July 2002 • NREL/SR-560-32455

Subcontractor Report

Residential Fuel Cell Demonstration Handbook

National Rural Electric Cooperative Association Cooperative Research Network

E. Torrero
Cooperative Research Network
National Rural Electric Cooperative Association
Arlington, Virginia

R. McClelland
Energy Signature Associates, Inc.
Pittsburgh, Pennsylvania

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

July 2002 • NREL/SR-560-32455

Residential Fuel Cell Demonstration Handbook

National Rural Electric Cooperative Association Cooperative Research Network

E. Torrero
Cooperative Research Network
National Rural Electric Cooperative Association
Arlington, Virginia

R. McClelland
Energy Signature Associates, Inc.
Pittsburgh, Pennsylvania

NREL Technical Monitor: H. Thomas

Prepared under Subcontract No. AAD-1-30605-12

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

SUMMARY

Objectives

Dispersed generation and its companion fuel cell technology have attracted increased interest by rural electric cooperatives and their customers. This is due in part to the co-ops inherently low customer density, long distribution lines, and potential load growth patterns. In addition, fuel cells are a particularly interesting source because their power quality, efficiency, and environmental benefits have now been coupled with major manufacturer development efforts.

This Residential Fuel Cell Demonstration Handbook is intended as a guide for rural electric cooperatives engaged in field testing of equipment and in the assessment of related application and market issues. The latter effort would be through a Residential Fuel Cell Owners Group imbedded in this co-op demonstration program.

The resulting CRN program will secure valuable application and operating experience from multiple manufacturers at diverse sites and climates. This will enable co-ops to better understand the related benefits of, and barriers to, fuel cell distributed generation as well as any related interconnect issues. Moreover, participants will secure informed insight into fuel cell and manufacturer capabilities, plans, and potential technology market applications thereby enhancing future co-op business and distribution planning.

Implementation and Reporting

An initial CRN Residential Fuel Cell Demonstration Seminar is planned so that co-ops can review the program and acquire an important upfront fundamental understanding of the technology. Although the program encompasses multiple sites and manufacturers, obviously each demonstration participant's direct real-world experience is inherently limited to only one site and to a single manufacturer's fuel cell design and power plant.

Thus, experience exchange between all of the demonstration participants is crucial to program operation. Straightforward Letter Report protocols have been developed for preparation by participants at their individual site key milestones. These Letter Report submissions are targeted for specific participant milestones such as site selection, installation, and commissioning. For example, included at site selection are brief Letter Reports encapsulating: the selected site profile, site energy survey, grid and fuel interconnection plans, and an environmental check list. Installation and Commissioning Letter Reports cover such elements as: installation costs and experience, grid electric interconnect description and assessment, and out-of-the-box performance.

Operational reporting consists principally of Residential Fuel Cell Service Report incident reports as needed, as well as monthly meter readings using specially developed analysis spreadsheets. The completed Residential Fuel Cell Service Reports will then be data based by the program and electronically distributed back to all the participants periodically. Simple data loggers will also be specified to take power quality reports and hourly energy performance data. The circulation of this field experience, coupled with periodic Owners Group meetings, will provide key information development and exchange while streamlining participant effort.

Demonstration Site Application

Fuel Type

While a number of elements will influence site selection and economics, two key factors will be fuel availability and customer loads. The fuel can be either utility gas, which is natural gas whose major component is methane, or LPG. The latter is principally composed of propane. Because of the fuel processing design inside the unit, this fuel type will need to be specified before the unit is manufactured. Also, not all of the demonstration unit manufacturers may be able to supply both natural gas and propane fuel options for these precommercial demonstration residential fuel cell power plants. Unlike an ordinary gas furnace or water heater it is not clear that a fuel cell can be field converted from natural gas to propane or vice versa.

Site selection fuel type has additional impacts that can influence decisions. Natural gas will usually have a fuel cost component of about five cents per kWh. This is about one-half of that of LPG which will run about ten cents per kWh for fuel and also need a 500 to 1000 gallon site tank. In contrast, LPG is relatively universally available by truck delivery while the availability of natural gas will be more limited such as to towns. If market application information indicates that fuel cells are more likely to be used at remote locations, then it may be prudent to select a propane fueled unit even though the related kWh fuel cost is likely to be far more expensive.

Electric Load

Additional factors influencing site selection include the site's electric load, particularly if the unit is to run grid independently at least some of the time. Relative to fuel cell economics, two factors stand out. First, the customer's per kilowatt-hour cost is very sensitive to the size of the annual load. Second, the relative slope of electric cost reductions due to increased load are likely to be greater for the fuel cell than for conventional co-op grid rates. Thus, fuel cell applications will tend to favor larger sized dwellings with greater electric loads. The end result is that customer annual loads, their causes, and their distributions are a major factor in understanding residential fuel cell potential markets and applications.

Also, fuel cell power plants will be expensive even in a mature market and when using propane the fuel cost of electric output will be on the order of ten cents per kilowatt-hour due to the conversion efficiency alone. Thus, it will not make sense to use a fuel cell power plant to supply major space heating resistive loads such as full-house baseboard units. On the other hand, to achieve any kind of meaningful market interest, particularly in the high-end markets more likely to be able to afford a fuel cell, the fuel cell power plant will clearly have to be able to power dwellings having a 3-ton central air conditioner. This is also the same load that would be found in a typical heat pump absent its supplemental heaters.

Grid Independent / Grid Parallel / Dual Operating Mode

All of the manufacturers ultimately plan to develop residential fuel cell power plants that are capable of grid independent operation; most will also be capable of running in a grid parallel mode. While grid interconnect protection is obviously an important issue, the practical design issues for a grid parallel fuel cell are a relatively straightforward development of a detection and control card capable of interrupting the unit's inverter in the event of a grid upset. The design of a residential fuel cell for grid independent operation is in many ways far more challenging since the unit's control system, inverter, and fuel processor need to be capable of responding to wide load swings while constantly producing grid quality power.

Thus, residential fuel cell units will likely have the capability to satisfy two distinct markets. The first is isolated operation at remote sites; the second, is the capability for distributed generation on the grid. Both modes of operation can be important to co-ops and their operating region. For example, given reasonable reliability and costs, grid independent operation can provide co-ops and their customers with a potential alternative to costly line extensions to serve distant small loads. Conversely, grid parallel units, particularly those with remote dispatch for daytime power output in excess of customer loads, can provide an added dispersed generation source to the grid while concurrently enhancing customer appeal as dual mode units. Such dual mode units would automatically disconnect the dwelling from the grid during any outage and then supply grid independent site power until the grid returned to normal.

Other Key Site Factors

These residential fuel cell demonstration units will, in most instances, be preproduction units having limited field history and reliability experience. As a result, an automatic transfer switch should be included with the installation where an equivalent is not already provided by the manufacturer as part of the fuel cell power plant package. Moreover, even though these units might operate principally in an isolated grid independent mode, a grid backed installation would be greatly preferred since the initial fuel cell reliability will be undemonstrated and may be problematical.

Most of the units available for the demonstration program will likely be targeted for outdoor installations. If an indoor unit is selected, a suitable indoor location will need to be found and clearances checked against the unit's final production dimensions. Another factor for consideration is service personnel travel time and reasonable anytime access for both participant and external service personnel. These same considerations would apply to possible visitors or the media if a public awareness program involving site visits or tours is contemplated.

Exploring thermal recovery benefits will be of great interest, if not essential, in enhancing early entrance markets, reducing effective electric generation heat rates, and building a well rounded assessment. Thus, sites compatible with the unit's thermal recovery options, if such options exist, should be given elevated consideration. Depending on the unit, thermal recovery may be for water heating, supplementing forced air system space heating, and possibly as enhanced source temperature for heat pumps.

The installation of a demonstration residential fuel cell will clearly garner considerable media and customer interest that can work to benefit the participating cooperative. Thus, the capture of such interest may justifiably mitigate some site selection criteria. However, such a public awareness program may pose parking and access considerations if tours or group visits are contemplated. One option might be to team up with a builder for a "model of the future." However, unless elaborate and expensive on-site computer control of simulated loads is contemplated, an unoccupied dwelling is unlikely to yield meaningful test data. Depending on load confirmation monitoring, an alternate option might be to serve one or more units of a garden apartment or a resort rental complex.

Grid Interconnect and Power Quality

Grid Parallel Operation

The first, and most critical, are Grid Interconnect factors since the fuel cell is connected both to the customer's loads and to a relatively stiff electric grid. Important elements are the ability of the unit to follow the grid's voltage and frequency over an acceptable range and to halt power production in the event of a grid upset beyond stated limits. A key need is for the power plant to reliably detect a grid outage and promptly halt power production so as not to hinder recloser operation or to island. Islanding is the introduction, or potential introduction, of power into an otherwise dead grid. This poses a serious hazard to any co-op distribution service personnel attempting to repair grid service.

An additional criteria is the Power Quality Interconnect, principally with the customer and secondarily with the grid. This encompasses such elements as voltage sags and swells, flicker, harmonics, DC power components, and various secondary factors. The level of this concern will be a function of the power quality from the fuel cell power plant itself, the customer's loads, and also of the relative stiffness between the grid and fuel cell at the customer's load point.

Grid Independent Operation

In this instance power flows from the fuel cell power plant only to the customer's dwelling. There is no connection to the grid except for perhaps a manual or automatic transfer switch that allows the customer's dwelling to select either fuel cell or grid power. Since there is no ability to connect the fuel cell to the grid, no Grid Interconnect concerns exist.

However, in this instance the fuel cell must meet all the dwelling's loads and can expect no support from the grid. Thus, the fuel cell will likely have a battery storage system sized equal to, or greater than, the cell stack's capacity. The batteries would be charged by the cell stack at night during off-peak hours and used to supplement the cell stack's capacity during daytime peak loads. Such an installation will require application preplanning and most likely some preinstallation metering to assure that the customer's loads will not exceed the fuel cell's capacity. In addition some type of load shedding or load control devices may be required and the fuel cell may have some type of internal disconnect for certain dwelling fault clearing events.

In this instance Power Quality Interconnect would be important to the dwelling customer, but not the grid. Of keen interest would be voltage regulation with regard to sags, swells, spikes and other elements, particularly when large loads such as a heat pump compressor are added or removed from the fuel cell power plant's load. Other areas include flicker, harmonics, and any possibly of DC voltage components.

Further Discussion

Because of the importance of these issues to co-ops, the electrical Section C of this demonstration Handbook contains an extensive analysis. This includes a detailed overview of both of Power Quality Interconnect and Grid Interconnect issues. Also described are potential fuel cell power plant interconnect and power quality specifications and a power plant testing protocol. The later may be implemented through a cooperative demonstration effort between CRN and CERL-DoD.

Interconnects

Fuel

Both technical and market application factors influence the fuel choices for residential fuel cell power plants. Because most fuel cell stacks work by converting hydrogen fuel into direct current in a battery-like electrochemical reaction, the power plant's input fuel must be converted into hydrogen to enable the fuel cell to operate. Both LPG propane and utility natural gas are suitable fuels but the fuel type will likely have to be specified when the fuel cell unit is ordered. For LPG propane installations, a 500 to 1,000 gallon tank will typically be required depending on other site needs. Methanol can also be used but at a significant site cost premium.

In order to confirm residential fuel cell efficiency and calculate related operating costs, the gas use of the fuel cell will need to be measured. As shown in Figure B-2 in the fuel section of this Handbook, the meter consists of a standard utility-grade, temperature compensated gas meter, preferably mounted outside the dwelling.

Electrical

Several criteria influence the resulting electric interconnect and metering. Clearly, understanding both grid parallel and grid independent operations will be key to assessing the market and technology potential of residential fuel cells. Grid parallel operation provides a useful assessment of how well the power plant interfaces with the grid from a safety viewpoint and how the power plant's inverter copes with voltage flickers, spikes due to lightning, and the like. In contrast, grid independent operation fully stresses the cell stack, batteries, and inverter in load swings and day-night demand shifts. For this reason, the demonstration's interconnect system is structured to enable ready assessment of both grid independent and grid parallel modes of operation.

An additional criteria in planning the interconnect is service reliability in the event of a fuel cell power plant shutdown. Since these units are intended for residential or related applications, the householder or customer will need reasonable assurance that power will remain available even if the fuel cell is not operating. For these reasons, an automatic transfer switch should be incorporated in the interconnect if suitable controls are not provided by the manufacturer.

The likely interconnect is shown in Figure C-2 in the electrical section of this Handbook. To minimize wiring changes inside the customer's main panel and allow for servicing of the installation and power plant, the interconnect configuration would mount a new fused disconnect fed by a replaced service entrance cable from the existing grid electric meter. This new fused disconnect would feed the grid side of the automatic transfer switch. The center output of the automatic transfer switch would then connect to the customer's existing breaker panel. The other, fuel cell, side of the transfer switch would connect to the fuel cell power plant. The cable to the fuel cell power plant would include an added electric meter to measure the fuel cell's power output as well as a service disconnect switch at the power plant. To enable grid parallel operation without rewiring, a bypass switch is connected across the transfer switch.

Water

A fuel cell operates much like a battery in that an electrochemical reaction produces direct current power. However, unlike a conventional battery, a fuel cell does not run down or need recharging. This is because additional chemical "fuel" is being continuously supplied to the cell stack in the form of hydrogen. This hydrogen is supplied by reacting the power plant's inlet hydrocarbon fuel with steam in a reformer. For example, two molecules of water are required for each molecule of methane in the natural gas fuel. Because the hydrogen from the fuel ultimately combines with oxygen from air flow to the cell stack, the unit actually makes up to twice as much water as it needs. This can be recovered from the cell stack exhaust for recycling to the reformer.

Many, if not most, of the demonstration residential fuel cells have, or at some point are planning to have, a water recovery system. Even so, a water connection has been specified by most of the demonstration units and some of these precommercial demonstration units may not recover water at all. Even when water recovery is not practiced or not yet available, the fuel cell water consumption would represent a relatively small, one or two percent of normal dwelling water use. This is based on a typical residential water use of 80 to 100 gallons per day per person.

Water quality varies significantly across the country. Even a moderate level of hardness would leave behind an unworkable 1.5 pounds of solids inside a 3 kW power plant at the end of the first operating year. As discussed in Figure D-2 in the water section of this Handbook, various site water treatment options may be needed as part of any water supply interconnect.

Thermal Recovery

This interface will depend on both the fuel cell manufacturer's specific design and on the particular site's thermal recovery use. Options and systems are discussed in the application and markets section of this Handbook. The minimum cost thermal recovery configuration is shown in Figure F-5 of that section. Where thermal recovery is used, the instrumentation should include a related Btu meter.

Instrumentation

The residential fuel cell's input, output, efficiency and power quality need to be verified as part of the demonstration program. The related metering also provides a valuable cross-check on information collected by the power plant itself and can serve as a useful troubleshooting supplement. The related metering and the data collection will be unintrusive and straightforward.

The basic instrumentation system planned for the program is relatively low cost and easily implemented. Details are in the instrumentation section of this Handbook as Table E-1. The energy logging system consists of normal utility meters with pulse outputs. These pulse counts are captured by a $715 UltraLite Logger. This would be downloaded to a laptop once each month when the fuel cell's gas and electric meters are read.

A critical factor will the fuel cell power plant's interaction with the customer loads and the co-op electric grid. Until recently a major difficulty in power quality (PQ) analysis at ordinary customer sites was the cost and complexity of conventional Digital Fault Recording equipment. Furthermore, this was compounded by significant technical labor to pull-up each individual event record and then analyze its waveform trace. In addition, the results from such a record analysis approach were not particularly repeatable since they depended on individual interpretation as to what is a voltage sag, swell, flicker, etc. As a result of increased interest in power quality by both electric suppliers and customers, significantly less expensive systems with automated analysis are now available.

The selected $1,800 PowerTronics unit is an automated, line-powered system for installation at the customer's main circuit breaker panel on the fuel cell's bus. This logger has preset limits for recording events such as: impulse voltages, sags, surges, dropouts, power failures, high frequency noise, and line frequency events and would be downloaded to a laptop each month. This system and related Windows95 software will automatically analyze, timestamp, tabulate and count the various events. Capabilities include the automatic production of summary graphs, pie charts, text and tables that can also be pasted into other windows applications.

Application and Market Issues

Introduction

Two basic types of risks are inherent in any residential fuel cell endeavor. One portion of the issues associated with residential fuel cells are *technical*, and can therefore be readily assessed by gas and electric meters and by calculations of reliability and availability. Such risks are principally associated with the cell stack, a high value component having both life and potential catastrophic failure risks. In general, such technical risks attract keen interest in demonstration programs and, although often difficult to fully quantify, are relatively straightforward to incorporate into program assessments.

However, another set of equally critical issues are associated with fuel cell application and market factors. These *application-price-market-business* issues will be just as, if not, more important in assessing residential fuel cell technology and its future. Market and related application risks, although often of equal or greater import, are much more difficult to determine and quantify.

Application Economics

Residential fuel cells face difficult challenges. The resulting 3 to 10 kW fuel cell power plant equipment is much smaller in capacity and higher in unit cost than that required for commercial building or transportation applications, which are in the 50 to 200 kW size range. Thus, the capital cost of the equipment is relatively high; plus, the ratio of average to peak use of a typical residential consumer connected to the power plant is low. For example, a large home with all-electric appliances including air conditioning, but with gas water heating and space heating, might have an average load equal to 2 kW or less on a year-round basis. Even so, the peak electric demand needed to be supplied by the fuel cell or grid could be well over 10 kW, such as during meal time in the summer when the air conditioning is running.

Thus, a key component of fuel cell application risk is whether or not manufacturers can achieve projected targets for sales versus price. To achieve commercial market pricing, hundreds, if not thousands, of units will need to be produced and sold by a manufacturer. Misassessed customer needs or cost sensitivities, under-implemented market plans, and/or missed production cost goals can have a major impact on technology viability. So too can reliability and service repair costs, as well as customer acceptance issues.

These areas are just as important as are technical issues. Given that manufacturers meet an admittedly ambitious $4,000 installed cost goal with customer thermal recovery for water heating, the best that could be achieved is around nine cents per kilowatt hour. This cost is then broken down into fixed and variable components that suggest that a monthly rental “tariff” would make the most sense for a residential fuel cell customer offering. Such concepts illustrate the importance of an active CRN Residential Fuel Cell Demonstration Owners Group.

Average and Peak Load Impacts

As indicated by the economic analysis, a key factor is the size of the customer’s load since this impacts both the kWh base over which the fuel cell’s fixed cost is allocated and concurrently the actual ability of the fuel cell to serve that customer’s load. Probability distributions of loads are developed from actual customer loads for various customer classes like resistance heat versus heat pumps and air conditioning. These suggest that central air conditioned and heat pump residences, having average loads in the 1 to 2 kW and 2 to 3 kW ranges respectively, can be key market defining applications.

Customer peak loads are also crucial in analyzing potential applications and markets. Here the factor is not so much the overall cents per kWh economics, but rather assessing whether customer peak loads will fit within the size of the fuel cell power plant’s overall capacity. Residential fuel cells typically have a 3 to 7 kW cell stack supplemented by 3 to 10 kW of DC batteries. Capacitors may also be included for short-term motor starting loads. This composite DC buss feeds a DC-to-AC inverter sized for the power plant’s maximum specified load. Normal operation would charge the batteries during the night when the dwelling’s loads are low and the charged batteries would then assist the unit’s supply of customer loads during peak, and perhaps, normal daytime operation.

Dwelling data has been analyzed to determine peak and average loads for various residential demands such as space heating, cooling, cooking, water heating, and other uses. These peak loads are around 4 kW each for typical major appliances but vary significantly in load factor. The "best" load from a fuel cell point of view is a dual-fuel heat pump and, to a lesser extent, an electric water heater. However, electric water heating can have 4.5 kW demands lasting from three to nine or more hours per day. Depending on the power plant's cell stack size and on the other loads in the dwelling, this may present a problem. Also, in a heat pump application where the supplemental resistance heaters in the air handler are likely to need to be replaced in order to reduce the load on the fuel cell, the simplest procedure may be to convert the electric water heater to gas and then circulate some of that hot water to an air handler hydronic coil to replace the heat pump's supplemental heaters.

Thermal Recovery Benefits

Thermal recovery to offset electric water heating can be particularly economic for grid-connected distributed generation scenarios and has a two-fold advantage. First, it improves the fuel cell economics and might offset a significant amount of the propane cost fueling the power plant. Second, the absence of the 4.5 kW load per element in the electric water heater considerably increases the ability of the fuel cell to meet the dwelling's other loads, particularly if an electric heat pump is part of that customer's energy portfolio. This, of course, assumes that the customer's heat pump supplemental heaters have been converted to a "dual-fuel" option as discussed in this Handbook.

