Pressurized Circulating Fluidized Bed (PCFB) Repowering Project

**Annual Report
August 1991 - December 1992**

April 1993

Work Performed Under Contract No.: DE-FC21-91MC27364

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

**By
DMEC-1 Limited Partnership
Des Moines, Iowa**

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List of Acronyms

DMEC-1	Des Moines Energy Center
PCFB	Pressurized Circulating Fluidized Bed
DOE	Department of Energy
ACTF	Advanced Ceramic Tube Filter
CCT	Clean Coal Technology
ORNL	Oak Ridge National Laboratory
NEPA	National Environmental Policy Act
EIV	Environmental Information Volume
EPA	Environmental Protection Agency
RAM	Reliability, Availability and Maintainability
EPRI	Electric Power Research Institute
HRE	Heat Recovery Economizer
CFB	Circulating Fluidized Bed

1.0 Executive Summary

This report provides a summary of activities by the DMEC-1 Limited Partnership on the PCFB Repowering Project from project initiation in August 1991 through December 1992. This project is in its first budget period of activities where finalizing preliminary design, cost, and business aspects are the focus.

In August of 1991, Iowa Power, Dairyland Power Cooperative, Pyropower Corporation and Black & Veatch initiated the preliminary design of the DMEC-1 Pressurized Circulating Fluidized Bed (PCFB) Repowering Project. As a result of a July 1992 merger between Iowa Power and Iowa Public Service, Midwest Power was formed. The DMEC-1 project will demonstrate "First Generation" PCFB technology and will result in an existing steam turbine being repowered with steam from a PCFB boiler. Exhaust gases from the PCFB boiler will be expanded through a gas turbine to provide additional power output.

The technical and cost baselines of the Cooperative Agreement were based on conceptual engineering and design. These baselines will be refined during the first budget period. Other activities in the first budget period of the Cooperative Agreement includes tasks to evaluate alternate hot gas filters and the concept of a topping combustor. The Statement of Work in the first budget period of the Cooperative Agreement also includes the development of the preliminary design of the power plant, preparation and submittal of environmental information, performance of studies and system analysis, and refinement of cost and schedule baselines.

The preliminary design is progressing. As the design is refined and modified, cost and schedule baselines will be updated. Environmental information has been obtained and submitted to The Department of Energy (DOE) with no obvious problems or concerns identified. Testing analysis and evaluations of systems continue.

A key feature of design verification testing has been and will continue to be the testing of ceramic barrier filtration technologies including the Asahi Advanced Ceramic Tube Filter (ACTF) and Westinghouse's Candle Filter. At the time of this report testing has been completed on the Asahi ACTF and tests have been initiated on the Westinghouse filters. In general terms, the Asahi design was successful in reducing the outlet dust loading to required levels but certain problems were encountered which led to some premature ceramic tube failures.

Analysis of the topping combustor resulted in the conclusion that the topping combustor, fired by natural gas or fuel oil, did not satisfy the objective of providing cost effective peaking capacity in this project. Overall plant heat rate improvements, while topping are offset by higher fuel cost and decreased power output. DOE approval was therefore requested to delete the topping combustor from the DMEC-1 PCFB Demonstration Project.

Deletion of the topping combustor in this project is not to be construed that topping combustors are not feasible on PCFB systems. The further advancement of the technology (advanced PCFB) is to include provision of a "coal fired" topping combustor operating continually. This concept is proposed as part of the Clean Coal Technology (CCT) V program for repowering DMEC-2.

This document provides detailed discussion of accomplishments and activities completed during Phase I of the DMEC-1 PCFB Repowering Project.

2.0 Introduction and Background

In August of 1991, Iowa Power, Dairyland Power Cooperative, Pyropower Corporation, and Black & Veatch initiated the preliminary design of the DMEC-1 Pressurized Circulating Fluidized Bed (PCFB) Repowering Project. As a result of a July 1992 merger between Iowa Power and Iowa Public Service, Midwest Power was formed. Midwest Power has assumed the role of General Partner for the DMEC-1 Limited Partnership and has assumed the associated responsibilities of the project. The project is named after the plant's location, i.e., the Des Moines Energy Center. The project has been awarded \$93,253,000 of cost sharing from the DOE Round 3 CCT Program.

The DMEC-1 project will demonstrate "First Generation" PCFB technology and will result in an existing steam turbine at the DMEC-1 site being repowered with steam provided by a PCFB boiler. Exhaust gases from the PCFB boiler will be cleaned at 1600° F and exhausted through a gas turbine which will provide over 20 percent of the resulting plant's net power output. The resulting improvement in the net plant heat rate of the DMEC-1 site will be about 15 percent better than that of the original steam plant, while emissions will be controlled within New Source Performance Standards.

Repowering of the existing steam turbine at DMEC-1 will result in about 87 MWe gross power output. The plant will be designed to fire a range of coals including high sulfur bituminous coals from Illinois, Iowa, and low sulfur subbituminous Western coal from the Powder River Basin in Wyoming. The PCFB will replace a retired pulverized coal fired boiler to repower an existing steam turbine. The steam conditions in the boiler are expected to be 506,200 lb/hr at 1300 psig and 955° F. Approximately 65 MWe will be produced from the steam turbine. The gas turbine will provide an additional 22 MWe of power.

The PCFB Repowering Project will combine the new technology of the AHLSTROM PYROFLOW® PCFB process with a conventional steam generation power plant. The unit will be designed and furnished by Pyropower Corporation, San Diego, California, the U.S. subsidiary of A. Ahlstrom Corporation of Helsinki, Finland. The project will be a commercial scale-up from an existing PCFB test facility located in Karhula, Finland. Black & Veatch, Engineers - Architects, Kansas City, Missouri, will be responsible for engineering of the balance of the plant.

This section will provide an overview discussion of the "First Generation" PCFB technology planned for demonstration at DMEC-1 and will summarize the status of each of the activities to be carried out during the first budget period of the project.

2.1 Description of the DMEC-1 Site

The Des Moines Energy Center (DMEC) is located southeast of the City of Des Moines, Iowa, in the City of Pleasant Hill. The plant is located adjacent to the Des Moines River on Highway 46.

