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
M37 – M48

Period covered: from *01.02.2007* to *31.01.2008*

Date of preparation: 31/03/2008

Start date of project: *01.02.2004*

Duration: *59 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/SOFCPower	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-DTU - National Laboratory for Sustainable Energy	Risø	DK
CR	28	Stiftelsen - SINTEF	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	Wärstilä Finland Oy	Wärtsilä	FIN
CR	39	University of Genoa	UNIGE	IT

- *CO = Coordinator CR = Contractor

Executive summary

(publishable summary)

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

Project Approach

The project addresses the extension of the lifetime of SOFC stacks to several 10,000 hours as one of the pre-requisites for commercially viable stationary fuel cell applications. Whilst the engineering problems of de-signing and producing SOFC systems for small and medium scale Combined Heat and Power generation (CHP) generally appear to be solvable (cf. Siemens, CFCL and HEXIS developments), however, materials problems relating to system performance degradation 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.

Solutions can mainly be sourced in finding new and modifying extant materials capable of withstanding the operating conditions over longer time periods. Long-term stable operation is not the sole goal, though, since reliable operation under everyday conditions also requires ‘robustness’ of the technology. Reliable operation of SOFC components will therefore necessitate thermal, load and redox cycling, operation at optimised efficiencies (high fuel utilisation) and with a variety of fuels, including naturally occurring fuel contaminants.

The Real-SOFC project aims at improving the durability of SOFC stacks by supplying a broad understanding of degradation processes in steady-state and transient operation and developing a range of new materials and protective measures to achieve 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 secure IPR protection) that are then again fed into the project for testing (‘feedback loop’, cf. Fig. 1.1).

The project therefore addresses the following essential properties of SOFC materials:

- high power density of SOFC cells obtained by high performance cathodes (currently the performance lim-iting bottle-neck); in this way obtaining a margin for lowering the operating temperature whilst maintain-ing the power output obtained from state-of-the-art cathode materials

- resistance of anodes against redox cycling, fuel gas impurities and coking; less sensitive anodes will operate on biogeneous fuels, unprocessed natural gas and reformats with low water content,
- low chromium emission, high conductivity and low scale growth for interconnect steels (including protec-tive and contact layers applied on the interconnects),
- well-matched properties for sealants, steels and cells, i.e. adherence,

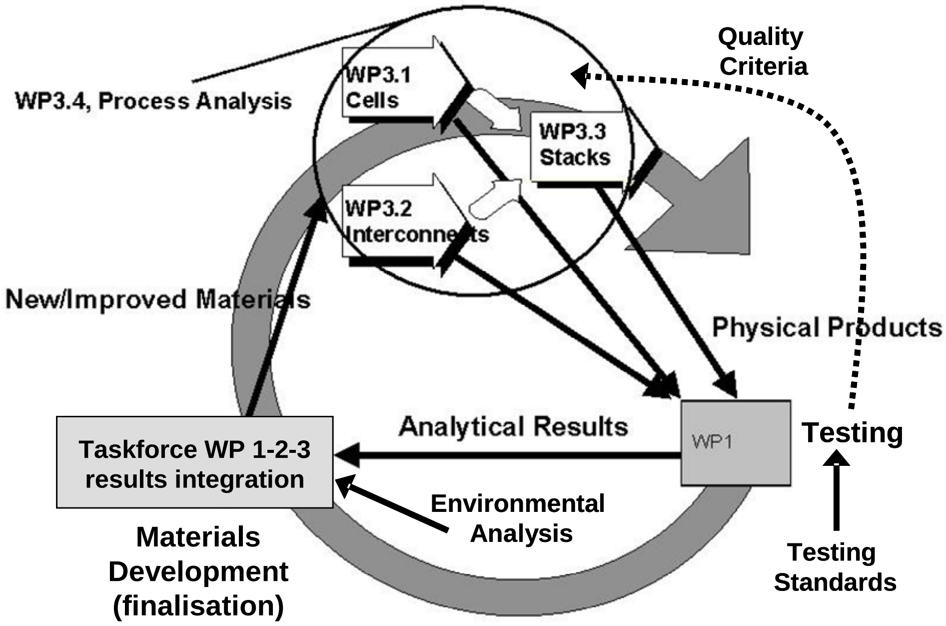

Fig. 1.1: ‘Feedback’ loop of analysis and testing (WP 1), materials and process development (WP 2) and component manufacture (WP 3). The testing items are produced under industrial, pre-commercial conditions and assure that testing results are as close to real SOFC operating conditions as possible. (Improved) products from WP 3 are again delivered to WP 1 for the next round of testing. In the fourth project year WP 2 finalised its work and was replaced by ‘Task Forces’ performing the integration of materials into components.

