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*

Executive Summary
(publishable)

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

Revision [draft 1]

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	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 Andrew	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	HCST	D
CR	19	Haldor Topsoe 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	Risoe	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

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Project Approach

The aim of the Integrated Project Real-SOFC is to contribute towards solving the persisting generic problems of ageing with planar Solid Oxide Fuel Cells (SOFC) in a concerted action of the European fuel cell industry and research institutions. This includes gaining understanding of degradation processes, finding solutions to reduce ageing and producing improved materials that will then be included in components and tested in stacks. In this process consideration will also be given to the design of cost effective materials, low cost components and optimised manufacturing processes.
In close co-operation between industry and research institutions the following steps are to be accomplished (cf. Fig. 1):

- improved understanding of ageing in planar SOFC stacks considering all modes of operation, including long-term testing over 10.000 hrs., thermal cycling up to 100 cycles, and the influences of fuel composition; these results will flow into
- adaptation of materials and protective coatings in order to reduce ageing to well below 0,5%/1000 hrs. as for instance necessary for stationary SOFC applications; the modified materials then are used in
- manufacturing of improved components under commercial conditions and subsequent characterisation in long-term and cycling tests – re-referring to step 1.

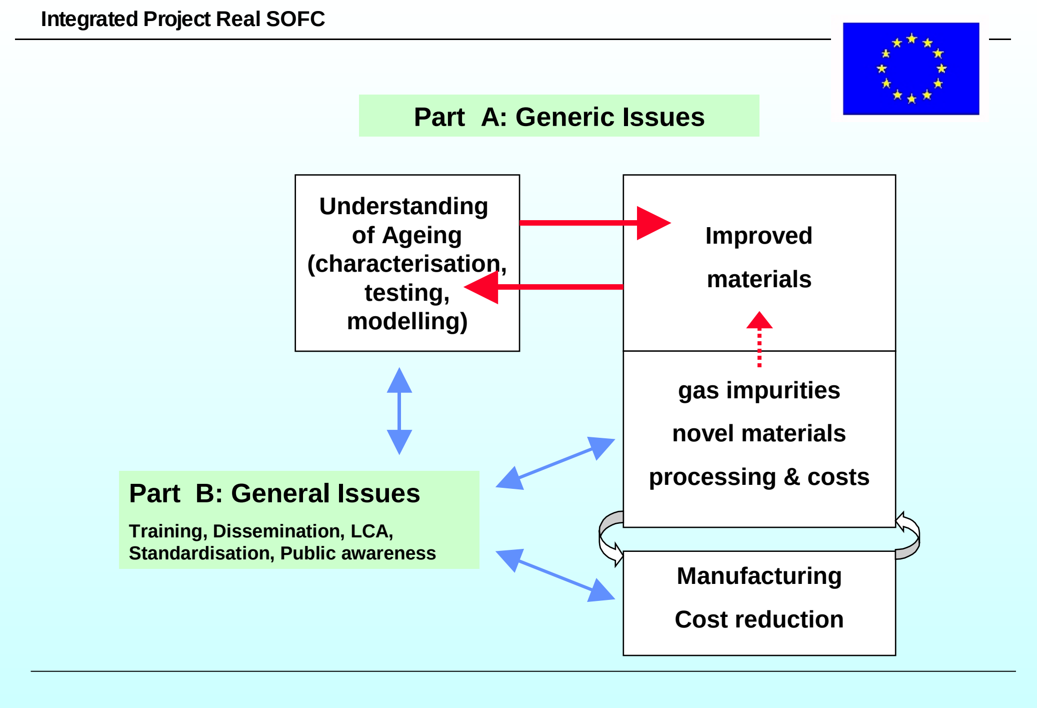

Figure 1: Basic structure of Real-SOFC

Following the state-of–the-art first testing campaign at the start of the project two further 'feedback loops' are planned for a second and third generation development of cells and stacks.
Besides the materials development the project addresses the topics of

- Life Cycle Analysis as an essential tool for assessing the environmental impact and recycling of the materials used,
- quality assurance and common understanding of standardisation issues as a means of improving industry competitiveness, and
- training and dissemination as a tool of human resource management and a contribution towards gender equality.

Project Objectives

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 (sulphur and cokeing 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, FCT, Delphi, Webasto, Hexis, and Versa developments etc.) 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 reformate 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).
Topics covered in the project include the following essential properties of SOFC materials:

- high power density (obtaining a margin for lowering the operating temperature whilst maintaining power output) of SOFC cells obtained by high performance cathodes and
- resistance of anodes against redox cycling, fuel gas impurities and coking (working towards the aim of operation with biogeneous fuels, unprocessed natural gas and reformates)
- low chromium emission, high conductivity and low scale growth with interconnect steels (including protective and contact layers applied on the interconnects) and
- well matched properties of glass sealants to steel and cell, i.e. good adherence and good thermal expansion coefficient match.

