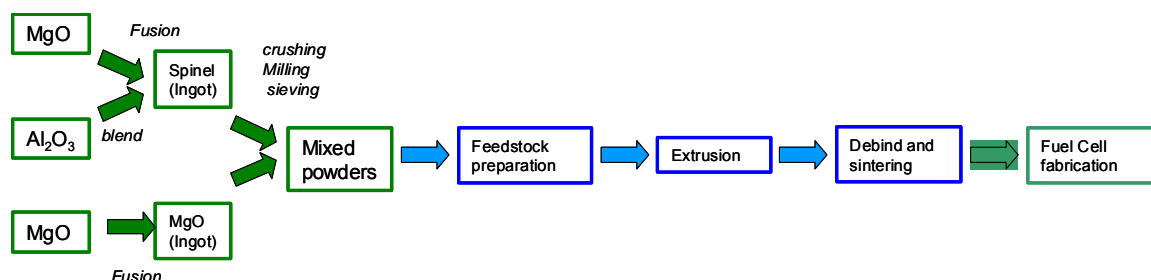


Figure 7.8. Coarse powder processing route.

In this process the Magnesia and Spinel coarse powders were formed independently and then mixed together in the required ratio prior to feedstock manufacture. This allows for accurate control of the chemistry of the resulting mixed powder and hence accurate control over CTE.

As each phase is ground separately improved particle size distribution can be achieved, which in turn gives improved control over the sintering characteristics and porosity formation. Substrates were manufactured using this route and fuel cells were fabricated. Electrochemical performance was found to be broadly comparable to that obtained from fuel cell fabricated on substrates produced via the 500kg fused ingot route. Physical properties, such as CTE and porosity were also similar.

Further work is required to verify these initial results before this processing route could be adopted as a production standard but the advantages of this approach were clearly demonstrated.

### Large Ingot

The production of MMA powder using a larger 2 tonne fused ingot was investigated. The processing route was essentially the same as that use for the production of powder from the 500kg ingot but some refinements were required. This work was undertaken to demonstrate that the manufacturing method was scaleable and that cost reduction could be achieved.

It was anticipated that the 2 tonne fusion would behave differently as compare to the 500kg fusion. This was due to the larger thermal mass of the ingot and the rate of cooling which could be achieved. It was expected that the slower cooling rate of the 2 tonne ingot would cause excessive grain growth or possibly segregation of the Magnesia and the Spinel phases.

During the crushing and grinding of the ingot it was found that a larger average particle size distribution (PSD) was produced from the 2 tonne ingot as compared to the 500kg ingot when processed using the same parameters, indicating the presence of larger grains. This situation was recovered by modifying the grinding process.

When the powder processing had been determined substrate manufacture was completed and the microstructure of the substrates compared to those produced via the 500 ingot route. The structures produced were very similar:

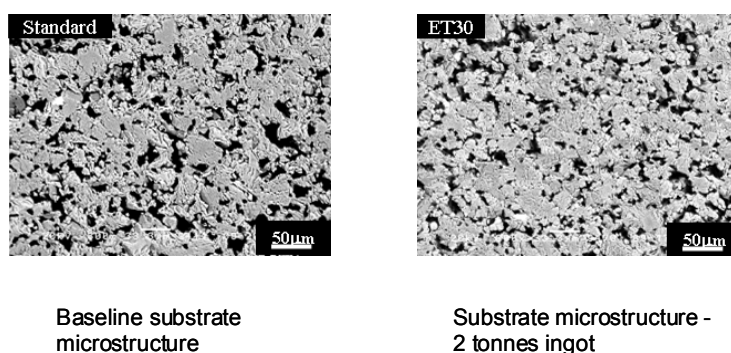


Figure 7.9. Substrate microstructures.

Other physical characteristics, such as porosity, permeability and strength were also determined and found to be comparable with the baseline substrates.

Following fabrication of the fuel cell electrochemical testing was carried out. Again the performance of the fuel cell fabricated on the substrates produced from the 2 tonne fusion route performed in the same way as the baseline fuel cells.

Overall, the issues associated with scale up of ingot size were shown to be minor and easily solved with optimisation of the powder grinding process. The 2 tonne fusion route was found to produce acceptable substrates which could be used in fuel cell manufacture. The scale up also demonstrated an improvement in substrate production costs and a 47% reduction in powder costs was achieved.

## **8 Verification of system concepts and sub-systems (WP5)**

### **8.1 Verification of atmospheric SOFC systems**

#### **8.1.1 Concept verification unit site planning and preparation**

A lab facility for the atmospheric SOFC unit was designed and constructed. Most of the site planning and preparation work concentrated on safety issues, such as designing and installing a suitable emergency ventilation blower, gas alarm system and fire extinguishing systems. Interactions between the safety systems were also necessary so that e.g. ventilation would be automatically turned to maximum power in the case of a gas leak in the premises. At the end of the construction work, a complete safety assessment of the lab facility was carried out. This was done by an external party and it included e.g. HAZOP analysis, testing of the emergency ventilation system with smoke tests as well as testing of the gas alarm systems.

#### **8.1.2 Concept verification unit procurement and construction**

Manufacturing of the 50 kWe SOFC unit was an essential part of the project to develop and learn manufacturing and assembly technology for the future units. Manufacturing and assembly schedule as well as close cost follow-up have been in great importance of this development phase. Modular design has been the main factor to shorten the manufacturing and assembly timeline. Installation of modules as larger entities has proven to be faster method than install complete unit from smaller parts and components. The modular design has improved manufacturability, cost control and project execution significantly.

Manufacturing of the verification unit took place in five different locations. Manufacturers for each module were selected based on quotations and evaluation of the capability and quality. Module manufacturing was done in parallel manner. After manufacturing, modules were tested according to specific testing procedures. After verification of the manufacturing quality, modules were sent to main assembly where they were connected to a unit. After main assembly, there were specific test procedures to verify the manufacturing and assembly quality before the unit transfer to laboratory for installation and commissioning.

#### **8.1.3 Concept verification unit installation and verification**

Wärtsilä fuel cell commissioning is divided into subtasks including e.g. unit installation, safety and functionality checks, and stack module assembly including amendment of possible defects. The process assures high quality level as all processes and components are tested prior performance validation. The performance validation test of WFC50 unit was conducted by Wärtsilä and VTT, Wärtsilä being responsible in unit operation and VTT in conducting and interpreting measurements determined in IEC 62282-3-2.



Figure 8.1. WFC50 installed at the test site.

WFC50 unit efficiency was measured at 52% power level to be  $37.5\pm 1.9\%$ . The current total harmonic distortion (THD) was measured to be within the limits defined by the authorities. The exhaust gas of the unit at 34% power level was measured to contain no sulphur dioxide and nitrogen oxides, below  $1\ \mu\text{g}/\text{m}^3$  of particles, below 5 ppm of methane, below 100 ppm of carbon monoxide and below 200 ppm of hydrogen. The sounds pressure level measured from 1 m distance from the unit was at rated power level below 67 dB(A) and the sound power level was determined to be below 85 dB. The rated power level (50 kW) of WFC50 could not be achieved during the first performance validation test due to problems with stack module temperature control. Further development and testing of WFC50 are continued outside the LARGE-SOFC program.

## 8.2 Review of current test equipment and capability for pressurised SOFC hybrid

The small scale pressurised test rigs were initially designed to test single fuel cell tubes at conditions close to those anticipated in the RRFCS product. The rigs were capable of achieving the average conditions in terms of temperature and pressure but could not simulate the full system cycle envelope. Furthermore a requirement arose where a larger fuel cell sub assembly (a 6 tube bundle) required testing. Under the Large SOFC project modifications have been carried out to the rigs which have addressed these issues.

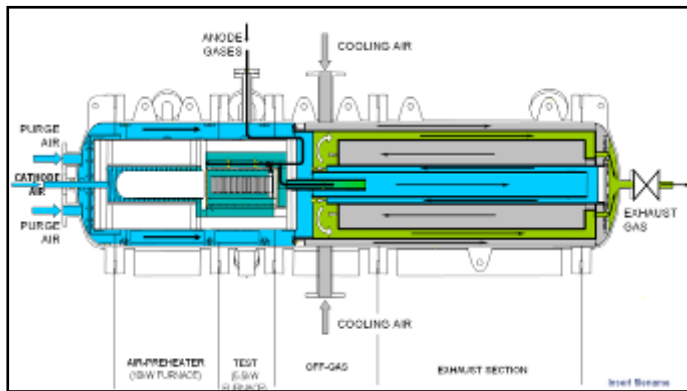


Figure 8.2. Small scale pressurised test rigs at RRFCS

The modifications include:

### **Increasing air mass flow**

A higher air mass flow was required due to the desire to test larger fuel cell sub assemblies. The original rig was designed to test a single fuel cell tube but a requirement arose to test a larger assembly referred to as a bundle. This sub assembly incorporate 6 tubes and so is capable of producing 6 times the power of a single tube. More air is therefore required in order to support this.

The original rig supplied an excess of air for testing of single tubes and so it was only necessary to increase the air flow by a factor of three to allow the testing of the bundle. This was achieved by increasing the capacity of the air preheater and up rating the mass flow controllers on the rig.

The modifications required were mainly to the electrical supply to the air heaters and to the instrumentation and control system. The heaters themselves were capable of handling the additional thermal loads but were operating closer to their limit. Careful control of heater element temperature was therefore required in order not to burn out the heaters.

### **Increasing maximum operating temperatures**

The modifications to the air preheater described above were also found to give the necessary improvement in maximum operating temperature.

### **Improving the temperature distribution**

During the work to improve the air preheater it was found that the temperature distribution in the test box was excessive. This was due to air leakage inside the rig and a poor design of the test box. The higher mass flows made the problem worse as compared to the original rig design and so improvements were required.

Special attention was paid to the assembly processes for the rig and a number of leakage points were identified. Areas of specific concern were with the mating faces between the test box and the air preheater and around the instrumentation leadouts. With the additional instrumentation in the air preheater and the instrumentation added to the bundle test piece

significantly more leadouts were required and each one contributed a small degree to the overall air leakage. By careful sealing air leakage was almost eliminated and the temperature distribution improved significantly.

A further improvement was gained by improving the air flow through the test box. The initial test box design resulted in an uneven air flow around the Bundle. This caused uneven fuel cell performance and additional variation in temperature. Computational Fluid Dynamics (CFD) was used to model the air flow and an improved test box design was determined.

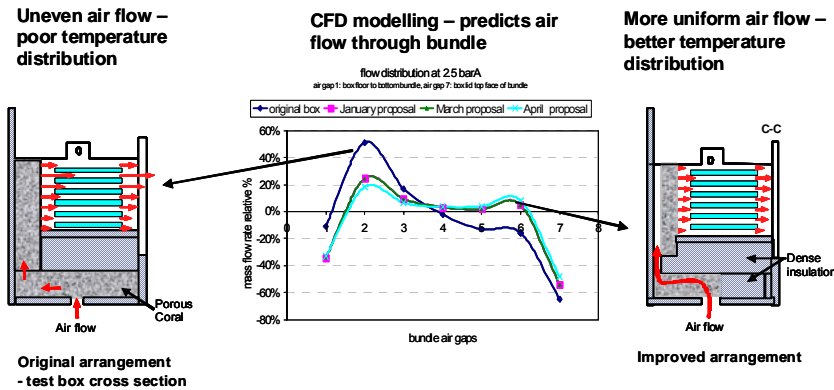


Figure 8.3. Improved air flow through test box.

