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Proceedings of the Workshop on Very High Efficiency Fuel Cell/Gas Turbine Power Cycles

Mark C. Williams
Charles M. Zeh

October 1995

U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

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Proceedings of the Workshop on Very High Efficiency Fuel Cell/Gas Turbine Power Cycles

Technical Coordinators
Mark C. Williams
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Sponsored by

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October 19, 1995

Foreword

The First Workshop on Very High Efficiency Fuel Cell/Gas Turbine Cycles was held October 19, 1995, at the Morgantown Energy Technology Center (METC) in Morgantown, West Virginia. About 75 persons attended this workshop, which was sponsored by the Office of Fossil Energy, U.S. Department of Energy (DOE). The meeting was hosted at METC in conjunction with the Advanced Turbine System Annual Program Review Meeting. The goals of the turbine and fuel cell programs are to develop cleaner, more efficient, and less expensive power systems for utility and industrial electric power generation and cogeneration applications.

This workshop was attended by engineers, scientists, and others in industry, academia, and Government interested in the new fuel cell/gas turbine cycles. The workshop was facilitated by Ronald H. Wolk. The purpose of the workshop was to provide a forum for the exchange of ideas and discussion of results and future plans related to research on these new cycles. Results of these discussions are reflected in this document.

The papers printed in this document have been produced from camera-ready manuscripts or electronic files submitted by the authors. They have been neither refereed nor extensively edited.

Conference Technical Coordinators:

Mark C. Williams
Charles M. Zeh

Contents

Executive Summary

The U.S. Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) held a workshop on October 19, 1995, to explore the subject of Very High Efficiency Fuel Cell/Gas Turbine Power Plants. The purpose of the workshop was to bring together a broad cross section of knowledgeable people to discuss the potential benefits, markets, and development costs associated with bringing this new technology to the commercial marketplace. The combination of these two technologies has the potential for enormous synergies in that it offers a solution to two important problems: the low efficiency and relatively high nitrogen oxides (NO_X) emissions of small gas turbines, and the high cost of small fuel-cell power plants.

Small gas turbines, with capacities of less than 10 megawatts (MW), typically have efficiencies in the 25 to 30 percent range. Small fuel cells are predicted to cost $1,000 to 1,500 per kilowatt (kW) when commercially available in the years after 2000. By combining the two systems and in effect allowing the fuel cell 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 58 to 63 percent range, NO_X emissions are essentially eliminated, and the capital cost of the combined system is markedly reduced relative to the cost of a stand-alone power plant of either type.

If the early efforts are successful in commercializing these products, the foundation will be laid for scaling up the technology to large-scale power plants. This is important since the combination, at the scale of 200 MW or more, can achieve efficiencies of 75 percent or more. This is significantly higher than other technologies for generating electricity from natural gas. As a result, carbon dioxide (CO_2) emissions could also be significantly reduced. In comparison, the best currently available, large scale, combined-cycle power plants have an efficiency of about 58 percent. That level will likely increase to 60 to 62 percent over the next decade, as a result of the Advanced Turbine System (ATS) program sponsored by DOE. The highest efficiencies currently projected for several fuel cell technologies, which are now under development, are in the range of 55 to 65 percent for stand-alone, fuel-cell power plants.

The participants in the workshop included representatives from DOE, The Electric Power Research Institute (EPRI), The Gas Research Institute (GRI), gas and electric utilities, environmental organizations, gas turbine and fuel cell vendors, and other interested parties.

In order to convey the current state of technology to this diverse audience, seven formal presentations were given (see Technical Presentations). The presentations focused on the cycle analysis studies that have been done as well as suggestions from gas turbine and fuel cell vendors on how to arrange these components in practical and reliable configurations. In addition, the speakers provided their insights in regard to potential markets for the technology, the timing of those markets, and the size of units for those markets.

Larry Rath of METC summarized recent METC results on the analysis of a number of cycles that utilized various combinations of gas turbines and fuel cells. Dave Archer of Carnegie Mellon University provided insights into the characteristics of the various systems and recommendations for development of smaller sized products. Harry Moorehead of Westinghouse announced a new product line, which Westinghouse plans to offer beginning in 1999, in the 3- to 20-MW range. These units will utilize tubular solid oxide fuel cells (SOFCs) as the combustors for gas turbines. George Steinfeld of Energy Research Corporation presented their analytical work on 20 and 200 MW systems that utilize molten carbonate fuel cells (MCFCs) as a bottoming cycle for advanced gas turbines. The larger unit requires a high-temperature, ceramic heat exchanger to transfer heat. David White of Solar Gas Turbines discussed how they envision utilizing their current line of smaller gas turbine components together with planar SOFC units. Dan Nathanson of Ztek discussed their plans to utilize their planar SOFC system as a combustor for a gas turbine. Terry Knickerbocker of Allison discussed how they envision putting their line of small gas turbines together with fuel cells.

The various generic configurations and efficiencies which are possible for large, natural gas-fired power plants in the range of 300 to 1000 MW are shown in Table 1. Typical ratios of fuel cell power to gas turbine power for power plants are in the range of 1.5-3 to 1. Therefore, combination power plants that utilize very large high efficiency gas turbines, such as the ATS machines, will be in the upper end of the size range cited.

Table 1. Efficiencies of Large-Scale Natural Gas-Fired Power Plants

Technology Configuration	Efficiency Percent LHV	Efficiency Percent HHV
GTCC Utility-Size Gas Turbine - HRSSC	56	61
ATS Utility-Size Advance Gas Turbine - HRSG	62	56
SOFC Steam-Turbine Fuel Cell - HRSG	63	58
MCFC Steam-Turbine Fuel Cell - HRSG	65	60
I-MCFC-CC GT Fuel-Cell - HRSG (includes high-temperature heat exchanger)	74	67
SOFC-CC Fuel Cell-GT-HRSG	74	67

The vendors that spoke at the conference reported that they see potentially attractive markets for smaller power plants, in the range of 1 to 20 MW, which would utilize existing, smaller, lower-temperature gas turbines. While the efficiencies that would be obtained are significantly lower than those of the larger systems noted above, they appear to be competitive with other power plants in this size range, including small stand-alone combined cycles and fuel cells. The synergy resulting from combining the two systems appears to be beneficial. Information provided to the audience is summarized in Table 2.

Table 2. Mature Price Targets for Smaller Power Plants

Vendor	Product Size, MW	Efficiency LHV	Fuel Cell	Gas Turbine	Availability	Mature Price Target, $/kW
Westinghouse	3, 10, 20	60-62	Tubular SOFC	Allison	1999	1200-800
Solar	1-2	58-63	Planar SOFC	Turbo-expander	2004	<650
ERC	20; 200	65	Direct MCFC	Unspecified	2001	1022; 974
Ztek	sub- to multi-MW	<70 at <1-10 MW	Planar SOFC	Unspecified	>2000	<900
Allison	10-25	59-62	Unspecified	Allison 501-KB/KM or ATS	ATS engine in 1998-2002	425-450 for engine only

Following the seven presentations, participants divided into five groups to discuss each of the nine questions presented below.

1. What are the potential driving forces that make it desirable to invest significant funds to develop this technology for very high efficiency power generation? Consider (a) as a response to CO_2 buildup in the atmosphere, (b) to reduce the rate of depletion of fossil fuels, (c) as a new competitive approach for generation, and (d) to provide policy options to Government planners.

2. What are the potential market niches for this technology? What is the size of each of these niches as a function of date? What are the product cost goals for each of these niches? Consider distributed power systems smaller than 20 to 50 MW, central station systems larger than 200 MW, and others.

3. What are the key technical issues that must be resolved to insure feasibility? What is the probability of success? Consider (a) identification of basic research information that must be collected to support development programs; (b) identification and evaluation of optimum systems; (c) necessary adaptations for fuel cell components (e.g., fuel cell configurations); (d) necessary adaptations for gas turbine components; and (e) system integration issues.

4. To which stage (feasibility, demonstration, or commercialization) of technology development should support be provided?

5. What is a reasonable range for the estimated costs of each phase (research, development, demonstration, and commercialization) of this program?

6. What is the estimated date of availability of products as a function of size?

7. Can traditional rivals, the fuel cell and gas turbine communities, work together on this program?

8. Who are the potential financial supporters of this program (vendors, utilities, Government, United States, overseas)?

9. What are your recommendations for an action plan for METC to consider for this technology?

After the entire body reassembled, each group reported its responses to the questions. The entire body then was able to develop a consensus on the questions in a fairly rapid manner. Their conclusions were as follows:

Drivers

The technology should be developed to meet a verifiable market need and not for public policy reasons.

Public policy drivers, such as CO_2 reduction and fossil fuel conservation, are not important considerations at this time. They may emerge later if laws that restrict or tax CO_2 emissions are passed.

Market Niches

The vendor community appears to have thought out the potential markets for these products. Units in the range of 1 to 20 MW with 60 percent efficiency appear to have an attractive market in the 2000 to 2010 time frame. One vendor, Westinghouse, is working with a focus group of utilities to define the specifications for a product of interest.

The Distributed Generation (DG) market is favored because:

- The smaller plant size reduces initial investment cost and therefore risk.
- This product offers strong competition to other DG options.
- Demonstrating the technology at small size will help build the confidence of potential buyers in the performance and reliability of the technology.
- The ability to make modifications or technical changes in a small plant is easier and less expensive than in a large plant.

Markets for large (>200 MW) central station plants with efficiencies of 75 percent or more may emerge after the year 2010, if the technology is proven to be reliable at a DG scale.

High efficiency power production at remote sites where fuel is expensive or difficult to obtain represents an important market niche.

Key Technical Issues

Fuel cell cost and durability are the leading technical issues that must be resolved. Current DOE programs are focused on these issues. The size of current fuel-cell products in the development and demonstration phase at this time would meet the requirements of the combined product in the 2000 to 2005 time frame.

Integration and control of the combined system is an issue that can only be resolved through field experience. Smaller scale operation in distributed generation units would provide the needed information.

Further development of recuperators and high-temperature, ceramic heat exchangers is required for specific cycles.

Appropriate Support

There was reasonable consensus that DOE support would be most valuable in the near future, for funding additional technical feasibility and market penetration studies.

Significant cost-shared support to resolve key technical issues was recommended to continue to a point somewhere between completion of the development and demonstration phases. Support for actual commercialization was seen as inappropriate for Government, and to be the responsibility of the private sector.

Estimated Program Cost

The overall financial requirement for the program is uncertain because different vendors are at different stages in the development cycle, with several having made substantial investments already. There was no consensus on the likely cost of a program to bring the technology to the point of commercialization. However, it was generally agreed that the cost would exceed $100 million.

Timing of Product Availability

Two vendors, Westinghouse and Solar, announced plans for having products in the 1- to 20-MW range by the year 2000, assuming that sufficient funding from private and Government sources was available to support the effort. Other vendors thought that they could have products available in this size range in the period of 2000 to 2010.

Ability of Vendors to Work Together

The consensus was that vendors in the gas turbine and fuel cell communities can work together. Based on the work done to date, it was apparent that both communities had identified synergies that could expand their individual product markets.

Potential Sources of Financial Support

The consensus for a successful approach to funding this development was a partnership between DOE and the private sector, with the proportion of private-sector funding increasing as the technology proceeded through the traditional research, development, and demonstration phases.

As a result of the restructuring of the electricity industry that is now underway, there was little prospect for significant support from utilities, independent power producers, or venture capitalists.

Recommended Action Plan

Since the combination of fuel cells and gas turbines appears to offer superior efficiency to other power generation approaches as well as potentially attractive market opportunities in the near and long term, it was concluded that the DOE should begin a formal program within existing development activities to support the development of this technology.

The initial step recommended was the development of a program plan to bring this technology to the point of commercialization. The extremely successful ATS program was suggested as a model.

Economic and market studies are needed in the near term to define how these products would be positioned to compete initially in the distributed generation market, and later in the central station market. The majority of the work that has been done to date has focused on cycle performance.

Support is now needed from DOE to pay for creditable, independent, cost, and performance studies that are based on the preliminary cycle studies that have been completed.

New work in this area should be done as part of either the ATS or Fuel Cell programs, rather than by launching a major, new initiative at this time. Support for some of the technology programs required for this development could be obtained by redirecting existing developers to evaluate combined fuel cell/gas turbine systems.

Communication efforts about the promise of this technology versus market needs should be increased, so that a broad audience could be educated about the potential benefits. Those who are working in this field should present papers in the near future at gas turbine and fuel cell conferences, including the annual METC meetings in these areas, the Fuel Cell Conference, ASME Gas Turbine Conferences, Powergen, the American Power Conference, and others.

The workshop should be repeated in the near future to obtain the perspectives of the additional people who become informed about the potential of this combination of technologies.

Background Information

The U.S. Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) has been conducting studies to assess the efficiency of advanced power generation cycles that utilize combinations of fuel cells and gas turbines. These studies have indicated that this combination could increase the overall efficiency for the conversion of natural gas into electricity to over 75 percent. Successful development of these cycles would provide a new and potentially valuable option to those who develop and implement our public policy. It could be an important option in terms of dealing with the global climate change issues that are now facing the world, since higher efficiency reduces CO_2 emissions. It is also important relative to the increased use of coal, since this same cycle could be used in conjunction with coal gasification. The increased efficiency of the cycle could also significantly extend the period of use for fossil fuels.

The key components of these technologies — coal gasification, high-efficiency gas turbines, and fuel cells — are now being demonstrated or developed under current DOE funded programs, including Clean Coal Technology, Advanced Turbine Systems, and solid oxide and molten carbonate fuel cell development programs. Success in these efforts will provide the foundation upon which the new technologies could be commercialized. Many of facilities that currently exist, or are now under construction, could be utilized for testing of key components and to demonstrate integration on a prototype scale.

The electric utility industry in the United States is in the process of restructuring itself. Changes in regulations have allowed new companies to enter the power generation business. This situation, coupled with lower-cost natural gas supplies and extremely efficient, large, combined-cycle power plants, has resulted in additional and lower cost electricity supplies being added to the market. In order to meet this new competition, electricity companies in many areas are reorganizing into separate generation, transmission, and distribution companies. Competition in all aspects of the business is becoming the reality. This situation will open up the market for new products that could be used by either current electricity customers as well as those now providing generation or distribution services. Small-scale distributed generation equipment may become competitive at many locations. This new market could be served by new high-efficiency products based on combinations of fuel cells and gas turbines.

Interest in these very high efficiency cycles is developing in many countries around the world. Evaluation work is now under way in Japan, Netherlands, Great Britain, Denmark, Germany, and certainly in other places as well. In several of these countries, the interest is driven by lack of indigenous fossil fuel resources and a desire to reduce the cost of their imported fuel supplies. In others, the driver is to develop new ways to limit CO_2 emissions. Increased efficiency is the simplest way to do that. Therefore, cycles that can generate electricity at 75 percent or higher efficiency are of great interest.

The major development challenges that must be overcome in bringing this technology to commercialization are primarily associated with the fuel cells that would be utilized in these cycles. The majority of the power generated in these cycles, on the order of 60 to 75 percent, comes from the fuel cells. Currently, demonstrations of a number of fuel cell power plants are planned on the schedule shown in Table 3:

Table 3. Schedule of Fuel-Cell Power-Plant Demonstrations

Company	Technology Demonstration Size kW	Start-up
ERC	Internal Reforming MCFC -- 2,000	1996
MC-Power	External Reforming MCFC -- 250	1996
Westinghouse	Tubular SOFC -- 100	1996
Ztek	Planar SOFC -- 25	1997

Since the components in fuel cells are modular, scaling up the output of the fuel-cell power plant is often a matter of adding additional cells rather than increasing the size of the cells. The key challenges are in demonstrating the durability and reliability of these components for tens of thousands of hours under the rigors of actual field tests, and reducing their cost. Currently, fuel cell stacks and components are manufactured in relatively small pilot facilities with production capacities of less than 10 MW per year. This means the cost is extremely high compared to market requirements. One of the key challenges facing fuel-cell development organizations is the problem of production volume as a function of cost. Studies of the manufacturing costs for fuel-cell stacks indicate that raw material and manufacturing costs are in the range of $200 to 300/kW for production volumes of 100 to 400 MW per year. An investment of hundreds of millions of dollars is required to build a factory of that size. However, since current sale prices are usually based on current manufacturing costs, it is difficult to increase demand to the level that would support the assumption of the large investment risk for the factory. Therefore, the dilemma facing the vendors is to determine whether and when to take on the risk of a large investment to build a production facility of the required size to reduce their product costs to a level consistent with market requirements.

Existing gas turbine products will integrate well with the fuel-cell products that will result from the demonstrations that are now scheduled and are likely to become available in the period of 2000 to 2005. The large ATS gas turbines will be introduced to the market in that same period. If the initial fuel cell/gas turbine products that are now proposed in the 1 to 20 MW range for introduction in the 2000 to 2005 period are successful, the foundation will be laid for larger products utilizing advanced gas turbines after 2005.

Development of Participant Consensus

Seven technical presentations gave the participants a comprehensive overview of the work that had been done in the United States. Then, the participants were divided into five groups to discuss each of the nine questions listed in the summary. A Facilitator and Scribe worked with each group to make sure that each of the questions was thoroughly discussed and the consensus view of the group was captured. After the participants reassembled, each Scribe reported the responses of the group to the body. The body was then asked by the Workshop Facilitator to comment on a straw-man consensus response proposed by the Facilitator, which in his view represented the consensus view of the five groups. Since the reports of the individual groups were reasonably consistent, it was possible to modify the proposed straw-man responses within a fairly short period, and to achieve a set of responses that satisfied the group. These consensus views were reported in the Executive Summary of this report and will not be repeated here.

The reports of the five individual groups are presented below. Responses provided by each individual group to the individual questions are designated by the letters A, B, C, D, and E in the information provided below each question.

1. What are the potential driving forces that make it desirable to invest significant funds to develop this technology for very high efficiency power generation? Consider (a) as a response to CO_2 buildup in the atmosphere, (b) to reduce the rate of depletion of fossil fuels, (c) as a new competitive approach for generation, and (d) to provide policy options to Government planners.

Competition

Group A End-customer needs include (1) above all else, reliable generation; (2) low life-cycle cost; (3) ability to finance a project; (4) reasonable return on the investment, commensurate with risk; and (5) must be competitive with existing options.

Group B Competitive utility market: commercial and retail levels, low capital cost, less value for efficiency, and cost of electricity (COE) - near-term and long-term effects.

Group C Near term: competitive cost of electricity.

Group D Rephrase: Assume, besides funding, what other issues (e.g., competition, and higher future fuel prices) are critical to cause this to go forward?

Group E New competitive approach: COE costs; capital costs.

Emissions

Group C Near term: emission control; long term: CO_2 reduction and control.

Group D Gas turbine emissions today not low enough for international market? Gas turbine future alone should be acceptable.

Group E Environmental: best NO_X performance; regulations; large power plant permits not renewed. Distributed generation opportunities: non attainment areas.

Policy

Group A NOT for policy interests.

Group B Invest to broaden product line.

2. What are the potential market niches for this technology? What is the size of each of these niches as a function of date? What are the product cost goals for each of these niches? Consider distributed power systems smaller than 20 to 50 MW, central station systems larger than 200 MW, and others.

Group A The following table also answers question no. 6.

Potential Market Niches for First Commercial Units

Time Frame	Applications	Capacity
Near-term (< 10 years)	Cogen. & Dist. Power	app. 5 to 20 MW
Mid-term	Cogen. & Dist. Power	20 to 50 MW
Long-term	Central, Dist. & Cogen. Power	< 50 MW

Group B Distributed power (near term; i.e, 5 to 10 years) = < 20 MW (including co-generation); 2005 to 2010 = < 20 percent of market. The combination of FC/GT allows larger size applications (multi-MW). Longer term = 100+ MW systems may occur after distributed generation creates commercial products. Year 2010+ = 80 percent or more of market. The niche is the international market.

Group C Near term: customer-owned generation — industrial markets, large commercial, military bases, nonattainment areas; utility owned distributed generation. Long term: central stations, distributed power (in nonattainment areas) = 1 MW size, Far East "downwind of China" = 50 MW or larger (later). Cost goal is dependent upon price of electricity to user. Other factors: 4 to 1 turndown is valuable.

Group E Remote locations: 1 to 3 MW located on-site and/or at end-of-line. DoD applications = <1 MW. About 20 MW distributed-power market. Avoid large market (high risk, least $/kW). 50 to 150 MW biomass viable.

3. What are the key technical issues that must be resolved to insure feasibility? What is the probability of success? Consider (a) identification of basic research information that must be collected to support development programs; (b) identification and evaluation of optimum systems; (c) necessary adaptations for fuel cell components (e.g., fuel cell configurations); (d) necessary adaptations for gas turbine components; and (e) system integration issues.

Fuel Cell

Group A Low cost, high-volume manufacturing of fuel cells.

Group B "Gotta Make the Fuel Cell Work" (RAM, Cost). Pressurization; high temperature seals.

Group C Cost reduction of fuel cell. Demonstration of fuel cell hardware durability and performance. Packaging, pressurized operations, operating transitions. Sulfur tolerance. Fuel cell failure modes. Potassium transport from fuel cell.

Group D Prove fuel cell reliability: demonstrate life; improved sulfur tolerance or lower cost cleanup; improved materials - improved thermal cyclability; lower cost; and higher temperature operating cost reduction key.

Group E Fuel cell reliability. High temperature fuel cell material issues (1800 °F).

System

Group A System reliability and operability: (1) startup, (2) matching loads, and (3) system upsets.

Group C Hardware integration. System optimization studies. Dual fuel capability. Footprint.

Group E System integration (i.e., Start up combustor).

High Temperature Heat Exchanger

Group A High temperature (1500 to 1800 °F) heat exchanger (ceramics).

Group B High temperature heat exchanger for some applications.

Group D Improved heat exchanger materials (for indirect fuel cells).

Gas Turbine

Group B Availability of gas turbine equipment: ability to integrate with fuel cell (temperature, pressure ratio); recuperation (>100 MW); intercooling.

