Project no.: *SES6-CT-2003-502612*
Project acronym: *Real-SOFC*
Project title: *Realising Reliable, Durable, Energy Efficient and Cost Effective SOFC Systems*

Instrument: *Integrated Project*

Thematic Priority: *6 - Sustainable Energy Systems Research - activities having an impact in the medium and longer term*

Publishable Executive Summary
M25 – M36

Period covered: from *01.02.2006* to *31.01.2007*

Date of preparation: 15/03/2007

Start date of project: *01.02.2004*

Duration: *48 months*

Project coordinator name: *Dr. Robert Steinberger-Wilckens*
Project coordinator organization name: *Forschungszentrum Jülich GmbH*

Revision []

Table 1.1: List of project partners

Participant Role*	Participant Number	Participant Name	Participant Short Name	Country
CO	1	Forschungszentrum Jülich GmbH	FZJ	D
CR	3	Rolls Royce Fuel Cell Systems Limited	RRFCS	UK
CR	4	Ugine-Alz (Groupe Arcelor)	U&A	F
CR	7	Commissariat à l'Energie Atomique	CEA	F
CR	8	University Court of the University of St Andrews	USTAN	UK
CR	9	Deutsches Zentrum für Luft- und Raumfahrt e.V.	DLR	D
CR	10	EBZ Entwicklungs- und Vertriebsgesellschaft Brennstoffzelle mbH	EBZ	D
CR	11	Energy Research Centre of the Netherlands	ECN	NL
CR	12	Electricité de France	EDF	F
CR	13	Swiss Federal Laboratories for Materials Testing and Research	EMPA	CH
CR	14	ENERGOPROECT AD - Science Research And Technological Institute	ENERGO	BG
CR	16	Gaz de France	GDF	F
CR	18	H.C. Starck GmbH & Co.KG	HCST	D
CR	19	Topsøe Fuel Cells	TOFC	DK
CR	20	HTceramix SA	HTC	CH
CR	21	The Imperial College of Science, Technology and Medicine	Imperial	UK
CR	22	FOUNDATION FOR RESEARCH & TECHNOLOGY HELLAS-Institute of Chemical Engineering & High Temperature Processes	FORTH-ICEHT	EL
CR	25	Plansee SE	Plansee	A
CR	27	Risø National Laboratory	Risø	DK
CR	28	SINTEF - Stiftelsen for industriell og teknisk forskning ved Norges Tekniske Høgskole	SINTEF	NO
CR	29	Hexis AG	HEXIS	CH
CR	32	University of Birmingham	UBHAM	UK
CR	33	University of Chemical Technology and Metallurgy	UCTM	BG
CR	37	VTT - Technical Research Centre of Finland	VTT	FIN
CR	38	Wärtsilä Corporation	Wärtsilä	FIN
CR	39	University of Genoa	UNIGE	IT

- *CO = Coordinator CR = Contractor

Executive summary

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Project Approach

The project addresses the extension of the lifetime of SOFC stacks to several 10 000 hours, not only under steady state operation, but also under cycling (thermal and redox) conditions and with a variety of fuel impurities and compositions (specifically sulphur and coking tolerance). The solutions to these problems are prevalently a question of the choice of materials. Whereas the engineering problems of designing and producing SOFC systems for small and medium scale Combined Heat and Power generation (CHP) appear generally solved (cf. SWPC and SulzerHexis developments) the materials problems at the basis of the degradation mechanisms still constitute a dramatic challenge for the market entry of SOFC technology. Failing to meet the aim of securing 40.000 to 150.000 hrs. of operating time will in the medium term eliminate the chance of market access for SOFC technology in stationary applications, which is considered the prime SOFC market. Furthermore the reliable, long-term operation under 'everyday' conditions, i.e. part load, intermittent, cycling and with dry methane or reformat including sulphur impurities has to be secured.

As a consequence, the project aims at improving the control of durability in SOFC stacks by supplying a broad understanding of degradation processes and developing a range of new materials and protective measures for enhanced lifetime. The results are used by the industrial partners in the project to further develop their cells and stacks (outside of the project in order to achieve IPR protection) that are then again fed into the project for testing. This 'feedback loop' procedure constitutes the core of the project (Fig. 1.1).