### Testing at reduced partial pressure of Oxygen

The RRFCS system cycle is designed to operate at pressure however the percentage of oxygen is lower than would be found in air. To simulate testing under the correct conditions it was necessary to reduce the oxygen partial pressure and this was achieved by diluting the Cathode flow with Nitrogen. The modifications to the rig involved adding additional mass flow controllers to the Cathode 'air' supply to meter the amount of Nitrogen being added. Instrumentation was also added to monitor the actual gas composition entering the test box to provide a feedback loop to the control system. Overall the test set up worked in depleting the oxygen content whilst maintaining rig pressure at the desired level.

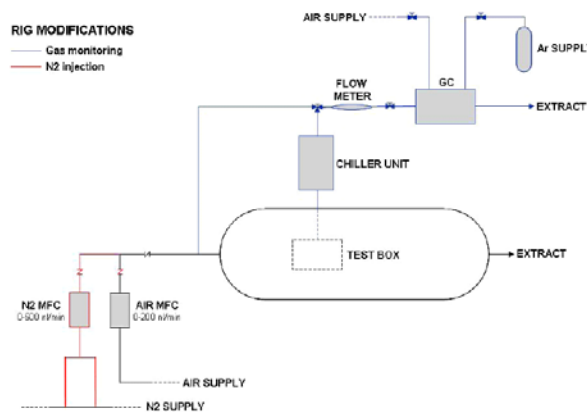


Figure 8.4. Rig modifications.

An issue highlighted with this set up was the amount of Nitrogen being consumed during the test being excessive. This problem was due to internal leakage in the rig. The improvements mentioned above have had a dramatic effect in improving this test set up.

## Summary

During rig re commission testing it was found that the majority of the improvements have been successful in achieving a more representative test environment. The performance improvements can be summarised as follows:

| Parameter             | Design condition  | Baseline condition | Achieved condition     |
|-----------------------|---|--------------------|------------------------|
| Cathode composition   | Variable PO <sub>2</sub> , PCO <sub>2</sub> and PH <sub>2</sub> O | Air                | 5 - 21% O <sub>2</sub> |
| Flow rate             | 650nl/min   | 200nl/min          | 650nl/min              |
| Maximum pressure      | 6 – 7 Bar   | <7Bar              | 4 – 6 Bar              |
| Maximum Temperature   | 950°C   | 900°C              | 935°C                  |
| Temperature variation | <50°C   | 300°C              | 65°C                   |

This task has also reinforced the need to manage air accurately and minimise leakage. This lesson has been read across to the development of full system scale rigs

Overall Large SOFC has allowed these small scale pressurised rigs to be developed and improved to give a facility which is capable of testing larger sub assemblies at more representative conditions. Full system conditions have not quite been achieved with these small scale pressurised test rigs and it has been concluded that it would be uneconomic to develop these rigs further. The lessons learned here however have been invaluable and will be applied to the next generation of small scale pressurised test rigs where full system conditions will be achieved.

## 8.3 Component testing of 50 kW atmospheric SOFC unit

### Tested and validated working examples of gas and air re-circulation equipment

Two air blowers and one anode gas re-circulation blower were tested and characterized in simulated process conditions. For the air blowers, one of which was a vertically standing radial blower with a high-speed motor and active magnetic axial bearings and the other a commercially available off-the-shelf, small scale roots type positive displacement automotive supercharger directly coupled to a customized motor, an applicable test set-up, as specified in the original plan, was an adapted standard fan performance set-up and procedure ("ISO 5801: 2007. Industrial fans – Performance testing using standardized airways"). Since Wärtsilä fuel cell systems operate at near atmospheric pressures, characteristic performance map was limited to 500 mbar-g.

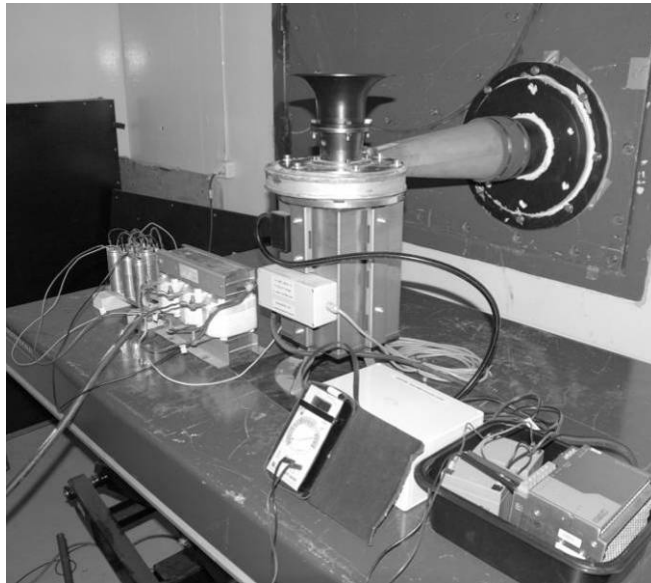


Figure 8.5. Centrifugal air blower ready for testing.

Validation and performance characterization of the anode gas re-circulator was carried out in simulated process conditions as described below in Figure 8.5 however, with cold or hot air instead of actual process gas mixture. Appropriate adjustments to measured values were then done in accordance with fan laws to compensate for difference in gas properties in order to construct characteristic performance map for the blower also in process gas conditions and to validate fluid mechanical design.

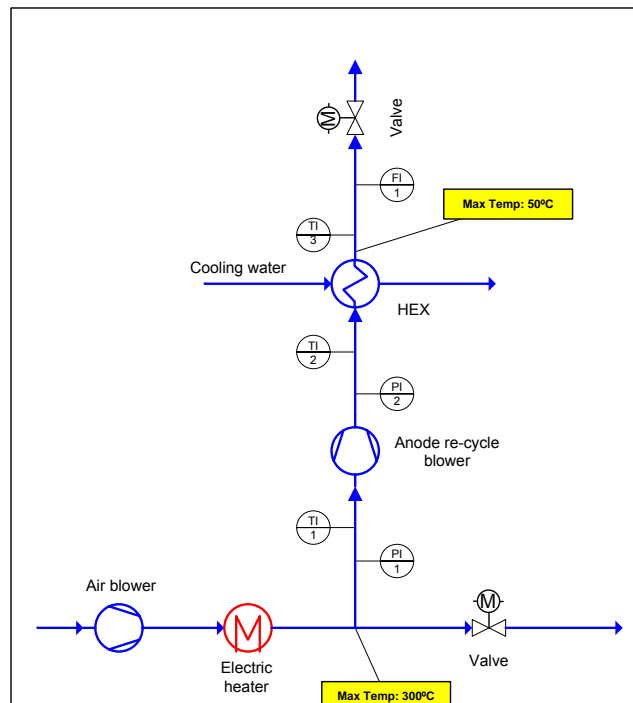


Figure 8.6. Test set-up for anode re-circulator blower performance tests with hot air.

Tests provided confirmation to simulated results of the aerodynamic performance of all of the blowers and gave encouraging feedback to particularly anode gas blower development. A mechanical failure was encountered during testing of the centrifugal air blower, which will require further analysis and design work and left results of electro mechanical performance of this particular blower only partial. There was, however, enough of test data for constructing characteristic map of the aerodynamic performance in order to validate its design.

#### Tested and validated working examples of heat exchangers

One plate type welded counterflow heat exchanger for atmospheric SOFC cathode side has been tested within Large SOFC project. The plate material is 253MA and outer structures have been made out of AISI316L. The heat exchanger has been oversized to meet the tight pressure loss restriction.

The testing of the heat exchanger has been made in complete 20 kW SOFC system with real stacks. The testing contained thermal cycling and operation at full load. The heat exchanger survived all parts of the testing very well. The pressure loss met the requirement rather well. The temperatures altered somewhat from the design values due to over sizing and heat losses to the environment. During the operation there was no scaling effects or corrosion to be seen. The heat exchanger had not been cut open as the pressure loss remained constant and gave no reasons for this procedure. The manufacturing technology of the heat exchanger was welding and it proved to be a suitable for high temperatures.

The heat exchanger test was successful and it gave valuable feedback for heat exchanger design, dimensioning, optimization and further testing.

Another Wärtsilä cathode side heat exchanger testing was performed according to plans in Forschungszentrum Jülich within WP3.

#### *Tested and validated working examples of pre-processing and internal fuel processing equipment*

Major fuel preprocessing issues – fuel reforming, anode circulation, steam production, and sulphur removal – have been studied within the project.

The integrated reformer consists of two heat exchangers, reformer and an electric heater. A block schematic of the system is presented in Figure 8.6. System is intended to heat up the gas to reforming temperature, reform the gas and then heat up the gas to stack operating temperature. The unit is designed to be compact with low pressure drop.

The concept was tested in a 20 kW scale SOFC unit. The system performed acceptably, and the components in question worked pretty much as designed. Hence it can be concluded, that the validation of the working preprocessing components described here are validated satisfactorily.

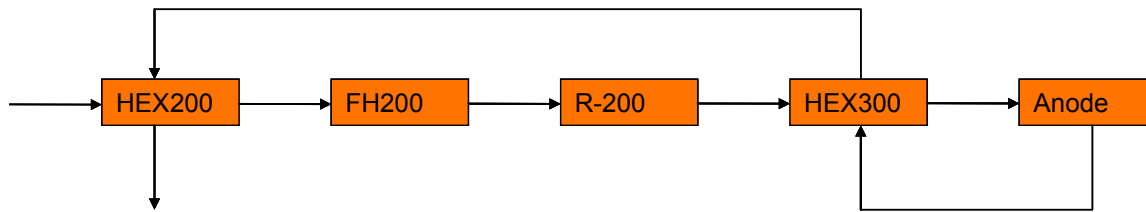


Figure 8.7. Block presentation of the integrated reformer.

Anode circulation effect on reforming was studied in laboratory scale to provide some background for system optimisation. As a result, very low O/C ratios may be used compared to traditional approach. However, more microscopic analysis would be needed to verify safe operation also for long-term operation of a real SOFC system.

Steam generation, to provide water needed in reforming reactions, was tested in four different solutions. The in-house designed humidifier suffered from poor controllability and monitoring options. Commercial electric steam generator E-2000 suffered from too small capacity and reliability issues, in addition to control difficulties due to dependency on inlet pressure. Spray evaporator with a nozzle was promising, but large size, small operation range and possible nozzle reliability issues were deemed risky. Porous material evaporator was concluded to be the most promising, although it has some manufacturing issues that require further evaluation and development.

Five different adsorbents were tested for THT sulphur removal from natural gas. Four of the adsorbents exhibited similar and decent behaviour, and one was clearly unsuitable for THT.

## 9 Fuel flexibility (WP6)

### 9.1 Potential biofuels for SOFC

Industrial developments in EU on biomass conversion are driven by the biofuels directive. Directive 2003/30/EC on the Promotion of the Use of Biofuels or Other Renewable Fuels for Transport set 2 % (energy bases) obligation by 2005, 5.75 % by 2010 and a recent EU decision is to increase the share to 10 % by 2020. It is quite obvious that the biofuels target cannot be met by 1st generation biofuels (Figure 9.1).

