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CARBONATE FUEL CELL POWERPLANT DEVELOPMENT AND COMMERCIALIZATION

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INTRODUCTION

Carbonate fuel cell (CFC) powerplants offer the potential for ultra-high efficiency energy conversion and the enhancement of the quality of our environment. Concerns for the global environment are driving future power generation systems toward technologies that produce extremely low environmental emissions. Because of their high efficiencies, CFC powerplants will help in reducing carbon dioxide emissions. Since combustion is not utilized in the process, CFC's generate very low amounts of nitrogen oxide (NO_x). Table 1 shows the comparative emissions for a 2-megawatt (MW) powerplant versus other competing technologies.

Emission Estimates for 2-MW Powerplants

	Combustion Turbine/ Generator Simple Cycle Natural Gas Fuel	Combustion Turbine/ Generator Simple Cycle Natural Gas Fuel	Diesel Engine/ Generator	Direct Carbonate Fuel Cell Commercial Units
Efficiency	30% - 25%	30% - 25%	37% - 30%	60% - 54%
Heat Rate, Btu/kWh	11380-13650	11380 - 13650	9220 - 11380	5690 - 6320
Emissions: Uncontrolled NOx lb/MWh	5.2 - 6.2	5.9 - 7.1	33.3 - 41.4	0.0025 - 0.003
Controlled NOx[5] lb/MWh	1.0 - 1.2	1.2 - 1.4	6.7 - 8.2	NA
Uncontrolled CO lb/MWh	1.4 - 1.7	1.3 - 1.6	7.2 - 8.9	0.00014 - 0.14
Uncontrolled SO_2 lb/MWh	0.011 - 0.013	0.28 - 0.34	0.23 - 0.28	0.00011 - 0.00012
Uncontrolled HC lb/MWh	0.53 - 0.63	0.49 - 0.58	2.7 - 3.3	Negligible

Carbonate fuel cell powerplants have been exempt from air permitting requirements in northern and southern California and in Massachusetts. The CFC is attractive for both polluted urban areas and remote applications. It is ideal as a distributed generator; that is, it can be sited at or near the electricity user--for example, at electrical substations, at shopping centers or apartment complexes, or in remote villages--minimizing long-distance transmission lines.

In the U.S., the CFC Program is a cost-shared, market-driven program. The U.S. program is being implemented by the U.S. DOE's FETC. The CFC developers enjoy the support of user groups comprised of utility and other end-user members. DOE cooperates with the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI) to fully and efficiently leverage funding for the U.S. CFC Program.

Worldwide Carbonate Fuel Cell Status

Worldwide, the goal is to develop a CFC responsive to the needs of existing and emerging power markets. Both internally manifolded and externally manifolded configurations are still being pursued. Most configurations are generally being pressurized. Both internally reforming and externally reforming concepts continue to be pursued. Combinations such as pressurized internally manifolded, internal reforming fuel cells are being considered.

The goal of the U.S. CFC Program is to develop and commercialize low-cost, packaged, simple, and modular fuel cell systems. DOE is accelerating the drive for private sector commercialization of multifuel, CFC powerplants.

The two U.S. CFC developers, Energy Research Corporation (ERC) and M-C Power (MCP), have made impressive progress under the 1990 program research and development announcement (PRDA). ERC is developing an externally manifolded, externally reforming CFC and has constructed a 2- to 17-MW per year CFC manufacturing plant. ERC has constructed a 100-kilowatt (kW) test facility in Danbury, Connecticut, and has scaled up to a 6-ft^2 (0.56 M^2) area stack (1-6).

MCP is developing an internally manifolded, externally reforming CFC and has constructed a 4- to 12-MW per year CFC manufacturing plant. MCP has constructed a 250-kW acceptance test facility in Burr Ridge, Illinois, and has scaled up to an 11.4-ft^2 (1.06 M^2) full-area stack (1,7-11).

DOE, in conjunction with EPRI, GRI, San Diego Gas and Electric, the Santa Clara Demonstration Group, and the Department of Defense, is also funding product development tests (PDT's) concurrently with system development at ERC and MCP. A successful demonstration track record will enhance support for CFC technology from utilities and other end-users in the distributed, repowering industrial and commercial markets.