The DMEC was first constructed in 1925 with the installation of two steam turbine generators and six stoker fired boilers and was originally known as Des Moines Power Station. Between 1925 and 1964, five steam turbine generators and five pulverized coal fired boilers were added to meet growing electricity demand in central and southwest Iowa. The station capability was approximately 335 MWe between 1964 and 1975. The units operated in base load mode up to the late 1970s. Operation of the facility throughout the 1980s was reduced due to the addition of other more efficient large steam generating units to the system. Steam turbine #6, which will be repowered in the DMEC-1 project, was mothballed in 1985.

During Round 3 of the CCT, the Dairyland Power Cooperative Alma Project was selected by DOE. In May of 1991, a Partnership Agreement between Dairyland Power Cooperative and Iowa Power (now Midwest Power) was reached to transfer the project from Dairyland's Alma site to DMEC. A Cooperative Agreement with the DOE for the DMEC-1 Project has been signed by the Partnership and DOE. As a result of a merger in July 1992, Midwest Power assumed the role and responsibilities of the DMEC-1 General Partner.

2.2 Balance of Plant

The DMEC-1 project will require the refurbishment or replacement of major equipment. Turbine generator 6 will be refurbished to serve as the steam powered turbine generator. The existing turbine generator is rated at a nominal 65 MWe. It is a non-reheat turbine that is designed to operate at 1250 psig and 950° F with a steam flow of up to 561,000 lbs/hr. The generator is hydrogen cooled (up to 30 psi hydrogen pressure) and operates at 3,600 rpm.

In addition, the existing coal handling facilities, structure, and some of the major auxiliaries such as the boiler feed pumps, condensate pumps, circulating water pumps, fuel oil, condensate and surge tanks, deaerator, feedwater heaters, auxiliary

heat exchangers, etc. will most likely be refurbished with some components being replaced. Since the design life of the repowered facility will be 30 years, an examination of refurbishment versus new equipment will be performed to determine which option has the lowest life cycle cost. New equipment includes the main step up transformer; main auxiliary and reserve auxiliary transformers; a modern digital control system; instrumentation for the PCFB; the gas turbine; new electrical distribution system and switchgear; new demineralizer; modernization of the steam turbine and generator auxiliaries; re-tubing of the condenser and some of the feedwater heaters; replacement of the cooling towers; and new motors and pumps for cycle support processes.

2.3 Pressurized Fluidized Bed Combustion

The PCFB process utilizes a combined cycle which employs a combination of a gas turbine and steam turbine to generate power. The pressurized combustion chamber is used to burn coal to produce steam for the steam turbine which produces 75-80 percent of the plant output. The hot flue gases are filtered and expanded through a turbine to generate the remaining 20-25 percent of the plant output and to supply the compressed air for the PCFB combustor.

Coal and sorbent are supplied to the PCFB combustor as a paste using a technology similar to that used in pumping concrete. The materials are injected into the PCFB combustor with the assistance of a steam atomizer to distribute the particles. As combustion occurs, sulfur is absorbed by the sorbent. Particles of coal and sorbent become entrained with the flue gas and are collected in a cyclone and returned to the combustor. The finer particles continue with the hot gases to a ceramic filter where final removal of particulates is achieved. The cleaned flue gas is expanded through the gas turbine and remaining useful heat in the exhaust is recovered in a conventional heat recovery unit. The clean exhaust is released to the stack.

3.0 Project Objectives

The primary objective of this cooperative project is to demonstrate PCFB repowering technology. If the demonstration project is successful, PCFB technology could become commercialized during the 1990's and will be capable of (1) achieving significant reductions in the emissions of sulfur dioxide and the oxides of nitrogen, as compared to existing facilities, which would minimize environmental impacts such as transboundary and interstate pollution and (2) providing for future energy needs in an environmentally acceptable, efficient, and cost effective manner.

3.1 Overview and Objectives

Specifically, the DOE will share cost with the Participant in the project to demonstrate that PCFB combined-cycle technology, when operating at a commercial scale, is a cost effective, reliable, and environmentally superior technology which can achieve significant reductions of SO₂ and NO_x emissions when compared to existing and future coal-burning power plants. The project will be the first commercial scale-up of a pilot plant system. The PCFB process components will be designed and built by Pyropower Corporation of San Diego, California. The technical challenges associated with this project will include the first use of a commercial size PCFB combustor module in a full-scale utility demonstration. The project will be accomplished in three phases; design, construction, and operation. Phase 1 (design) is comprised of two budget periods. Budget Period 1 includes preliminary engineering while Budget Period 2 is detailed engineering. Budget Period 1, the current period, is scheduled to be complete by June 30, 1993.

3.2 Budget Period 1 Objectives

The activities in Budget Period 1 include completing the preliminary design, performing studies and system analysis, permitting, and refining cost and schedule baselines for the project. One of the key analyses being addressed in Budget Period 1 is the choice of a filter for the PCFB process.

Specific goals for Budget Period 1 include the following.

- Update and refine preliminary engineering to establish the project cost and schedule baselines.
- Conduct process verification testing providing performance data for hot gas filter options, gas turbine materials and coatings and fuel options.

- Finalize plans for appropriate agreements.
- Complete the preliminary design, site and plant arrangement drawings, Project Design Manual and other documentation.
- Provide information and support for DOE to satisfy responsibility under the National Environmental Policy Act (NEPA).
- Provide a draft Environmental Monitoring Plan.
- Formalize the permitting plan.
- Preliminary demonstration plan.

3.3 Accomplishments

The first budget period is currently underway and several project activities have been accomplished.

3.3.1 Finalization of Site, PCFB Island, and Balance of Plant Design Criteria

In May of 1991, the site for the PCFB demonstration project was relocated from the Alma site owned by Dairyland Power Cooperative, to the Des Moines Energy Center. Relocation of the project resulted in some changes to the project design criteria. Re-siting considerations included the capacity of the repowered steam turbine, steam conditions, coal types and equipment delivery methods. Table 1 summarizes some of the re-siting considerations.

