

Molten carbonate fuel cell (MCFC) characteristics, technologies and economic analysis: Review

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ABSTRACT

The MCFC seems a valid alternative to the traditional plant. MCFC power plants are prime candidates for the utilization of fossil based fuels to generate high efficiency ultra clean power. Large-scale commercialization, especially in the distributed generation and cogeneration market, remains a possibility. However, fuel cells are considerably more expensive than comparable conventional technologies and therefore a careful analysis of economics must be taken. In general, the use of a fuel cell at this facility would not be economically feasible at this time. But, a parametric study was conducted to determine scenarios including variation in electric and natural gas rates along with reduced installation costs.

Keywords: Molten carbonate fuel cell (MCFC), fuel cell technology, Economic analysis.

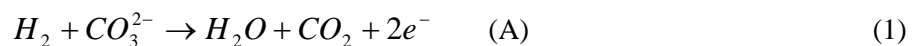
1. INTRODUCTION

In spite of public perception, the MCFC has continued to make remarkable advances in both technical and economic respects during the last 10 years. This combined technical and marketing effort is under way in spite of a downturn in the public image of the MCFC and its commercial potential [1]. Fuel cells of today have many technological advances including: high fuel efficiency, ultra-clean emissions, improved reliability, quiet operation, scalability, operation from readily available fuels and the ability to provide both electricity and heat [2].

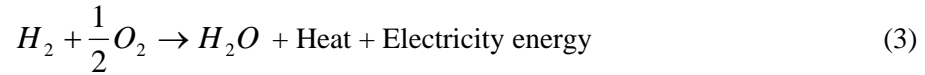
MCFC power plant can be applied to various power plants, such as alternative thermal power plants, dispersed power and integrated coal gasification combined cycle power plant [3]. At a temperature level of 650 °C the MCFC incorporates all the advantages of high temperature fuel cells, · internal reforming of hydrocarbons for simplest system design and highest efficiency; · useful high temperature heat for industrial steam generation; without have to cope with the problems of ceramic fuel cell manufacturing [4]. The aim of this paper is to review technical and economic challenges of MCFC. The following sections outline is fundamentals of molten carbonate fuel cell, MCFC characteristics and technologies, MCFC economic analysis and conclusion.

2. FUNDAMENTALS OF MOLTEN CARBONATE FUEL CELL

All of the hydrogen-oxygen fuel cells; the MCFC is the only one, which employs a molten salt electrolyte. In particular, the technology of MCFC is now at the stage of scale up to commercialization and many developers have shown significant progresses. MCFCs are planar cells formed by a matrix (tile) filled with carbonates and coupled with two electrodes where the following reactions occur:



Therefore, the net cell reaction is



On the anodic side, the water gas shift reaction occurs too [6],



hence the outlet anodic gases content more water than the inlet gases. The higher partial pressure of water leads to an additional decrease of the cell voltage and cell efficiency [5].

The factors involved in determining the operation for a MCFC are the same as those for other types of fuel cells. They include stack size, heat transfer rate, energy conversion efficiency, cell potential level, load requirement, and cost, and so on.

The polarization curves for various hydrogen-oxygen fuel cells are presented in Fig. 1 [5]. They are averaged over performances of single cells in the most frequent conditions of operation for a given fuel cell type. A striking feature of the voltage versus the current density dependence for the MCFC is its linear character. The MCFC nominally operates at the current density of 100-200 mA/cm² (typically 160 mA/cm²) and cell potential of 0.75-0.95 V (typically 0.75 V) at the atmospheric pressure and 75% fuel (hydrogen) utilization [7].