Furthermore the topic of low cost materials is addressed through the introduction of standardised commercial powders and development of low-cost processing methods.
The project also includes activities in the area of standardisation of test procedures for achieving comparability of testing results and a common standard of quantification of degradation, 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.

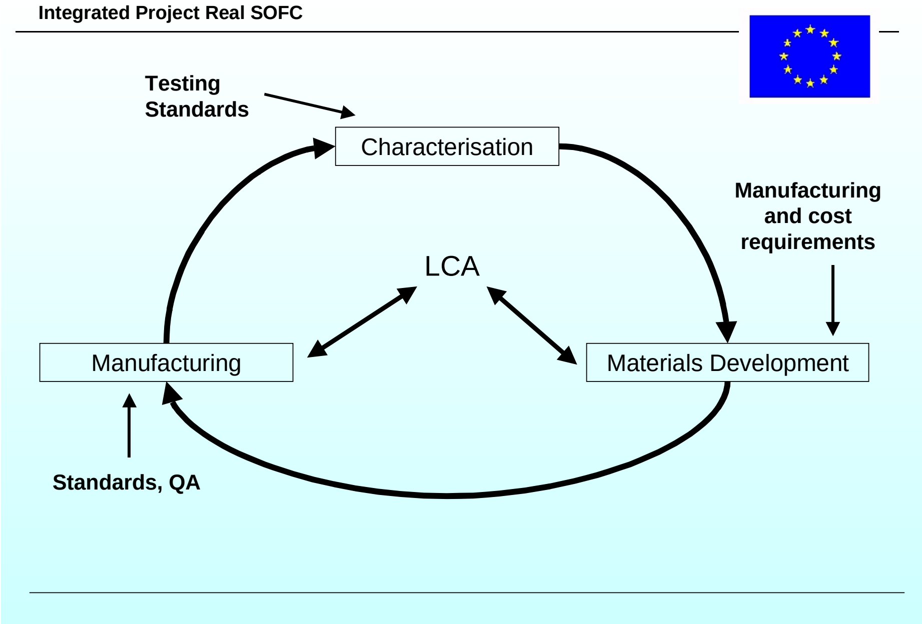

Figure 2: The Real-SOFC 'feedback loop'. Interdependency of work packages 1, 2 and 3 in the characterisation, materials development and manufacture of improved components, respectively, and the interaction with the work packages concerning standardisation and life cycle analysis

Project Partners

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

Project Implementation

At the end of the first year of operation (end of January 2005) the annual reports and the implementation plan for the months 13 to 30 (18 months) were submitted to the Commission as input to the first Annual Review Panel. This took place in Brussels on the 14th and 15th of April 2005.

Following the discussions with the Review Panel the implementation plan was adjusted and re-submitted with all documentation on Nov. 5th, 2005. Due to changes in the project scope and description that followed from requests of the Panel (cf. Section 2.2) a contract amendment was required by the Commission. As an overall result of changes and ensuing formal procedures the process of establishing the new Implementation Plan was delayed and failed to meet the deadline of Month 18. As a consequence the Project Management chose to speed up the preparation of the annual documentation and the new Implementation Plan (Month 25 to 42) in order to streamline proceedings before and after the Review Panel.

Following suggestions from the Panel the individual goals of Work Tasks were integrated into a more concise project programme and streamlined towards the main focus of reduction of ageing processes. The mission of the project can be summarised in tasks as indicated in Table 1.2.

Table 1.2: Main project tasks list

Objective	Activity
Joint testing resource / comparability of results	Standardisation of testing procedures
Quantifying degradation phenomena	Testing of components under various conditions under comparable conditions
Understanding degradation phenomena	Modelling of degradation mechanisms
Improvement of long-term performance through lowering of operating temperature	Improved cathodes coupled with improved interlayers or the use of new electrolyte materials
Chromium tolerant cathodes	Use of alternative cathode materials
Improvement of anode stability under redox cycling conditions	Alternative anodes and microstructure modification
Sulphur tolerant anode	Anode material modifications
Coking tolerant anode	Anode material surface treatment
Low-chromium emitting interconnect steels	Characterisation and identification of suitable steels
Protective layers	Optimised materials

Results of most of the listed activities will already be incorporated into the 2nd Generation of components. The 3rd Generation will then either see further optimisation, inclusion of alternate materials, processing and materials still under first characterisation at the time of setting up the third 18-month-plan.