The initial CFC PDT's are being conducted in California in 1996-97. ERC is currently conducting a 2-MW PDT in Santa Clara, California, funded by the Santa Clara Demonstration Group, EPRI, and DOE. In 1996-97, MCP will conduct a 250-kW PDT in San Diego, California, funded by DOE, GRI, and San Diego Gas and Electric at the Miramar Naval Air Station.

DOE's FETC recently competed a Product Design and Improvement (PDI) PRDA to resolve technology, system, and network issues. There remain major issues in CFC performance and operation (12-15). Major issues are cost, thermal cycling, cathode corrosion, footprint, packaging and integration, and networking. The PDI objective is to aim current CFC stack development toward the development of a packaged, commercializable CFC product. The PRDA will bring a multifueled, integrated, simple, low-cost, modular, market-responsive CFC powerplant to the marketplace. The development program will be based on a commercialization plan to manufacture, package, demonstrate, and aggressively market CFC powerplants. The PDI PRDA will culminate in the manufacture and construction of high-performance, low kW-cost, 500- to 2,000-kW CFC powerplant module(s). Cost targets are $1500/by 2000-2001.

In Japan, Hitachi, Toshiba, Mitsubishi Electric Company (MELCO), IHI, and Sanyo are continuing the development of the CFC. Japanese funding for CFC's is at least equivalent to U.S. funding for the technology. The Japanese research is focusing on performance, reliability, and stability. Three companies--IHI, MELCO, and Hitachi--have tested 100- to 200-kW stacks. IHI has built a 40-kW integrated system in order to do research on system configuration and system conditions. This system is a networked system with two CFC's in series. The Japanese market for CFC appears to be 20 to 50 MW, which is larger than in the U.S. CFC. Toshiba is targeting the even larger 30- to 500 MW market for CFC's. Target costs for CFC's are $1500-2000/kW.

A New Energy and Industrial Technology Development Organization (NEDO) 1-MW combined IHI-Hitachi demonstration is planned for 1998. Both IHI and Hitachi will provide two internally manifolded, pressurized, externally reforming 250-kW CFC stacks for the demonstration. The success of this test will determine the direction of NEDO fuel cell funding. MELCO is testing both internally and externally manifolded CFC's. MELCO is also planning a 200- to 300-kW MELCO test in the 1998 timeframe.

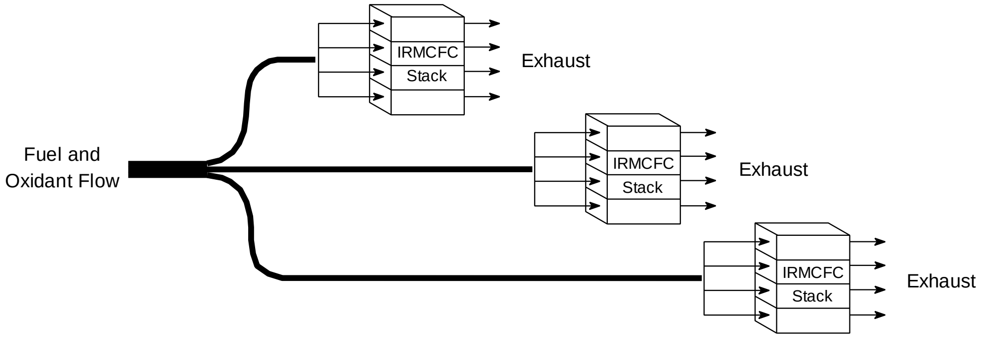
In Europe, ECN, ANSALDO, and Daimler-Benz are emerging as important CFC developers. ECN is an internally manifolded CFC developer while Daimler-Benz is an externally manifolded developer. A 300-kW Daimler-Benz CFC test at Ruhr Gas is planned for mid-1997. The stacks will be provide from ERC's manufacturing facility in Torrington, Connecticut.

CFC Networks

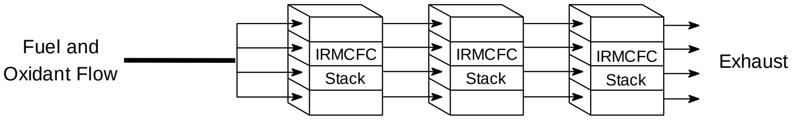
As multiple stacks are utilized, CFC networking--both electrical and reactant flow--is becoming an important consideration which is receiving more interest. In conventional fuel cell systems, multiple stacks have been arranged in parallel with regard to the flow of reactant streams. Networking (16-20) improves upon conventional CFC system designs in which multiple stacks are typically arranged in parallel with regard to the flow of reactant streams.

