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Operating experience with a 250 kW_{el} molten carbonate fuel cell (MCFC) power plant

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Abstract

The MTU MCFC program is carried out by a European consortium comprising the German companies MTU Friedrichshafen GmbH, Ruhrgas AG and RWE Energie AG as well as the Danish company Energi E2 S/A. MTU acts as consortium leader. The company shares a license and technology exchange agreement with Fuel Cell Energy Inc., Danbury, CT, USA (formerly Energy Research Corp., ERC). The program was started in 1990 and covers a period of about 10 years. The highlights of this program to date are:

- Considerable improvements regarding component stability have been demonstrated on laboratory scale.
- Manufacturing technology has been developed to a point which enables the consortium to fabricate the porous components on a 250 cm^2 scale. Several large area stacks with 5000–7660 cm^2 cell area and a power range of 3–10 kW have been tested at the facilities in Munich (Germany) and Kyndby (Denmark). These stacks have been supplied by FCE.
- As far as the system design is concerned it was soon realized that conventional systems do not hold the promise for competitive power plants. A system analysis led to the conclusion that a new innovative design approach is required. As a result the ''Hot Module'' system was developed by the consortium. A Hot Module combines all the components of a MCFC system operating at the similar temperatures and pressures into a common thermally insulated vessel.

In August 1997 the consortium started its first full size Hot Module MCFC test plant at the facilities of Ruhrgas AG in Dorsten, Germany. The stack was assembled in Munich using 292 cell packages purchased from FCE. The plant is based on the consortium's unique and proprietary ''Hot Module'' concept. It operates on pipeline natural gas and was grid connected on 16 August 1997. After a total of 1500 h of operation, the plant was intentionally shut down in a controlled manner in April 1998 for post-test analysis.

- The Hot Module system concept has demonstrated its functionality.
- The safety concept has been convincingly proven, though in part unintentionally.
- The electrical power level of 155 kW (ca. 60% of maximum power) achieved allows validation of the concept with reasonable degree of confidence.
- Horizontal stack operation—an essential innovation of the Hot Module concept—is feasible.
- The fuel processing subsystem worked reliably as expected.
- After initial problems in the inverter control software, the electrical and control subsystem operated to full satisfaction.
- Stable automatic operation not only under various load conditions, but also in idle mode, hot parking mode, and grid-independent mode has been demonstrated.

Together with progress achieved by FCE in the qualification of large direct fuel cell (DFC) stacks the basis was laid for the next test unit of similar design, which will be operated in Bielefeld, Germany. The pre-tests of the stack took place already in July 1999 with good results. Additionally, projects for the test of the DFC Hot Module operating on biogas and other opportunity fuels are under preparation.

Keywords: Molten carbonate fuel cell (MCFC); European consortium; Carnot's law; Field tests

1. The significance of fuel cells

Fuel cell technology is a basic innovation, at best comparable to, e.g. the steam engine or the integrated circuit. For the first time in the history of energy technology fuel cells offer an alternative to thermodynamic power conversion without the efficiency limits imposed by Carnot's law.

The various fuel cell technologies cover a wide spectrum of applications ranging from battery applications through electrical propulsion up to power stations due to their inherent modularity, high efficiency, and cleanliness.

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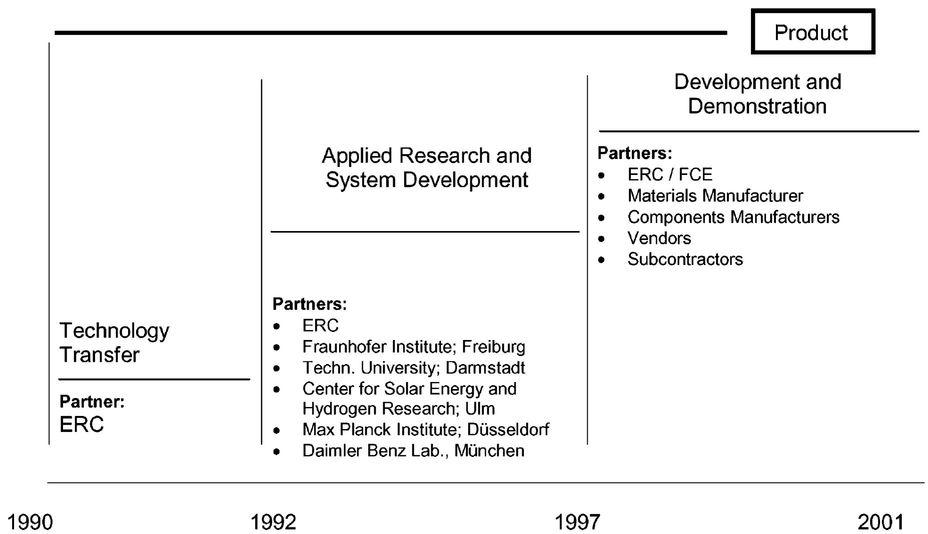