The steam turbine at DMEC-1 has a greater capacity than the original turbines planned for Alma. As a result, the plant capacity (including the gas turbine) has been increased in scale from the original Alma capacity of about 41 MW gross to the DMEC-1 site of about 87 MWe gross. This will require a larger gas turbine, PCFB, and related process components sized to meet the heat input requirements of the DMEC-1 steam turbine. The steam conditions of the two turbines are different, requiring a different pressure parts configuration in the PCFB boiler and heat recovery systems. In order to provide Midwest Power with the flexibility to use the most cost effective coal in the event of changing market conditions, and to satisfy DOE's desire to demonstrate the PCFB on a range of high and low sulfur fuels, the plant will now be designed to burn a range of fuels including low sulfur Western subbituminous coal and high sulfur Midwestern bituminous coal. The Alma plant was to be designed specifically for Midwestern bituminous coals.

Table 1
Comparison of Alma and DMEC-1 Site Design Criteria

<u>Parameter</u>	<u>Dairyland Alma Site</u>	<u>Midwest Power DMEC-1 Site</u>
Application	Repowering	Repowering
Steam Turbine Conditions		
Flow, 1000 lb/hr	233	506
Pressure, psig	860	1300
Temperature, °F	900	950
Output, MW	32	65
Matching Gas Turbine Output	9	22
Design Fuels	Illinois No. 6	Western Subbituminous Illinois No. 6 Iowa Coal
Typical Design Variables		
Design Moisture	10.0	10-31
Design Ash	15.0	5-16
Design Sulfur	3.7	0.4-4.0
Delivery Options	Barge, Rail, Truck	Rail, Truck

Table 2 provides a comparison of Illinois No. 6 and Powder River Basin coals, included in the range of coals for the DMEC-1 design. Of greatest significance are moisture, ash, and sulfur. The Western coal has significantly higher moisture. Since water must be added to the fuel to make a paste, this is an important issue. Preliminary studies have indicated that the Western coal can be fed as a paste in a cost effective manner.

The differences in ash and sulfur content of the Illinois and Western coals are also important. The total amount of ash and spent sorbent generated during the combustion of Illinois coal will be about 2.5 times greater than the amount generated with the Western coal. Ash cooling and depressurization systems must be designed with this consideration in mind.

The Alma site is located on the Mississippi River, where large components can be delivered by barge. The DMEC-1 site is limited to rail or truck delivery. As a result, the pressure vessel for the DMEC-1 project will be field erected as opposed to the original plan of a shop fabricated pressure vessel for Alma.

3.3.2 Calculation of Full and Part Load Plant Performance

Full load performance for the gas turbines under evaluation for use in the DMEC-1 project, has been performed. Table 3 provides preliminary results of the predicted plant performance analysis. Repowering with the PCFB is anticipated to improve the heat rate of the plant by about 15 percent while reducing plant emissions to compliance with New Source Performance Standards.

As is the case for any repowering of an aged low pressure non-reheat steam turbine, the heat rate of the DMEC-1 unit will be limited by the efficiency of the existing steam turbine and plant station service requirements. With a new conventional reheat steam turbine, net plant efficiencies of over 42 percent (8100 Btu/kwh net) are achievable with the PCFB cycle planned for demonstration in the DMEC-1 project. Efficiencies as high as 45 - 46 percent (7400 - 7600 Btu/kwh net) are achievable with the Advanced PCFB cycle where higher gas turbine inlet temperatures are utilized.

Table 2
Composition of Planned Fuels for the DMEC-1 Project

	Western Coal <u>Typical</u>	Illinois Coal <u>Typical</u>
Carbon (%)	48.7	61.8
Hydrogen (%)	3.3	4.2
Sulfur (%)	0.4	3.0
Nitrogen (%)	0.7	1.0
Chlorine (%)	0.0	0.1
Oxygen (%)	11.6	7.6
Moisture (%)	30.6	12.7
Ash (%)	4.7	9.6
Heating Value (Btu/lb)	8,350	11,100

Table 3
Predicted DMEC-1 Plant Performance

<u>Material and Gas Flows</u>	<u>Western Coal</u> Flow Rate, lb/hr	<u>Illinois Coal</u> Flow Rate, lb/hr
Coal Paste	143,700	95,600
Limestone	3,200	10,700
Combustion Air	824,400	824,400
Stack Exhaust Gas	962,300	910,400
Ash and Spent Sorbent	9,000	20,300
 <u>Regulated Emissions</u>		
SO ₂ Reduction for All Fuels	90 (%)	90 (%)
NO _x , lb/MMBtu	0.3	0.3
Particulates, lb/MMBtu	0.03	0.03
 <u>Power Output (Gross)</u>		
	<u>MWe</u>	
Gas Turbine	21	16.6
Steam Turbine	65	63
Approximate Improvement in Net Plant Heat Rate After Repowering with the PCFB	15 (%)	15 (%)

3.3.3 Submission of Environmental Information to DOE to Support Fulfillment of the Requirements of the National Environmental Policy Act (NEPA)

The intent of the CCT Program is to demonstrate the efficient production of energy with significant reductions in the emissions of sulfur dioxide and nitrogen oxides in comparison to existing commercial technologies. Because the project is receiving federal funding through the U.S. DOE CCT Program, the DMEC-1 Project must comply with the National Environmental Policy Act (NEPA). Prior to receiving federal funding for construction or operation NEPA activities must be fulfilled.

In June 1992, the final Environmental Information Volume (EIV) was submitted to DOE in support of the NEPA environmental review process. The EIV provided the background environmental and socioeconomic data characterizing the proposed project and identified the expected impacts from project construction and operation. Only July 8, 1992, Midwest Power and Black & Veatch personnel assisted with a public scoping meeting conducted by DOE and held in Pleasant Hill.

At the request of DOE and DOE's support contractor, Oak Ridge National Laboratory (ORNL), additional site environmental investigations were undertaken, including the following:

- Archeological, historic, and cultural resources investigation;
- Ambient noise survey and impacts assessment;
- Threatened and endangered wildlife species investigation; and
- Wetlands, plant communities, and protected plant species investigation.

Formal reports of the additional site investigations were provided to DOE and ORNL. In addition, Midwest Power and Black & Veatch personnel have answered all questions and requests for information from DOE and ORNL to further assist with completion of the NEPA review process. The Environmental Impact Statement is currently being developed by DOE.