As illustrated in Figure 1a, the initial oxidant and fuel feeds are divided into equal streams which flow in parallel through the fuel cell stacks.

In a CFC network, reactant streams are ducked such that they are fed and recycled among multiple CFC stacks in series. Figure 1b illustrates how the reactant streams in a fuel cell network flow in series from stack to stack. By networking fuel cell stacks, increased efficiency, improved thermal balance, and higher total reactant utilizations can be achieved. Networking also allows reactant streams to be conditioned at different stages of utilization. Between stacks, heat can be removed, streams can be mixed, and additional streams can be injected.



(a) Parallel Flow of Reactant Streams Through Stacks



(b) Series Flow of Reactant Streams Through Stacks

Figure 1. CFC Networks

CFC stack networks produce more power than conventional configurations because they more closely approximate a reversible process. The Nernst potential is the voltage which drives reversible electrode reactions. This reversible voltage, generated by the overall cell reaction, is a function of the local temperature, pressure, and reactant concentrations. As reactants are utilized, their concentrations change. Since Nernst potential is dependent upon the concentrations of reactants, it varies with the degree of utilization.

In a conventional powerplant, the fuel is utilized in a single stack, and all the current is generated at a single voltage. In networks, stacks in series each utilize only part of the fuel. The network can produce more power because most of the total charge is transferred at increased voltages. When the total fuel utilization of each system is optimized for maximum efficiency, the efficiency of the fuel cell stacks networked in series can be nearly 10 percent greater than that of the stacks arranged in parallel.

Arranging fuel cell stacks in series offers several other advantages over conventional fuel cell powerplants. Placing stacks in series also allows reactant streams to be conditioned at different stages of utilization. Between stacks, heat can be consumed or removed (methane injection, heat exchange), which improves the thermal balance of the system. The composition of streams can be adjusted between stacks by mixing exhaust streams or by injecting reactant streams.

IHI has already developed a networked CFC system with two 20-kW CFC's in series. Additional networked systems are anticipated.

High-Efficiency CFC Gas Turbine Systems

One of the most promising developments in CFC powerplants is the conceptual development of very high efficiency fuel cell gas turbine powerplants (21-29). The combination of the CFC and turbine has the potential for enormous synergies, in that it offers a solution to two important problems: the low efficiency and relatively high NO_x emissions of small gas turbines and the high cost of small CFC powerplants.

Because of the synergistic effects leading to the higher efficiencies and lower emissions achieved by combining a fuel cell and a gas turbine into a power generation system, many potential system configurations have been developed (29). Studies have indicated that this combination has the potential to increase the overall efficiency for the conversion of natural gas into electricity to over 70 percent. These systems are the logical extension of fuel cell and gas turbine development and represent the most promising fossil energy powerplants ever conceived. Figure 2 shows that the efficiency expected from high efficiency fuel cell gas turbine powerplants is higher than either system by itself.

One powerplant configuration developed is the natural gas, indirect-fired, carbonate fuel cell bottomed, combined cycle for distributed power and on-site markets in the 20- to 200-MW size range shown in Figure 3. Most of these large fuel cell/gas turbine systems utilize a steam cycle to achieve high thermal efficiency. In addition, smaller systems not incorporating a steam turbine are ideal for the distributed power and on-site markets in the 1- to 5-MW size range.

