ERDC/CERL TR-00-33

Construction Engineering Research Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Phosphoric Acid Fuel Cells

Franklin H. Holcomb, Michael J. Binder, William R. Taylor, J. Michael Torrey, and John F. Westerman

December 2000

20010221 107

Foreword

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Reimbursable Work Unit V69, "New TI Design of PAFC Power Plants." The technical monitor was Robert Billmyre, CEMP-ET.

The work was performed by the Energy Branch (CF-E), of the Facilities Division (CF), Construction Engineering Research Laboratory (CERL). The CERL Principal Investigator was Franklin H. Holcomb. Part of this work was done by Science Applications International Corporation (SAIC) under. contract No. DACA88-98-D-0003, Task 7. J. Michael Torrey and John F. Westerman are associated with SAIC. Larry M. Windingland is Chief, CEERD-CF-E, and L. Michael Golish is Chief, CEERD-CF. The associated Technical Director was Gary W. Schanche, CEERD-CVT. The Acting Director of CERL is William D. Goran. The technical editor was William J. Wolfe, Information Technology Laboratory.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Acting Director of ERDC is James R. Houston and the Commander is COL James S. Weller.

Contents

Preceding Page S Blank

List of Figures and Tables

Figures

Tables

1 Introduction

Background

In fiscal year 1993 (FY93), Congress appropriated $18 million to advance the use of phosphoric acid fuel cell (PAFC) power plants at Department of Defense (DOD) installations. An additional $18.75 million was appropriated in FY94 to expand the program. The Army, Air Force, and Navy/Marine Corps each received $6 million for the purchase, installation, and operation of the fuel cell power plants in FY93, and $6.25 million in FY94. By November 1997, DOD had installed 30 PAFC power plants throughout the continental United States and Alaska. The program has successfully demonstrated the capability of the PAFC technology by generating more than 101,977 MWh of electricity through September 2000. The U.S. Army Construction Engineering Research Laboratory (CERL), a part of the U.S. Army Engineer Research and Development Center (ERDC), managed this program. CERL's activities included developing turnkey PAFC packages, devising site selection criteria, screening DOD candidate installation sites using selection criteria, evaluating viable applications at each candidate site, coordinating fuel cell site designs, overseeing installation and acceptance of the power plants, and monitoring and reporting the performance of the fleet. Information on the program is available through the world-wide web (WWW) at:

http://www.dodfuelcell.com

This report describes PAFC power plant technology and discusses the practical application of PAFC power plants within the DOD. This report is meant to fill the need for a reference document to those facilities interested in evaluating and/or installing PAFC power plant technology.

Objectives

The general objectives of this demonstration project were: (1) to stimulate growth in the fuel cell industry to lower costs through economies of scale and competition, and (2) to determine the role that fuel cells should play in DOD's long-term energy supply strategy.

The specific objective of this part of the project was to develop a design document, based on field experience, that would give DOD installation managers sufficient information to screen, site, install, operate, and maintain PAFC fuel cells at their locations.

Scope

PAFC power plants were installed at a wide variety of building types at DOD bases (Figure 1). These included central heating plants (11), hospitals (7), dormitories/barracks (3), gymnasiums/pools (3), office buildings (2), an industrial laboratory, a laundry, a kitchen, and a control center. Each participating DOD base received a complete PAFC power plant package that included design, installation, training, and approximately 5 years of system maintenance. The package also included a laptop computer with diagnostics and remote monitoring capabilities.

Mode of Technology Transfer

It is anticipated that the material collected and developed during this study may be presented in workshops and as a Proponent Sponsored Engineer Corps Training (PROSPECT) course through the Corps of Engineers, Huntsville Engineering and Support Center. This material will also be made publicly available through the world-wide web at:

www.cecer.army.mil

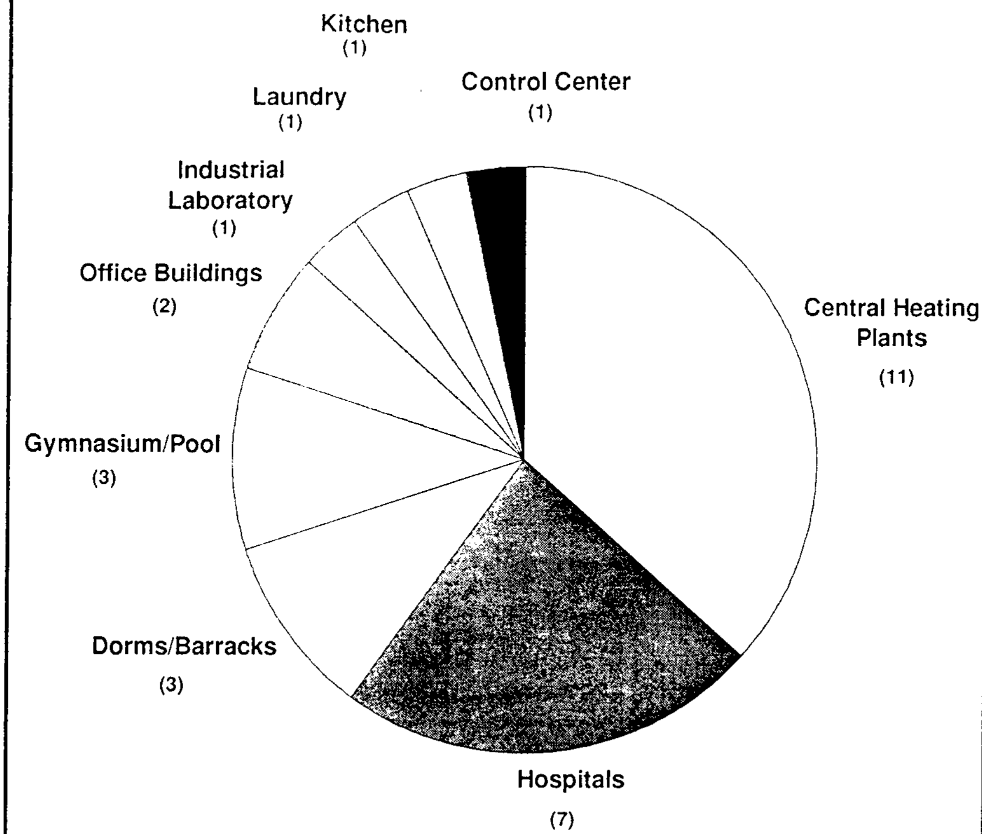


Figure 1. DoD fuel cell demonstration program building applications.

2 PAFC Power Plant Description

Fuel cells produce electricity through an electrochemical process. PAFC power plants offer several benefits; they are very fuel-efficient, and produce little noise or air pollution. To be commercially viable, fuel cell systems are integrated into a complete system that incorporates all necessary ancillary equipment.

Process Overview

Fuel cell power plants typically consist of three main sections: (1) the fuel processing section, (2) the power section (fuel cell stack), and (3) the power conditioner (Figure 2). The following paragraphs give an overview of each section and respective energy flows.

Fuel Processing

A fuel cell needs hydrogen and oxygen to operate. In the fuel processor section, hydrogen is extracted or reformed from a hydrogen-rich fuel (typically natural gas for DOD applications) for processing by the fuel cell stack. Once an acceptable form of hydrogen is available, it is passed on to the fuel cell stack section.

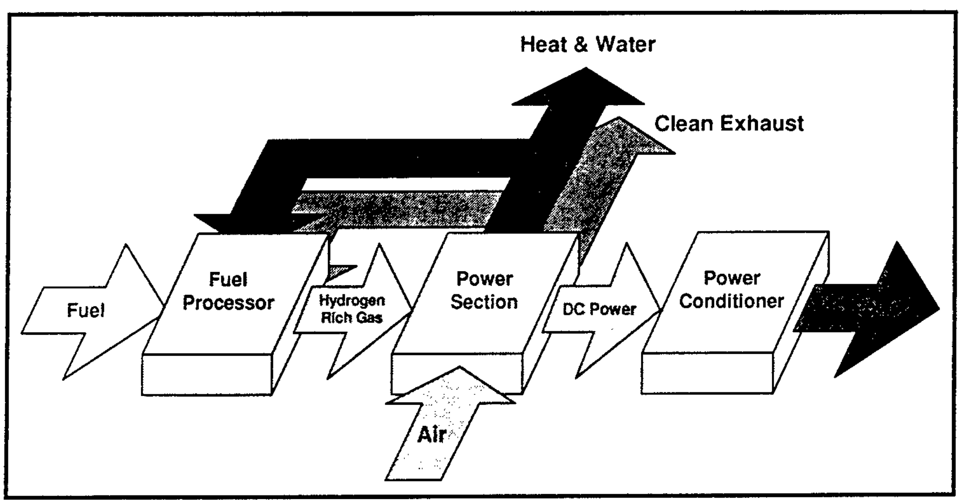
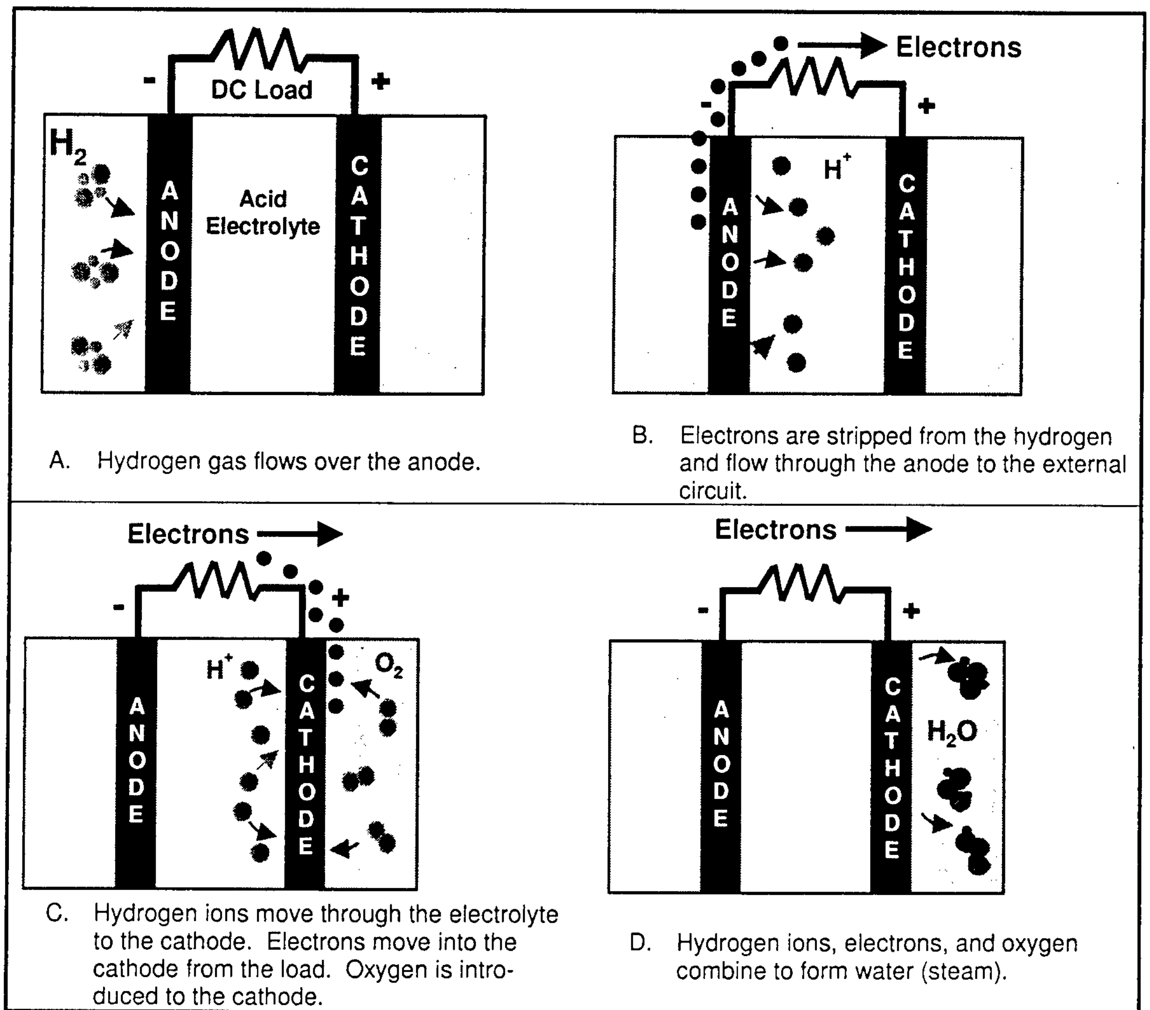


Figure 2. Typical fuel cell power plant configuration.

Power Section

The power section houses the fuel cell stack, which is a series of individual cells linked together electrically. An individual cell is composed of two electrodes (an anode and a cathode) and an electrolyte material such as phosphoric acid. The fuel cell process begins by feeding a hydrogen fuel through a porous electrode (the anode) in the presence of a catalyst. The negatively charged electrons are stripped from the hydrogen fuel and then make their way through the external electrode circuit. The remaining positive ions travel through the electrolyte to the other porous electrode (the cathode), where they combine with oxygen ions that form when the free electrons combine with oxygen fed in at the cathode. The by-products of the reaction are heat, water (in the form of steam), and electricity produced from the flow of electrons from the anode to the cathode. Cells are then "stacked" in series with their respective electrodes to create a prescribed direct current (DC) voltage level. Figure 3 shows diagrams of the fuel cell process.



A. Hydrogen gas flows over the anode.

B. Electrons are stripped from the hydrogen and flow through the anode to the external circuit.

C. Hydrogen ions move through the electrolyte to the cathode. Electrons move into the cathode from the load. Oxygen is introduced to the cathode.

D. Hydrogen ions, electrons, and oxygen combine to form water (steam).

Figure 3. Overview of fuel cell process.

Power Conditioner

The power conditioner includes an inverter to convert DC electricity to alternating current (AC) electricity. The power conditioner also regulates the fuel cell's voltage and current output to accommodate variations in load requirements and protect the fuel cell and utility grid.

Interface Requirements

PAFC power plants, like those installed during the DOD Fuel Cell Demonstration Program, are packaged units that have ready-to-connect electrical and thermal interface systems. The heat generated by the fuel cell's electrochemical process can be used to provide hot water to various building applications. Piping and electrical wiring interfaces are simplified by the integrated package design.

PAFC Power Plant Applications

PAFC power plants have been installed in a variety of building applications. Interfacing the PAFC power plant is a function of compatibility with both the electrical and thermal loads at individual buildings. The following sections discuss potential building types and summarize electrical and thermal application issues related to PAFC power plant integration.

Building Applications

At each DOD Fuel Cell Demonstration Program site, a number of buildings were evaluated for their potential to use the electrical and thermal output of the PAFC power plant. The building types shown in Figure 1 had one or more thermal applications that could be integrated with the fuel cell. In evaluating potential buildings, it is important to understand what building systems could be interfaced. Table 1 summarizes potential thermal loads by building type.

Central Heating Plants

These facilities consist of one or more boilers and steam or hot water distribution system that provides thermal energy to outlying buildings. The key PAFC power plant interfaces are either preheating boiler make-up water or heating the return condensate or hot water from the distribution loop.

Table 1. Potential thermal applications at various building types.

	Boiler Make-up Water	Boiler Return Loop	Domestic Hot Water	Space Heating	Absorption Cooling	Pool Heating
Central heating plant	X	X				
Hospital	X	X	X	X	X	X
Dormitory/barracks			X	X	X	
Gymnasium/pool			X	X	X	X
Office building			X	X	X	
Laundry			X	X	X	
Kitchen			X	X	X	

The make-up water requirement for a central heating plant is a function of the distribution system's integrity. Distribution systems with leaks will require a higher volume of make-up water than systems that are thermally tight. The boiler return loop provides an integration point for the fuel cell, but is dependent on the typical return temperatures and how they match up with the characteristics of the PAFC power plant.

Hospitals

Hospitals are very energy intensive. Larger facilities may have their own central plant systems where boiler make-up water or the return loop are potential thermal interfaces to the PAFC power plant. In addition to these loads, domestic hot water (DHW), space heating, space cooling (with absorption chillers), and therapy/swimming pools represent potential thermal applications.

Dormitory/Barracks

Large scale residence facilities represent potential for thermally integrating a PAFC power plant. DHW loads are usually the largest thermal loads for this building type and can be further enhanced when laundry facilities are part of the DHW system. Recirculation loops also represent a potential thermal load for the fuel cell. Particularly at military bases, DHW demand is concentrated in the early morning and evening periods. The integration of a PAFC power plant could require a storage tank, depending on the site thermal load usage profile.