3.3.4 Specification Development for Major Equipment Components, Bid Solicitations, and Evaluations

In support of development of an updated cost estimate and schedule, specifications were developed for quotations for supply of the gas turbine and ceramic filler.

Detailed specifications were issued to candidate gas turbine suppliers. Firm priced quotations have been received and are in evaluation.

Specifications have been issued for budgetary quotation for filter components and for supply of complete filter systems. A detailed specification was issued in mid-1992. Quotations are currently being evaluated.

Other specifications which have been issued and quotations received, include:

- Coal feed system components.
- Limestone feed system.
- Ash cooling and depressurization system.
- Heat recovery system.
- Booster and filter air compressors.
- After cooler and pre-cooler.
- Pressure vessels for furnace and filter.
- Pressure parts.
- Control and shutdown valves.
- Steam drum.
- Start-up burner.
- Temperature control unit.
- Large bore piping.
- Erection of PCFB Island.

Several evaluations of alternative equipment subsystems have been performed or are planned.

Fuel Feed System. Preliminary evaluation indicates that a paste feed system is the preferred option for both the high moisture Western subbituminous fuel and for the lower moisture Midwestern bituminous fuels. Paste feeding tests will be performed with both fuels.

Gas Turbine Inlet Air. Alternative systems for conditioning the inlet air to the gas turbine have been evaluated.

Pressure Part Arrangement. Alternative configurations for pressure parts arrangement to optimize plant cost and maintainability are under evaluation.

Ceramic Filter. Candle and tubular filter designs are being evaluated.

Topping Combustor. A detailed report evaluating the impacts of the use of an oil or natural gas fired topping combustor at DMEC-1 has been completed. The evaluation compared the trade offs of increasing the output of the gas turbine by raising the turbine inlet temperature versus the costs for burning oil and/or gas and the costs for adding a topping combustor to the project. Results indicate the addition of the topping combustor to the DMEC-1 project does not provide the desired peaking capacity, does substantially increase the capital cost of the project, and does increase the cost of generation because of increased fuel cost. Because of site-specific reasons, approval was requested from DOE to delete the topping combustor from the DMEC-1 project. Consideration of the benefits of large scale demonstration of a topping combustor are under consideration, as a bridge to the future demonstration of topping utilizing coal derived gas.

3.3.5 Development of Site and Plant Arrangements

Figure 1 provides the existing plant arrangement and the planned new plant arrangement. The new PCFB and ceramic filter will be placed in the location that the retired boiler #10 and precipitator occupied. The gas turbine and its generator will be located where the boiler #6 was located. Much of the existing steam turbine and associated auxiliaries will be refurbished and reused. The existing coal conveyors, building structure, and major components will be refurbished and reused to the extent practical.

3.3.6 Development of a Plant Control Philosophy

Alternative approaches for start-up, load following, controlled shutdown, and emergency shutdown have been developed. Plant start-up, load following, control, and controlled shutdown will employ conventional techniques and systems similar to approaches utilized in gas turbine and fossil fired power plants.

Emergency shut down may require the application of high temperature valves which are an extension of technology applied in the catalytic cracking industry. Multiple suppliers of these valves have been identified and an evaluation of their respective technical approaches is underway. Transient analysis of the response characteristics of the gas turbine generator under a rapid loss of load conditions is under development. Preliminary analysis indicates that a single shaft gas turbine operated under design conditions planned for the DMEC-1 project may not be

Existing Plant Arrangement

Detail of Planned Plant Arrangement

Existing and Planned Plant Arrangements

Figure 1

subject to over-acceleration even if the generator trips and the hot emergency shutdown valves fail. Further evaluation of this fail-safe approach is planned.

3.3.7 Refinement of a Project Schedule and Plant Cost Estimate

The updated plant cost estimate will be developed late in Budget Period 1, following receipt and evaluation of all quotes to specifications. Costs for the balance of plant and for the PCFB island will be compiled into the estimate. An updated detailed project schedule will also be submitted at that time. The current schedule is shown in Figure 2.

3.3.8 Process Design Verification Testing of Proposed Fuels and Sorbents at the Ahlstrom Karhula PCFB Testing Facility

The Electric Power Research Institute, in cooperation with Midwest Power, has arranged for the shipment of 500 tons of coal from the Wyoming Powder River Basin and 100 tons of Iowa Industrial Limestone for design verification tests at the Ahlstrom PCFB Testing Facility located in Karhula, Finland. To date, over 3000 hours of testing funded privately by Ahlstrom and EPRI have been completed at Karhula, including evaluation of Illinois No. 6 coal, Polish coal, and Australian coal. Limestones from Wisconsin and Sweden have also been evaluated. Testing results have been very promising, with combustion efficiencies in excess of 99.5 percent, and very low emissions of NO_x , SO_2 , N_2O , CO , and particulates. In all of these areas, the performance of the PCFB testing facility has exceeded expectations.

Ceramic Filter Testing. A key feature of the pilot plant testing has been and will continue to be the testing of ceramic barrier filtration technologies including the Asahi Advanced Ceramic Tube Filter (ACTF) technology and Westinghouse's Candle Filter Technology. Testing had been completed on the Asahi ACTF filter and the filter pressure vessel has been modified to accommodate a Westinghouse candle cluster. A detailed report on the results of the Asahi ACTF testing is still under preparation for submittal to EPRI who co-funded the testing. No detailed results of the filter testing will therefore be presented until the EPRI report has been submitted. In general terms, the Asahi design was successful in reducing the outlet dust loading to the level required by gas turbine manufacturers but some premature ceramic tube failures occurred. Shakedown testing of the Westinghouse candle filter

Current Schedule
Figure 2

was initiated in the fall of 1992. This test was successfully concluded in early November. This was followed a week of inspection and minor pilot plant modifications. Long term testing was initiated with Rawhide and Illinois No. 6 coals.