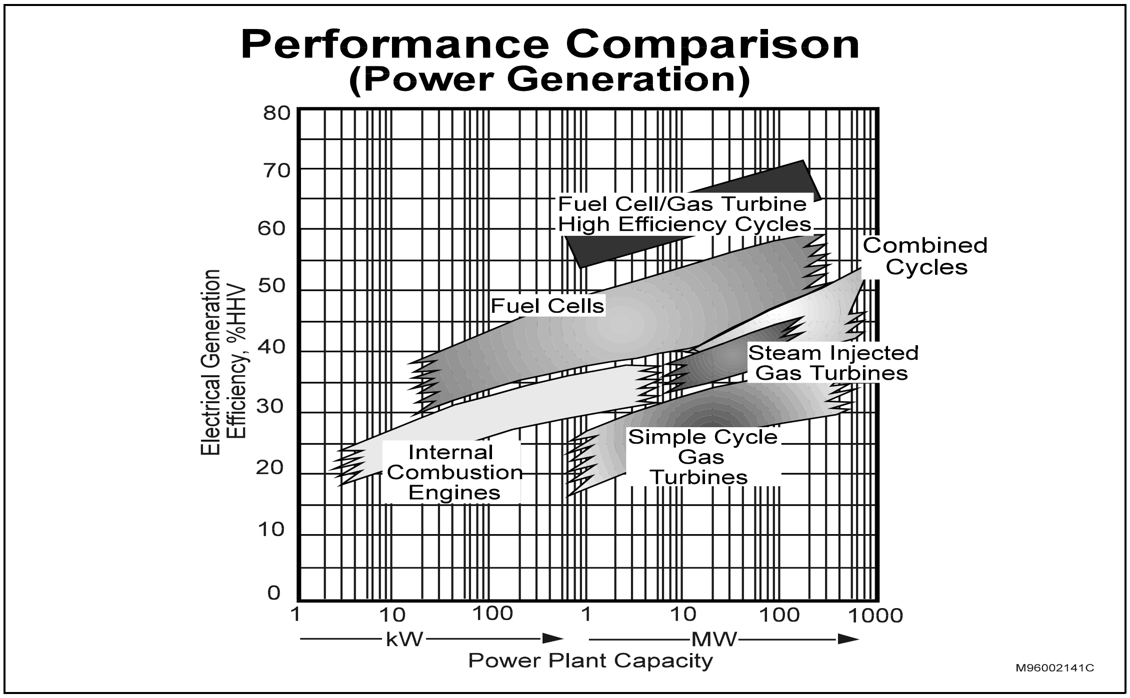


Figure 2. Powerplant Efficiencies

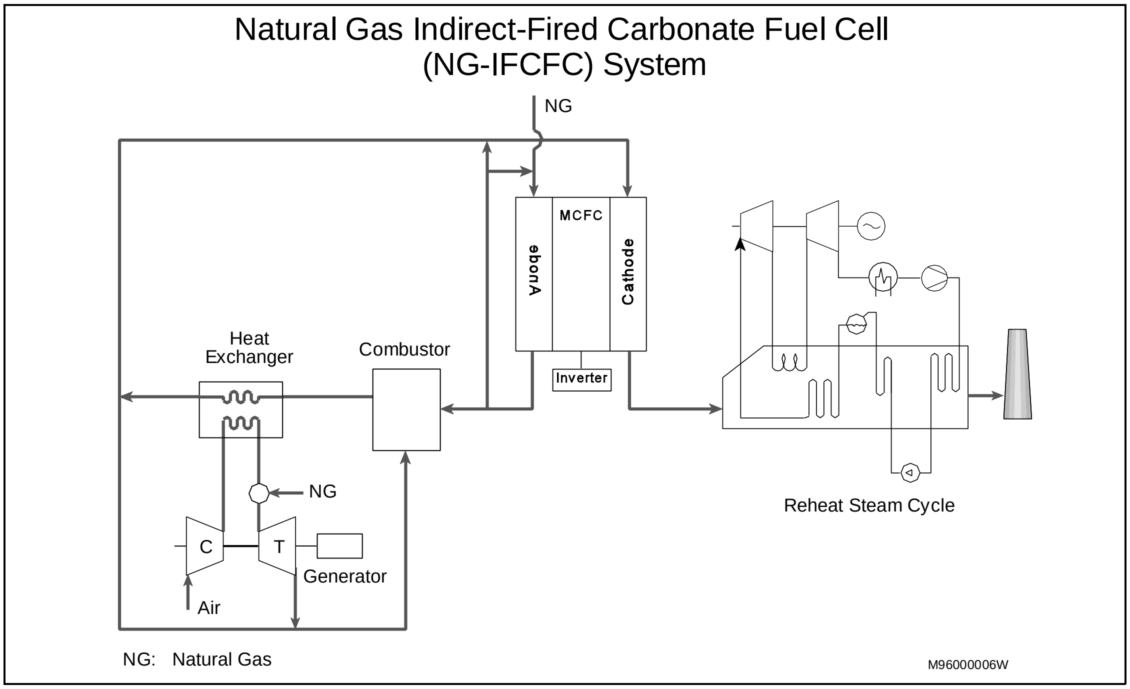


Figure 3. Indirect CFC Powerplant

Another configuration is the fuel cell topper shown in Figure 4. By allowing the fuel cell in this powerplant to serve as the combustor for the gas turbine and the gas turbine to serve as the balance of plant for the fuel cells, the combined efficiency is raised to the 60 percent range, even at sizes of less than 3 to 10 MW, and NO_x emissions are essentially eliminated.