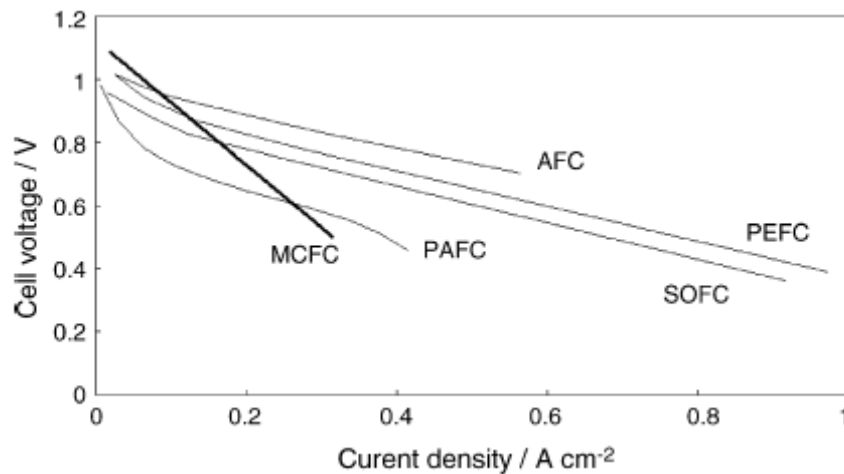


Fig. 1 Polarization curves for various hydrogen-oxygen fuel cells [5].

The thicknesses of electrodes and electrolytes are compared for various fuel cells in Fig. 2 [5]. As can be seen, the MCFC has one of the thickest electrode-electrolyte assembly (1-3 mm) and definitely the thickest electrolyte (0.5-1.5 mm) among all the hydrogen-oxygen fuel cells. Thick electrolyte neutralizes the phenomenon of NiO cathode dissolution in molten carbonate, which may lead to formation of Ni dendrites and consequently to short circuit between the electrodes. Fortunately, due to the high conductance of molten salts, the ohmic drop in the MCFC remains still acceptable even if a matrix electrolyte is relatively thick.

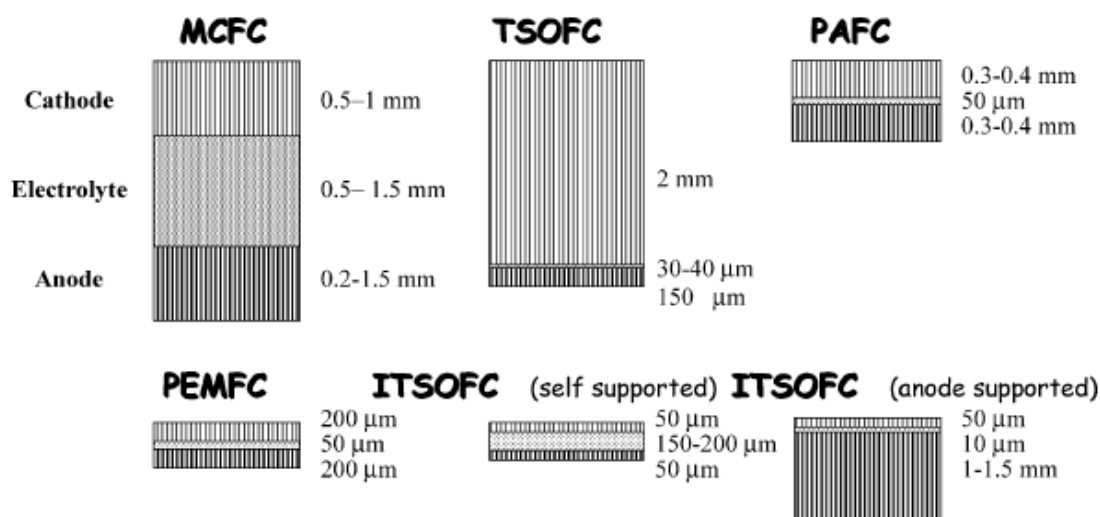


Fig. 2 Thickness of electrodes and electrolytes for various hydrogen-oxygen fuel cells [5].

3. MCFC CHARACTERISTICS AND TECHNOLOGIES

Characteristics of molten carbonate fuel cell (MCFC) were critically compared to those of polymer electrolyte membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC) and solid oxide fuel cell (SOFC). In comparison to the other fuel cells, the MCFC operates with the lowest current densities due to limited zones of effective electrode reactions and low solubility of oxygen and hydrogen in molten carbonates; also it has a thickest electrodes-electrolyte assembly. In consequence, the applications of MCFC are almost limited to stationary power generators. The intrinsic features of cogeneration of electricity and heat from internally reformed carbonaceous fuels in molten carbonate fuel cell, favours the position of MCFC at the marketplace of stationary power and heat cogeneration units (Fig. 3). On the other hand, material and design innovations, which have crucial impact on further development of fuel cells, are potentially much easier to be achieved for the PEMFC and SOFC than the MCFC. Therefore, one may expect severe competition between these technologies in the section of medium-size power generators in the first decades of 21st century [5].

