ABSTRACT
Sulzer has been involved, since 1991, in the development of SOFC (Solid Oxide Fuel Cell) technology. Founded in 1997, Sulzer Hexis Ltd. is preparing the market entry of fuel cell systems for residential applications. Such systems will supply the basic electrical power of single and multi family houses. The exhaust gas from the fuel cell module is coupled with a conventional heating/cooling unit. This combination of electricity and heat production is the key to a more efficient utilization of fossil fuels. It exceeds by far the combination of conventional central power stations and decentralized heating equipment. From 1998 to 2000, Sulzer Hexis will perform field tests. Several gas suppliers and city utilities in Switzerland, Germany and Japan are supporting these efforts. With the help of the experience gained from the current field tests, Sulzer Hexis is developing a prototype fuel cell unit which will be launched in the market in 2001.

THE SULZER HEXIS SOFC SYSTEMS AND STACK TECHNOLOGY
At the end of the 1980's, Sulzer decided to develop high temperature SOFC technology with the objective of manufacturing small sized combined heat and power generation (CHP) systems. This fuel cell type is very challenging from the materials point of view. The most important advantage offered by such systems is a rather simple and compact fuel processing, which is a very strong argument for SOFC application in residential CHP. Other advantages in comparison to other fuel cell types are related to the high temperature at which heat is generated. At 900 to 1000°C, the heat can be used directly for the reformation of the fuel. After leaving the thermally self sustaining SOFC, the exhaust gas has a temperature of approx. 300 °C. This heat can be used in a simple manner for heating purposes (or for an absorption air conditioner). Due to the high temperature differences between exhaust gas and warm water the corresponding heat exchangers are very compact. The highest temperature in the system, including the afterburner at the outer rim of the circular stack, is still low enough to avoid the formation of NOx. The outstanding feature of the round, planar Hexis stack concept is the multifunctional metallic current collector. These current collectors (interconnector) act simultaneously as a guide for fuel and air, as temperature equalizers and as an efficient heat exchanger for the in-flowing gases (HEXIS=Heat EXchanger Integrated Stack). At the outer rim of the cell, the unreacted fuel is burnt off as shown in Figure 1,
illustrating a cell (=repeat element) of a Hexis stack. These elements have a typical diameter of 120 mm and an active area of 100 cm².

**Figure 1:** Sulzer Hexis SOFC stack concept

Due to this open geometry, pressure differences are small and therefore sealing problems are minimized. A test stack with five repeat elements has been tested for more than 10,000 hours (under controlled laboratory conditions) with hydrogen as fuel. All components fulfilled their requirements. A very critical component in such hybrid stack concepts is the coating of the metallic current collectors (which restricts the evaporation of chromium). Sulzer Innotec has developed a corresponding thermal spray process. Over the test period degradation as a result of aging was negligible, as shown in Figure 2. The electrical efficiency, referred to the lower heating value, amounts to 35%. For this test the ceramic cells were manufactured by ECN/Netherland and the metallic current collectors by Plansee/Austria.

**Figure 2:** Negligible degradation of a five cell stack
Stacks prepared for system testing consist of up to 70 repeat elements resulting in an electrical performance of approx. 1 kW. These stacks are integrated into a thermally insulated enclosure, fitted with additional air pre-heaters (heat exchange from exhaust gas), reformer and an auxiliary heater for starting up the system. As shown in Figure 1, the fuel flows through the cells on the anode side from the inner channel to the outside of the stack. The air, provider of oxygen for the electrochemical reaction, is first blown through the porous thermal insulation located around the stack. This dynamic insulation reduces radial heat losses to a minimum. The preheated air then flows in counter-current direction into the metallic current collectors (=integrated heat exchangers), absorbs the heat from the electrochemical reaction, reaches operation temperature and then flows on the cathode side from the inside out. If natural gas is used as fuel, the normal grid pressure of approx. 18 mbar is sufficient for operation. The exhaust gas heats the thermally integrated steam reformer and is then coupled to a conventional heating system (hot water storage). The DC power generated by the system is fed into the electricity grid via an inverter.