Group C Turbine modifications; combustor developments for lean fuels.

Group E High temperature combustor and fuel system (>1600 °F).

4. To which stage (feasibility, demonstration, or commercialization) of technology development, should support be provided?

Group A Heavy Government investments for rapid demonstration of feasibility. Moderate to heavy, cost-shared Government investments in demonstrations. Minimum Government subsidies for commercialization.

Group B DOE and others provide support through demonstration. End user participation ("for public good") in Demo will become less in the future; may be more willing if business potential is there. Partnership; risk sharing.

Group C DOE funding will accelerate commercial availability. DOE support should continue to somewhere between the development and demonstration phases.

Group E All stages required: feasibility, demonstration, commercialization, currently in feasibility stage, and some components in demonstration.

5. What is a reasonable range for the estimated costs of each phase (research, development, demonstration, and commercialization) of this program?

Group B Big program = $100 million; jointly shared.

Group C $125 to $250 million of forward costs for commercial product availability.

Group E Combined costs for 1-3 MW for research, development, and demonstration: $60 to 400 million subsidy; commercialization required; planar higher cost, and carbonate lower.

6. What is the estimated date of availability of products as a function of size?

Group B See response to question no. 2. Commercial orders accepted: SOFC 1999+ (3,5, 10 MW); MCFC 1996-97 (110) turbo-charged system.

Group C 2005-2010 with Government support for delivery of products on normal commercial terms; < 10 MW size.

Group D 1-10 MW by 2000 (60 percent efficiency). 1-10 MW by 2004 (70 percent efficiency), assuming: timeliness and support, cost acceptable, and market pull is an issue.

Group E Tubular: 1999 at 1-3 MW; 2000 at 20-50 MW. Planar: 2001 at 1-3 MW; 2004 at all sizes. Must be in market by year 2000. Electrification/distributed power has a narrow window: U.S — Urban Market; and Foreign — Rural Market.

7. Can traditional rivals, the fuel cell and gas turbine communities, work together on this program?

Group A They have to work together in order to sell these systems: (1) customers want to deal with a single source of responsibility for the tandem system (A&E, packager); and (2) companies exist that handle both fuel cells and gas turbines.

Group B "We already are."

Group C Yes, with some exceptions at the CEO level.

Group D Yes -- 11, no -- 0, undecided -- 5.

Group E Yes, the program will help the entire industry. Westinghouse does not make small gas turbines. Solar rivalry, non-existent. Improve already good cooperation. Break DOE stovepipe.

8. Who are the potential financial supporters of this program (vendors, utilities, Government, United States, Overseas?

Vendors

Group A Vendors - later significant funding must come from vendors.

Group B Manufacturers - feasibility to commercialization (fuel cells and gas turbines). Utilities and IPPs - business opportunity will determine support.

Group C Vendors would continue traditional level of funding.

Group D Vendors -- <50 percent.

Group E Manufacturers -- Yes.

Governments

Group A Federal and State Government: initial funding must come from Government. In order to get private investment: Government should be the first market; Government should encourage export through credits and trade shows; and inform potential investors (via seminars, conferences) about this technology in terms they can understand.

Group B Government -- through demonstration.

Group C Major support required from DOE.

Group D Government 50-percent funding (optimistic).

Group E National labs -- no; DoD/ARPA -- yes.

Utilities

Group A Utilities.

Group D Utilities (outside of EPRI, the likelihood is 0 percent).

Group E Utilities are getting out of R&D; TVA possible.

International

Group A Possible international partners.

Group B Foreign - potential source: coop program; could address international markets.

Group C Overseas governments are providing major support for internal projects.

Group E Overseas demo possible.

Industry Groups/Others

Group A EPRI; GRI.

Group D Venture capital: not today; market pull critical. Niche markets: U.S. - no; international: market pull.

Group E GRI - possible; EPRI - possible; IPP's/ENRON - not likely.

9. What are your recommendations for an action plan for METC to consider for this technology?

Planning

Group A Develop a plan similar to the Advanced Turbine Systems Program: different output ranges, efficiency goals, cost goals, and milestone goals.

Group B Develop a program: There are enough benefits and interest to put a program together. Define goals and generic and specific development objectives.

Group C Use feasibility studies to define most promising product configurations.

Group D Team leader (METC, GRI, or EPRI) required: to put the program together, to help form industrial consortium group, and to facilitate communications (such as e-mail forum).

Group E Get involved now, invent the future. Develop program like ATS or Biomass Rural Development. Possible blend with ATS with time shift (+/-). Refocusing/vectoring/coordination necessary (probably fuel cell program).

Communication

Group A Distill the results of the workshop into recommendations and distribute them to vendors, utilities, and Government entities.

Technical Feasibility and Economic Studies

Group B Evaluate realistic system in parallel with optimized cycles. Define shortest path to marketable system.

Group C DOE should fund economic feasibility studies by A&Es to develop good cost information on combined product.

Group D Keep fuel cell program on track. All systems need reduced fuel cell risk.

Group E SOFC and MCFC better candidates than phosphoric acid. All systems need reduced fuel cell risk.

Market Assessment

Group B Need to look at and get input from market (utilities, etc.). Program must be market driven!

Group D Conduct rigorous market assessment (do next year). Government, EPRI and GRI, and industry should fund. Market study should include impact of market pull, and niche markets (Utility shakeout and timeline, cost of fuel, and date of commercial and economic feasibility).

Funding

Group E New fully-funded program independent of ATS and FCs. Turbine vendors need to help lobby 104th Congress. Need program plan to present.

Technical Presentations

Configuration and Performance of Fuel-Cell Combined-Cycle Options

L.K. Rath, P.H. Le, and F.A. Sudhoff
U.S. Department of Energy
Morgantown Energy Technology Center
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Morgantown, WV 26507

Abstract

The natural gas, indirect-fired, carbonate fuel-cell-bottomed, combined cycle (NG-IFCFC) and the topping natural-gas/solid-oxide fuel-cell combined cycle (NG-SOFCCC) are introduced as novel power-plant systems for the distributed power and on-site markets in the 20-200 megawatt (MW) size range. The novel NG-IFCFC power-plant system configures the ambient pressure molten-carbonate fuel cell (MCFC) with a gas turbine, air compressor, combustor, and ceramic heat exchanger.

The topping solid-oxide fuel-cell (SOFC) combined cycle is not new. The purpose of combining a gas turbine with a fuel cell was to inject pressurized air into a high-pressure fuel cell and to reduce the size, and thereby, to reduce the cost of the fuel cell. Today, the SOFC remains pressurized, but excess chemical energy is combusted and the thermal energy is utilized by the Carnot cycle heat engine to complete the system.

ASPEN performance results indicate efficiencies and heat rates for the NG-IFCFC or NG-SOFCCC are better than conventional fuel cell or gas turbine steam-bottomed cycles, but with smaller and less expensive components. Fuel cell and gas turbine systems should not be viewed as competitors, but as an opportunity to expand to markets where neither gas turbines nor fuel cells alone would be commercially viable. Non-attainment areas are the most likely markets.

Background

Because of the abundance and relatively low cost of natural gas, gas turbine systems are well accepted in the power generation community. There are many advantages to using gas turbine systems. Nominally clean fuels are required to protect the turbine machinery, so the systems tend to also produce low pollutant levels. When bottomed with a steam turbine, the energy from the exhaust stream can be used to inexpensively produce electric or cogeneration power. In addition, gas turbines provide low maintenance and rapid startup.

There is, however, a limit to their use imposed by material properties — the temperatures needed to achieve high efficiency exceed what current materials can reasonably provide. While rapid strides have been made in the last few decades to achieve 50 to 56 percent efficiency for the lower heating value (LHV) gas turbine combined cycles, values above 62 percent appear to be difficult to achieve. Over the next 10 years, the U.S. Department of Energy's (DOE's) Morgantown Energy Technology Center (METC) will co-sponsor research on its Advanced Turbine System (ATS) Program to develop large, utility-scale units that are expected to achieve gas/steam cycle systems at 62 percent efficiency. A simple advanced gas turbine system is illustrated in Figure 1. These improvements will be made possible if new high-temperature materials are developed as planned. Such thermal systems can achieve higher efficiencies if the turbine inlet temperature is increased by approximately 150 to 200 °C. However, it will then become ever harder to meet the environmental standards because nitrogen oxide (NO_x) production tends to increase non-linearly with increases in temperature. A new breakthrough technology is needed to achieve higher efficiencies and maintain low pollutant levels. This technology is the fuel cell.

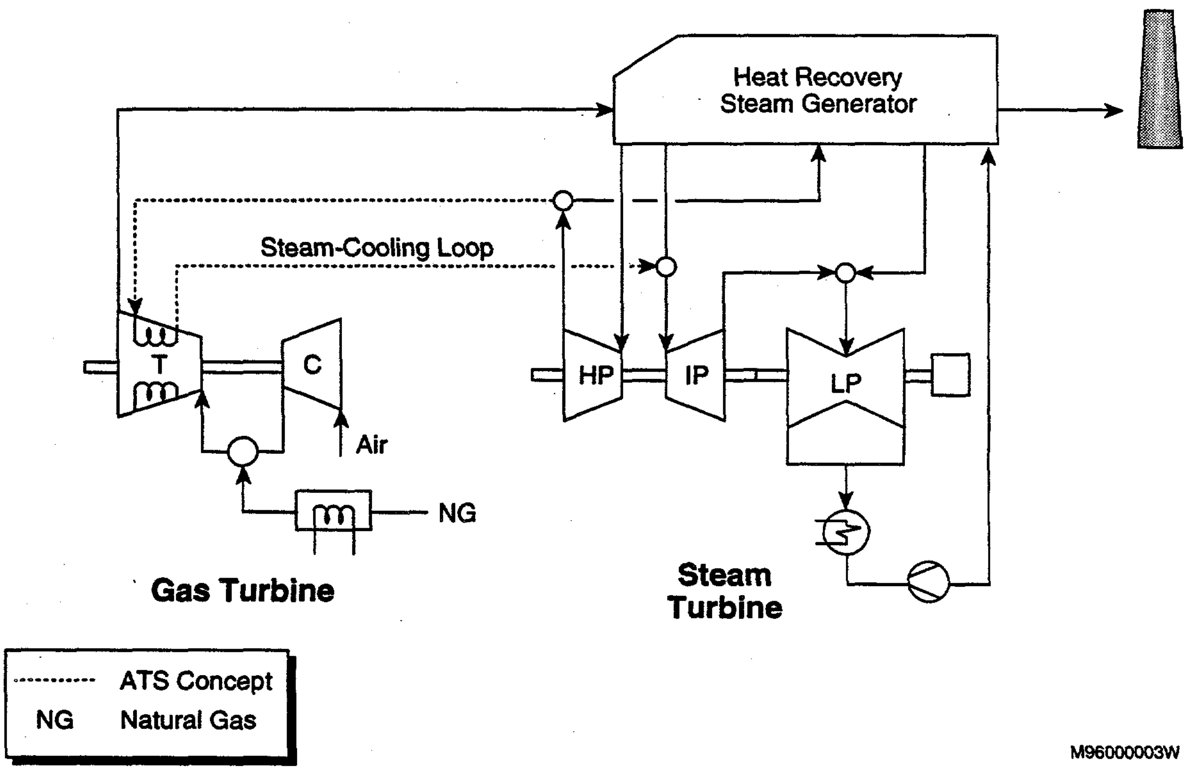

Figure 1. Simple Advanced Gas Turbine System

DOE has identified both fuel cells and advanced gas turbines as preferred sources of future electric power. DOE/METC is investigating the possibility of bringing both of these technologies together for the first time. Table 1 compares the system efficiencies of the power generation technologies discussed in this paper.

Table 1. Comparison of Power Generating Technologies

Technology	Configuration	LHV%	HHV%
GTCC uility size	gas turbine-hrsg	56	51
ATS utility size	adv. gas turb-hrsg	62	56
SOFC-ST	fuel cell-hrsg	63	58
MCFC-ST	fuel cell-hrsg	65	60
NG-IFCFC	GT-fuel cell-hrsg	74	67
NG-SOFCCC	fuel cell-GT-hrsg	74	67

Fuel-Cell Technology

The different types of fuel cell use different types of electrolytes as the principal component by which power is converted, and the type of fuel cell is named after the electrolyte. The fuel cell is a device that oxidizes fuel directly into electrical power without the enthalpy of combustion raising the temperature (Appleby and Foulkes 1989). In the MCFC, the oxidizer (air and carbon dioxide [CO_2]) passes through a semi-permeable membrane to the fuel compartment or anode where it electrochemically reacts with the fuel. Similarly, in the SOFC, the oxidizer (air) passes through a semi-permeable membrane to the anode and electrochemically reacts with the fuel. Figures 2 and 3 illustrate the basic MCFC and SOFC systems.

In the MCFCs, electrons are released at the anode/electrolyte interface by the reaction of hydrogen ions with carbonate ions. Water, CO_2, and heat are released by the anode reaction. Carbonate ions are created at the cathode/electrolyte interface by the electrochemical reaction of oxygen, CO_2, and two electrons. MCFC stack designs incorporate either internal or external manifolding. Internal and external reforming of methane to hydrogen and CO_2 are being considered in several commercialization concepts. All MCFC concepts employ flat cell components in the cell package (i.e., anode, matrix to hold carbonate, cathode, current collector, and separator plate). Energy Research Corporation and MC-POWER Corporation are leading MCFC manufacturers.

The MCFC was selected for the novel bottomer configuration because the temperature required for its operation is nominally about the same as that of the gas turbine exhaust. MCFCs operate at about 550 °C (1,050 °F), while SOFCs may operate at 1,000 °C (1,832 °F). Recognizing the synergism, we examined the possibility that the clean air exhaust

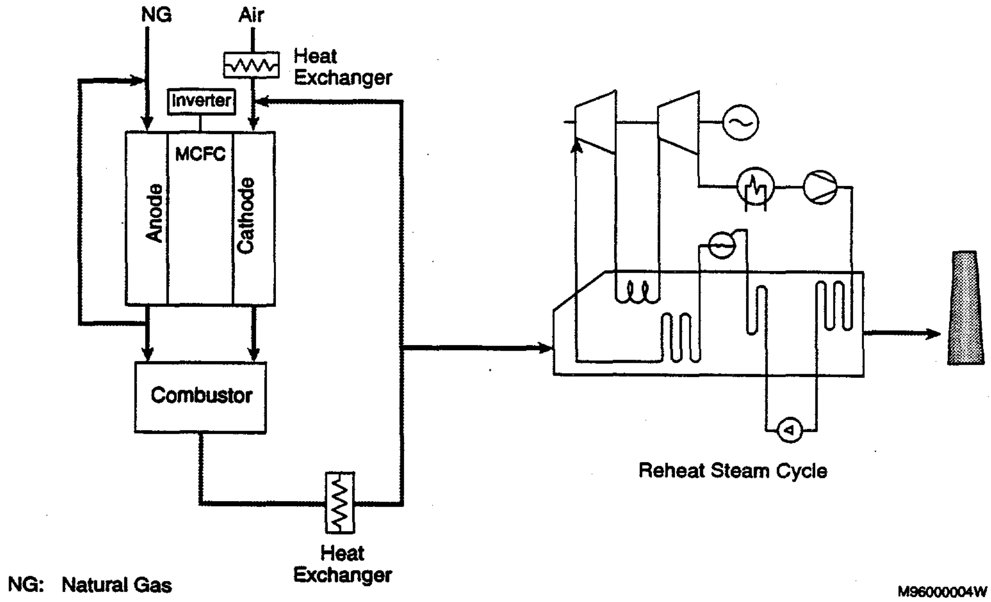

Figure 2. Basic Molten-Carbonate Fuel-Cell System

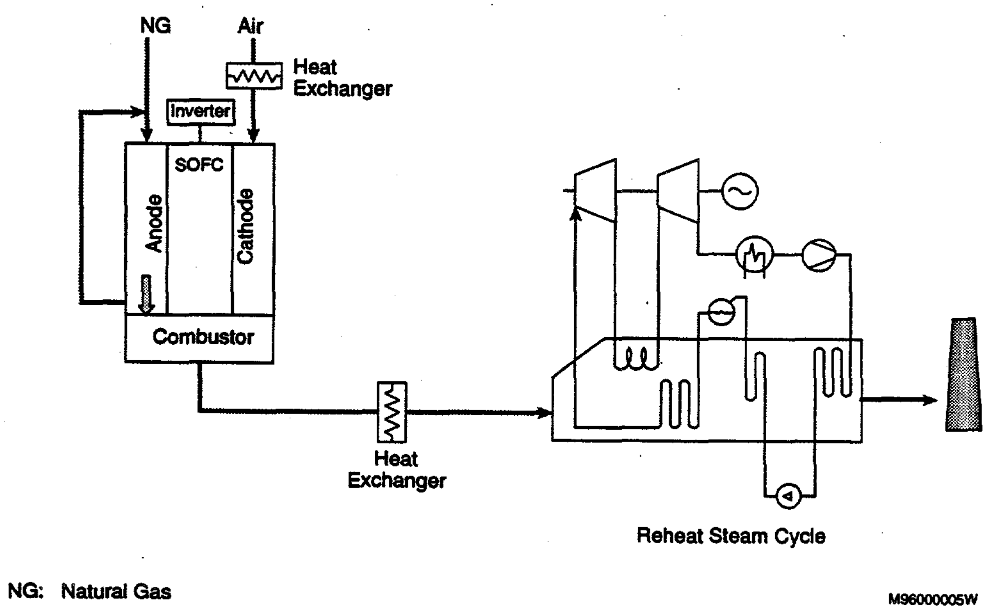

Figure 3. Basic Solid-Oxide Fuel-Cell System

from the turbine could drive the fuel cell. This would all but eliminate a need for a heat exchanger to couple the two units. Figure 4 illustrates the NG-IFCFC system.

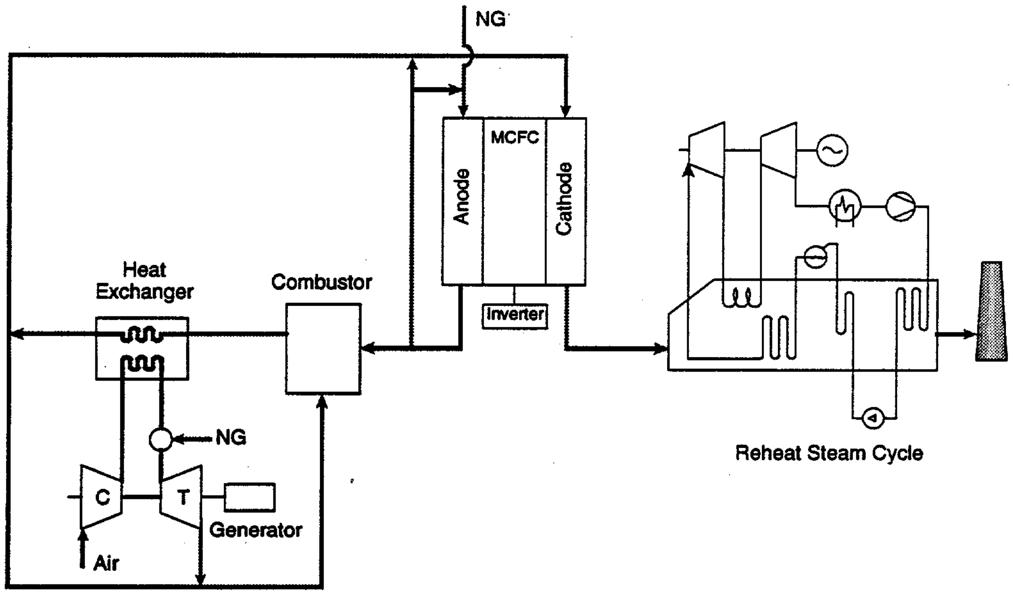

Figure 4. Natural Gas/Indirect-Fired Carbonate Fuel-Cell System

In the SOFC, electrons are released at the anode/electrolyte interface by the reaction of hydrogen and oxygen ions. Water and heat are released by the anode reaction. Oxygen ions are created at the cathode/electrolyte interface by the reaction of oxygen and two electrons. The solid state character of all SOFC components means that there is no restriction on cell configuration. Westinghouse Electric Corporation is the developer of the most common tubular bundle configuration. Ztek, Incorporated, and others are researching a flat plate or monolithic design. The SOFC can operate at pressures ranging up to 30 atmospheres. Carbon monoxide (CO) or ammonia, poisons to other fuel cells, can be used as a fuel in the SOFC.

The SOFC was selected for the topper configuration because the fuel cell operates satisfactorily under high pressure and the fuel-cell exhaust is about 1,000 °C (1,832 °F). About 50 percent of the fuel is converted to electrical energy in the SOFC. High-temperature fuel-cell exhaust drives the expansion turbine where most of the remaining chemical energy is captured. Once again, the coincidence of the synergistic effects leads to elimination of several heat exchangers. Figures 5 and 6 illustrate the NG-SOFCCC system. Slight modifications to the compressor exhaust flow stream result in a less expensive steam cycle and slightly improved system efficiency for the system shown in Figure 6.