Gymnasium/Pool

Gymnasiums require DHW as well as space heating and cooling. A significant load could also be heating the swimming pool. An indoor pool with year round use would likely provide a steady thermal load for the PAFC power plant. Outdoor pools may be subject to higher heat losses than indoor pools, but they often do not operate year round except in mild climates.

Office Buildings

Office buildings do not usually have large DHW loads. Space heating is a potential thermal application, but may be limited to weekday hours. Space cooling is also a potential thermal application for the PAFC power plant where absorption chilling equipment is an option.

Laundry

Commercial or industrial type laundries that operate two or more shifts per day, 6 days per week may represent a significant thermal load for the fuel cell. Washers require hot water that can be supplied by a fuel cell, but steam requirements cannot be met with the PAFC power plant.

Kitchen

DHW loads for washing and food preparation are the most significant thermal loads in a kitchen or galley. Temperature requirements for individual loads should be observed since health standard requirements must be met. As with other DHW loads, a hot water storage tank may be required to accommodate variations in loads.

Electrical Application Issues

Consideration must be given to matching a building application's electric load with the fuel cell's electric capacity. Although a fuel cell may be much smaller than a building's peak load, building loads typically drop off significantly during off-peak times (i.e., evenings/weekends, depending on the site). The total range of electric demands for a building must be determined to ensure that the fuel cell's electrical output does not exceed the building load. At DOD Program bases, this was not a major concern since most buildings were connected to the base electric grid where the fuel cell's output could be easily absorbed. Premium power applications, such as computer centers or certain hospital loads, are also an application for the PAFC power plant. PAFC power plants have also been configured to operate when the utility grid is unavailable, acting as an uninterruptible power supply (UPS) system.

Thermal Application Issues

PAFC power plant thermal output can be used to preheat boiler make-up water, for heating swimming pools, and for DHW used for showers, laundry, and kitchen loads. With an optional high-grade heat exchanger, high-temperature thermal output can be used for boiler plant aerators, space heating loops, absorption chillers, and industrial processes. PAFC power plants are not compatible with high-temperature steam thermal applications.

PAFC Power Plant Benefits

Environmental Benefits

Since fuel cells generate electricity through an electrochemical process, many of the environmental pollutants associated with combustion-based generation do not exist. One PAFC manufacturer, ONSI Corporation, manufactures a fuel cell that has been exempted from air permitting requirements by the South Coast Air Quality Management District (SCAQMD), which has the most stringent permitting requirements in the United States. Fuel cells also produce water as a by-product, which is mostly utilized internally for cooling purposes. This water is very pure and any small amount discharged is not considered a pollutant.

Fuel Efficiency

Initial electrical efficiencies of PAFC power plants are approximately 36 percent higher heating value (HHV), or 40 percent lower heating value (LHV). If waste heat from the PAFC power plant is used in a cogeneration system, total efficiency can exceed 85 percent. Current conventional coal-based combustion technologies, by comparison, operate at efficiencies of 33 to 35 percent (HHV).

Back-up Power

Fuel cells can be configured to provide back-up power. Some PAFC power plants have been used to back-up critical computer loads, acting as a UPS.

Clean Power

Fuel cells can provide premium power to facilities where "clean" power is required for sensitive electronic equipment.

Energy Savings

Because of the PAFC power plant's high efficiency and thermal output capability, site energy costs can be reduced by displacing energy provided through traditional utility service. The level of energy savings depends on the price differential between natural gas and electricity, thermal utilization, and other factors.

Low Noise

Fuel cell noise emissions are quite low compared to traditional combustion technologies. For the PC25C power plant, the noise specification level is 62 dBA at 30 ft.

Siting Options

Packaged PAFC power plants are self-contained units with interface outlets ready to be connected to building loads. Because of low emissions, there is further flexibility to site them in urban areas.

3 PAFC Power Plant Applications and Screening

PAFC Power Plant Potential Applications

To begin, a budget for performing an initial site screening/evaluation should be established. The scope of the evaluation should be defined including target dates, project criteria, technical and economic constraints, allowance for alternative technology options, etc. The potential for project funding should also be identified.

PAFC Power Plant Applications Screening

Objectives

The basis for considering PAFC power plant technology should be explicitly stated. PAFC power plants could be selected based on potential energy savings, the need for back-up power generation, clean or premium power requirements, environmental generation constraints, broad scale deployment feasibility, research and development purposes, etc.

Screening Criteria

If several potential PAFC power plant sites are being considered, screening criteria should be established. Target ranges for project budget, energy load size, seasonal load profiles, space availability, project payback periods or rates of return, energy rates, fuel availability, thermal load temperatures, and other factors could be used to compare alternative sites. Sites can then be ranked based on the most important factors. Sites that do not meet the minimum screening criteria can be eliminated from further consideration. Table 2 presents a list of issues to investigate during the screening process.

Table 2. Site screening issues for PAFC power plants.

Site Screening Area	Relevant Issues
Natural gas service	Availability and proximity of gas line Sufficient gas line capacity Costs for gas line upgrade or installation Firm gas availability from utility Cost premium of firm vs. interruptible gas
Electrical service	Load size larger than fuel cell (all year long) Availability of 480 Volt service Transformer size (>= 300 kVA) Power quality interruptions/issues Proximity of electrical interconnection point
Thermal load issues	Site temperature match fuel cell output Requirement for high-grade heat exchanger Load demand profile (constant vs. intermittent) Thermal storage required Duration of heating/cooling seasons (heating degree days) Potential displaced site thermal energy
Site characteristics	Adequate space to locate the fuel cell Drainage or contamination issues
Utility issues	Interconnection safety requirements Utility stand-by service charges Electric demand reduction ratchet penalty Electric rate schedule and costs Fuel cell displacing lower value electricity block rates Natural gas rate structure and costs

Energy Rates

Energy rates are often the first screening criteria used when culling through sites located over a wide range of geographical locations. When PAFC power plants are used to displace utility provided energy, utility rates are a good measure for ranking the highest potential energy savings sites. Areas should be ranked by electric rates and natural gas (or other fuel) rates, as well as the electric rate minus gas rate (E-G) differential expressed in like units (e.g., million Btus - MMBtu). Higher E-G rate differentials indicate a higher spread between the cost of generation (fuel cost) and the value of displaced electricity which results in higher potential energy savings.

PAFC Power Plant Site Evaluations

Once a potential site has been selected for further evaluation, data needs to be collected to perform an analysis. The following sections describe areas of analysis relevant when considering applications for PAFC power plants.

Location/Siting

Determine where the PAFC power plant should be sited, taking into consideration the minimum required footprint for the PAFC power plant and its proximity to the electrical, thermal, and natural gas interface locations. The PAFC power plant should be sited as close as possible to all building interfaces to minimize the length of piping and wiring runs required. The PAFC power plant should be sited nearest to the thermal interface to minimize the length of thermal piping since the cost of running thermal piping is usually higher than the electrical wiring. Thermal energy losses and related costs are also factors in long piping runs.

Fuel Availability

PAFC power plants require hydrogen as a fuel source. Natural gas, propane, and other fuels can be reformed to provide hydrogen to the PAFC power plant. The source of the fuel must be identified. If natural gas is the fuel of choice, determine if it is available in sufficient quantity to operate the fuel cell. Seasonal load requirements, such as peak winter heating demands, must be factored into this determination. If natural gas is not available in sufficient quantity, contact the natural gas utility to determine if they could upgrade the service to provide for the new PAFC power plant load. In many instances, a utility will upgrade to a new service at no charge when a customer is installing a substantial gas load such as a PAFC power plant.

Fuel Cell Interfaces

Determine the PAFC power plant interface requirements and create single line diagrams showing interface equipment, pumps, transformers, length of the piping and wiring runs, etc.

Thermal Interface

Match the site thermal load temperatures and flows with the PAFC power plant specifications. The PAFC power plant should not be interfaced directly with a thermal loop that has a higher temperature than the PAFC power plant's maximum delivery temperature. The fuel cell thermal output can be used to add heat to selected site loads, thus reducing the Btu's required from traditional thermal systems (e.g., boiler or steam line). For most new and retrofit applications, a traditional thermal source complements or backs up the fuel cell thermal output. Appendix A presents single line diagrams for five example applications and example load calculations: a boiler, swimming pool, space heating system, absorption chiller, and domestic hot water system.

Electrical Interface

The voltage output of the fuel cell must be matched with the building's electrical voltage. The PAFC power plant electrical output may be connected to an existing electrical panel or to a new panel. If the fuel cell's output voltage level is not available at the building, then the PAFC power plant should be interfaced with an intermediate transformer to step up or step down the voltage to the required level. In cases where the building is connected to a DOD distribution system, a step up transformer could be used to increase the voltage for delivery elsewhere on the base.

Input Fuel Interface

The PAFC power plant requires a maximum rate of fuel depending on its rated size and efficiency. The piping to the fuel cell should be sized to accommodate this maximum rating. It should be noted that a PAFC power plant's efficiency will degrade over time and a higher input fuel rate will be required. Sizing for the input fuel piping should account for the higher rate required at the lower operating efficiency.

Operating Schedules

PAFC power plants should normally operate on a continuous basis since power plant start-up times are several hours and because there is a negative impact on the fuel cell stack due to cycling the power plant on and off. When the entire output of the PAFC power plant cannot be used by the building, the schedule for ramping down the PAFC power plant to a lower power output during these times should be specified. Changing the electrical output to match building load requirements does not negatively impact the fuel cell, whereas cycling the power plant on and off does have a negative effect.

Conceptual Designs

Addressing the above interface issues results in an overall conceptual design for the PAFC application. Single line diagrams should be developed for the power plant location and the major fuel cell interfaces. Issues that must be addressed during the detailed design phase should be noted. Projected operating schedules and energy utilization levels should also be developed.

PAFC Power Plant Cost Estimates

The conceptual design provides a framework for assessing the overall project requirements. Power plant costs, ancillary equipment, and utility and installation costs should be estimated for budgetary purposes as well as for use in an economic analysis.

Power Plant/Options

Commercially available power plants incorporate both the standard power plant and optional systems that may be required. The following sections give power plant cost information.

Power Plant

Since fuel cells are evolving into a fully commercial product, pricing is also evolving. The goal for many fuel cell power plants is <$1,500/kW. ONSI's PC25C unit under the DOD Fuel Cell Demonstration Program cost $636,525 in FY94 ($3,183/kW). The original FY93 Program fuel cell cost was $1.1 million ($5,500/kW).

Double-Wall Heat Exchangers

When the PAFC power plant thermal output is to be interfaced with potable water applications such as domestic hot water, a double-walled heat exchanger should be installed. This option was part of the base system under the DOD Fuel Cell Demonstration Program.

High Grade Heat Exchangers

The ONSI fuel cell had an option where a high grade heat exchanger could be added to provide hot water up to 250 °F. ONSI's standard heat exchanger could provide hot water up to only 160 °F. The high grade heat exchanger was a second heat exchanger added to the fuel cell where approximately 50 percent of the total available thermal output was available at the higher temperature. The cost during the DOD Fuel Cell Demonstration Program was approximately $13,000.

Alternate Fuels

Reformers can be configured to convert different feedstock fuels into hydrogen. Typical fuels include natural gas, biogas, propane, and coal. During the DOD Fuel Cell Demonstration Program, a dual fuel option (propane or natural gas) was available for $15,000.

Grid-Independent Operation

PAFC power plants, in addition to operating in parallel with the utility grid, can operate in a grid-independent mode. The ONSI PC25 had a grid-independent option as part of the DOD Fuel Cell Demonstration Program and cost ~$34,000 (included site integration design and installation).

Ancillary Equipment

Various ancillary equipment may be required for a fuel cell installation. The following sections describe various options.

Electrical Transformer

The cost for an electrical transformer should be included if required to integrate with a building. The cost during the DOD Fuel Cell Demonstration Program was ~$33,000 (included site integration design and installation).

External Heat Exchanger

When the fuel cell thermal output was used to heat a swimming pool, an external heat exchanger kept the corrosive pool water separate from the fuel cell thermal loop. A titanium or stainless steel heat exchanger can be used, but are generally more expensive that other heat exchangers. Costs vary by size of heat exchanger required.

Absorption Chiller

With a high grade heat exchanger option, the PAFC power plant can be integrated with an absorption chiller. During the DOD Fuel Cell Demonstration Program, a 20-ton absorption chiller cost $70,000 and a 30-ton absorption chiller cost $100,000 (included site integration design and installation).

Storage Tank

Site thermal load demands vary by time of day. A storage tank may be installed to cover peak demand periods. For the DOD Fuel Cell Demonstration Program, a 1,000 gal storage tank cost ~\$21,000 plus ~\$16/gal for every additional gallon of storage (included site integration design and installation).

Utilities

A variety of considerations and costs are involved with integrating a PAFC power plant with utility systems.

Natural Gas Utility

Connection of the PAFC power plant should be coordinated with the natural gas utility. If the delivery pressure needs to be upgraded, then the cost should be negotiated with them. The utility may agree to cover the upgrade cost if the evidence shows that they will recover their costs through increased gas sales. The issue of firm vs. interruptible gas service should also be addressed. Since cycling the power plant is not recommended, interruptible gas service may not be acceptable. The Defense Energy Support Center (DESC) should be consulted when making a fuel supplier choice. Complete information on the DESC is available at: http://www.desc.dla.mil/main/deschome.htm.

Electric Utility

To interconnect a fuel cell with an electric utility grid, the requirements of interconnection need to be determined. The PAFC power plant may have adequate protection built in, or additional interconnect protection may need to be installed. An electric utility may apply a stand-by rate schedule that will impact the economics. Also, installation of a PAFC power plant may move the site to a different applicable rate schedule. These issues should be explored with the utility. Costs associated with any grid interface work should be included in the budget.

Installation

Installation cost should be factored into the total cost of a PAFC power plant. During the DOD Fuel Cell Demonstration Program, the base installation cost was ~\$160,000 (\$800/kW). This did not include the cost of design for various options and ancillary equipment discussed above. The following sections outline installation considerations that should be factored into the costing.

Site

The plan should include a pad for the PAFC power plant. Any special grading or testing for ground contamination should be included. Fencing or decorative walls may be required. Relocation of underground utilities should be noted.

Mechanical

The mechanical drawings should address pipe size and length of piping runs, motor specifications, relocation of systems, etc.

Electrical

The details for integrating the PAFC power plant should include panel specifications, additional protection equipment if required, location of transformers, etc.

Operation and Maintenance

The fuel cell will have scheduled and unscheduled maintenance activities. During the DOD Fuel Cell Demonstration Program, maintenance costs were approximately $26,000 per year. Fuel cell stack degradation will eventually require the stack to be replaced. This should be taken into consideration for budgeting purposes.

PAFC Power Plant Economics

Energy Savings

Energy savings from the PAFC power plant operation must be calculated. The basic formula is:

$$\textit{Electric Savings} + \textit{Thermal Savings} - \textit{Input Fuel Cost} - \textit{Maintenance Cost}$$

Simple payback periods can be calculated by dividing the net energy savings into the total PAFC power plant installation cost. A life-cycle cost analysis should also be conducted.

Project Assessment

The viability of the conceptual design and the likelihood of projected net energy savings and life-cycle cost analysis results should be assessed. The decision to proceed should consider all the relevant issues.

4 PAFC Power Plant Design and Construction Considerations

PAFC Power Plant Package Systems

PAFC package systems are fully integrated power plants that incorporate the fuel cell stack and balance-of-plant equipment (typically a fuel processor and power conversion/interface equipment). At this writing, there is only one commercially available PAFC power plant, the ONSI Corporation PC25.™

ONSI Corporation manufactures the PC25C, a 200 kW PAFC power plant (previous versions were PC25A and PC25B). These self-contained, factory assembled PAFC power plants run on natural gas, operate in parallel with the utility grid, and have an internal heat exchanger that can deliver hot water to a building. A separate Cooling Module comes with the power plant and enables the fuel cell to reject excess heat when the customer's thermal load is less than the fuel cell output. The PC25C features unattended operation and can automatically shift to selected power levels in the grid-connect mode. When necessary, the power plant disconnects from the utility grid during power outages and shuts down safely when there is a power plant malfunction. Table 3 lists technical characteristics for the PC25C standard configuration.

Table 3. ONSI PC25C power plant characteristics (standard configuration).

Characteristic	Measure
Rated electric capacity	200 kW/235 kVA
Voltage/frequency	480 Volts, 3-phase, 4-wire, 60-Hz
Fuel input	Natural gas: 4 to 14 in. water column
Fuel consumption	1900 SCFH Nominal; 40% electrical efficiency at LHV basis
Sound level	62 dBA at 30 ft
Power plant dimensions	10 ft (w) x 18 ft (l) x 10 ft (h)
Cooling module dimensions	4 ft (w) x 14 ft (l) x 4 ft (h)
Ambient temperature range	-20 °F to +110 °F
Thermal output (H_2O)	700,000 Btu/hr at 140 °F

PAFC Power Plant Options and Configurations

The ONSI PC25C is available with several options as discussed below.