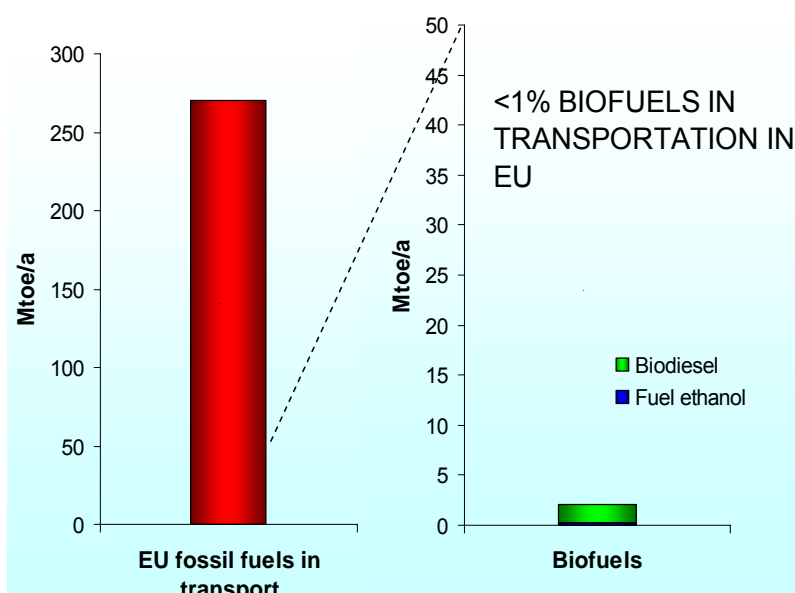


Figure 9.1. Comparison of the availability of biofuels and fossil fuels in transport in 2005.

There are large uncertainties related to bioenergy markets due to competing uses of biomass. National compulsory blending is on its way in many EU countries which will increase the value of transportation biofuels. Country specific targets vary on energy structure of the country, policy etc. Grading of transportation biofuels based on sustainability criteria is on its way which will emphasise R&D on second generation (lignocellulosic feed) biofuels in Europe. CO<sub>2</sub>-trade and feed-in-tariffs for bio-electricity will affect costs. The bottleneck is price and availability of feedstock.

In order to introduce biofuels as SOFC fuels several issues has to be considered. The availability of biofuel is the most critical factor and it is affected i.a. by availability of biomass, maturity of the biofuel production technology, existence of the infrastructure, and competition with different energy sectors. The costs of biofuel depends besides the availability, but also on efficiency, health and safety issues, legislation, fuel upgrading needs and integration issues.

Optimisation between fuel cleaning demands for SOFC and development of SOFC to tolerate dirtier fuel is one alternative. H<sub>2</sub>, CO, CH<sub>4</sub>, NH<sub>3</sub> are fuels and CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>O diluents for SOFC. There are limited data on impurities available. In REAL-SOFC project the limit for sulphur was set to below 1 ppm. Halogenes are corrosive agents with a deteriorative concentration limit of 1 ppm. C<sub>2</sub>-C<sub>6</sub> organic compounds act as fuel but can also cause plugging and coking. For siloxanes there are commercial removal techniques decreasing the amount of siloxanes down to 5 ppb. The limit for acetylene (C<sub>2</sub>H<sub>2</sub>) is 0.1 vol-% and for ethene below 1000 ppm. The limits for toluene (benzene) and naphthalene are tested at FZJ in Large-SOFC project. The tolerancy of SOFC towards impurities depends i.e. on the FC materials and processing conditions. Lowering the operating temperature or decreasing S/C ratio, the efficiency of the stack increases but the tolerance of SOFC towards impurities decreases. SOFC has to compete with gas engines which are market leaders and hence higher tolerance towards impurities would be beneficial.

Biogas is one of the most potential biofuels for SOFC because of several reasons. Increasing amounts of bio-wastes are available and biogas production is commercial technology. The variations in gas compositions, especially with landfill gas (Table 9.1), are a challenge because expensive tailored gas-cleaning is required. Raw biogas (Table 9.2) from all sources contains hydrogen sulphide and organic sulphur, which has to be removed for avoiding catalyst poisoning. Also halogenated hydrocarbons have to be removed because of same reasons. Siloxanes would burn to solid silica and cause deposits. Condensed water vapour may cause instrument fouling and compressor/fan impact/erosion damage. The competition with gas engines and micro turbines will be tight and hence the development of technoeconomically feasible biogas cleaning system is the key. At landfill sites the advantage of SOFCs would be operability at low CH<sub>4</sub> concentration, where gas engines cannot function.

Table 9.1. Variation in gas composition within a few months at one landfill

| FUEL          | CH <sub>4</sub> | CO <sub>2</sub> | N <sub>2</sub> | (CH <sub>4</sub> : CO <sub>2</sub> ) | (CH <sub>4</sub> : N <sub>2</sub> ) |
|---------------|-----------------|-----------------|----------------|--------------------------------------|-------------------------------------|
| Most Methane  | 60              | 25              | 15             | 2.4:1                                | 4:1                                 |
| Typical       | 40              | 30              | 30             | 1.3:1                                | 1.3:1                               |
| Least Methane | 35              | 25              | 30             | 1.4:1                                | 1.1:1                               |

Table 9.2. Biogas composition

| Typical Values<br>(May be exceeded at specific sites<br>treating unique wastes.) | Municipal<br>WWTP Sludge<br>Digestion | Industrial<br>Waste<br>Digestion | Animal Manure<br>Digestion | Landfill Gas            |
|--|---------------------------------------|----------------------------------|----------------------------|-------------------------|
| Methane – CH <sub>4</sub><br>Carbon Dioxide – CO <sub>2</sub>                    | 50-70%<br>30-45%                      | 60-80%<br>20-40%                 | 50-70%<br>30-50%           | 45-60%<br>35-40%        |
| Water Vapor – H <sub>2</sub> O<br>(Saturated at digester temperature)            | 1-4%                                  | 1-4%                             | 1-4%                       | 1-2%                    |
| Hydrogen Sulfide – H <sub>2</sub> S<br>and Total Reduced Sulfur – TRS            | 150-3,000<br>ppmv                     | Up to 30,000<br>ppmv             | Up to 5,000<br>ppmv        | 10-1,000<br>ppmv        |
| Siloxanes – HCSi   | ~10 ppmv                              | negligible                       | negligible                 | ~10 ppmv                |
| Hydrocarbons - HC<br>Halogenated Hydrocarbons - HCX                              | negligible                            | negligible                       | negligible                 | <2500 ppmv<br><100 ppmv |
| Nitrogen – N <sub>2</sub><br>Oxygen – O <sub>2</sub>                             | < 5 %<br>< 1%                         | negligible                       | < 5 %<br>< 1%              | <10%<br>< 3%            |

Biomass steam/air gasification may be feasible in small scale (down to about 1 MW<sub>e</sub>) if the gas cleaning costs can be kept low. Most challenging impurities are benzene, ethene, and naphthalene. There are large variations in gas quality and impurities and hence tailored gas-cleaning required. Several gasification-SOFC-integration tests have shown a lot of challenges in gas cleaning, heat integration, and net efficiency.

Biomass oxygen gasification is under demonstration. It may be feasible in large scale (above 100 MW<sub>e</sub>). Syngas cleaning is under demonstration. Sulphur and nitrogen are the most challenging impurities. The target is to achieve impurity levels: total S < 60 ppbv, halides < 10 ppbv, NH<sub>3</sub> < 10 ppmv, HCN < 10 ppbv, particulate < 0.1 ppmw. Dry gas cleaning may be the most potential for SOFC.

Synthesis gas processes (Figure 9.2) are commercial technology. Fischer-Tropsch diesel (FTD) and methanol are potential when easy transportation and storage are determining. In case of FTD and synthetic natural gas (SNG) the competition within energy sectors will be the determining factor. Transportation fuels are usually more valuable than bioelectricity. Compared to fossil NG the price of SNG is about doubled.

FTD may be available within a few years depending on competition within energy sectors. FTD can use existing diesel infrastructure and this is one reason why the focus is on FTD in Germany and in Finland. In Germany Choren has a pilot plant in Freiberg running and demonstration plant starting up. In Finland two consortiums, Neste-Stora Enso and UPM-Andritz/Carbona are planning demonstration plants.

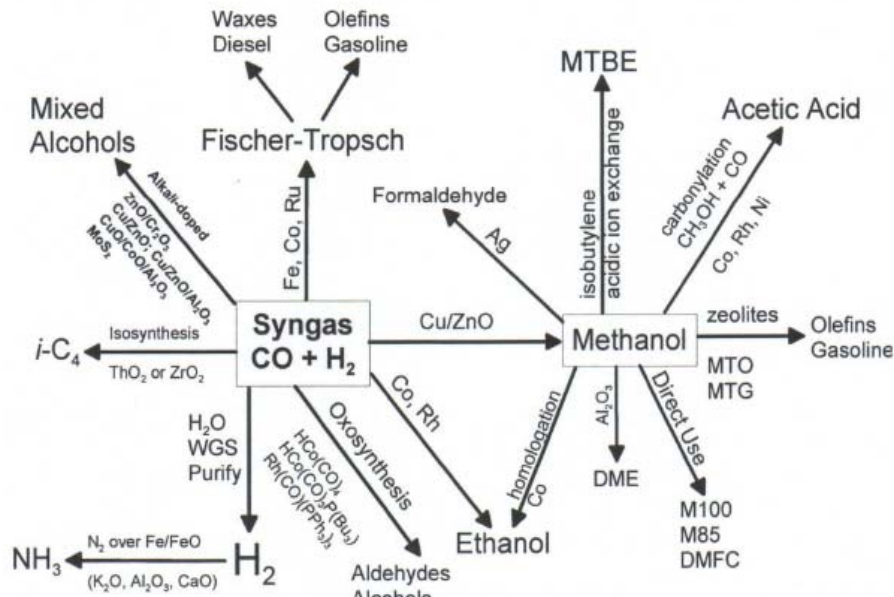


Figure 9.2. Synthesis gas processes.

SNG from syngas may be feasible in countries having existing, distributed NG infrastructure (Figure 9.3). Fossil NG will initially be the main fuel for SOFC. Gas market directive 2003/55/EC opens the NG network for SNG. SNG can also be upgraded from fermentation biogas. In feeding of SNG from biogas to NG pipeline following aspects has to be taken care of: cleaning and upgrading processes are established but expensive, profitability is country specific, critical aspects are standards and access rights.

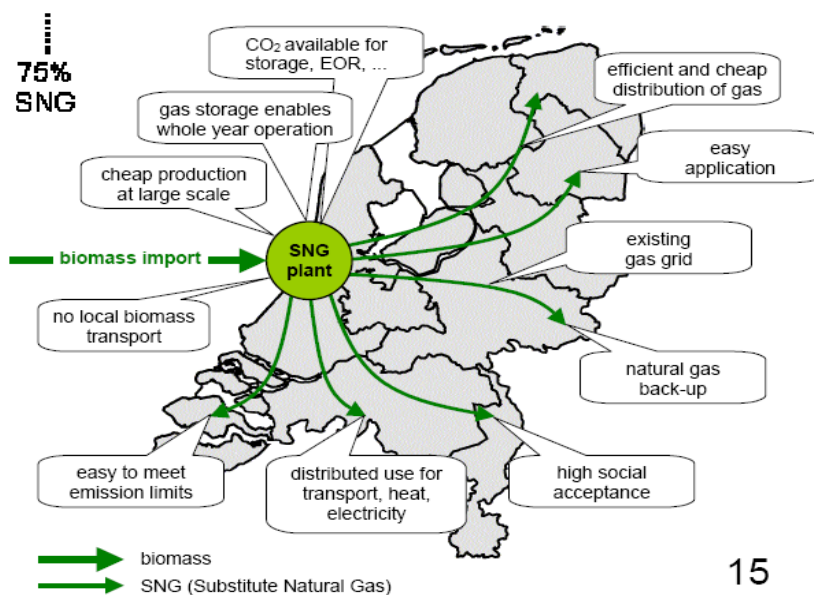


Figure 9.3. Advantages for installing a SNG plant in the Netherlands.

Feasibility of methanol from syngas depends on a potential infrastructure. Advantages for methanol are easy storage and transportation. Methanol may be potential fuel for intermediate temperature SOFCs, because methanol can be efficiently reformed at 300 - 600 °C. Methanol is produced presently from NG.