Fig. 1. The phases of the European direct fuel cell program.

Of all existing or emerging fuel cell technologies the molten carbonate fuel cell (MCFC) is specifically suited for stationary cogeneration applications in small to medium power range (several hundred kilowatts up to several megawatts). At a temperature level of 650 °C the MCFC incorporates all the advantages of high temperature fuel cells,

- internal reforming of hydrocarbons for simplest system design and highest efficiency;
- useful high temperature heat for industrial steam generation;

without having to cope with the problems of ceramic fuel cell manufacturing.

2. The European MCFC development consortium

The largest European program for the commercialization of the molten carbonate fuel cell technology is carried out by the European molten carbonate fuel cell development consortium (ARGE MCFC). The consortium consists of the following companies:

- MTU Friedrichshafen GmbH (Germany), within the DaimlerChrysler group in charge of off-road propulsion and decentralized energy systems.
- Energi E2 S/A (Denmark), a Danish utility company.
- Ruhrgas AG (Germany), a German gas company.
- RWE Energie AG (Germany), a German electrical utility company.

MTU acts as consortium leader. The company shares a license and technology exchange agreement with Fuel Cell Energy Inc. of Danbury, CT, USA.

The consortium has launched a three-phase program for the commercialization of the MCFC technology in Europe. The overall program volume will be approximately US$ 100 million to be spent within 10 years from 1990 to 2000. Fig. 1 shows the phases of the program. During the first and second phases of the program, the ARGE MCFC has spent approximately US$ 35 million on basic technology research and development succeeding in resolving the fundamental materials, corrosion, and lifetime problems associated with MCFC technology. In this period, essential breakthroughs in the development of corrosion resistant long life cell components have been achieved and a highly innovative system design was developed.

3. The direct fuel cell

Similar to other fuel cells, the working principle of the MCFC is based on the indirect combination of hydrogen and oxygen to water via an electron carrying electrolyte (Fig. 2). On the anode side of the cell hydrogen reduces the CO_3^{2-} ion to CO_2 releasing the two electrons and generating the electrical power. On the cathode side new CO_3^{2-} ions are formed by combining the CO_2 of the anode exhaust and the oxygen from the air with two electrons taken from the outer load circuit, thus closing the chemical and electrical loops.

The hydrogen supply for the anode reaction is generated from natural gas within the fuel cell block by a process known as steam reforming. Assisted by a catalyst, the methane from the natural gas combines with water to combust the carbon and to release all the hydrogen from the methane as well as from the water. This process absorbs waste heat from the fuel cell and translates it back into primary energy, increasing the total system efficiency by approximately 12% points (Fig. 3).

After having removed the sulfur and higher hydrocarbons from the fuel, a molten carbonate fuel cell with internal reforming can be fed directly with a mixture of natural gas and water—we call it the direct fuel cell (DFC). Fig. 4 shows

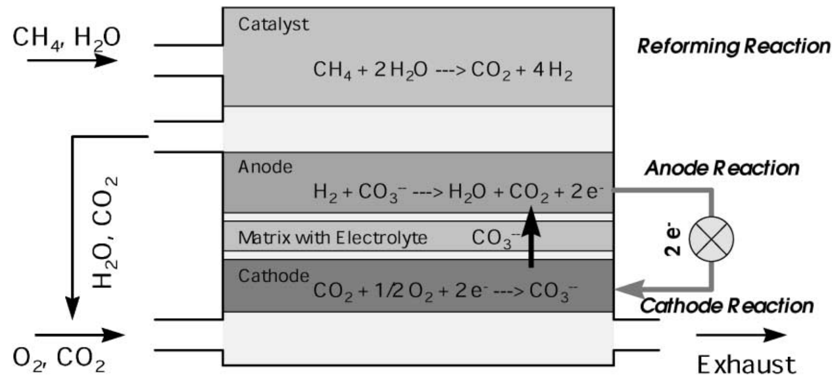

Fig. 2. Operating principle of molten carbonate fuel cell with internal reforming.