High-Grade Heat Exchanger (HEX 490)

In the standard configuration, the PC25C can deliver 700,000 Btu/hr of hot water. Fuel cell delivery temperatures are typically 140 °F, but can be as high as 160 °F. With ONSI's high-grade heat exchanger (HEX 490) option, approximately 350,000 Btu/hr (roughly half the total capacity) is available as pressurized hot water at temperatures up to 250 °F. With the high-grade heat exchanger option, the standard heat exchanger is still available to deliver 350,000 Btu/hr or more, depending on the load presented to the high-grade heat exchanger. Heat that is not transferred through the high-grade heat exchanger becomes available to the standard heat exchanger. The HEX 490 will deliver high temperature hot water when there is at least 5 gpm flow on the customer side of the heat exchanger and the HEX 490 outlet temperature is below a temperature set by the customer.

Grid-Independent Operation

The PC25C can be configured to operate independently of an electric utility grid. With the grid-independent option, a utility grid is not required although a generator is required for starting up the PAFC power plant. The electric output must be connected to load panels that do not exceed the power level of the fuel cell. When operating in the grid independent mode, the fuel cell responds instantaneously to load changes up to 50 percent of rating and ensures excellent voltage and frequency regulation. It is also possible to operate the fuel cell in a grid-connect mode and have it operate grid-independent during grid failures. The fuel cell must be physically connected to two loads (critical and noncritical loads). When the grid goes down, a motorized switch is engaged and power is restored to the isolated critical load within 3 to 5 seconds. This load cannot exceed the 200 kW power plant capacity. To operate as an uninterruptible power supply (UPS), a static switch can be integrated into the installation design. This approach ensures that continuous power flows to the critical load, such as a computer center.

Double-Wall Heat Exchanger

For cases where the thermal output is to be used for potable water, a double-wall heat exchanger inside the fuel cell is available. This allows for thermal loads such as kitchen loads to be directly interfaced with the fuel cell. All of the power plants in the DOD Fuel Cell Demonstration Program had the double-walled heat exchanger option.

Alternative Fuels

The PC25C can be configured to operate on propane. This is attractive when natural gas supply is either unavailable or interruptible. The reformer is capable of alternating between propane and natural gas instantaneously. Another fuel option is a gas-processing unit (GPU) developed by ONSI to run on anaerobic digester gas or landfill gas. Units have been demonstrated at wastewater treatment facilities and landfills. Because of the lower Btu content of these fuels, the power level of the fuel cell is derated.

PAFC Power Plant Applicable Codes and Standards

The installation of a PAFC power plant requires adherence to numerous codes and standards for both the power plant itself and the installation. The following sections discuss some of the major codes and standards requirements.

Uniform Building Code

The Uniform Building Code (UBC) is the most widely adopted model building code in the world and is a proven document meeting the needs of government units charged with enforcement of building regulation. Published triennially, the UBC provides complete regulations covering all major aspects of building design and construction relating to fire and life safety and structural safety. The requirements reflect the latest technological advances in the building, and fire and life-safety industry.

Uniform Mechanical Code

Provides a complete set of requirements for the design, construction, installation, and maintenance of heating, ventilating, cooling and refrigeration systems, incinerators, and other heat-producing appliances.

Uniform Plumbing Code

Published by the International Association of Plumbing and Mechanical Officials (IAPMO), the Uniform Plumbing Code covers all aspects of plumbing, including requirements for plumbing materials and IAPMO installation standards.

National Electric Code

The National Electrical Code (NFPA 70) provides "practical safeguarding of persons and property from hazards arising from the use of electricity." More specifically, the National Electric Code covers the installation of electric conductors and equipment in public and private buildings or other structures (including mobile homes, recreational vehicles, and floating buildings), industrial substations, and other premises (such as yards, carnivals, and parking lots). The National Electric Code also covers installations of optical fiber cable. Wiring, general electrical equipment, the use of electricity in specific occupancies (from aircraft hangars to health care facilities), and equipment (ranging from elevators to hot tubs) are covered, as well as special conditions (emergency and stand-by power, or conditions requiring more than 600 volts, for example) and communication systems.

National Fire Code

The National Fire Code consists of approximately 300 codes and standards as published by the National Fire Protection Association (NFPA). These codes address the practices to reduce the burden of fire on the quality of life by advocating scientifically based consensus codes and standards, research, and education for fire and related safety issues. The most widely applied codes are:

1. NFPA 70 – National Electric Code
2. NFPA 101 – Life Safety Code
3. NFPA 30 – Flammable and Combustible Liquids Code
4. NFPA 13 – Standard for the Installation and Maintenance of Automatic Fire Sprinkler Systems.

American Gas Association Requirements 8-90

The ONSI fuel cell has been certified by International Approval Services for compliance with American Gas Association (AGA) Requirements for Fuel Cell Power Plants 8-90. This requirement specification covers fuel cells that are constructed at one location and shipped as a packaged unit for installation at another site. The following sections summarize the most significant national codes and standards incorporated into AGA 8-90. Appendix B to this report gives a more detailed explanation of the components.

American National Standards Institute (ANSI)

ANSI has served in its capacity as administrator and coordinator of the United States private sector voluntary standardization system for 80 years. The Institute is a private, nonprofit membership organization supported by a diverse constituency of private and public sector organizations. ANSI Z21.83 has been published and provides a means of testing and certifying the safety of stationary fuel cell power plants having a capacity of less than 1 MW.

American Society of Mechanical Engineers (ASME)

ASME is in international engineering society that conducts one of the world's largest technical publishing operations. ASME International is a nonprofit educational and technical organization serving a worldwide membership. Its mission is to promote and enhance the technical competency and professional well being of engineers through quality programs and activities in mechanical engineering. To this end, ASME has developed the Boiler and Pressure Vessel Code, which is referenced as part of the AGA certification. Additionally, ASME is working on a fuel cell standard, ASME PTC 50, which will apply to fuel cell performance. Publication of this standard is not expected until 2002.

The National Fire Protection Association (NFPA)

NFPA is a non-profit organization that publishes the National Electrical Code®, the Life Safety Code®, the Fire Prevention Code™, the National Fuel Gas Code®, and the National Fire Alarm Code®. The mission of NFPA is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating scientifically based consensus codes and standards, research, training, and education. NFPA 853 covers the installation of stationary fuel cells of at least 50 kW output. Publication is expected to occur in 2000.

Underwriters Laboratories, Inc. (UL)

UL is an independent, not-for-profit product safety testing and certification organization. UL has tested products for public safety for more than a century with more than 14 billion UL Marks applied to products worldwide.

The Occupational Safety and Health Administration (OSHA)

OSHA is a division of the U.S. Department of Labor. OSHA is committed to the reduction of injuries, illnesses, and deaths in the workplace.

Institute of Electrical and Electronics Engineers (IEEE)

IEEE Standards Coordinating Committee 21 (SCC21) oversees the development of standards in the area of fuel cells, photovoltaics, distributed generation, and energy storage. SCC21 coordinates efforts in these fields among the various IEEE societies and other appropriate organizations to ensure that all standards are consistent and properly reflect the views of all applicable disciplines. Working Group 1547 - Standard for Distributed Resources Interconnected with Electric Power Systems - establishes criteria and requirements for interconnection by distributed resources with electric power systems. The purpose is to provide a uniform standard for interconnection of distributed resources with electric power systems and requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection.

PAFC Power Plant Permitting Requirements

Permitting requirements for the installation of a PAFC power plant vary by region and should be addressed accordingly. The following sections discuss these requirements generally.

Environmental Permits

Permits are generally required when a construction project involves air pollution sources. Submission of source-specific information is required before an application can be approved. The type of information and the level of details associated with information required of a permit applicant varies depending on the scope of the proposed project, predicted emissions, and potential health effects. Permits are obtained through State or Federal agencies charged with reducing air pollution to meet State and Federal health standards. One of the most stringent agencies charged with control of emissions, the South Coast Air Quality Management District in Southern California, exempts PAFC power plants from any air permits. Under "Rule 219 – Equipment Not Requiring a Written Permit Pursuant to Regulation II," PAFC power plants may be sited in downtown Los Angeles and are exempt from any air permits. Many states and local pollution control districts have adopted a similar stance on PAFC power plants.

Construction Permits

Permits are required for all new construction and remodeling projects. Building permit requirements vary by local government agencies that are responsible for issuing permits and enforcing applicable codes and standards. Enforcement is conducted by means of onsite inspections. Typically, permits are required for each type of trade-specific work that will be conducted as part of the construction project.

Building Permit

This permit covers the design and construction of structures. The permit is required to locate, erect, construct, enlarge, alter, repair, or relocate any building, fuel storage tanks, structure, or utility, or change of occupancy type.

Electrical Permit

This permit covers the design and application of electrical interfaces. The permit is required for installation, alteration, repairs, replacement, or relocation of any electrical material, appliance, or equipment.

Plumbing Permit

This permit covers the design and installation of plumbing fixtures and interfaces. A permit is required for installation, alteration, replacement, or relocation of plumbing fixtures and sprinkler systems.

Mechanical Permit

This permit covers the design and installation of heating, ventilation, air conditioning, and refrigeration equipment. A permit is required for installation, alteration, repairs, replacement, or relocation of heating, ventilation, air conditioning, and refrigeration equipment.

Natural Gas Infrastructure Considerations

Gas Availability

The ONSI PC25C consumes 1,900 standard cubic feet (SCF) of natural gas per hour. The gas line should be sized for up to 3,000 SCF per hour to accommodate increased fuel consumption as the fuel cell stack efficiency degrades over time. The PAFC power plant requires a natural gas delivery pressure of 4 to 14 in. of water column. Since the fuel cell represents a significant gas load, the natural gas utility should be involved in the development process. The minimum Btu content (HHV) of the natural gas is 980 Btu/cu ft. Table 4 lists natural gas constituent maximums.

Table 4. ONSI PC25C allowable natural gas constituents.

Pipeline Natural Gas Constituent	Maximum Allowable Percent Volume
Methane	100
Ethanes	10
Propane	5
Butanes	1.25
Pentanes, hexanes, C_6+	0.5
CO_2	3
O_2 (continuous)	0.2
N_2 (continuous)	4.0
Total sulfur	30 max/6 avg. ppmV
Ammonia	1 ppmV
Chlorine	0.05 ppmW

Firm vs. Interruptible

The PAFC power plant efficiency degrades over time. One factor that contributes to this degradation is cycling the power plant. Because of this, it is generally not recommended that the natural gas supply be interruptible. There are also costs associated with starting up the fuel cell after it has been shut down. Firm gas, while more expensive, enables the PAFC power plant to operate continuously.

Defense Energy Support Center (DESC)

Natural gas can be obtained through the DESC at prices that are very competitive. Interruptible gas supply should be carefully analyzed before proceeding with this supply alternative. For more information, visit the DESC website at: http://www.desc.dla.mil/main/deschome.htm

Electric Distribution System Considerations

Electric Utility Interfaces

The PC25C is designed to operate safely when connected to the utility grid, and to disconnect from the grid when abnormal grid or power plant conditions occur. It has an integrated utility grid protection system that automatically disconnects from the utility grid when there is no power. There is a ground fault detection system that provides a safety shutdown function in the event of an electrical short to ground. The power plant has the capacity to be shut down remotely via modem. The standard ONSI grid protection package has been accepted by a large number of utilities and includes:

1. Functions implemented in solid state control software
2. Functions implemented in control hardware
3. Fuses in the inverter
4. Motorized circuit breaker that trips on command or by undervoltage trip mechanisms
5. Output impedance that limits fault current to approximately 10 per unit
6. Surge arrestor at the AC output.

Base Grid Distribution

At DOD bases, the base typically owns the distribution system. Electricity generated by the fuel cell is usually connected to an individual building. When that building's electrical demand drops below the output of the fuel cell, the excess power is sent to the base distribution grid. As long as the base minimum load is greater than 200 kW (with PC25C), there is no danger of exporting to the electric utility grid.

Service Voltages

The PC25C must be connected to a 480 volt service. In cases where 480 volt service is not available, the fuel cell must be connected to a transformer that converts the 480 volt output to the appropriate building or distribution grid voltage.

Thermal Recovery System Considerations

Interface Temperatures

For the low-grade heat exchanger, the PC25C is rated to deliver approximately 140 °F hot water (up to 160 °F temperatures have been field measured). The quantity of heat that can be recovered depends on the site load requirement, the inlet temperature to the fuel cell, and the flow rate. In general, the lower the temperature of the inlet water, the greater the potential heat recovery from the fuel cell. Figure 4 shows the heat recovery potential from the fuel cell as a function of the inlet temperature. As the fuel cell inlet temperature approaches 90 °F, the fuel cell cannot deliver the full 700,000 Btu/hr rated output.

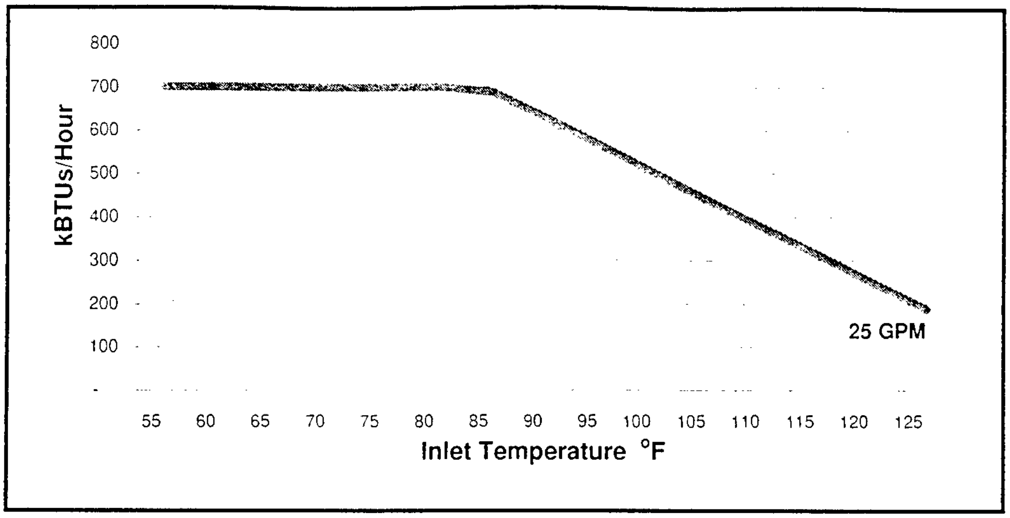


Figure 4. Fuel cell thermal output as a function of inlet temperature.

Note that this chart is for illustrative purposes and assumes a 25 gpm flow rate with a maximum delivery temperature of 140 °F when the fuel cell is operating at a 200 kW electrical output.

Application Load Characteristics

Typical applications for the fuel cell were discussed previously. For applications where the thermal load requires temperatures greater than 140 °F, the high-grade heat exchanger option would be required. Thermal load profile characteristics are a factor in how much thermal output would be used. For example, if the average thermal load of a building is 700,000 Btu/hr, the fuel cell will not necessarily be able to displace the entire load due to timing of the load requirement. Below are considerations for individual application types.

Boilers

The two thermal loads for a boiler plant are make-up water and return water. If a boiler distribution system is well maintained, make-up water requirements will likely be low. For high make-up water requirements, boiler make-up water represents a good application for a PAFC power plant. Load characteristics will depend on the loads on its thermal loop, time of year, and site specific factors. Most boilers have a log that documents fuel consumption and make-up water requirements. This information is useful in identifying potential fuel cell thermal utilization. Boiler return temperatures for steam boilers are high enough to require the high-grade heat exchanger option. (Refer to the boiler diagram [Figure A1] in Appendix A to this report.)

Swimming Pools

Swimming pools have both make-up water requirements (due to evaporation and spillage) and pool reheat requirements. The thermal load demand will vary depending on whether the pool is indoors or outdoors, the ambient temperature and humidity, the wind velocity, whether the pool is covered or not, the pool size, and other site specific variables. Indoor pools generally have lower heat losses than outdoor pools, but also tend to be open year round. (Refer to the pool diagram [Figure A2] in Appendix A to this report.)

Space Heating Loops

Hot water space heating loops generally operate at temperatures that require the high-grade heat exchanger option. Thermal utilization is limited to the months where space heating is required (4 to 7 months). Heating degree days for a location can be used to determine the potential load requirements. The heating load can be extended year around by using the heating loop to control humidity in a cool-reheat application. (Refer to the space heating diagram [Figure A3] in Appendix A to this report.)