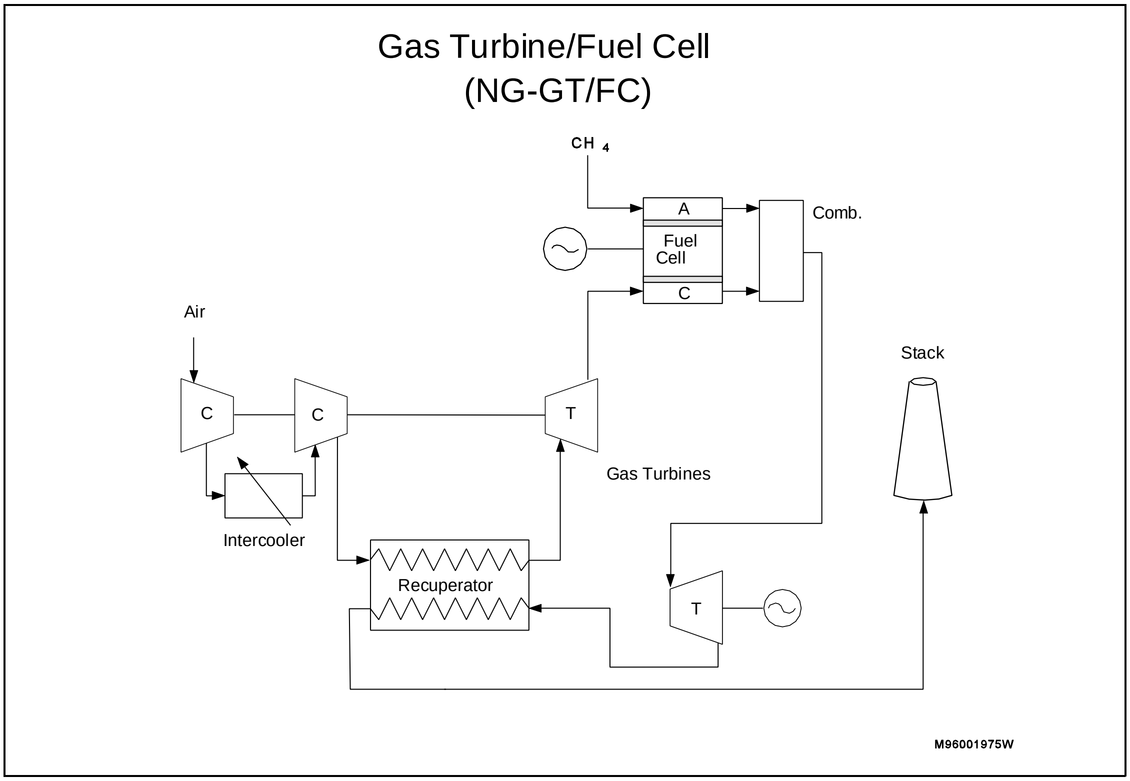


Figure 4. Fuel Cell Topper

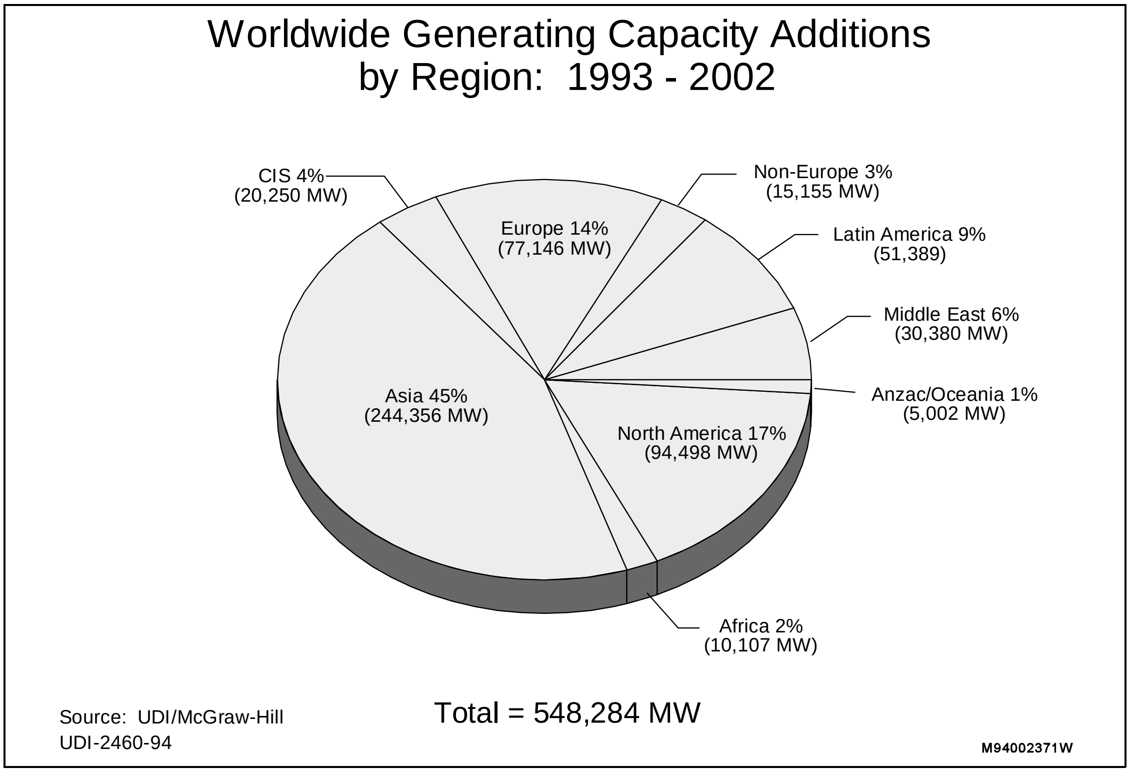
The capital cost of the combined powerplants is expected to be markedly reduced relative to the cost of a stand-alone CFC powerplant of that size and equal to or less than a gas turbine powerplant of that size.

If the early efforts are successful in commercializing these combination cycle products, the foundation will be laid for scaling up the technology to large-scale powerplants. This is important, in that the combination at the scale of 200 MW or more can achieve efficiencies of 75 percent. This is significantly higher, relative to other technologies for generating electricity from natural gas, and as a result, has the potential to significantly reduce carbon dioxide emissions. In comparison, the best currently available, large-scale, gas-fired, combined-cycle powerplants have an efficiency of about 58 percent. That level will likely increase to 60 to 62 percent over the next decade.

Potential CFC World Power Markets

By the year 2010, it is estimated that approximately 130 gigawatts (GW) of new generating capacity will be installed in the U.S., while in world markets and within a much closer timeframe, nearly 550 GW of generating capacity will be added (30). CFC commercialization opportunities in the U.S. market are focused in several areas: repowering, central powerplants, industrial generators, and commercial/residential generators.