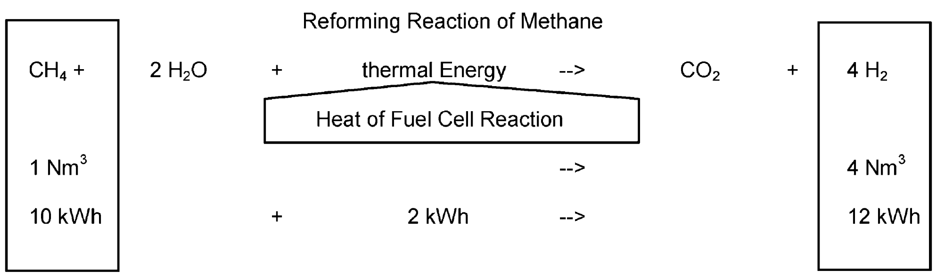

Fig. 3. Increase in efficiency of high temperature fuel cells by internal reforming (2 kW h primary energy production from "waste" heat and 12% gain of efficiency at 60% fuel utilization).

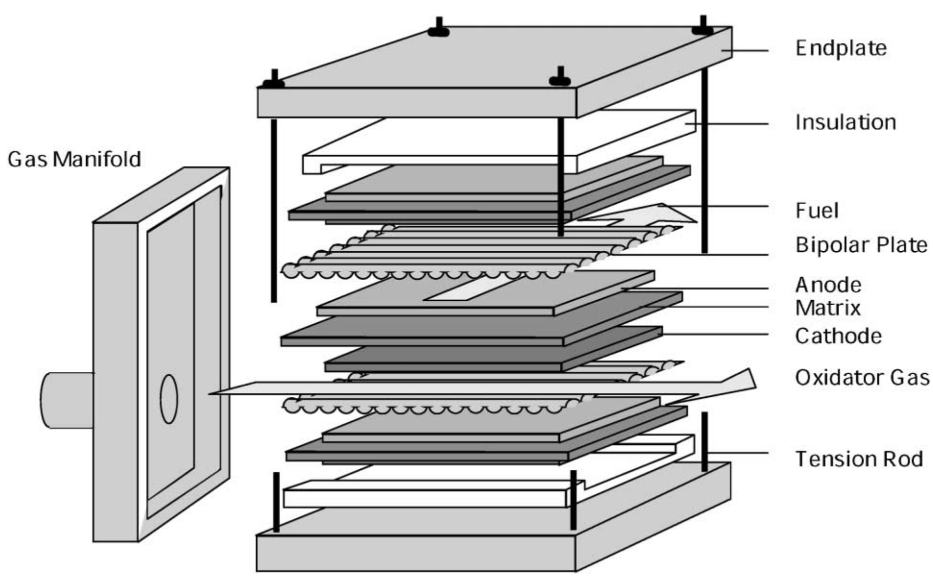

Fig. 4. Structure of a cross-flow fuel cell stack.

the principal structure of a cross-flow molten carbonate fuel cell stack. Only one of four gas manifolds is shown in this drawing.

4. The fuel cell system problem

The ARGE's work in MCFC system design came to a turning point in 1992 when we realized that conventional system designs do not hold the promise for competitive power plants. As a rule of thumb, the fuel cell stack contributes only one-third to the cost of the overall system. In a standard configuration the cost of conventional components would keep the system too expensive, even if the cost of the fuel cell stack itself could be reduced to zero. Neither technological breakthroughs nor large production volumes can be expected for the peripheral equipment to bring down the cost sufficiently.