Absorption Cooling

Using the high-grade heat exchanger option, the PAFC power plant can provide heat to an absorption chiller to provide cooling a building. Absorption chillers are one way to create a thermal load for a fuel cell when no other loads are available. If electric rates are high in the cooling season, then displaced cooling using an absorption chiller can be cost effective. Sites with longer cooling seasons and need continuous cooling are the best candidate sites for this technology. (Refer to the absorption chiller diagram [Figure A4] in Appendix A to this report.)

Domestic Hot Water

DHW is used for a variety of purposes including showers, laundry, kitchen loads, etc. In dormitories, thermal loads typically peak in the morning and evening periods with little or no demand in the middle of the day and night. To provide a buffer to accommodate the load spikes and to maximize the heat recovered from the fuel cell, a thermal storage tank should be considered. If the hot water loop has recirculation, this should be evaluated as a potential heat recovery load. Values for typical dormitory hot water loads are provided in the ASHRAE Handbook of Applications in the chapter on Service Water Heating. (See DHW [Figure A5] diagram in Appendix A.)

Thermal Integration Considerations and Flow Rates

The PAFC power plant should be integrated with a building's thermal application such that the existing system can still operate during times when the fuel cell is not available. In a retrofit situation, the PAFC power plant would provide supplemental heat to the existing thermal system, reducing or eliminating the normal energy requirement. Examples of this would be reducing the amount of gas normally consumed by a boiler or the amount of steam provided to a hot water generator. When the fuel cell is not operational, the existing thermal system would still operate as it did prior to the PAFC power plant retrofit. For new installations, a secondary thermal source should be integrated with the building application to meet load requirements during times when the PAFC power plant is unavailable.

The flow rates of building thermal loops can exceed the capacity of the PAFC power plant heat exchanger. For the PC25C, the design point for the heat exchanger is 25 gpm. A flow rate of 30 gpm or more is possible, but the pressure drop increases significantly and a larger pump would be required. Figure 5 shows the pressure drop curve for the standard heat exchanger (HEX 880).

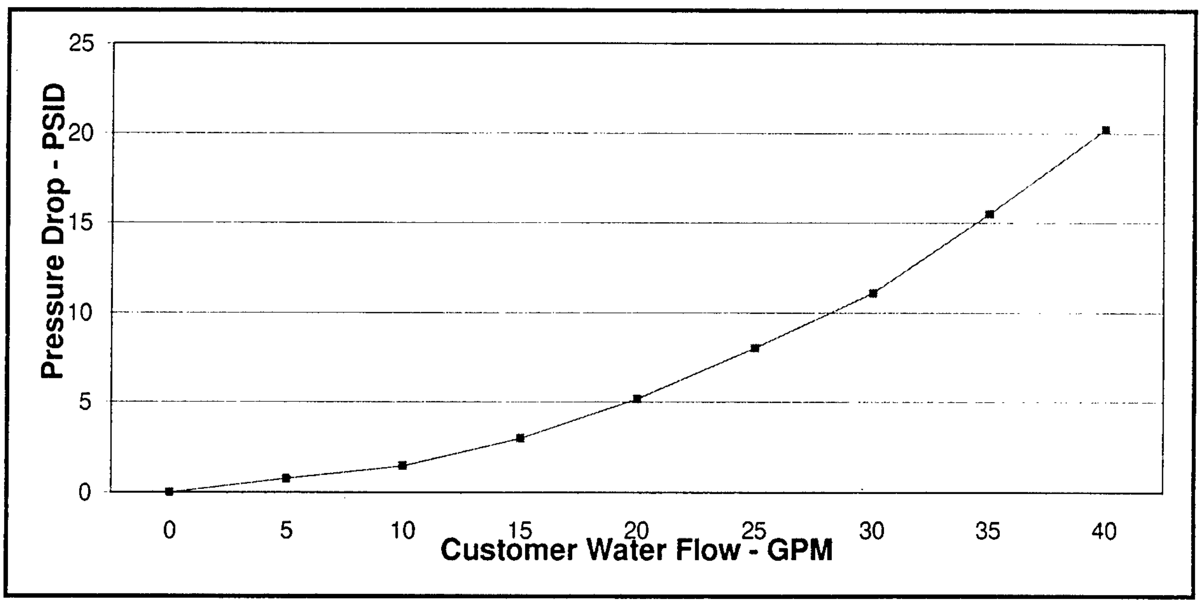


Figure 5. ONSI PC25 HEX 880 customer side pressure drop vs. flow.

PAFC Power Plant Water Treatment System (WTS) Considerations

Makeup water quality has been an issue for some installations. Changes to the PC25C have corrected many of these issues.

Water Conductivity

In desert locations, water conductivity has been a source of power problems for the PC25B. A water treatment system external to the fuel cell, which incorporates a reverse osmosis system, has been applied to correct the problem. The PC25C is a closed water system (after system start-up) and is less sensitive to water conductivity.

Resin Filters

Filters must be replaced every 3 months. In areas where there is high conductivity, the filters must be replaced more often. Filter replacement can be conducted while the power plant is operating.

PAFC Power Plant Example Design Drawings

There are several design drawings available from the DOD Fuel Cell Demonstration Program. Typical installation drawings are described briefly with examples provided.

Site Plan

The site plan should include the layout of the fuel cell and related equipment as it is to be installed at the site. Should show dimensions. General notes regarding foundation, grading, trench specifications, wall penetrations, etc., should be included. Appendix C to this report includes an example site plan.

Mechanical/Electrical Layout

The mechanical and electrical interface piping and wiring should be laid out. Location of the natural gas line, electrical interface, thermal interface tie ins, nitrogen tank lines, make-up water inlet, and cooling module piping should be shown. General notes regarding the connections should be provided. Appendix C to this report includes an example mechanical and electrical layout plan.

Mechanical Plan

The mechanical drawing should provide an equipment schedule, including pumps, valves, nitrogen tanks, sensors, etc. The diagram should show pipe diameters, flows, pressures, etc. A sequence of operation should also be provided to specify when pumps operate or valves open. Appendix C to this report presents an example mechanical plan.

Electrical Plan

The electrical wiring diagram should provide a one-line diagram of the electrical interface wire specifications, building interface, connection to the cooling module, and an electrical symbol list. A ground grid plan should also be included. Appendix C to this report includes an example electrical plan.

PAFC Power Plant Acceptance Test Procedures

Construction Documentation

A complete set of stamped as-built construction drawings should be provided by the installation contractor.

Visual Inspection

A qualified engineer should inspect the fuel cell installation to ensure that construction was completed per the drawing specifications.

Acceptance Test Procedures

The fuel cell should be run at three different power levels (100 kW, 150 kW, and 200 kW) to ensure that the operating parameters are within specification. Leading and lagging power factor should be demonstrated. At 200 kW, the following should be demonstrated: <3 percent total harmonic distortion; 60 Hz + 3 Hz frequency; 2 hours of normal thermal heat recovery. The ASME has assembled a power test code (PTC) committee, PTC 50, which is preparing fuel cell test procedures. These procedures may provide added guidance for acceptance test procedures.

5 PAFC Power Plant Commissioning and Operation

PAFC Power Plant Inspection

Delivery

The power plant is shipped as two modules (a power module and a cooling module). The power module is shipped by land transportation by means of an air-ride cab and air-ride single drop low boy trailer. If shipped by another method, an external shock-absorbing fixture will be required. The cooling module is shipped by common carrier from a separate manufacturing facility. Power plants are shipped with a protective plastic wrap and are covered with a tarpaulin during transit. Upon delivery, the installation contractor should remove the plastic wrap, inspect the unit, and have a crane available for unloading.

Inspection

The power module, cooling module, and protected hardware box should be visually inspected for damage that may have occurred during shipment. If damage has occurred, a claim should be filed with the carrier and the manufacturer should be notified. The equipment in the protective hardware box should be inventoried to ensure that no parts are missing. Missing parts should be reported to the manufacturer so that replacement parts can be supplied.

Unloading

The power module is set in place with a crane and suitable rigging equipment. Rigging should include four swivel hoist rings and four leg bridge slings. Care should be taken to ensure that the power module does not tilt more than 45 degrees from its shipped position. The cooling module should also be moved with a crane equipped with a spreader bar. Table 5 lists dimensions and weights of the power module and cooling module. Appendix D to this report includes photographs of the installation process.

Table 5. ONSI PC25C power plant dimensions and weight.

Equipment	Length (ft)	Width (ft)	Height (ft)	Weight (lb)
Power module	18	10	10	40,000
Cooling module	14	4	4	1,700

Installation

Site Preparation

Before the arrival of the power and cooling modules, the site should be prepared for placement of the equipment from the delivery trucks to the installation location. The equipment pad should be of adequate structural integrity and should be large enough to site the required equipment with the required clearances. The power module requires 8 ft of clearance on all sides to allow for proper maintenance access. The cooling module requires 2 ft clearance on all sides to ensure proper air flow. Utility services that are required at the equipment pad are water supply, 480 VAC – 3 phase electric access, and a natural gas line. The water connection is required to fill a water storage tank, to fill the piping for the thermal management system, and to provide make-up water during operation (if sufficient make-up water is not generated by fuel cell). The city water connection should have a nominal pressure of 55 psig. The electric interface to the utility grid is used for plant start-up and will have a maximum draw of 95 kW. The natural gas line should be sized to accommodate 3,000 SCFH at 4 to 14 in. of water supply pressure.

Power Module Hardware

Installation of the power module hardware consists of installing the power plant exhaust cover, the inlet ventilation air hoods, the water treatment system canisters, and frame tie down caps.

Plumbing Interface

Five fluid systems are associated with the fuel cell, requiring a total of seven interface connections. If the high grade heat recovery option is provided with the fuel cell, two additional connections will be required. Table 6 lists the systems and connections.

Table 6. Thermal interface connection specifications.

System	No. of Connections	Material	Size
Natural gas supply	1	Steel pipe SCH 40	2-in.
Nitrogen supply	1	Copper tubing	¾-in.
Ancillary cooling module	4	Copper tubing	2-in.
Heat recovery loop	2	Copper tubing	2-in.
Make-up water supply	1	Copper tubing	¾-in.
High-grade recovery loop	2	Copper tubing	2-in.

Electrical Interface

There are three electrical interfaces in the standard grid connect configuration. Ground wires should also be connected to ground rods for the power module, cooling module, and nitrogen cylinders (if required by code). Table 7 lists the loads and connections.

Table 7. Electrical interface connection specifications.

Interface	Conductors	Conduit Size
Power module output	Power: (3) #500 MCM Ground: (1) #2	4 in.
Cooling module Power and control	Power: (6) #12 Ground: (1) #2	1 in.
Telephone	4 pair telephone cable	1 in.

PAFC Power Plant Monitoring

Performance monitoring is available for the fuel cell through the use of the ONSI Remote Automated Diagnostics and Data Acquisition and Recording (RADAR) monitoring system or, optionally, through independent monitoring equipment.

RADAR

ONSI's system is integrated into the PC25C and enables remote access to the PAFC power plant. For the customer to access the PC25C remotely, they must purchase the optional RADAR system software. Overall system and subsystem operation can be monitored through RADAR. Fuel cell operators can interface with this system remotely over a phone line or directly with a notebook computer.

Independent Monitoring

Independent performance monitoring can be conducted by measuring the flows of energy into and out of the fuel cell. Each monitoring system is different and depends on the specific requirements of the site. One option is to integrate monitoring points into an existing energy management system. Table 8 lists recommended performance monitoring points.

Table 8. Independent PAFC power plant monitoring points.

Energy Path	Measurement	Sensor Type
Natural gas consumption	Gas flow (SCFH)	Gas meter with pulse initiator
Electric demand/consumption	Electric power (kW)	Electric demand & watt-meter
Heat rejected	Heat transfer (Btu's)	Btu meter
Heat recovered	Heat transfer (Btu's)	Btu meter
High temp heat recovered (for high-grade heat option)	Heat transfer (Btu's)	Btu meter

Specification Notes

Depending on the gas line installation and placement of the gas meter, the meter may need to be pressure and temperature compensated. If the fuel cell is providing power to both a grid connected and grid independent mode, multiple watt meters will be required.

PAFC Power Plant Troubleshooting

The plant will disconnect itself from the grid and shift to idle when it no longer senses a specific voltage level from the utility grid. When other system characteristics are out of range, the fuel cell may go into an automatic shutdown to prevent damage to the power module or present a danger to the site. When either condition occurs, the operator should refer to the service manual. The service manual is furnished by the manufacturer and contains detailed power plant troubleshooting procedures.

Power Plant Diagnostics

When an event occurs, an automatic notification via telephone is made and an event is logged. A problem will be identified in the Power Plant Events History Display falling into one of three categories: (1) an automatic power plant shutdown, (2) an automatic reduction of electric output, or (3) an observed process parameter or condition not expected. During an event or shutdown, the ONSI

RADAR system records performance parameters at one to several second intervals. These data points can be used to determine what occurred at the point of automatic shutdown.

Makeup Water Quality

High water conductivity, often found in desert environments, can be the cause of fuel cell operational problems. Resin filters may have to be changed more often, or special water reverse osmosis systems may have to be installed to deal with various water quality issues.

PAFC Power Plant Repair

Factory Authorized Maintenance

Service should be conducted by trained and authorized service personnel. For all service, the service manual should be consulted to identify procedures and appropriate warnings. Some procedures can be performed while the power plant is operating. Unnecessary or frequent shutdowns should be avoided to minimize degradation in performance and eventual shortening of the useful life of the power module.

Training

ONSI provides a fuel cell training class at their facility in Connecticut and makes available onsite training for site personnel. Participants are educated on the fundamental operation of the fuel cell and procedures for startup, shut-down, and routine maintenance activities.

PAFC Power Plant Scheduled Maintenance

The fuel cell power plant requires routine maintenance on intervals as frequent as every 2000 hours of operation (four times per year) to once every 40,000 hours of operation (once every 5 years). The following sections summarize maintenance requirements.

Water Treatment System

The water treatment system purifies water recovered from the condensate from one of the heat exchangers and the cell stack cooling loop. Routine maintenance activities required for this system occur quarterly and annually:

1. Quarterly Maintenance
   a. Replace mineral demineralizer beds
   b. Clean water tank
   c. Clean water filters
2. Annual Maintenance
   a. Clean deaerator column
   b. Pump maintenance.

Process Air and Fuel Supply Systems

The process air system provides air to the cathodes and provides combustion air to the reformer. The fuel processing system converts natural gas into a hydrogen-rich fuel for the stack.

1. Quarterly Maintenance: Replace air filters
2. Annual Maintenance
   a. Lubricate bearings on process air blower
   b. Clean condenser
   c. Check spark plug
   d. Check flame sensor.

Ancillary Cooling System

The ancillary cooling system provides cooling for the power conditioning system by means of the remote cooling module and the power module heat recovery loops.

1. Quarterly Maintenance: Lubricate pump bearings
2. Annual Maintenance
   a. Pump maintenance
   b. Clean filter
   c. Analyze glycol solution.

Cell Stack Cooling System

The cell stack cooling system maintains the stack temperature, supplies process steam to the fuel processing system, and cools the reformed fuel.

1. Annual Maintenance: Inspect accumulator
2. Bi-Annual Maintenance
   a. Pump maintenance
   b. Check flow switch
   c. FO400 Replacement.

Compartment Ventilation System

The compartment ventilation system provides thermal control of the interior of the power plant module and prevents the build-up of combustible gases.

1. Quarterly Maintenance: Replace air filters

Electrical System Assembly

The electrical system consists of a converter (changes direct current power into alternating current power), controls, auxiliary electric loads, and monitoring system.

1. Annual Maintenance
   a. UPS functional check
   b. Check panel boards
   c. Test automatic transfer switch
   d. Check motor starters
   e. Provide power conditioner maintenance
   f. Calibrate I/O devices
   g. Check power supply voltage
2. Bi-annual Maintenance
   a. Replace air conditioning filter
   b. Coolant flow switch (FS400) and FO400 replacement.

Cell Stack

Throughout the life of the cell stack, the electrical output will decrease for a given fuel consumption rate. As this occurs, the quantity of heat produced will increase. Once the cell stack has operated for more than 40,000 hours, the performance will have dropped noticeably. At this point, the operating efficiency of the fuel cell should be continuously monitored. When the electrical efficiency has dropped to the point where the cost of electricity produced by the fuel cell no longer meets the cost advantage of purchasing electricity from the utility, the cell stack should be replaced.

6 Conclusion

This program has demonstrated the application of PAFC power plants at over 30 DOD sites across the continental United States (the contiguous 48 States and Alaska). These power plants have subsequently performed in a wide variety of geographic and climatic conditions. This program has contributed much experience in the siting, installation, operation, and maintenance of these units.