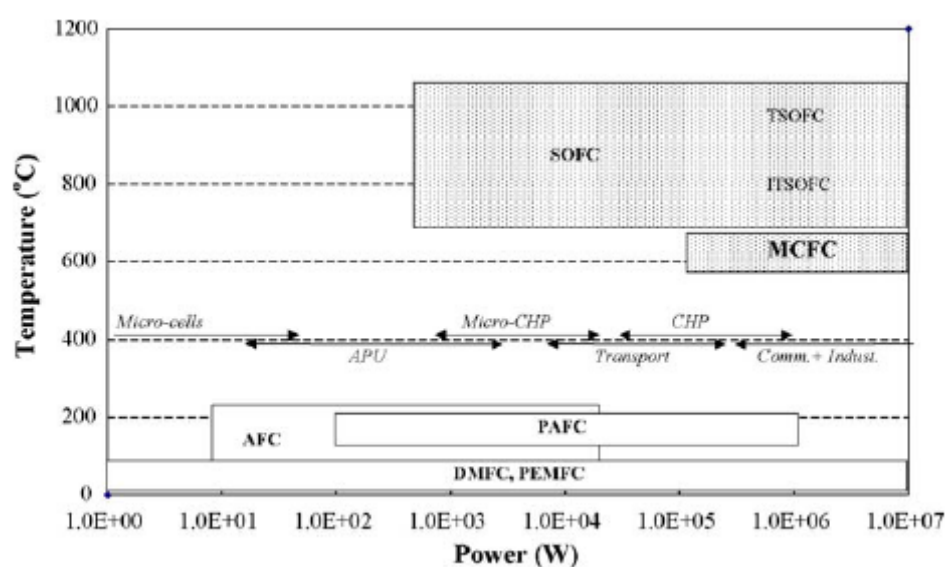


Fig. 3 Position of MCFC at fuel cell market place. Shaded area: possible internal reforming [5].

The MCFC Research association has been conducting R&D of the 1000 kW class MCFC Power Plant under contracting research with New Energy and Industrial Technology Development Organization (NEDO) as a part of New Sunshine program, promoted by the Agency of Industrial Science and Technology (AIST), Ministry of International Trade and Industry (MITI). The plant consists of four 250-kW stacks, a reformer, two cathode gas recycle blowers, a turbine compressor, a heat recovery steam generator (HRSG) (Fig. 4). The power plant is the first Japanese practical external reforming pressurized type MCFC power generation plant intended for large-scale commercial plant in the near future. The construction of the 1000 kW MCFC power plant started in autumn of 1995 on Kawagoe test station in Kawagoe Thermal Power Station of Chubu Electric Power, which is located in the prefecture of Mie, Japan. The construction and installation of the plant progressed very well, and process and control (PAC) testing of the power plant (not including fuel cell stacks and inverters) was carried out through March-November of 1998. After the PAC test, the cell stacks and inverters were installed in the test site. The power generation test will be continued up to January 2000. This test will confirm the 1000 kW rated power, the plant efficiency, the decay rate stack, partial load characteristics and after matters [3].