Materials and components of two subsequent waves of improvements, termed 'Generation 2' and '3', with subsequently improved operating behaviour (as far as long-term stable operation is concerned) constitute the project main outcome.

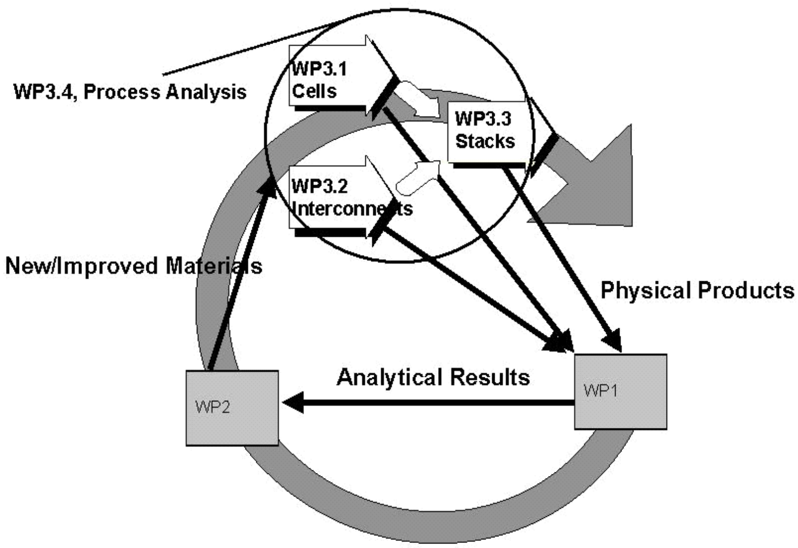

Fig. 1.1: 'Feedback' loop of analysis and testing (WP 1), materials and process development (WP 2) and component manufacture (WP 3). The testing items are produced under industrial, pre-commercial conditions and assure that testing results are as close to real SOFC operating conditions as possible. (Improved) products from WP 3 are again delivered to WP 1 for the next round of testing.

Project Objectives

The objectives of the project include the following goals:

- reduction of chromium poisoning by developing high power density cathodes (obtaining a margin for lowering the operating temperature whilst maintaining power output),
- combination with interconnect steels with low chromium emission, high conductivity and low scale growth (including protective and contact layers applied on the interconnects),
- increasing the resistance of anodes against redox cycling, fuel gas impurities and coking by implementing modified and new anode materials (working towards the aim of operation with biomass derived fuels, unprocessed natural gas and reformates)
- achieving improved thermal cycling capability by matching properties of glass sealants to steel and cell, i.e. achieving good adherence and thermal expansion coefficient match.
- reducing cost and increasing reliability of production by lowering the sintering temperature for dense electrolytes

The topic of low cost materials is also addressed through the introduction of standardised commercial powders, tailored to the needs of the consortium members.

The project pursues activities in the area of standardisation of test procedures for achieving compatibility of testing results, and dissemination and training that contribute towards developing the network of human resources necessary in Europe for commercialisation of SOFC technology and for raising public awareness.

The period M25 to M36 of the project was dedicated to:

- finalisation of modelling work in WP 1 and conclusions thereof in the context of a workshop held in Lucerne in June/July 2006
- integration of Generation 2 materials into components and prototype testing
- performance evaluation of Generation 2 (G2) prototypes and definition of G2 cells and stacks
- start of long-term test of G2 stacks
- characterisation of Generation 3 materials and subsequent prototyping of G3 components and exploratory stack tests
- definition of a joint quality assurance system for SOFC cells
- definition of interface description between SOFC stacks and systems, i.e. requirements from system operation to stack performance etc.
- evaluation of environmental limitations and workplace hazards issuing from materials used and developed in WP 2
- organisation of Manufacturing Workshop in June 2007
- co-organisation of Degradation Workshop with FCTestQA
- possible participation in Hanover fair 2007
- organisation of Summer School in Greece in autumn of 2006

Project Partners

See Table 1.1 for a list of partners, their role and country of origin.