The configuration of the Asahi filter previously tested is shown schematically in Figure 3. A total of 21 beta cordierite tubes were installed in the vessel between three water cooled tube sheets. Each tube was 170 mm in diameter (OD) and 6210 mm long including the associated sleeves and bellows. Dirty gas entered the top of the vessel and flowed down into the tubes. The ash was deposited on the inside of the tube and the clean gas exited the vessel through the two side gas outlets. Back pulse air used to periodically clean the tubes was introduced through the gas outlets and then preheated in regenerators. Ash cleaned from the tubes fell into the bottom of the vessel and was subsequently evacuated from the vessel by the ash removal system.

The Westinghouse candle filter arrangement is illustrated schematically in Figure 4. A metallic cluster is supported from a single water cooled tube sheet. This cluster supports three arrays of candles with the candles of each array being connected to an individual plenum. The top and middle arrays of the cluster each have 38 candles while the bottom array contains 52 candles. The candles are manufactured by Coors out of mullite material. Each candle is 60 mm in diameter (OD) and 1500 mm long. Dirty gas enters the side of the vessel and flows around a shroud before passing through the candles into the clean gas plenum of each array and out the top of the vessel. The ash that is collected on the outside of the candles is removed periodically with short pulses of high pressure air from the back pulse system.

Carbon Conversion Efficiency. Figure 5 shows a plot of carbon conversion efficiency versus load for Illinois No. 6 (high sulfur bituminous coal) and low sulfur subbituminous coal (Newlands and Rawhide). The data indicates conversion efficiencies between 99.8 and 100 percent from approximately 40 - 100 percent load. Combustion temperature ranged from 1500° - 1600° F with excess air levels of 4 - 30 percent. This excellent performance is attributable to the high partial pressure of oxygen inside the combustion chamber which leads to accelerated and improved combustion of the coal particles under pressurized conditions. The results compare favorably with coal gasification and contribute to the high cycle efficiency of the PCFB.

Asahi Filter Configuration
Figure 3

Westinghouse Filter Configuration
Figure 4

PCFB TEST FACILITY

Combustion Efficiency
Figure 5

SO₂ Removal. Figure 6 shows a graph of SO₂ removal efficiency versus Ca/S molar ratio for both the high sulfur and low sulfur coals. In order to achieve 90 percent removal, a Ca/S molar ratio of approximately 1.1 is required for the high sulfur coal while the low sulfur coal requires a Ca/S molar ratio of about 1.4. At slightly higher calcium sulfur ratios, 98 to 99 percent removal was demonstrated. The calcium considered in these ratios is that of the limestone. No fuel bound calcium is included.

NO_x Emissions. Figure 7 presents NO_x emissions as a function of load for the low sulfur coal indicating that the resulting emissions are well below current Federal standards. Ahlstrom Pyropower has also successfully used ammonia injection to provide non-catalytic reduction of NO_x emissions in ACFB boilers where very low NO_x emissions are required (approximately 0.1 lb/MMBtu or lower). This same technique has also been shown to be very effective for pressurized conditions and emissions as low as 0.04 lb/MMBtu have been demonstrated in the PCFB pilot plant.

CO Emissions. Figure 8 shows CO emissions as a function of load. The data points measured before the filter indicate the effect of gas residence time. While the test data are excellent, even better results would be expected in a commercial size plant due to the greater gas residence time that would occur.

N₂O Emissions. N₂O emissions have also been measured in the pilot plant. While N₂O emissions are not currently being regulated by the Environmental Protection Agency or state and county pollution control agencies, there is considerable test work being performed on operating units to determine what levels are being generated with various combustion technologies. Measurements to date in the pilot plant indicates N₂O levels of less than 0.03 lb/MMBtu being formed in a PCFB boiler at combustor temperatures of 1540°-1600° F.

3.3.9 Development of the Testing Program Plan for the Project Demonstration Phase

Midwest Power, Pyropower, and Black & Veatch are working cooperatively to develop a detailed testing program to support demonstration and commercialization of the PCFB technology. A two year testing program is planned, including the evaluation of the range of fuels from subbituminous to bituminous coal, discussed

PCFB TEST FACILITY

SO₂ Removal versus Ca/S Molar Ratio

Figure 6

NO_x Emission versus Load
Figure 7

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PCFB TEST FACILITY

CO Emission versus Load

Figure 8

previously. A data base will be developed to support Reliability, Availability, and Maintainability (RAM) analysis for components and subsystems. Currently, an on-line data acquisition system is planned to allow direct access to operating data for analysis. This approach will allow engineers to follow plant performance on a real time basis, and to analyze data both in the plant and in a home office environment.

4.0 Plant Description and Technical Information

In the PCFB process a gas turbine and steam turbine are utilized to operate in a combined cycle mode with the gas turbine providing 20-25 percent of the net output and the steam turbine providing the balance. The DMEC-1 project will repower a mothballed unit by replacing the existing pulverized coal-fired boiler with a PCFB boiler.

As part of the project several major pieces of equipment and systems will be refurbished. The following sections discuss in detail the PCFB and integration with existing facilities.

4.1 The PCFB Process

A schematic process flow diagram of the Pyroflow PCFB process and subsystems is shown in Figure 9. The PCFB process utilizes a combined cycle which employs a combination of a gas turbine and steam turbine to generate power. In a "First Generation" PCFB power station, the gas turbine will provide 20 percent - 25 percent of the net power station output with the steam turbine providing the remaining 75 percent - 80 percent output.

The process concept of the PCFB is quite simple. Coal and sorbent are fed to the system as a paste, utilizing existing technology used in the pumping of concrete, and atomized with steam to distribute the materials in the PCFB. The compressor section of the gas turbine provides pressurized air to the PCFB pressure vessel. The air flows from the top to the bottom of the vessel, cools the vessel and internal components, and enters the PCFB combustor through the grid at the bottom of the combustor and at various locations above the grid. The fuel and sorbent materials are mixed with the air in the combustor where combustion occurs at a temperature of about 1600° F. Because of the continuous mixing throughout the PCFB combustor, this temperature is relatively constant from the bottom to the top of the combustor. Heat is recovered from the hot flue gases similar to conventional boilers to generate steam which is used to power the steam turbine.

As particles are burned and sulfur is absorbed in the furnace by the sorbent, the finer particles of coal and sorbent become entrained with the flue gas and enter the hot cyclone. Here, the majority of the particles are collected and returned to the combustor through the loop seal. The finer ash particles continue with the hot gases to the ceramic filter where final removal of particulates is achieved.