Because of these potentials, thermal recovery should be considered as part of any site's demonstration planning where the selected manufacturer's fuel cell has that capability. This is particularly true for propane fueled installations and those sites where conversion from electric water heating is an alternative.

Customer Application Profiles

Since heat pumps and related air conditioning compressor loads are an important consideration in fuel cell sizing and economics, related customer profiles are developed by Census Division for City/Suburban/Town/Rural locations. Included are electric appliance saturations for key associated loads such as electric water heating, ranges, clothes dryers, and the like. Also included are existing propane and utility gas availabilities, as well as profile differences between city and rural areas. These provide a useful glimpse of the type and depth of residential fuel cell market applications that are likely to exist in various co-op regions of the country.

Outside of the New England and Middle Atlantic regions, heat pump applications typically represent around five percent of rural residences with the exception of the South Atlantic and East South Central regions where they average around 20 percent of residences, particularly among the high income levels and larger sized dwellings that can be key high-end residential fuel cell markets and applications. As could be expected, heat pump dwellings are most likely to have a full complement of electric appliances and are not likely to have either propane or utility gas presently available. This information can be found in Table F-3.

Central A/C and Heat Pump Considerations

Because of their widespread saturation in high-end residential markets, the fuel cell's ability to serve central A/C systems may well become a key long-term market and design criteria, particularly in the Southern U.S. The compressor of an electric central heat pump or the equivalent air conditioning system can make a reasonably attractive load at the 3 kW level. However, from a load-factor point of view, a central A/C system itself is not a particularly attractive load. For example, a central A/C unit might run

1,200 hours a year in a Midwest application compared to 2,500 hours a year for a heat pump compressor in the heating mode. Thus, a three-ton heat pump with summer cooling use will make a far more attractive fuel cell load than would a simple three-ton central A/C only system.

However, the ability to serve a heat pump is contingent on eliminating the heat pump's supplemental duct heaters which turn on a low outdoor temperatures. While the compressor load is a relatively attractive and steady 3 kW, the supplemental heaters, which operate for far less time at low outdoor temperatures, add loads of 4 to 8 kW. These supplemental heater loads extend beyond the fuel cell power plant's capability. Dual-fuel heat pump concepts enable a residential fuel cell to serve a dwelling by retaining the attractive compressor load portion but converting the peak demand supplemental heater portion to alternate fuel or to fuel cell thermal recovery.

To the extent that residential fuel cell thermal recovery and applications in heat pump residences are important to the participating co-op, or that dual-fuel heat pump applications are being promoted or under consideration for promotion by a co-op, a companion fuel cell and dual-fuel heat pump conversion installation can concurrently: provide data and learning experience with fuel cell thermal recovery, provide data and experience on the cost or savings of dual-fuel heat pump systems, and provide public awareness or education on the benefits of dual-fuel heat pumps. Thus, this type of installation is encouraged as part of the any residential fuel cell demonstration site as it can provide other immediate co-op customer benefits.

TABLE OF CONTENTS

SECTION C: FUEL CELL ELECTRICAL INTERCONNECT AND METERING

SECTION D: FUEL CELL WATER SUPPLY AND INTERCONNECT

SECTION E: FUEL CELL METERING AND INSTRUMENTATION

SECTION F: RESIDENTIAL FUEL CELL APPLICATION AND MARKETS

INDEX OF FIGURES

INDEX OF TABLES

Section A: Fuel Cell Demonstration Program Planning and Reporting

Introduction and Goals

The NRECA CRN residential fuel cell program is designed to demonstrate a number of residential fuel cell power plants from key manufacturers at various participant sites and to assess related technical and application issues within a shared information umbrella.

The overall effort is structured to measure the performance, durability, reliability and maintainability of these systems, to identify promising types of applications and modes of operation, and to assess the related prospect for future use. In addition, technical successes and shortcomings will be identified by demonstration participants and manufacturers using real-world experience garnered under typical operating environments. The overall program will provide participants with informed insight into manufacturer capabilities, plans, and potential technology application thereby enhancing future application, market, and business planning and investment decisions.

Program Impetus

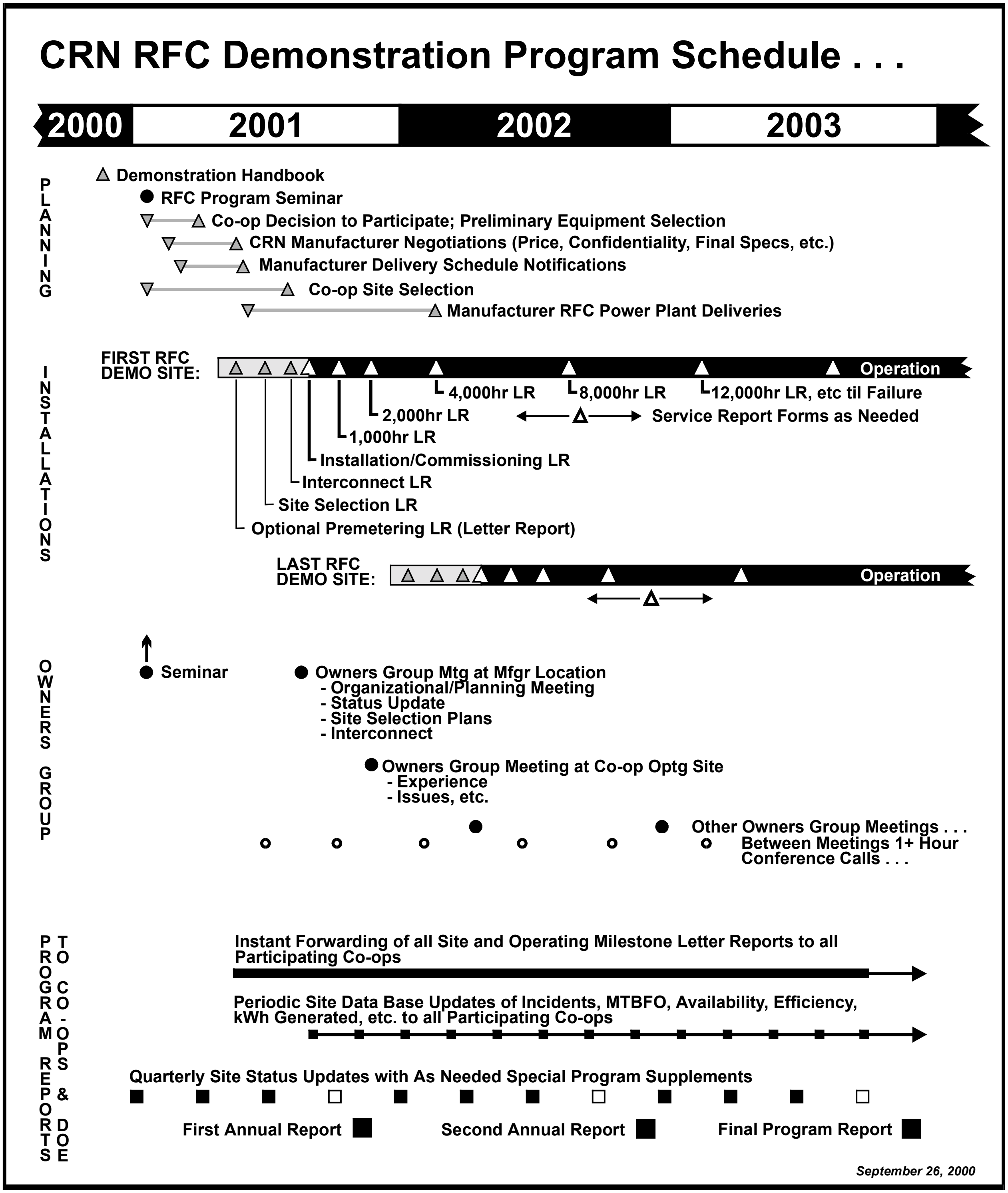
Dispersed generation continues to attract increased interest by cooperatives and their customers. Cooperatives have a particular interest due to an inherently low customer density, growth patterns at the end of long lines, and a continued influx of customers and high-tech industry seeking to diversify out of urban environments. Fuel cells are considered a particularly interesting candidate because of their power quality, efficiency, and environmental benefits.

For the most part, cooperatives serve less populated rural and agricultural areas of the nation, representing some of the country's least developed and roughest terrain. Even so, cooperatives sell about 10 percent of the nation's power to 30 million customers in 46 states, and own almost half of the distribution line miles in the country. In order to deliver power to their customer owners, cooperatives average six customers per mile compared to the rest of the electric utility industry's average of over thirty customers per mile.

An added complication is that much of the rural electric growth occurs at the end of long feeders. Overlaying these requirements are ongoing societal trends creating further demands for enhanced power supply and distribution. Such drivers include the diversification from an urban to a rural environment by high tech industries, data processing centers, telephone order centers and the like. Corollary trends are the rise of the "electronic home office" as well as the siting of residences in remote, difficult to serve, areas. Costly transmission and distribution right-of-ways must be acquired in order to upgrade or provide new lines for increased power supply to these locations via conventional central service. For example, single phase distribution laterals cost on the order of $14,000 per mile and a single to three phase conversion can cost as much as $40,000 a mile.

Distributing generation, such as by microturbines or fuel cells, throughout a system may offer the potential benefits of reduced transmission and distribution costs. Capital expenditures for distribution system equipment can be deferred and costs minimized for upgrading or reconditioning power lines.

Figure A-1
Program Schedule and Key Events



CRN Residential Fuel Cell Program

Overview

An overall schedule for the CRN's Residential Fuel Cell Demonstration program is shown in Figure A-1, Program Schedule and Key Events. The program begins with a key seminar to review the overall effort and for participating co-ops to hear directly from the fuel cell manufacturers, so that the most informed equipment choices can be made. Given present manufacturer projections, installations would begin in the Fall of 2001 and, for various manufacturers, stretch through 2002. Field operation and testing would continue into 2003 and may stretch beyond that point depending on equipment availability and individual participating co-op's desires and goals. The main part of the program reporting would end with a Final CRN and DoE reports at the end of 2003.

Site Selection

Table A-1
Preliminary Site Selection Check List

Site Selection Considerations . . .

While the program is labeled "Residential" the sites don't have to be . . .

Existing residence (Service and PR access issues, if any?)

Dual Fuel Heat Pump Included?

Builder's Model ("Smart Home" load simulation = $5K to $10k)

One or two garden apartments

Small main street store with apartment overhead

Small convenience market (Load size?)

Local Sheriff Office or Dispatch Center, Branch Bank, etc.

Remote water irrigation or oil field application, etc

(So as to get real customer experience, a co-op facility might only be a good second or third choice.)

Partial site selection check list:

- ✔ **Load profile OK?**
- ✔ **Local code considerations?**
- ✔ **Grid back-up if RFC outage?**
- ✔ **Outside access, if basement?**
- ✔ **Ease of media or site tours?**
- ✔ **No life or other critical loads?**
- ✔ **Fuel availability?**
- ✔ **Service travel time?**
- ✔ **Protection, if outdoor?**
- ✔ **Installation clearances?**
- ✔ **Legal agreements: liability, etc**
- ✔ **Etc...**

A preliminary Residential Fuel Cell Program Participant Site Check List is provided in Table A-1. This highlights some of the information that would be helpful to both the demonstration participant, the program and the manufacturers in better understanding the selected or proposed site.

The installation of a demonstration residential fuel cell will clearly garner considerable media and customer interest that can work to benefit the participating cooperative. Thus, the capture of such interest may justifiably mitigate some of the above site selection criteria. However, such a public awareness program may pose parking and access considerations if tours or group visits are contemplated. One option might be to team up with a builder for a "model of the future." However, unless elaborate and expensive on-site computer control of simulated loads is contemplated, an unoccupied dwelling is unlikely to yield meaningful test data. Depending on load confirmation monitoring, an alternate option might be to serve one or more units of a garden apartment or a resort rental complex.

Installation and Metering

Upon conformation of the requested fuel cell selection, the individual cooperative would receive the planned delivery date from the manufacturer, as well as related installation and operating manuals. The individual demonstration participant would then complete site planning, permitting if required, and any preliminary site construction, as well as installation of the fuel cell power plant as may be supervised by the manufacturer.

While some metering may be part of the unit, detailed manufacturer specifications for this area are not yet available. In any event, even if applicable metering were part of the package, the unit's input, output, and corresponding efficiency will need to be verified by independent field metering. Fortunately, this metering will be unintrusive and relatively inexpensive. This information is covered in this Handbook's Section E covering Metering and Instrumentation.

Site Selection, Installation and Related Letter Reports

Overall Philosophy

Participants should plan to fill out the various Letter Reports at the applicable program milestones. These are really the only way the program can readily capture your demonstration experience and ideas. Also, the reports from other demonstration participants are the best way of finding out what others have learned and of sharing your experience with them.

These participant Letter Reports will cover installation experience and costs, as well as ongoing operating experience. While the goal is to maximize information transfer while minimizing reporting effort, a certain amount of effort and data collection will be unavoidable. A brief look at these various Letter Reports follows.

Pre-site-selection Metering Letter Report

In may instances, the actual customer electric billing records may not be sufficient to determine if a fuel cell would be a good fit at a that specific site. It will probably be important to meter the site for a month or longer to collect 15-minute or shorter demands. Also, an inexpensive energy survey on-off logger may need to be placed next to the wiring for the residence's electric water heater to determine the prospective loading for any future fuel cell power plant thermal recovery.

Site Selection Letter Report

This Letter Report describes the selected site and reports on related program timing and plans. Included would be any load monitoring results, prospective installation sketches, interconnection and thermal recovery plans and various key details. Examples of the types of information that will be collected by the program and of interest to other participants includes:

- Co-op contact personnel
- Overall site photos
- Photos of gas-electric-etc interfaces
- Simple sketch of planned fuel interconnect
- Is thermal recovery planned?
- Permits likely to be needed, if any
- Interface voltage and likely variation
- Electric load/power factors, if known
- Gas Heating Value history, if applicable
- Elect/Gas/Fuel costs, rate schedules
- Projected timetable
- Site type, location, etc.
- Photos of power plant location
- Simple sketch of physical installation
- Simple sketch of planned elect interconnect
- Sketch of thermal recovery, if applicable
- Site energy use
- Electric use, demands, etc as exist
- Gas/fuel supply/pressure, if existing
- If gas, is propane-air peak shaving used?
- Customer or public awareness plans?

Most, if not all, of this information will normally be required in any event by a prudent co-op or manufacturer in confirming the planned site will be a good match with the selected residential fuel cell power plant. Two person-days are estimated to be needed to complete this Site Selection Letter Report.

Installation Letter Report

This Letter Report would highlight the installation experience, report the out-of-the-box efficiency and estimate what the installation cost would have been given a normal, non-demonstration residential fuel cell installation.

To make reporting of the installation cost portion straightforward, an Excel spreadsheet has been developed that can be filled out directly by the contractors. Moreover, if the co-op plans to have bidding for the installation, this spreadsheet can also serve a dual purpose as a bid response or checklist. Descriptions and check lists will be provided for these various Letter Reports.

Interconnection Letter Report

For grid parallel capable residential fuel cell power plants, this Interconnection Letter Report will review the interconnection protocols as reported by the manufacturer specifications and installation-service manuals. The feeder and distribution laterals to the fuel cell installation would also be defined, as well as the size of the site-interconnect transformer and any other residences on the secondary side of that interconnect transformer. In the unlikely event that any additional interconnection protective relaying is required, the Interconnect Letter Report would provide the rationale and describe any added protective relay functions. The Interconnection Letter Report is estimated to require three person-days.

Operating Plan and Related Reporting

Monthly Meter Readings

Monthly Meter Reading forms will be provided to each participant for the collection of standard data such as fuel consumption, electric output, hours operated, availability, and related data. More importantly, a Residential Fuel Cell Monthly Reading Spreadsheet like Excel will be provided to demonstration participants for the collection and analysis of these monthly meter readings. This spreadsheet will have a simple one-time setup to incorporate meter calibration factors, index rollovers, fuel Btu and the like.

Service Reports

A Service Report form covers grid interconnect issues, scheduled or unscheduled maintenance, shutdown causes, service hours worked, evaluation of manufacturer response and parts availability, and related site service call information. In addition to being a useful site log and troubleshooting reference, this form provides a low-effort means to collect key reliability and service incident data.

Upon forwarding of a copy of the Residential Fuel Cell Service Report to EnSig, the information will be put into a data base like Microsoft Access. It will then be automatically distributed back to the originating co-op and to all of the other CRN participants on a monthly or bimonthly basis.

Milestone Operating Reports

In order to secure appropriate information, operating plan and milestone periods will be used to secure information on power plant electrical and overall efficiency, harmonics, and all other aspects of field operating experience. These will be developed by a combination of reported operating experience and by CRN Program analysis of site logged data.

Residential Fuel Cell Owners Group

The operation of such a group will significantly improve information transfer, ideas, and assessments between the users. This will also be a communications channel of value to all parties in enhancing information exchange during the critical site selection, installation, and initial results collection phases of the demonstration.

The Owners Group will enable participants to become more familiar with actual field operation of the various technologies, to better assess the various manufacturers and their equipment, and to maximize feedback to the manufacturers. The Owners Group also provides a mechanism whereby common issues, needs, and efforts can be addressed to benefit the productivity and efficiency of all participants. Examples might be: early entrance market definition, overall economic quantification, service and maintenance issues, protective relaying, system dispatch and monitoring needs, business issues and criteria, sharing prepared media packages and/or customer group presentations, etc.

CRN Demonstration Reports

Subject to program timing and information needs by the participants, a CRN Residential Fuel Cell Demonstration Report in anonymized DoE format would be issued each twelve months. This program report would include installation, operation, and maintenance experience as well as test results and their analysis based on data collection and experience from the installed units.

However, since multiple manufacturers will likely be shipping units at various times after the first demonstration installations, these interim annual reports may not be able to cover a complete year of experience on all units and manufacturers within the program. As the program becomes more established and the relative manufacturer availability dates become better defined, CRN and the demonstration participants may wish to review and adjust the number and timing of CRN Residential Fuel Cell Demonstration reports.

Section B: Fuel Cell Input Requirements and Metering

Fuel Types

Reformer Influence

Both technical and market application factors influence the fuel choices for residential fuel cell power plants. Because most fuel cell stacks work by converting hydrogen fuel into direct current in a battery-like electrochemical reaction, the power plant's input fuel must be converted into hydrogen to enable the fuel cell to operate. The overall reactions for the three most commonly used fuels are shown in Table B-1 below:

Table B-1
Hydrogen Conversion in Reformer

Input Fuel								Amount of Input to "fuel" reformer reaction
Natural Gas:	CH_4	+	$2H_2O$	$\longrightarrow$	$4H_2$	+	CO_2	20%
Propane:	C_3H_8	+	$6H_2O$	$\longrightarrow$	$10H_2$	+	$3CO_2$	17%
Methanol:	CH_3OH	+	H_2O	$\longrightarrow$	$3H_2$	+	CO_2	11%

Also shown on the right of this table is the amount of the fuel which must be "diverted" to make the reformer reaction work since this conversion to hydrogen consumes heat. This is because hydrogen, in effect, is a "higher form" of hydrocarbon energy. Heat must be added to the input fuel, like natural gas, in order to split apart the methane molecule (CH_4) and turn it into hydrogen. In theory this extra reaction energy would be recovered in the cell stack. However, the cell stack is only about 50 percent efficient in turning hydrogen into DC power with the balance being converted to heat. This explains why a methanol fuel cell might be a bit more efficient than a propane or natural gas fuel cell which are about equal to each other. Of course, any efficiency differentials may be more than offset by fuel price differences and fuel processing equipment complexities.

As evidenced by the above formulas, these various hydrogen producing fuels are rather simple, light molecules consisting of only a few atoms (C, H, O) with a hydrogen to carbon ratio of 4 to 1 for methane and methanol and 2.7 to 1 propane. In contrast, fuel oil is a amorphous mix of many types of much larger, heavier molecules. Also the hydrogen to carbon ratio for Number 2 fuel oil is on the order of 0.15 to 1. A complication with reforming is that as the input fuel molecules get larger with more carbon atoms and less hydrogen content, the reformer equipment becomes much more complex. Also, it is much more difficult to reform such liquid fuels with out inadvertently depositing some of the fuel's carbon inside the reformer. This is no small concern as a fuel cell power plant running at 3 kW and running on hydrocarbon fuel will take about 20 pounds of carbon into its reformer every day. Also, these heavier liquid fuels tend to have higher levels of sulfur that can poison typical reformer catalysts. Thus, it is unlikely that residential fuel cells powered on Number 2 fuel oil or similar liquids will be available for any conceivable near term residential fuel cell market.