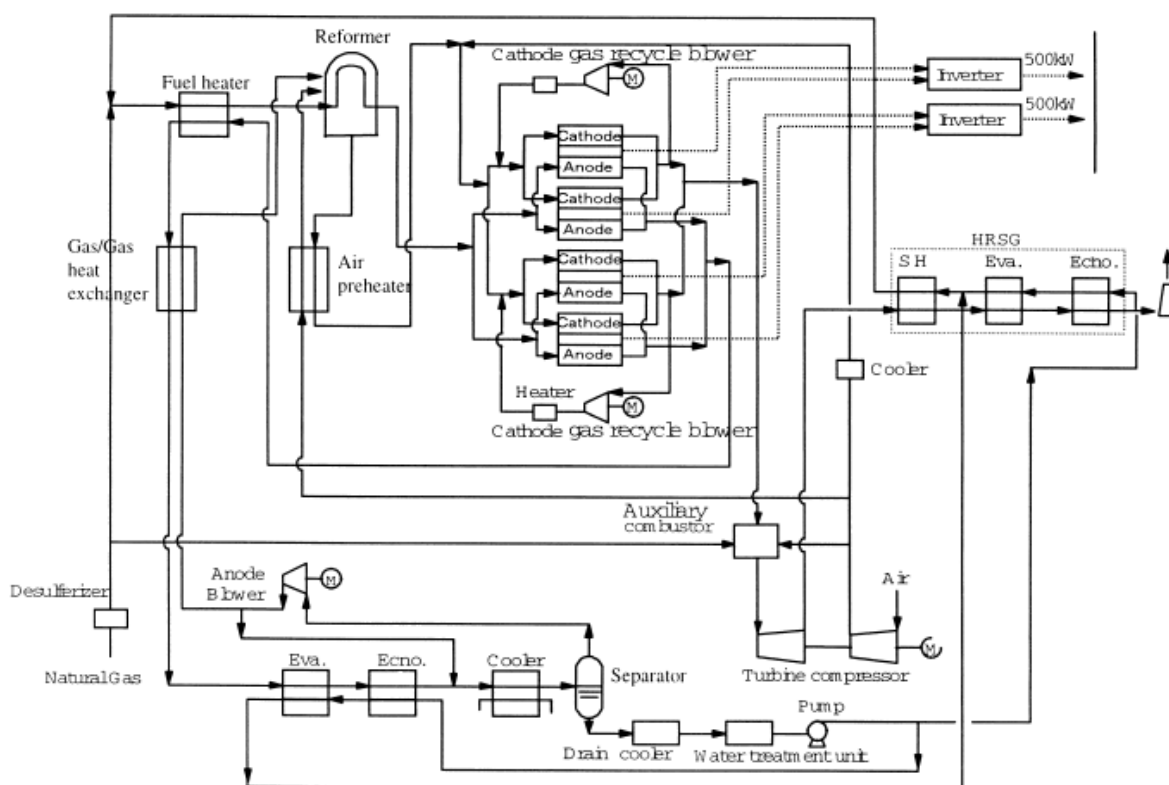


Fig. 4 Process flow diagram for 1000 kW power plant [3].

A Hot Module has demonstrated combines all the components of an MCFC system operating at similar temperature 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 (Fig. 5). The electrical power level of 155 kW (ca. 60% of maximum power) achieved allows validation of the concept with reasonable degree of confidence. Together with progress achieved by FuelCell Energy's (FCE) in the qualification of large direct fuel cell (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 operated in Bielefeld, Germany. The pre-tests of the stack took place already in July 1999 with good results. 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 [4].