This design document was developed to help transfer the information gained from this experience to the facility engineer of designer interested in evaluating or installing PAFC power plant technology. PAFCs (and fuel cells in general) offer an efficient and nonpolluting method of power generation, and have proven themselves to be beneficial in accomplishing the overall mission of the DOD. The success of the applications documented in this study indicate that PAFC fuel cells can play an integral role in the DOD's long-term energy strategy.

Appendix A: PAFC Thermal Interface Example Diagrams

DIAGRAMS:

1. BOILER
2. SWIMMING POOL
3. SPACE HEATING SYSTEM
4. ABSORPTION CHILLER
5. DOMESTIC HOT WATER SYSTEM

DISCLAIMER

The diagrams in this Appendix are for illustrative purposes only and do not represent any specific recommendations or requirements for DOD facilities. Each application is different and requires the consideration of a qualified engineer.

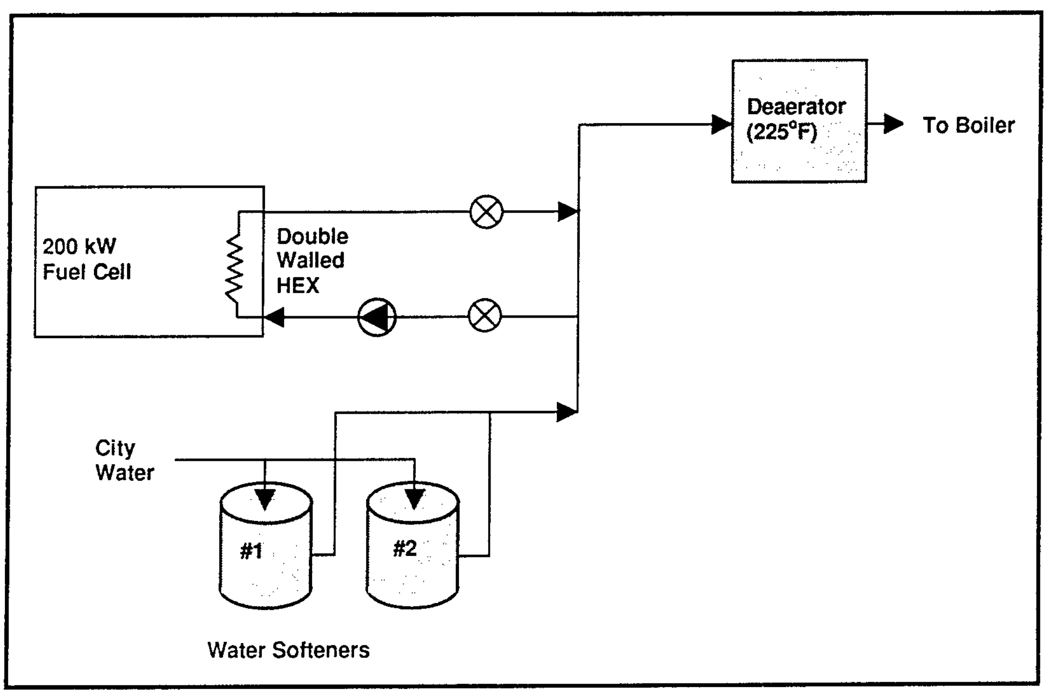


Figure A1. PAFC thermal interface for boiler.

Boiler make-up water passes through water softeners prior to entering the deaerator. When make-up water is called for, a 25 gpm pump diverts water through the fuel cell heat exchanger and delivers preheated water to the deaerator. The fuel cell interface was located after the water softeners to avoid introducing high temperature water into the water softeners.

An example calculation is provided below for determining the amount of thermal energy supplied by a fuel cell given the following input values and constants:

Pump flow = 25 gpm

Inlet water temperature = 55 °F

Fuel cell outlet temperature = 110 °F

8.35 lb per gal of water

0.001 Thousands of Btu per lb of water per degree temperature rise

Fuel Cell kBtu/hr:

= (gal/min) * (min/hr) * (lb/gal - H_2O) * (kBtu/lb- °F) * (Outlet-Inlet Temp.)

= (25 gpm) * (60 min/hr) * (8.35 lb/gal) * (0.001 kBtu/lb - °F) * (110 °F – 55 °F)

= 688 kBtu/hr (thermal supplied by fuel cell to boiler make-up loop during hours of operation).

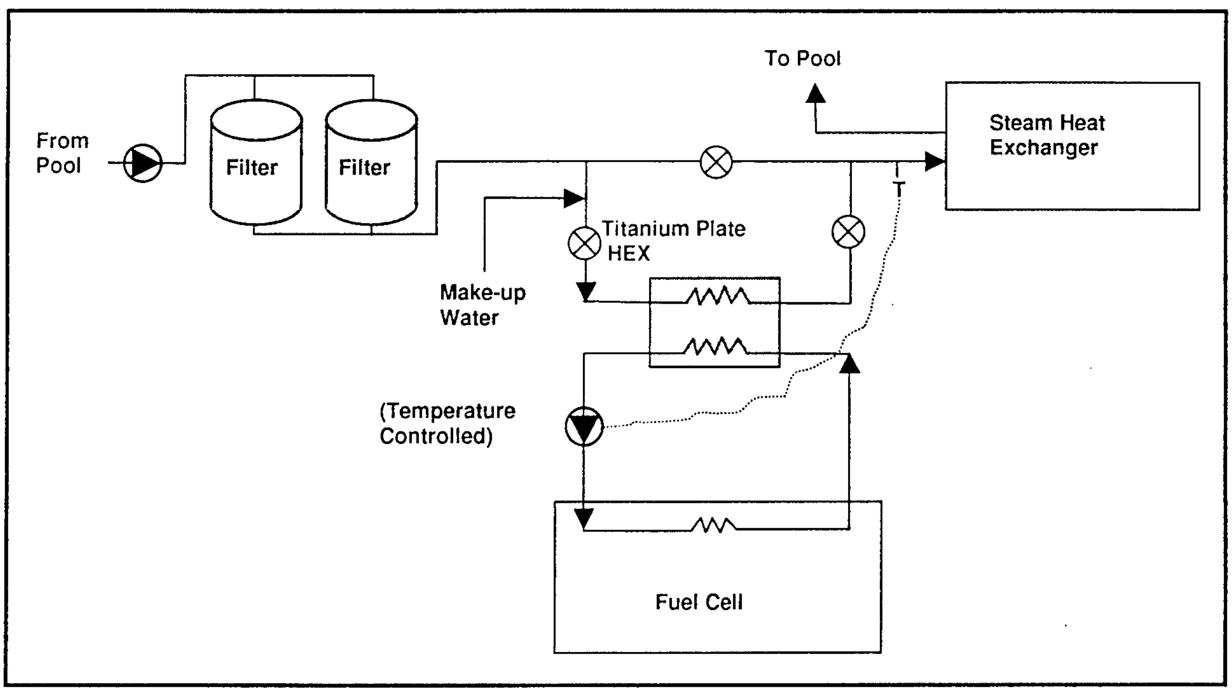


Figure A2. PAFC thermal interface for swimming pool.

The fuel cell is used to preheat pool make-up and return water prior to entering the existing steam driven pool heater. When the fuel cell cannot provide enough heat for the pool, then the steam heater will come on to bring the water temperature up to target levels. An intermediate heat exchanger (HEX) is used to keep the corrosive pool water separate from the fuel cell's internal heat exchanger system. Consider the following example:

	Summer*		Winter**	
Description	**Day**	**Night**	**Day**	**Night**
Air temp (°F)	66	60	62	54
R/H (%)	73	89	78	64
Water temperature (°F)	80	80	80	80
Solar insulation (Btu/sq ft-Day)***	1,800	—	1,300	—
Absorption rate	0.75	—	0.75	—
Pool hours covered		7pm – 8am		6pm – 9am

* Summer = June – August

** Winter = September – May

*** Ref.: SDG&E, Solar Radiation Data

	Summer		Winter	
Description	**Day**	**Night**	**Day**	**Night**
Total loss rate (kBtu/hr)[1]	1790	629	2302	812
Evaporative losses (kBtu/hr)[2]	—	69	—	92
Rad./convection losses kBtu/hr)[3]	—	560	—	720
Hours per day	11	13	9	15
Total loss (MBtu/day)[4]	19.7	8.2	20.7	12.2
Solar gain (MBtu/day)[5]	16.4	—	11.9	—
Heating load (MBtu/day)[6]	3.3	8.2	8.8	12.2
Heating load rate (kBtu/hr)[7]	300	629	978	812

Equations:

#1 = 10.5 * Pool Surface Area (sq ft) * [T_{H_2O}(°F) - T_{AIR} (°F)] * 1 kBtu/1,000 Btu

#2 = Evap. loss (kBtu/hr) = 0.1 * Surface area (sq ft) * [Vapor press, H_2O (In Hg) -Vapor Press, Air (In Hg)] * 1 kBtu/lb; reduced by 90% when covered at night.

#3 = (#1 - #2), reduced by 70% when covered at night.

#4 = #1 * hours/day * 1 MBtu/1000 kBtu

#5 = solar insulation (Btu/sq ft-Day) * pool area (sq ft) * 1 MBtu/1,000,000 Btu * absorption rate

#6 = (#4 - #5)

#7 = (#6 / hours/day)

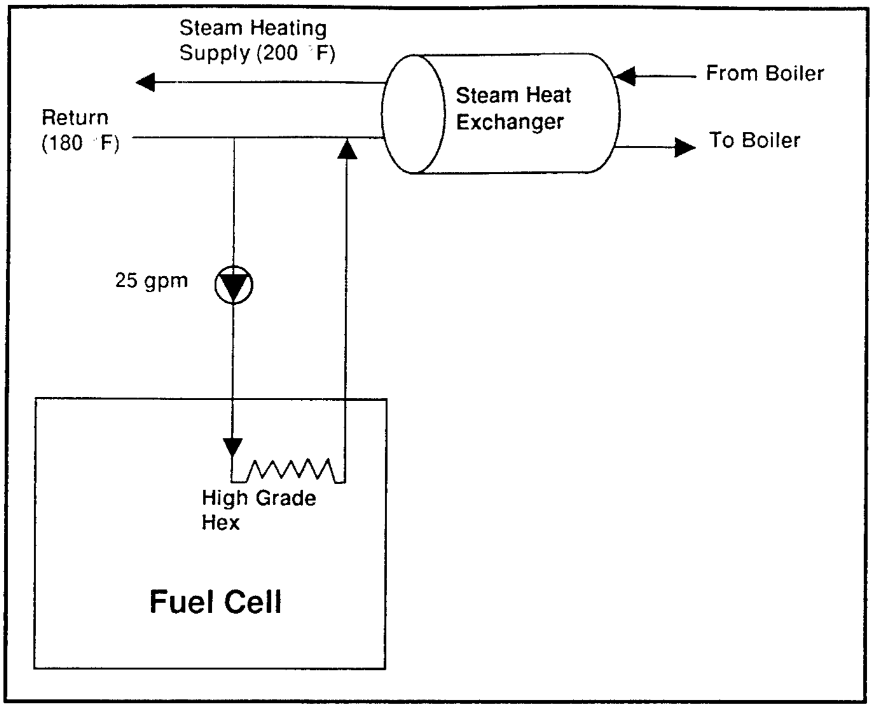


Figure A3. PAFC thermal interface for space heating system.

A fuel cell high-grade heat exchanger is needed to interface the thermal output with the 180 °F to 200 °F space heating loop. A pump pulls 25 gpm from the building return loop into the fuel cell heat exchanger and back into the space heating loop. When the fuel cell heats the loop up to the required temperature, the existing steam heater will not be required.

The example calculation provided below determines the amount of thermal energy supplied by a fuel cell given the following input values and constants:

Pump flow = 25 gpm

Inlet water temperature = 180 °F

Fuel cell outlet temperature = 200 °F

8.35 lb / gal of water

0.001 thousands of Btu / lb of water / °F temperature rise

Fuel Cell kBtu/hr:

= (gal/min) * (min/hr) * (lb/gal - H_2O) * (kBtu/lb - °F) * (Outlet-Inlet Temp.)

= (25 gpm) * (60 min/hr) * (8.35 lb/gal) * (0.001 kBtu/lb - °F) * (200 °F - 180 °F)

= 250 kBtu/hr (thermal supplied by fuel cell to space heating loop during hours of operation).

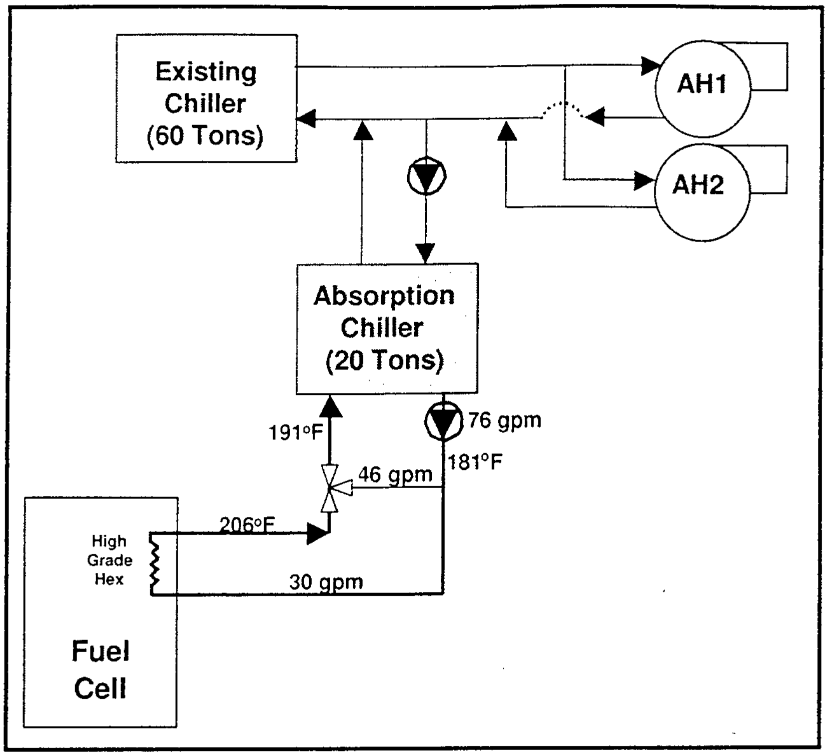


Figure A4. PAFC thermal interface for absorption chiller.

The fuel cell's high-grade heat exchanger is the primary heat source for the absorption chiller. The absorption chiller is used to "pre-cool" the existing chilled water return loop prior to entering the conventional chiller. Hot water from the fuel cell is circulated to the absorption chiller with a by-pass for moderating the temperature and achieving a minimum overall circulation requirement of 76 gpm.

With a high-grade heat exchanger output of 350,000 Btu/hr, the fuel cell can provide enough heat to the absorption chiller to generate 20 tons of cooling. Assuming this energy displaces work that otherwise would be provided by an electric chiller, and assuming a coefficient of performance (COP) of 4.0 for the electric chiller, the fuel cell would displace 17.6 kW during building cooling periods:

17.6 kW = [20 tons * 12,000 Btu/ton-hr] / [3413 Btu/kW-hr * 4.0]

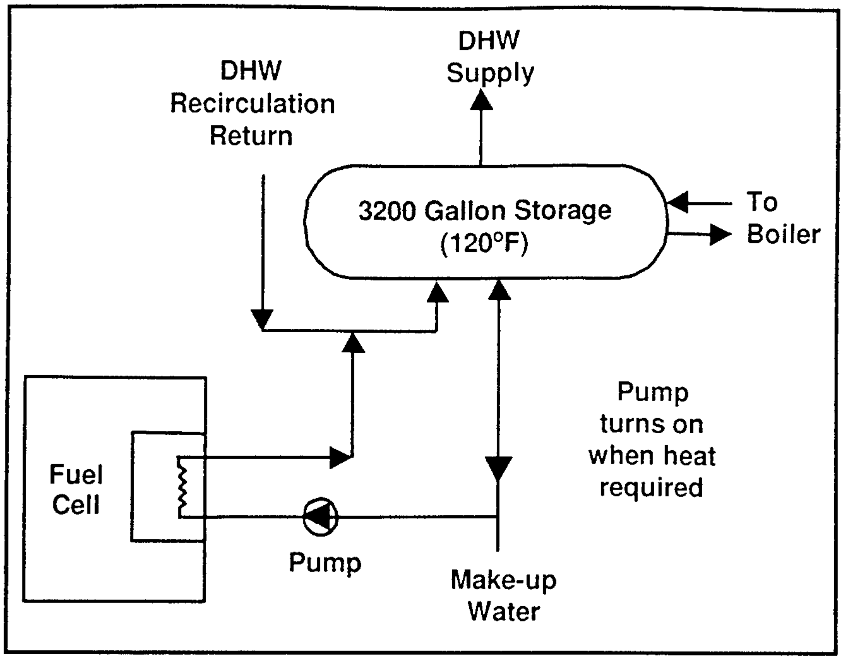


Figure A5. PAFC thermal interface for domestic hot water.