In addition to the water requirements (H_2O) which usually enter the reformer as steam except for methanol reformers, the states and energy densities of the three fuels and the amount of water required are significantly different. These are shown in Table B-2 on the next page. Moreover, the fuel cell is more like an chemistry converter than it is like a normal combustion process such as a furnace or water

Table B-2
Fuel Utilization and Cost Profile

Input Fuel		Use State	Reformer Feed Rate at 3 kW (Cu Inches/ Second)	Specific Gravity of Fuel Relative to Air	Typical Utilization: Dollars per Million Btu	Typical Utilization: Quantity Used per Month at 2kW = 15.1 Mil Btu HHV =
Natural Gas:	CH_4	**Gas**	**14.7**	**0.60**	**$5.10**	**14.4 MCF**
Propane	C_3H_8	**Gas**	**5.7**	**1.58**	**100¢/gal = $10.90**	**162 Gal**
Methanol	CH_3OH	**Liquid**	**0.03**	**650.0**	**~200¢/gal = $31**	**239 Gal**

heater. Thus, while orifices can be changed in the field to convert a natural gas furnace, for example, into one using propane, this is unlikely to be the case for a residential fuel cell. Thus, the fuel type will likely need to selected before the unit is delivered. For reference comparison purposes, the above table also shows prospective fuel costs and monthly use for a residential fuel cell running at an average 2 kW load for one month. The basis for these estimates is detailed under the individual fuel headings of this section.

At least with initial CRN demonstration power plants, not all units will be able to be ordered from a broad fuel catalog. However, it is anticipated that residential units will ultimately be available from most, if not all, manufacturers with either natural gas or propane fuel capability.

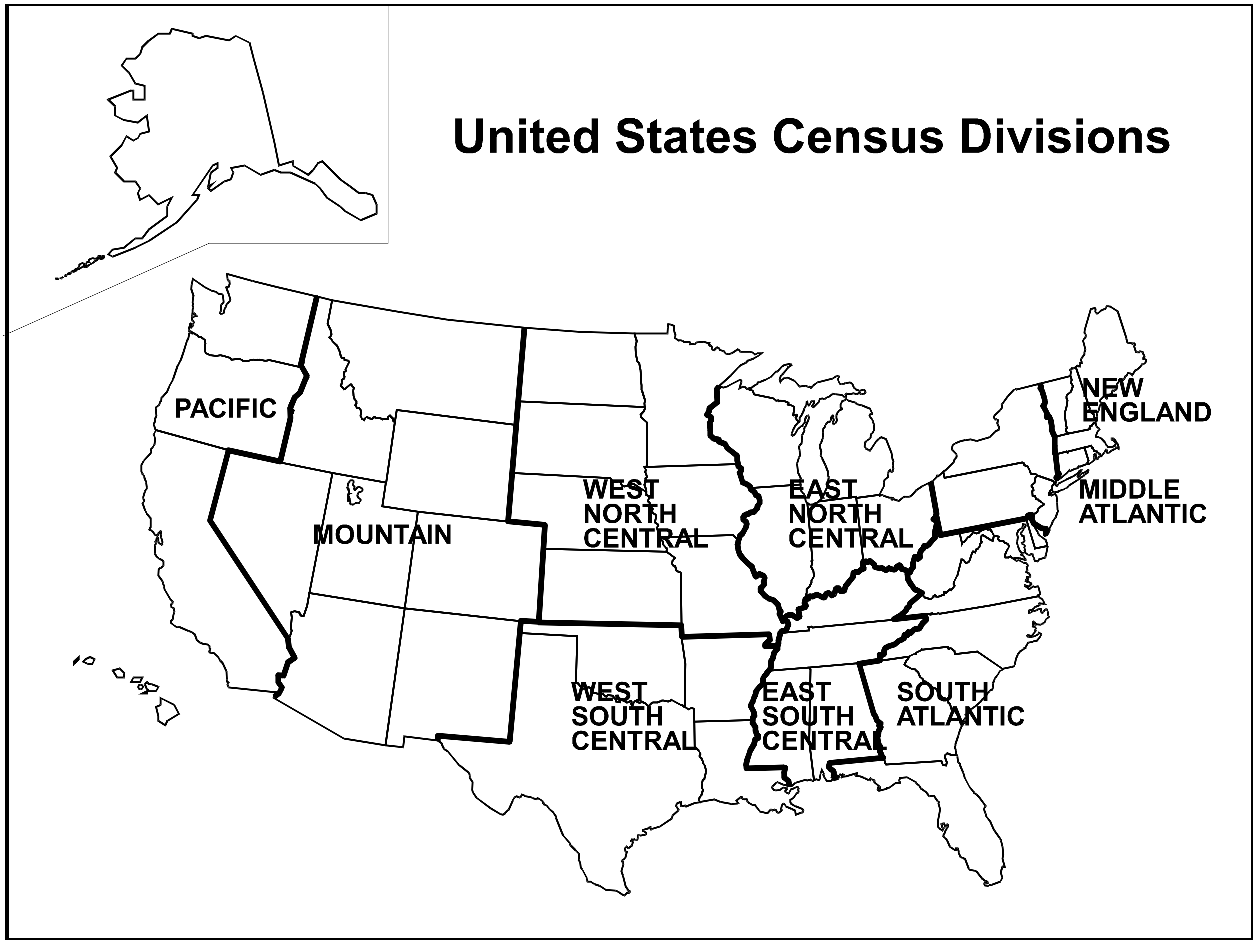
Market Availability

An added factor is determining the fuel type is the existing and potential availability of key residential power plant cell fuels, particularly natural gas and propane, in predominantly rural areas. Fortunately, some guidance is available from the Department of Energy's Energy Information Administration. This agency conducts periodic energy surveys for residential markets. The 1993 survey collected data from over 7,000 residential consumers across the country in the ten census divisions. These census areas are shown in Figure B-1 and are actually subsampled in City, Suburban, Town, and Rural locations. Since anonymized data files are available for each interview, it is possible to use data base software to construct a picture of related dwelling characteristics by geographic area and by city-suburban-town-rural environments.

Table B-3, entitled Residential Fuel Cell Potential Market Application Profiles, shows the availability of natural gas and propane across the country. These results have been compiled by census division and by the type of environment. These are expressed as a percent of saturation where for example the 19 percent under "Have Utility Gas" in "Middle Atlantic - Rural" means that 19 out of 100 dwellings in the rural portion of the Mid Atlantic Census Division could be expected to have Utility Gas available for use by residential fuel cells. The weighted averages shown in the table are composite saturations. In this instance, Town-plus-Rural potentially represents an approximation of the type of customers probably served by rural co-ops.

As with all information of this type, the data must be used with a reasonable amount of care. Although the overall sample is statistically large, the individual subsamples, such as for towns and for rural subcomponents, have sample sizes on the order of 100 to 200 within each of the census divisions. Although these levels of sample sizes are not particularly large, the data results are reasonably consistent

Figure B-1
United States Census Divisions



with what might be expected. For example, the saturation of utility gas decreases relatively consistently from city to rural areas. Concurrently, the use of propane progressively increases as the locations become more rural.

With respect to co-op application of residential fuel cells, the results are encouraging. For example, the data shows that 16.6 percent of the rural living locations in the East South Central Region already have utility gas and 34.4 percent have propane. Overall, the percent of dwellings that have either utility gas or propane averages over 50 percent for rural locations. Of course, this includes owned and rental dwellings, including apartments which may be more likely to have gas and are less likely to use fuel cells. However, other information acquired from the same Census shows that such rentals are only 16.7% in rural and 31.5% in town locations, compared to 46.5% and 25.3% respectively for city and suburban locations.

Thus, the Table B-3 gas availability data is encouraging. It shows a reasonable chance that suitable demonstration and potential market entry locations can be found where propane or utility fuel gas is already utilized. Indeed, on a composite basis almost 20 percent of rural locations have propane with

Table B-3
Residential Fuel Cell Potential Market Application Profiles

Percent of Dwellings that HAVE UTILITY GAS

Census Division	City	Suburban	Town	Rural	Composite All Four	Composite of Town plus Rural
New England	78.6	50.7	67.3	7.1	57.7	43.8
Middle Atlantic	96.1	84.0	76.7	19.0	78.6	49.0
East North Central	98.4	99.7	87.9	39.6	88.3	59.4
West North Central	86.1	98.0	74.2	16.5	69.8	51.4
South Atlantic	59.2	45.4	51.3	17.5	45.5	30.2
East South Central	87.9	77.2	67.3	16.6	57.8	29.9
West South Central	82.9	78.3	92.3	30.7	77.4	70.5
Mountain	87.8	85.6	77.3	44.6	80.6	60.6
Pacific	94.5	78.3	53.1	33.1	81.1	45.1
Composite	86.8	75.7	72.5	23.9	71.6	47.8

Percent of Dwellings that HAVE LPG

Census Division	City	Suburban	Town	Rural	Composite All Four	Composite of Town plus Rural
New England	4.2	13.4	7.5	24.9	10.5	14.3
Middle Atlantic	0.0	4.1	2.3	20.1	4.4	10.8
East North Central	0.0	0.0	5.8	36.1	6.4	23.7
West North Central	3.7	0.0	15.0	45.4	15.1	27.0
South Atlantic	4.4	4.7	11.5	33.0	11.6	24.9
East South Central	1.9	0.6	12.5	34.4	14.6	28.6
West South Central	0.5	2.8	0.9	39.4	6.3	14.6
Mountain	1.4	1.5	14.4	28.9	6.7	21.8
Pacific	0.1	0.3	7.5	9.3	1.8	8.3
Composite	1.3	2.8	7.7	31.2	7.7	19.6

Percent of Dwellings that HAVE UTILITY GAS OR LPG AND WHICH DO NOT USE ELECTRIC RESISTANCE HEAT

Census Division	City	Suburban	Town	Rural	Composite All Four	Composite of Town plus Rural
New England	75.5	62.3	67.4	32.0	63.2	53.6
Middle Atlantic	92.9	83.0	72.4	37.8	79.0	55.8
East North Central	92.5	95.6	86.9	67.2	88.6	75.2
West North Central	78.6	98.0	80.6	58.6	77.6	71.9
South Atlantic	51.4	44.8	54.5	42.7	48.2	47.1
East South Central	69.1	69.2	69.0	46.7	61.1	52.6
West South Central	68.0	63.4	77.4	63.0	69.0	72.3
Mountain	76.5	87.2	83.2	66.7	77.1	74.8
Pacific	80.7	64.4	48.3	39.9	70.2	44.9
Composite	77.5	71.7	70.5	49.9	70.5	60.0

Source: EnSig proprietary analysis of raw 1993 EIA Census Data

comparable saturations for propane cooking, water heating and space heating of 18, 11, and 20 percent respectively. Thus, in many propane using locations that use is not simply for casual cooking and a fair sized storage tank may already exist.

Natural Gas

Usage Profiles

Gas using appliances are generally designed to use natural gas at house line pressures which are generally in the six inches of water range. This would be equivalent to 3.47 ounces or 0.217 psig. Table B-4 provides a rough comparison with other gas using appliances. A residential fuel cell would have about the same connected load as a gas water heater or range but with a much higher monthly and annual use because a fuel cell would run more continuously. In effect the fuel cell would have the fuel connection requirement of a water heater and the annual use of a furnace.

Table B-4
Common Appliances and Comparative Gas Use

Appliance	Typical Annual Gas Use	
Residential Fuel Cell:		
1 kW average load	**90**	**Million Btu HHV**
2 kW average load	**181**	
3 kW average load	**270**	
Range	**10**	
Water Heater	**35**	
Furnace (North Central U.S.)	**75 to 150**	
Outdoor Post Lamp	**20**	**Million Btu HHV**

Natural Gas Consumption and Pricing

At an average output of 2 kW and a LHV efficiency of 36.7 percent, a residential fuel cell would use about 20,600 Btu per hour HHV or 181 million Btu per year. Moreover, since a fuel cell would tend to have a relatively stable seasonal use which is always attractive to a utility, it may be possible to secure an incentive rate for its gas use for this emerging market. However, such incentive rates are unlikely to be in place for demonstration unit timing.

Until relatively recently, natural gas was historically sold on a dollar-per-thousand-cubic-foot basis which is called an MCF where M stands for thousand and NOT million. Other tariffs may be per hundred cubic feet which is abbreviated as CCF. Around the 1970’s many tariffs were converted to a dollar-per-million-Btu basis, usually abbreviated MMBTU or MilBtu. Another term sometimes used is a Therm which is 1×10^5 Btu. There are 10 Therms in a DekaTherm which is also a million Btu.

The average residential price for natural gas was \$6.30 per million Btu in 1999 with commercial customers in the nation paying an average of \$5.10. Given that residential and commercial gas rates have similar block structures and that a residential fuel cell would be the last item in the consumption block, a range finding estimate for its natural gas fuel might be \$5.10 per million Btu. However, a much better option would be to use the Table B-4’s data and work through the local gas utility’s rate schedule with, and without, the fuel cell to derive the incremental natural gas cost for a residential fuel cell.

In order to calculate many gas bills, as well as residential fuel cell efficiency, gas meter readings must be converted by a two step process. The first conversion is from Actual Cubic Feet into Standard Cubic Feet. After the Standard Cubic Feet are known, the local natural gas's energy content is then used to convert the SCF consumption into Btu energy readings. This latter conversion uses the energy content in Btu for a Standard Cubic Foot of natural gas and is commonly known as Heating Value. Two choices are available. These are Higher Heating Value (HHV) and Lower Heating Value (LHV). Both are measured as Btu per SCF where a Btu is the amount of energy required to heat one pound of water one degree Fahrenheit. As a point of reference, there are around 1000 Btu's in a cubic foot of natural gas depending on its composition and 3412.6 Btu's in one kilowatt-hour of electricity.

Heating Value and Efficiency Calculations

Historically, natural gas heating values were measured by burning a controlled volume to heat a water bath and this became the Higher Heating Value. When hydrocarbons burn, the oxygen in the air combines with the hydrogen in the fuel to form water vapor as shown below. The LHV value assumes that the byproduct H_2O leaves as uncondensed water vapor. The HHV of 1012 Btu per SCF

Methane Combustion	Heating Value in Btu/SCF	
	Lower (LHV) *Water Vapor*	Higher (HHV) *Condensed*
$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$	911.45	1012.32

assumes that the combustion product is condensed to liquid water. Just as boiling water to make steam requires energy, the condensation of steam, or in this instance water vapor in the combustion product, releases energy. This shows up as the over hundred Btu difference between HHV and LHV.

Since the original calorimeters for natural gas were water bath units which obviously condensed the combustion products, Higher Heating Value became the standard by which natural gas energy is priced and sold. However, few practical uses capture this condensation energy with the exception of some of the ultra high efficiency home furnaces which have extensive heat exchange surface to actually condense the water vapor in their exhaust. An artifact of all this is that mechanical and aeronautical engineers have traditionally used Lower Heating Value because it more closely approximates the real work that is available in most thermal processes. This is the reason, for example, that most microturbines calculate their heat rate in terms of Btu (LHV) per kilowatt-hour.

A somewhat common misconception is that natural gas is all methane which is CH_4. While methane is indeed the largest constituent, ranging from probably 90 to 95 percent, other components include ethane C_2H_6, propane C_3H_8, and even butanes and higher hydrocarbons. Each of these constituents has a different heating value per cubic foot. Additionally, most natural gas contains nitrogen and lesser amounts of CO_2, both of which are diluents and reduce the heating value. The exact gas composition in a given city depends both on the geographic area where the gas was produced and on the amount of "clean-up" higher hydrocarbon removal and gas processing that occurred between the well and the pipeline. Thus, there is no such thing as a standard gas composition and, therefore, no such thing as a universal HHV and LHV multiplier. These have to be determined on a site area basis.

Since natural gas at typical pressures obeys the partial pressure gas law of content relationships equaling volumes, natural gas heating values are often determined by measuring the volumetric composition of the various components in natural gas by an automatic gas chromatograph. A microprocessor then calculates the overall heating value by multiplying the various volume percentages by the heating values of the individual components. This is illustrated in Table B-5 for a sample natural gas composition.

Table B-5
Calculation of Natural Gas Heating Values

Component in Natural Gas	Volume Percent	Heating Value of One Pure SCF LHV	Heating Value of One Pure SCF HHV	Calculated Values LHV	Calculated Values HHV
Methane	**90.2%**	**911.45**	**1012.32**	**822.13**	**913.11**
Ethane	**4.6%**	**1622.10**	**1173.42**	**74.62**	**53.98**
Propane	**2.5%**	**2322.01**	**2523.82**	**58.05**	**63.10**
Nitrogen	**2.7%**	**0.00**	**0.00**	**0.00**	**0.00**
COMPOSITE NATURAL GAS HEATING VALUE (Btu /SCF)				**954.79**	**1030.19**

This heating value can also vary seasonally due to varying mixtures of local production gas in a utility's system, the use of propane-air for peak shaving on abnormally cold winter days, and changes in the sources of pipelines supplying a region. Different pressure bases for determining a Standard Cubic Foot will also change the calculated results.

Both types of heating values will likely be needed within the residential fuel cell demonstration program. Higher Heating Value (HHV) is universally used to calculate pricing from any tariffs that are energy content rated. Thus, HHV will be needed to calculate the cost of fuel cell operation on a monthly or hourly basis, as well as the cost per kWh. On the other hand, most fuel cell manufacturers rate the machine's efficiency or heat rate using Lower Heating Values. Consequently, the calculation of comparable efficiency or degradation will need to be based on LHV data. In either instance, the Btu's are calculated by multiplying the Standard Cubic Feet of gas use by the appropriate lower or higher heating value. These heating values will need to be secured from the local supplier.

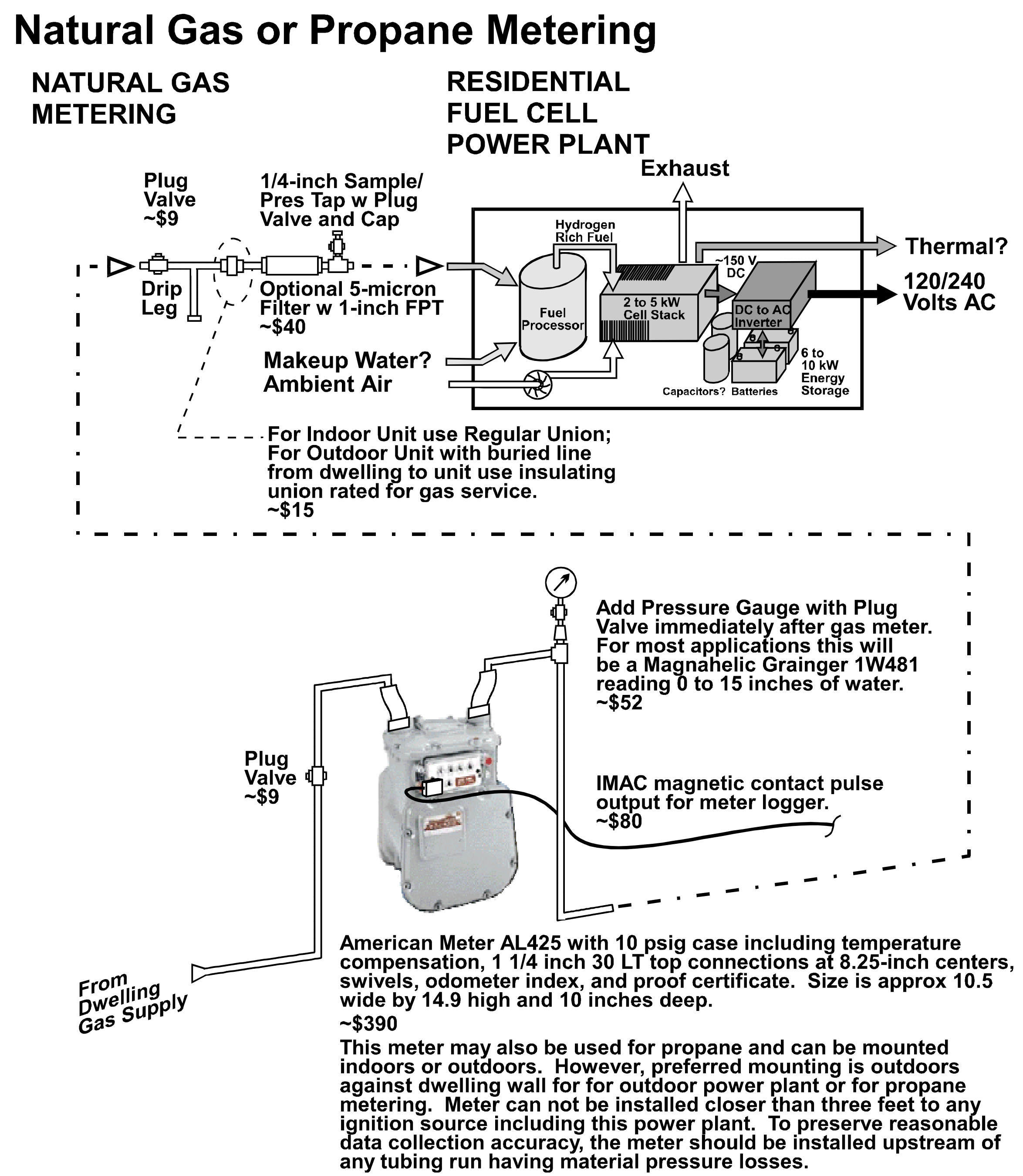
Heating value records are usually readily available. Six to twelve readings over a year's period will generally be sufficient to make a judgment as to whether a uniform HHV and LHV can be assumed for the demonstration cycle or whether some kind of seasonal variation needs to be considered. It is also possible to take a site gas sample at the gas meter's pressure gauge location. This could then be analyzed by a laboratory, or in some instances by the local gas company, to measure the local heating value. However, this extra effort would not normally be needed within the scope of the demonstration program.