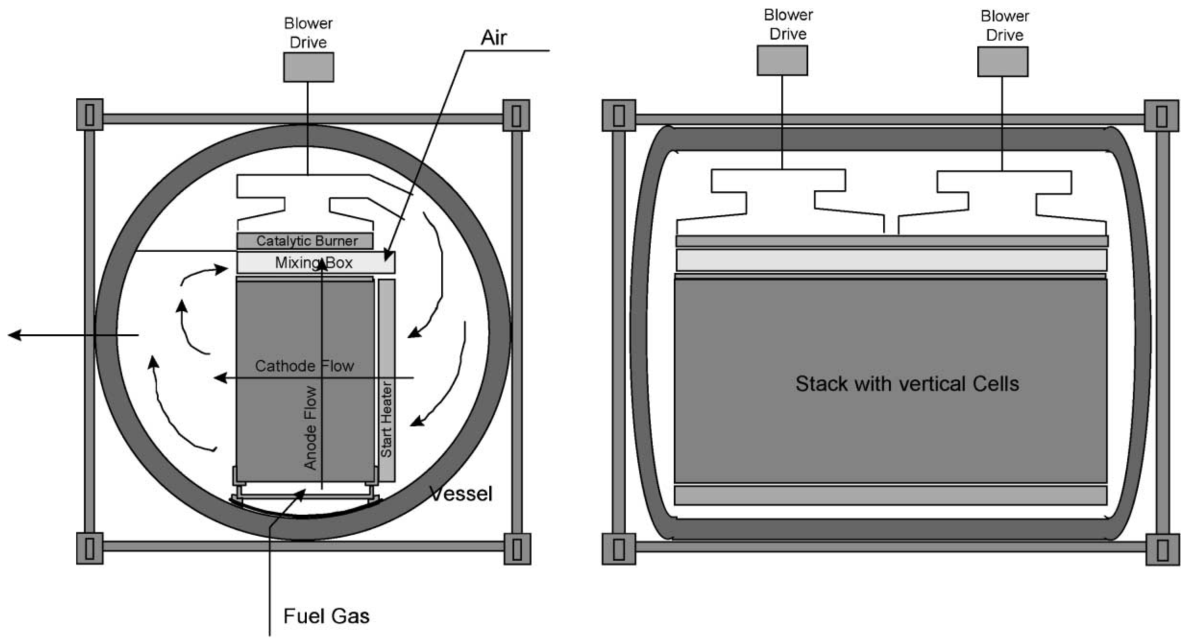

Fig. 5. Basic design of the Hot Module.

5. Optimization by simplification and integration

5.1. The Hot Module concept

These findings have led us to the invention of an innovative design approach characterized by the term Hot Module (Fig. 5). A Hot Module combines all the components of an MCFC system operating at similar temperatures and pressures into a common thermally insulated vessel. A typical configuration contains the MCFC stack, a catalytic burner or the anode tail gas and a cathode recycle loop including mixing-in of fresh air and anode exhaust. The cell stack is resting in a horizontal position on the fuel-in manifold, thus providing excellent gas sealing by gravity forces. On the top of the stack the gases exiting from the anodes are mixed into the cathode recycle loop together with fresh air supplied from the outside. The mixture is transported through a bed of combustion catalyst located on top of the mixing area and blown back to the cathode input by the cathode recycle blowers on the top end of the vessel. No gas piping or sealed cathode manifolds are necessary. For startup, an electrical or gas fired heater is arranged along the cathode input of the stack.

The Hot Module is complemented by a fuel processing system of a similar high degree of mechanical integration. All heat exchangers necessary for pre-heating of the fuel gas and evaporation of the reforming water are integrated into a common duct supplied with the cathode exit of the Hot Module. The reactors for the desulfurization and pre-conversion of higher hydrocarbons in the fuel gas are skid mounted alongside this duct to form a compact unit finding its place at one end of the cylindrical stack module. The other end of the stack module is taken by an electrical and electronics compartment containing the control electronics and a state-of-the-art efficient liquid cooled IGBT inverter. The whole arrangement is truck transportable and intended to be installed within buildings as well as in the open.

The capacity of the plant can be increased either by increasing the number of cells in the stack or by connecting multiple modules together. Fig. 6 shows the direct fuel cell Hot Module prototype as planned today within the power range of 400 kW.

6. Scope of applications

High quality of electricity, high temperature useful heat, and a wide range of useable fuels make the direct fuel cell cogeneration plant extremely versatile in application. We expect the focus to be in commercial and light industrial cogeneration, i.e. production of electricity and process steam. Steam is widely used as a heat carrier in light industries dealing with organics, e.g. the food industry including beverages, dairy products, meat processing, etc. Combined with efficient absorption cooling devices, the DFC power plant is ideally suited to supply large buildings with all required forms of energy. In hospitals, not only air conditioning and sterilization needs can be satisfied; the electrical redundancy from the grid gives the necessary reliability for crucial electricity demand.