NH<sub>3</sub> as carbon-free fuel may be feasible in large-scale installations where safety issues are easier to take care of. NH<sub>3</sub> offers energy efficiencies at least equal to methanol but on a local level is CO<sub>2</sub> free and furthermore, offers zero emission potential. NH<sub>3</sub> production from peat (analogous to biomass) gasification has been demonstrated (Figure 9.4). 100% NH<sub>3</sub> has been successfully used as a fuel in SOFC.

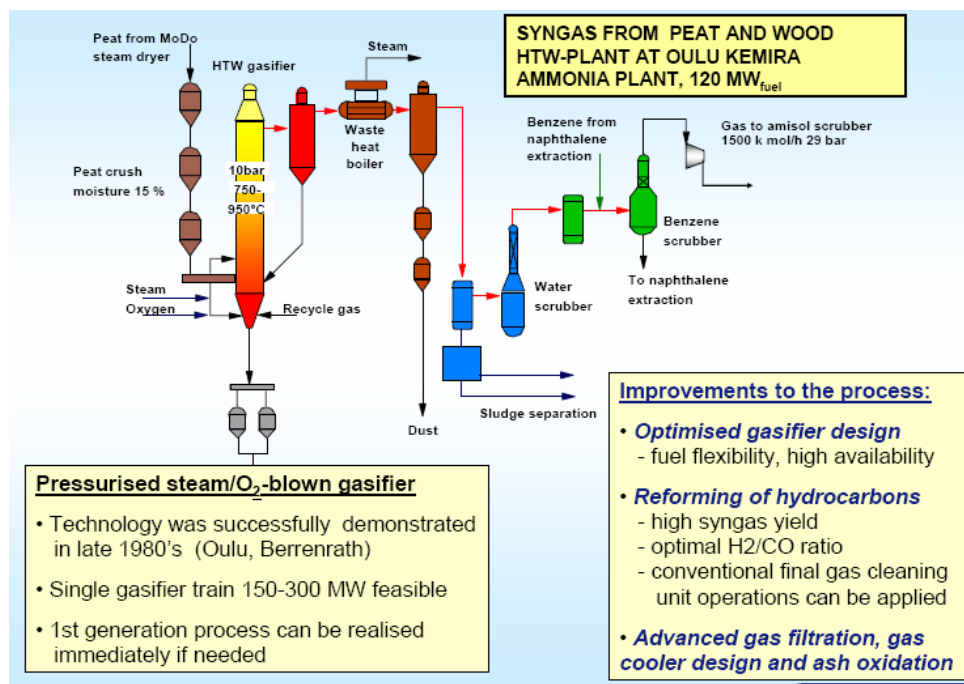


Figure 9.4. Ammonia production from peat by oxygen gasification. HTW plant at Oulu, Finland in 80ies.

Alternatives for replacing fossil diesel are biodiesel (Table 9.3) from esterification (FAME), hydrocracking (NExBTL), and by catalytic upgrading from synthesis gas via biomass gasification (FTD). Production of FAME is commercial and its specifications have been standardised in EN14214. In Finland two NExBTL plants producing 70,000 t biodiesel a year are in operation. The product is presently used in transportation sector.

Table 9.3. Properties of diesel and biodiesels.

|  | NExBTL     | GTL Fischer-Tropsch Diesel | FAME      | Diesel fuel 2005 (summergr.) |
|--|------------|----------------------------|-----------|------------------------------|
| Density at +15 °C (kg/m <sup>3</sup> )   | 780 – 785  | 770 – 785                  | ~885      | ~835                         |
| Viscosity at +40 °C (mm <sup>2</sup> /s) | 3.0 – 3.5  | ~3.2 – 4.5                 | ~4.5      | ~3.5                         |
| Cetane index or number                   | 98 – 99    | ~73 – 81                   | ~51       | ~53                          |
| 10 % distillation (°C)                   | ~260 – 270 | ~260                       | ~340      | ~200                         |
| 90 % distillation (°C)                   | 295 – 300  | 325 – 330                  | ~355      | ~350                         |
| Cloud point (°C)                         | -30 ... -5 | ~0 ... +3                  | ~0 ... -5 | ~-5                          |
| Heating value (MJ/kg)                    | ~44        | ~43                        | ~38       | ~43                          |
| Heating value (MJ/l)                     | ~34.5      | ~33.8                      | ~34       | ~36                          |
| Polyaromatic content (wt-%)              | ~0         | ~0                         | ~0        | ~4                           |
| Oxygen content (wt-%)                    | ~0         | ~0                         | ~11       | 0                            |
| Sulfur content (mg/kg)                   | <10        | <10                        | <10       | <10                          |

Bio-ethanol is used as fuel in transportation sector, which causes uncertainties in its availability. There are pilot plants on production of 2nd generation lignocellulosic bio-ethanol in Sweden and in Canada.

## 9.2 Gas impurities – tolerance of SOFC

Jülich has determined maximum allowed levels of contamination for toluene, hydrogen cyanide and hydrogen chloride. Tests were conducted as single cell measurement using Jülich standard-type anode substrate cells (ASC) with LSM cathodes.

The cells are placed inside alumina housing between Ni- and Pt-meshes, which serve as current collectors. Fuel and air chambers in the housing are separated from each other using a gold wire sealing. Electrochemical measurements were performed at 800 °C under Jülich standard conditions (1000 ml.min<sup>-1</sup> hydrogen (+3 vol% water vapour) as fuel and 1000 ml.min<sup>-1</sup> air). Steady-state measurements of the voltage as function of time at constant current density and temperature for evaluation of the long-term endurance of the cells are performed at a constant current load of 0.5 A.cm<sup>-2</sup>.

The contaminant toluene was added to the hydrogen fuel gas stream using a parallel gas line in which inert gas (N<sub>2</sub> or Ar) was bubbled through a flask containing toluene. The amount of toluene added was controlled by the temperature of the flask and the inert gas flow rate. The hydrogen chloride was added in a similar manner, where the flask was filled with a 6 M HCl solution. The hydrogen cyanide was directly mixed to the hydrogen fuel gas stream from a gas bottle containing 1% HCN in N<sub>2</sub>.

All cells were initially characterized by measuring their current-voltage curves. Prior to the introduction of the contaminant to the hydrogen fuel gas stream, the cells were operated at constant current for at least 1000 h to set the baseline.

The Figure 9.5 shows the time dependence of the cell voltage of measurement M2815. The cell has been operated over a total of 2133 h, including a 500 h period with 25 vppm toluene added to the hydrogen fuel gas, a 482 h period with 50 vppm toluene and a final period period of 785 h with 100 vppm. During the total duration of the test no noticeable loss in performance was observed.

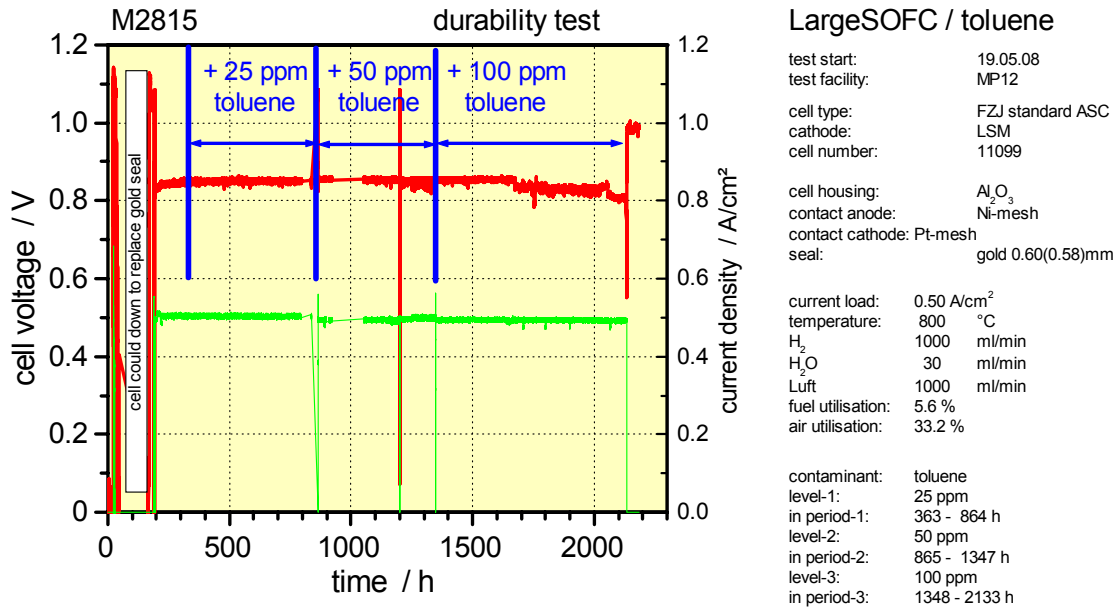


Figure 9.5. Cell voltage as a function of operating time at 0.5 A/cm<sup>2</sup> and 800 °C with hydrogen and an increasing amount of toluene up to 100 ppm in the fuel gas stream.

The Figure 9.6 shows the time dependence of the cell voltage of measurement M2810. This cell has been operated over a total of 2350 h, including a 525 h period with 5 vppm HCN added to the hydrogen fuel gas, a 650 h period with 10 vppm toluene and the final period over 856 h with 20 vppm. During the total duration of the test no noticeable loss in performance was observed.

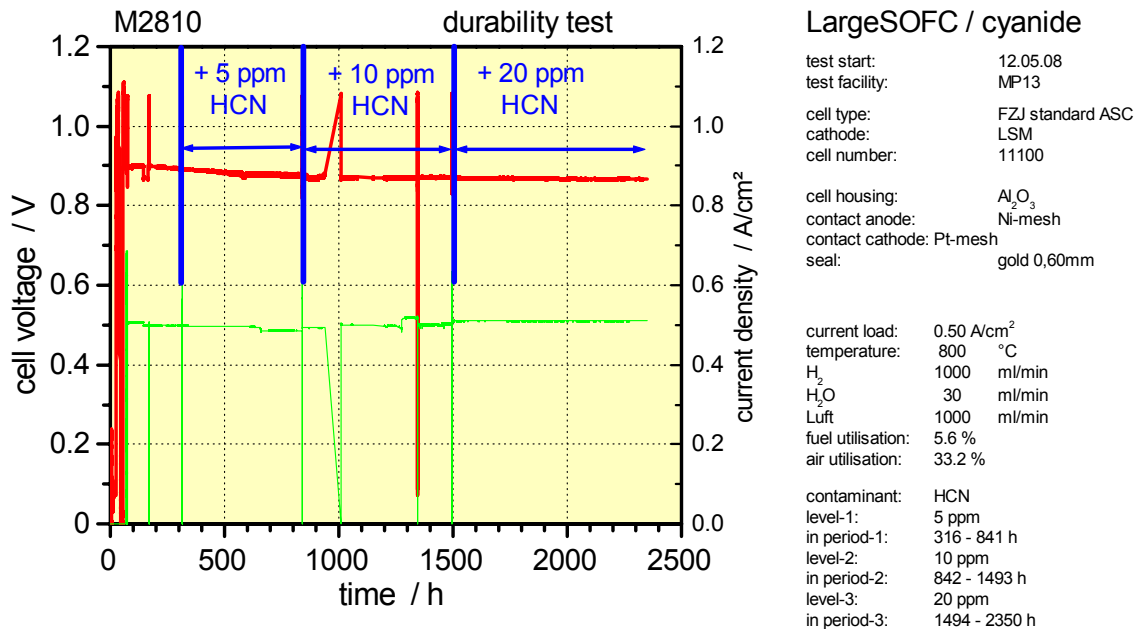
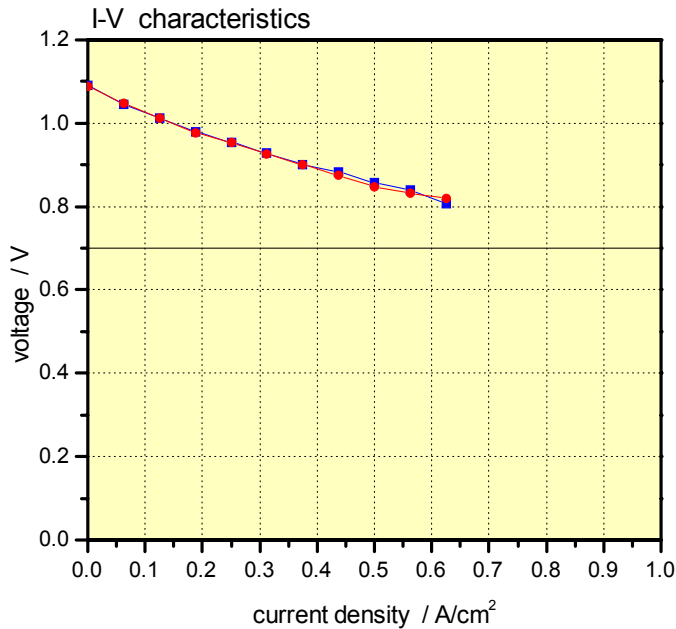


Figure 9.6. Cell voltage as a function of operating at 0.5 A/cm<sup>2</sup> and 800 °C with hydrogen and an increasing amount of hydrogen cyanide up to 20 ppm in the fuel gas stream.