Fuel cell thermal output is used to heat the make-up requirement for domestic hot water usage. When there is no demand for hot water, water from the storage tank is circulated back through the fuel cell to replenish the recirculation loop and storage tank heat losses. Fuel cell loop setpoint temperature is slightly higher than boiler temperature to permit the fuel cell to supply heat to the boiler. The boiler operates as necessary to supplement fuel cell heat.

An example calculation is provided below for determining the amount of thermal energy supplied by a fuel cell given the following input values and constants:

Pump flow = 25 gpm

Inlet water temperature = 55 °F

Fuel cell outlet temperature = 110 °F

8.35 lb per gal of water

0.001 Thousands of Btu / lb of water / °F temperature rise

Fuel Cell kBtu/hr:

= (gal/min) * (min/hr) * (lb/gal - H_2O) * (kBtu/lb - °F) * (Outlet-Inlet Temp.)

= (25 gpm) * (60 min/hr) * (8.35 lb/gal) * (0.001 kBtu/lb - °F) * (110 °F – 55 °F)

= 688 kBtu/hr (thermal supplied by fuel cell to DHW loop during hours of operation).

preparation of welding and brazing requirements that affect procedure and performance. The purpose of the Welding Procedure Specification (WPS) and Procedure Qualification Record (PQR) is to determine that the weldment proposed for construction is capable of having the required properties for its intended application.

The National Fire Protection Association (NFPA)

NFPA is a non-profit organization that publishes the National Electrical Code®, the Life Safety Code®, the Fire Prevention Code™, the National Fuel Gas Code®, and the National Fire Alarm Code®. The mission of NFPA is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating scientifically-based consensus codes and standards, research, training, and education.

NFPA 70: National Electric Code

The NFPA 70 (the National Electric Code) covers electric conductors and equipment installed within or on public and private buildings or other structures, including mobile homes and recreational vehicles; floating buildings; and other premises such as yards, carnivals, parking and other lots and industrial substations; conductors that connect the installations to a supply of electricity; and other outside conductors and equipment on the premises; optical fiber cable; buildings used by the electric utility, such as office buildings, warehouses, garages, machine shops; and recreational buildings that are not an integral part of a generating plant, substation, or control center.

NFPA 86C: Standard for Industrial Furnaces

Using a Special Processing Atmosphere. Covers requirements for safeguarding against fire and explosion hazards in industrial furnaces using flammable or special processing atmospheres, Class C industrial furnaces. This standard covers many common safety requirements such as location, construction, heating system, safety equipment, testing, maintenance, and fire protection. This standard also provides safety requirements for the generation, storage, and use of special atmosphere gases.

Underwriters Laboratories, Inc. (UL): UL 795 Commercial-Industrial Gas Heating Equipment

UL is an independent, not-for-profit product safety testing and certification organization. UL has tested products for public safety for more than a century with more than 14 billion UL Marks applied to products worldwide.

UL 795 covers factory-built gas appliances having inputs of more than 400,000 Btu per hour, per individual combustion chamber which require flame failure and other precautions and which are intended primarily for commercial and industrial installation. The appliances covered by these requirements are gas burners, comfort heating furnaces, heaters and gas-fired boiler assemblies except water tube boilers having outputs of 10,000 lb of steam per hour or more. Gas-heating equipment covered by these requirements may be operated without a competent attendant being constantly on duty at the burners while the burners are in operation.

The Occupational Safety and Health Administration (OSHA): OSHA – General Industry Standards 29 CFR #1910.212

OSHA is a division of the U.S. Department of Labor. OSHA is committed to the reduction of injuries, illnesses, and deaths in the workplace.

Machinery and Machine Guarding. This standard covers methods of machine guarding to protect the operator and other employees in the area of the machine from hazards such as those created by point of operation, ingoing nip points, rotating parts, flying chips, and sparks. Guarding methods include barrier guards, two hand tipping devices, and electric safety devices.

Appendix C: Example PAFC Power Plant Installation Drawings

DIAGRAMS (11 x 17-in. Format):

1. Cover - Project Cover Sheet and Drawing List
2. S1 - Site Foundation Plan, Details
3. S2 - Power Plant Foundation Design, Notes, and Details
4. ME1 - Mechanical / Electrical Layout Plan
5. M1 - Mechanical Piping And Instrumentation Diagram
6. M2 - Mechanical Piping Details
7. E1 - Electrical Wiring Diagrams
8. E2 - Electrical Details

DISCLAIMER

The diagrams in this Appendix are for illustrative purposes only and do not represent any specific recommendations or requirements for DOD facilities. Each application is different and requires the consideration of a qualified engineer.

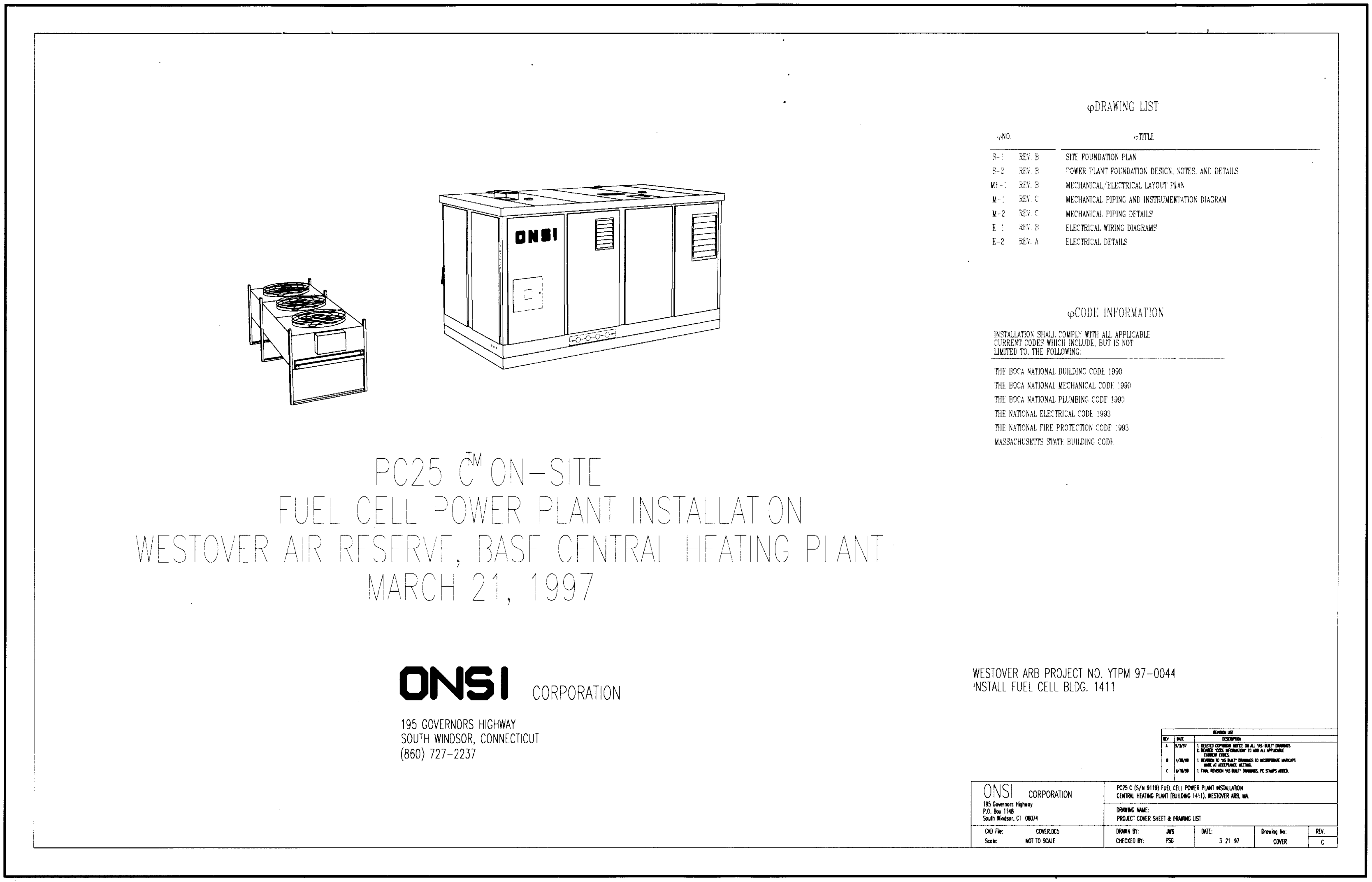


Figure C1. Project cover sheet and drawing list.

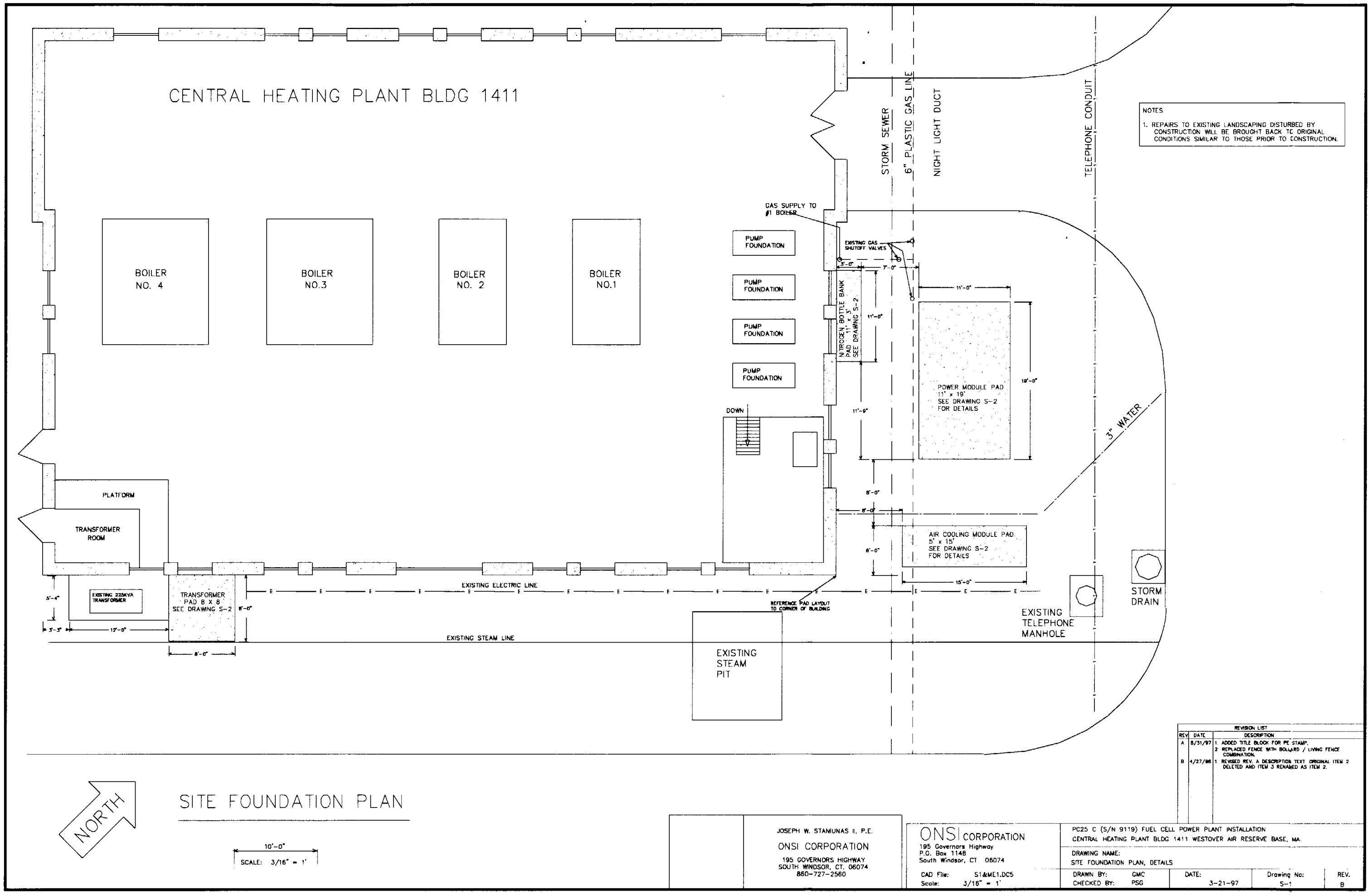


Figure C2. Site foundation plan, details.

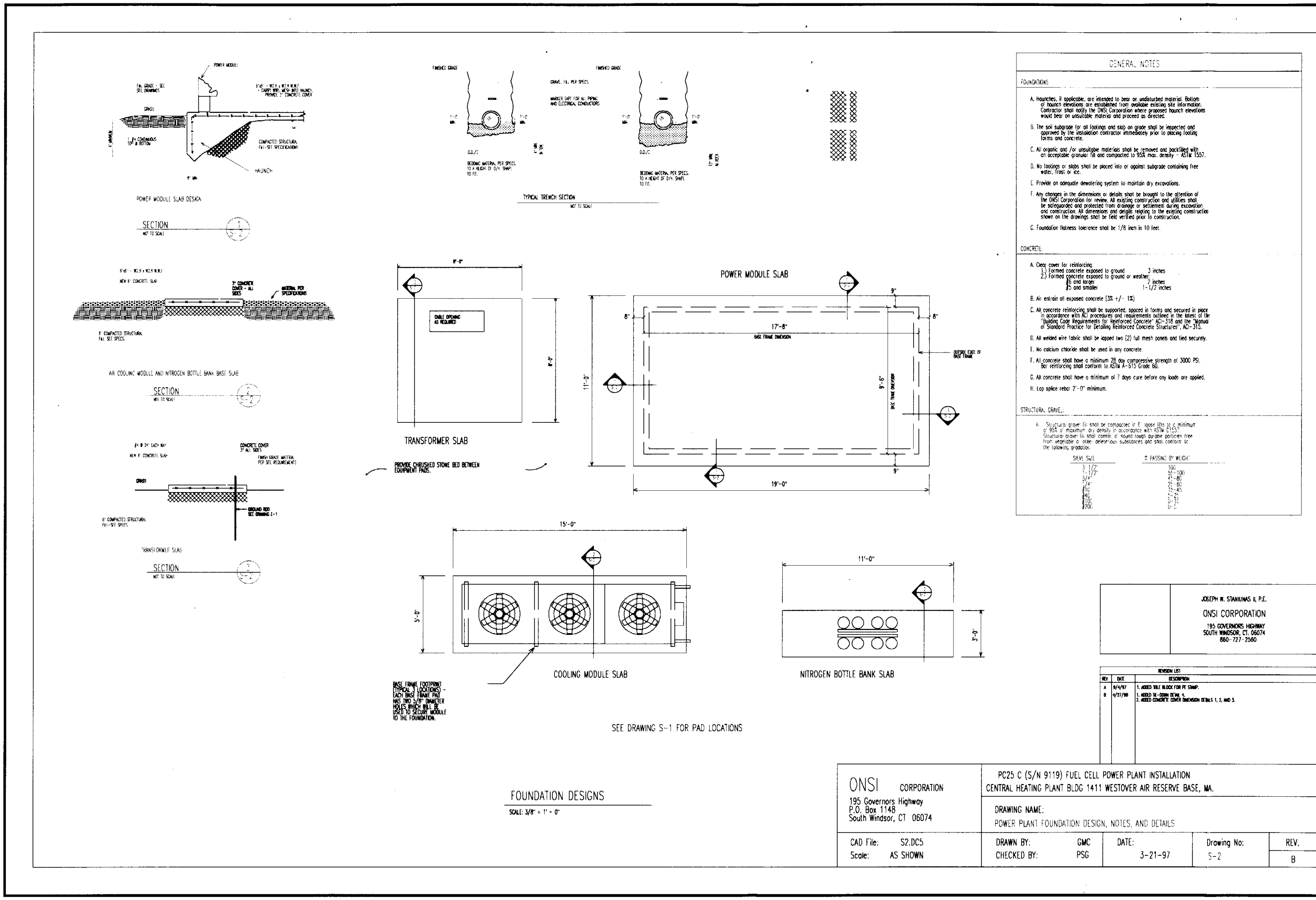


Figure C3. Power plant foundation design, notes, and details.