Another focus of the application of the DFC Hot Module cogeneration plant is the utilization of opportunity fuels, e.g. biogas generated both by digestion or pyrolysis, residual hydrocarbon gases from production processes, landfill gas, etc.

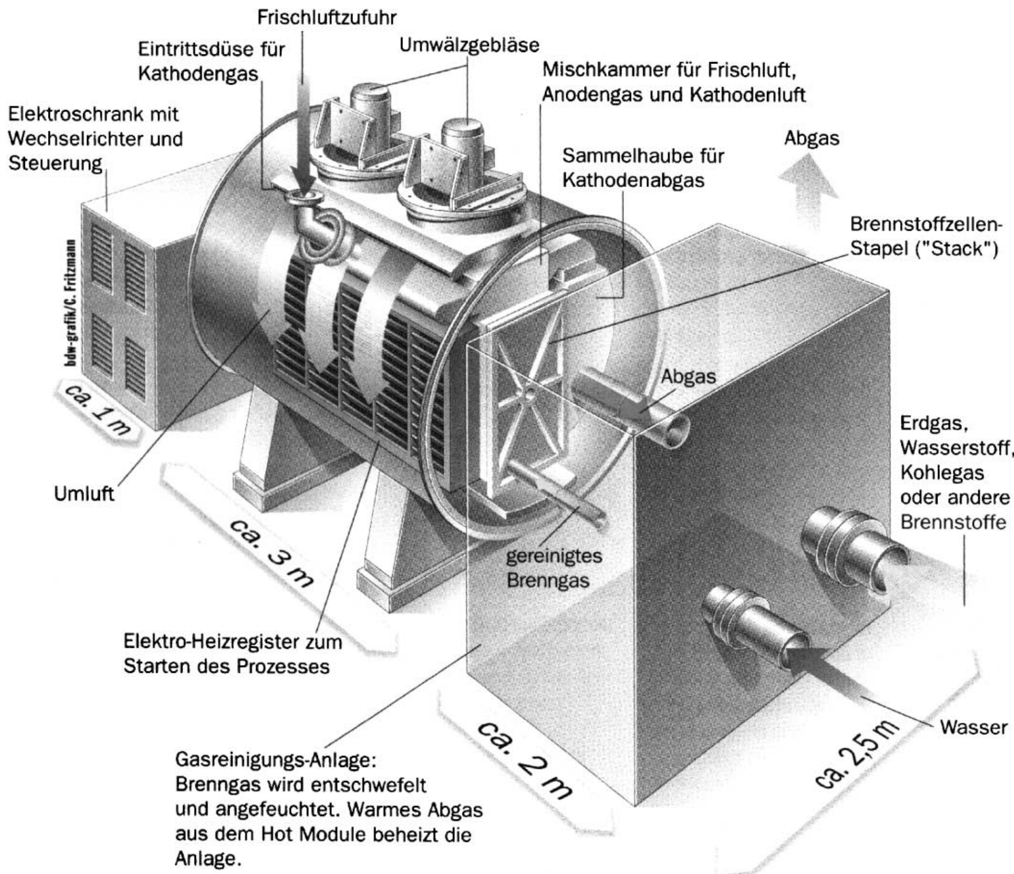

Fig. 6. Direct fuel cell cogeneration Hot Module prototype.

7. Qualification and future development

In the years 1995 and 1996 various tests on full-scale dummy set-ups of the Hot Module confirmed the mechanical, pneumatic and thermal viability of this integrated design approach.

In August 1997 the consortium started its first full size Hot Module MCFC test plant at the facilities of Ruhrgas AG in Dorsten, Germany (Fig. 7). The plant is based on the consortium's unique and proprietary "Hot Module" concept with the following key features:

- Single stack Hot Module.
- The 292 cells of 0.6 m × 1.2 m cell area (FCE technology).
- Peak electrical stack capacity of 270 kW.
- Pipeline natural gas operation.
- Fuel clean-up system with integrated desulphurizer and heat recovery steam generator.
- Grid-connection via advanced IGBT inverter.
- Automatic operation with programmable controlled logic.
- Graphical user interface on computer monitor.
- Comprehensive safety systems.
- Authority approval.