The Figure 9.7 shows the current-voltage characteristics of the cells in the measurements operating on pure hydrogen and with 5 vppm hydrogen chloride as contaminant in the fuel gas stream. No noticeable loss in performance can be observed.

**SOFC cell 10760-3 - M3240**  
(40 x 40 mm<sup>2</sup>, LSM)  
Project: LargeSOFC



Start: 23.09.2009 09:41:43  
Meßplatz: MP12

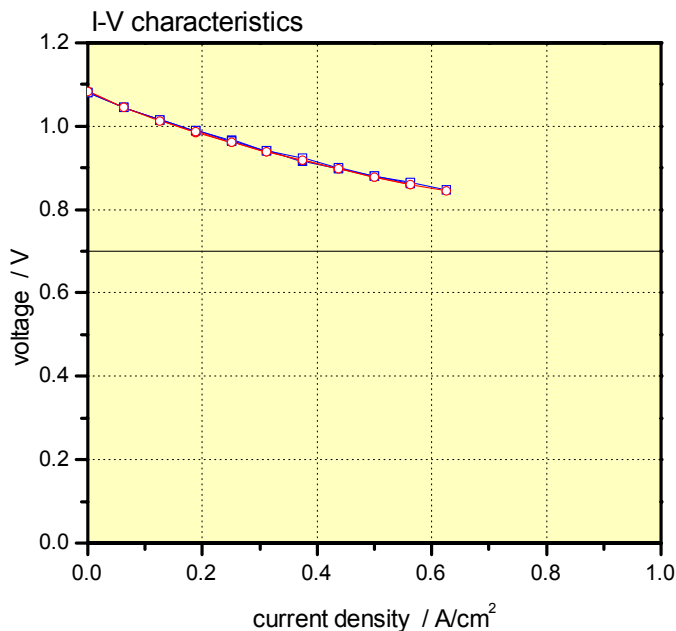
SEK: 10760-3  
Elektrolytdicke: 10µm  
Funktionsschichtdicke: 7µm

Gehäuse: Al<sub>2</sub>O<sub>3</sub>  
Kontaktschicht Anode: Ni-netz  
Kontaktschicht Kathode: Pt-netz  
Abdichtung: Gold 0,59-0,60 mm

|     | T   | H <sub>2</sub> | H <sub>2</sub> O | Ar     | HCl | air    |
|-----|-----|----------------|------------------|--------|-----|--------|
|     | °C  | ml/min         | ml/min           | ml/min | ppm | ml/min |
| —■— | 806 | 1000           | 30.0             | —      | —   | 1000   |
| —●— | 801 | 1000           | 30.0             | 2      | 5   | 1000   |

Nr Start  
—■— KL17 07.12.2009 07:54  
—●— KL18 07.12.2009 10:03

**SOFC cell 10753-6 - M3216**  
(40 x 40 mm<sup>2</sup>, LSM)  
Project: Large SOFC



Start: 26.08.2009  
Meßplatz: MP13

SEK: 10753-6  
Elektrolytdicke: 10µm  
Funktionsschichtdicke: 7µm

Gehäuse: Al<sub>2</sub>O<sub>3</sub>  
Kontaktschicht Anode: Ni-netz  
Kontaktschicht Kathode: Pt-netz  
Abdichtung: Gold 0,61 mm

|     | T   | H <sub>2</sub> | H <sub>2</sub> O | Ar     | HCl | air    |
|-----|-----|----------------|------------------|--------|-----|--------|
|     | °C  | ml/min         | ml/min           | ml/min | ppm | ml/min |
| —■— | 821 | 1000           | 30.0             | —      | —   | 1000   |
| —●— | 819 | 998            | 30.0             | 2      | 5   | 1000   |
| —□— | 821 | 1000           | 30.0             | —      | —   | 1000   |
| —○— | 820 | 998            | 30.0             | 2      | 5   | 1000   |

Nr Start  
—■— KL9 04.12.2009 07:29  
—●— KL10 04.12.2009 10:04  
—□— KL11 07.12.2009 08:10  
—○— KL12 07.12.2009 10:15

Figure 9.7. Current-voltage characteristics at 800 °C with hydrogen and with 5 vppm hydrogen chloride added to the fuel gas stream.

The start of the durability tests with hydrogen chloride as contaminant in the fuel gas stream was considerably delayed because of technical problems. Figure 9.8 shows the time dependence of the cell voltage in the first 50 h of operation of both cells with 5 vppm hydrogen chloride in the hydrogen fuel gas stream. Also here no noticeable effect on the performance can be observed.

It is intended to continue the operation of the cells with hydrogen chloride as contaminant in the fuel gas stream up to at least 1000 h. The results will be disseminated in a scientific publication in the course of 2010.

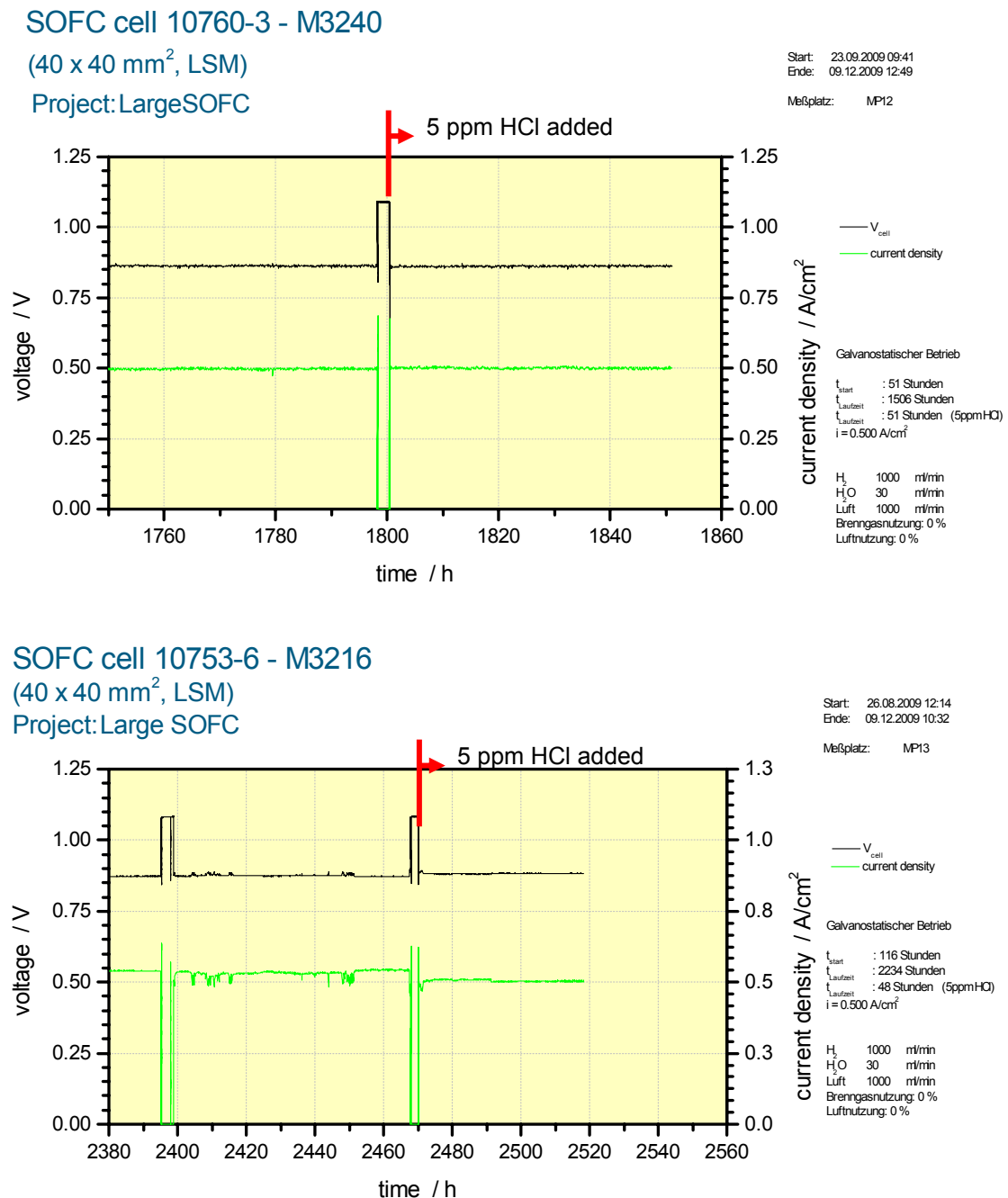


Figure 9.8. Cell voltage as a function of operating time at 0.5 A/cm<sup>2</sup> and 800 °C with hydrogen and 5 vppm hydrogen chloride in the fuel gas stream.

## 9.3 Gas cleaning for SOFC

Fuel cells require cleaner feed gas than conventional combustion engines, for which the gas cleaning has been developed. All sulphur species are poisonous for catalytic processes employing reduced metals or metal oxides. The basic problems in biological gas upgrading are safety problems caused by using oxygen (air) and biogas at high temperature. Biogas cleaning (Figure 9.9) involves the removal of moisture, VOCs (volatile organic compounds), particles, sulphur compounds, halogens, and siloxanes. The removal of moisture from landfill gases is very important, because they contain silicon compounds, which could deposit and block gas lines and harm the stack. Oxygen damages anode of fuel cells and  $N_2$  from air dilutes the biogas.

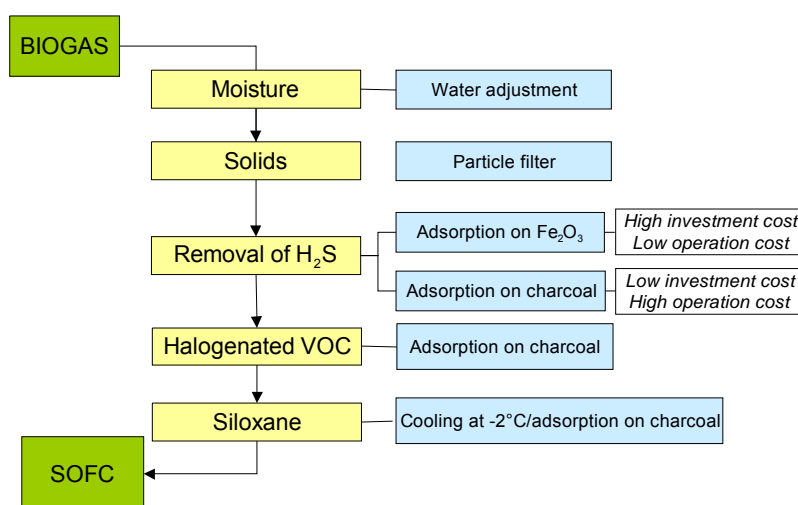


Figure 9.9. Biogas cleaning.