As shown in Figure 5, the worldwide market for additional electric generation capacity dwarfs the domestic market. Nearly 550,000 MW of new capacity will be added by 2002. Estimates of plant repowering installations between 1999 and 2010 range from 15 percent to approximately 65 percent of the installed generating capacity. Most repowering will occur in central powerplants: CFC installations of 100 MW or more are targeted to this market, powered initially by natural gas and later by coal gas.


Worldwide Generating Capacity Additions by Region: 1993 - 2002

Total = 548,284 MW

Source: UDI/McGraw-Hill
UDI-2460-94

Figure 5. World Power Market

New generating capacity of approximately 100 GW will be required in the central powering market by 2010. Coal gas-powered CFC powerplants are targeted to this market, with plants sized at 100 MW or more.

The market for additional industrial capacity by 2010 is estimated at 3 GW, and the market for additional commercial/residential capacity at 6 GW. These markets are targeted for early entry and will be a proving ground for natural gas CFC powerplants sized from 500 kW to 20 MW.

Distributed Generation Markets

CFC powerplants should play a role in distributed generation applications. Areas of environmental constraints, high electric costs, poor transmission and distribution assets, and low-cost natural gas cost favor the use of CFC's in distributed generation applications (31-33). DOE, GRI, and EPRI have realized the importance of this market and are encouraging development of technologies responsive to them. Large-scale plants will compete in the baseload power generation market, while smaller plants will penetrate the distributed power and on-site generation markets (Figure 6).