The stack was assembled in Munich using cell packages purchased from FCE. It was grid connected on 16 August 1997.

After a total of 1500 h of operation the plant was intentionally shut down in a controlled manner in April 1998 for post-test analysis:

- The Hot Module system concept has demonstrated its functionality.
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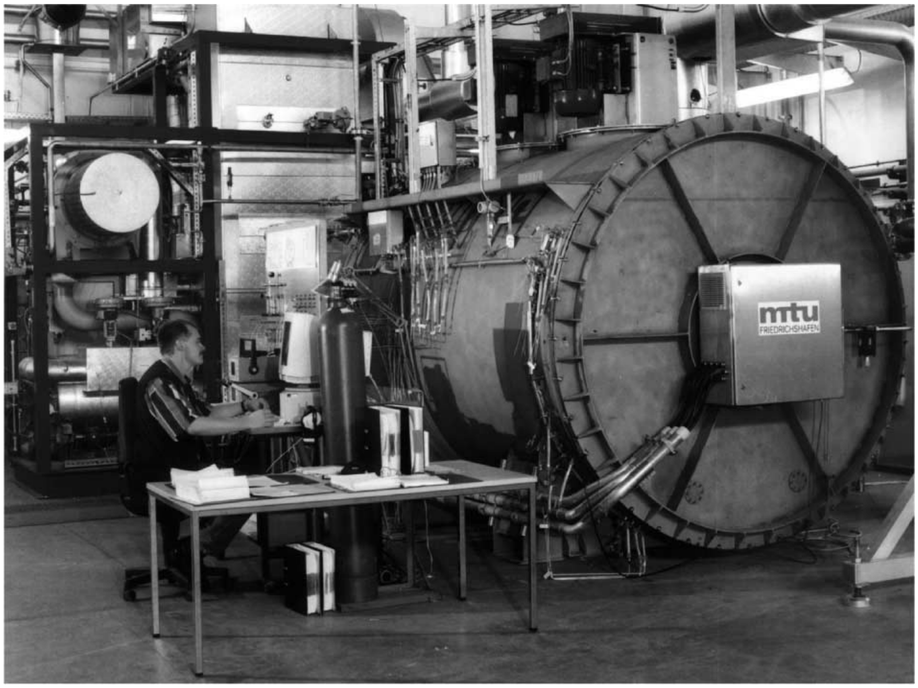

Fig. 7. The Hot Module during test at the Ruhrgas test facility, Dorsten, Germany.

8. Things to come

After the successful test of the Hot Module system the ARGE DFC plans to sell a number of pre-commercial field test units to be operated within key applications in industrial and commercial cogeneration. This third phase of the ARGE's program is intended to achieve operational experience on the side of the supplier and confidence in this new technology on the side of the customer, paving the way to commercial application of our innovative product concept.

Together with progress achieved by FCE in the qualification of large DFC stacks and the results of the first test of a DFC Hot Module the basis is given for the next test unit of similar design, which is operating now in Bielefeld, Germany. The plant includes many improvements concerning the detailed mechanical design and the control mechanisms with respect to simplification of the automatic operation and increase of operational reliability. Within this field test the operation of the heat utilization will be demonstrated the first time by production of high pressure steam. The conditioning and first tests of the stack took place already in July 1999 with good results.

The combination of the direct fuel cell Hot Module cogeneration plant with high efficient absorption cooling devices opens an important perspective to create a system with a broad application range in the market of air conditioning and cooling. Due to the fact, that the coefficient of power (COE) for lithium bromide-based absorption cooling systems can be increased up to 1.5–1.7 using higher temperatures for the separation process at the hot end of the absorption cooler, the overall efficiency of such kind of system is substantially higher in comparison with conventional air conditioning systems. Additionally, this combination will increase the annual operation time of the plant substantially and sustainably due to the overlapping of annual thermal energy and cooling power demand. Annual operational times of up to 8.000 h a year are predicted for such systems compared with 2.500–3.500 for electrical power and heat producing systems only. This shortens the pay back period of the investment cost considerably.

Additionally, projects concerning the test of the DFC Hot Module operating on biogas, landfill gas and other opportunity fuels are under preparation. The driving force for application of biogas technologies is not the production of electricity and heat in the first instance but the possibility of waste material management and disposal avoiding deposition or other environmental pollutant techniques.

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