Results produced at UNIGE during this research activity can be summarized as follows:

- Fuel cleaning for gases was first tackled from a general point of view: five categories of unit operations have been described and analysed in terms of potential scavenging efficiency.
- An extensive review on the character of interaction gas-solid has been produced: here, the most important adsorbent properties and the dynamics of adsorption over a fixed bed were evaluated. Fuel cleaning by catalytic/chemical conversion has been here discussed and relevant examples of typical technologies have been reported. Furthermore, membrane permeation processes have been also discussed in terms of their suitability for gas cleaning.
- Data collection and literature review work was carried out in order to highlight the main contaminants composition in three different type of gases, namely: Landfill, Anaerobic Digester and Producer/Syn Gas. These can be summarized into four categories: Sulphur compounds, VOCs, Halogens and Inorganic compounds such as Siloxanes. Optimal polishing methods for each biogas type have been discussed and comparative tables, such as the one reported below, were produced. In **bold** font the most suitable removal method for each contaminant category is highlighted.

| Biogas            |                   |   |
|-------------------|-------------------|---|
| Contaminants      | Methods           | Notes   |
| Sulphur compounds | <u>Adsorption</u> | low T and P   |
|                   | HDS               | requires H <sub>2</sub> ; adsorption needed                                       |
|                   | SCSO              | requires air; adsorption needed   |
| VOCs              | <u>Adsorption</u> | high humidity (>50%) could create problems  |
|                   | Permeation        | high plant costs  |
| Siloxanes         | <u>Adsorption</u> | humidity could create problems; possible simultaneous removal of H <sub>2</sub> S |
|                   | Refrigeration     | \   |
|                   | Liquid absorption | \   |
| HCl               | <u>Adsorption</u> | possible simultaneous removal of SO <sub>2</sub> with the same bed                |

- Adsorption of one or more contaminants over a fixed bed of specific adsorbents was selected as the **best clean up** technology, which requires coupling with other unit operations when the level of impurities is particularly high. In order to support this choice, a number of examples of existing biogas plants were reported as well as the relevant purification methods.
- Activated Carbons are the optimal choice for adsorption of a number of impurities also because they are a cost effective and flexible technology. Regeneration or safe disposal do not affect negatively on the overall energy and cost balance of the plant.
- According to each biogas composition, the yearly biogas requirement for a 250 kW SOFC was calculated. Moreover, for a low/moderate level of impurities, a two adsorption columns set up was designed and the yearly change over of adsorbent material was calculated.
- Choice of the optimal reactor for Producer gas methanation was investigated, since both Landfill and Anaerobic digester biogas are rich in methane, and the yearly requirement of biogas calculated for a 250 kW SOFC with internal reforming. Fluid bed gasification was selected as optimal technology for the thermo-chemical conversion of biomass: fluidisation provides scalability, feed flexibility and low tar emission.
- Equilibrium calculations have been carried out in order to ascertain which fluid bed gasification would provide the best Producer gas composition after further methanation.
- Optimal operative conditions and maximum methane yield were investigated for three methanation reactors, namely adiabatic, isothermal and multi-stage adiabatic reactor. Results from calculations have been summarized by comparative tables; below a

typical example is presented, where methane yield was calculated at different reaction temperatures and compared to the ideal equilibrium Gibbs reactor:

Table 9.4. Methane yield calculated at different reaction temperatures and compared to the ideal equilibrium Gibbs reactor.

| <b>ADIABATIC</b>      |                    | <b>T<sub>in</sub>=200 °C</b>     | 250           | 300           | 350           | <b>GIBBS</b>               |
|-----------------------|--------------------|----------------------------------|---------------|---------------|---------------|----------------------------|
| Gas                   | Initial Comp.      | <b>T<sub>out</sub>=554.36 °C</b> | 560.53        | 566.69        | 572.83        | <b>T<sub>eq</sub>= 250</b> |
| H <sub>2</sub>        | 29%                | 15.20%                           | 16.13%        | 17.07%        | 18.03%        | 0%                         |
| CO                    | 31.60%             | 27.36%                           | 28.42%        | 29.48%        | 30.53%        | 3.70%                      |
| CO <sub>2</sub>       | 23.10%             | 27.95%                           | 26.82%        | 25.70%        | 24.58%        | 53%                        |
| <b>CH<sub>4</sub></b> | <b>13.60%</b>      | <b>21.83%</b>                    | <b>20.92%</b> | <b>20.01%</b> | <b>19.09%</b> | <b>39.60%</b>              |
| N <sub>2</sub>        | 2.70%              | 3.05%                            | 3.01%         | 2.97%         | 2.94%         | 3.70%                      |
| H <sub>2</sub> O      | 0.00%              | 4.61%                            | 4.70%         | 4.77%         | 4.83%         | 0.00%                      |
| Total                 | 100.00%            | 100.00%                          | 100.00%       | 100.00%       | 100.00%       | 100.00%                    |
| Flow                  | <b>in</b> [kmol/s] | <b>out</b>                       | <b>out</b>    | <b>out</b>    | <b>out</b>    | <b>out</b>                 |
|                       | 0.002154           | 0.001907                         | 0.0019316     | 0.0019568     | 0.0019827     | 0.001519                   |

- Producer/Syn gas clean up was also discussed by distinguishing tar removal technologies from sulphur and halogen compounds polishing. Hot tar removal is either being demonstrated only at pilot scale or proved to be a serious issue in the overall plant balance. Cold tar removal by means of scrubbers and ceramic/sand filters was advised as best option, which should be followed by adsorption on two columns in series, in order to achieve the removal of trace sulphur and halogens compounds. Yearly requirements of adsorbent materials have been calculated for a 250 kW SOFC.

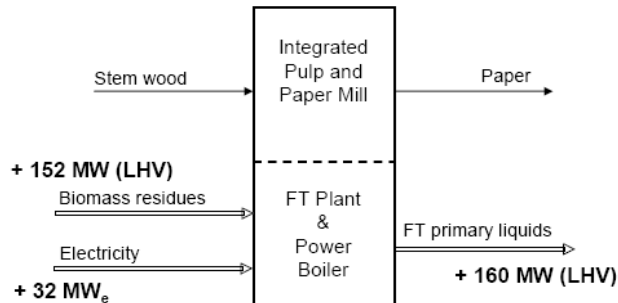
## 9.4 Costs of biofuels

The production costs for biofuels are clearly higher than those of present fossil fuels. Integration with pulp mill has been evaluated to reduce the costs (Figure 9.10). Production costs for FTD, methanol (MeOH, CH<sub>3</sub>OH), SNG and H<sub>2</sub> similar, the end-use determines the preferred choice (Figure 9.11). Competition within energy sectors has to be considered. Sugar cane bio-ethanol is the lowest cost 1<sup>st</sup> generation biofuel.

## Co-Production of FT Liquids at a Large Paper Mill

**NET CHANGES WITH INTRODUCTION OF FT PLANT (260 MW<sub>feed</sub>)**  
 Integration of steam system in conjunction with power boiler rebuild

Incremental energy flows (LHV basis)



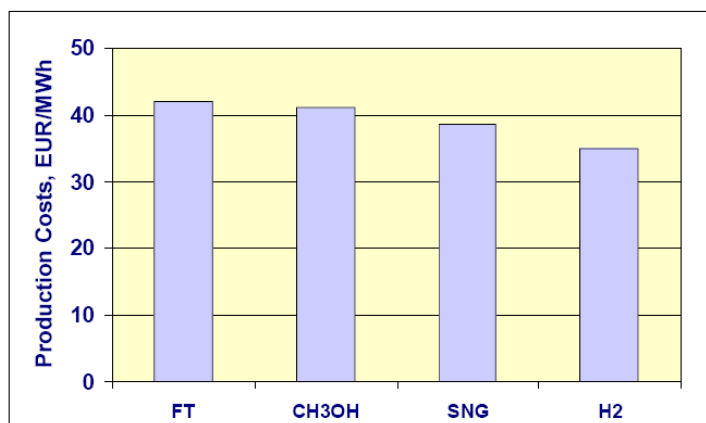
Notes: (1) Feedstock drying: from 50 % moisture to 30 % with secondary heat; from 30 % to 15 % with by-product steam. (2) FT reforming loop included.



Figure 9.10. Co-production of FT liquids at a large paper mill

## Estimated Production Costs

260 MW<sub>feed</sub>; Feedstock at 10 EUR/MWh; Interest on capital 10 %, 20 a



Investments\*: FT 235 MEUR, CH<sub>3</sub>OH 220 MEUR, SNG 220 MEUR, H<sub>2</sub> 210 MEUR

Notes: (1) Feedstock drying: from 50 % moisture to 30 % with secondary heat; from 30 % to 15 % with by-product steam. (2) FT: Fischer-Tropsch primary liquids; reforming loop included.

\*estimated for mature technology; costs as of 2004



Figure 9.11. Estimated production costs for FTD, methanol, SNG, and hydrogen.

# 10 Grid connection, safety and LCA

## 10.1 Grid connection

Initially the detailed task objectives, way of working and work split were agreed between the task. Out of the three types of grids to be considered (electrical, gas and heat), the electrical grid connection was considered to be the most demanding in respect to standards and regulations. Hence, it was decided that the report should focus on the electrical grid connection and cover the other grids less extensively. The electrical grid connection issues were discussed. An initial outline for the report was defined together with a statement of fundamental functional limitations and boundaries.

It was agreed that VTT prepare an initial draft of the electrical grid connection part of the report, based on the agreed outline. This report focuses on the codes and regulations relevant for Finland and the demonstration site in particular. RRFC was to address the regulation issues for GB and countries in central Europe.

During the latter part of the reporting period the work of reviewing all relevant standards and regulations was initiated. For the electrical grids, particular focus was placed on islanding issues and requirements of an isolating transformer at the grid interface. Contact was established with the local grid operators at the demonstration sites and negotiations of the interconnection details were undertaken and permission to operate the demonstration unit has been obtained.

VTT and Wärtsilä focused on gas- and heat grid related issues whereas RRFCs and The Switch concentrated on electricity grid connectivity. The report comprehensively addresses the spectrum of regulation regarding electrical grid connectivity of distributed generators as well as regulations regarding connection to heat and gas grids. The task objectives had been achieved and the task hence completed apart from the arrangement of a power electronics and grid connection workshop which had been added as a milestone to the task.

The power electronics workshop was arranged by Wärtsilä in November 2008 in Espoo, Finland. The aim of the workshop was to gather the experiences and knowledge related to power electronics and electrical grid interface issues facing fuel cell system developers. Special emphasis was paid on islanding protection issues as these are widely appreciated as a significant technical barrier to the emerging of distributed energy production. All task participants were represented at the workshop. Also, a project-external expert on grid connections from Vaasa University of Technology was present on invitation. In the first part of the workshop the participants presented their activities and ambitions relating to power electronics and grid connection issues. Good discussion regarding preferred topologies and related challenges was generated during the presentations. The latter part of the workshop concentrated on open questions and challenges relating to electrical grid connection of fuel cell systems. Also this topic resulted in open and fruitful discussions.

## 10.2 Safety and standards

A review of safety issues around the operation of pressurised test rigs has been collated for UK by RRFCS.