INITIAL FIELD TESTS IN 1997

After having solved the fundamental materials problems, the systems development focused on the thermal and structural integration into a system environment and into the building infrastructure. The system concept was qualified under real operation conditions with the following partners:

- The first field test system left the Hexis laboratories in May 1997. It was installed at the city utility of Winterthur, Switzerland. This system was completely controlled from the Hexis laboratory via modem. It was powered by natural gas. After several modifications/optimizations of the stack and the system using ECN cells and metallic Plansee current collectors, an electrical output of over 1 kW was connected and fed into the electrical grid in July 1998. This field test unit was also used to test and qualify different cell technologies from different Hexis partners under real operating conditions such as: VPS (Vacuum Plasma Spray) type stack of the partner Medicoint/CH at 850°C operating temperature (supported by the BFE, the Swiss Federal Office of Energy), or an intermediate temperature CGO (Ceria Gadolinium) type stack from ECN/NL operating at 650°C (supported by the European Commission).

- A second field test system of the same type was installed in mid 1997 at the Dortmund Energy and Water Supply GmbH (DEW) in Germany. The fuel cell stack installed was powered by natural gas from the low pressure gas grid. This system was completely remote controlled and operated from a desk in Winterthur/CH.

The practical experience with these first field test systems was encouraging enough to start the development of an improved field test unit and to find additional partners for the extended field test phase from 1998 to 2000. The motivation of these partners to participate in such field tests are twofold: they want to get first hand practical experience with this new technology and are supporting the product definition in the prototype development. Furthermore the field test partners participate in the development of the business strategies for 2001 and later.
EXTENDED FIELD TESTS 1998-2000

The experience gained from the initial field test systems in Winterthur and Dortmund played an important role in the development of field test systems for long-term tests. As shown in Figure 3, the design for the extended field units is compact enough to be installed in a standard heating room of a single family house.

**1 kWe cell stack:**
- 70 cells in series
- 120 mm diameter
- Area/cell: 100 cm²
- 950°C operating temperature
- Thermally self sustaining

**Reformer:**
- Steam reformer
- Thermally integrated into exhaust gas stream

**Burner:**
- Production of extra heat (max. 10 kW)
- Connection to conventional heating system

(not indicated: inverter, control units)

Figure 3: Photo/cross section of field test system (first installed at end of 1998)

By the end of 1998, four systems were installed and are planned to be tested over a three years period. In 1999 three additional systems will be constructed and installed. The partners carry the entire cost of the long-term tests. This allows Sulzer Hexis to use their own resources solely for product development, preparation of the pilot production and marketing. Figure 4 shows the partners and their characteristics:

| Company                                | Location                  | Characteristics                                                                 |
|----------------------------------------|---------------------------|---------------------------------------------------------------------------------|
| Dortmund Energy and Water Supply GmbH | Dortmund, Germany         | Regional energy supply company (field tests, partner since 1994)                |
| City utility of Winterthur             | Winterthur, Switzerland    | Regional energy supply company (field test, partner since 1997)                 |
| Office for Energy and Technical Installations | Basel, Switzerland       | Innovative authority (extended field tests 1998-2001) Sulzer Infra as service partner |
| EWE, Ltd.                              | Oldenburg, Germany        | Regional energy supply company (extended field tests 1998-2001)                 |
| Thyssengas GmbH                        | Duisburg, Germany         | Gas supply company (extended field tests 1998-2001)                             |
| Tokyo Gas Co., Ltd.                    | Tokyo, Japan              | Gas supply company (extended field tests 1998-1999)                             |

Figure 4: The partners for the Sulzer Hexis field tests and company characteristics
Figure 5 shows the stable performance of a thermally self sustaining system operated in Duisburg/Germany at Thyssengas with natural gas from the low pressure grid. This stack is using electrolytes manufactured by the Sulzer Hexis partner Nippon Shokubai/Japan. The electrodes were developed and manufactured by Sulzer Innotec and contacted with Plansee metallic current collectors.