Advantages to both types of fuel cell, such as environmental friendliness, make them the ideal power system of the future: NO_X, sulfur oxide, CO, and other pollutant exhaust products are insignificant. As attempts are made to improve the efficiency of gas turbines, ever higher temperatures will also be needed to compete with fuel-cell efficiency. These high

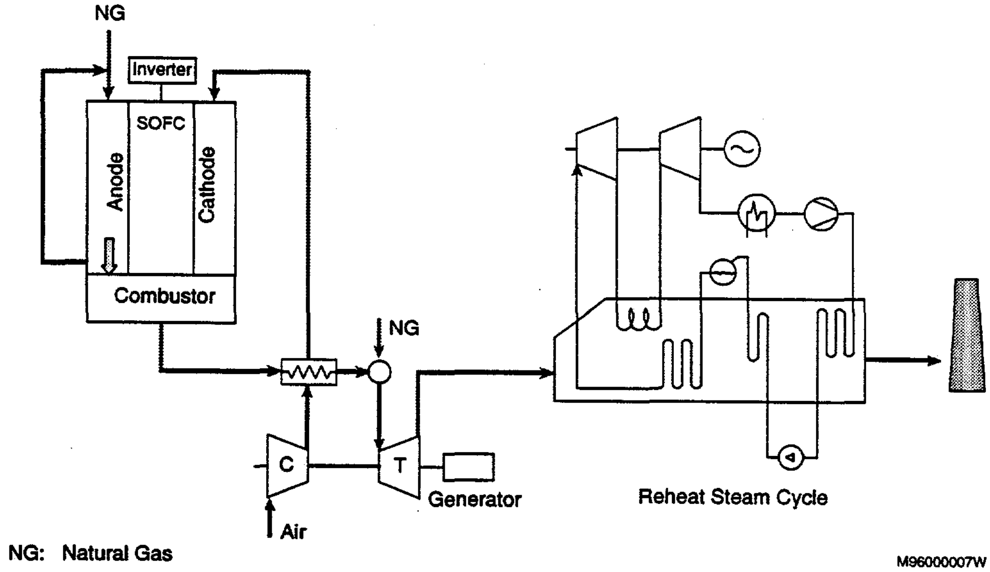

Figure 5. Natural Gas/Solid-Oxide Fuel-Cell Combined-Cycle System, Alternative 1

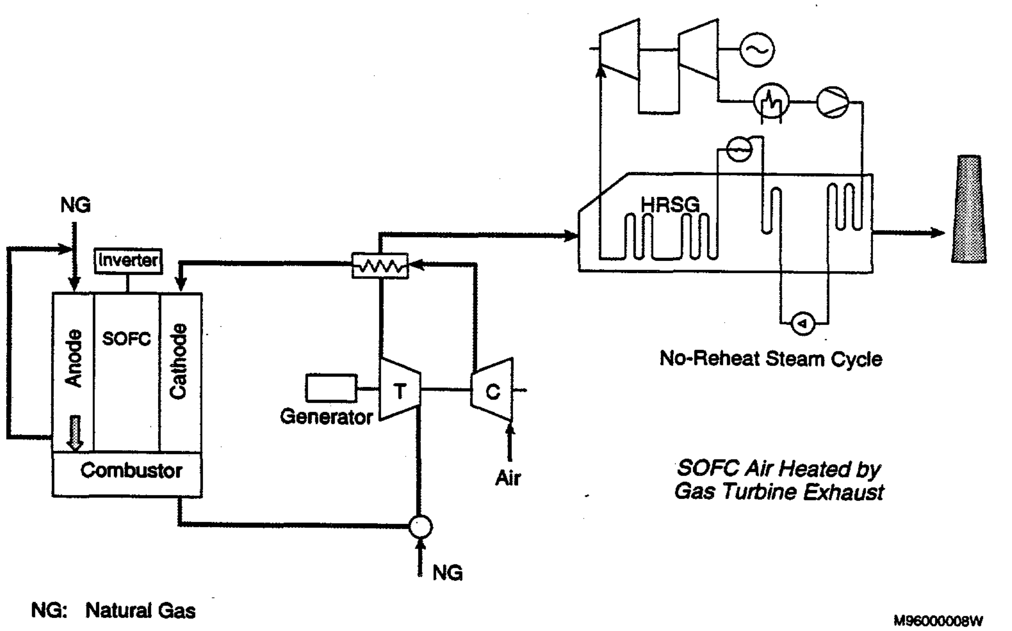

Figure 6. Natural Gas/Solid-Oxide Fuel-Cell Combined-Cycle System, Alternative 2

temperatures will cause an increase in NO_X emissions. This will not occur with fuel cells, which release chemical energy as a stream of electrons rather than thermal energy. Fuel-cell efficiencies are controlled by Gibbs' Free Energy rather than by high-temperature operation. Some chemical energy is unconverted and some heat is generated by the fuel cell. This provides a source of conventional heat energy that can be used by a traditional heat engine. Thus, ultimately, to achieve 70+ percent LHV power efficiency, we must unite the two prime mover systems.

There are other operational benefits to fuel cells. They will operate efficiently in small sizes and even at partial loads, and because of this, are ideal for distributed power generation. These benefits in turn result in the potential to completely eliminate high voltage lines, reducing health concerns.

Status of Fuel-Cell Commercialization

Fuel-cell technology has evolved from small, curious, laboratory cell tests in the 1980s to fuel-cell-stack demonstration testing of complete systems (Williams and George 1990, 1991; Energy Research Corporation 1987). Systems testing is the precursor to commercialization, and small units in the 100-kilowatt (kW) range are commercially available. Thus, the fuel cell is no longer a technology of the distant future. Stack life for the MCFC has been extended from 100 hours in the early 1980s to some 5,000 hours for small stacks in recent years. Testing is underway to warrant MCFC units for 25,000 hours, and within several years, vendors expect to warrant their units for 40,000-hours operation. The largest MCFC stack now being manufactured and tested is 2-MW size.

Tubular and planar SOFC testing is still behind the MCFC in terms of stack size. However, single tubular SOFCs have been tested for 50,000 hours. Stacks up to 100 kW have been demonstrated. For monolithic SOFCs, a type of planar SOFC, higher power densities appear feasible. These units potentially will provide eight times the power of present fuel cells in half the stack volume.

Power Conversion Configurations

While a fuel cell is extremely efficient, not all of the fuel's energy is electrochemically converted to electric power. About 50 percent of the fuel that comes into either an MCFC or SOFC is converted to electric power. The excess fuel is then consumed in a secondary combustor to generate thermal energy for the expansion turbine or additional thermal energy for the bottoming steam cycle. Moderate- to high-temperature product streams and other exhaust streams always result from the fuel conversion, and these energy streams have to be thermally converted to electric power. Two possible configurations that compare ways of using the fuel-cell exhaust stream energy are shown in Figures 4 to 6.

Many other configurations are possible. The NG-IFCFC configuration in Figure 4 shows the compressed air for the gas turbine being heated by the exhaust of the fuel cell by passing through a heat exchanger. The air is further heated by an off-base combustor to turbine inlet conditions. Only hot air passes through the turbine.

Combustion products from the turbine, exiting at approximately 500 °C (950 °F), nominally drive a steam cycle. The turbine exhaust is best utilized in the NG-IFCFC system as part of the oxidant feed to the MCFC. CO_2, provided by the combustor exhaust, is combined with the turbine exhaust and is passed to the fuel-cell cathode. Ultimately, the fuel-cell cathode exhaust is at higher temperatures than the turbine exhaust, and hence, it could be used more effectively by a steam turbine. The waste heat is effectively shared by two power sources in the NG-IFCFC, thereby increasing the overall cycle efficiency.

As an alternative, a gas turbine could be used to provide a high-temperature, pressurized air stream that then passes into a pressurized SOFC. The NG-SOFCCC system in Figure 5 shows this configuration, where the SOFC is a topper for the high-pressure gas turbine. Total system air and fuel are first compressed and processed through the fuel cell. Fuel is supplied to the anode and compressed air is supplied to the cathode. The pressurized fuel-cell exhaust is further heated by completing the combustion of exhaust gases. At the turbine operating pressure, the combusted fuel-cell exhaust is next processed to the gas turbine. The expansion turbine captures the remaining expansion energy. Depending on the turbine inlet temperature and pressure ratio, the exhaust is at 425 to 500 °C (800 to 950 °F).

An alternative system is presented in Figure 6. In this configuration, the turbine exhaust is used to heat the inlet air to the fuel cell. This improves the efficiency of the fuel cell, but reduces the efficiency of the heat-recovery steam generator by supporting a generic no-reheat steam cycle. The system efficiency is slightly higher and system cost is lower using this configuration.

There is little difference in the cost performance trade-off between the MCFC and SOFC units. The gas turbine units are similar. Both systems still have the exhaust stream from the fuel cell to deal with. The exhaust stream temperature in the NG-IFCFC system is high and can be used to generate a reheat steam cycle. In the NG-SOFCCC configuration, the turbine exhaust is probably best utilized by heating the compressor discharge air; turbine exhaust temperatures are high enough to provide a fair Rankine bottom cycle. DOE is examining these and other configurations to evaluate which provide the most effective utilization of the fuel-cell exhaust stream.

Advantages of the Fuel-Cell Combined-Cycle System

Many hardware limitations are overcome using integrated gas-turbine/fuel-cell systems compared to using either a gas turbine or a fuel cell bottomed with a steam turbine. Problems overcome and advantages of the fuel-cell combined-cycle systems include:

- Operating at ambient pressure, the MCFC provides thermal energy for an efficient reheat steam-bottoming cycle, using cathode exhaust stream energies.

- Gas turbine provides flexibility to move available heat from the fuel-cell exhaust into first, the Brayton cycle and then, the Rankine cycle.

- The fuel cell provides high efficiency at lower temperatures, where a Carnot cycle engine is ineffective.

- Fuel-cell combined-cycle systems provide a way of optimizing system economics through fuel flexibility without turbine cleanup problems.

- MCFC exhaust is approximately 600 to 700 °C (1,110 to 1,300 °F), which increases the performance of the indirect-fired system.

- The recycle stream is combusted and used to preheat compressor discharge air, reducing the amount of fresh fuel consumption required to obtain the gas turbine inlet temperature.

- At high compression ratios, a heat exchanger is not required for pre-heating the fuel-cell air.

- The combustor in the indirect-fired cycle operates with high-temperature exhaust air, which makes the system prone to fuel-bound NO_X. This effect is partially mitigated by using partially consumed air from the fuel cell as a product.

- Fuel-cell exhaust can be added effectively into the pre-mixed system, reducing NO_X formation.

- The pressurized fuel cell reduces SOFC and balance of plant (BOP) costs.

The potential benefits are obvious. A calculated LHV efficiency of about 74 percent is possible for a NG-SOFCCC operating under high pressure, including thermal losses as well as losses for auxiliary equipment. A primary benefit of coupling the two power generation systems is that the overall costs of fuel-cell systems could be lowered significantly, allowing for an early introduction of the technology.

Synergistic effects will open markets to the combined heat-engine/fuel-cell system. Fuel-cell and gas-turbine systems should not be viewed as competitors, but as an opportunity to expand into environmental markets in non-attainment areas. This would allow the fuel cell to be introduced with a system that has a high response, low cost, and fuel flexibility. And the gas turbine could then meet stringent emission regulations. However, for systems with increased efficiency, the availability of high-temperature (ceramic) heat exchangers is still problematic and becomes a critical issue.

Cycle Efficiency Calculations

As separate systems, both the advanced turbine and the fuel cell have reached the pinnacle of high efficiency. Theory and ASPEN simulations support combining these two power generation systems to produce a super efficient system. Calculations were carried out by DOE using the ASPEN code modified to calculate the conversion of chemical to electric power, as well as the conversion of thermal energy to electric power. Although higher steam-turbine efficiency is expected to be available by the turn of the century, we conducted this ASPEN study assuming current steam-turbine technology. Hence, the calculations reflect a conservative viewpoint.

Calculations of the primary systems show that the LHV efficiency of an MCFC bottomed by a steam cycle could achieve roughly 65 percent. The simulations of the high-pressure NG-SOFC bottomed by a steam turbine show about 63 percent efficiency. Calculations are based on firing the fuel cell with a stoichiometric mixture of methane and air. For a natural gas, indirect-fired, gas turbine, steam-bottomed system, the efficiency is expected to be about 55 percent. A high-pressure gas turbine was used in the system simulations. For both systems, calculations include reasonable assumptions of parasitic losses for the compressor, turbine, and fuel-cell sub-systems.

When the combination system was analyzed, the hot air from the gas turbine was exhausted into the fuel cell as the bottomer, as well as into the off-base combustor. The products all eventually exhausted into a steam Rankine cycle. The turbine air was in excess of what can be used by the fuel cell since hot air must be used by the off-base combustor.

Various splits of the exhaust air to the fuel cell and the off-base combustor are being considered because the ratio has a tremendous effect on the cost and efficiency of the system. Heat to raise the turbine air to the inlet temperature is supplied by a heat exchanger using the fuel product gases from the off-base combustor. Since this combustor does not need natural gas, the fuel can be almost any reasonable fuel, adding fuel flexibility that is otherwise not available to a stand-alone fuel-cell system. The design assumes a 10-percent pinch and high-temperature materials for the first few tube rows to accommodate the high temperatures. Costs of the heat exchanger unit are not expected to be unduly great because much of the recuperation can be done with metal tubes.

The calculations indicate the efficiency of the combination power systems can be greater than 73 percent for the NG-IFCFC or MCFC bottomer, and possibly as high as 74 percent for the pressurized NG-SOFCCC topping cycle. System efficiency differences are not significant. Every effort was made to simulate the fuel-cell-gas turbine system using the same premises. Unfortunately, MCFC and SOFC systems required different gas turbines, resulting in different fuel cell to turbine ratios, steam cycle temperatures, etc. For this preliminary analysis, efficiencies were assumed to be equal, although cycle efficiency is known to decrease with smaller scale units.

Parasitic losses could reduce any of these system efficiencies. Higher efficiencies are possible by using greater fractions of turbine exhaust air in the carbonate fuel cell. The larger the fraction of air in the fuel cell instead of the combustor, the more the two systems act in series instead of in parallel, and the better the composite performance. The NG-SOFCCC operates completely in series, and fuel cell to turbine ratios are greater in the NG-SOFCCC. Thus, the efficiency increases because the fuel-cell power output increases and the efficiency of the fuel cell is greater than that of current turbines. However, the system costs also increase. Optimization will be determined by the market place and this will tend to favor the turbine. We have not tried to optimize this balance. We only indicate that the use of the lower efficiency turbine system will not compromise the combination system efficiency.

Discussion

The electric power in Figure 4 was assumed to be provided by a MCFC operated at ambient pressure, a current design gas turbine, and a steam cycle. In an indirect-cycle, air exhausts from a gas turbine and provides a natural source of heated air for the fuel cell. Thus, the MCFC operates properly with air that is preheated to approximately 550 °C (1,025 °F); this is the normal temperature for gas turbine exhausts operated at between 8 and 30 atmospheres.

A high efficiency is projected if all the energy from the cathode recycle stream of the fuel cell can be used by the Brayton cycle instead of the Rankine steam cycle. This comes about from two factors being present in the indirect-cycle configuration:

1. The cathode recycle heat provides energy that heats the compressor discharge air rather than ambient air, and thus, gains a net power compared to the usual fuel-cell configuration; and

2. The fuel-cell exhaust stream passes into the combustor and again provides heat to the compressor discharge air.

In the NG-SOFCCC configuration of Figures 5 and 6, the SOFC is operated at high pressure. Typical anode and cathode inlet temperatures approach 550 °C (1,050 °F), fuel-cell operation is at about 800 °C (1,500 °F), and the final exhaust temperature is near 1,000 °C (1,832 °F). The galvanic fuel-cell efficiency decreases with increases in temperature as projected using the Nernst equation. At high temperatures, the reaction kinetics are improved and fuel-cell resistance losses are decreased. The tradeoff for the fuel cell is that the voltage, power, and surface area dictate operation at higher temperatures.

Summary

The NG-IFCFC and NG-SOFCCC are introduced as novel power-plant systems in the distributed power and on-site markets at 20 to 200 MW size. The NG-IFCFC power-plant system configures the ambient pressure, carbonate fuel cell with a gas turbine, air compressor, combustor, and part-ceramic heat exchanger. The NG-SOFCCC power-plant system configures a high-pressure fuel cell with a high-pressure gas turbine and a steam turbine. ASPEN performance results indicate efficiencies and heat rates for the NG-IFCFC and NG-SOFCCC are similar. Key parameters such as temperatures and pressures are within current limits of industrial practice. The efficiencies are comparable to conventional MCFC or SOFC steam-bottomed systems, but with smaller and less expensive components.

The potential benefits are obvious. High electrical conversion efficiencies are possible. The combination of fuel cells and Carnot cycle systems provides a cost-effective new system with greater flexibility to meet local demands. Competing manufacturers of gas turbines and fuel cells must work together to integrate this technology into the most efficient and cost-effective system possible. Much work remains to be accomplished. DOE and METC are the ideal organizations to lead this development because of their system analysis capabilities, experience with heat engines and fuel cells, and the lead in identifying the fuel-cell/heat-engine concept.

References

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Fuel Cell/Gas Turbine Systems — Power Generation With Heat and Fuel Recovery

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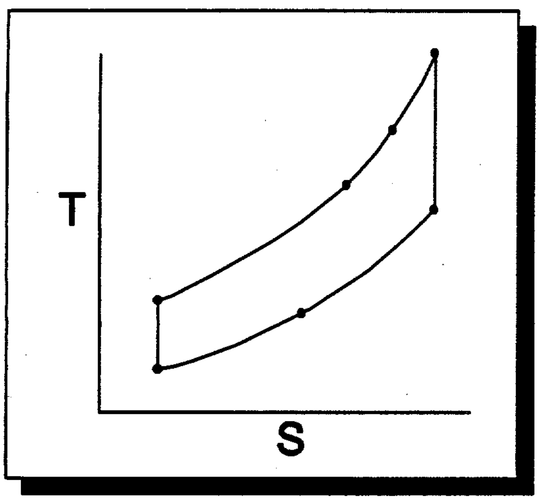
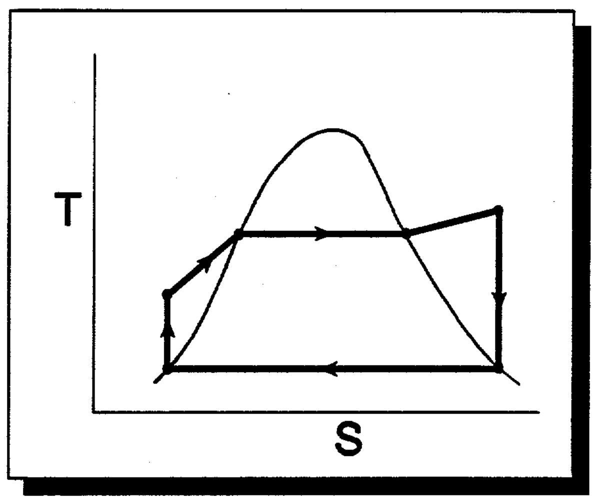




Considerations:

- Recovery of fuel and reject heat: power generation
- Higher temperature fuel cells (MCFC, SOFC)
- Gas turbine based power cycles/systems

Comments:

Fuel Cell

- Stack (current flow in series, reactant flow in parallel)
- Multiple stacks (reactant flow in series, co- or counter-current; network)

Direct Methane Oxidation

$CH_4 + 2O_2$ ------ $CO_2 + 2H_2 + W$ (direct oxidation)

Simultaneous Reactions

$CH_4 + H_2O + Q$ ------ $CO + 3H_2$ (internal reforming)

$CO + 3H_2 + 2O_2$ ------- $CO_2 + 3H_2O + Q + W$

Cycles

- Regenerative Brayton
- Combined Brayton — Rankine

Representations

- Simplified flow diagrams
- Thermodynamic T-S diagrams (air-fuel-combustion products working fluid)

Issues Deferred:

Fuel Cell

- Reforming
- Heat transfer; electrode to reactants, heat transfer surface

Heat Cycle

- Heat transfer, ΔT in recuperator
- Pressure loss in equipment, ducts
- Compressor, expander efficiencies

Regenerative Brayton Features:

- Low pressure ratio
- Air-fuel preheat in recuperative exchanger
- Partial combustion in fuel cell
- Direct heat removal by excess air, maintains ΔT
- Combustion of residual fuel, air in auxiliary combustor
- Expansion in turbine to cell inlet temperature
- Heat rejection from turbine exhaust gases in recuperator

Example: Regenerative Brayton

Input:

- SOFC
- 1700 - 1900 °F
- Efficiency = 60% reversible or 52% conventional
- Fuel use = 93%
- Compressor, turbine efficiency = 83%, 89%
- Recuperator ΔT = 30 °F

Output

- Excess air = 710%
- Turbine top temperature = 1938 °F
- Pressure ratio = 1.48
- Recuperator T range = 127 - 1729 °F

- Fuel cell/total power = 69%
- Overall plant efficiency = 75%

Regenerative Brayton

Advantages

- Simple, adaptable to low capacity systems
- Low pressures in fuel cells
- Maximum fuel cell contribution to generation, efficiency
- Low pressure ratios, temperatures in compressor, turbine

Disadvantages

- High heat exchange surface area in recuperator
- Compressor, turbine adaptation to cell operating conditions
- Sensitivity to machine efficiencies, ΔP's, recuperator ΔT

Combined Brayton-Rankine Features:

- High pressure ratio
- Air-fuel preheat by indirect heat removal in fuel cell
- Partial combustion in fuel cell to maintain cell operating T
- Combustion of residual fuel and air in auxiliary combustor to reach high T.I.T.
- Expansion in turbine
- Heat rejection from turbine exhaust gases in HRSG of Rankine cycle

Combined Brayton-Rankine:

Advantages

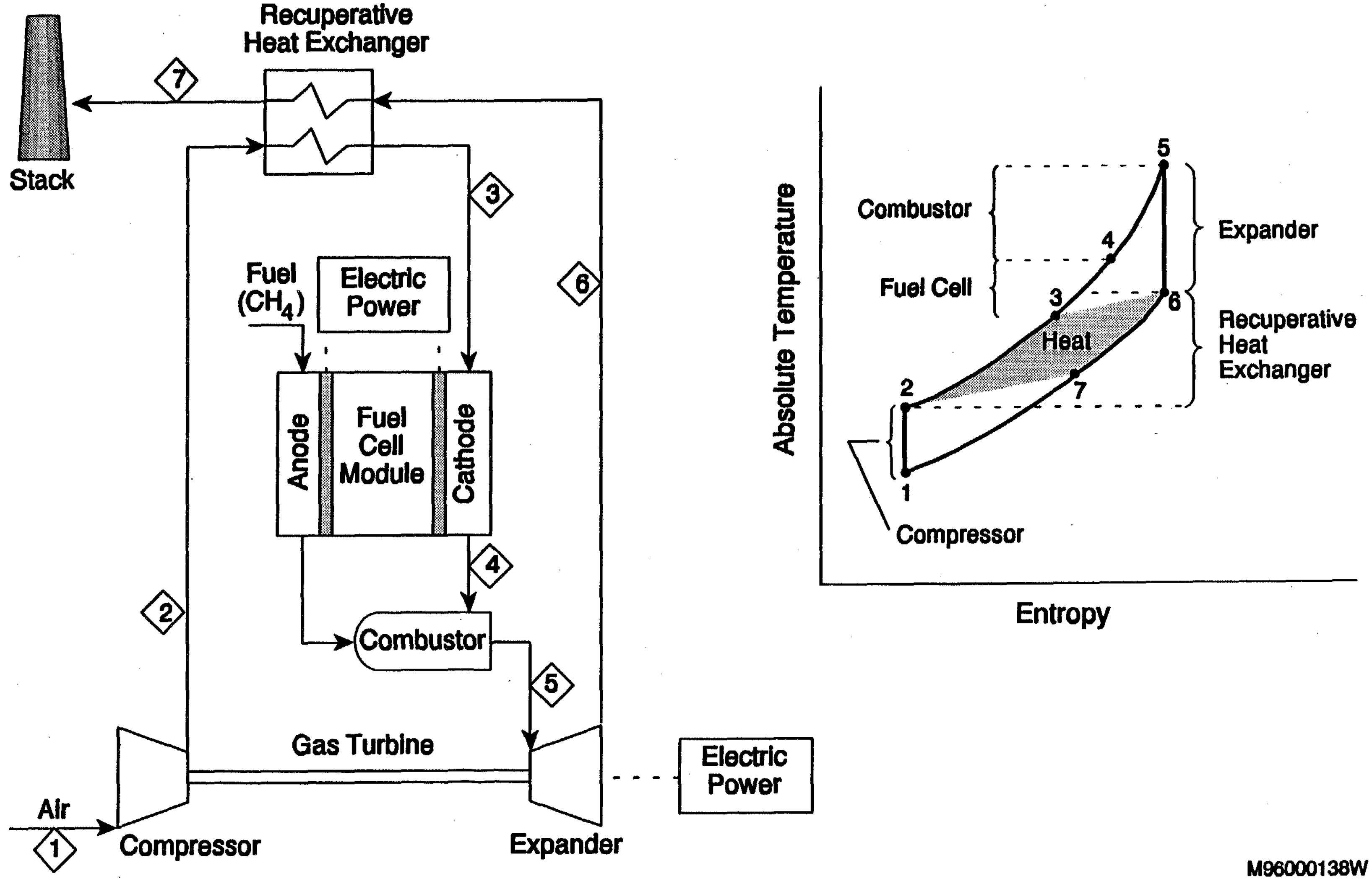
- Integrated gas turbine, steam turbine hardware systems developed
- High efficiency bottoming cycle enhanced by fuel cell topping

Disadvantages

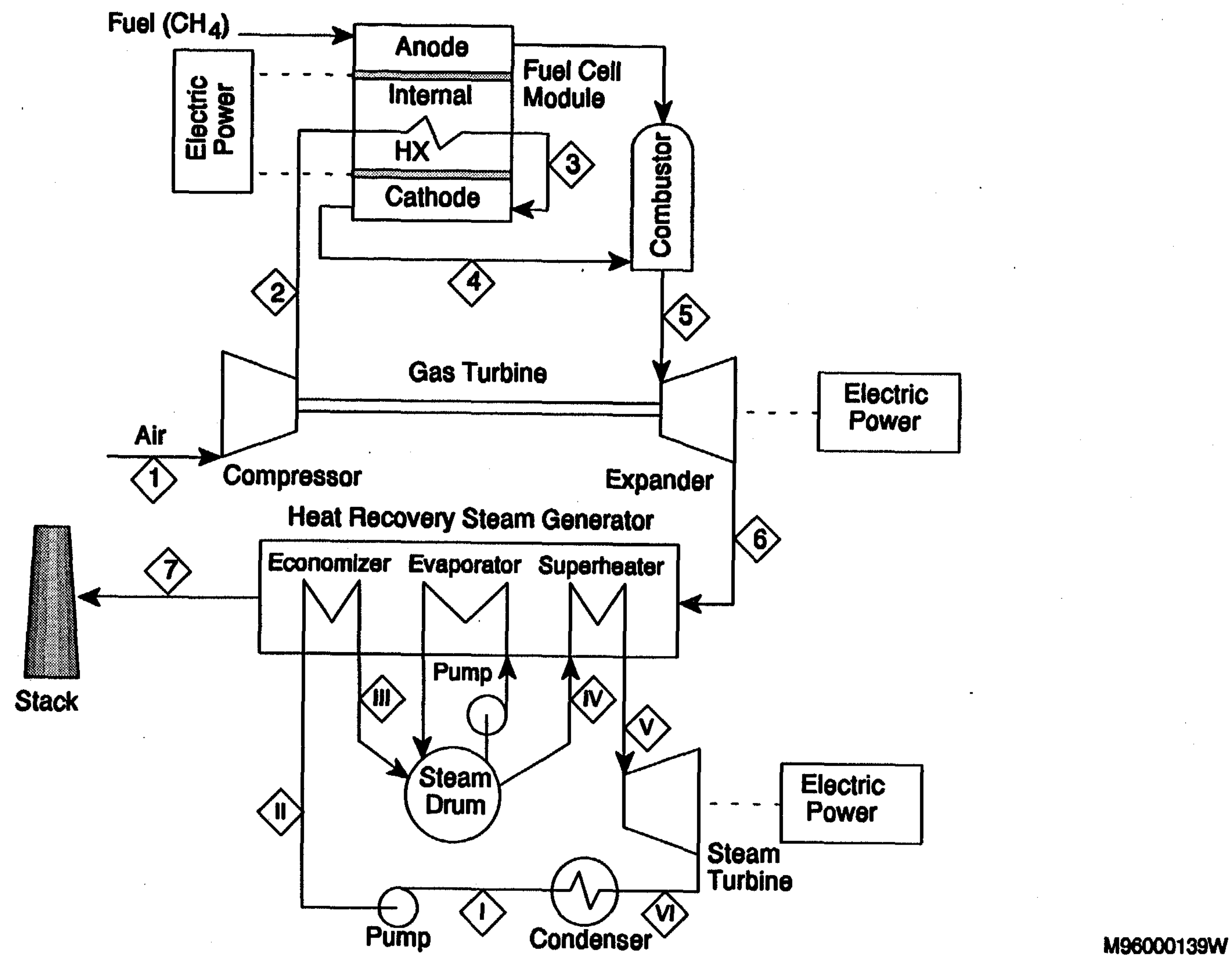
- Complex system adapted to large capacity
- Gas turbine modifications required
- High pressures in fuel cell

Recommendations: Further Study of Fuel Cell/Regenerative Brayton Cycle Gas Turbine Systems

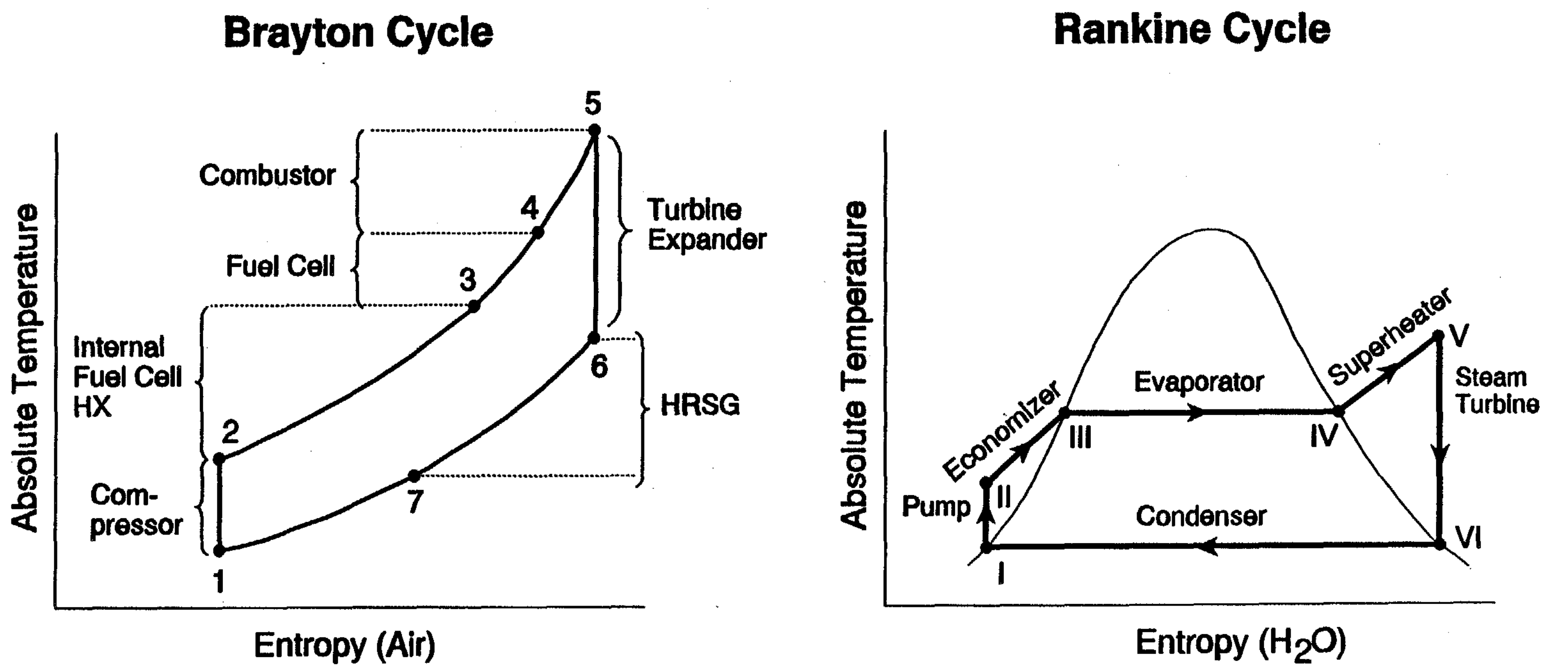
- Molten carbonate, solid oxide fuel cells
- Market, 1 - 10 MW plants
- Preliminary plant designs; performance evaluations; capital, operating cost estimates; environmental assessments
- Effects of plant configuration (provisions for fuel reforming, heat removal, networking) design parameters, operating conditions (T, ΔT, P, ΔP)
- Adaptability of available compressor, turbine, heat exchanger equipment
- Overall system operation, control



Regenerative Brayton Cycle Fuel Cell Power Generation System



Combined Brayton-Rankine Cycle Fuel Cell Power Generation System



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Combined Brayton-Rankine Cycle Thermodynamics

High Efficiency Fuel Cell/Advanced Turbine Power Cycles

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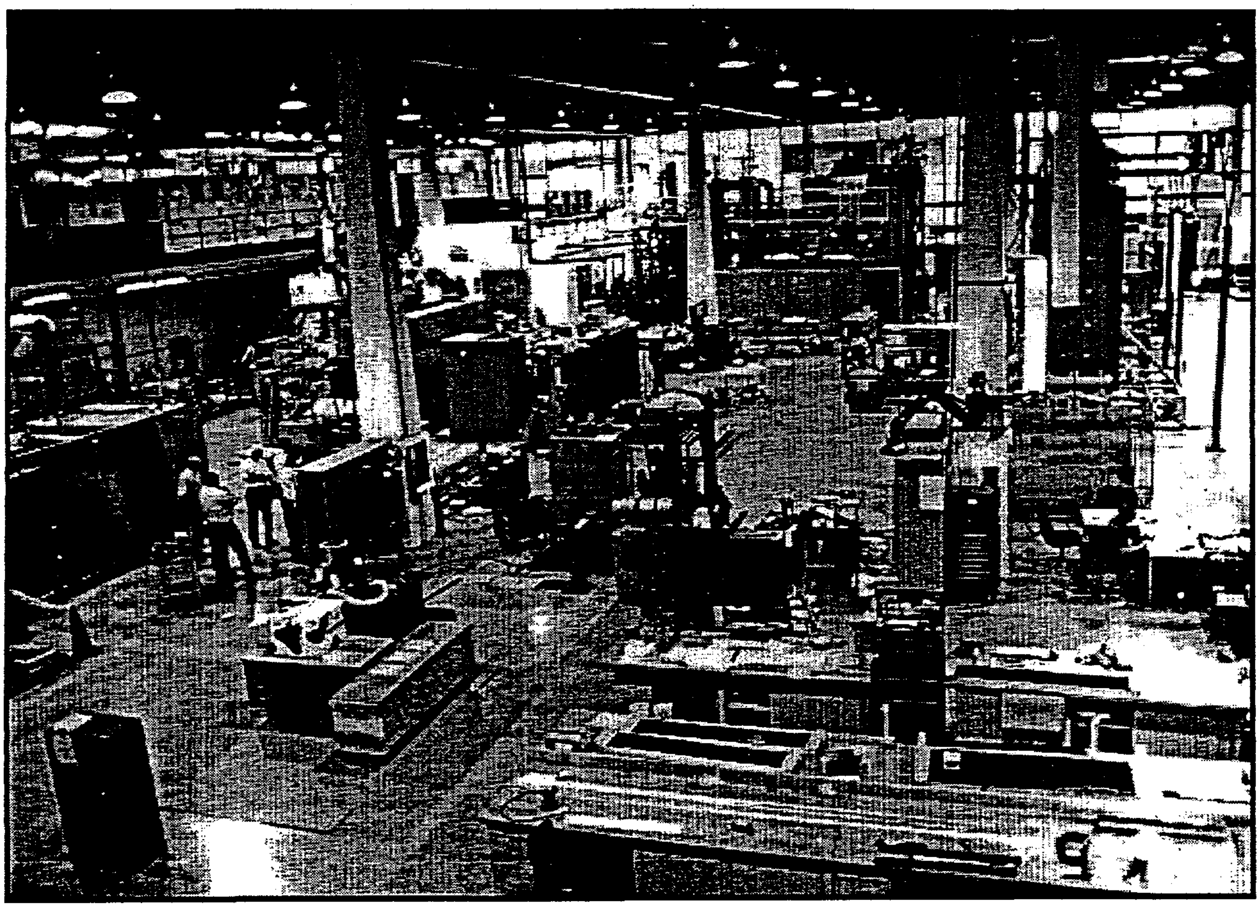
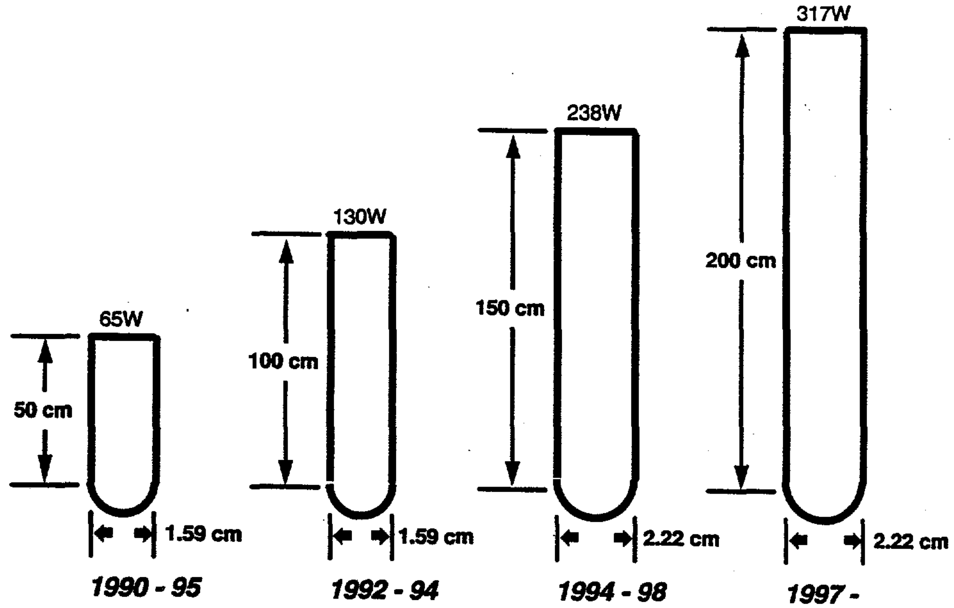
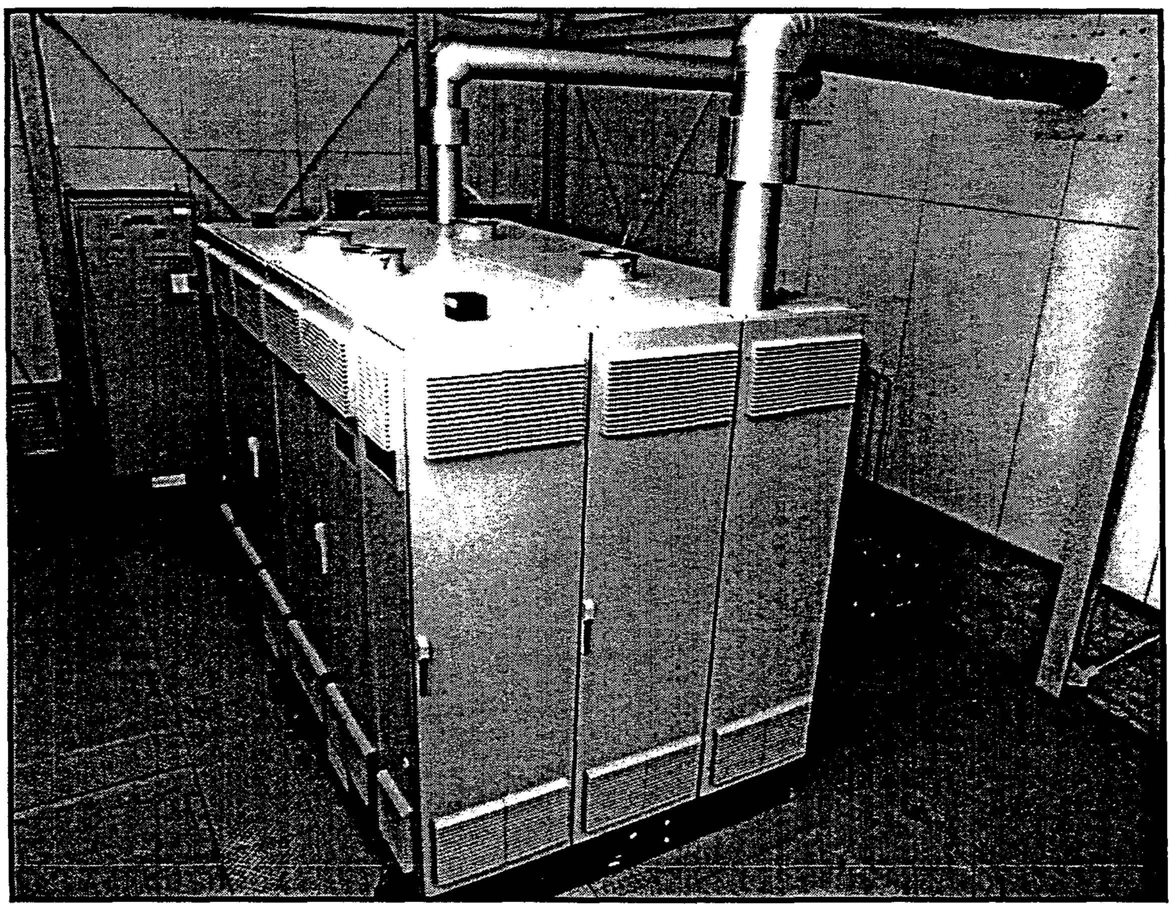


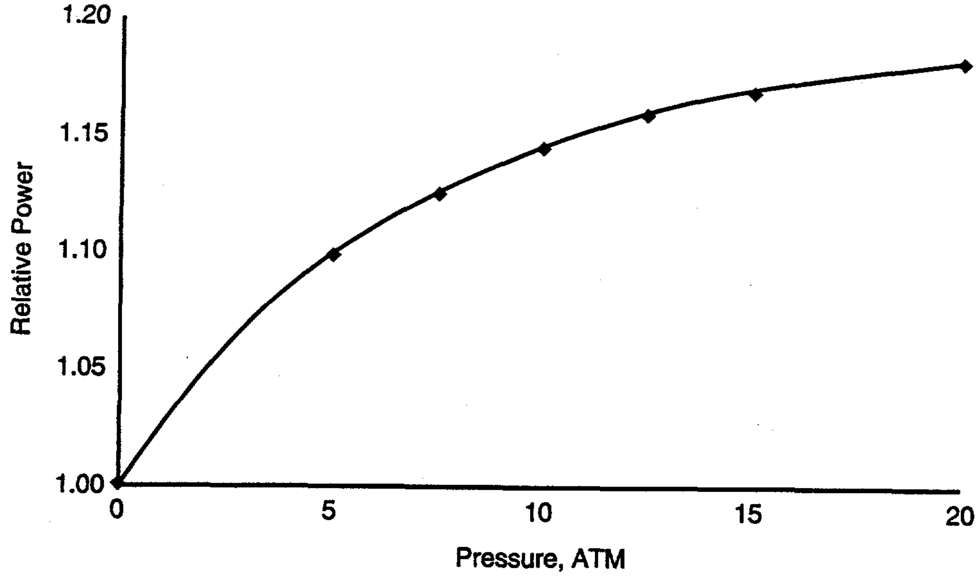
Westinghouse SOFC Pilot Manufacturing Facility