The safety documentation package for the 50 kW CHP unit was focused on following points:

- Fuel Cell standardization
- Safety management
- Reliability and maintainability aspects

The work included review of articles, selection of the most applicable methods, maintenance and reliability data collection related to WFC50 project and reporting of the findings. When looking at the results, the first thing is that it was possible to turn theory into practice by using prevailing product information. However, in the spare part optimisation more accurate data is needed before the statistical tools can be applied in full extent.

In the maintenance study was presented a principle that the supportability cost should be optimised. Meanwhile, in spare part study the effect of the spare part availability target was calculated by varying target setting. It was interesting to see how big cost impact the spare part storage can have, and if there is possibility to reduce the unrealistic high availability targets, big saving can be achieved in the supportability costs. This applies especially for unique prototype units, and the support costs/ unit will be significantly reduced in the case of serial production.

It is evident that when safety analyses are performed, it also increases the engineers' awareness of safety thinking, and safety will be better taken into consideration during design. The standardization review must be performed for the each coming project case by case, because the legislation will change especially considering new technologies and the updated system configuration may require re-study of standards having different scope. The advantage of this report is obvious, when it lowers the threshold to start the standardization review.

## 10.3 Life-cycle analysis

Life Cycle Assessment is a tool for evaluating the effects of a product on the environment over the entire period of its life at every stage of the life cycle there are emissions and consumption of resources, in fact, the environmental impacts from the entire life cycle of products and services need to be addressed. To do this, life cycle thinking is required. Therefore, the considered system covers all processes in the lifecycle from extraction of natural resources via generation of electricity and/or heat down to the construction of the energy conversion equipment. In this way, SOFC systems with different fuels suitable for fuel cells have been compared, using a life cycle approach, and with a conventional engine technology using a traditional fuel.

A review of the state of the art, concerning the environmental aspects of the system, has been carried out. Firstly the fuel production has been considered. It is possible to find useful

information about methanol production, particularly for the renewable origin, which is in a development stage. Then, the further fuel options are considered. Successively, the focus has been moved on fuel cell unit manufacturing. Some studies have been presented, showing which can be the level of the approach in dealing with such a delicate part of the process. Finally, the whole life of the system has been considered, summarizing the recent evaluations of the environmental impact related to the fuel cells. In this case, the alternatives options in respect to SOFCs will be accounted not as a direct comparison, as done for fuels, but as a useful tool for a comparison and/or transfer of methodology of the analysis criteria. At last, a specific overview about the Life Cycle Assessments of Solid Oxide Fuel Cells which have been developed has been carried out.

The framework of this study follows the indications provided by the international standards of the ISO 14040 series (ISO 14041, ISO 14042, and ISO 14043). Figure 10.1 shows a scheme of a LCA according to the ISO 14040 Standard.

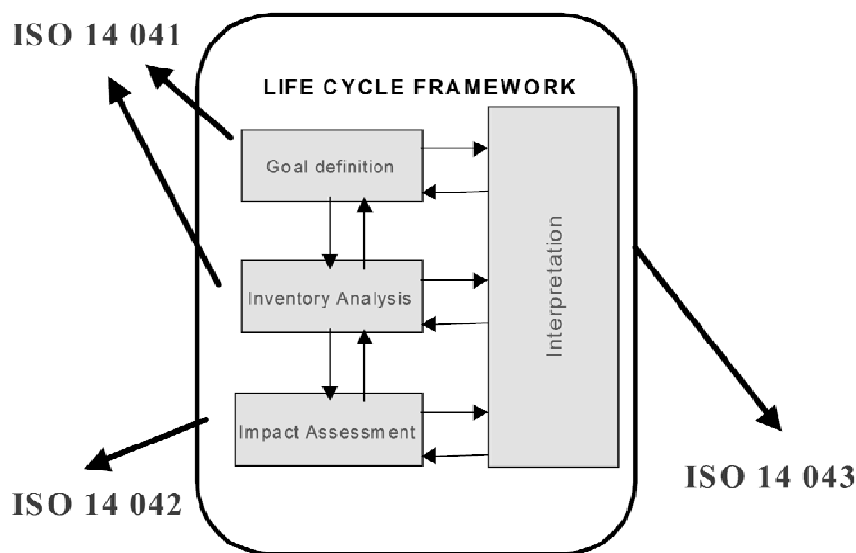


Figure 10.1. Life Cycle Framework.

The work has primarily regarded the analysis of the objectives. It has included the definition of the scope and the objectives of the LCA study: functional unit, system boundaries, product system and scenarios to be compared. It has been stated that the functional unit is 1 kWh of electricity generated. As a general rule, the selection of system boundaries must reflect the goal of the production process and the system boundaries consist in core module and up-stream processes according to a scheme embedded in the framework of Type III Environmental Declarations (ISO 14025). In this study, the up-stream processes consist in fuel production (fuel extraction and refining), while the core module consists in manufacturing and use phase (fuel storage, construction, operation and maintenance of energy conversion equipment). The system boundaries are clearly described in Figure 10.2. The selected scenarios considered different fuel cases (i.e. methanol for natural gas, bio-methanol from syngas, natural gas, syngas, biogas from landfill), two pressure options (i.e. atmospheric/pressurized operation), and a comparison with a conventional power plant.

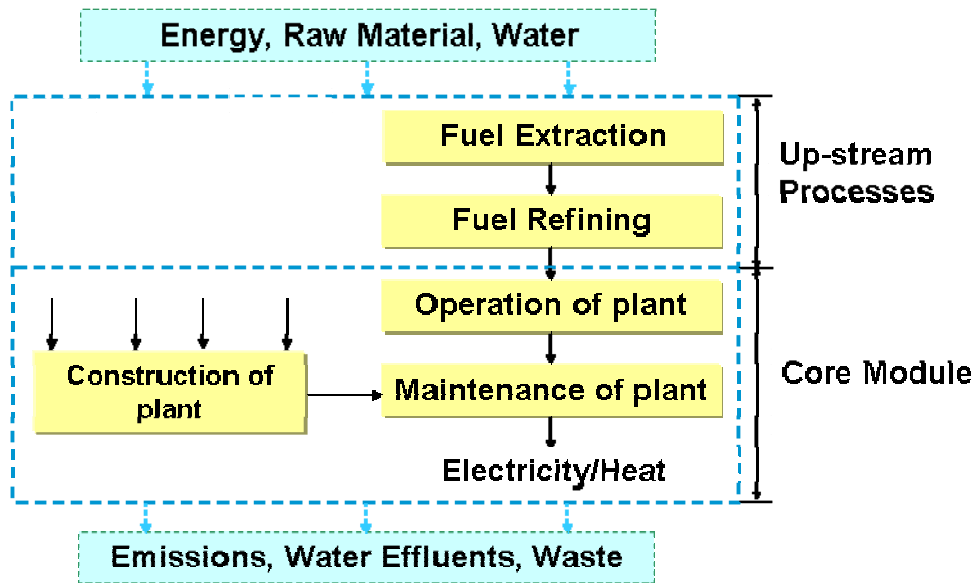


Figure 10.2. The System Boundaries.

According to the international standards of the ISO 14040 series, the second step of the LCA study is represented by Life Cycle Inventory, i.e. the main part of the whole study related to life cycle of the system product. The inventory phase regarding the up-stream processes and the core module has been performed and reported. In particular, core module inventory has firstly involved the analysis of SOFC infrastructure, the manufacturing of the fuel cell unit, then, the use phase has been evaluated, by means of the analysis of fuel cell operation and fuel cell maintenance.

Once the inventory phase has been completed, the characterization phase has evaluated the significance of the potential environmental impacts. The potential environmental impacts can be calculated using characterization methods that make it possible to associate the scale of a pollutant emission to selected so-called characterization/conversion factors. Therefore, inventory assessment and interpretation have been applied to analyze the different impacts incurred from the alternative scenarios selected. The results of the life cycle analysis for the generation of 1 kWh of electricity have been reported as outputs of the characterization process, under the following categories: emission of greenhouse gases (expressed as the sum of global warming potential, GWP, 100 years, in kg CO<sub>2</sub> equivalents); emission of ozone-depleting gases (expressed as the sum of ozone-depleting potential, ODP, in kg CFC 11-equivalents, 20 years); emission of acidifying gases (expressed as the sum of acidifying potential, AP, in kg SO<sub>2</sub> equivalents); emission of gases that contribute to the creation of ground-level ozone (expressed as the sum of ozone-creating potential, POCP, kg C<sub>2</sub>H<sub>4</sub> equivalents); emission of substances to water contributing to oxygen depletion (expressed as the sum of oxygen consumption potential, EP, in kg PO<sub>4</sub><sup>3-</sup> equivalents). In addition, this study included two categories that reflect the use of non-renewable/renewable resources with energy content, expressed in MJ equivalents, and a category that reflects the use of non-renewable resources without energy content, expressed in kg. As concerns conversion factors, this study selected a method coherently with the Environmental Product Declarations (EPD, an application of ISO 14025 Standard) requirements, suitable to be used for the creation of EPD, as defined in the document “General Programme Instructions for Environmental Product Declarations, EPD” ([www.environdec.com](http://www.environdec.com)). SimaPro 7.1 (by PRé Consultants) has been selected as suitable professional software tool in order to perform the Life Cycle Assessment.

The life cycle analysis performed shows favourable environmental performances for a Solid Oxide Fuel Cell system in comparison with a conventional power plant. Fuel production phase strongly influences the environmental impacts of the electricity generation via SOFC. It is clear that bio-fuels can significantly reduce the environmental burdens associated with the up-stream processes. Besides, it results that, if there are not significant changes for the environmental profile of the manufacturing stage, the pressurization of the fuel cell unit entails lower impacts than the atmospheric units, as effect of a higher efficiency. In particular, focusing on global warming, the bio-methanol solution seems highly attractive from the life cycle point of view.

Moreover, a document defining common and harmonised calculation rules has been compiled, including rules for product category description, material content of the product to be declared, functional unit, units, rules for the LCA (i.e. system boundaries, data collection and cut-off rules, data quality, allocation, calculation procedures), instructions on the content and format of the type III environmental declaration, additional environmental information. The aim of this document is to ensure that similar procedures are used when creating EPDs (Environmental Product Declarations), in accordance with the ISO standard on Environmental labels and declarations - Type III environmental declarations - Principles and Procedures (ISO 14025).

# 11 Training, dissemination and public activities (WP7)

## 11.1 Technology workshops

Two categories of workshops have been considered. First, internal, specialists' workshops have been held regularly in the frame of the overall project meetings where WP leaders were given the opportunity to report about progress and results of the work.

Second, 2 public workshops, open to other system manufacturers and developers or adopters, were carried out in Bruges, Belgium. This allowed the integration of further expertise and the coordination of European-wide activities, which was especially valuable in the light of the oncoming JTI developments.

In June 2008, the workshop "High Temperature Fuel Cell Systems – Balance of Plant & Market Perspectives" attracted 29 participants from the SOFC and MCFC areas and encompassed 19 presentations ranging from materials problems with balance of plant components to problems of integration into electricity grids and upcoming funding opportunities. The general feedback was very positive. A clear synergy in development between MCFC and SOFC could be identified, maybe also including results from PACF development.

In June 2009, 25 participants (including many attendees from non-SOFC companies) attended the workshop "Large Fuel Cell Systems: Experiences and Trends". 20 talks were given. The general feedback was again very positive. A clear synergy in BoP development between different fuel cell technologies could be identified, and interest in continuing this type of meetings was clearly pronounced.

The presentation slides were made available to all participants via a private area of the project website.

The series of workshop will be continued on an independent basis in 2010 and (hopefully) the following years.