Work packages and tasks not listed in Table 1.2 do not directly address the topic of reducing degradation. Still, they are far from being obsolete and contribute indirectly to the overall goals of the project:

- screening of materials and development of new materials processing for achieving higher performance and lower costs
- supplying components for testing
- building a common understanding of SOFC specifications between research and industry community and defining interfaces between cells / stacks / SOFC systems, thus providing important system specifications to cell and materials suppliers
- analysing environmental implications of the materials used in the project in order to ensure that no problems of environmental impact or workplace hazards prevent industrialisation of results
- supporting the building of human resources and public awareness in the field of SOFC

Results of the 2nd year

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

- finalisation of State-of-the-Art characterisation of components
- good performance at steady state conditions was found as opposed to partly severe degradation under transient conditions (cyling) and high current loads; therefore concentration on more severe testing conditions is proposed and will be turned into standard test protocols
- qualification of commercially available powders for interlayers, cathodes and anodes was concluded; powders produced at laboratory scale up to now are available at an industrial scale
- anode development towards redox stability proved difficult in view of retaining mechanical stability; all qualified materials (SrTi, Ti-Ceria, LSMC) showed low stress tolerance and thus could not be used in anode supported cells. Tests with electrolyte supported cells were similarly in vain. IP-SOFC application of LSMC in contrast was successful since the anode has to tolerate less mechanical stress in this concept. This supports the basic concept of the project that the inclusion of several cell types offers a larger variety of application paths and a comparison of results of material development across a wider field of application, thereby mobilising synergies in generic materials research work. One main conclusion is that with 'classic' planar cells the modification of microstructure is more promising than the use of new materials. This will have to be further proven in the third project year.
- electrolyte layer process development was of little success and will be terminated. Solely the PVD application of films rendered helpful results in providing dense, very thin layers. This technique could be used for electrolyte as well as for barrier layers.
- LSCF cathodes have been extensively optimised with regard to stochiometry and processing and now yield high performance results. They are regarded as major Generation 2 item.
- new cathode materials were characterised but up to now have not yet reached the status of being sufficiently understood in order to be included in cells for testing. It could be shown that several materials only function in combination with specific interlayers and electrolytes, and malfunction in other layer contexts. This work needs further development towards integration into actual cells.
- characterisation of interconnect steels and protective layers has resulted in two conclusions:
  1. the Plansee and Thyssen steels IT11 and CroFer22APU perform best in the three vital categories oxide scale growth, adhesion and electrical conductivity
  2. nevertheless, protective coatings are required in order to drastically reduce chromium evaporation.

  As a result future work will exclusively encompass these two steels with protective layers and also one mass-manufactured, low-cost steel from U&A. The hypothesis is that in case the protective layer can successfully suppress corrosion phenomena the low-cost steel might be the better choice from a commercial point of view.
- 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 performance excluded from testing. Experience was gained with refurbishing these items and some

could be returned to the testing circus successfully. This demonstrates that the SOFC technology albeit all pessimistic forecasts can be more flexible than anticipated.

- The scheme of distributing test items to several testing laboratories and comparing results has led to a better understanding of the dependence of test results on test rig layout, adherence to testing procedures and adequate handling of components. Although cell test results seem to be systematically difficult to compare, stack test results are fully reproducible.
- The materials inventory of two stack types has been concluded with the – little surprising – result that from the point of view of the current designs and weight contributions steel makes up the major material. Though this may be a somewhat uninteresting result the underlying message is that a model is in place that can easily accommodate other designs and produce inventory data. The environmental impact and, more specifically and importantly, workplace hazard assessment will follow in the third year.

Results from the materials development and characterisation referring to limited applicability of materials in certain contexts 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 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 Testing Procedures and Standards, and Quality Assurance was held in June 2005. 60 participants from institutions all over the world participated. The strong industrial representation and the quality of presentations made the meeting a valuable contribution to co-ordinating industrial activity.

A Summer School concentrating on testing methods was held in September 2005 in Switzerland, attracting about 50 participants from 24 countries.

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

Technology Implementation Activities

The project is still in an early state in view of establishing a commercialisation plan and few project results have ripened enough to be filed as patents or IPR. Nevertheless, by way of the project structure, the implementation of project results into commercial products is directly guaranteed through the participation of commercial cell and stack suppliers.

Results, mainly from the second project year, are being currently published at conferences and in journal papers. 9 presentations have been held in 2005 and 5 abstracts filed for conferences taking place in 2006. 10 journal papers were submitted of which 2 have already appeared.