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Project Implementation

Following the discussions with the Review Panel after the second project year the implementation plan was extensively reworked. Three main changes were made:

- a ‘test matrix’ was established that made the performance of tests (who, when, what, why) more transparent and also made the following up of actions more practical
- benchmark testing conditions were defined to simulate SOFC system performance and to introduce more severe testing conditions
- materials development not showing promising results were terminated within the third project year

Results of the 3rd year

The main outcome of the third project year was as follows:

- establishment of new testing procedures based on more severe exposure of components; testing now orients itself along the lines of operating conditions expected in ‘real’ systems, on the other hand sufficiently severe conditions that will deliver degradation effects of an order of magnitude that can be sufficiently detected by post-test analysis. This includes currents up to 700 mA/cm² and 80% fuel utilisation in hydrogen and methane operation and the application of simulated reformate.
- continued characterisation of 2nd Generation and first 3rd Generation components
- improved understanding of chromium (cathode) and sulphur (anode) poisoning mechanisms
- characterisation of gold and silver impregnation of the anode towards improved coking behaviour showed extended coking resistance up to S/C ratios down to 0.3. On the other hand performance of the anode dropped. Further investigation of this effect is under way.
- continuation of anode development towards redox stability with SrTi. The milestone of proof-of-concept in a cell suitable for testing was accomplished.
- termination of electrolyte layer process development. Solely the apatite development was pursued further. EB-PVD has proven to be useful for applying thin electrolytes as well as barrier layers between YSZ and LSCF cathodes.
- inconclusive results on PSCF cathodes. Contrary to results produced in other projects, performance was lower or comparable and stability lower. Verification / falsification of these results is under way.
- first results on nickelates. They were characterised as cathode materials but have not yet reached the level of performing better than the standard LSM cathodes. It is understood that the extensive optimisation of processing and sintering parameters has not been applied as with LSM. Also, the long-term stability still needs to be studied.
- characterisation of interconnect steels and protective layers was continued under more severe conditions (also including high fuel utilisation conditions for the anode face of the interconnect). Optimal pairs of steels and protective layers are being selected. Unprotected steels are only characterised for baseline comparison.
- cells and stacks for testing were largely produced and delivered to plan. Quality assurance criteria for stacks were introduced and items with lower than desired performace excluded from testing.
- the environmental impact analysis of two stack types (F-type Jülich and hypothetical DLR) has been concluded. The impact of steel manufacturing is most

prominent in the inventory, indicating that ceramic materials recycling might not be advisable. Workplace hazard and environmental legislation assessment have been completed.

- organisation of the summer school on basic SOFC technology and the (internal) workshop on modelling of degradation effects. Preparation of the final summer school on manufacturing of SOFC was started and the curriculum established. A public workshop on degradation issues is being organised in Sept. 2007 in collaboration with the FCTesQA project. The programme was finalised during a planning meeting in January of 2007.

Results from the materials development and characterisation referring to limited applicability of materials in certain contexts (e.g. LSM vs. LSCF/CGO vs. PSCF, LSMC, steel-protective layer combinations etc.) support the basic concept of the project that the inclusion of a variety of cell (and stack) types offers more flexibility in application of materials and a comparison of results of across a wider field of operational conditions, thereby mobilising synergies in the more generic materials research work. The discussion of materials performance under a variety of applications leads to closer interaction of project partners working with differing system operation conditions and to learning across technology borders. Especially the potential of individual developments and the possibilities to overcome any limitations are far better explored. This insight serves to build a general understanding of SOFC materials interactions and establishes important input to a 'Meccano set' of SOFC materials where developers – across various applications, cell and stack types, and required operating conditions – can select the suitable solutions including knowledge on the limitations.

Training and Dissemination Activities

A workshop on 'Modelling and understanding degradation in SOFC' was held in Hertenstein-Weggis (CH) from 2 -3 July 2006. Thirty participants from institutions all over the world participated. The quality of presentations made the meeting a valuable contribution to the subject.

A Summer School concentrating on 'Solid Oxide Fuel Cell Technology' was held in September 2006 in Greece, attracting about 46 participants, whereof 24% were female participants, from 14 different countries.

Five students took opportunity of the student exchange programme with generally excellent results.

Technology Implementation Activities

Implementation of the results from the materials development continues within the scope of WP 3 (manufacturing) and WP 1 (testing). Due to the participation of major European SOFC manufacturers this process is seen as direct access to industrial implementation of results. Use of powders and steels from project partners is gradually evolving as promising results become apparent. Nevertheless, this says nothing about the cost side which obviously has to keep pace in order to secure commercial success.