## 11.2 Summer schools

In continuation to the school series of the Real-SOFC project run out throughout 2004 to 2007, the first summer school took place in September 2008 in Almyrida, Greece, and covered the topic of "Introduction to SOFC technology". It offered the opportunity of receiving training in all aspects of basic SOFC technology at post-graduate level. 46 students (including a large number of engineers) from 18 countries (11 EU) attended the school. As the year before, ECTS points were on offer. 13 students chose to sit through the exam to obtain the credit points. After the school, the full presentations were made available to the participants for download at the semi-public area of the project website.

The general feedback, based on a questionnaire distributed to the participants where they were asked to give their views on the school, was quite positive.

The second school, which was held near Ancona, Italy, in September 2009, dealt with the topic “SOFC system technology”, continuing the scheme of alternating introductory courses (even years) with specialised courses (uneven years). 36 students from 12 countries (7 EU) attended the school. 13 of them chose to sit the ECTS exam to obtain the granted credit points. Again, the full presentations were made available to the participants for download at the project website after the school.

On the whole, the students positively acknowledged content, teaching, organisation and location of the school. It has been therefore decided to continue the series of summer schools on an independent basis in 2010 and (hopefully) the following years.



### 11.3 Exhibitions in industrial and education context / Interaction with the press

This task mostly focused on the presentation and the website of the project.

Technical papers and posters were presented at different conferences and were made available for download at the restricted area of the website ([www.largesofc.com](http://www.largesofc.com)) whereas the semi-public area, accessible with special passwords to all LargeSOFC members and participants, contained presentation slides, participant lists and other documents of workshops/courses. Within the public area, general information on the project as well as information on publications and public events were regularly updated.

Presentations and technical papers are listed in Appendix 1.

## 12 Acknowledgments

The project officer in the Commission during most of the project was Mrs. Mirela Atanasiu supported by Mr. Carlos Saraiva-Martins. The authors wish to acknowledge the support of the project officers and especially Mrs. Mirela Atanasiu for the process enabling the acceptance of the project by the Commission. At the end of the project responsibility was taken over by Mr. Francesco Ferioli.

Authors would like to acknowledge valuable contribution of Erkkö Fontell (Wärtsilä), Jonathan Lewis (RRFCS), Helge Holm-Larsen (TOFC) and Rolf Rosenberg (VTT) in the planning and application phase of Large-SOFC project. Mr Olivier Tarnowski from RRFCS also made an important contribution leading the RRFCS effort during a significant period of the project.

Execution of work would not have been possible without devoted efforts of a number of researchers and technicians in the participating organisations, which is gratefully appreciated.

The project has been funded by the sixth framework programme of the European Community for research, technological development and demonstration activities. In addition, the National Funding Agency for Technology and Innovation (Tekes) and the participating organisations have funded the Large-SOFC project. All funding organisations are acknowledged for their support.

## References

- [1] Turbec T100 Series 3, 2002, "Installation Handbook".
- [2] Pascenti, M., Ferrari, M. L., Magistri, L., Massardo, A. F., 2007, "Micro Gas Turbine Based Test Rig for Hybrid System Emulation", ASME Paper GT2007-27075.
- [3] Ferrari, M. L., Pascenti, M., Bertone, R., Magistri, L., 2008, "Hybrid Simulation Facility Based on Commercial 100 kWe Micro Gas Turbine", *Journal of Fuel Cell Science and Technology*, Vol. 6, pp. 031008\_1-8.
- [4] LARGE-SOFC European Integrated Project No. 019739, D3.1 Report, December 2007.
- [5] Ferrari, M. L., Pascenti, M., Magistri, L., Massardo, A. F., 2008, "Emulation of Hybrid System Start-up and Shutdown Phases with a Micro Gas Turbine Based Test Rig", ASME Paper GT2008-50617.
- [6] LARGE-SOFC European Integrated Project No. 019739, D3.3 Report, June 2008.
- [7] Ferrari, M. L., Pascenti, M., Magistri, L., Massardo, A. F., 2010, "Micro Gas Turbine Recuperator: Steady-State and Transient Experimental Investigation", *Journal of Engineering for Gas Turbines and Power*, Vol. 132, pp. 022301\_1-8.
- [8] Young, H. D., 1962, "Statistical Treatment of Experimental Data: An Introduction to Statistical Methods", McGraw-Hill, New York.
- [9] McDonald, C. F., 1996, "Heat Recovery Exchanger Technology for Very Small Gas Turbines", *Int. Journal of Turbo and Jet Engines*, Vol. 13, pp. 239-261.
- [10] McDonald, C. F., 2003, "Recuperator Considerations For Future High Efficiency Microturbines", *Journal of Applied Thermal Energy*, Vol. 23, pp. 1453-1487.
- [11] LARGE-SOFC European Integrated Project No. 019739, D3.16 Report, June 2009.
- [12] LARGE-SOFC European Integrated Project No. 019739, D3.17 Report, December 2009.
- [13] Agnew, G. D., Bozzolo, M., Moritz, R. R., Berenyi, S., 2005, "The Design and Integration of the Rolls-Royce Fuel Cell Systems 1MW SOFC" ASME Paper GT2005-69122.
- [14] Ferrari, M. L., Pascenti, M., Magistri, L., Massardo, A. F., 2009, "Hybrid System Emulator Enhancement: Anodic Circuit Design", ASME Paper ICEPAG2009-1041, International Colloquium on Environmentally Preferred Advanced Power Generation 2009, Newport Beach, California, USA.
- [15] Ferrari, M. L., Pascenti, M., Massardo, A. F., 2008, "Ejector Model for High Temperature Fuel Cell Hybrid Systems: Experimental Validation at Steady-State and Dynamic Conditions", *Journal of Fuel Cell Science and Technology*, Vol. 5, pp. 041005\_1-7.

**Publications, conference presentations and posters**

1. Rosenberg, R. *Presentation of Large-SOFC project*. The European Hydrogen and Fuel Cell Review Days 2007, 10-11 October 2007, Brussels, Belgium.
2. Kivisaari, T. and Hottinen T. *Presentation/poster "Co/Counter-Flow SOFC Stack Modelling for System Development Purposes at Wärtsilä Finland Oy"* (Wärtsilä). 2007 Fuel Cell Seminar & Exposition, October 15-19, 2007, San Antonio, Texas, USA.
3. Rosenberg, R., Blum, L., Göös, J., Jacobsen, J., Jansson, P., Kiviaho, J., Steinberger Wilkens, R. and Tarnowski, O. *European Integrated Project Large-SOFC*. Proc. Fuel Cell Forum 2008, 30 June - 4 July 2008, Lucerne, Switzerland. European Fuel Cell Forum ([www.efcf.com](http://www.efcf.com)).
4. Rosenberg, R. *European Integrated Project Large-SOFC*, 5<sup>th</sup> Int. SOFC Summer School, 1-5 September 2008, Chania, Crete.
5. Rosenberg, R. *Poster of Large-SOFC. The Stakeholders' General Assembly of the Fuel Cells and Hydrogen Joint Undertaking*, October 2008.
6. Di Felice, R. *Biogas processing and Clean up*. Large Fuel Cell Systems: Experiences and Trends, 26-27 May 2009, Brugge, Belgium.
7. Franzoni, A., Magistri, L., Tarnowski, O. and Massardo, A.F. *A thermoeconomic comparison between SOFC hybrid systems and the most worldwide used technologies towards competitive innovative plants*. ASME Turbo Expo 2009, June 8-12, 2009, Orlando, USA. Technical Paper GT2009-59962. (<http://www.asmeconferences.org/te09/>).
8. Travis, R. *Solid Oxide Fuel Cell Systems Development at Rolls Royce Fuel Cell Systems*. Rolls Royce Fuel Cell Systems, 7<sup>th</sup> International Fuel Cell Science, Engineering & Technology Conference. June 8 –10, 2009, Newport Beach, California, USA. ([www.asmeconferences.org/FuelCell09/](http://www.asmeconferences.org/FuelCell09/)).
9. Pagliai, P., Barattini, L. and Di Felice, R. *Poster of International Workshop on the Effects of Fuel and Air Quality to the performance of Fuel Cells*, Berlin 9-11 September 2009.
10. Rosenberg, R. *European Integrated project LARGE-SOFC*. LargeSOFC Summer School on SOFC Systems, 31 August to 4 September 2009, Ancona Italy.
11. Rosenberg, R., Kiviaho, J., Göös, J., Jansson, P., Tarnowski, O., Jacobsen, J., Blum, L. and Steinberger-Wilckens, R. *LargeSOFC – Towards a large SOFC power plant*. Presentation of Large-SOFC project. 2009 Fuel Cell Seminar & Exposition. November 16-19, 2009. Palm Springs, USA. (<http://www.fuelcellseminar.com/>)
12. *Large SOFC Poster*. Parliament Magazine, Issue 299, 14 December 2009.
13. Rosenberg, R., Kiviaho, J., Göös, J., Jansson, P., Tarnowski, O., Jacobsen, J., Blum, L., Steinberger-Wilckens, R., Di Felice, R., Massardo, A., De Vos, Y., von Witzleben, M. and Kämäri, O. *Developments Towards A Large SOFC Power Plant*. Proceedings of European Fuel Cell Technology and Applications – "Piero Lunghi Conference" 15-18

December 2009. ENEA – Italian National Agency for New Technologies, Energy and Sustainable Economic Development. Rome (2009), 217-218.

14. Product Category Rules (PCR) for electricity generation through Solid Oxide Fuel Cells (SOFC) systems has been indicated on IEC website ([www.environdec.com](http://www.environdec.com)). UNIGE 2009, PCR in the preparation phase in the international EPD® system.
15. Oasmaa, A., Monteverde, M. and Di Felice, R. *Report on biofuels for SOFC applications*. Deliverables 6.1 and 6.15 from EC FP6 Project “Towards a Large SOFC Power Plant” no. 019739. Published on 1 January 2010. ([http://www.vtt.fi/files/projects/largesofc/large\\_sofc\\_biofuels\\_wp6\\_public.pdf](http://www.vtt.fi/files/projects/largesofc/large_sofc_biofuels_wp6_public.pdf)).
16. Strazza, C. and Del Borghi, A. *Analisi del ciclo di vita (LCA) e definizione di regole specifiche (Product Category Rules, PCR) per la produzione di energia elettrica mediante celle a combustibile a ossidi solidi (SOFC)*. SEP Pollution Congress, Padua, 22 April 2010.

### **Large-SOFC Summer Schools**

*5th International Solid Oxide Fuel Cell Summer School: Introduction to Solid Oxide Fuel Cell Science and Technology*, 31 August – 5 September 2008. Almyrida, Crete.

*LargeSOFC Summer School on SOFC Systems*, 31 August – 4 September 2009, Ancona Italy.

### **Large-SOFC Workshops**

*High Temperature Fuel Cell Systems: Balance of Plant & Market Perspectives*, 24–25 June 2008, Brugge, Belgium. Public Workshop.

*Large Fuel Cell Systems: Experiences and Trends*, 26-27 May 2009, Brugge, Belgium. Public Workshop.

### **Press releases**

*Press release*, dated 8 January 2007, was prepared by co-ordinator in co-operation with all partners. Press release has been a basis for general information given of the Large-SOFC project i.e. in the public website.

*The press information package* at present comprises the public website, a set of slides presenting the project and a written description published in CD and presented at the Lucerne Fuel Cell Forum 2008.

### **Website**

The first version of project website was created by co-ordinator in February 2007, and since then website has been improved and developed continuously based on the comments and information received from partners. The website is divided in the public and restricted areas. The public area consists of general information of the Large-SOFC project and partners, i.a. public presentations. Website address: <http://www.largesofc.com>.