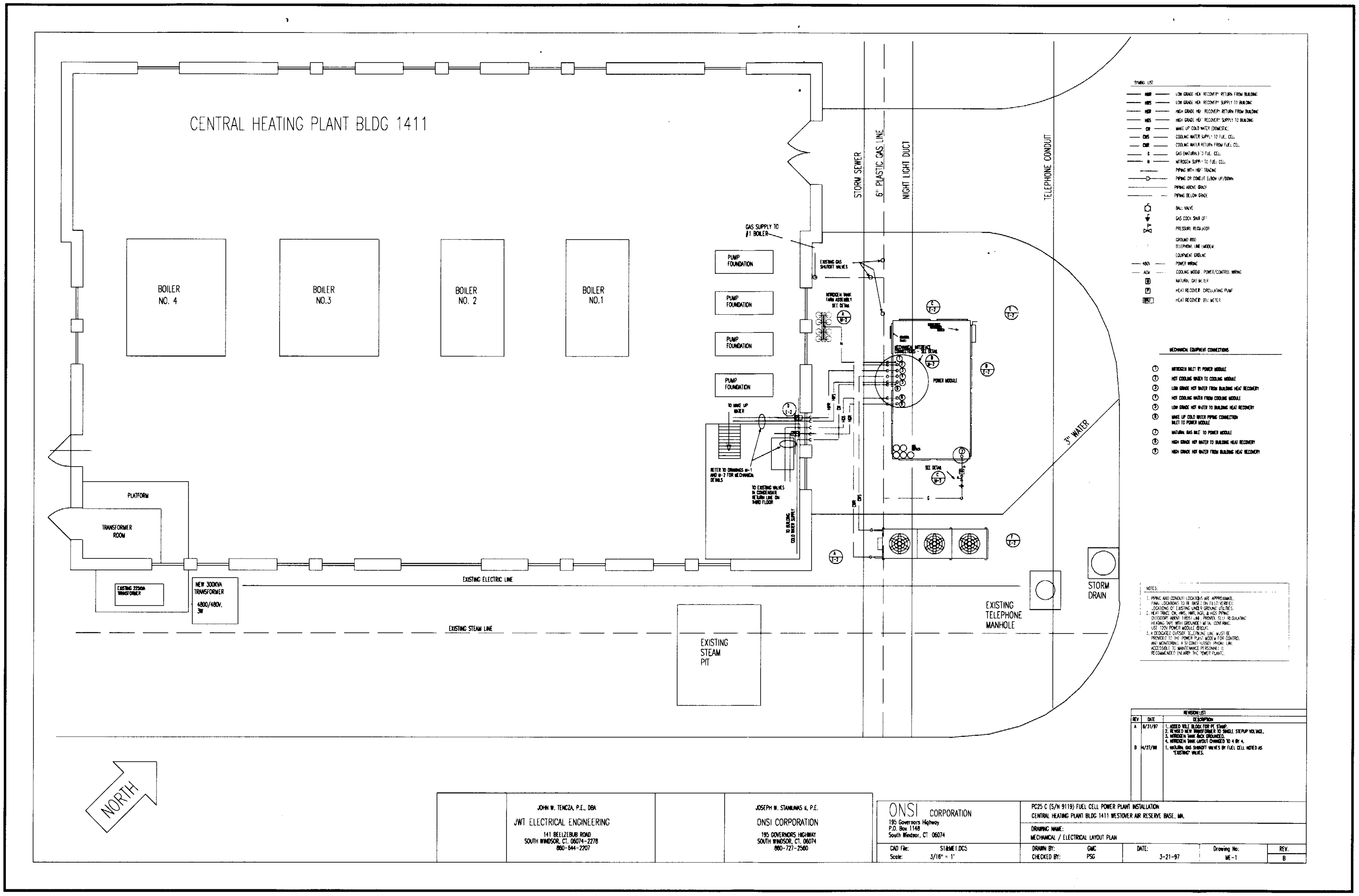


Figure C4. Mechanical / electrical layout plan.

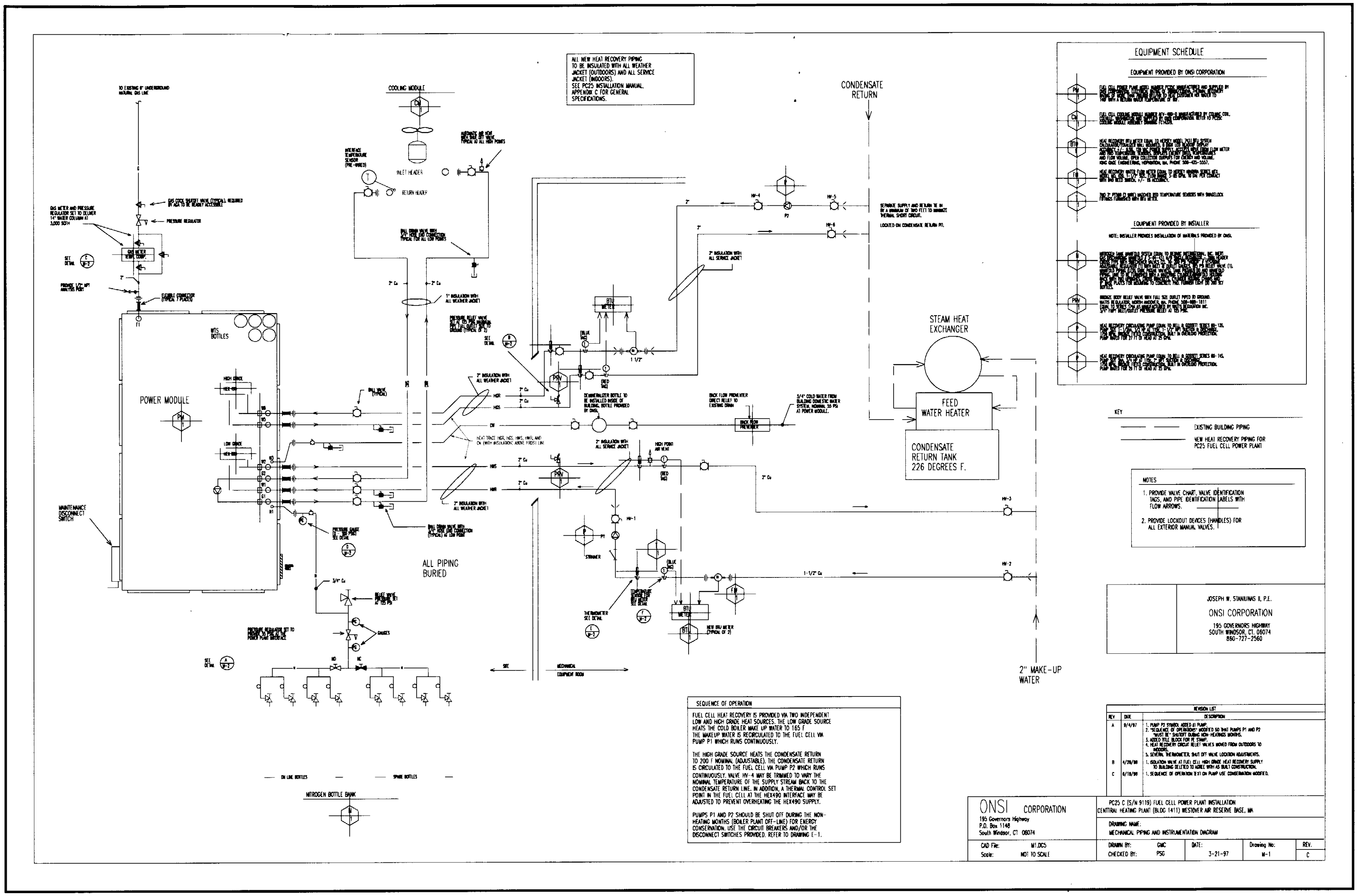


Figure C5. Mechanical piping and instrumentation diagram.

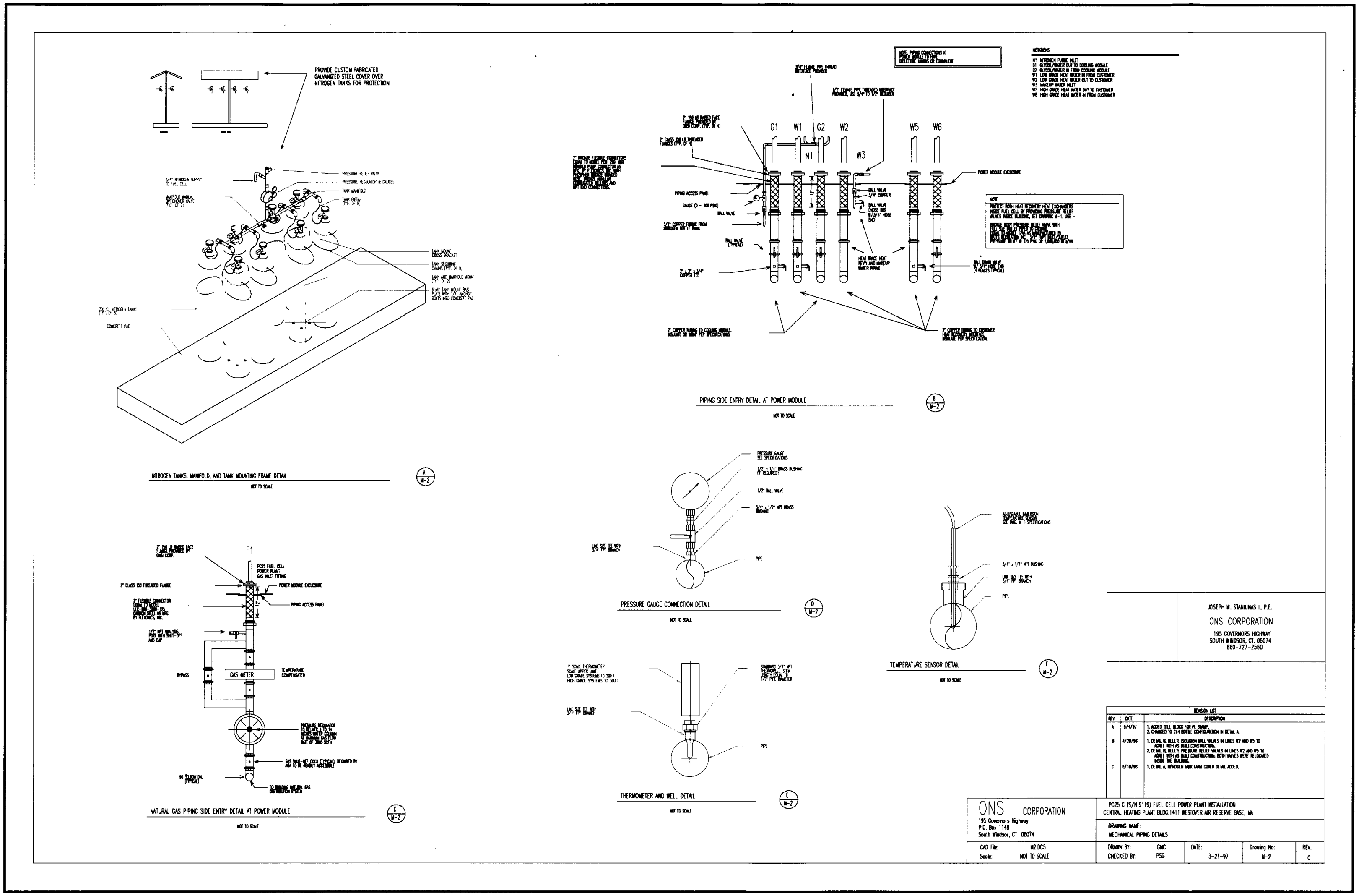


Figure C6. Mechanical piping details.

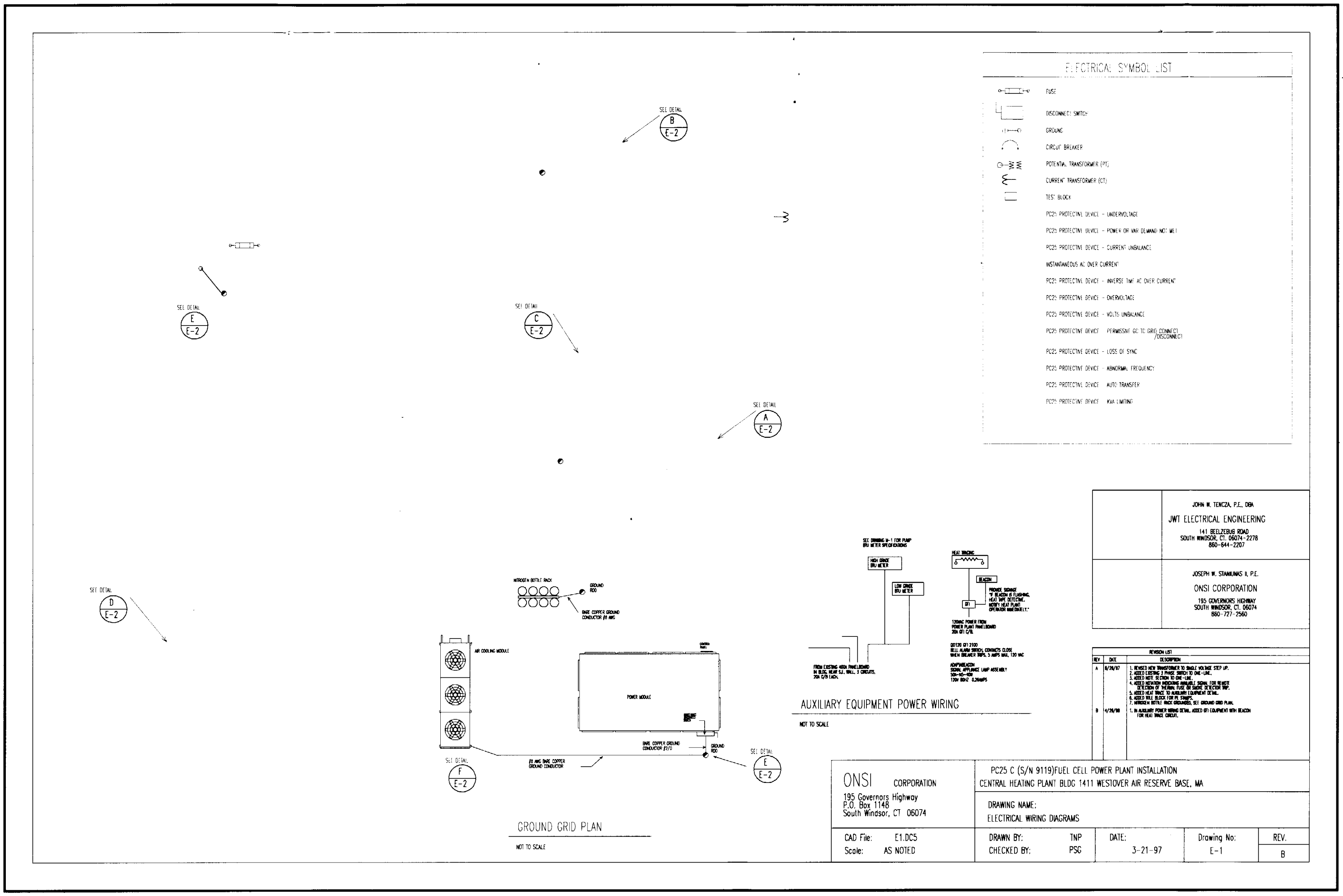


Figure C7. Electrical wiring diagrams.