![Graph showing electrical characteristics](image)

Figure 5: Performance of a 1 kWe field test system (status February 99)

The next step in these field tests is the simulation of thermal transients and optimization of the stack and the system in that respect.

The modularity of the field test system architecture allows an operation with alternative fuels. In mid 1998 a five cell stack in combination with a modified steam reformer and with the latest stack and cell technology showed a promising electrical efficiency of 45% with diesel oil. For 1999, Sulzer Hexis has defined a project which is supported/co-financed by the Swiss Oil Industry (EVUP). It is planned to operate a system of the extended field test type with heating oil by the end of 1999. This is a significant extension of the potential market for Hexis systems.

**PROTOTYPE DEVELOPMENT**

Parallel to the field tests, the development of prototypes is being pursued. The first commercial equipment will be available in the year 2001 and will be characterized by reliability, robustness and user-friendliness. It will feature both local programming and remote control, depending on the requirements of the operator. A standard version of the Hexis will be dimensioned for operation on natural gas, but in future there will also be systems running on alternative fuels such as oil, bio-gas, etc.. The electrical power will amount to approx. 1.5 kW with an electrical efficiency of about 25% (full load) and 40-50% at partial load. The overall efficiency will be around 90%. Up to about 3 kW of thermal power can be generated by the stack; any heat required in excess of this will be supplied by an auxiliary burner. A hot water storage tank will allow waste heat to be saved for later utilization. With the current prototype architecture the long-term cost goal
of approx. 1000 US$/kW\text{el} is achievable in long term (industrial production) but not yet in the initial phase (market entry from 2001 on). In parallel Sulzer Hexis and the partners for ceramic cells and metallic current collectors will develop the scale up of the components from 120 to 200 mm. This opens, with the same systems architecture, the attractive market segment of 3-5 kW\text{e} units for multi family houses.

**First Field Test Systems 1997**

- **Cell Stack**
- **Reformer**
- **Burner**

**Field Tests Systems 1998-2000**

**Prototype 2001 (Development)**

- **D=385 mm**
- **H=512 mm**

*) "Manufacturing Costs":
1. Systems integration
2. Mass production

**Figure 6:** Evolution of the system design

**PILOT PRODUCTION**

Sulzer Hexis is preparing a pilot production facility for market entry. Together with partners, the corresponding scale up is being prepared. As an example Figure 7 shows the equipment for the coating of the metallic current collectors. The capacity is sufficient and optimized for 5'000 systems/year.

**Figure 7:** Thermal spray coating of metallic current collectors
SUMMARY

Sulzer Hexis has successfully started a field test phase with several partners worldwide. With these field test systems as reference and with the practical experience from real operation, Sulzer Hexis is in the position, together with the field test partners, to develop an integrated, compact SOFC system for residential application. Market entry is planned in 2001. The efforts of Sulzer Hexis and partners are now concentrating on transferring the current technology to a pilot production.

The planning of the market entry from 2001 onwards will depend on whether Hexis can capitalize on their technological lead. However, the support from the Sulzer corporation, public funding, the enthusiasm of organizations and firms, as well as the sympathy of interested professional groups and far-sighted people, make it possible and worthwhile to take up this great challenge.

ACKNOWLEDGMENTS

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FOGA (Research Fund of the Swiss Gas Industry): Stack test stands and development of the first Hexis field test unit.

NEFF (Swiss National Energy Foundation): Lab-systems development such as the 1 kW lab system and the 7 kW lab prototype system module for 50 kWe CHP systems.

DEW (Dortmunder Energie und Wasser) & Ministerium für Wirtschaft, Mittelstand und Technologie des Landes Nordrhein-Westfalen in operation of SOFC stacks under changing natural gas compositions.

BEW/BFE (Swiss Federal Office of Energy): Materials development such as current collector coatings, stack optimizations, natural gas reformers and intermediate temperature type of ceramic cells.

BBW (Bundesamt für Bildung und Wissenschaft): Joule projects for an intermediate temperature (700°C) SOFC and a partial oxidation reactor.

EVUP (Erdölvereinigung der Schweiz): Development of an oil fuel processor and demonstration of a corresponding field test unit.
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