Natural Gas or Propane Fuel Interconnect

In order to confirm residential fuel cell efficiency and calculate related operating costs, the gas use of the fuel cell will need to be measured. As shown in Natural Gas or Propane Metering and Interconnect which is Figure B-2 on the next page, the related equipment is relatively straight forward and inexpensive.

Gas meters and regulators are typically rated in SCFH, which is Standard Cubic Feet Per Hour with the gas flow at 14.73 psia and 60 °F, even though the actual flow through the meter will vary with the pressure and temperature inside the meter. For example, a residential fuel cell rated at 15.08 million Btu per Hour LHV and using a 945 Btu per cubic foot Lower Heating Value gas would have a gas flow rate

Figure B-2
Natural Gas or Propane Metering and Interconnect



CAUTION: EXACT COMPONENTS AND INSTALLATION CAN BE A FUNCTION OF THE PARTICULAR SITE AS WELL AS LOCAL CODE AND GAS COMPANY REQUIREMENTS. THUS, THESE AREAS SHOULD BE REVIEWED BY THE ABOVE, AND/OR YOUR LOCAL ENGINEER, BEFORE EQUIPMENT IS ORDERED AND INSTALLED.

ALSO, BE SURE TO READ AND ADHERE TO THE RELATED MANUFACTURER'S INSTALLATION, OPERATING, AND SERVICE INSTRUCTIONS.

of 19.68 Standard Cubic Feet per Hour (SCFH). However, an outside meter at 30 °F at 1000 feet of altitude delivering gas at 6-inches of water pressure would actually be measuring 18.12 Actual Cubic Feet per Hour. Gas meters are an "actual cubic foot" measuring device! Because natural gas is essentially an "ideal" gas at these temperatures and working pressures, it is subject to the normal gas law where PV/T equals a constant. This means that both pressure and temperature can greatly influence the output readings of a gas meter.

The entire gas industry generally uses a standard measurement base of 60 °F and the error in a demonstration fuel cell program meter reading without temperature correction will be significant:

$$\text{Gas Meter Temperature Correction Multiplier} = \frac{460\ °F + 60\ °F}{460\ °F + \text{Temperature of Gas Flowing Through Meter } °F}$$

For example, at 100 °F an uncompensated meter will be reading fast by almost eight percent. Conversely, at -10 °F the meter will be slow by over thirteen percent! Also, hand correction is not very practical because the temperature of the gas flowing through the meter will vary somewhere in a band encompassing soil temperature to site ambient air temperature.

Fortunately, temperature compensated meters like specified for this demonstration are readily available. These use a relatively inexpensive $40 bimetal linkage, much like the pendulum on very accurate mechanical clocks, to automatically compensate for temperature by changing the rate of the meter's dials. These meters have an accuracy of plus or minus one percent or better and assure that both monthly volume readings, as well as any hourly readings and flow pulse counts, will be accurate.

Before leaving the factory, gas meters are proof tested and usually calibrated to a pressure of 14.73 psia which is pounds per square inch absolute pressure. The standard conditions at which natural gas is measured are typically 14.73 psi absolute pressure and a temperature of 60 °F. All gas meters need to be corrected for the gauge pressure of the gas flowing through the meter and for the absolute normal air pressure at the elevation where the meter is installed. Gauge pressure is known as psig and is measured by a pressure gauge immediately downstream of the gas meter. This gauge needs to be reasonably accurate and sized so that the meter reading is more-or-less in the upper range of the dial. Also, this pressure reading should be taken when the power plant is running at a relatively normal load so as to register the effect of any upstream pressure losses due to the gas flow. The gauge line should include a valve so that the gauge can be shut off when not being read as well as to provide a location for taking any needed gas samples.

In order to calculate the necessary one-time pressure correction for the gas meter, both the site pressure and the gas pressure inside the gas meter need to be determined. The pressure correction for the meter readings is then:

$$\text{Standard Cubic Feet} = \text{Cubic Feet Measured by Meter} \times \text{Gas Meter Correction Factor}$$

$$\text{Gas Meter Correction Factor} = \frac{\text{Atmos Pressure @ Elevation} + \text{Psig at Meter}}{\text{14.73 psia Standard Gas Meter Proof Pressure}}$$

Example:

Step 1 Determine the elevation of the demonstration site by going to the USGS topographic maps which can be found at: http://www.topozone.com and enter the city nearest your site. Then drill down to the 1:25,000 resolution and large image to find the elevation of your site to the nearest 50 feet or so. For this example, assume the site elevation is determined to be 1220 feet. Then go to http://waves.ncdc.noaa.gov/shore/smoum6.htm and look in the table at the bottom to find the barometric pressure in inches of mercury (InHg) that corresponds with that altitude. At 1220 feet, the resulting standard local atmospheric pressure will be 28.626 inHg which is inches of mercury. This can be converted into psia as follows:

$$\text{psia} = 0.4912 \times \text{Inches of Mercury} = 0.4912 \times 28.626 = 14.061 \text{ psia.}$$

In this instance assume that the pressure gauge at the gas meter reads 6.5 inches of water. Then, the pressure inside the gas meter relative to atmospheric pressure would be:

psig = 0.03613 x Inches of Water = 0.03613 x 6.5 = 0.235 psig ...and...

the Gas Meter Correction Factor would be: GMCF = (14.061 + 0.235) / 14.73 = 0.9705

Step 2 Assume that a monthly reading is taken on June 30 and the meter reads 0154<u>0</u> and a subsequent reading on August 1 is 1711<u>0</u>. Thus, the Actual Cubic Feet used over the period is 17110 - 01540 or 15,570 ACF. The Standard Cubic Feet (SCF) used would be calculated as:

SCF = GMCF x ACF = 0.9705 x 15570 = 15,110 ...and...

If the LHV and HHV per cubic foot were 945 and 1050 Btu's per SCF respectively, the related energy input to the fuel cell during the period would be:

LHV = 14,279,000 and HHV = 15,866,000 Btu's during the period.

Table B-6
Some Useful Conversion Factors

Standard Atmospheric Pressure
= 14.696 Psia
= 1013.25 milliBar
= 29.921 Inches of Mercury (InHg)
= 760 Millimeters of Mercury (mmHg)

Pounds per Square Inch (Psi)
= 0.4912 x (Inches of Mercury-InHg)
= 0.01934 x (Millimeters of Mercury-mmHg)
= 0.03613 x (Inches of Water-InH2O)
= 0.0625 x (Ounces of Pressure-Oz)

Table B-6 provides some conversion factors that may be helpful to making the above conversion calculations. Given the above methodology, one question that might be asked is: "Why would not normal atmospheric pressure changes due to weather fronts also affect the gas meter calibration factor and the resulting reading accuracy?" The answer is indeed that weather changes do affect gas meter accuracy. Dependent on the geographic location and actual weather conditions, barometric pressure could be expected to vary about plus or minus one-half inch of mercury between high's and low's. This would be equivalent to about ±0.25 psia. Thus, the meter calibration factor could be expected to swing about two percent each way. However, these cycles should routinely average out over the days within a monthly meter reading period. The only time this might be an issue is when "snapshot" readings are being taken by timing the meter's pulses to get an instant efficiency reading by reading the short-term the fuel input and the electric output.

Natural Gas Fuel Supply Piping

More detailed specifications and sources will be supplemented as needed in advance of any actual installation. In the interim, Figure B-2 covering Natural Gas or Propane Metering can help assess the likely fuel interconnect needed for a successful residential fuel cell demonstration program. As indicated in the figure, the preferable meter location would be outside against the dwelling wall for an outdoor power plant installation. In any case it is important to know and follow the local codes and regulations as they relate to the particular site.

Although some jurisdictions may allow the use of copper tubing inside a dwelling, it is preferable and perhaps safer to use black-steel Schedule 40 pipe. To assist in site planning, the pressure drop calculations in Table B-7 should be helpful in planning the power plant installation. The related pressure calculations will be reasonably accurate for natural gas pressures in the "inch" range. Intermediate, or longer, distances than in the table can be found by prorating the table's information. As long as the meter's correction factor is calculated at the pressure drop associated with the 3 to 5 kW operating level, all of Table B-7's pressure drop variations at the meter will yield acceptable accuracy spreads. The resulting meter readings would be in the 0.6 percent accuracy range even if the meter is downstream of the pressure variation.

Table B-7
Natural Gas Pressure Drops

Length	Cell Stack Load	Pressure Drop (Inches of Water): 1/2-inch Tubing	Schedule 40 Steel Pipe: 1/2-inch	Schedule 40 Steel Pipe: 3/4-inch
50 Feet	8 kW	4.41 in.	0.63 in.	0.16 in.
	5	1.88	0.27	0.07
	3	0.75	0.11	0.03
	1	0.16	0.03	0.01
100 Feet	8 kW	Too High	1.26 in.	0.32 in.
	5	Too High	0.54	0.14
	3	1.50	0.21	0.05
	1	0.32 in.	0.06	0.02
Equivalent Feet of Length to Add For:	*Elbows, FO Valves*	*2 Feet*	*2 Feet*	*2 Feet*
	3/4-inch Filter	*3 Feet*	*3 Feet*	*10 Feet*
	Gas Meter	*2 Feet*	*2 Feet*	*5 Feet*

For a typical site, 1/2-inch Schedule 40 pipe should be sufficient. However, if higher pressure drop piping is used, it is important to confirm that the normal house line pressure less the pressure drop in the piping will not reduce the inlet pressure at the power plant to less than the manufacturer's allowable level. Please bear in mind that all fittings, valves, and any tubing or connectors should be approved for natural gas service.

If advance calculations indicate that the piping pressure drops will change significantly as the fuel cell increases or decreases in load, the gas meter should preferably be installed upstream of the drops so as to enhance overall measurement accuracy. This is because large pressure drop changes in the piping upstream of the gas meter will cause some variation in the Gas Meter Correction Factor as the fuel cell power plant changes load. For the same reasons, the gas meter pressure that should be used is when the fuel cell is operating at its normal daytime loading. This will help enhance accuracy by effectively calibrating the meter when it is actually measuring gas at normal loads.

Propane

Background

As discussed in the introduction to this section, propane is very suitable for reforming to produce the hydrogen needed to run residential fuel cell stacks. Moreover, as shown in Table B-3, propane is already likely to be available in one out of three residential sites on a national average. In addition, if an ultimate early market entrance goal were to be to supply fuel cell service at remote locations with high line extension costs, such remote sites are far more likely to be served by propane than by utility natural gas. Although more fungible than natural gas, propane's disadvantage is that its fuel cost is essentially double that of utility supplied natural gas, at least on a national average basis.

Commercial LPG is mostly propane (C_3H_8) in contrast to natural gas which is mostly methane (CH_4). Propane is an easily liquefied hydrocarbon that is produced as a by-product of natural gas wells and by refinery operations. The larger size of propane molecules relative to natural gas's methane means that propane is shipped in liquid form and that a liquid-gas pressure interface in the tank will exist at most temperatures as shown on the next page.

Propane weighs 4.23 pounds per gallon in its liquid form but has a boiling point of -44 ºF. Thus, it partially converts to a gas until the point where the pressure in the tank equals the related interface pressure-temperature relationship shown above. For example, the gas pressure gauge on an above-ground propane cylinder would read 23.5 psig if the surrounding outdoor temperature were 0 °F. Since soil temperatures will be higher than ambient air temperatures in very cold climates, this explains why underground storage tanks are sometimes required to get suitable propane vaporization, particularly at large use rates in cold climates.

Temperature of Tank (ºF)	-40	-30	-20	-10	0	20	60	80	100
Pressure of Gas Layer (Psig) above Liquid	1.5	5.6	10.7	16.7	23.5	40	90	125	175

When mixed with air the flammability limit of propane is from 2 to 10 percent, whereas natural gas is 5 to 15 percent. As stated earlier, LPG and propane are often identified interchangeably by the public. In reality, LPG is generally specified to be at least 90 percent propane with the balance being butane (C_4H_{10}) and other hydrocarbons.

A very troublesome feature of propane is that its specific gravity as a gas is 1.58. This means that it is heavier than air and will tend to “pool” in a basement, for example, to cause an explosion. In contrast, natural gas has a specific gravity of 0.61 which is three-fifths of air and is more likely to dissipate in the event of a leak. Both natural gas and propane are odorless but have an odorant added to them to aid in warning of a leak.

Use

Fuel cell power plants are generally designed to use propane at house line or higher pressures. A typical propane system will have two regulators. The first regulator, which is at the tank, is generally set at 10 psig. The second regulator, which is where the propane line enters the dwelling, is generally set to 13 inches of water or 0.46 psig. In contrast natural gas house line pressures are generally in the 6 to 10 inches of water pressure range. While some of the residential fuel cells might to be designed for house line propane pressures, most outdoor units appear to be designed for propane pressures well up in the pound range. Code requirements normally limit gas pressures inside any occupied area, subject to some specific exceptions, to less than 2 psig for obvious and valid safety reasons.

Table B-8
Common Appliances and Comparative Propane Use

Appliance	Typical Annual Propane Use		
Residential Fuel Cell:			
1 kW average load	970	Gallons	*= 81 Gal/month*
2 kW average load	1950		*160 Gal/month*
3 kW average load	2900		*240 Gal/month*
Range	109		*9 Gal/month*
Water Heater	380		*32 Gal/month*
Furnace (North Central U.S.)	820 to 1640	*Nov*	*225 Gallons*
		Dec	*330 Gallons*
		Jan	*330 Gallons*
		Feb	*330 Gallons*
		Mar	*225 Gallons*

Table B-8 compares annual fuel cell use with that for other propane using appliances. Since it may be helpful in assessing the incremental storage capability from any existing on site propane tank, the table also shows relative monthly propane consumption in italics. A residential fuel cell would have about the same connected load as a propane water heater or range but has a much higher monthly and annual use because it runs more continuously. In effect a fuel cell would have the fuel connection requirement of a water heater and the annual tank use of a furnace.

Pricing

Natural gas prices vary geographically and perhaps slightly from season to season. Average industrial prices are around $3.00 to $4.00 per million Btu; commercial prices are around $5.50. In contrast propane prices fluctuate much more than natural gas both geographically and seasonally. Prices also vary significantly by the amounts purchased. For example, home tank prices might be 80¢ to $1.00 per gallon at the same time that a 10,000 gallon delivery might cost 35¢ per gallon. Commercial quantities in the 1,000 to 2,000 gallon range might cost 50 to 60¢ per gallon. To place these in perspective, a gallon of propane typically contains 91,700 Btu when vaporized. Thus, to convert propane to natural gas prices, multiply the propane prince in ¢/gallon by 0.1095 to get $/Million Btu natural gas equivalent.

Tanks often supplied by the dealer in return for the propane sale, particularly for a steady use levels that would be consistent with a residential fuel cell running at an average load of 2 kW. However, the "premium" for a dealer owned tank might be as much as 30¢ per gallon. This would amount to an extra annual charge of $585 for a residential fuel cell averaging a 2 kW load. When looking at adding additional propane tanks, it is also useful to inquire what discounts may exist for the larger purchase volume associated with a 1000-gallon over a 500-gallon tank. Even at propane costs in the range of 90¢ or more per gallon, large fill propane pricing might be available in to 60¢ to 70¢ per gallon range depending on dealer, location, season, and user negotiations.

Site Storage

Propane tank systems and costs vary significantly depending on the storage volume and on the cents per gallon cost of the propane refills. Table B-9 shows typical tank sizes and fill volumes for residential applications. Please note that a propane tank can only be filled to 85 percent of capacity since some ullage must be allowed for the vapor layer above the liquid in the tank. Also shown in the table are the cost of new or additional propane storage capacity.

Table B-9
Common Residential Propane Tank Sizes and Storage Volumes

Nominal Tank Size (gallons)	Diameter (feet)	Length (feet)	Actual Propane Capacity (gallons)	Estimated Cost of Added Propane Storage Tank
500	3.1	10	425	Above Ground: $1,200 Buried: $1,500
1,000	3.4	16	850	Above Ground: $1,900 Buried: $2,300

The complexity of the site propane approvals also depends significantly on the site storage volume. Approvals should be relatively straightforward for a site with up to two 1,000 gallon tanks. Installation is also relatively simple on built-in feet or by burial. Required separation would be 10 to 25 feet from structures depending on the site, codes, the local fire marshal, etc. These details are in shown on Figure B-3's Allowable Propane Tank Locations. An added constraint is that the fill opening of the tank should be no further than 85 feet from a driveway or the intended location of the delivery truck.

The heat required to vaporize propane depends somewhat on the temperature of the liquid but is about 680 Btu per gallon. If unusually cold climates are coupled with high fuel cell power plant propane pressure requirements, it may make sense to consider a buried tank. An added reason is because the tank temperature will drop below ambient as the propane vaporizes. With a buried tank, the soil temperature will help reliably vaporize the propane in extremely cold climates.

Measurement

The gas metering and interconnect configuration shown earlier in Figure B-2 will work equally well for propane or natural gas. To maximize accuracy and minimize problems, the meter should be placed after any secondary regulator so that it is measuring the gas consumption at the pressure range entering the residential fuel cell.

A secondary concern is that LPG-propane fills may have differing heating values depending on the relative amount of higher hydrocarbons like butane, etc. contained in the mix. For example, propane has a vaporized heating value of 2523 Btu per CF HHV while butane is 3270 Btu. This would obviously show up as errors in the calculated fuel cell energy input when the gas meter's measured cubic feet are multiplied by an assumed heating value for propane alone. This potential error may be able to be resolved by queries of actual dealers and suppliers once the program is activated. If the gas Btu composition does becomes a concern at some point, a simple procedure will be developed by the program where all the co-op participant needs to do is a simple ten-minute job every month or so of filling a small evacuated sampling flask and sending it off to a lab for a gas analysis report.

Table B-10
Other Pressure Drops

Natural Gas:

Pressure	Multiply Table B-7 Pressure Drops by:
10" = 5.8oz = 0.36psig	1.00
2 psig	0.90

Propane:

Pressure	Multiply Table B-7 Pressure Drops by:
13" = 7.5oz = 0.47psig	0.39
2 psig	0.35
5 psig	0.30
10 psig	0.24
15 psig	0.20
20 psig	0.17

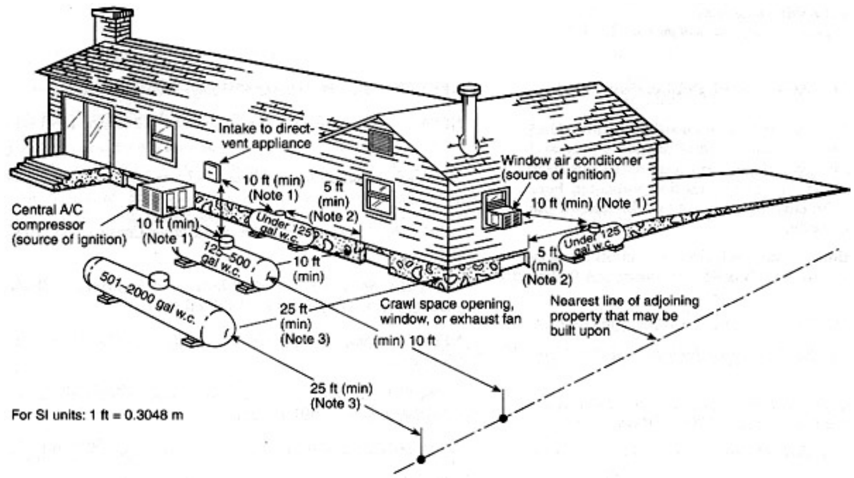
Installation Piping

Figure B-2 on Natural Gas or Propane Metering can help assess the likely fuel metering needed for a successful propane fueled residential fuel cell demonstration program. As indicated in the figure, the preferable meter location would be outside against the dwelling wall for an outdoor power plant installation. In any case it is important to know and follow the local codes and regulations as they relate to the particular site.