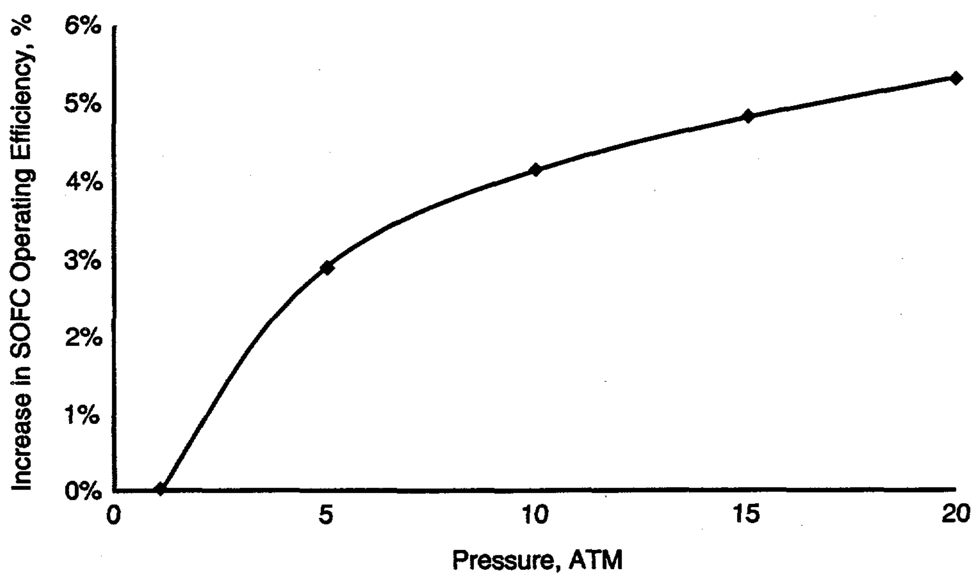
Cell Scale-Up Plan: 89% H_2, 11% H_2O, 85% Fuel Utilization



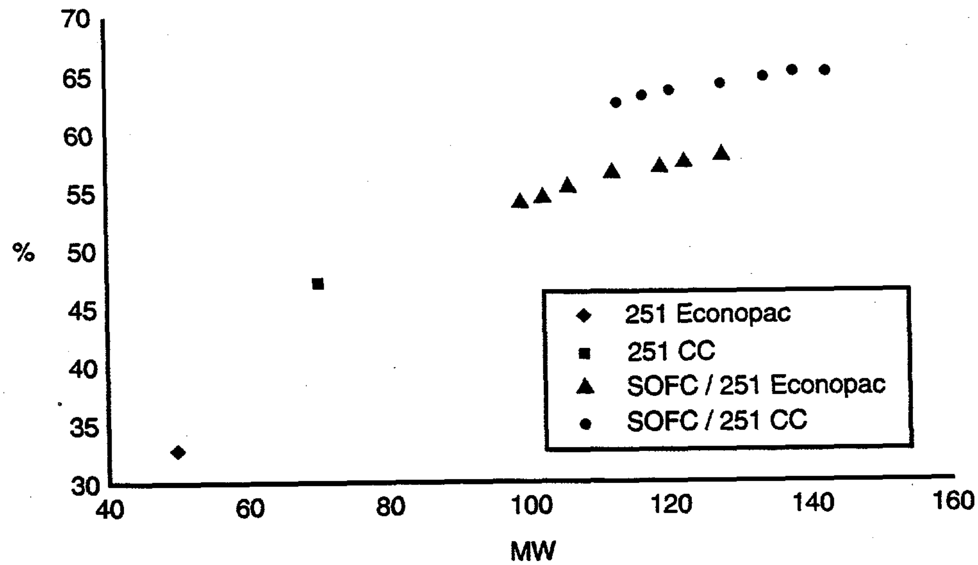
Westinghouse 25 KW SOFC Unit at the Utility's Facility on Rokko Island



Pressure Effect on SOFC Power



Pressure Effect on SOFC Efficiency

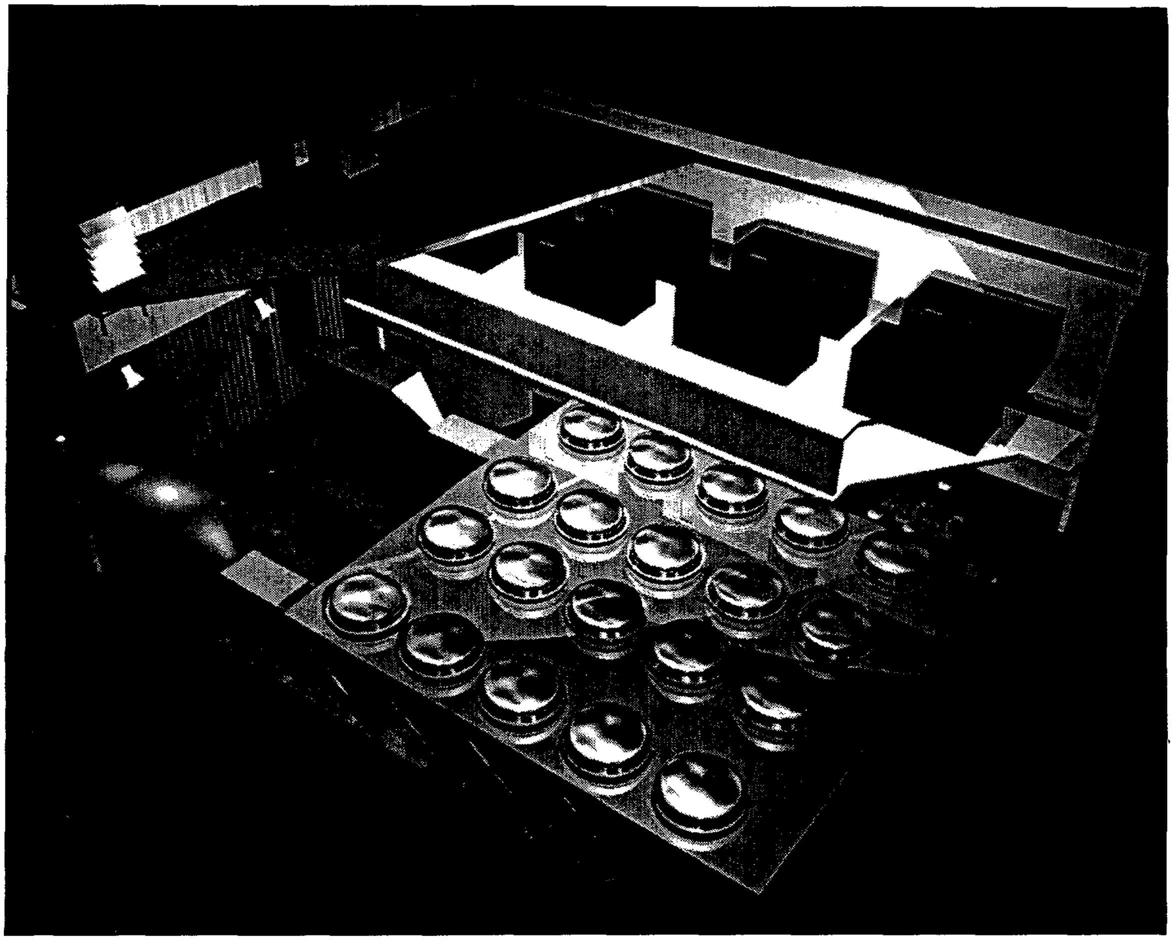


SureCELL™ Versus Conventional Gas Turbine Plants

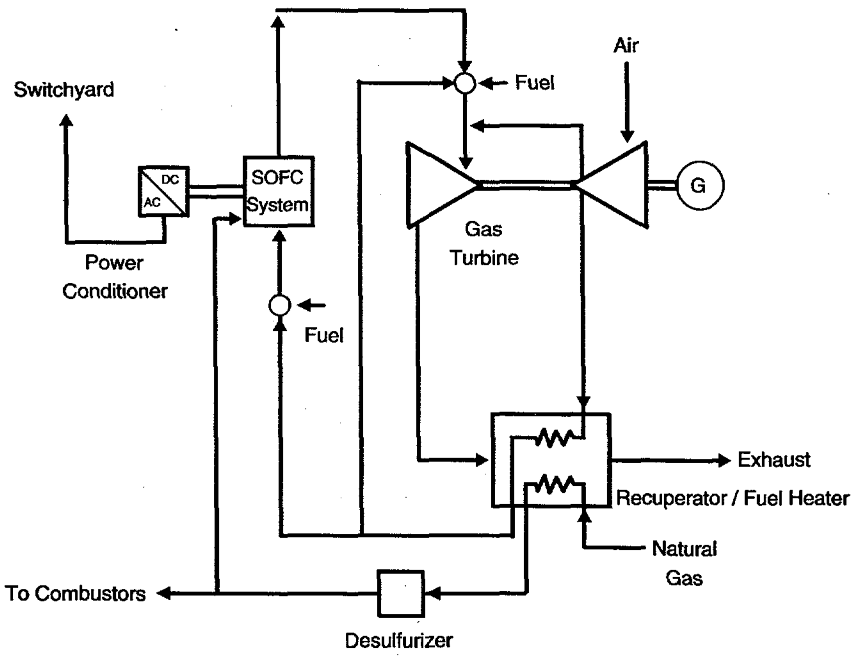
SureCELL™ Product Line for Distributed Power Applications

Table 1.

Product	Number of CT's	Number of SOFC Modules	Cycle Efficiency (LHV)
3 MW	1	1-2	60%
10 MW	1	6-8	60%
20 MW	2	12-16	62%



20 MW Pressurized-SOFC/Gas Turbine Power Plant



10 MW SOFT/CT Power Plant

SureCELL™ Plant Concept Design Requirements

• Application	- Natural Gas AC Power to Grid - No Heat Supply to Customer
• Duty Cycle	- 4:1 Turndown Capability
• Design Basis	- Minimum COE/Mature Components
• Plant Operation and Staffing	- Automatic, Remotely Monitored - On-site Operators Not Required
• Installation	- Indoors, 0.25 acre max footprint
• Equipment Design Lifetimes	- SOFC: 10 Years - Other Plant Equipment: 30 Years
• NO_X	- 5 ppmvV Max
• Plant Component Transportation	- Basis - Unrestricted US Trucks - 8.5' W, 13.5' H, 25' L, 40,000 lbs

Westinghouse SOFC Market Entry

•	1995	Verify pressurized SOFC reforming
•	1996-98	Design and verify pressurized SOFC generator
•	1996-99	Develop improved SOFC manufacturing process
•	1999	Integrated SOFC/CT plant on-line
•	1998-99	Westinghouse production factory investment
•	2000-05	Integrated plant sales growing to 500MW/yr
•	2003-05	Westinghouse production capacity expansions
•	1005+	Entry to larger plant segments/production growth

High Efficiency Carbonate Fuel Cell/Turbine Hybrid Power Cycles

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Abstract

Carbonate fuel cells developed by Energy Research Corporation, in commercial 2.85 MW size, have an efficiency of 57.9 percent. Studies of higher efficiency hybrid power cycles were conducted in cooperation with METC to identify an economically competitive system with an efficiency in excess of 65 percent.

A hybrid power cycle was identified that includes a direct carbonate fuel cell, a gas turbine and a steam cycle, which generates power at a LHV efficiency in excess of 70 percent. This new system is called a Tandem Technology Cycle (TTC). In a TTC operating on natural gas fuel, 95 percent of the fuel is mixed with recycled fuel cell anode exhaust, providing water for the reforming of the fuel, and flows to a direct carbonate fuel cell system which generates 72 percent of the power. The portion of the fuel cell anode exhaust which is not recycled, is burned and heat is transferred to the compressed air from a gas turbine, raising its temperature to 1800 °F. The stream is then heated to 2000 °F in the gas turbine burner and expands through the turbine generating 13 percent of the power. Half the exhaust from the gas turbine flows to the anode exhaust burner, and the remainder flows to the fuel cell cathodes providing the O_2 and CO_2 needed in the electrochemical reaction. Exhaust from the fuel cells flows to a steam system which includes a heat recovery steam generator and staged steam turbine which generates 15 percent of the TTC system power.

Studies of the TTC for 200-MW and 20-MW size plants quantified performance, emissions and cost-of-electricity, and compared the characteristics of the TTC to gas turbine combined cycles.

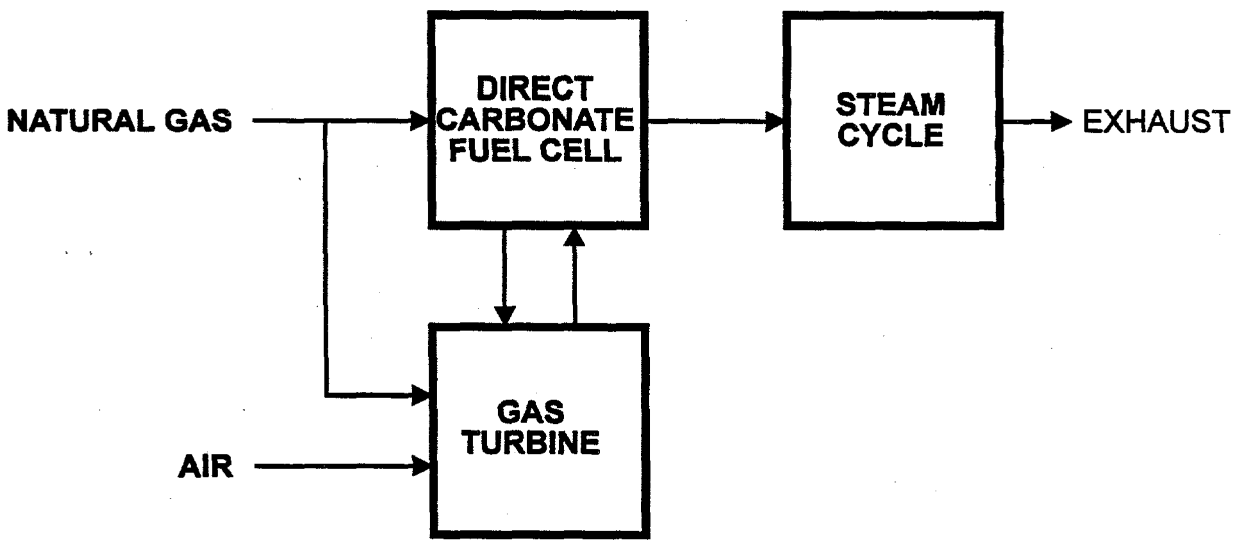
A 200-MW TTC plant has an efficiency of 72.6 percent, and is relatively insensitive to ambient temperature, but requires a heat exchanger capable of 2000 °F. The estimated cost of electricity is 45.8 mills/kWhr which is not competitive with a combined cycle in installations where fuel cost is under $5.8/MMBtu. Emissions from the TTC are well below existing or proposed standards. Based on equilibrium levels the TTC NOx emission level is 25 percent of the level from a combined cycle. The SOx level from a TTC is 4 percent of the level from a combined cycle because the sulfur is removed from the fuel used in the fuel cells. The CO_2 emission is 25 percent below the combined cycle reflecting the improved efficiency.

A 20-MW TTC plant for near-term application was studied in which a moderate (1500 °F) temperature heat exchanger was used, and steam was provided from the steam system rather than by recycle of the anode exhaust. This TTC system has an efficiency of 65.2 percent and a cost-of-electricity of 50 mills/kWhr, and is competitive with a combined cycle for fuel costs above $2.5/MMBtu. Emissions from the 20-MW TTC are well below existing or proposed standards.

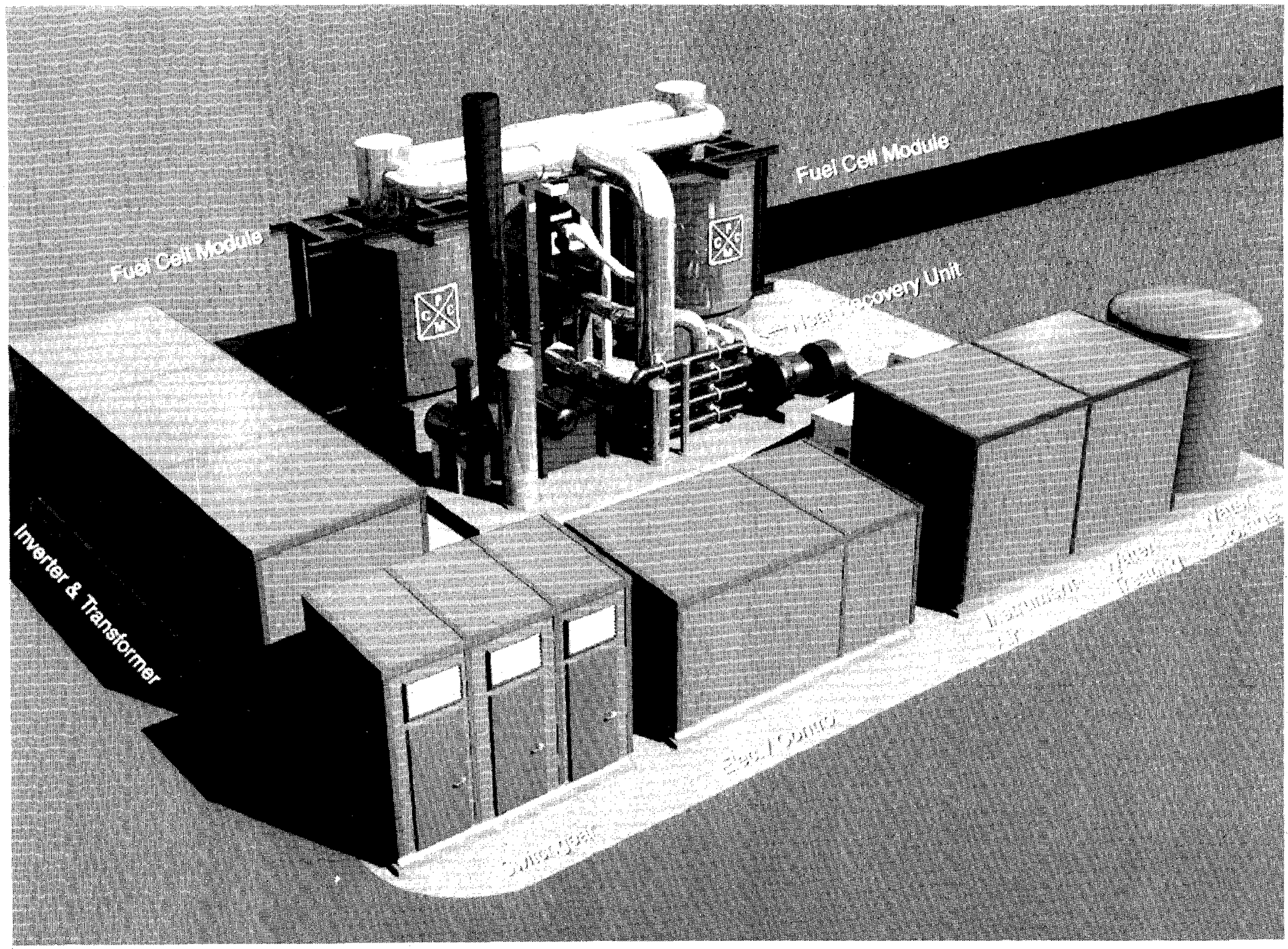
A 20-MW TTC plant can be implemented without significant development for applications in the year 2001 and beyond. Development needs include design studies to optimize the system process and develop a plant layout, and design studies on gas turbine design modifications. The next logical step would be a 20-MW plant demonstration with existing technology.