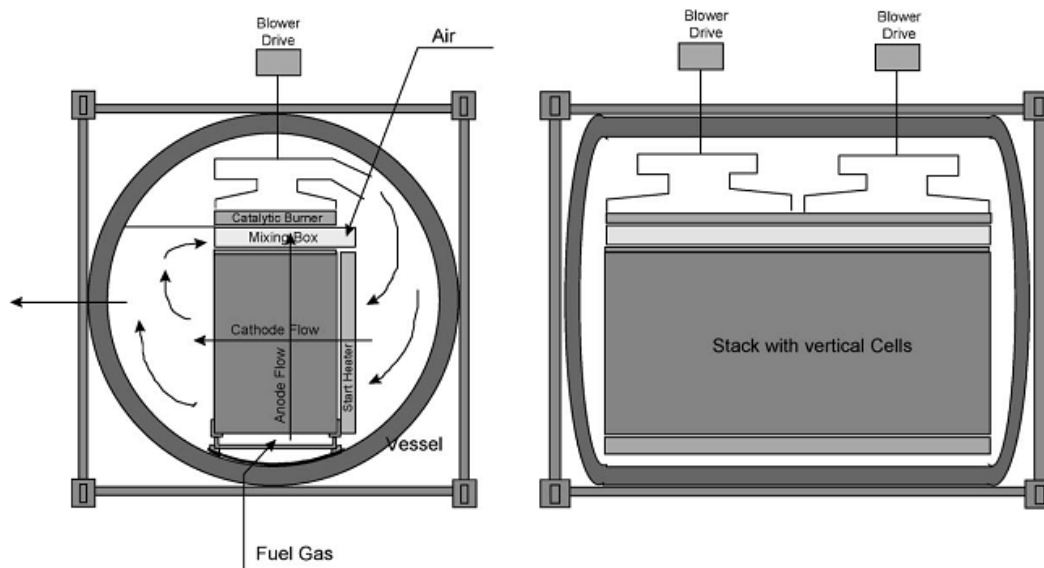


Fig. 5 Basic design of hot module [4].

The Molten Carbonate Fuel cell (MCFC) technology has been developed in USA, Japan, Korea and Europe for many years. What has started about 30 years ago as an interesting laboratory object has now matured to a potential alternative to conventional power generation systems. Especially the combined heat and power (CHP) generation is an area, where MCFC power plants can be applied with great advantage, due to the high efficiencies which can be achieved. The present paper will discuss some aspects of the development work going on with a focus on the role of the molten carbonate to commercialization. The carbonate fuel cell demonstrations to-date have been able to show the highest fuel-to- electricity conversion efficiencies (>50%) of any stand-alone fuel cell type. Carbonate fuel cell technology is more fuel flexible than lower temperature fuel cell technologies and is well suited to marine, military, and traction application. An outlook will be given for the future prospects of this young technology in a changing energy market [9].

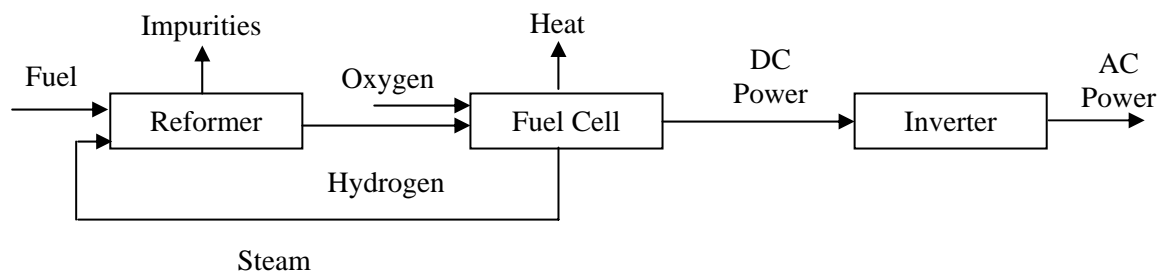
Technologies for natural gas fueled MCFC power plants can utilize CO rich and H₂ lean fuel, such as gasified biomass or gasified waste as a Pt catalyst is not used and Pt poisoning by CO does not occur. This feature has become very importance due to the worldwide CO₂ depression requirements. The single cell performance was verified with CO rich fuel. It is necessary that the shift reaction is fast compared to the anode reaction to replenish the H₂ consumed at the anode. The result is that the long-term performance of the single cell decreased very slowly with high CO fuel. To conclude that the wet ability within the electrodes is affected by the fuel composition and that the electrolyte maldistribution might be responsible for causing such unstable performance. To improve this situation, a new anode with a modified porosity for preventing cathode flooding was tested. Using the improved anode, the single cell showed stable performance. Stacks were tested with various gas compositions and showed stable performance even with high CO and high fuel utilization conditions. Gasified biomass or waste can contain many kinds of impurities such as H₂S, HCl, HF, NH₃, etc. The effects of these impurities were taken into account for single cells, and the permissible limits were estimated [8].