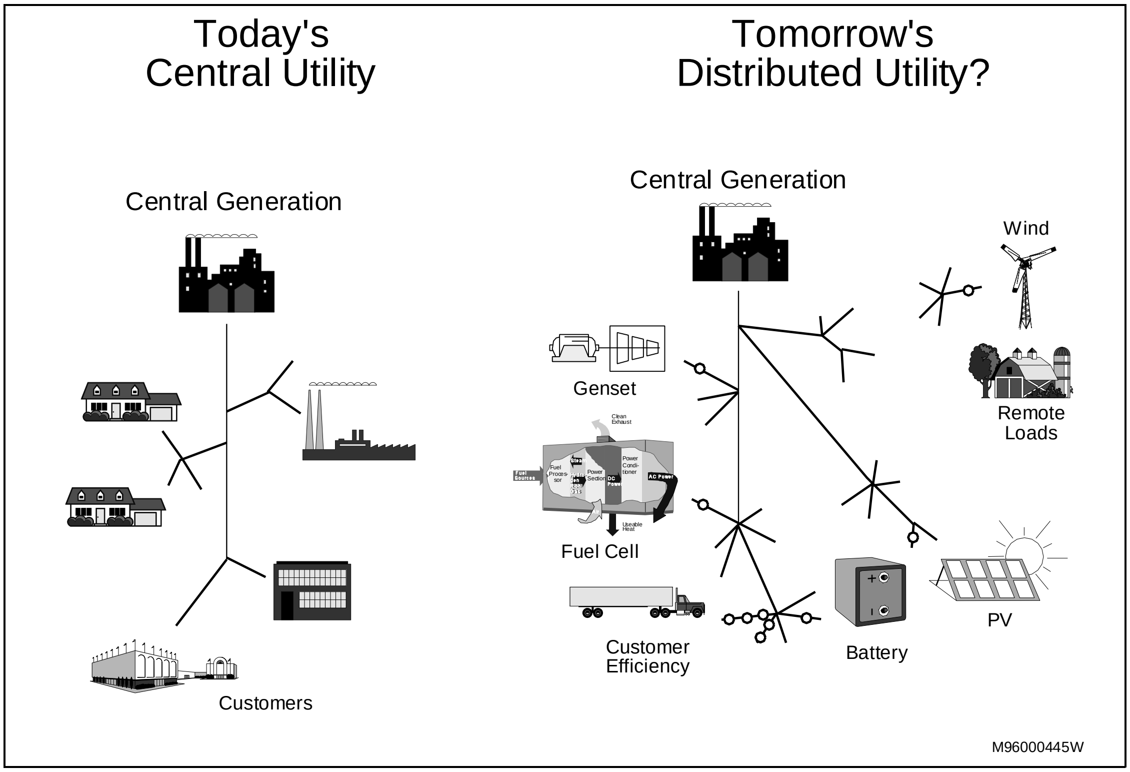
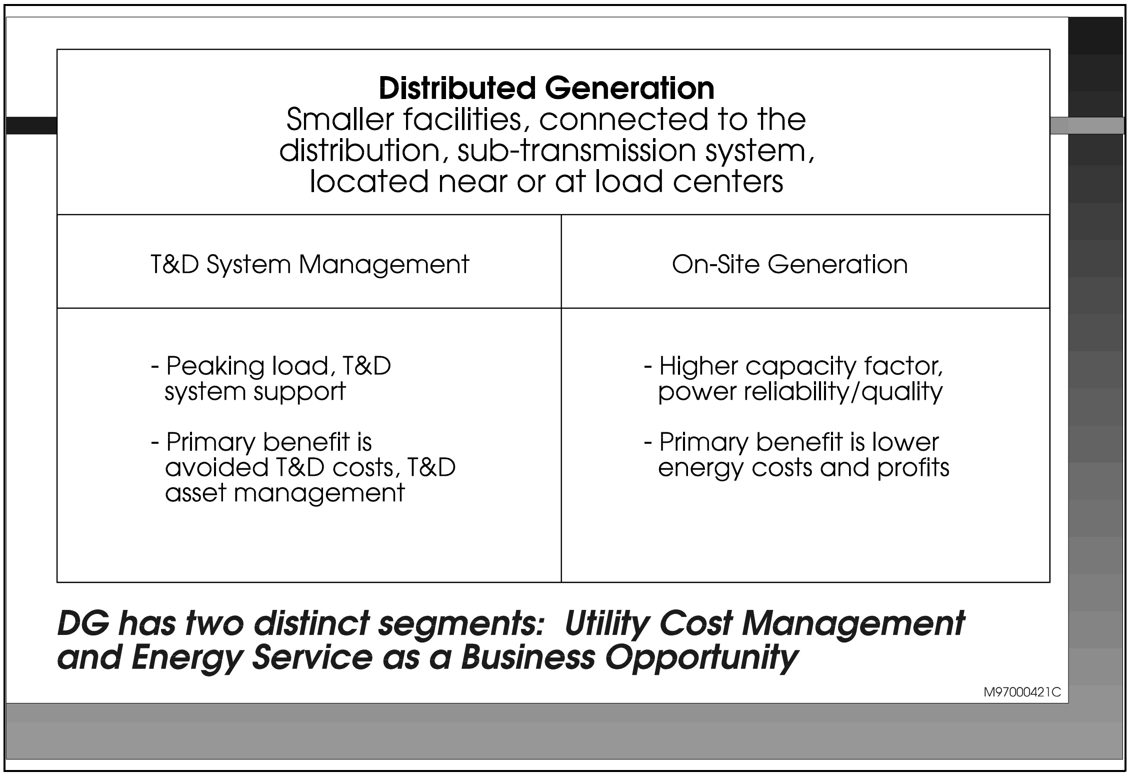