Objectives of Advanced Technology Cycle Studies

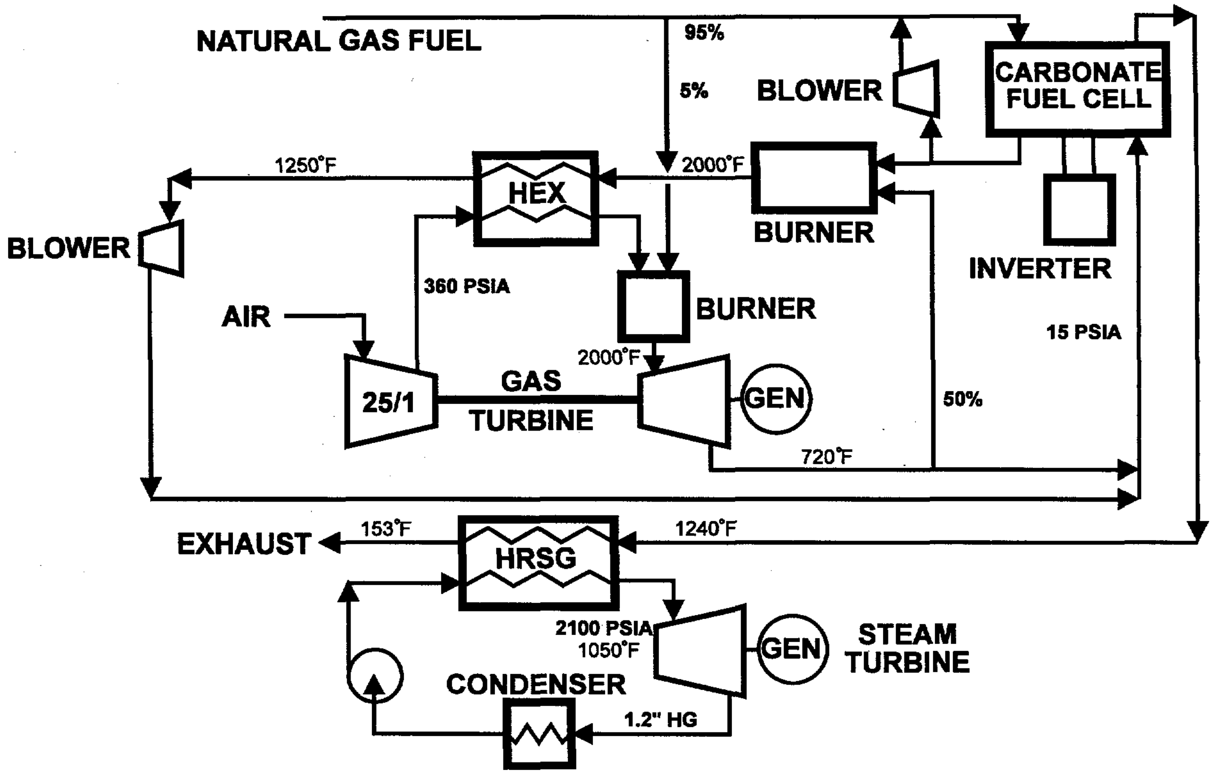
- Joint ERC/METC evaluation of 200-MW Direct Fuel Cell/Turbine Hybrid System
- ERC evaluation of 20-MW Hybrid System
- Goals are (1) high efficiency, and (2) competitive cost



Tandem Technology Cycle, Simplified Schematic



2.85-MW Commercial Power Plant Layout



Tandem Technology Cycle

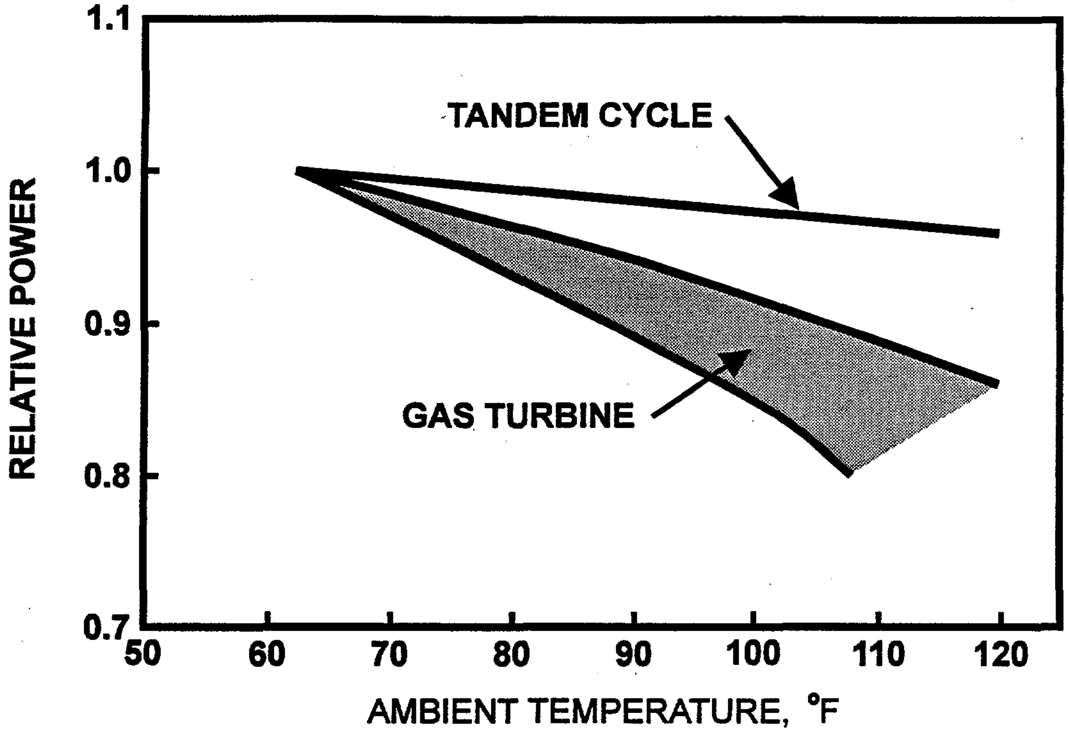
Tandem Technology Cycle Performance
200-MW Plant Study Results

- Power Generation, MW

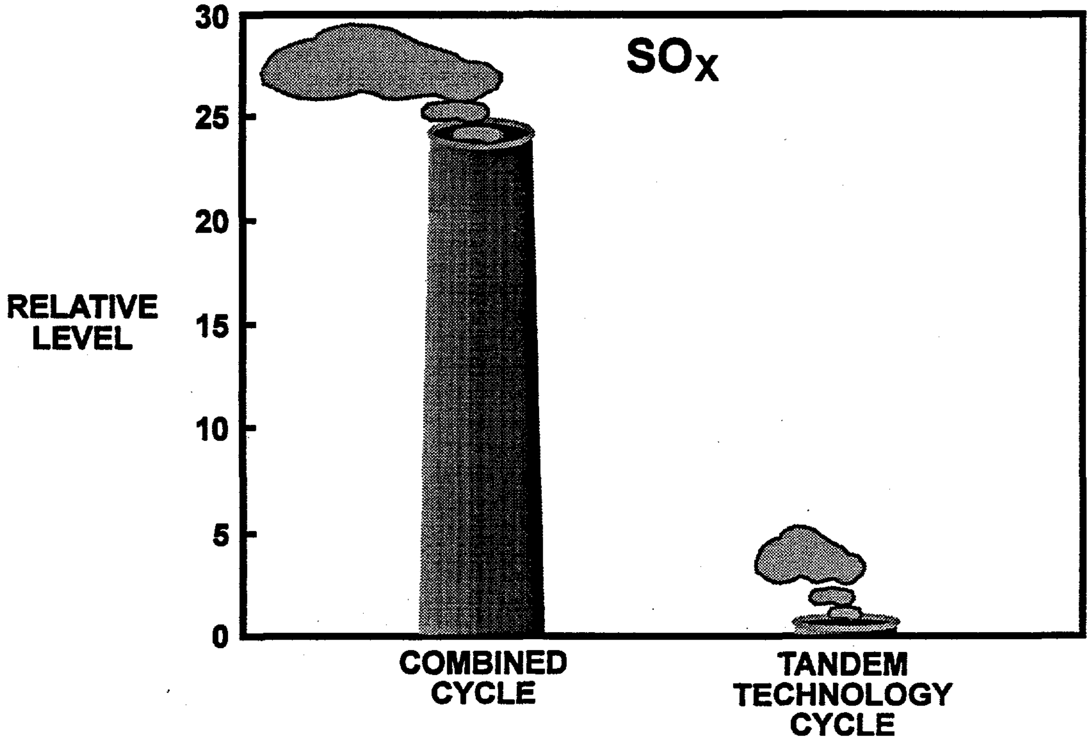
Gas Turbine	27.1
Fuel Cell	157.6
Steam Turbine	32.8
Parasitic Power	-11.1
Total	206.4

- Net AC LHV Efficiency, %

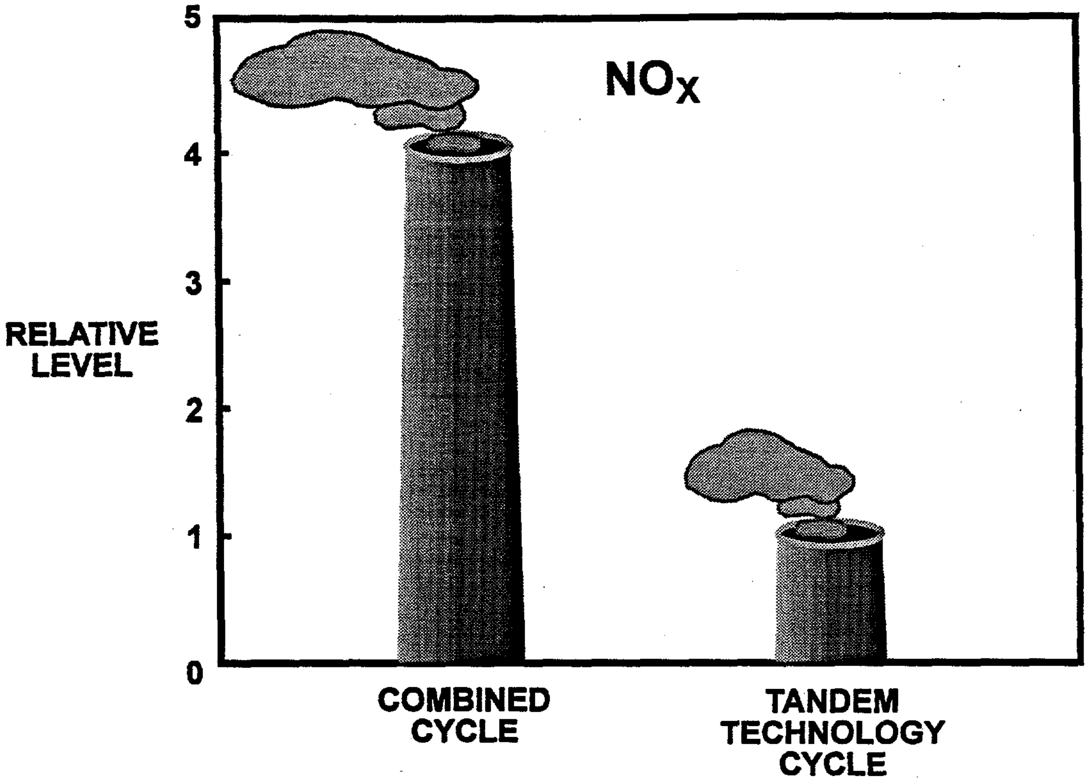
Fuel Cell	55.1
FC + GT	61.7
Steam System	34.1
Overall	72.6



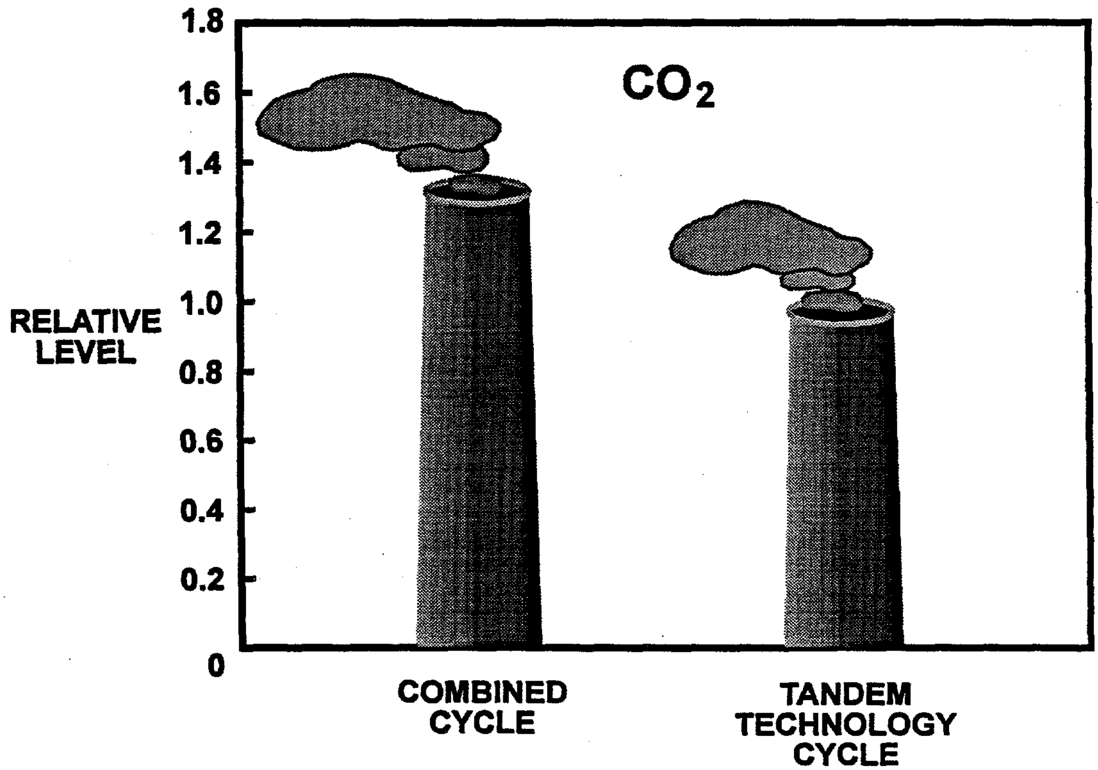
Air Temperature Versus Power Output
Tandem Cycle Power Output Remains Within 4 Percent



SOx Emissions



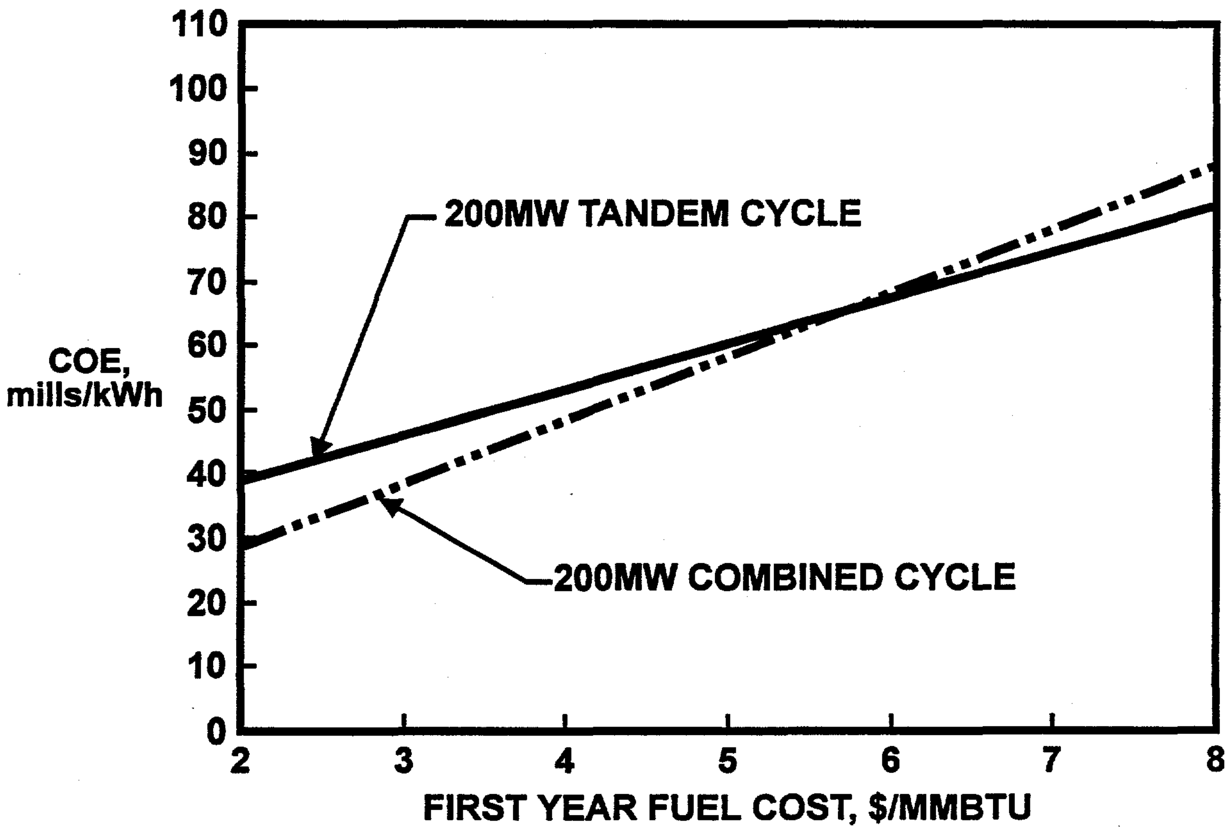
NOx Emissions



CO_2 Emissions

Levelized Cost of Electricity, 200-MW System
(1995 dollars, without inflation)

	Levelized Cost (mills/kWhr)
Fuel	21.4
Plant	12.5
O&M	12.1
Total	46.0



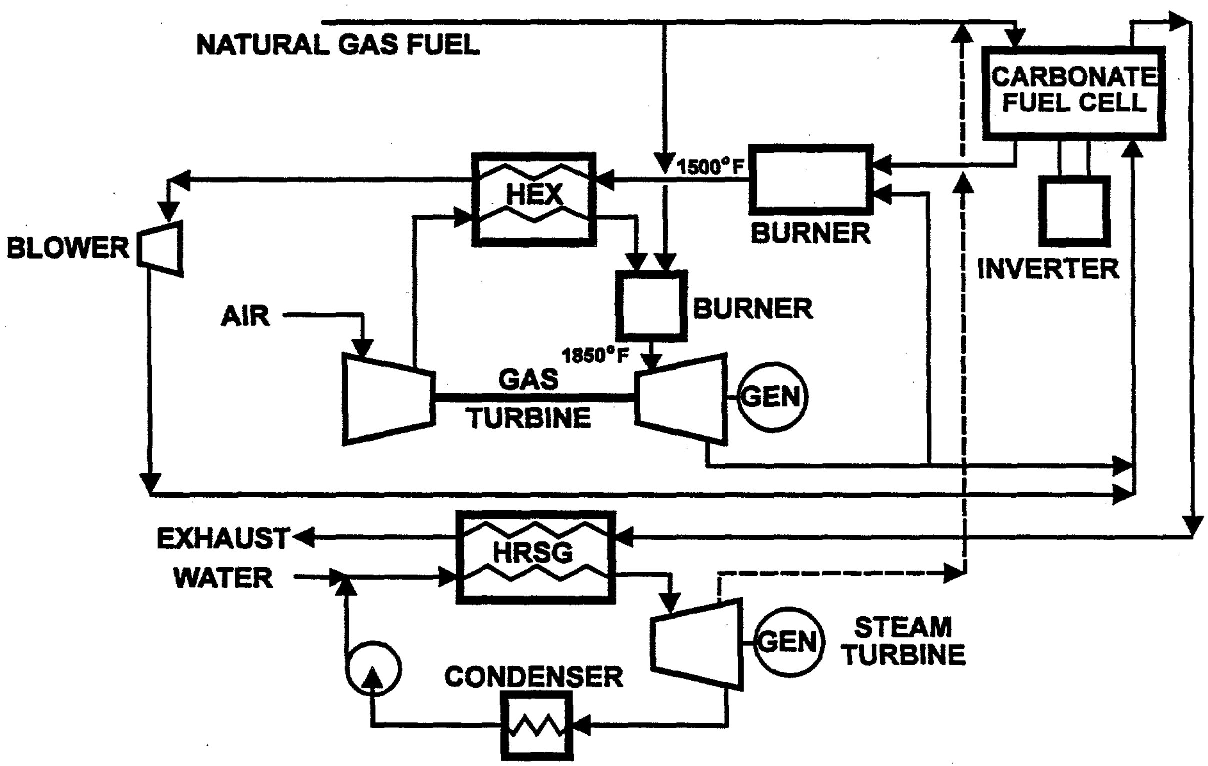
Cost of Electricity, Tandem Cycle Versus Combined Cycle

Conclusions: 200-MW Tandem Cycle

- LHV Efficiency above 70 percent achievable for large systems
  - Requires 2000 °F heat exchanger
- Good performance over a large range of ambient conditions
- Competitive with combined cycle at fuel costs above $5.80/MMBtu
- NOx emissions well below existing or proposed standards

Near-Term System:

- Moderate temperature heat exchanger (1500 °F)
- No anode recycle
- 20-MW size



Tandem Technology Cycle Alternative, Without Anode Recycle

Performance of Tandem Technology

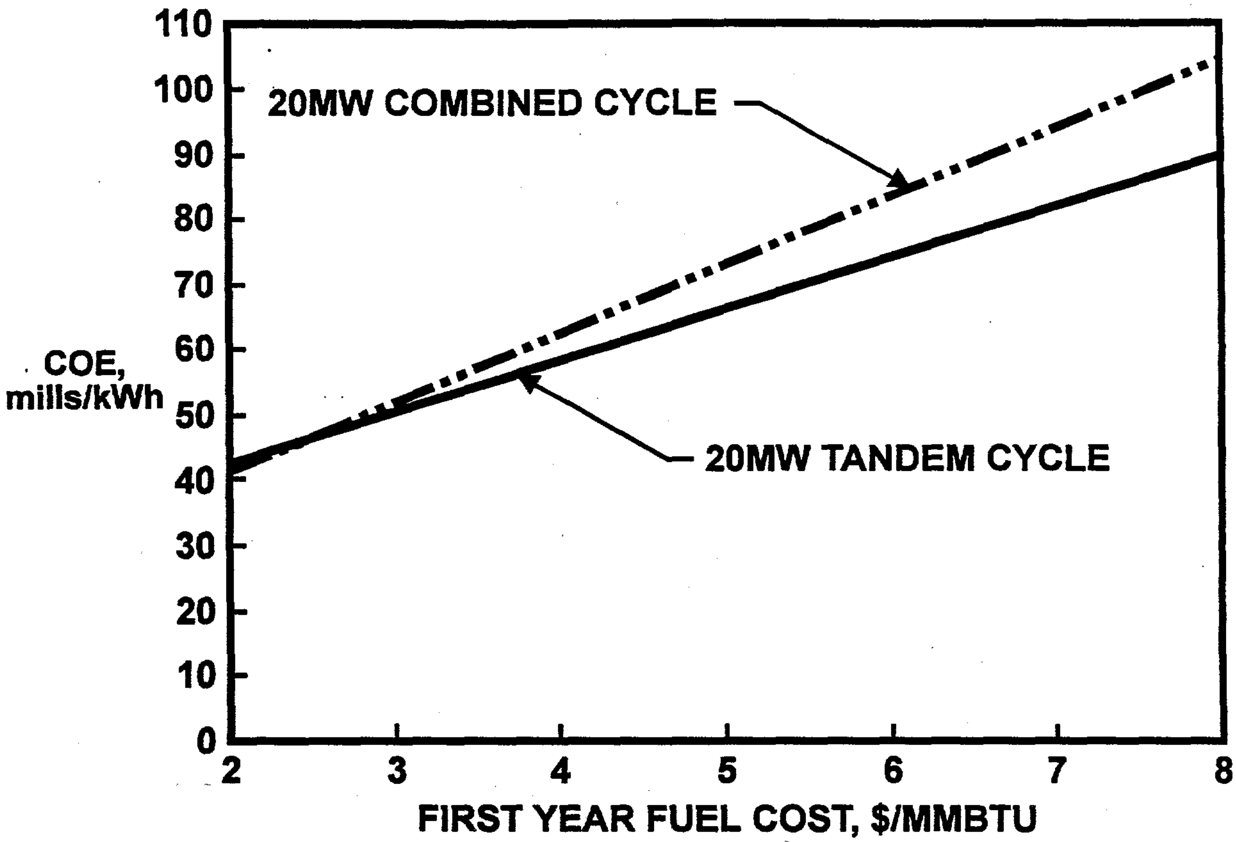
Power Generation, MW	200 MW	20 MW
Gas Turbine	27.1	4.2
Fuel Cell	157.6	14.3
Steam Turbine	32.8	4.1
Parasitic Power	-11.1	-0.8
Total	206.4	21.8

Efficiency of Tandem Technology

Net AC LHV Efficiency, %	200 MW	20 MW
Fuel Cell	55.1	56.8
FC + GT	61.7	52.9
Steam System	34.1	29.7
Overall	72.6	65.2

Levelized Cost of Electricity, 20-MW System
(1995 dollars, without inflation)

	Levelized Cost (mills/kWhr)
Fuel	23.8
Plant	13.2
O&M	13.0
Total	50.0



Cost of Electricity, Tandem Cycle Versus Combined Cycle

Conclusions: 20-MW Tandem Cycle

- LHV efficiency of 65 percent achievable with existing technology
- Competitive above $2.50/MMBtu fuel cost
- NOx emissions well below existing or proposed standards
- Can be implemented, near term (year 2001 and beyond) without significant development

Development Needs

- Design studies: (1) optimization and plant layout; (2) gas turbine design modification
- 20-MW demonstration with existing technology

Fuel Cell and Advanced Turbine Power Cycle

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Overview

Solar Turbines, Incorporated (Solar) has a vested interest in the integration of gas turbines and high temperature fuel cells and in particular, solid oxide fuel cells (SOFCs). Solar has identified a parallel path approach to the technology developments needed for future products. The primary approach is to move away from the simple cycle industrial machines of the past and develop as a first step more efficient recuperated engines. This move was prompted by the recognition that the simple cycle machines were rapidly approaching their efficiency limits. Improving the efficiency of simple cycle machines is and will become increasingly more costly. Each efficiency increment will be progressively more costly than the previous step.