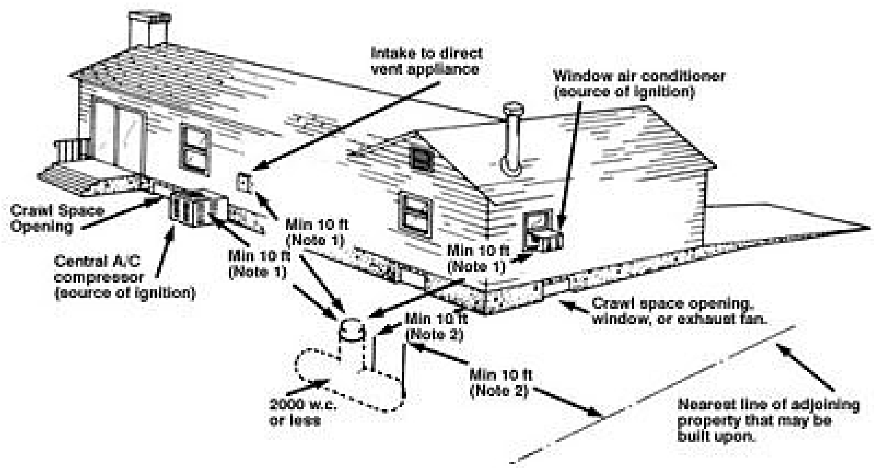
Figure B-3
Allowable Propane Tank Locations

Propane Tank Location Constraints . . .

Aboveground:



Buried:



Regardless of its size, any ASME container filled on site must be located so that the filling connection and fixed maximum liquid level gauge are at least 10 ft. from any external source of ignition (e.g., open flame, window A/C, compressor), intake to direct-vented gas appliance, or intake to a mechanical ventilation system.

Location of the fill opening for the tank should not be further than 85 feet from the driveway or the intended location of the delivery truck.

CAUTION: EXACT COMPONENTS AND INSTALLATION CAN BE A FUNCTION OF THE PARTICULAR SITE AS WELL AS LOCAL CODE AND PROPANE DEALER REQUIREMENTS. THUS, THESE AREAS SHOULD BE REVIEWED BY THE ABOVE, AND/OR YOUR LOCAL ENGINEER, BEFORE EQUIPMENT IS ORDERED AND INSTALLED.

ALSO, BE SURE TO READ AND ADHERE TO THE RELATED MANUFACTURER'S INSTALLATION, OPERATING, AND SERVICE INSTRUCTIONS.

To assist in site planning, Table B-10 may be helpful in planning the related installation in terms of pressure drop calculations. Simply pick the fuel and pressure and determine the multiplier on the Table B-7 calculated pressure drops. Intermediate or longer distances than in the table can be prorated. As long as the meter's correction factor is calculated at the pressure drop associated with the 3 to 5 kW operating level, all of the table's pressure drop variations at the meter will yield acceptable metering accuracies in the 0.6 percent range even if the meter is downstream of the pressure variation.

The pressure drops shown in the above table start with a standard house line propane pressure of 13 inches of water. As indicated by these tables, the pressure drops will change within the piping as the fuel cell increases or decreases in load and as the line pressure increases. This is because propane has a higher energy density with therefore less line velocity for the same Btu input to the fuel cell and because pressure drop is a function of line velocity raised to the third power. Thus, a relatively small change in line flow can have a major impact on the resulting velocity induced pressure drop. For these types of reasons, the gas meter should preferably be installed upstream of the drops so as to enhance the overall measurement accuracy. This is because large pressure drop changes in the piping upstream of the gas meter will cause some variation in the Gas Meter Correction Factor. For the same reasons, the gas meter pressure that should be used is when the fuel cell is operating at its normal daytime use. This will help enhance accuracy by effectively calibrating the meter when it is actually measuring gas at normal loads.

For a typical site 1/2-inch Schedule 40 pipe or tubing should be sufficient for the fuel cell line. However, if higher pressure drop piping is used, it is important to confirm that the normal house line pressure less the pressure drop in the piping will not reduce the inlet pressure at the power plant to less than the manufacturer's allowable propane inlet pressure. Please bear in mind that all fittings, valves, and any tubing or connectors should be approved for LPG-propane service.

Methanol

To some degree, the interest in the PEM (Polymer Electrolyte Membrane) fuel cells for residential fuel cells is a spin-off from the methanol automotive and transportation fuel cell programs. Methanol is a commodity feedstock used in the production of MTBE, formaldehyde, acetic acid, and other chemicals. Total methanol use in the nation is over 2.5 billion gallons annually with 75 percent of that supplied by 17 plants in the U.S. The energy efficiency of converting natural gas to methanol is around 63 percent and, when used in a residential fuel cell, methanol becomes essentially "twice reformed" natural gas.

Methanol, which can be purchased in the local hardware store as wood alcohol, is a clear liquid that weighs 5.53 pounds per gallon. The heating value of methanol is 64,240 Btu per gallon HHV and compares to about 125,000 Btu's per gallon for gasoline. Thus, twice as much has to be shipped or carried to do the same job as gasoline. Methanol is also toxic, although its proponents argue that gasoline is also, and dissolves readily in water. Methanol is somewhat less ignitable than gasoline but has a wider flammability range from 7 to 36 percent. One troublesome feature is that a pure methanol fire burns with a clear, very light blue flame which is virtually impossible to see in daylight.

No practical infrastructure exists for supplying methanol for residential fuel cell use. For this type of demonstration, 55-gallon drums of "chemical" methanol would need to be purchased and hand transferred to a site double-wall, above-ground storage tank. The resulting fuel cost would be \$30 to \$60 per million Btu, which would equal 30¢ to 60¢ per kWh for the fuel component alone!

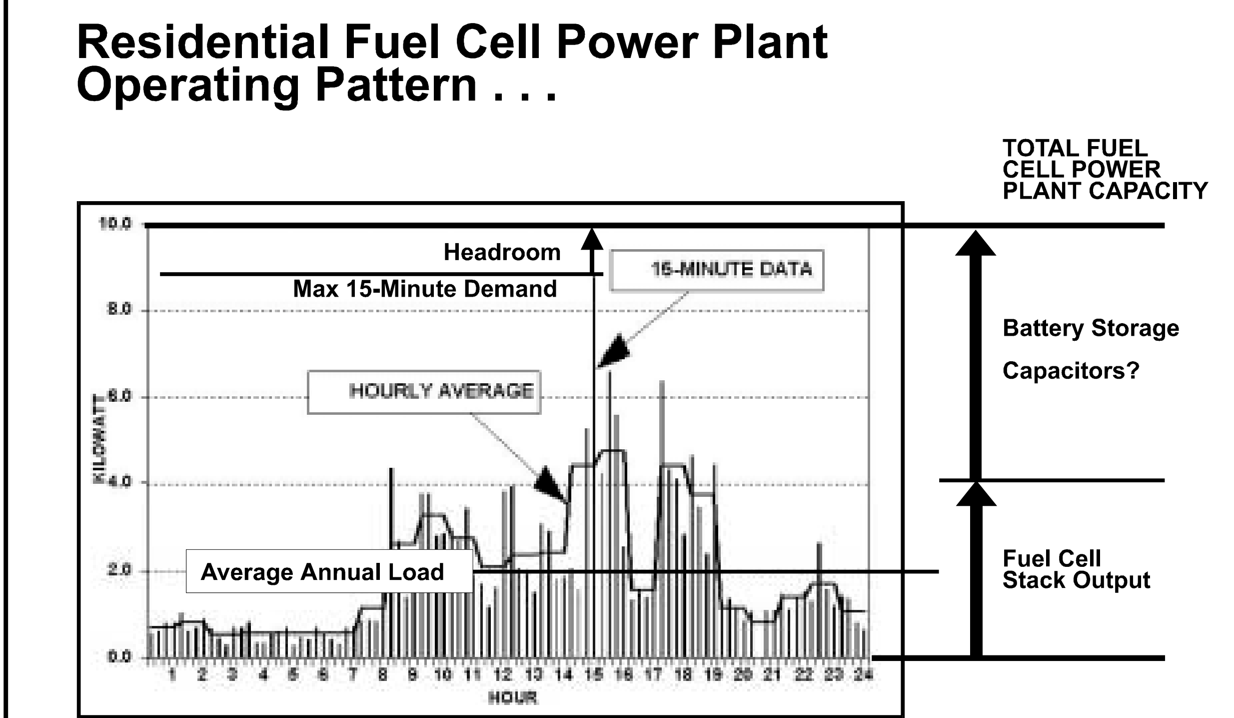
Section C: Fuel Cell Electrical Interconnect and Metering

Market Configurations

All of the manufacturers ultimately plan to develop residential fuel cell power plants that are capable of grid independent operation; most will also be capable of running in a grid parallel mode. While grid interconnect protection is obviously an important issue, the practical design issues for a grid parallel fuel cell are a relatively straightforward development of a detection and control card capable of interrupting the unit's inverter in the event of a grid upset. The design of a residential fuel cell for grid independent operation is in many ways far more challenging since the unit's control system, inverter, and fuel processor need to be capable of responding to wide load swings while constantly producing grid quality power.

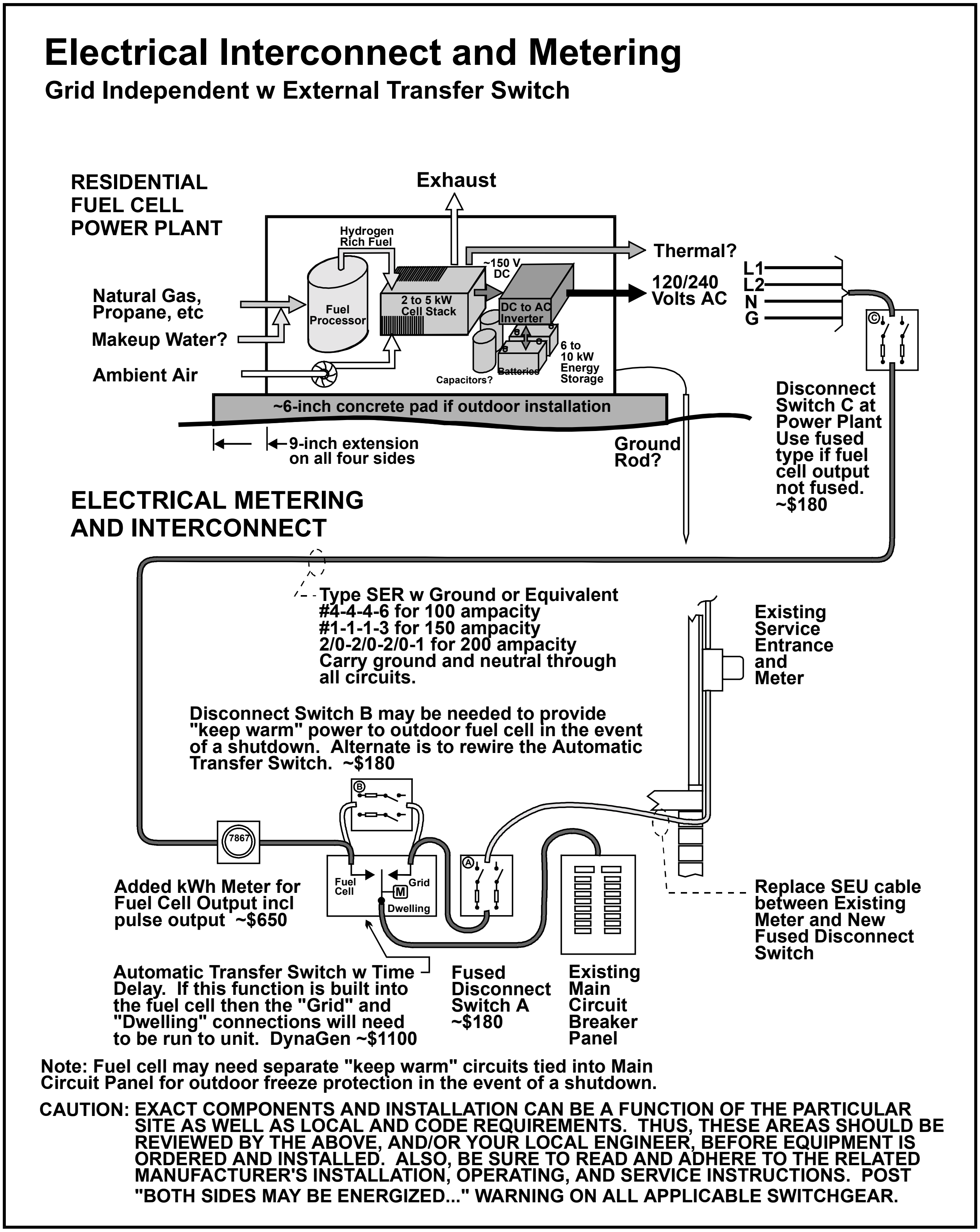
Thus, residential fuel cell units will likely have the capability to satisfy two distinct markets. The first is isolated operation at remote sites; the second, is the capability for distributed generation on the grid. Both modes of operation can be important to co-ops and their operating region. For example, given

Figure C-1
Fuel Cell Load Application Profile



Cooling Peak Day -- Western Utility
Source: Peter Bos, SSFCCG

Figure C-2
Power Plant Electrical Interconnect



reasonable reliability and costs, grid independent operation can provide co-ops and their customers with a potential alternative to costly line extensions to serve distant small loads. Conversely, grid parallel units, particularly those with remote dispatch for daytime power output in excess of customer loads, can provide an added dispersed generation grid source while concurrently enhancing customer appeal if such units can automatically disconnect from the grid and run in a grid independent mode during a grid outage.

As shown in Figure C-1, most residential fuel cells are inherently designed with battery capacity to serve grid independent daytime peaking loads within the dwelling. This configuration could also benefit distributed generation applications. For example, since the batteries and charger are already built-in, it is conceptually possible in the future to have a smaller sized cell stack that uses both its output and the grid at night to charge the batteries for full daytime operation. Thus, the unit could function as a combination distributed generation and day-to-night load leveling device. As a result of the two basic modes of fuel cell operation and potential market applications, the demonstration program's planning is configured to test both the grid parallel and the grid independent modes of operation as illustrated in Figure C-2's Power Plant Electrical Interconnect.

Interconnect Planning

Several criteria influence the resulting electric interconnect and metering. Clearly, understanding both grid parallel and grid independent operations will be key to assessing the market and technology potential of residential fuel cells. Grid parallel operation provides a useful assessment of how well the power plant interfaces with the grid from a safety viewpoint and how the power plant's inverter copes with voltage flickers, spikes due to lightning, and the like. In contrast, grid independent operation fully stresses the cell stack, batteries, and inverter in load swings and day-night demand shifts. For this reason, the interconnect system in Figure C-2 is structured to enable ready assessment of both grid independent and grid parallel modes of operation.

An additional criteria in planning the interconnect has been service reliability in the event of a fuel cell power plant shutdown. Since these units are intended for residential or related applications, the householder or customer will need reasonable assurance that power will remain available even if the fuel cell is not operating. For these reasons, an automatic transfer switch has been incorporated in the interconnect. Based on preliminary manufacturer specifications, this will be required with some of the demonstration units.

Demonstration Interconnect Configuration

Basic Operation

To minimize wiring changes inside the customer's main panel and allow for servicing of the installation and power plant, the interconnect configuration would mount a new fused disconnect fed by a replaced service entrance cable from the existing grid electric meter. This new fused disconnect would feed the grid side of the automatic transfer switch. The center output of the automatic transfer switch would then connect to the customer's existing breaker panel. The other, fuel cell, side of the transfer switch would connect to the fuel cell power plant. The cable to the fuel cell power plant would include an added electric meter to measure the fuel cell's power output and incorporates a service disconnect switch at the power plant. To enable grid parallel operation without rewiring, a bypass switch is incorporated across the transfer switch.

Table C-1
Conductor Ampacity and Voltage Drop

Conductor Size	Ampacity of SER Cable	Voltage Drop for 50 Feet Each Way at Stated Amps			
		50 amp	100 amp	150 amp	200 amp
#4	100	1.5	3.1	Not Suitable	Not Suitable
#3	110	1.2	2.4	Not Suitable	Not Suitable
#2	125	1.0	1.9	Not Suitable	Not Suitable
#1	150	0.8	1.5	2.3	Not Suitable
1/0	175	0.6	1.2	1.8	Not Suitable
2/0	200	0.5	1.0	1.4	1.9

Obviously both actual site conditions and code requirements will influence the exact configuration and the wiring type and sizes. Also, the manufacturer's specifications, installation and operating instructions, should be confirmed early in the site selection and installation planning. If the unit is to be installed outdoors, consideration should be given to using a ground rod at the unit to assure that the working area remains at equal potential to the system ground.

It is critical that all applicable switches be marked with appropriates safety warnings such as: "DANGER: This device is energized by two sources ..." Depending on the detailed fuel cell specifications, site configuration, and customer equipment, an added factor in determining wire sizing could be voltage drop in addition to wiring ampacity. Table C-1 shows the voltage drop for various conductors and distances up to the maximum allowed current.

Electric Meter

The meter in the fuel cell circuit need not be exotic. However, correlating a normally metered demand with the peak loads on the fuel cell is a useful program output. Thus, the meter should include a 15-minute demand register so that this reference information can be secured. The meter should have a pulse output for a data logger. To assure reasonable resolution while providing the ability to troubleshoot with an ordinary multimeter, the electric meter should be set with a Kh pulse constant equaling 5 watts. Some solid state electric meters define a pulse as either an "on" or an "off", whereas the definition here is that a pulse is a complete "on-off" cycle. Since the fuel cell may be using some type of "keep warm" power through the interconnect, the meter should have a dual register or should be programmed or detented so that it will not run backwards.

Automatic Transfer Switch

Unless a similar function is already built into the residential fuel cell unit, an automatic transfer switch will need to be included with the installation so that grid power can continue to be provided to the demonstration dwelling in the event of a power plant shutdown or maintenance service. Automatic transfer switches are generally high priced units with designs targeted at commercial and industrial customers. However, DynaGen has developed an AST1000 series switch targeted for residential applications. Also, ASCO now has a 165 series UL-NEC-NFPA approved residential transfer switch for about the same cost. In addition, more expensive alternates are available from Cutler-Hammer.

Interconnect Configurations

Types and Concerns

Grid Parallel

Based on preliminary manufacturer specifications, most commercial and many demonstration residential fuel cells will have the capability to operate in a grid parallel configuration as well as in a grid independent mode. As shown in the first box of Figure C-3 on the next page, power flows from the fuel cell to the customer's dwelling and may also flow to, or from, the grid. The timing, amount, and direction of power flows relative to the grid depends on:

- whether the unit is configured during operation to act as a dispersed generator with export power to the grid,
- the size of the fuel cell power plant's cell stack and battery capacity relative to the dwelling's load at that particular instant of the day,
- the dwelling's daytime/nighttime and on-peak/off-peak relative loads,
- whether any anti-export controls are present and activated in the unit or at the site,
- etc.

Thus, this type of unit has *two* types of interconnect criteria.

The first, and most critical, are Grid Interconnect factors. Important elements are the ability of the unit to follow the grid's voltage and frequency over an acceptable range and to halt power production in the event of a grid upset beyond stated limits. A key need is for the power plant to reliably detect a grid outage and promptly halt power production so as not to hinder recloser operation or to island. Islanding is the introduction, or potential introduction, of power into an otherwise dead grid. This poses a serious hazard to any co-op distribution service personnel attempting to repair grid service.

An additional criteria is the Power Quality Interconnect, principally with the customer and secondarily with the grid. This encompasses such elements as voltage sags and swells, flicker, harmonics, DC power components, and various secondary factors. The level of this concern will be a function of the power quality from the fuel cell power plant itself, the customer's loads, and also of the relative stiffness between the grid and fuel cell at the customer's load point.

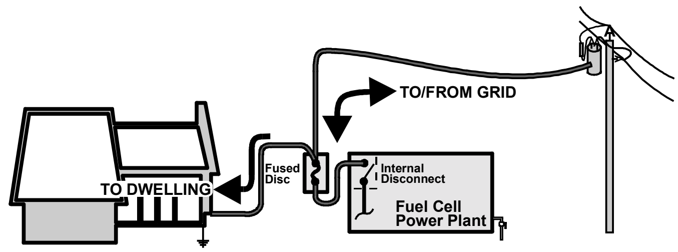
Grid Independent

The middle box of Figure C-3 shows the same fuel cell power plant in a grid independent interconnect configuration. In this instance power flows from the fuel cell power plant only to the customer's dwelling. There is no connection to the grid except for perhaps a manual or automatic transfer switch that allows the customer's dwelling to use either fuel cell or grid power. Since there is no ability to connect the fuel cell to the grid, no Grid Interconnect concerns exist.