Figure 6. Central and Distributed Generation

GRI has identified (34) two distinct distributed generation market segments (Figure 7)--the utility transmission and distribution cost management and energy service. Many organizations have a stake in the future of distributed generation. Electric utilities will be able to avoid transmission and distribution costs, and energy service



Distributed Generation
Smaller facilities, connected to the
distribution, sub-transmission system,
located near or at load centers

T&D System Management	On-Site Generation
- Peaking load, T&D system support - Primary benefit is avoided T&D costs, T&D asset management	- Higher capacity factor, power reliability/quality - Primary benefit is lower energy costs and profits

DG has two distinct segments: Utility Cost Management and Energy Service as a Business Opportunity

M97000421C

Figure 7. Distributed Generation Segments

companies will be able to provide better quality service with on-site generation using CFC and other powerplants.

Fuel cells have many attributes which make them suitable for distributed generation applications (33). These include low emissions, high efficiency, production of high-grade waste heat, modularity, reliability, unmanned operation, and fuel flexibility, to name a few. These smaller applications favor CFC's for their high-efficiency, low-emission, and load-following capabilities. In addition, the attractiveness of economical and reliable on-site power generation may significantly expand the market for small-scale commercial and industrial powerplants. The Clean Air Act mandates significantly reduced emissions of sulfur and nitrogen compounds from existing powerplants and sets strict limits on emissions from new sources. In the short term, these restrictions may encourage the use of under-utilized fuels, particularly natural gas, by electric power producers.

The modular nature of fuel cells allows power capacity to be added wherever it is needed. In the typical central power configuration, additional capacity is sited at the central plant or at substations. In a distributed generation application, capacity is placed close to the demand. In high-growth or remote areas, distributed placement offsets the high costs of acquiring rights-of-way and installing transmission and distribution lines. A distributed configuration also eases public concerns about exposure to electromagnetic fields from high-voltage lines.

Smaller-scale distributed configuration powerplants are perfect for commercial buildings, prisons, factories, hospitals, telephone switching facilities, hotels, schools, and other facilities. In these applications, consumers get the best of all worlds--high-quality power that is economical and reliable. On-site power conditioning eliminates the voltage spikes and harmonic distortion typical of utility grid power, making fuel cell powerplants suitable even for sensitive electronic loads like computers and hospital equipment, and in many cases, utility grid backup reduces the need for expensive uninterruptible power supply systems.

Many factors will influence the emergence of distributed generation markets. Siteability, regulations, the Clean Air Act, regulatory uncertainty, integrability of technologies with the electric grid, and a general lack of information and end-user experience regarding distributed generation applications all will play a role in the extent to which it proceeds and CFC technology penetrates the market.

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