The topic of low cost materials is addressed through the introduction of standardised commercial powders and development of low-cost processing methods. The choice of materials to be implemented follows the rules of the eco-design concept in which environmental impacts as well as sociological, technical and legal framework conditions are taken into account.

The project also includes activities in the area of standardisation of test procedures for achieving interchange-ability 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.

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 which will be assessed in ‘proof-of-concept’ tests.

During the fourth year of the project, the focus lay on integration of results into pre-commercial components, and testing and analysis, whilst the materials development and many other activities ended between Month 45 and 48.

The period M37 to M48 of the project was dedicated to:

- integration of Generation 3 materials into components and prototype testing
- characterisation of Generation 3 materials and subsequent prototyping of G3 components and exploratory stack tests
- performance evaluation of Generation 3 (G3) prototypes and final definition of G3 cells and stacks
- start of long-term test of G3 stacks
- definition of a joint quality assurance system for SOFC cells, as to be used for entrance test in Real-SOFC cell testing
- definition of interface description between SOFC stacks and systems, i.e. requirements from system operation to stack performance etc.
- final evaluation of environmental limitations and workplace hazards issuing from materials used and developed in WP 2
- organisation of Accelerated Testing Workshop in June 2007
- co-organisation of Fuel Cell Degradation Workshop with FCTest^{QA} in Sept 2007
- organisation of the Summer School in Varna, Bulgaria, in Sept. 2007

<u>Project Partners</u>

See Table 1 for a list of partners, their role and country of origin.

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<u>Project Implementation</u>

Following the discussions with the Review Panel after the third 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

Table 1.1 shows the work package structure of the project and the responsible partners.

Table 1.1: Work packages and responsible managers

Work Package	Manager	Deputy
Project Coordinator (PC)	Dr. R. Steinberger-Wilckens (FZJ)	Dr G. Rietveld (ECN)
WP 1 Testing	Dr G. Rietveld (ECN)	Prof A. Atkinson (IMPERIAL)
WP 2 Development	Dr Julie Mougin (CEA) Dr F. Tietz (FZJ)	Dr F. Tietz (FZJ) Dr Julie Mougin (CEA)
WP 3 Cell and Stack Delivery	Dr O. Bucheli (HTc)	Dr O. Tarnowski (RRFCS) (*)
WP 4 Standardisation	Dr R. Rosenberg (VTT)	Prof V. Kozhukharov (UCTM)
WP 5 Environmental Aspects	Dr M. Zahid (EDF)	Dr G. Schiller (DLR)
WP 6 Training and Dissemination	Dr P. Holtappels (EMPA)	Dr S. Neophytides (FORTH)

(*) as of July 2007 replacing Dr. Stephen Pyke

Results of the 4th year

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

- conclusion of the ‘sensitivity matrix’ testing covering current densities up to 700 mA/cm² and fuel utilisations up to 7% both for hydrogen and methane fuels
- finalised characterisation of 2nd Generation
- definition of the 3rd Generation components
- initialisation of 3rd Generation long-term proof-of-concept testing
- termination of materials development according to plan