However, in this instance the fuel cell must meet all the dwelling's loads and can expect no support from the grid. Thus, the fuel cell will likely have a battery storage system sized equal or greater than the cell stack's capacity. The batteries would be charged by the cell stack at night during off-peak hours and used to supplement the cell stack's capacity during daytime peak loads. Such an installation will require application preplanning and most likely some preinstallation metering to assure that the customer's loads will not exceed the fuel cell's capacity. In addition some type of load shedding or load control devices may be required and the fuel cell may have some type of internal disconnect for certain dwelling fault clearing events.

Figure C-3
Residential Fuel Cell Interconnect Types and Issues

Grid Parallel . . .

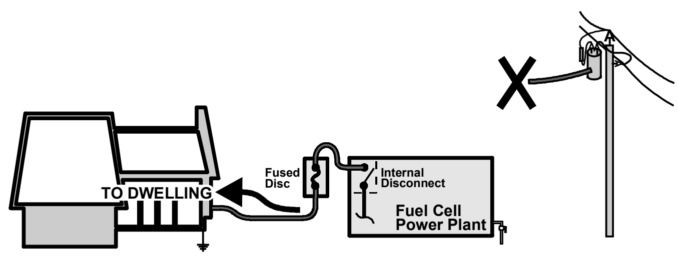


Power Flow: **Power flows from the fuel cell to the customer's dwelling and to/from the grid, both of which are connected in parallel. Dependent on the time of day, the fuel cell capacity versus dwelling loads, state of fuel cell battery charge, any anti-export controls or settings, etc. power may flow from or to the grid. The typical configuration would likely have limited export at certain times of the day and strive for no export at night.**

Interconnect: **Fuel cell interconnects to the grid through a fused disconnect, which is accessible to distribution service personnel, and an internal disconnect under control of the power plant. In the event of a short-term grid upset the inverter would typically interrupt or stop commuting. In the event or a longer upset, the inverter would open an internal disconnect and after disconnect would likely go to idle while continuing to monitor the grid and awaiting to reconnect after a presettable time delay after the grid returns to normal.**

Key Interconnect Issues:
GRID: ***GRID INTERCONNECT re Islanding, Reconnect Timing, etc. Some interest in POWER QUALITY.***
CUSTOMER: ***Potential POWER QUALITY type issues depending on grid versus power plant stiffness.***

Grid Independent . . .

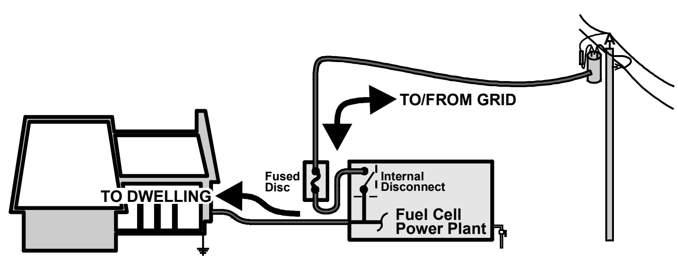


Power Flow: **Power flows from the fuel cell only to the customer's dwelling. Thus, the fuel cell must meet all dwelling loads. This will require application preplanning and perhaps some load monitoring ahead of installation. The fuel cell will likely have a substantial battery storage system which is charged by the cell stack at night and helps supplement the cell stack capability during peak daytime loads.**

Interconnect: **Fuel cell interconnects to the dwelling through a fused disconnect and perhaps an internal disconnect for certain dwelling fault clearing events.**

Key Interconnect Issues:
GRID: ***NONE***
CUSTOMER: ***Potential to substantial POWER QUALITY type issues depending on customer and loads..***

Combination Grid Parallel and Grid Independent . . .



Power Flow: **Power flows from the fuel cell to the customer's dwelling and to/from the grid in normal operation. In the event of a grid upset the power plant interrupts, and in the event of a serious grid event, disconnects itself and the dwelling from the grid and runs independently. After a suitable delay when the grid returns to normal, the inverter interrupts and grid parallel operation is restored.**

Interconnect: **Fuel cell interconnects to the grid through a fused disconnect. An internal fuel cell disconnect is provided for certain grid parallel upsets and may be provided for certain dwelling grid independent fault clearing events.**

Key Interconnect Issues:
GRID: ***GRID INTERCONNECT re Islanding, Reconnect Timing, etc. Some interest in POWER QUALITY.***
CUSTOMER: ***Potential to substantial POWER QUALITY type issues depending on customer and loads..***

In this instance Power Quality Interconnect would be of interest to the dwelling customer, but not the grid. Of keen interest would be voltage regulation with regard to sags, swells, spikes and other elements, particularly when large loads such as a heat pump compressor are added or removed from the fuel cell power plant's load. Other areas include flicker, harmonics, and any possibly of DC voltage components.

Combination Grid Parallel and Grid Independent

This system would normally run in grid parallel with power flowing to the customer's dwelling and to or from the grid. The direction of the grid flow would depend on the fuel cell power plant's capacity and dispersed generation settings. In it's normal grid parallel mode, the fuel cell power plant would essentially follow the grid's voltage and frequency as long as the these parameters are within preset limits. In the event of a grid upset, the power plant would interrupt and wait for the grid to return to normal.

However, in the event of a serious grid upset or power outage, the system would disconnect the dwelling from the grid and operate in a grid independent configuration. This would be by a built-in automatic transfer device, or by the external automatic transfer switch shown at the bottom of Figure C-2's Electrical Interconnect and Metering diagram. Indeed considering the likely cost of a residential fuel cell even in a mature market, an important if not vital selling point will be the capability for any distributed generation grid parallel fuel cell to be able to provide some type of backup power to the customer in the event of a grid outage such as caused by a hurricane, blizzard, or ice storm.

Also, it is possible that a more mature market power plant could have additional options for co-op or customer use such as grid load displacement. This might use a grid tuning software overlay in conjunction with the existing components, batteries and albeit possibly a smaller cell stack. As a result, a portion of the nightly battery charge could be supplied from the grid as well as the cell stack. Such a configuration would have all of the normal residential fuel cell and dispersed generation advantages in addition to using the fuel cell's existing built-in battery capability to load shift some or all of the customer's load from on-peak daytime to off-peak nighttime grid supply.

Power Quality

Background

Power quality refers to the degree to which the customer's service voltage continuously approximates a normal 60 Hertz sine wave at the expected normal voltage. Of course, some degree of power quality deterioration has always been present on the grid from time to time. Causes include lightning pulses, faults and system recloser operations, and in certain applications voltage drops at the end of long lines and wave form disturbances due to customer loads like welders or arc furnaces.

Power quality has clearly received increased attention in recent years. Interestingly, both the reason for the increased attention, and the resulting customer impact, have a common genesis. Both the cause and the impact arise because of the changes increasingly found in customer loads:

- Over the last two decades, the accelerated use of electronic equipment has combined with government mandated energy conversation policies to significantly change the loads found in commercial buildings. And, to a lesser degree, these same drivers also apply to residences. For example, switching power supplies are ubiquitous and now found in computers, monitors, printers, television sets, microwave ovens, and many other applications. As a result, these devices do not consume power proportionately over the entire waveform but rather turn on and off during segments of the supply voltage cycle. The resulting distorted current draws then combine with normal voltage drops in the local distribution wiring to yield distorted 60 Hertz voltages to other customer loads. Also, electronic ballasts for fluorescent lighting, while increasingly common since they are low in audible noise and high in efficiency, generate similar harmonics.

Moreover, electric motors now consume almost 60 percent of all the power generated in the U.S. and the increasingly common variable speed drives produce substantial harmonics. An added factor is the Energy Policy Act of 1992's mandating of increased efficiency motors. Reducing the stator and rotor losses by increasing the copper area is a key to meeting the resulting standards. However, this concurrently produces inrush starting currents that are as much as 50 percent higher than for normal motors. This can then lead to objectionable sags or voltage reductions on in-house circuits.

- At the same time that customer loads are contributing to increased power quality issues, customer loads themselves are also becoming increasingly sensitive to power quality issues. Examples include the increasingly common home computer and home offices that are now frequently protected with surge suppressors and low-cost UPS systems, the latter is yet another switching power supply. Other examples are interrupt sensitive VCR and electronic clocks, and the more common application of microprocessors in appliances, wall thermostats, and heating/cooling equipment. As a result, increasingly common commercial power quality symptoms include warm, overloaded neutral conductors in three phase systems. This is because many of the harmonics generated by customer loads will not cancel out, but are rather additive, yielding abnormal current levels in neutral circuits.

Thus, power quality has received more attention in recent years as the complexity and impact of customer loads increase. Although power quality is often thought of as an industrial or commercial customer problem, this may spread into the residential sector as the applications of high-starting-current motors increase in high efficiency cooling and heat pump equipment and as customer loads concurrently become increasingly sensitive. In any event power quality is certainly an area that merits review where a stand-alone residential fuel cell is serving a residential load that is isolated from the grid and even where that power plant is running in parallel with the grid.

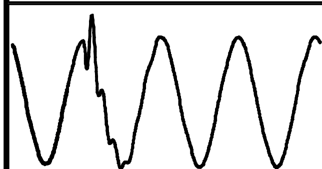
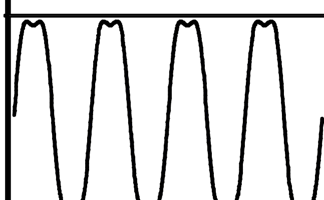
Categorization and Monitoring

Various customer voltage issues such as transients, sags, interrupts, and other types of continuous or transient occurrences are illustrated in Figure C-4's Typical Power Quality Events. Also shown are typical causes and potential mitigating solutions.

An added historic problem in dealing with power quality issues has been assessing and categorizing power quality events in some type of a consistent, repeatable manner. For example, a 10 percent sag could mean an eleven volt decline from a normal 110 volts to a 99 volt line voltage or it might represent a decline to 10 percent of rated voltage which would mean a line voltage of only 11 volts. Fortunately, the IEEE P1159 recommended practice standard, along with work by EPRI and Electrotek, have developed the standardized definitions shown in Figure C-5 that reports Power Quality Event Occurrence definitions. To prevent confusion power quality ranges are also now characterized relative to "pu" or

Figure C-4
Typical Power Quality Events

Power Quality Variation Categories . . .

Example Waveshape or RMS variation	Power Quality Variation and Category	Method of Characterizing	Typical Causes	Example Power Conditioning Solutions
	**Impulsive Transients** **Transient Disturbance**	**Peak magnitude** **Rise time Duration**	**Lightning** **Electro-Static Discharge** **Load Switching** **Capacitor Switchg**	Surge Arresters Filters Isolation Transformers
	**Oscillatory Transients** **Transient Disturbance**	**Waveforms** **Peak Magnitude** **Frequency Components**	**Line/Cable Switching** **Capacitor Switching** **Load Switching**	Surge Arresters Filters Isolation Transformers
	**Sags/Swells** **RMS Disturbance**	**RMS versus time** **Magnitude Duration**	**Remote System Faults**	Ferroresonant Transformers Energy Storage Technologies UPS
	**Interruptions** **RMS Disturbance**	**Duration**	**System Protection** **Breakers** **Fuses** **Maintenance**	Energy Storage Technologies UPS Backup Generators
	**Undervoltages/ Overvoltages** **Steady-State Variation**	**RMS versus Time** **Statistics**	**Motor Starting** **Load Variations** **Load Dropping**	Voltage Regulators Ferroresonant Transformers
	**Harmonic Distortion** **Steady-State Variation**	**Harmonic Spectrum** **Total Harmonic Distortion** **Statistics**	**Nonlinear Loads** **System Resonance**	Active or Passive Filters Transformers with cancellation or zero sequence components
	**Voltage Flicker** **Steady-State Variation**	**Variation Magnitude** **Frequency of Occurrence** **Modulation Frequency**	**Intermittent Loads** **Motor Starting** **Arc Furnaces**	Static Var Systems

Source: Electrotek / EPRI

Figure C-5
Power Quality Event Occurrence Definitions

Typical Power Quality Monitor Definitions . . .

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
Transients			
Impulsive			
Nanosecond	5 ns rise	< 50 ns	
Microsecond	1 µs rise	50 ns - 1 ms	
Millisecond	0.1 ms rise	> 1 ms	
Oscillatory			
Low Frequency	5 kHz	0.3 - 50 ms	0 - 4 pu
Medium Frequency	5 - 500 kHz	20 µs	0 - 8 pu
High Frequency	0.5 - 5 Mhz	5 µs	0 - 4 pu
Short Duration Variations			
Instantaneous			
Sag		0.5 - 30 cycles	0.1 - 0.9 pu
Swell		0.5 - 30 cycles	1.1 - 1.8 pu
Momentary			
Interruption		0.5 cycles - 3 sec	< 0.1 pu
Sag		30 cycles - 3 sec	0.1 - 0.9 pu
Swell		30 cycles - 3 sec	1.1 - 1.4 pu
Temporary			
Interruption		3 s - 1 min	< 0.1 pu
Sag		3 s - 1 min	0.1 - 0.9 pu
Swell		3 s - 1 min	1.1 - 1.2 pu
Long Duration Variations			
Interruption, Sustained		> 1 minute	0.0 pu
Undervoltages		> 1 minute	0.8 - 0.9 pu
Overvoltages		> 1 minute	1.1 - 1.2 pu
Voltage Imbalance		steady state	0.5 - 2%
Waveform Distortion			
DC Offset		steady state	0 - 0.1%
Harmonics	0 - 100th H	steady state	0 - 20%
Inter-harmonics	0 - 6 kHz	steady state	0 - 2%
Notching		steady state	
Noise	broad-band	steady state	0 - 1%
Voltage Fluctuations	< 25 Hz	intermittent	0.1 - 7%
Power Frequency Variations		< 10 sec	

Table Source: Electrotek

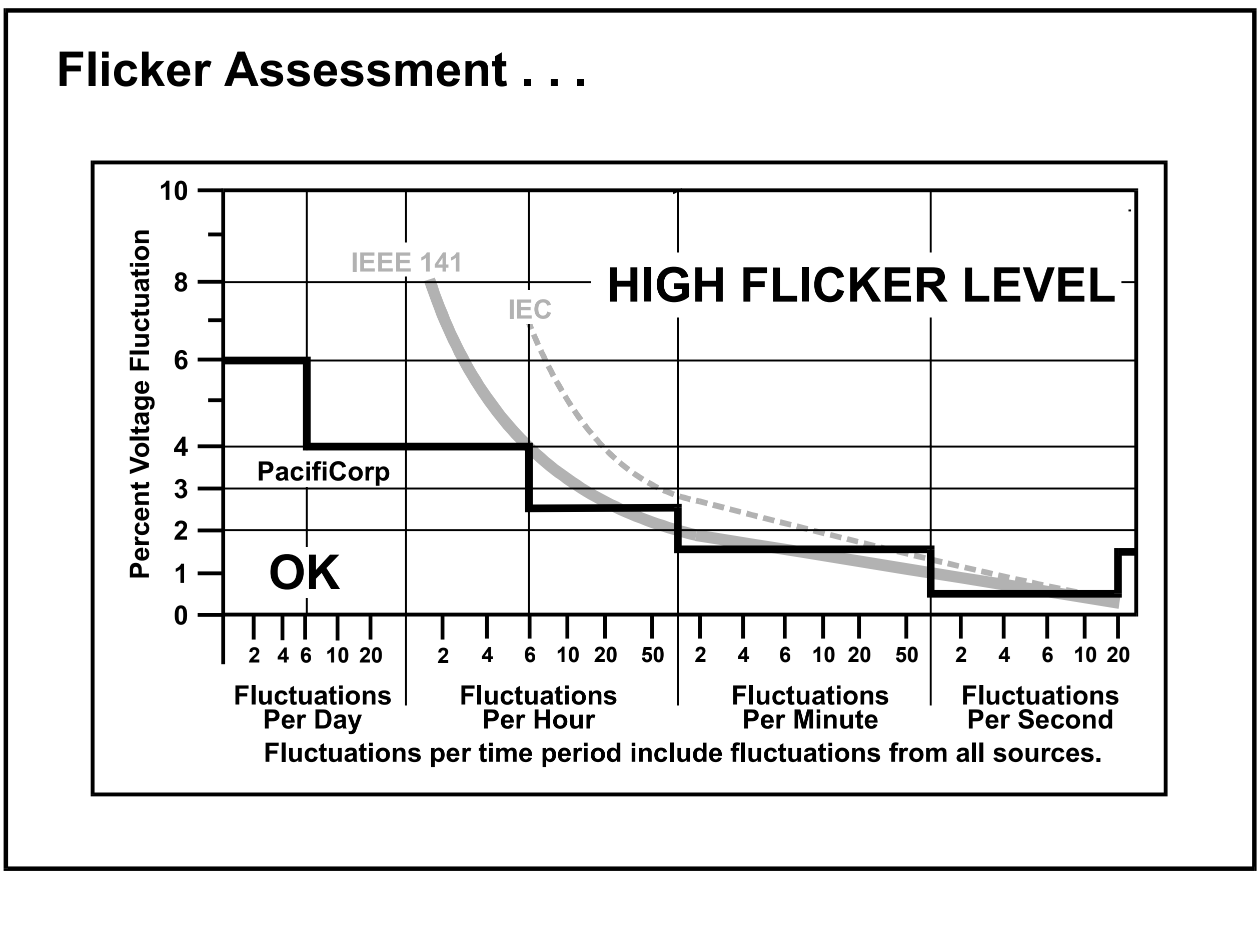
Note: Until recently a 20 percent sag at a nominal voltage of 120 volts RMS might refer to either a drop of 20 percent which is 24 volts yielding a line voltage of 96 volts ...or... alternately to a 96 volt drop to a 20 percent voltage that would be 24 volt RMS line voltage! To prevent this type of confusion modern PQ ranges are now characterized by "pu" or per unit. Thus, a temporary sag of 0.1 to 0.9 pu means, for example, that a nominal 120 volt RMS line voltage has declined to a voltage between 12 and 108 RMS line voltage.

peak unit. For example, a "sag" means that a nominal 120 volt rms voltage has declined by 0.1 to 0.9 pu, or to a voltage between 12 and 108 rms line voltage, that lasts between one-half second to three seconds.

Until recently, monitoring power quality voltage excursions in any kind of a meaningful, comparative manner was also a time consuming, labor intensive process. Trip points would be set for the monitor which would then watch the customer's voltage wave forms and record a series of digital files showing the waveform during various trigger events. The resulting records would then have to be uploaded to a viewing computer were each of the resulting waveforms would be displayed and then hand inspected for categorization and severity. However, the acceptance of common definitions has combined with relatively low-cost high-speed microprocessors to yield another major benefit. Modern, relatively low cost power quality monitors like the $1,800 PowerTronics PQR-1010 selected for this program can now automatically categorize and report power quality events such as sags, swells, interrupts. With minimal prior site effort, premonitoring with the PQR-1010 enables valuable comparisons of customer or grid quality to be made with, and without, residential fuel cell power. Moreover, needed power quality checks can be performed automatically during the demonstration with essentially no user labor and effort. The resulting event output tables from the PQR-1010 can then be downloaded for statistical review. Further details can be found in the Power Quality Logging section on page E-3 of this handbook.

Flicker

Figure C-6
Flicker Occurrence Definitions



Although a difficult to quantify and to resolve, flicker is relatively easy for consumers to recognize. As shown in Figure C-6, Flicker Occurrence Definitions, various curves define the point where periodic voltage variations represent a problem. The original research goes back more than 50 years and is based on using incandescent bulbs for task lighting. The IEEE 141 curve represents a proposed U.S. standard. For example voltage fluctuations of over 3 percent that occur more than 10 times per hour would represent an unacceptable flicker level. The IEC curve represents an active European standard.

Although flicker is usually associated with such items as compressor motor start current draws in residences or arc furnaces in industry, it can also be associated with wind turbines or photovoltaic systems having fluctuating power outputs. However, this is not necessarily felt to be a concern in this fuel cell power plant demonstration. Indeed, to the extent that a fuel cell inverter may have the capability to produce leading or lagging reactive power to rapidly regulate line voltage, such fuel cell additions could potentially enhance overall feeder quality.

Because flicker events can be triggered by voltage reductions as low as a few percent, and the trigger point varies by the frequency of occurrence, flicker measurement requires special equipment. Typical instruments cost on the order of $15,000 to over $20,000. For these reasons and because flicker is not judged to be a particular fuel cell issue, no measurements are contemplated for this program. However, if this changes, the CRN program may contemplate securing a loaner instrument for limited field measurements.