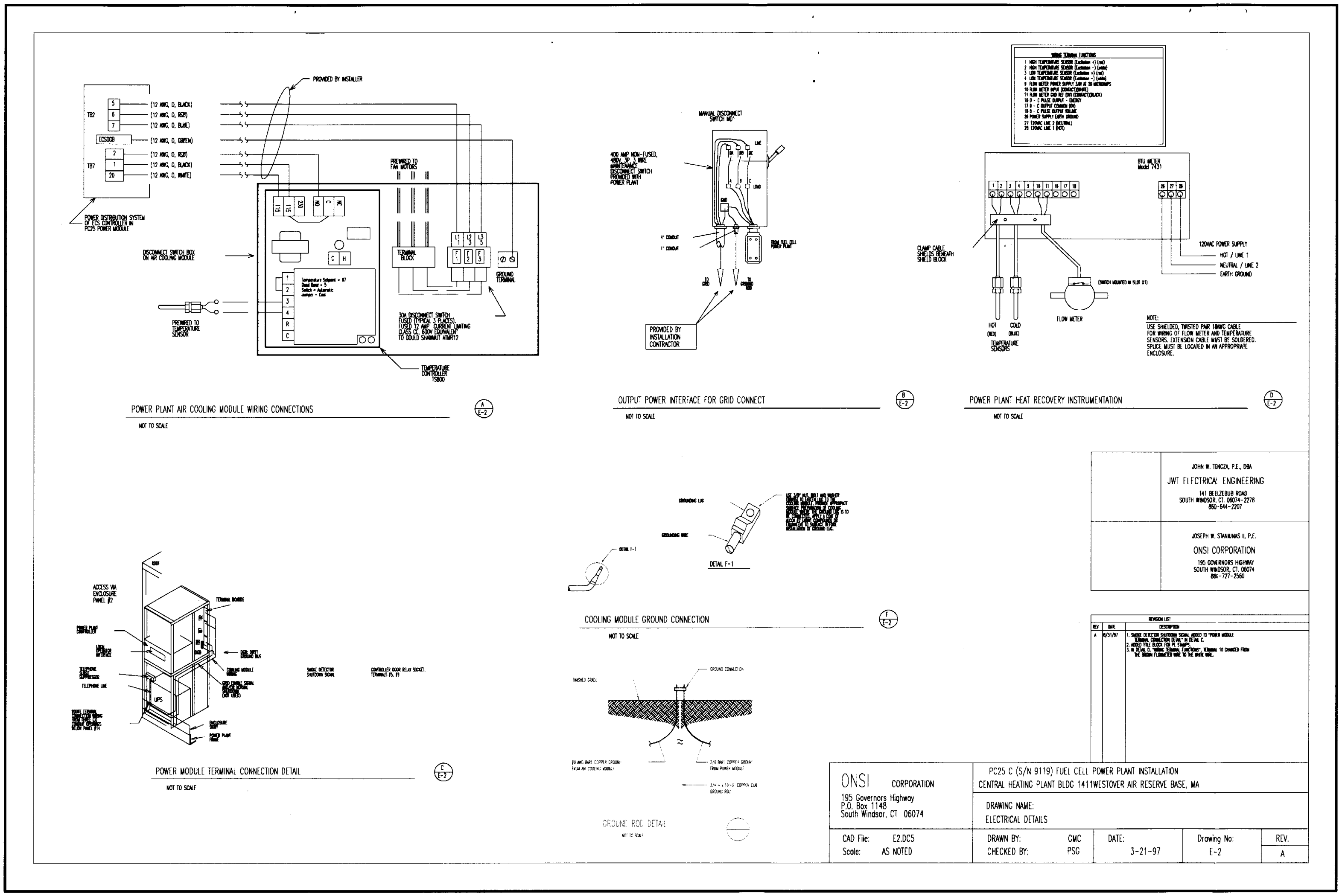


Figure C8. Electrical details.

Appendix D: Little Rock Air Force Base Fuel Cell Installation Photographs

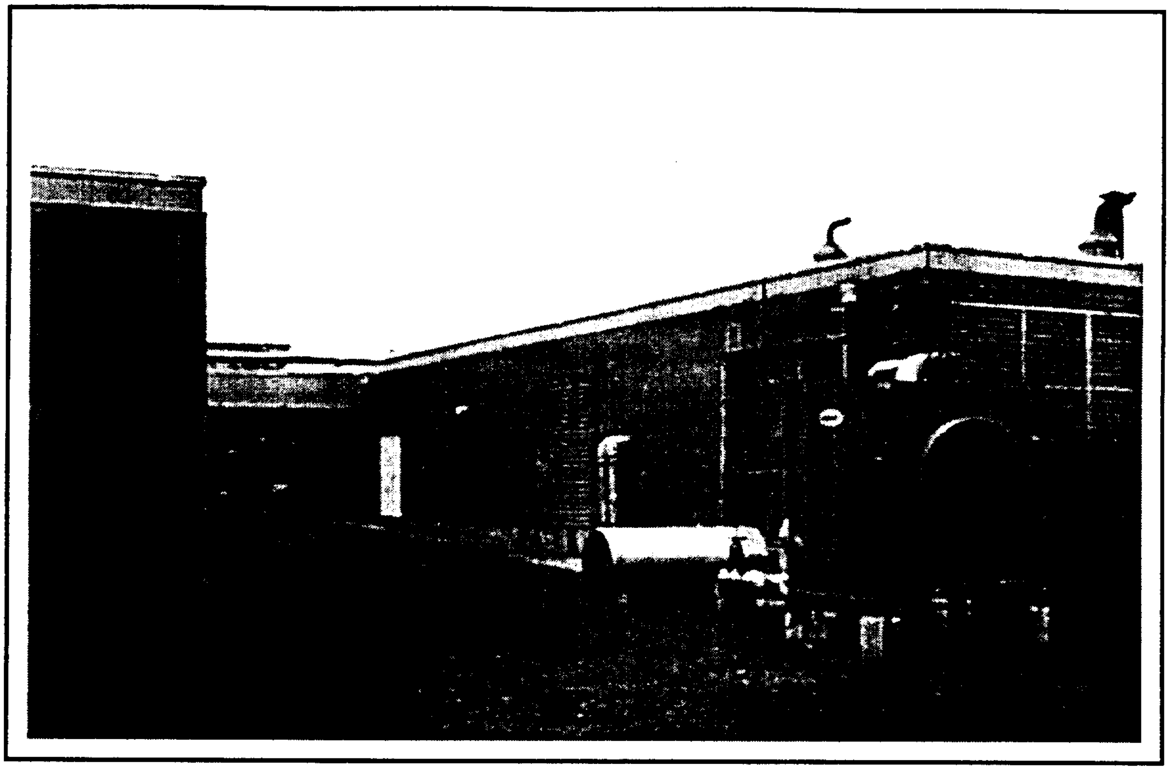


Figure D1. Fuel cell site prior to installation.

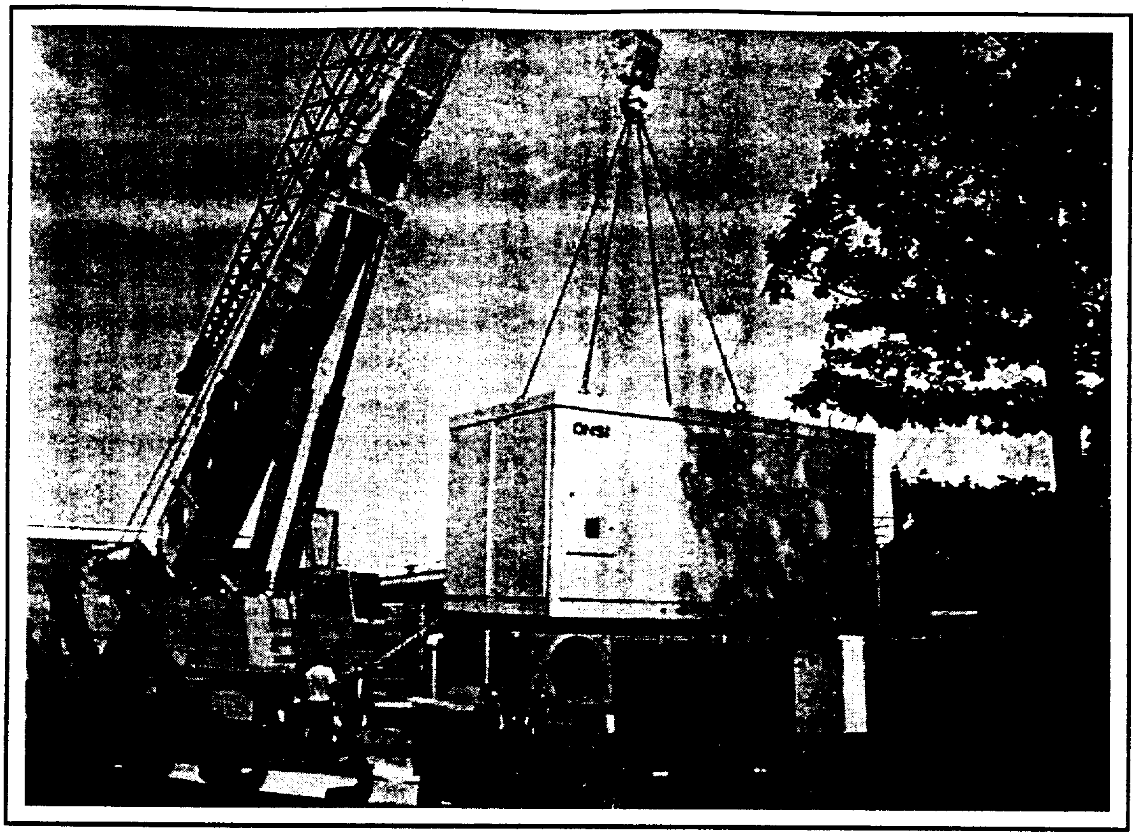


Figure D2. Crane lifting PC25C power plant off transport truck.

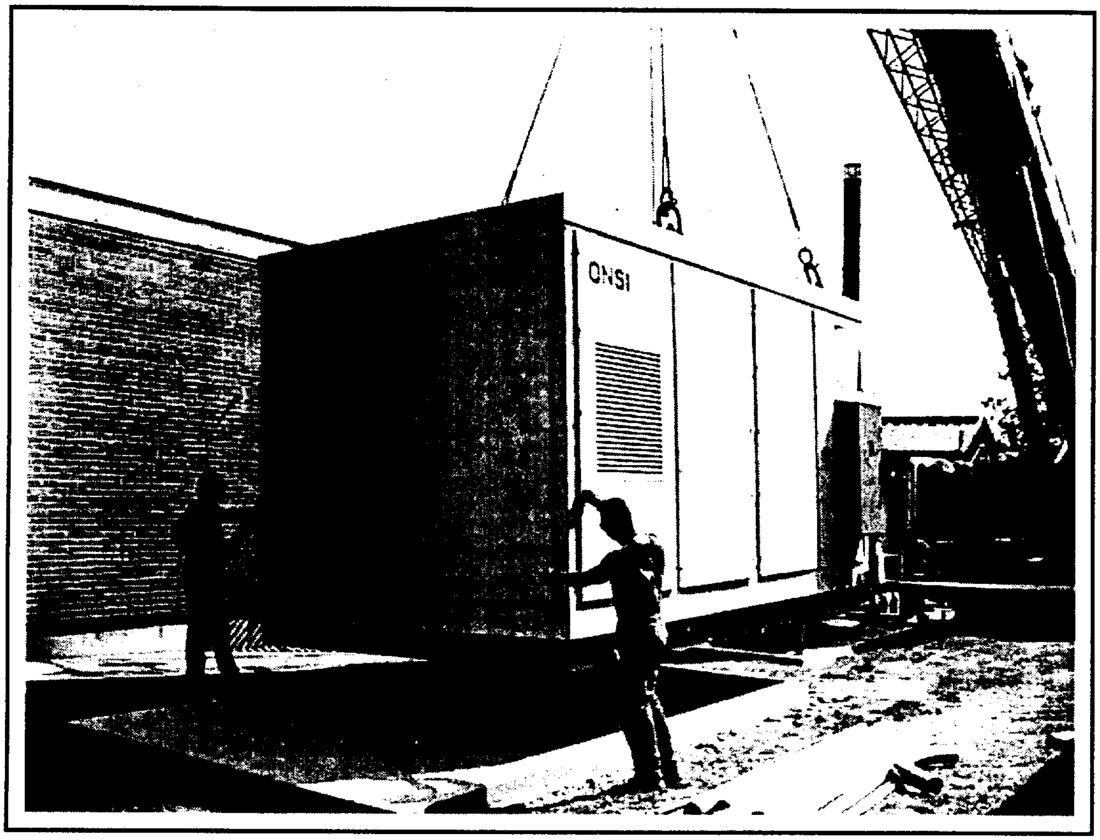


Figure D3. Crane setting PC25C onto pad.

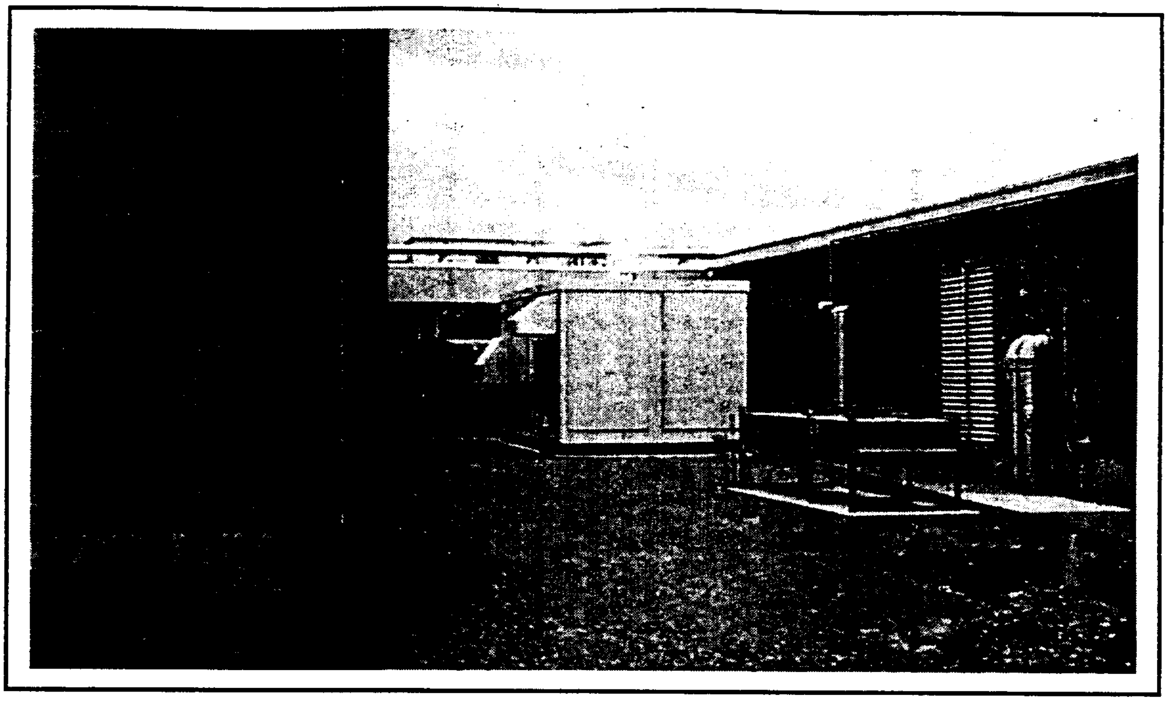


Figure D4. Fuel cell installed at site with cooling tower in foreground.

CERL Distribution

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: HECSA Mailroom (2)
ATTN: CECC-R
ATTN: CEMP-ET

Engineer Research and Development Center (Libraries)
ATTN: ERDC, Vicksburg, MS
ATTN: Cold Regions Research, Hanover, NH
ATTN: Topographic Engineering Center, Alexandria, VA

Defense Tech Info Center 22304
ATTN: DTIC-O

10
5/00

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) 12-2000	**2. REPORT TYPE** Final	**3. DATES COVERED (From - To)**
4. TITLE AND SUBTITLE Phosphoric Acid Fuel Cells		**5a. CONTRACT NUMBER** DACA88-98-D-0003
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Franklin H. Holcomb, Michael J. Binder, William R. Taylor, J. Michael Torrey, and John F. Westerman		**5d. PROJECT NUMBER** Reimbursable Funding
		5e. TASK NUMBER 7
		5f. WORK UNIT NUMBER V69
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center (ERDC) Construction Engineering Research Laboratory (CERL) P.O. Box 9005 Champaign, IL 61826-9005		**8. PERFORMING ORGANIZATION REPORT NUMBER** ERDC/CERL TR-00-33
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Headquarters, U.S. Army Corps of Engineers (HQUSACE) 441 G Street, NW. Washington, DC 20314-1000		**10. SPONSOR/MONITOR'S ACRONYM(S)** CEMP-ET
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

14. ABSTRACT

In fiscal year 1993 (FY93), Congress appropriated funds to advance the use of phosphoric acid fuel cell (PAFC) power plants at Department of Defense (DOD) installations. By November 1997, DOD had installed 30 PAFC power plants throughout the continental United States and Alaska. The program successfully demonstrated the capability of the PAFC technology by generating more than 101,977 MWh of electricity through September 2000. The U.S. Army Engineer Research and Development Center (ERDC), Construction Engineering Research Laboratory (CERL) developed turnkey PAFC packages and managed the program. This report describes PAFC technology and discusses the practical application of PAFC power plants within DOD, and is meant to serve as a reference document to those facilities interested in evaluation and/or installing PAFC power plant technology.

15. SUBJECT TERMS

fuel cells	phosphoric acid	energy conservation
power plant technology	fuel technology alternatives	energy costs

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Franklin H. Holcomb
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	SAR	84	**19b. TELEPHONE NUMBER (include area code)** (217) 352-6511, X-7412