Flow PCFB Process Flow Diagram

Pyroflow PCFB Process Flow Diagram

Once cleaned, the hot pressurized flue gases are expanded through the gas turbine. The resulting mechanical power drives the compressor and the gas turbine's generator. The remaining useful heat exhausted from the gas turbine is recovered in a conventional heat recovery unit to preheat process water in route to the PCFB boiler. Clean exhaust is then released to the stack.

4.2 PCFB Island

The major systems associated with the PCFB boiler island are described in the following paragraphs.

4.2.1 Coal Feed System

Figure 10 provides a schematic of the paste coal feed system. In the DMEC-1 demonstration plant, the coal feed system will be designed for 100 percent redundancy. Each gravimetric feeder will be located at the bottom of one of the existing coal silos. Two sets of gravimetric feeders will each feed one coal/water paste preparation and mixing system, which in turn will feed two individual paste feed pumps.

In the paste preparation system, coal crushed to $1/4"$ x 0 and water will be combined in a two-stage mixer to a net surface moisture content of 20 to 25 percent. This moisture level is just sufficient to allow efficient and reliable performance of the paste pumps. Feeding of both subbituminous coals with moisture contents in the range of 25 - 30 percent and lower moisture bituminous coals will be an important aspect of the demonstration. Testing of these fuels has been performed at the Ahlstrom PCFB testing facility to evaluate fuel feeding considerations.

The piston-type pumps employed for paste feeding are conventional technology and utilized for pumping solid water slurries in applications such as concrete handling. Paste pumping systems have been evaluated extensively at the Ahlstrom Karhula R&D Center, in the Karhula PCFB Testing Facility, and in other pressurized fluidized bed systems such as the Grimethorpe plant in England and The American Electric Power's Tidd plant.

The paste pumps will pressurize the paste mixture to about 180 to 200 psig to force the paste through the feed lines, which penetrate the pressure vessel carry the paste into the PCFB combustor. As the fuel enters the combustor a steam atomizer will be used to assist distribution of the fuel throughout the lower combustor region.

Schematic of Fuel Feed System
Figure 10

One of the advantages of the PCFB technology over pressurized bubbling beds, is the enhanced mixing that occurs in the circulating fluidized bed system. This enhanced mixing means the PCFB requires fewer fuel feed points. In this project, the boiler will be designed to achieve full load when operating on two fuel feed points, 1/3 to 1/10 the number typically required in a bubbling bed boiler. The benefits are twofold; not only is mechanical complexity reduced, but the fewer feed points allow enhanced opportunity to introduce redundancy into the design.

Limestone sorbent will be both blended with the coal and fed in a pneumatic trim system for absorption of SO₂ emissions. Two new limestone silos will be added, each feeding to a paste feed train and limestone pneumatic train. Blending sorbent with the coal reduces costs by minimizing the size of the sorbent trim feed system.

4.2.2 The Limestone Feed System

The system for blending the limestone with the fuel and injecting both as a paste will be complemented by a "trim" limestone feed system. The rate of variation in limestone injection rates through the paste feed system is relatively slow due to the residence times and inventory of paste in the paste mixing tanks. The limestone trim system is sized to allow for rapid response to variations in SO₂ emissions resulting from short term variations in fuel quality, process disruptions, or other factors which might result in changes in the amount of SO₂ generated. Figure 11 provides a schematic of the limestone feed system. This system is comprised of two sets of 100 percent capacity limestone gravimetric feeders withdrawing limestone from the two storage silos. Each feeder will discharge into a surge silo from which the limestone is either conveyed to the paste system or directed into a lock hopper system. In the lock hoppers, the sorbent will be pressurized using air from the discharge of gas turbine compressor that has been boosted in pressure by a motor driven compressor. The pressurized sorbent will then be conveyed pneumatically to the combustor.

The lock hoppers will be accessible for on-line maintenance. A separate sand lock hopper will be provided which can load one charge of bed inventory into the combustor for initial start-up.

4.2.3 PCFB Hot Loop

The circulating fluidized bed hot loop is the heart of the Pyroflow PCFB process technology. The hot loop is shown in Figure 12. It is comprised of the

Schematic of Limestone/Sand Feed System

Figure 11

Schematic of PCFB Hot Loop
Figure 12

circulating fluidized bed combustor, the hot cyclones, the loop seal returns, and the water and steam cooled heat transfer surfaces.

Coal and sorbent pressurized by their respective feed systems are fed into the lower PCFB combustor, which under full load operating conditions will operate at about 160 - 200 psig. The design of the PCFB combustor will apply the same proven principles used to design atmospheric Pyroflow CFB units.

The combustor uses membrane wall construction. In the demonstration project, natural circulation will provide water from the drum through the downcomers to cool these waterwalls, ensuring cooling even during shutdown conditions. The lower section of the combustor, where the solids density will be highest, is lined with abrasion resistant refractory. This refractory provides for protection of the lower combustor walls from erosion during operation. It also provides a region for safe slumping of the bed during a shutdown condition.

In the refractory lined zone of the combustor, the fuel and sorbent are mixed with air provided by the compressor section of the gas turbine. About 60 percent of the air fed to the combustor is primary air which is injected through the grid in the lower combustor. This air provides for the fluidization and mixing of the fuel and sorbent. The startup burners will be fired with No. 2 oil or natural gas during a cold startup condition to preheat the combustor and ceramic filter to a temperature sufficient for stable firing of coal.

The remaining 40 percent of the air to the combustor is added as secondary air at points above the combustor grid. The reasons the combustion air is separated into primary and secondary air streams are:

- To provide combustor temperature control.
- To promote staged combustion for minimization of the formation of NO_x .
- To promote solids mixing and circulation.
- To supply air for continuous fines combustion in the upper part of the combustion chamber.
- To improve load following operation.