- establishment of Task Forces in charge of integrating the developed materials into functioning components for testing
- continuation of anode development towards redox stability with SrTi; the milestone of proof-of-concept in a cell suitable for testing was accomplished; further work was agreed upon in order to prove the feasibility at 'real' cell size 5 x 5 cm^2
- further testing of LSCM material as anode material for ESC cells at ECN
- final approaches at apatite development; though EB-PVD proved to be useful for applying thin electrolytes as well as barrier layers between YSZ and LSCF cathodes, actual implementation in cells is now concentrating on tape cast foils for ESC
- finalisation of cathode materials development; characterisation on ASC cells and choice of best performing 4 variants to be compared in long-term cell tests and a stack experiment at TOFC (scheduled for year 5)
- finalisation of nickelates characterisation; results were disappointing with regard to performance
- conclusion of the characterisation of interconnect steels and protective layers, now also covering severe conditions simulating high fuel utilisation conditions for the anode face of the interconnect.
- production and delivery of cells and stacks for testing according to plan
- finalisation of the environmental impact analysis of three stack types; end-of-life options (recycling) were compared and workplace and environmental hazard evaluated; environmental legislation (current and future developments) relevant to fuel cell manufacturing and operation were reviewed and revealed no 'show stoppers'; one of the main results is that the impact of steel manufacturing is most prominent in the life cycle inventory, indicating that a reduction of the amount of steel per kW unit is advisable; as long as the ceramic only constitute a minor fraction of the inventory, separate recycling will not be feasible; a brochure ('flyer') of the main results was prepared for dissemination.
- organisation of the 4th SOFC Summer School on 'Manufacturing Technology' in Varna, Bulgaria; the school attracted 36 students (51 participants in whole) and was one of the most successful to date.
- a public international workshop on SOFC characterisation and accelerated testing was held in Grenoble in Sept. 2007; it served as a first platform to discuss possibilities of accelerating SOFC testing by for instance inviting experts from a variety of related fields (batteries, photovoltaics, power electronics) as well as from the area of theories of accelerated lifetime testing; over 60 participants attended.

- a public workshop on degradation issues was organised in Sept. 2007 in Herssonissos, Crete, in collaboration with the FCTes^{QA} project and had more than 70 attendees in the SOFC sessions.

As was already indicated in the Year 3 report, the materials development within Real-SOFC has not rendered any break-through's. Many of the materials entered into the R&D programme by the partners when writing the proposal did not prove to be superior to the solutions known and used at the start of the project (State of the Art, or 'Generation 1' components). This supports the impression that materials are less of an issue with SOFC performance improvement than the processing of the materials and layers, which in the end have more influence on performance and lifetime than the materials themselves. Nevertheless, the materials entered into the project as at-the-time (2003) recent developments (ITM steel, LSCF cathodes) have now been extensively characterised and constitute the mainstay of Generation 3, finally showing major improvements in stack durability. Few further options remain in the race (LSCM and SrTi anodes for redox stability and coking avoidance, gold doping of anodes, again for avoiding coking, and apatite electrolytes and a variety of cathodes for improved performance) and are in the process of being evaluated in their long-term characteristics during Year 5. It cannot be excluded at the time of writing that further efforts in optimisation of processing parameters might render improved results with some of the materials developed but cancelled out from further evaluation. This will, though, require more time than this project is still willing to allocate.

The most interesting question still remaining for analysis is the long-term stability of the cathode materials. Several cathode materials have been evaluated as performing comparably to LSCF. The question is, though, whether they will display the same (known) degradation as LSCF in the long term.

Training and Dissemination Activities

A workshop on 'Understanding SOFC's: What can we learn from "advanced methods" and "accelerated testing"?' was held in Grenoble (FR) from 10-11 July 2007. Sixty four (!) participants from institutions all over the world participated. The quality of presentations made the meeting a special contribution to the project. Especially the invitation to experts in Accelerated Lifetime Testing (ALT) from other technical areas (power electronics, photovoltaics, batteries) and the introduction to ALT theory by Prof. Meeker proved to be invaluable material for thought.

A Summer School concentrating on 'Solid Oxide Fuel Cell Manufacturing' was held in September 2007 in Varna, Bulgaria, attracting 36 participants and 15 lecturers, which was the maximum planned capacity. The participants came from 9 different countries and encompassed a reasonable fraction of 20% female students. As a novelty, ECTS credit points according to the Bologna agreement were granted by Sofia University for students passing a test on the school's content.

13 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.

The exchange of promising components between manufacturers and research institutions is beginning to show first results. Plansee steel has proven successful and has been integrated into the G3 stacks. This is of high value to the company both for proving the value of its product and also providing partners with hands-on experience. TOFC will be integrating the best four to five types of cathodes into a multi-cell stack for comparison reasons. This experiment will also deliver interesting results as to the performance of FZJ cells in a totally different stack environment.

No IPR issues were recorded in this process.