MCFC and microturbine technologies due to its high operating temperature and pressure give the possibility to use a turbine at the bottom of the cells to produce further energy, increasing therefore the plant's efficiencies. The basic idea using this two kinds of technologies (MCFC and microturbine), is to recover, via the microturbine, the necessary power for the compressor, that otherwise would remove a consistent part of the MCFC power generated. The purpose of this work is to develop the necessary models to analyze different plant configurations. In particular, it was studied a plant composed of a MCFC 500 kW Ansaldo at the top of a microturbine 100 kW Turbec. To study this

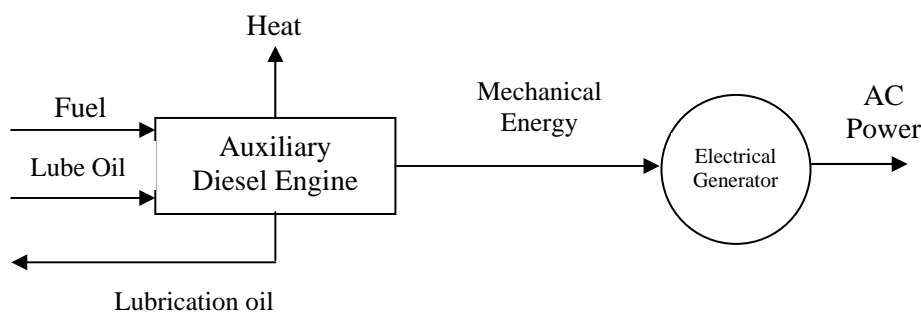
plant it was necessary to develop: (i) MCFC mathematical model, that starting from the geometrical and thermofluidodynamic parameter of the cell, analyze the electrochemical reaction and shift reaction that take part in it; (ii) plate reformer model, a particular compact reformer that exploit the heat obtained by catalytic combustion of the anode and part of cathode exhausts to reform methane and steam; and (iii) microturbine-compressor model that describe the efficiency and the pressure ratio of the two machines as a function of the mass flow and rotational regime. The models developed was developed in Fortran language and interfaced in Chemcad[®] to analyze the power plant thermodynamic behavior. The results show that global electricity efficiency surely can be kept easily over 50-55%, and a cogenerative efficiency about 75% [6].

A high efficiency and ultra-clean MCFC commercialization is based on FuelCell Energy's (FCE) Direct FuelCell[®] (DFC) technology that has progressed to commercial power plants for stationary applications such as distributed generation (DG), which is power production at or near the customer site. The DFC power plants are suitable for highly efficient electricity or CHP for stationary applications. Over 40 units ranging in 250 kW-1 MW size have been in field operation worldwide. These units have shown 45-48% LHV electrical conversion efficiencies and overall thermal efficiency approaching 80% in CHP applications. Lessons learned from this development will also be valuable to U.S. department of Energy (DOE) for the ongoing solid oxide fuel cell (SOFC) development and cost reduction, for fuel cell turbine hybrids and for hydrogen economy development with FutureGen [10].

A life cycle assessment (LCA) of a molten carbonate fuel cell (MCFC) plant for marine applications was studied. The results are compared to a benchmark conventional diesel engine (DE) which operates as an auxiliary power generating unit (Fig. 6). The LCA includes manufacturing of the main component of DE, MCFC stack and balance-of-plants (BOP), production of fuels, onboard operation and decommissioning aspect at the end-of-life of the systems. Environmental benefits from fuel cell operation are maximized with the use of hydrogen as an input fuel. The capability of using commercially available fossil fuel instead of pure hydrogen, such as diesel oil or methanol will be a long-term solution for fuel cell application onboard ships. The study shows that the manufacture of MCFC including stack and BOP components, supply of materials and energy for the production contributes significantly to environmental impact compared to that of DE for the same functional unit mainly due to special materials used in the stack and the weights of the BOP components. Additionally, recovering valuable materials through re-use or recycle will reduce the overall environmental burden of the system over its life cycle [11].



(a) Fuel Cell System



(b) Diesel Electric System

Fig. 6 Components of compared systems [11].