As opposed to the bubbling pressurized fluidized beds which require variation in the inventory of solids within the fluidized bed to increase or reduce load, load variations in the PCFB process can be accomplished by varying the fuel input rate and the ratio of primary to secondary air. The result is a variation in the heat release rate, and in the profile of the density of solids in the combustor. A change in the solids density profile will change the heat transfer coefficient throughout the

combustor. This allows relatively easy adjustment in the rate of heat removal. This procedure is used during start-up, for load following and for combustor temperature control in atmospheric CFBs and will be applicable to the PCFB.

Unlike bubbling pressurized fluidized bed systems, there are no submerged heat transfer surfaces in the lower combustor of the PCFB process. Due to excellent solids circulation and mixing throughout the combustor, the temperature distribution throughout the PCFB combustor is relatively uniform. Thus, the entire height of the combustor is available for locating steam superheating surfaces. The risk of erosion of heat transfer surfaces is reduced in the PCFB as these surfaces are located well above the dense solids zone of the combustor and are constructed of flat sided double omega tubing. In this upper region, particles are smaller and their impact frequency on the surfaces of the combustor is relatively low. This also dramatically simplifies the operation of the PCFB versus bubbling bed designs.

"Double Omega", a special kind of superheating tubing, has been successfully utilized in operating atmospheric Pyroflow installations for the identical purpose. Double omega surface is effective because it presents a flat plane to the flow of hot gasses and solids in the combustor. Leading and trailing edges of the double omega platens are protected with applied erosion protective materials. Spray-type desuperheaters will be utilized for control of the superheat temperature.

The superficial velocity in the PCFB combustor is about 13 - 15 feet/second (4 - 5 meters/second), typical of velocities in atmospheric circulating fluidized bed (CFB) installations. The operating temperature is in the range of 1600° F. As the fuel is combusted and the sorbent is reacted with gaseous SO_2 , smaller particles are entrained in the upward flow of flue gases. The hot gases and entrained solids leave the combustor and enter the hot cyclones where most of the entrained particles are collected and recirculated to the combustor through the loop seals. In the demonstration plant design, two hot cyclones will be utilized, each handling one-half of the combustor exit gas flow. In the loop seals, a small amount of air is injected to refluidize the collected solids and return them to the combustor. This pressurized air is provided by a separate compressor.

The collection of entrained particles in the hot cyclones, and the recirculation of those solids through the loop seals to the combustor, promotes long solids residence time at the combustion temperature. The long residence time and the mixing effects of the fluidized suspension ensure high combustion efficiencies for a wide range of fuels, and promote the effective mixing of the fine sorbent with the

fuel for efficient SO₂ removal. The SO₂ emission results are equivalent to or surpass the capabilities of coal gasification while the calcium utilization results are superior to ACFB performance due to the different nature of the chemical reactions that take place.

In ACFB boilers, limestone is first calcined to calcium oxide before it reacts with SO₂ to form calcium sulfate. The sulfation reaction is prevented from going to completion by the relatively impervious layer of calcium sulfate that forms around the unreacted particles of calcium oxide. This layer impedes the diffusion of SO₂ through to the unreacted core of the particle.

Under PCFB conditions, the chemical reactions are quite different. The high partial pressure of CO₂ in the combustion chamber inhibits the calcination reaction from proceeding. The calcium carbonate is converted directly to calcium sulfate without an intermediate step by the following reaction:

CO₂ is expelled from the individual limestone particles in parallel with the diffusion of SO₂ and O₂ into the particle. This reaction mechanism maintains the porous nature of the particle and the sulfation reaction proceeds further towards completion than in the case of ACFB's. Thus, when compared to ACFB's, PCFB's will require lower Ca/S molar ratios for the same given SO₂ removal requirement.

The by-products of sulfur collection, CaSO₄ (and CaCO₃ + MgCO₃) mixed with coal ash, are inert and can be disposed by conventional means. Typically, the solids are delivered to the disposal site in dry form and are wetted after placement. Any unreacted calcium oxide in the waste will set up and form an impermeable solid waste. Reactivity tests have been performed on waste PCFB ashes and they qualify as nonhazardous.

Depending on sorbent reactivity and operating conditions, the anticipated calcium to sulfur ratio for the PCFB process is expected to be in the range of 1.5 for 90 percent sulfur removal. The actual ratio will be confirmed by pilot tests.

4.2.4 Pressure Containment

A steel pressure vessel encloses the PCFB hot loop. The combustor and hot cyclones are suspended from the top of the vessel. Platforms and necessary ladders for access to these components are mounted inside. Adequate space is provided in

the vessel to allow for removal of all combustor internals and to provide room for routine maintenance. External platforms will allow for access to the vessel, external equipment, and instrumentation.

4.2.5 Ceramic Filter

Flue gas which leaves the hot cyclones proceeds to the hot ceramic filter where entrained fly ash and sulfur laden sorbent are collected. The use of hot gas cleanup technology means that no further particulate cleanup is required to meet specifications for protection of the gas turbine against erosion or for emissions to the atmosphere. Candle and tube filters are currently under evaluation for the demonstration project.

4.2.6 Ash Depressurization and Cooling System

The hot ash is removed at two locations, i.e. from the PCFB hot loop and from the ceramic filter. These systems are currently designed as water cooled pressurized screw coolers and lock hoppers. The rate of ash removal from the combustor is controlled to maintain adequate bed inventory. Both systems include 100 percent redundancy to promote high plant availability. As an alternative to mechanical cooling with water cooled screws, non-mechanical ash cooling systems are also under evaluation.

4.2.7 Hot Gas Piping

The hot gas piping systems interconnect the compressor to the combustor and the ceramic filter to the turbine. These systems will employ commercially available materials and components. The primary design consideration is interfacing the various components (the combustor pressure vessel, hot filter, hot valves, and gas turbine), with proper tolerances for connections, expansion, and pressure loads. Coaxial or lined piping will be utilized consistent with the inlet and outlet configurations of the gas turbine.

4.2.8 Heat Recovery Superheater/Economizer

The heat recovery economizer (HRE) is utilized to recover remaining useful heat in the exhaust gases from the gas turbine. Following expansion of the clean pressurized gases in the gas turbine, the flue gases are reduced to atmospheric pressure and are in the temperature range of 800° F. These gases are ducted to the

heat recovery economizer which has a conventional finned-tube design. Surfaces and flue gas temperatures will be kept above the condensation dew point to avoid corrosion. The heat recovered in the HRE will be utilized for feed water heating. Optimal integration of this heat in the existing cycle will be accomplished by bypassing some of the existing feed water heaters with a major portion of the feed water flow.