Harmonics

Impact

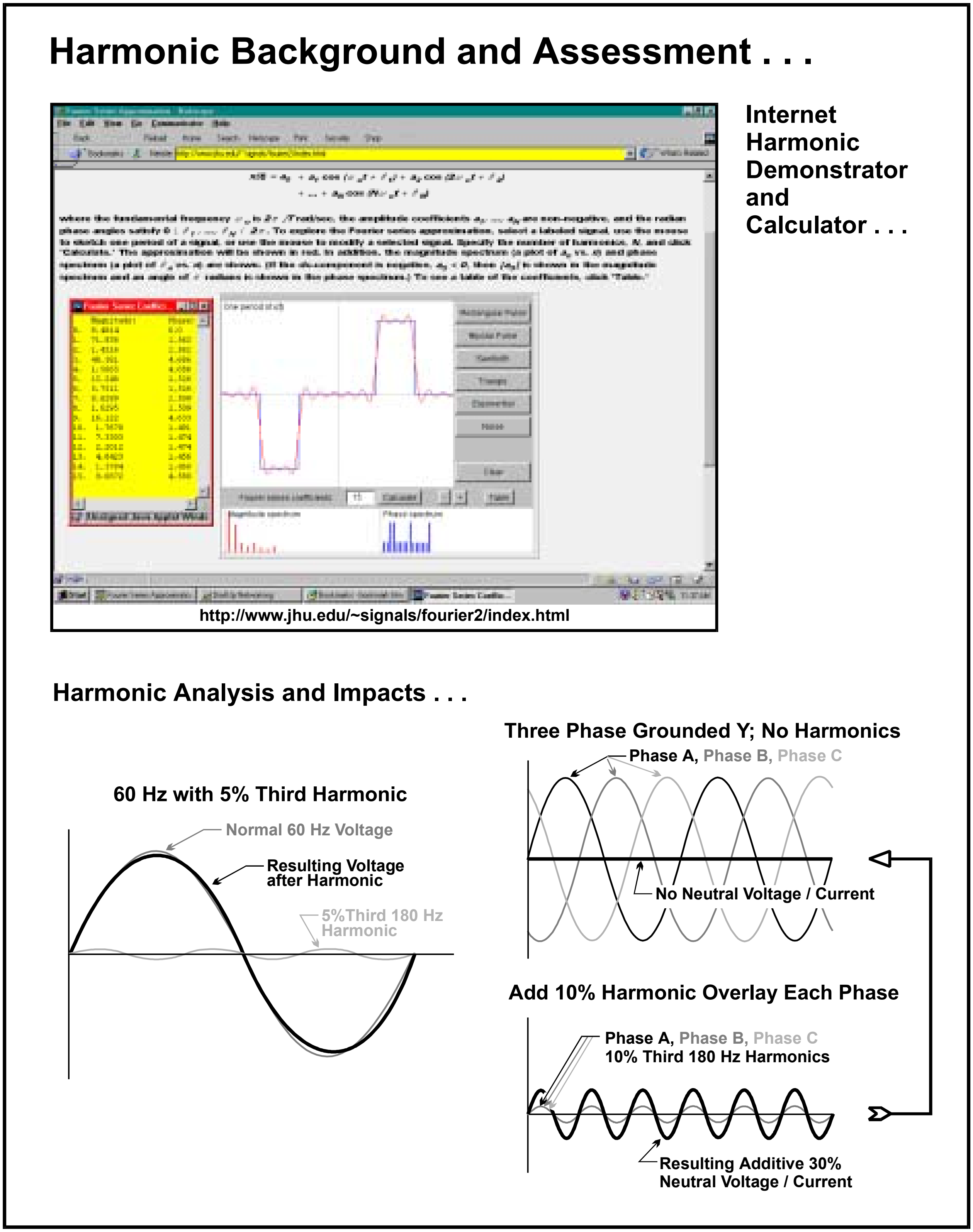
As discussed earlier, switching power supplies in commercial and residential electronic equipment, high-efficiency electronic lamp ballasts, variable speed motor drives, etc. do not draw current uniformly over the voltage wave form. This results in distortions to the normal current and voltage waveforms as shown in Figure C-7 which is Harmonic Background and Measurement. A harmonic is an even or odd multiple, of the primary frequency which is 60 Hertz. Thus, the third harmonic would be 3 times 60 Hertz which yields 180 Hertz and so forth. Indeed it can be shown that any repeating voltage form, even if significantly distorted beyond a recognizable normal sine wave, can be accurately represented by a series of harmonics. Thus, the resulted distorted voltage is the equivalent of the primary frequency and various harmonics of differing amplitudes and phasing that are all added together in the form:

$$\text{Final} = a_0 + a_1 \sin(\theta_1 + 1F) + a_2 \sin(\theta_2 + 2F) + \ldots\ldots\ldots\ldots + a_n \sin(\theta_n + nF)$$

This can be readily seen at the harmonic demonstrator internet site referenced in the upper part of Figure C-7. As that illustration amply demonstrates, even an old fashioned square wave inverter, such as found on some personal computer UPS equipment, can be approximated quite well by a series of harmonics. Indeed as might be expected since a vertical voltage rise or fall is quite a departure from a normal utility sine wave, the resulting square wave is extremely rich in large harmonics.

The top portion of the three phase illustration in Figure C-7 shows a normal grounded Y circuit that is relatively well balanced with no harmonics. Because of this the Phase A, Phase B, and Phase C currents will cancel out and the neutral will carry little if any current. However, if only a ten percent 3rd harmonic is added in the example, due to something like variable speed motor drives, the resulting harmonic current waveforms are actually additive in the neutral conductor. Indeed, one of the symptoms of excessive harmonic power quality problems in commercial installations is the overheating of the

Figure C-7
Harmonic Background and Measurement



neutral due to large harmonic currents. Other symptoms may be hot and noisy transformers, short lived induction motors, and the like. In extreme cases of harmonic distortion, another symptom may be fast running electronic clocks since many of these act as a zero crossing detector of an extra harmonic voltage wave on top of the normal 60 Hertz zero crossing.

Single phase non-uniform loads such as switching power supplies and electronic ballasts are particularly good at generating odd harmonics (i.e.: 3rd, 5th, 7th, 9th, etc.). Of particular concern for three phase installations, as described in Figure C-7, are the “triplen” harmonics such as the 3rd, 9th, 15th, etc. since the A Phase, B Phase, and C Phases of these will all be in phase with each other and thus sum together in the neutral conductor of a three phase system. These triplen harmonics will also cause circulating currents in the delta winding of grid system delta-to-wye transformers. In electric motors, negative sequence harmonics, such as the 5th, 11th, etc. have an opposite phase sequence to the fundamental frequency. They therefore produce opposite rotation fields causing motor overheating and mechanical oscillations.

Measurement

As shown by the 60 Hertz waveform in Figure C-7, even a five percent 3rd harmonic would be very difficult to detect by eye. Thus, the measurement of harmonics typically involves two approaches. The first, and now relatively uncommon approach, is to use an electrical notch filter to physically measure the voltage of the remaining harmonics. Now far more common is the measurement of say 1000 discrete points on the wave form for a period of say 12 cycles or 0.2 seconds. The first step is to solve for the exact fundamental frequency (F). Then, as seen from the earlier formula, each individual harmonic has an amplitude (a_i) variable and a phasing (θ_n) variable. Since t, which is actually a function of F, is known and A is known for each of the 1000 measurements, a series of simultaneous equations of the earlier formula can then be solved to find the values of the amplitude and phasing of each of the harmonics. With the power of modern microprocessors, such solutions can literally be done on the fly by digital recorders costing as little as $1,000 for a single phase harmonics analyzer.

Fuel Cell Inverter Implications

During the 1970’s and 1980’s, inverters which change direct current into AC power typically used low frequency switching SCRs producing square waves that required copious amounts of capacitive filtering. The result was excessively high levels of harmonics on the power output.

However, the modern inverter designs associated with residential fuel cell power plants in the 2000’s are far different. Modern inverters typically have low harmonic distortion. This is because insulated gate bipolar transistors (IGBTs) now dominate inverter designs based on high frequency switching and pulse width modulation waveform generation. Such designs typically satisfy the IEEE 519, Recommended Practices and Requirements for Harmonic Control in Electric Power Systems. Indeed modern well-designed distributed generation inverters can produce a lower distortion than typical utility line voltage. Even so, periodic harmonic measurements will be taken at the residential fuel cell installations to confirm acceptable levels of harmonic quality.

Interconnect Quality

Background

Although interconnect considerations principally concern the utility grid, some components like voltage and frequency control are also important when considering the residential fuel cell’s impact on the host site's own customer. This customer impact is important both when the unit runs in grid parallel and in grid independent configurations as illustrated in Figure C-3's Residential Fuel Cell Interconnect Types and Issues. However, some key interconnect considerations are purely grid interconnect issues such as a grid paralleled unit not islanding in the event of a grid outage.

The fact that the residential fuel cell uses an inverter, sometimes called a static power converter, is an important factor in these interconnect considerations. This is because an inverter has no inertia. It can essentially instantly connect and disconnect to the grid or customer load and does not have frequency stability problems as its loads change. Also inverters will typically contribute lower fault currents. Unlike inverters in the 1980's which used SCRs and produced step wave associated harmonics, residential fuel cell inverters are likely to use pulse width modulation and high frequency synthesis waveform generation with low harmonic distortion. However, to the extent that inverters switch in the 1500+ Hertz range, some generation may exist in the 25th to 35th or higher harmonic frequencies.

Typical Co-op Distribution Configuration

A typical co-op distribution configuration is shown in Figure C-8, Typical Co-op Distribution System and Fuel Cell Interconnect Issues. A typical co-op distribution system is shown in the figure. This is normally a radial system in that it branches out from a single point and only at that original point does power normally feed the system. While there are various types of possible distribution and grounding systems, like three phase unigrounded neutral, one of the most common is a multigrounded neutral system. Here the neutral is grounded every 1/4 mile and at equipment stations such as distribution transformers, capacitors, etc. In the 1930's the Rural Electrification Administration selected this multigrounded design for rural electrification because it provides for lower cost along with the potential for improved relaying of ground faults.

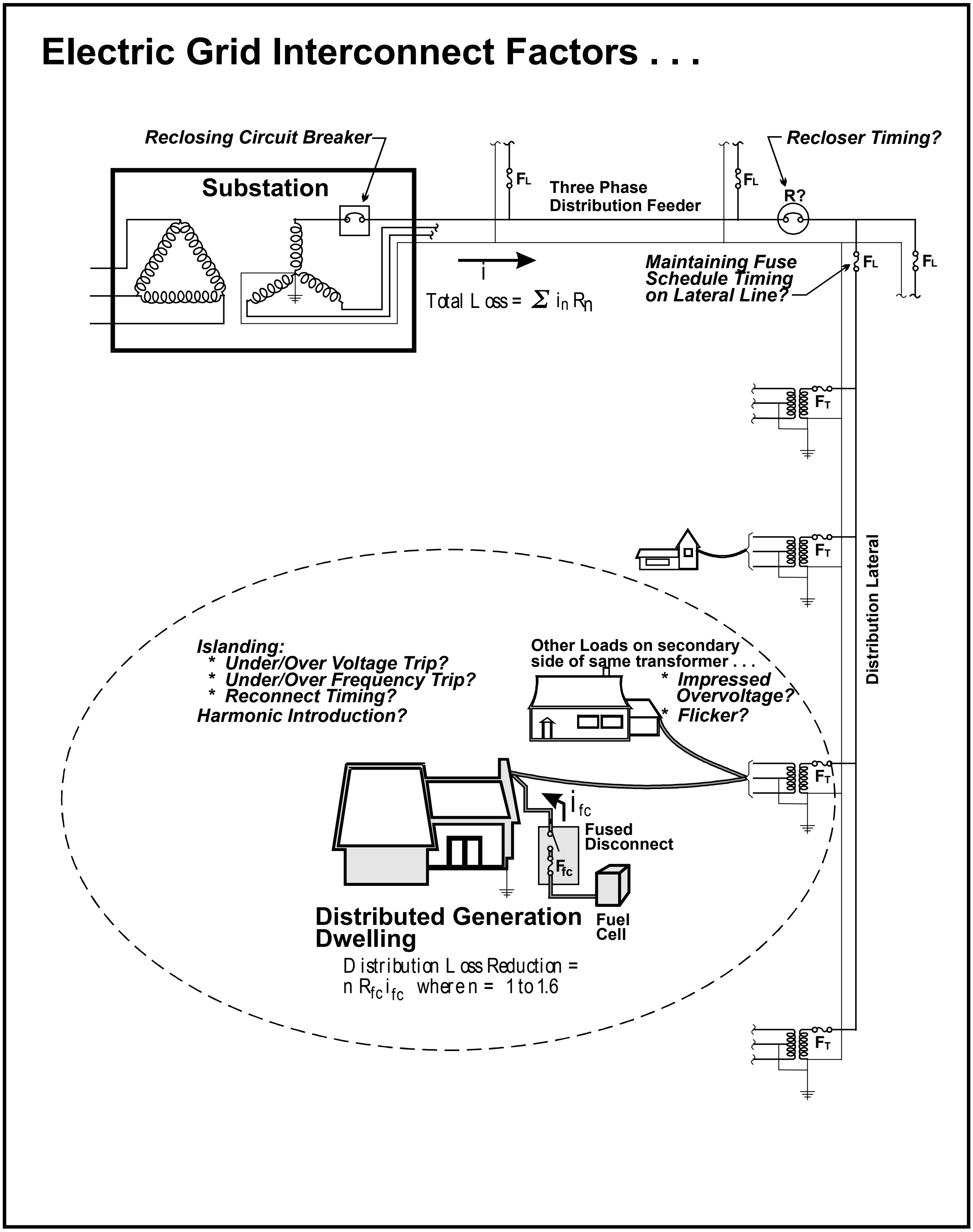
The system consists of a substation that powers a three phase distribution feeder. These primary distribution voltages are sorted in classes like 5 kV, 15 kV, 25 kV or 35 kV. The 15 kV class is by far the most popular and comprises about 80 percent of the circuits within the U.S. Within that class, typical voltages are 12.5, 13.2, and 13.8 kV with a potential normal peak loading in the range of 4,000 to 6,000 kVA, which would be the equivalent of several hundred amps.

Commercial customers are generally supplied by 480-volt three phase transformers either from the main distribution feeder or from a three phase distribution lateral. These feeders and their laterals can be around 3 to 15 miles or longer in length. In addition, a number of single phase distribution laterals powered by one of the distribution feeder phases will also probably exist to supply residential and farm loads.

In either case, distribution transformers then feed individual homes or farms which are typically 120/240 volts single phase for dwellings. In instances where customers are next to, or across-the-road from, each other a single distribution transformer may feed multiple customers. In many instances, a typical co-op distribution system for a residential fuel cell installation would have this three phase distribution feeder supplying a single phase distribution lateral with a distribution transformer dedicated to that particular residential load.

As noted in Figure C-8, one of the benefits of distributed generation may be a reduction of line losses. In effect, this can be viewed as a direct multiplier to fuel cell efficiency. For example, if a fuel cell power plant had a site fuel-to-power efficiency of 33 percent, but its operation concurrently eliminated 10 percent of line losses, then in effect that power plant's apparent efficiency would be 33%/0.9 or 36.7

Figure C-8
Typical Co-op Distribution System and Fuel Cell Interconnect Issues



percent! Indeed the same rules generally apply as locating capacitors. Thus, it is possible to show that optimally placed distributed generation can eliminate as much as 1.6 times its capacity in line losses. However, this presumes a locational flexibility beyond that usually achieved in the real world. Thus, a safer estimate is that no more than the unit's capacity is eliminated in line losses. Even so, this can be an important benefit and impressive improvement in residential fuel cell power plant efficiency, particularly for long heavily loaded distribution laterals where the fuel cell is located at the far end of the line. This poses the consideration, which is already being addressed by a separate CRN program, as to what practices or incentives can be used by co-ops in search of distributed generation capacity to encourage that production at the most helpful points on their distribution system.

Various types of grid connect concerns exist with such a residential fuel cell interconnection. One class of issues relate to the operation of the residential fuel cell in a grid interconnected mode under ordinary circumstances. As noted next to the Distributed Generation Dwelling in Figure C-8, these are normal power quality concerns. These relate to the ability of the fuel cell to successfully interface with the local grid under a suitable range of voltages, frequencies, and harmonics. Because of the advances in microprocessor controls and high frequency switching, pulse width modulation waveform generation inverters, these are not likely to be issues with residential fuel cells although they are discussed in more detail later in this section. A second class of issues are more related to the apparent size of the grid relative to the fuel cell. One important parameter is the relative stiffness of the grid relative to the fuel cell generator.

This stiffness concept, developed in recent years by an EPRI effort, is a good indicator of the degree to which the distributed generator, in this case the fuel cell, can influence the grid. "Stiffness" is in effect the size of the grid fault current available at that point to the maximum rated output current of the residential fuel cell. In this instance the Stiffness Ratio would be equivalent to the sum of the distribution transformer available fault kVA plus the residential fuel cell fault kVA divided by the residential fuel cell fault current. The greater the stiffness ratio, the less likely that the fuel cell can impact the grid.

A set of corollary power quality factors relate more to other customers, if any, on the same secondary side of the transformer although they would also impact the primary residential fuel cell customer. In this case, the applicable measurement is Load Ratio. This is the sum of the average loads for all customers on the secondary side of the transformer divided by the residential fuel cell distributed generation capacity installed on the same secondary side. In this instance some of the concerns would be flicker, impressed overvoltages, or even islanding. Islanding is such a critical issue that it will be discussed in its own segment.

Flicker could occur if there were widely and rapidly fluctuating amounts of power being exported to the grid. As discussed in the earlier power quality segment, this is felt to be much more of a concern from wind system fluctuations than from residential fuel cell installations. Impressed overvoltage would be a rather unusual condition where there are multiple customers in line on the same secondary transformer and where the fuel cell installation is at the far end of the line and where this entire secondary voltage normally runs high. In such a combination and where the dwelling loads are low such as at night, then excess fuel cell export power, if the system had been set up that way at its installation, could conceivably drive the secondary voltage high as it moved power down the secondary line and through the transformer on to the grid. Of course, if the fuel cell controls had been set to fold back power output under high voltage conditions, this problem would be unlikely to occur in any event. These types of application concerns feed into the IEEE Proposed Residential Fuel Cell Interconnect Requirements shown in Table C-4.

System Fault Protection and Islanding

Recloser Operation

Both studies and practical experience indicate that some 70 to 90 percent of the faults on an overhead distribution system are temporary in nature. Examples of these include contact with tree limbs, lightning flashover on insulators or crossarms, bird or animal contacts, conductors swinging together, etc. For this reason, system reliability is greatly enhanced by the universal use of various reclosing devices. An example is the reclosing circuit breaker shown at the substation in Figure C-8. This may be assisted by additional reclosers further out from the substation and is, in any event, backed up by fuses on the distribution laterals (F_L) and fuses at the individual distribution transformers (F_T) such as feeding the fuel cell site's dwelling transformer.

Reclosing circuit breakers at the substation and reclosers out in the system temporarily interrupt power, pause to allow deionization of the arc path, and then reestablish voltage. Reclosers are typically set for up to three tries before locking out the entire radial distribution feeder. Typical operations might be for the recloser to open to protect the system when the set overcurrent is exceeded for a duration of 0.2 to 5 seconds. If the fault is still present the recloser will reopen, wait for a few more seconds for any temporary fault to clear, and then reclose. The second and third closure attempts might be for as long as 15 to 60 seconds depending on how the recloser is set. If the fault is temporary, the event will have cleared and the distribution feeder and laterals will continue to supply all of the customers on it.

Recloser-Fuse Coordination

However, if the fault is permanent and was not cleared by the recloser interrupts, it is obviously undesirable to shut down the entire feeder and laterals because, for example, a pole has been knocked down next to the fuel cell customer in the middle of that distribution lateral. For this reason, each of the laterals contains a fuse (F_L) that is carefully sized to coordinate with the recloser operation. The concepts are two fold: if the fault is temporary the recloser interrupt will enable the arc to extinguish and the system to return to normal without any fuses blowing, but, if the fault is permanent the appropriate distribution lateral fuse will blow during the recloser cycling before the recloser gives up on the third try and locks open. Thus, the setting of the recloser operation and the sizing of the distribution lateral fuses are critical. This is known as coordination.

When the correct fuse link sizes are used in the system, no fuse will be blown or even damaged by a temporary fault beyond it. That means that the recloser will open the circuit at the substation or out on the system one, two, or three times without the fuse links being damaged. However, if the fault is permanent, the first fuse on the source side of the fault will blow during the recloser attempts isolating the distribution lateral with the permanent fault. This is the hallmark of proper distribution circuit reliability planning. Another concern is that voltage adjustment devices may need to be retuned if substantial distributed generation inputs are added downstream thereby increasing applicable customer voltages by reducing feeder or lateral voltage drops.

Residential Fuel Cell Relationship

However, if any significant distributed generation systems were to continue injecting power into the laterals and distribution feeder circuit during recloser openings or fault clearing attempts, those generators will contribute to a low recloser reading of fault currents and combine with the reclosed current to upset the fused link timing. If this were the only issue, a handful of scattered 5 kW residential fuel power plants are unlikely to represent a serious problem. However, if distributed generation has been fostered to materially improve a distribution line's capability, and has been successful at some point in the future in adding significant capacity to a distribution feeder, then a much more complex coordination timing issue will need to be managed.