4. MCFC ECONOMIC ANALYSIS

After an overview of current MCFC performance, compared with performance and cost of other fuel cells, improvements in power density and lifetime as well as cost reduction are identified as key priorities to accelerate the commercialization of MCFC. In spite of its unfavorable public image (compared to, in particular, PEMFC and planar SOFC) MCFC technology has progressed steadily and cost reduction has been significant. Large-scale commercialization, especially in the distributed generation and cogeneration market, remains a possibility but its chances are highly dependent on a forceful and consistent energy policy, for example taking into account the externalities associated with various modes of electric power production from fossil fuels. In spite of steady improvements in performance, important defects in fundamental knowledge remain about:

- (1) Wetting of materials by carbonate melts and how it depends on material properties, melt chemistry and polarization.
- (2) Kinetics of oxygen reduction at a variety of materials (melts as well as oxide semi-conductors) and how these kinetics depend on material properties, melt chemistry and polarization.
- (3) Corrosion of alloys (with passive layer formation), and dissolution/deposition mechanisms, especially applied to porous or layer composite substrates.

These must be addressed to stimulate further simplification of design and find solutions of lifetime issues. Limited lifetime is mainly caused by the corrosive and difficult-to-immobilize electrolyte, as well as the relatively unstable nickel oxide cathode. Recently, alternative concepts of molten-salt fuel cells have been capturing attention. The direct carbon fuel cell (DCFC), reviving an old concept, has caught the attention of energy system analysts and some significant advances have been made in this technology. Direct CO and CH₄ oxidation have also been a focus of study. CO is a major component of alternative fuel gases such as biomass gas and other low-Btu gases, which are naturally compatible with MCFC operation. Direct CH₄ oxidation led to the conclusion that it probably occurs at negligibly small rate under MCFC conditions. It was believed that this is due primary to the very small solubility of CH₄ in molten carbonate. As a result, direct (in-cell) and indirect (in-stack) internal reforming are now used in MCFC system design. Finally, the potential of nanotechnology for high-temperature fuel cells should not be a priori excluded [1].

Fuel cells can be attractive for use as stationary combined heat and power (CHP) systems. Molten carbonate fuel cell (MCFC) power plants are prime candidates for the utilization of fossil based fuels to generate high efficiency ultra clean power. However, fuel cells are considerably more expensive than comparable conventional technologies and therefore a careful analysis of the economics must be taken. The economic analysis and results are based in installation and operation of a DFC[®] 1500 MA and 300 MA. In general, the use of a fuel cell at this facility would not be economically feasible at this time. Although savings contributions from electric and heat recovery savings are significant, the costs associated with increased natural gas usage, maintenance charges and water/sewer usage are considerably greater. In certain areas, emissions reductions would help this measure but not enough to make it attractive for this facility. The results of simple payback period analysis were summarized in a contour plot generated utilizing EES (Engineering Equation Solver). Fig. 7 and 8 show simple payback periods for a variety of utility combinations. The parametric study indicated that in the future as electric and natural gas rates charge and fuel cell costs are reduced, this technology would become more attractive for the facility [2].