4.2.9 Topping Combustor

The future, "Advanced" version of the PCFB technology will be capable of achieving even higher thermal efficiencies through the addition of a topping combustor to raise the inlet temperature of the gas turbine. In the "Advanced" PCFB technology, the topping combustor will be fired by synthetic gas derived by devolatilizing a portion of the coal. As a bridge to the development and commercialization of the Advanced PCFB technology, incorporation of an oil or gas fired topping combustor into the DMEC-1 plant design has been evaluated. Due to the relatively high cost of oil and natural gas at this site and the increase in capital cost, the evaluations concluded that the topping combustor would not meet the DMEC-1 project objectives to provide electric power in an economic manner. Approval has been received from DOE to delete the topping combustor from the project scope.

4.3 Gas Turbine Island

The gas turbine island includes the gas turbine, generator, and hot valves. The compressor section on the gas turbine provides pressurized combustion air for the PCFB combustor. The gas turbine generator set includes all necessary auxiliaries including the lube oil system, startup motor, gear box, silencers, filters, controls, instruments, and PCFB system interface.

The hot clean gases from the ceramic filter are expanded through the expander section of the gas turbine to produce 20 to 25 percent of the power generated. This provides a net increase in station capacity and provides the combined cycle effect which produces an additional improvement in the net plant heat rate of 8 to 15 percent.

The use of hot gas cleaning technology in the PCFB process allows a great deal of flexibility in the selection of a gas turbine. This flexibility arises because a particulate free hot gas stream permits many commercially available turbines to be

adapted to the PCFB. The most significant modification is an adaptation of the turbine casing to allow extraction of air from the compressor section of the turbine for external firing in the PCFB and the return of hot flue gases to the expander section.

High temperature valves for safety and control are provided upstream of the gas turbine. These valves provide diversion of airflow for shutdown in the event of a loss of load on the generator. In the event that a shutdown is required, these valves will quickly isolate the turbine and PCFB.

4.4 Integration with Existing Facilities

In this project, an existing boiler will be replaced to repower an existing steam turbine. The steam turbine, manufactured by Westinghouse, was placed in service in 1954 and is rated at a nominal 65 MW. It is designed for superheated steam at 1250 psig and 950° F at a flow rate of 561,000 pounds per hour. The associated generator is a hydrogen cooled machine rated at a nominal 65 MWe. As a part of the project the turbine generator subsystems will be refurbished or replaced as needed. Figure 13 shows how the PCFB will be integrated into the existing systems.

In the existing cooling system, it is anticipated that the condenser will be refurbished and the cooling tower system will be replaced. The condensate system will be refurbished with some components such as the condensate pump motors requiring replacement.

Extensive refurbishment and modification to the feedwater heater system is expected. Use of existing feedwater heaters will be evaluated as the detailed steam cycle design is completed.

It is expected that the existing coal handling facilities and rail facilities will be reused with some modifications to replace deteriorated equipment and to upgrade it to meet the design requirements of the repowered plant.

As much of the existing buildings and structures will be modified and reused as possible for the repowered plant. Figure 14 is an artist's rendering of how the completed structure will appear.

PCFB Connection to Existing Equipment at DMEC
Figure 13

Artists Rendering of New Structure
Figure 14

5.0 Scope of Work/Responsibilities

The PCFB Demonstration project includes the demonstration facility design construction, and operation required to produce electricity, including the balance of plant facilities and the PCFB components. The project is divided into three phases per DOE guidelines. Phase 1 is design, Phase 2 is construction and Phase 3 is operation. Figure 2 is a schematic of the project schedule.

Phase 1 design is divided into Budget Period 1 preliminary design and Budget Period 2 detailed design. The PCFB system will be designed and furnished by Pyropower Corporation, San Diego, California. Black & Veatch, Kansas City, Missouri, will provide design engineering for the balance of the plant as well as construction management services.

5.1 Phase 1 Activities

The objectives of Phase 1 are the preparation of engineering drawings and specifications, and the preparation of permit applications for the plant construction and operation. Budget Period 1 is currently in progress and includes the preliminary design, along with permitting activities and project management and reporting.

As Phase 1 continues into Budget Period 2 additional activities will be completed. Included in the later stages of Phase 1 will be the development of a Preliminary Demonstration Test plan. In addition, the detailed design of the Power Island and the balance-of-plant will be completed. This includes development of specifications for the equipment and evaluating bids for long lead-time items of the PCFB. Also included will be the detailed design of such items as the steam generation building, mechanical, electrical, control and chemical systems.

5.2 General Project Reporting

As part of the Cooperative Agreement with the DOE, reports and project documents are submitted for review and approval. Much of the information concerns the manner in which the project will be conducted and managed as well as how the project progresses. In November of 1991, the first quarterly project review meeting was held with the DOE. The meeting resulted in initiation of work on the environmental information volume and on the project management and design documents. Documents submitted for DOE approval included the Project Instruction Manual and the Project Procurement Manual. These manuals in combination with

the Project Design Manual, Quality Assurance Program Manual and the Project Field Instruction manual document the technical, cost, and schedule baseline and satisfy the DOE requirement for a Project Management Plan. In addition, a Project Evaluation Plan was presented to represent goals and costs for the first budget period.

During later Quarterly Review meetings with the DOE, reports concerning technical data obtained from pilot plant process verification testing, design development, environmental monitoring, start-up and operation profiles, and predicted plant performance have been provided.

6.0 Conclusions

The activities of Phase I design are continuing. Accomplishments include encouraging pilot plant process verification test results for various fuel samples. Analysis of hot gas filter testing will require additional test runs. Study of the topping combustor led to the conclusion that it is not a good fit for this project. The topping combustor technology may achieve desired objectives in different applications.

The participants will continue to place emphasis on preliminary design efforts leading on into detailed engineering through the remainder of Phase I.

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Pressurized Circulating Fluidized Bed (PCFB)
Repowering Project

DOE