Recuperated engines would be followed by more efficient intercooled and recuperated (ICR) engines, and finally, by a humid air turbine (HAT) cycle system. This latter engine system would be capable of providing efficiencies on the order of 60 percent with potentially low exhaust emissions.

Because of the many unknowns facing industry in the first two decades of the next century, such as possible fuel shortages and severe emissions regulations, Solar adopted a backup approach. This approach was intended to provide efficiencies higher than 60 percent with emissions lower than any possible with a gas turbine. The backup path is dominated by the concept of fusing the technologies of SOFCs with those of advanced gas turbines.

There is a synergy between the two systems. The two systems together can reach higher efficiencies that either alone. Fuel cell systems using gas turbines in the "topping" mode as the bulk of the balance-of-plant will have lower capital costs, higher power densities, and lower losses when compared to other approaches. The topping mode refers to the system configuration in which the fuel cell replaces the gas turbine combustor. The gas turbine, on the other hand, uses the fuel cell as both a solid-state generator and a combustion system. This eliminates the need for a power turbine, gearbox, and conventional electrical generator.

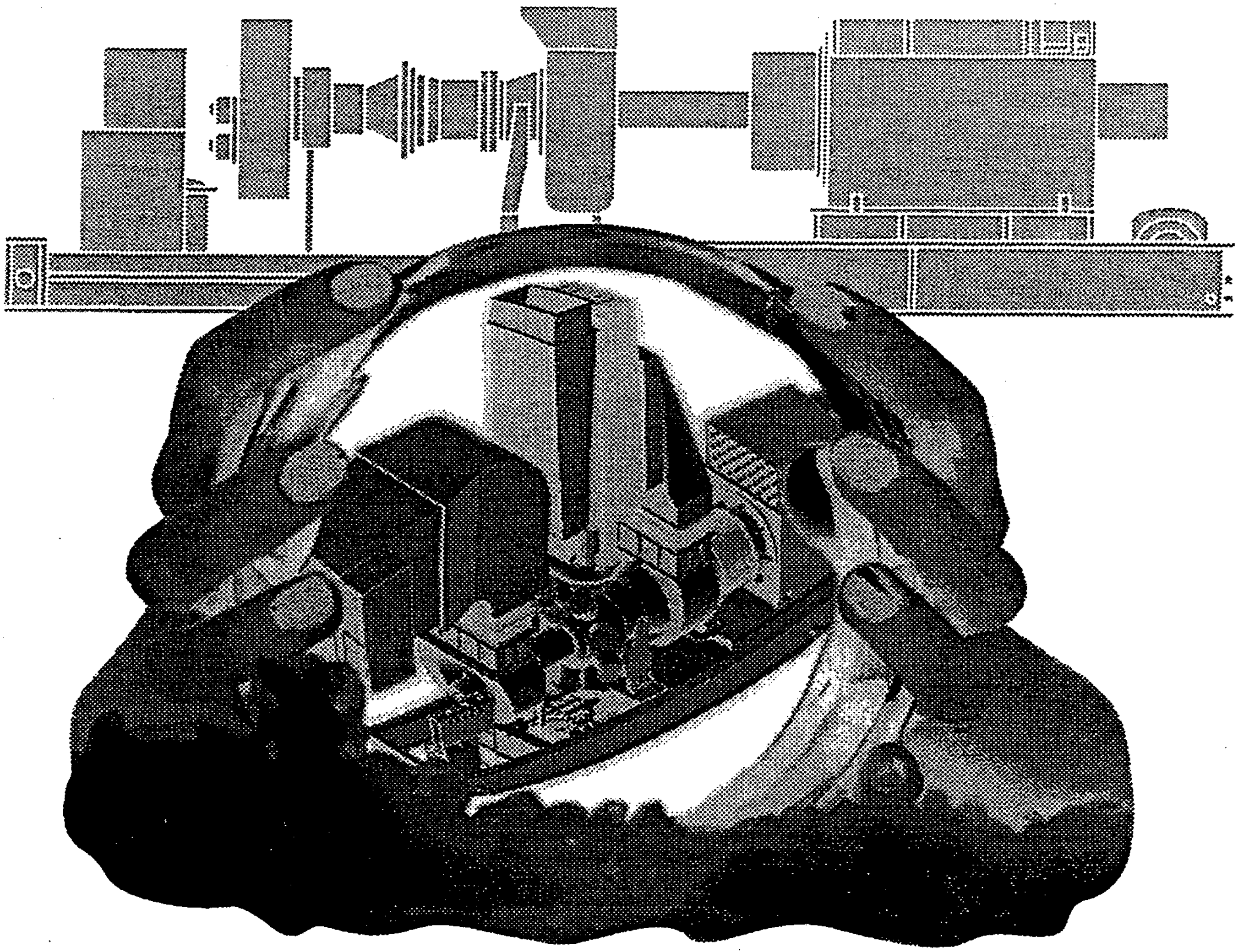
The preferred-cycle is one that employs the fuel cell as a topping system to the gas turbine. Approaches that use bottoming arrangements, where the fuel cell uses the gas turbine exhaust as the air supply, have not been ruled out, although these are likely to be both larger and less efficient unless complex steam bottoming systems are added. One advantage of the bottoming arrangement is that it will probably have a simpler control system than the topping approach. Indirect fired approaches have also been considered. In this approach, the exhaust of the fuel cell used in a bottoming configuration is added to an atmospheric combustion system that in turn is used to heat the gas turbine compressor air indirectly via a heat exchanger. The major problem is that it requires the development of high temperature ceramic heat exchangers if high efficiencies are to be obtained. These ceramic materials would also have to withstand high pressure drops over the "wall" of the heat exchange surface while operating at temperatures over 2,000 °F.

The combined SOFC and gas turbine (CSOGT) will be cost competitive with other future energy conversion systems that have similar efficiencies. This combination will, however, have an advantage because it will have lower NOx emissions than any heat engine system. The market niche for initial product entry will be the dispersed or distributed power market in non-attainment areas. Once established in this market, effort will be expended to penetrate all of the other power generating market segments. The first entry into the dispersed power market will take place between the years 2000 and 2004, with small units typically 1 to 2 MW. These units will probably sell initially for $650/kW, dropping to $500/kW when series production starts.

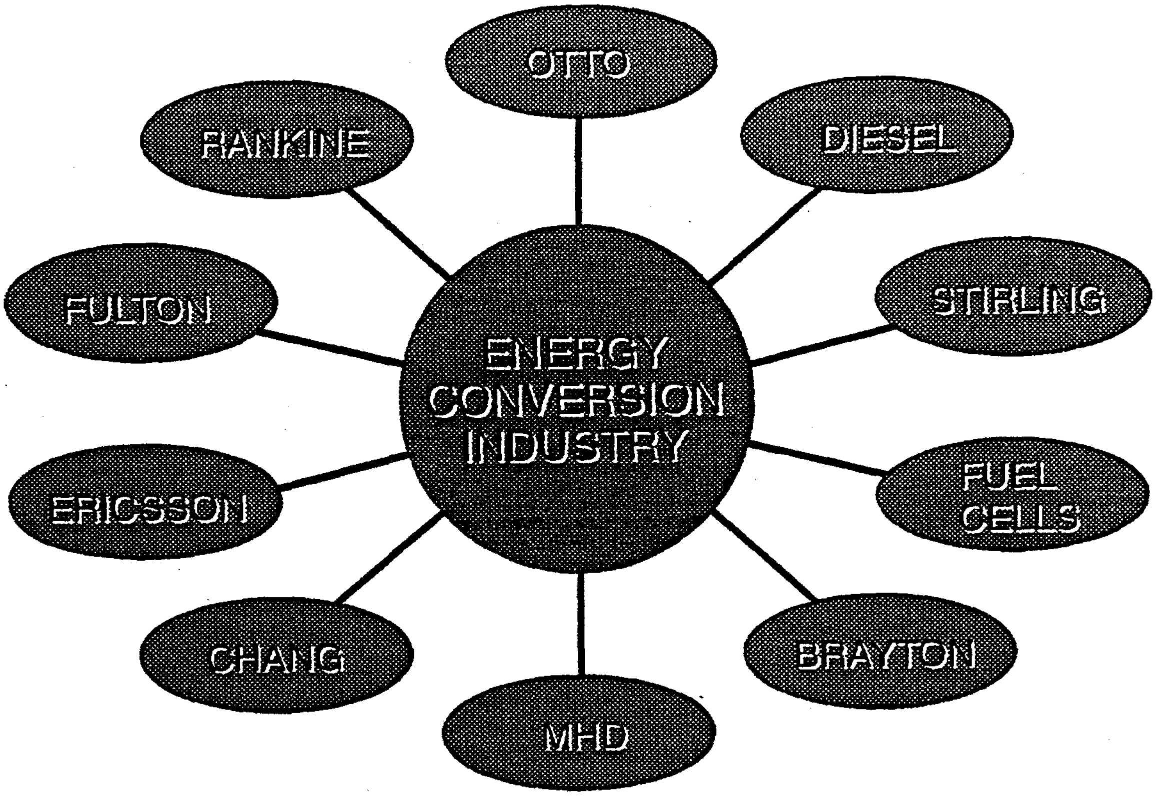
The development requirements are extensive if the combined SOFC and gas turbine or CSOGT system is to become a reality. For the fuel cell, the development of low-cost manufacturing is critically important. Material sulfur tolerance needs to be developed, because it will eliminate the requirement to remove sulfur from the fuel and the concomitant solid waste disposal problems. Sealing problems, particularly the manifold sealing problems, will have to be solved without significantly increasing production costs. Similarly, the integration of both heat exchange and fluid distribution systems with the stack proper will also have to be accomplished to attain the desired high efficiencies.

The gas turbine will also have development needs, with the start combustor and the control systems heading the list. After starting the combined system, the start combustor will probably have to endure the exhaust stream of the fuel cell, which will be oxidizing and at 1,750 °F or higher. The fuel system for the start combustor (like the combustor) will also have to survive temperatures on the order of 1,800 °F. Integration of the gas turbine with the fuel cell will require modifications to the construction of the gas turbine in order to accommodate the connecting ducts. Such connections will be available with recuperated engine configurations.

Integration of Gas Turbine and Fuel Cell



High Efficiency, Low Emissions Systems



Energy Conversion Industry

Socioeconomic Forces

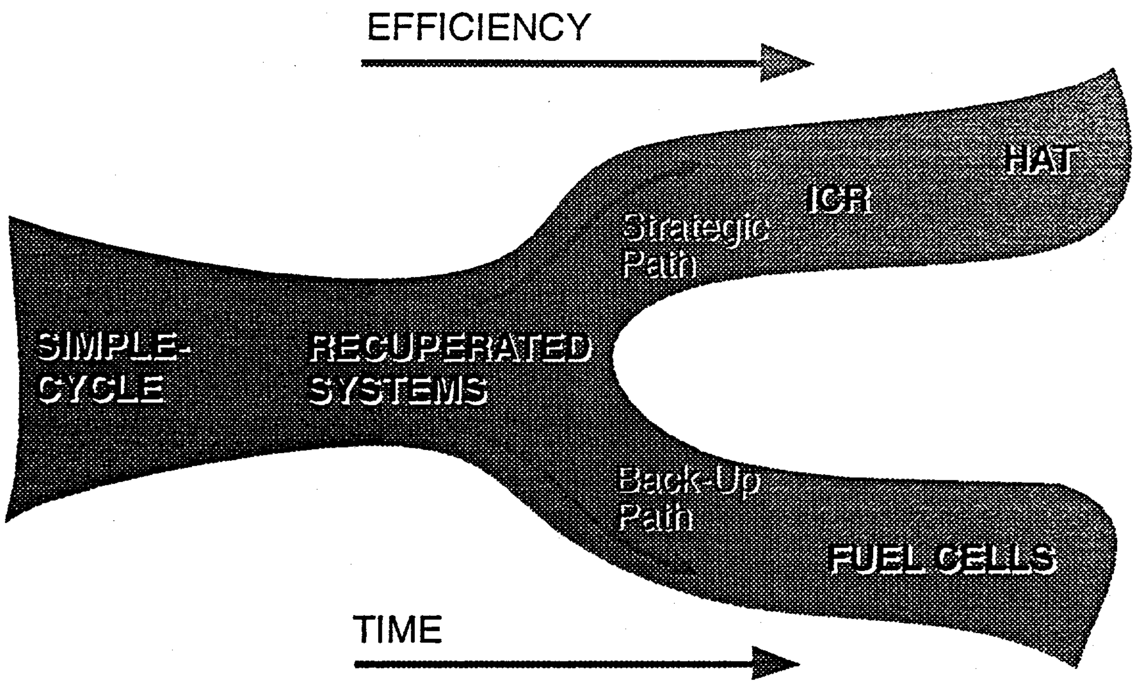
- Environmental Consciousness
- Conservation Needs
- Supplier Product Liability
- Product Recycling

Future Factors

- Demographic Changes
- Fuel Prices
- Emission Requirements

Overview

- Basis for Interest
- Preferred-Cycle Technology
- Cost Effectiveness
- Development Needs
- Market Niche
- Product Timing
- Product Cost Projections



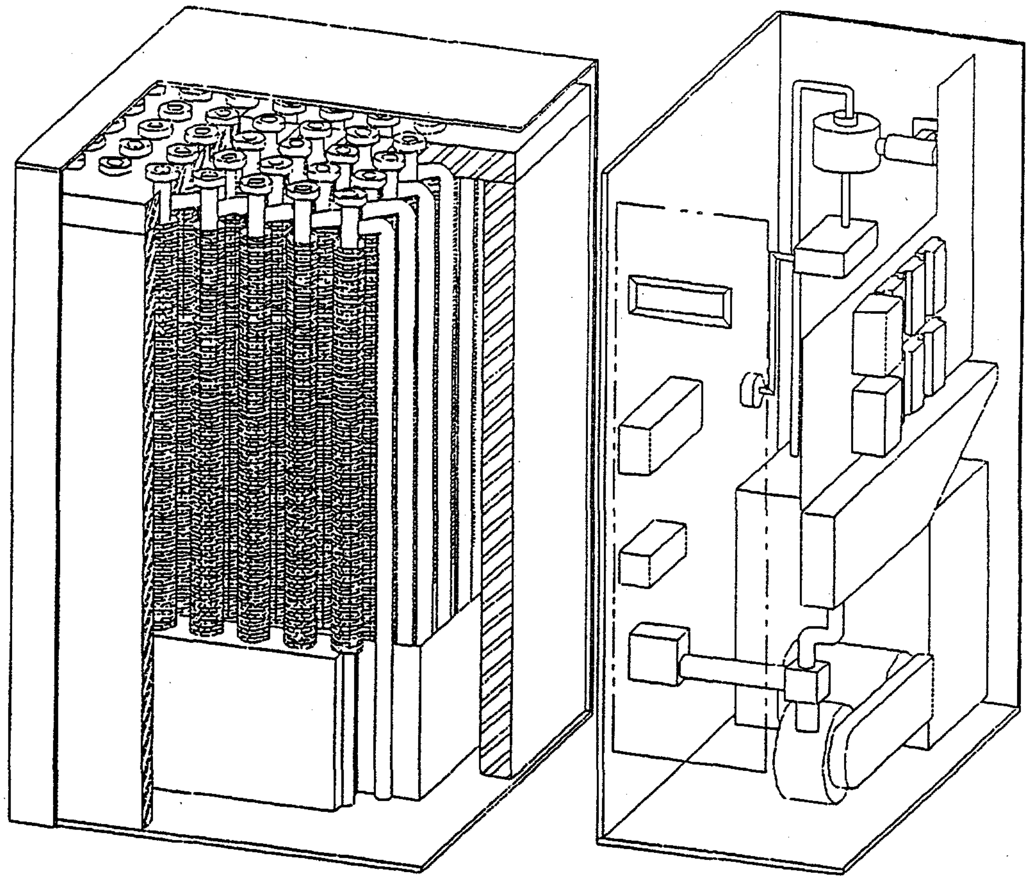
Parallel Paths

Cycle Selection

- Topping is Favored
  - Higher Oxygen Concentration at Cathode
  - Fewer Stacks
  - Higher Power Density

- Bottoming is Under Consideration
  - Easier Starting
  - Simple Control System

- Indirect Fired System
  - Needs More Study
  - Requires Material Development (Heat Exchanger)



Solid Oxide Fuel Cell System

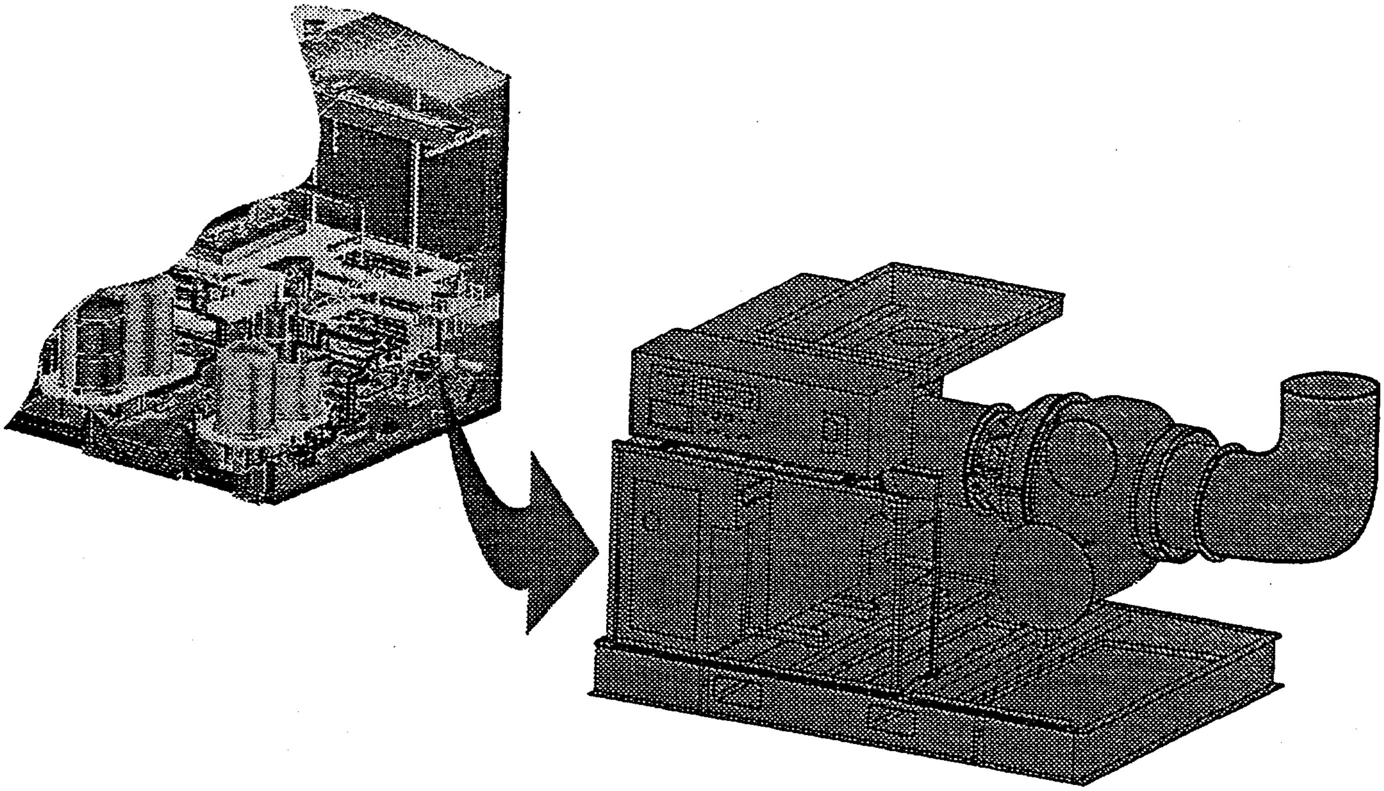
Gas Turbine Fuel Cell Integration: Solid Oxide Fuel Cells