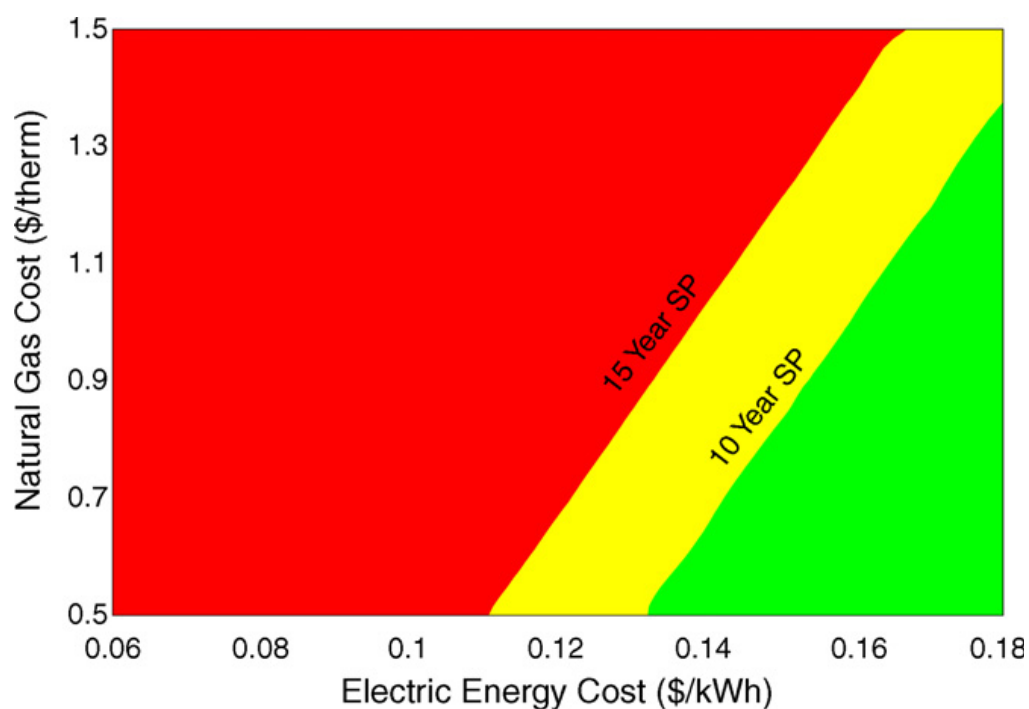


Fig. 7 Simple payback period vs. natural gas and electric rates ($\$5300 \text{ kW}^{-1}$) [2].

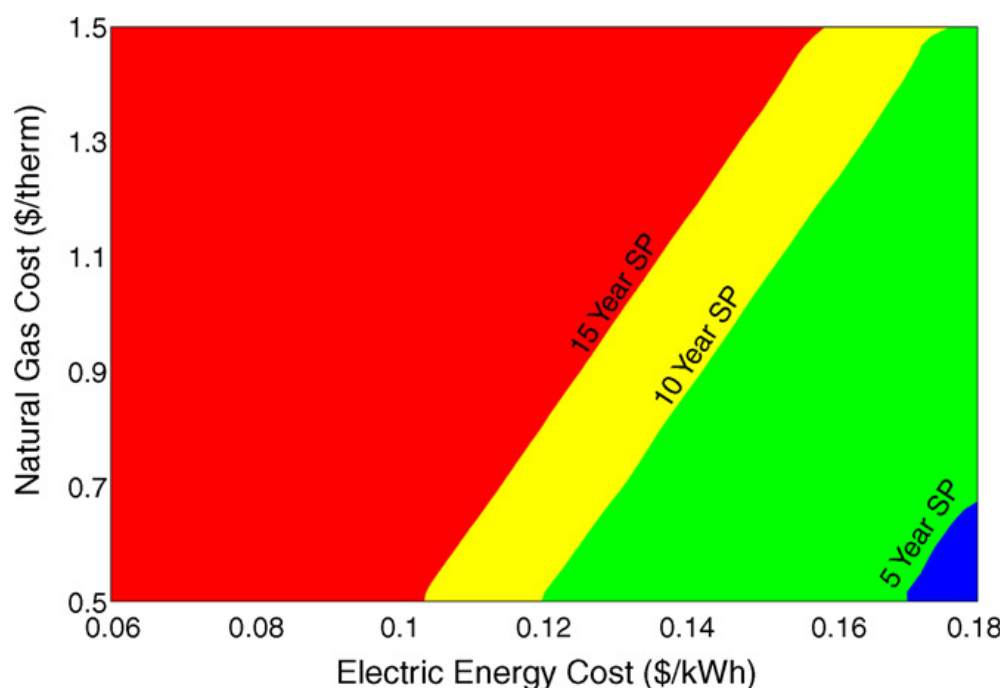


Fig. 8 Simple payback period vs. natural gas and electric rates ($\$4300 \text{ kW}^{-1}$) [2].

5. CONCLUSION

The paper presents characteristics, technologies and economic analysis of MCFC. The MCFC operates with the lowest current densities; also it has a thickest electrodes-electrolyte assembly. In consequence, the applications of MCFC are almost limited to stationary power generators. MCFC technology for commercial application is DFC power plant, which is suitable for highly efficient

electricity or combined heat and power (CHP) generation. In general, the use of a fuel cell at this facility would not be economically feasible at this time. The parametric study indicated that in the future as electric and natural gas rates charge and fuel cell costs are reduced, this technology would become more attractive for the facility.

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