Efficiency

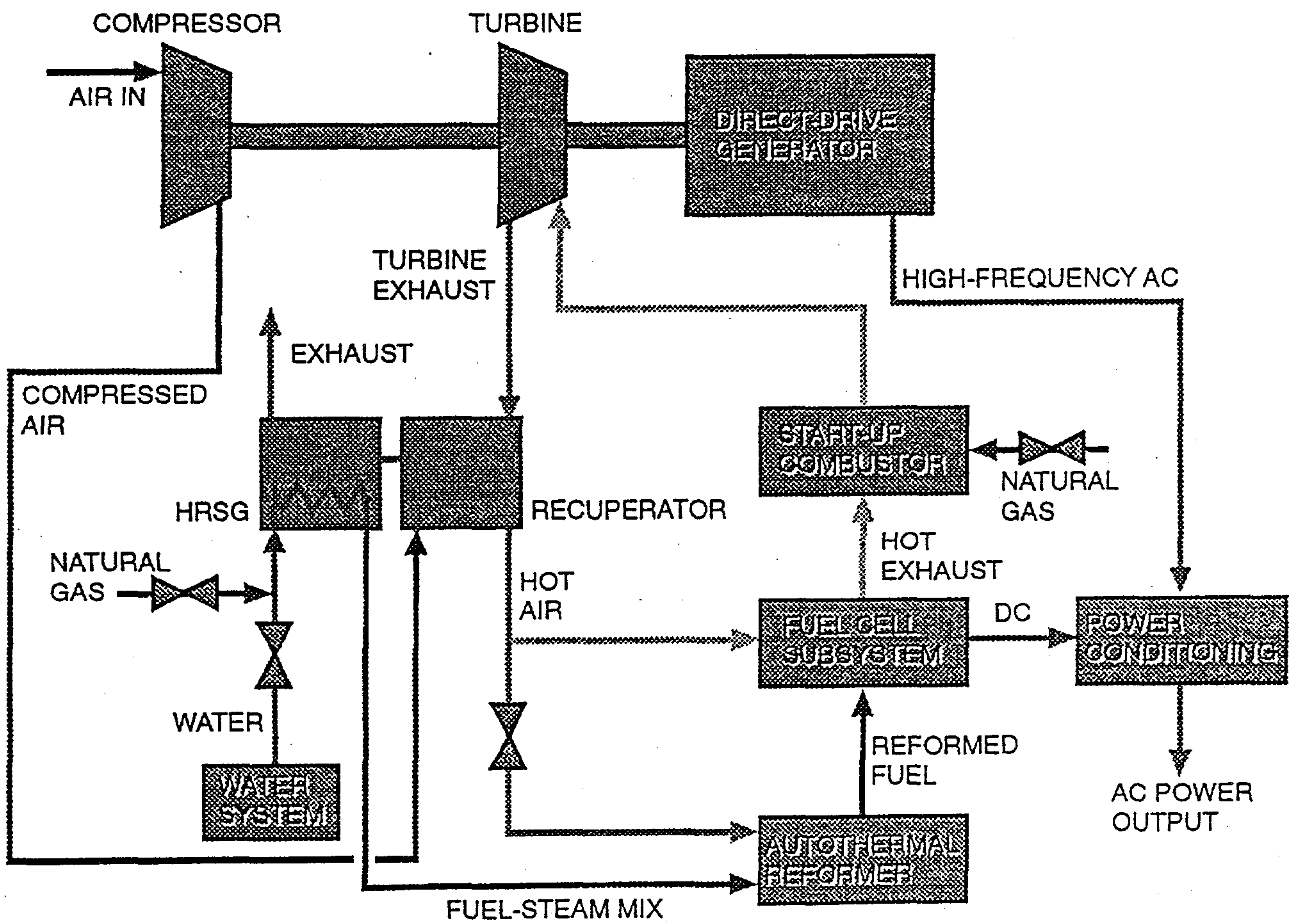
• No Carnot Cycle Limitations	
• Combined-Cycle Bottoming	75-80%
• Large, High Pressure Systems	65-70%
• Small, Low Pressure Systems	58-63%

Synergy

- Gas Turbine is Balance-of-Plant
- Fuel Cell Replaces Combustor and Generator



Fuel Cell Balance of Plant (BOP)



Integrated Gas Turbine and Fuel Cell

Environmental Technologies

- Air Quality Impact
  - Extremely Low NO_X, CO, UHC
  - Low CO_2
  - No Smoke

- Land Use Impact
  - Sulfur-Tolerant Fuel Cell
  - No Solid-Waste Streams

- Other
  - Low Noise
  - No Visible Plumes

Market Niche — Electrical Power Generation:

Dispersed Power Generation in Nonattainment Areas

- Initial Entry Size 1-to-2 MW
- Natural Gas Fueled
- Grid Interconnection: 480 Volts, 3-Phase, 60-Hz
- Commercial, Industrial, and Utility Customers

System Cost Trade-Off: Life Cycle

- Increasing Stack Content
  - Increases First-Cost, Efficiency

- Increasing Flexibility
  - Decreases Life-Cycle Cost

- Overall Cost-Effectiveness
  - Subsystem Efficiencies
  - Fuel Prices
  - Load Profiles
  - Capital Charges

Technical Development Needs: Gas Turbine

- Develop Uncooled, Start-Up Combustor
- Create Start-Up Combustor Fuel System
- Produce Control System (Based on Power Output)
- Integrate Fuel Cell Subsystems

Financial Development Needs

- Integrated System Producing between 1 and 2 MW

- Four Phase System
  - Phase 1: Study
  - Phase 2: Technology Development
  - Phase 3: Brassboard Evaluation
  - Phase 4: Prototype Field Test

- Total Cost between $16,000,000 and $25,000,000
  - Average Cost Share: 30%

- Manufacturing Development and Tooling
  - ROM $20,000,000

Summary

- Target Size: 1-to-2 MW
- Introduction in 2004
- Target Price < $650 kW
- Large Systems < $600 kW
- Dispersed Power Generation in Nonattainment Areas
- Fuel Cell Topping Cycle

Recommendations: METC Action Plan

- Initiate Funding of Cycle Studies
- Fund the Development of Needed Technologies
- Develop Brassboard Systems through Cofunded Programs
- Facilitate and/or Fund Prototype Production
- Monitor Field Testing

Ztek's Ultra High Efficiency Fuel Cell/Gas Turbine Combination

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Waltham, MA 02154

Ztek is proceeding on development of an ultra-high efficiency hybrid system of its Planar SOFC with a gas turbine, realizing shared cost and performance benefits. The gas turbine as the Balance-of-Plant was a logical selection from a fuel cell system perspective because of (1) the high-power-density energy conversion of gas turbines; (2) the unique compatibility of the Ztek Planar SOFC with gas turbines, and (3) the availability of low-cost commercial gas turbine systems. A Tennessee Valley Authority/Ztek program is ongoing, which addresses operation of the Advanced Planar SOFC stacks and design scale-up for utility power generation applications.

The advanced SOFC Fuel Cell/Gas Turbine hybrid approach discussed here is potentially capable of reaching electrical **efficiencies above 70 percent (LHV), or heat rate of less than 4,800 Btu/kWh (LHV).** This alternative has the distinct advantage of being applicable over a wide range of plant capacities, from sub-MW to multi-MW. Ztek's planar SOFC, which operates at 1,000 °C, has patented features which enhance direct integration with a gas turbine. This approach is based upon applying Ztek's Planar ATI® SOFC as a **C**ombustor **A**nd **R**ecuperator **R**eplacement for **A**dvanced **T**urbine **S**ystem (CARR-ATS). While its integration effort would be comparable to integrating a recuperator to the gas turbine, the SOFC would result not only in significant improved efficiency, but also added capacity and improved environmental performance. The SOFC will replace the combustor section, and displace the need for a recuperator for efficiency enhancement. Integrating Ztek's patented technology, therefore, can provide increased system efficiency and capacity with reduced NOx emissions.

The incentives and justification for the pressurized operation of the Ztek Advanced SOFC and integration with gas turbine bottoming systems are summarized below:

- The SOFC has **physically and chemically stable** electrolyte and electrodes which do not suffer adverse effects under pressurized operation.

- Ztek's Planar SOFC Technology is fully compatible with operation at ambient or elevated pressure conditions. The planar cell is **structurally compatible with operating at high pressure**, and tolerant to a finite pressure difference between opposing reactants, due to the mechanical design, materials, and the small free span chosen for the ceramic electrolyte supports.

- The pressurized operation of Ztek's Planar SOFC with its internal manifolding of controlled piping size will allow **high capacity module** integration.

- The performance of a fuel cell stack integration can increase with pressure due to favorable Nernst potential and enhanced flow uniformity at high pressure, resulting in **higher power density**. This further enhances the compactness and cost advantage in considerations of both the fuel cell stack, reactants piping, and the pressure vessel designs.

- Ztek's Planar SOFC design permits internal thermal management, resulting in a **high temperature exhaust gas** suitable for input to the integrated gas turbine. This is a significant benefit compared to other fuel cell designs which require external heat recovery and invariably reduce the exhaust temperature to a level too low to be useful.

In conclusion, the gas turbine represents a cost effective resource for the Balance-of-Plant in the fuel cell system, because of its energy conversion performance and the availability of off-the-shelf system components. The advanced thermal integration features of the Ztek Planar SOFC uniquely facilitate the hybrid system integration with a gas turbine. With the hybrid system integration, the Ztek Planar SOFC and gas turbine can mutually enhance the favorable characteristics of cost, efficiency, package flexibility, and environmental performance.

The Ztek Planar Solid Oxide Fuel Cell Technology has been developed under cost sharing of corporate funds and contracts with the Tennessee Valley Authority, the Electric Power Research Institute, the U.S. Department of Defense, and the U.S. Department of Energy.

Fuel Cell/Gas Turbine Integration

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P.O. Box 420
Indianapolis, IN 46206-0420

Allison Engine Company's interest in Very High Efficiency Fuel Cell/Advanced Turbine Power Cycles stems from:

- High system efficiency potential.
- Reduced emissions inherent to fuel cells opening markets in non-attainment areas.
- Unmanned operation (no boiler) particularly suited for distributed power.
- Existing product line matches fuel cell operating environment.

Figure 1 shows a schematic of a fuel cell/gas turbine cycle. The components within the dashed box represent the Allison 501-KB/KM engine family. The notes provide the range of ISO ratings and the range of conditions within which the fuel cell, heat exchanger, and burner would operate, such as air flow (Wa), compressor discharge pressure (CDP) and temperature (CDT), and turbine inlet temperature (TIT). Turbine outlet temperature (TOT) is shown for the heat exchanger design.

Figure 2 shows the potential overall cycle efficiency achievable by the addition of a fuel cell to the gas turbine cycle. The overall efficiency (EFFoa) is a function of the fuel cell to gas turbine power ratio (kWfc/kWgt) and the gas turbine cycle efficiency (EFFgt) as expressed by the equation at the top. The left end of the curves at zero power ratio are gas turbine cycles of 25, 30, 35, and 40 percent cycle efficiency. Moving to the right along the curves represents the inclusion of a fuel cell. The ratio of fuel cell to gas turbine power is dependent on the fuel cell technology within the operating environment provided by the gas turbine. The overall efficiency shown does not include gas turbine output gear box and generator losses, nor fuel cell output power conditioning losses. Substantial efficiency gains appear possible.

Table 1 shows a possible performance scenario for each of the Allison 501-KM engine models and also for the advanced turbine system (ATS) engine model. The upper portion of the table shows basic engine performance parameters. Simple cycle performance ranges from 2.8 to 5.2 MW, and 27 to 31.1 percent thermal efficiency for the 501-KM models. ATS performance is 12 MW and 42.5 percent thermal efficiency.

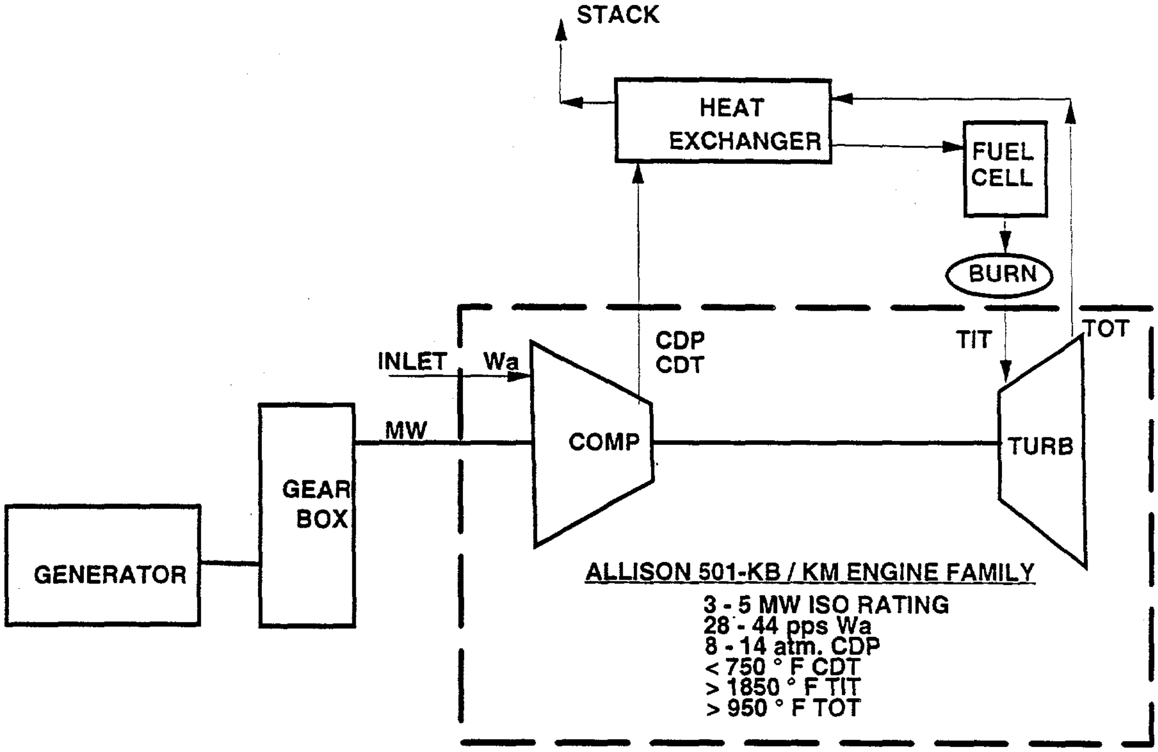

Figure 1. Schematic of Fuel Cell/Gas Turbine Cycle

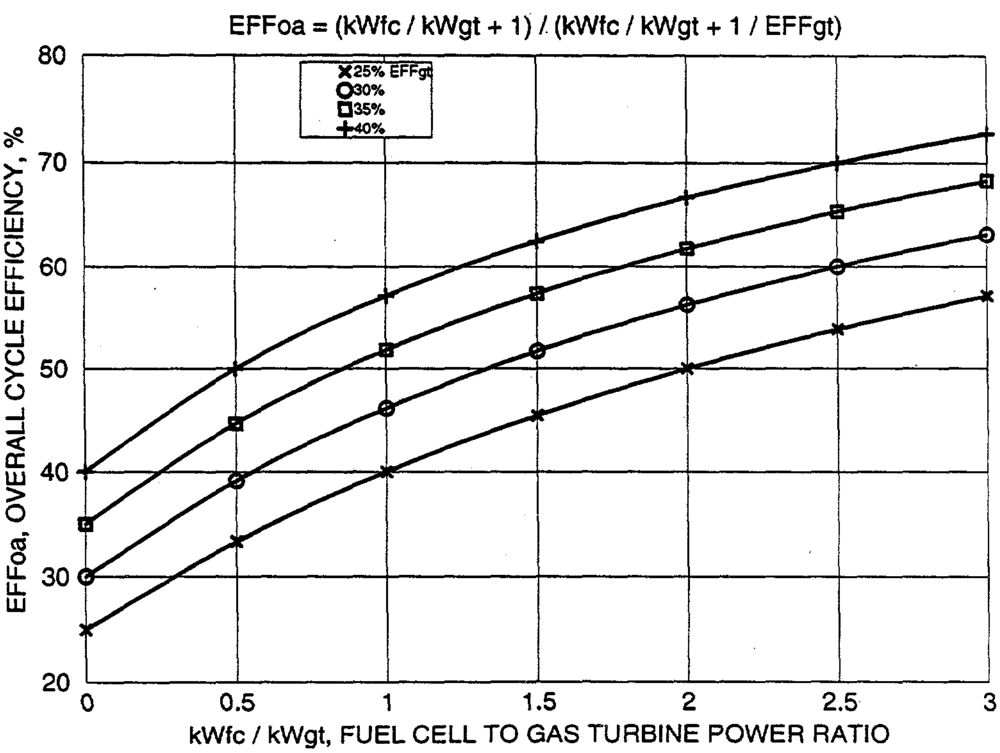

Figure 2. Overall Cycle Efficiency of Fuel Cell/Gas Turbine Cycle

Table 1. Fuel Cell/Gas Turbine Integration

ENGINE MODEL		501-KM3	-KM4	-KM5	-KM5S	-KM7	ATS
Air Flow	pps	27.9	33.8	33.8	33.8	44.4	59.3
Comp. Disch. Press.	atm	8.2	10.0	10.2	10.2	13.5	--
Comp. Disch. Temp.	°F	562	633	638	639	735	--
Turb. Inlet Temp.	°F	1875	1905	1985	2011	2016	--
Turb. Outlet Temp.	°F	1037	990	1037	1046	984	--
Output Power	MW	2.8	3.6	3.9	4.1	5.2	12.0
Thermal Efficiency (LHV)	%	27.0	28.9	29.6	30.4	31.1	42.5
RECUPERATED to 900°F							
Recup. efficiency	%	71.2	74.8	65.7	64.1	66.3	--
Output Power (5% loss)	MW	2.66	3.42	3.71	3.90	4.94	--
Thermal Efficiency (LHV)	%	34.5	34.7	34.9	35.7	33.9	--
FUEL CELL (0.2 MW/lb Air Flow)							
Fuel Cell Power	MW	5.58	6.76	6.76	6.76	8.88	11.86
Power Ratio (FC/GT)	--	2.10	1.98	1.82	1.73	1.80	0.99
FUEL CELL/GAS TURBINE SYSTEM							
Output Power (gross)	MW	8.24	10.18	10.47	10.66	13.82	23.86
Thermal Efficiency (LHV, gross)	%	62.0	61.3	60.2	60.2	58.9	59.5

Assuming current fuel cell technology will permit a 900 °F inlet temperature, the next portion of the table assumes a recuperator that raises the compressor discharge temperature to 900 °F. The required recuperator efficiency is a modest 65 to 70 percent for the 501-KW models. The ATS engine is designed for a high pressure ratio and firing temperature, making it unsuitable for recuperation, and will require additional fuel cell development to operate in this environment. Assuming a 5 percent power loss due to recuperator pressure loss, the 501-KW performance range is now 2.7 to 4.9 MW, and 33.9 to 35.7 percent thermal efficiency.

The next portion of Table 1 shows fuel cell performance assuming a fuel cell specific power output of 0.2 MW/lb/sec of air flow. Based on the air flow of each model, the fuel cell performance range is 5.6 to 8.9 MW with the 501-KW models, and 11.9 MW with the ATS model.

Next, compute the fuel cell to gas turbine power ratio to determine fuel cell/gas turbine system performance as shown in the last portion of Table 1. Overall performance (excluding mechanical and power conditioning losses) ranges from 8.2 to 13.8 MW and 58.9

to 62 percent thermal efficiency with the 501-KW engine models. Performance with the ATS engine model is 23.9 MW and 59.5 percent thermal efficiency.

Cost Effectiveness. Points of cost effectiveness of the system include:

- Optimum economics:
  - High cost of the fuel cell is offset by the low gas turbine cost.
  - Symbiotic technologies — the waste of one (fuel cell or gas turbine) is input to the other (gas turbine or fuel cell).
- Environmental control costs minimized by inherently low fuel cell emissions.
- Small MW package economics competitive by economy of scale of the gas turbine.
- Development costs primarily for the fuel cell.

Cost Estimates. Areas of gas turbine cost estimates for each phase of a program include:

- **Research:** costs mainly for overall cycle optimization.
- **Development:** (1) gas turbine/skid modification, (2) auxiliary equipment/component evaluation, and (3) balance of plant optimization.
- **Demonstration:** cost associated primarily with integrated system hardware; also cost of modifying gas turbine/skid.
- **Commercialization:** balance of plant cost a major factor.

Market Niche Objective. The market niche objective is distributed power generation (< 20 - 50 MW).

Timing. 501-KB/KM engines are currently in production, dependent on fuel cell timing. The ATS engine family will be available in the 1998 - 2002 time frame.

Cost Projections. Cost projections include $425 - $450 per kW installed for the 501-KB/KM engines. The total is dependent on fuel cell and balance of plant costs.

Appendices

Agenda

8:00a.m. - 8:30a.m.	Introductions Co-chairmen: Mark Williams and Chuck Zeh
8:30a.m. - 10:30a.m.	Technical Presentations Ron Wolk, Moderator Larry Rath -- METC Dave Archer -- Carnegie Mellon Harry Morehead -- Westinghouse George Steinfeld -- ERC David J. White -- Solar Dan Nathanson -- Ztek Terry Knickerbocker -- Allison
10:30a.m. - 10:40a.m.	Instructions for Breakout Sessions Ron Wolk
10:40a.m. - 11:00a.m.	Break
11:00a.m. - 12:30p.m.	Breakout Sessions Cycle Analysis Methodology Integration Issues R&D Needs Potential Approaches to Commercialization Markets
12:30a.m. - 1:15p.m.	Lunch
1:15a.m. - 2:45p.m.	Development of Action Plan Reports by Breakout Session Chairmen Synthesis of Recommendations for Action Consensus on Action Plan
2:45p.m.	Adjourn

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