More importantly, for the safety of co-op personnel and other customers on the grid, preventing a condition called islanding is critical. This would be, for example, where one or more residential fuel cell units on a distribution lateral continue to operate and energize that portion of the grid despite the fact that the related fuse, F_L or F_T, has opened due to a fault or been opened by co-op personnel attempting to service that portion of the distribution system. Thus, in the event of a recloser operation or system or line outage, a residential fuel cell power plant must cease providing power to the system, await a suitable time after the system returns to normal, and then resume where the mode of operation has been set to a grid parallel operation.

Fortunately, since the residential fuel cell power plant produces AC power by means of a non-inertial static power converter, in effect a DC-to-AC inverter, the reaction to a grid upset by a residential fuel cell power plant can be essentially instantaneous. This does not mean that the unit needs to disconnect from the grid, only that the inverter must stop operating when the grid voltage disappears, and must not return to operation until the grid returns to normal after an outage or recloser operation. An example of this type of a design is shown in Figure C-9. This is for the commercially available 200 kW ONSI phosphoric acid fuel cell, which has worked successfully and without any incident through thousands of grid upsets and over 3.5 million hours on electric grids throughout the U.S. and around the world.

Figure C-9, Actual Fuel Cell Interconnect Experience, shows a typical interconnect event for an ONSI 200 kW fuel cell at the Pittsburgh International Airport. This demonstration was a joint effort by the local gas and electric utilities and demonstrated a 480 volt, three phase distributed generation application on the local grid. The digital fault recorder shows the fuel cell inverter's successful response to a local grid upset shown by the arrow on the chart in the Grid Voltage panel. Within a fraction of a cycle, the fuel cell current output has interrupted as shown by the Fuel Cell Current Output. This means that the inverter essentially stopped operation and exporting power. The residual small current waveform during the interrupt from the 490 to 700 ms time marker simply reflects the connection of the fuel cell's outboard magnetics and filters since the unit is still physically connected to the grid although the inverter has stopped producing power. The interruption of power output to the grid is also confirmed by the decline in the Cell Stack Amps as the stack DC output is now being dumped into an onboard load resistor rather than into the inverter that has stopped operating.

The grid returns to normal at about 530 ms and the inverter controls continue to watch the grid for stability. The grid continues to be stable and at 800 ms the inverter resumes dispatch as evidenced by the returned current waveforms of the Fuel Cell Current Output. These are the AC current flows on Phase A, Phase B, and Phase C to that site's 480 volt grid interconnect transformer. If the grid upset had continued for over twenty seconds, the fuel cell would have opened its grid interconnect breaker and upon confirmation that the breaker was open reverted to a grid independent operation that could have then powered an isolated load. If that had been the case, the fuel cell would have continued to power that isolated load until the grid had reliably returned from normal. At that point, if the software permissions had been selected by the customer or grid, the unit would then automatically changeover and resume grid dispatch.

As the chart emphasizes, a fuel cell inverter has essentially an instantaneous response to a grid upset and can stop export power reliably until a grid upset or fault clears. Moreover, since the inverter can accurately distinguish between normal and upset grid conditions and the interrupt can be essentially

Figure C-9
Actual Fuel Cell Interconnect Experience

Typical Fuel Cell Inverter Interrupt Response to Grid Voltage Disturbance . . .

Records from Fuel Cell Power Plant Controller's Own Grid Event Logs

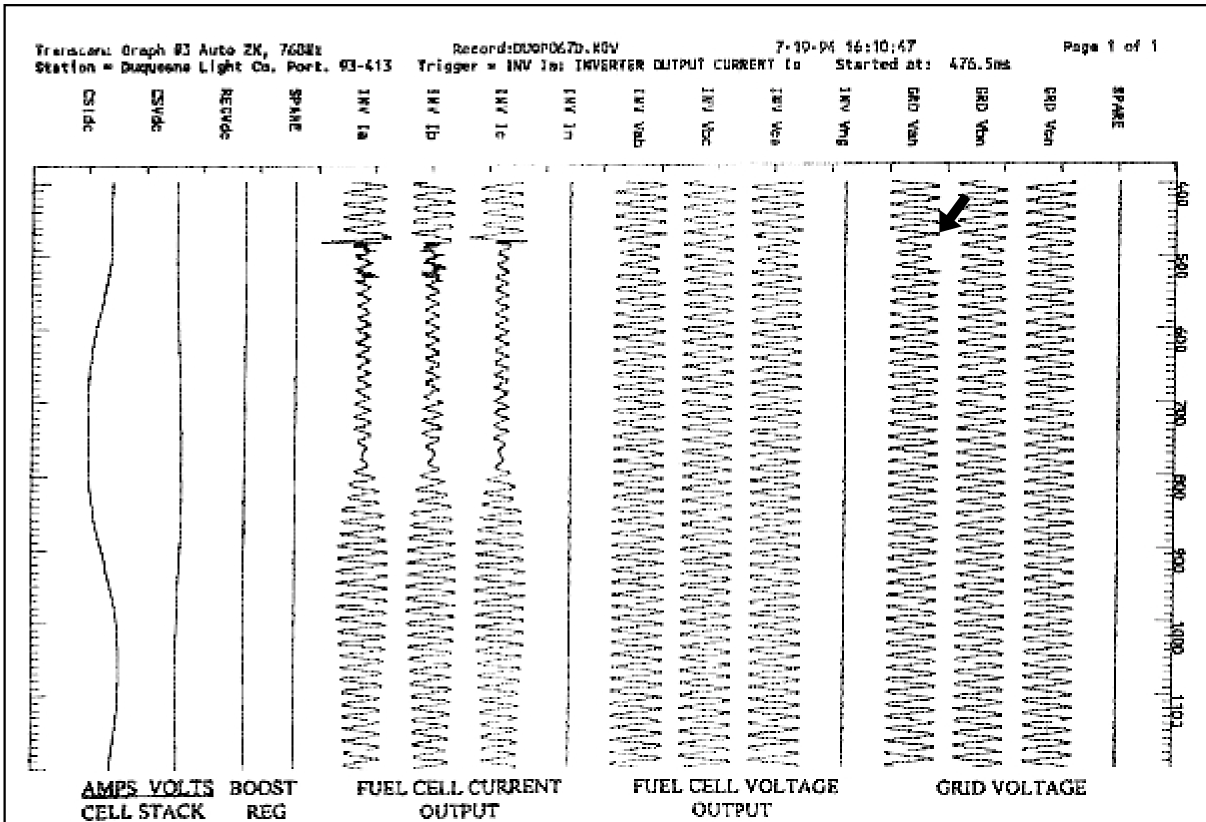
Date	Time	Project Time		FCGridLog
		Clock	Sec	
7/15/94	9:22:07 AM	8,831.42	0	inv Bridge 1 pole overcurrent
7/16/94	10:01:39 AM	8,856.08	0	inv Bridge 1 pole overcurrent
7/17/94	4:34:55 PM	8,886.63	0	inv Bridge 2 pole overcurrent
7/19/94	4:08:31 PM	8,934.19		GRIDOK flag disabled
7/19/94	4:08:46 PM		15	GRIDOK flag enabled
7/20/94	6:57:31 AM	8,949.01	0	inv Bridge 1 pole overcurrent
7/21/94	6:08:36 AM	8,972.19	0	inv Bridge 2 pole overcurren
7/25/94	3:24:19 AM	9,065.46		inv Bridge 1 pole overcurrent
7/25/94	3:24:20 AM		1	GRIDOK flag disabled
7/25/94	3:24:35 AM		16	GRIDOK flag enabled
7/28/94	8:26:48 AM	9,142.50	0	inv Bridge 1 pole overcurrent
7/29/94	7:47:54 PM	9,177.85		GRIDOK flag disabled

TYPICAL GRID FAULT

TYPICAL CONTROLLER TIMED GRID EVENT

TYPICAL GRID CAPACITOR SWITCHING

Electric Utility Digital Fault Recorder Log at Fuel Cell Interconnect



Fault Recorder Log: Duquesne Light

instantaneous, it is not necessarily required that fuel cell units go off the grid for extensive periods of time while reclosers are active. If the recloser sees an abnormal condition, so will the fuel cell and again rehalt grid parallel operation.

Concurrently, it is important that a residential fuel cell have the capability, and permission, to disconnect itself and customer dwelling from the grid in the event of a prolonged grid upset so that the fuel cell and customer dwelling can operate in an emergency powered, safely disconnected grid independent mode. Obviously, any residential fuel cell will be a major expenditure and a key market value to be derived from that purchase by the customer will be power supply security in the event of a grid outage.

Voltage / Frequency / Harmonic Constraints

Although normal grids are remarkably stable, to some degree there is no such thing as a steady state voltage on an electric grid. Both loads and generating capacity are in constant changes of flux. Most user equipment is not particularly sensitive to normal variations although unbalances of over three percent are a potential problem for three phase motors. ANSI, which is the American National Standard Institute, has developed a C84.1 standard that is widely used as the voltage guideline by utilities and their customers. This is summarized on Table C-2's Normal Voltage and Frequency Range.

As shown for a normal 120 volt service, the "favorable" range termed Range A is 114 to 126 rms volts which is plus or minus five percent. The same percentage variation would apply to the 240 volt nominal service. In contrast, the tolerable service voltage, Range B, is 110 to 127 volts which is a variation from

Table C-2
Normal Voltage and Frequency Range

Voltage: (ANSI C84.1)	**Favorable Range (Range A)**	**Tolerable Range (Range B)**	**Minimum Allowable**
120 Volts rms	**114 to 126 volts**	**110 to 114 volts and 126 to 127 volts** (110 = -8.3% 127 = +5.8%)	**108 volts**
Frequency:	**Preferred**	**Allowable Variation**	**Possible RFC Interconnect**
60 Hertz (cps)	**59.5 to 60.5** (+/- 0.5 Hertz)	**58.2 to 61.8** (+/- 3%)	**59.2 to 60.4** (-1.3/+0.67%)

Voltage Harmonics: (IEEE 519-1992)	**Maximum Allowable**
Grid to Customer	
Any Individual Odd Harmonics	**Max of 3%**
Any Even Individual Harmonic	***0.25 x Odd Limit***
Total of All Harmonics (square root of sum of squares)	**Max of 5%**
Distributed Generation Connected to Grid	
3rd to 9th Individual Odd Harmonics	**Max of 4%**
11th to 15th Individual Odd Harmonics	**Max of 2%**
17th to 21st Individual Odd Harmonics	**Max of 1.5%**
23rd to 33rd Individual Odd Harmonics	**Max of 0.6%**
35th or Greater Individual Odd Harmonics	**Max of 0.3%**
Any Individual Even Harmonic	***0.25 x Odd Limit***
Total of All Harmonics (square root of sum of squares)	**Max of 5%**

8.3 percent below normal to 5.8 percent above normal. The minimum acceptable voltage is 108 volts which is 10 percent below normal. Voltages that are in the "tolerable" Range B but outside of Range A, such as 113 volts are considered undesirable and recommended for correction as soon as reasonably possible, but are judged unlikely to cause damage to the customer's equipment.

It should be noted that these measurements are at the customer's service entrance and the voltage at the customer's actual point-of-use may be even lower due to line losses. For example, the normal wiring for a 15-amp circuit might be No 14. At ten amps with an appliance 40 feet from the service entrance, the additional voltage drop would be another 2.5 volts. As implied in the table, frequency requirements are somewhat less structured than voltage guidelines. In general it its felt that distributed generation units, such as fuel cells, should disconnect when the grid frequency goes out range by plus or minus 0.5 to 1.0 percent. This would put the interconnect range at 60 plus or minus 0.3 to 0.6 cycles respectively.

Harmonic restrictions have essentially two types of ranges. The first set of constraints shown in the table are for typical grid inputs to a customer. This obviously assumes that the customer loads itself are not generating harmonics that are feeding back into the grid. The second set are standards for residential fuel cell power plants that are connected to a presumably relatively harmonic-free grid since in effect a grid connected unit has really no choice but to match the waveform already on the grid. Only odd harmonics are shown in the table with even harmonics being more restricted. This is because even numbered harmonics, like the 2nd harmonic of 120 Hertz, can create a DC offset causing saturation in transformers and motors.

Residential Fuel Cell Interconnect Standard

The utility industry and other interested parties including prospective fuel cell manufacturers have been working together to develop an interconnection standard for distributed generation devices like residential fuel cells. This group is hosted by the IEEE SCC21 Standards Coordinating Committee and is known as the P1547 working group. The issues are obviously complex but that effort is well underway. One potential standard is shown on the next page in Table C-3: Potential Standard for Residential Fuel Cell Grid Interconnect. **The rural co-ops have a significant interest in distributed generation and have already developed an interconnect guideline based on the P1547 efforts. This very well written and quite useful guide is known as the Application Guide for Distributed Generation Interconnection and is http://technet.nreca.org/pdf/distgen/DGApplicationGuide-Final.pdf It may be downloaded from the NRECA's Technet site as the above pdf file.**

The resulting fuel cell interconnect standard is relatively straightforward and largely traceable to the grid standards shown in Table C-2. As is the case with the existing 200 kW ONSI fuel cell that has operated for millions of hours of reliable interconnects, the use or microprocessor-based algorithms is a permissible means for accomplishing grid protective functions. Thus, external protective relaying is not a required part of a utility grid interconnect requirement. Also, a suitable isolation method for required grid upset disengagement is for the inverter (SPC) to simply stop switching.

Obviously, a key function of the voltage and frequency interconnect limits is to ensure that islanding does not occur in the event of a grid upset or outage. This has worked well with the existing phosphoric acid fuel cells as evidenced by the digital fault recorder chart shown in Figure C-9. Sandia National Laboratories has developed substantial inverter testing experience, particularly from photovoltaic inverters that are less than 10 kW in size and equivalent to residential fuel cell outputs. Most, if not all, of this experience is directly applicable to residential fuel cell power plants. The only real difference is

Table C-3
Potential Standard for Residential Fuel Cell Grid Interconnect

Class A: 0 to 10 kW Residential Fuel Cell using Static Power Converter (SPC)

Stiffness Ratio at Interconnect µ 100 where:

$$\text{StifR} = \frac{\text{Available Fault kVA at Area Grid} + \text{Maximum kVA Output of Residential Fuel Cell}}{\text{Maximum kVA Output of Residential Fuel Cell}}$$

No other Dwellings on Interconnect Transformer ...or... Load Ratio µ 2 where:

$$\text{LoadR} = \frac{\text{Sum of the Total Individual Average Dwelling Loads (kW)}}{\text{Rated Output of Residential Fuel Cell (kW)}}$$

Protection Requirement:	Method to Meet Requirement:
Anti-islanding protection, synchronization, and other functions needed:	Voltage and frequency relays to detect islanding (27/59 and 81U/O). Manufacturer interrupt or trip settings would be +60.5/-59.3 Hertz for frequency and +132/106 for voltage but can be relaxed at the discretion of the utility to avoid nuisance trips. A manufacturer active anti-islanding algorithm to supplement voltage and frequency protection in the SPC is encouraged but is not required.
Grade of relay:	Utility grade relays, industrial-grade relays, electronic controls or microprocessor-based algorithms internal to the generator are all suitable as long as they meet the stated objectives. External test ports are not required if equipment is proven to be relatively drift free and stable in the long term.
Isolation device controlled by the relay functions:	An SPC may simply stop switching.
Fault protection of the generator:	Molded-case circuit breaker of fuse rated to clear available utility fault current is suitable.
Automatic restart:	Not required but encouraged. If included, it should occur no sooner than 5 minutes following normal restoration of utility voltage.
Utility disconnect switch:	Utility accessible and lockable visible-break, load break switch. Utility accessible removable, lockable plug is acceptable option.
Transformer:	A dedicated transformer is not required.
Data logging, remote control, remote metering, etc.	None required.
Lightning protection equipment:	Not required but recommended in any area with a flash density greater than 5 flashes/km^2/year.

Source: Integration of Distributed Resources in Electric Utility Systems: Current Interconnection Practice and Unified Approach Power Technologies, Schenectady, New York EPRI TR-111489 1989 and IEEE P1547 Resource but as modified by P1547 at http://technet.nreca.org/pdf/distgen/P1547StdDraft05Revised.pdf

Table C-4
Sample Residential Fuel Cell Power Plant Test Procedure

<u>Baseline Interconnect and Performance Testing:</u> Key concerns are the ability of the selected residential fuel cell units to meet manufacturer specifications for efficiency and for stated interconnect protective functions and settings. A sample protocol is listed below.

Initiation

- **Start the unit and run for 72-hours at manufacturer's recommended configuration.**
- **If control algorithms allow, run the unit in grid parallel configuration at stabilized 25-percent cell stack output increments, otherwise at whatever reasonably full output level that the unit's control algorithm allows, while measuring fuel-to-AC efficiency, exhaust emissions, cell stack voltage and current, cell stack inlet-outlet gas composition, etc.**
- **Measure above factors and timing during and after a zero to full load step change until fuel processor output stabilizes.**
- **Measure battery charge profile from a 40 percent battery storage level until bulk charge completion and then at 25 percent inverter load till the initial storage point returns. Calculate overall DC-to-charge and charge-to-AC efficiency losses.**

Grid Independent

- **Measure overall inverter DC-to-AC efficiency, voltage regulation, frequency regulation, and harmonic distortion from zero to full load rating for power factors from 0.3 to 0.7 and for resistive, reactive, nonlinear and composite loads.**
- **Confirm full load rating for 5-hours and overload capability duration for 20, 50 and 100 percent overloads.**
- **Measure sag, voltage regulation, and ability to start as a first load and as a last load, a 3-ton heat pump (nominal 3 Hp, 20 run amps, 105 locked rotor amps) and, if possible, a 4-ton heat pump (nominal 3.5 Hp, 30 run amps, 155 locked rotor amps).**

Grid Parallel

- **Measure overall inverter DC-to-AC efficiency, voltage regulation, frequency regulation, and harmonic distortion from zero to full load rating for power factors from 0.3 to 0.7 and for resistive, reactive, nonlinear and composite loads.**
- **Measure disconnect and restart times using a simulated grid for 50, 88, 110, and 137 percent of normal voltage. Measure disconnect and restart time for frequency over 60.6 Hz and under 59.3 Hz using a slew rate of 0.5 Hz per second. Repeat tests for a resonant LRC load with a Q of 2.5; for resistive loads; for inverter to load ratios of 0.5 and 1.5; and for RC load of 0.94 leading and RL load of 0.94 lagging.**

Other Related as Applicable

- **Measure conducted noise at switching frequencies in the 3 to 300 kHz range.**
- **Measure THD and individual harmonics up to 3 kHz at 100 percent of rated load for resistive and for resistive plus 3-ton simulated heat pump.**
- **Measure conducted EMI and radiated RFI. Note interference, if any, on radio and on projection TV-antenna assembly located at eight feet when powered by inverter.**
- **Measure acoustic noise on dBA and dBC curves at 0.5 meter.**
- **Measure surge protection using steps from 1,000 to 6,000 open circuit volts for 100 kHz ring wave and 1.2 by 50 microsecond pulse, and for an 8 by 20 microsecond 3,000 amp closed circuit pulse.**
- **Optionally operate for 24 hours at full load in chamber at manufacturer's highest rated ambient temperature and for a similar time at idle at manufacturer's lowest rated temperature with full load swing at end of both tests.**

that the inverter in the latter is powered by direct current from a cell stack and battery system; rather than, from a photovoltaic array and similar batteries.

As a result of the Sandia experience and the need for sound assurance that islanding will not occur even at the worst interconnect conditions, the IEEE P1547 will almost certainly include a particularly discerning anti-islanding test protocol. This would be to run that particular test when the inverter is operating into a grid resonant load with a Q of 2.5. Q denotes a relatively high "quality factor" or amount of energy stored in the resonant load. This high level of "ringing" would tend to encourage continued inverter operation into a load. Assuming that the resonant circuit consists of a resistance, capacitance, and an inductance in parallel, then the calculations would be as follows:

$f_{Resonant} = (1 / 2\pi) \times (1 / LC)^{0.5}$ ...or... where f is 60 Hertz: $LC = 0.00000704$

$Q = R \times (C/L)^{0.5}$ ...or... where Q is 2.5: $R = 2.5\ (C/L)^{0.5}$

where C is in Farads, L is in Henrys, and R is in Ohms.

Sandia has a number of interesting pages on their internet site. Co-op personnel desiring further information on anti-islanding interconnect standards and testing procedures are encouraged to review that information.

Of course in addition to interconnect standards, a number of other standards and test information would be useful for residential fuel cell power plants. Areas of interest include such elements as:

- fuel-to-AC efficiency
- exhaust emissions
- load following
- ability to serve heat pump compressor loads
- battery storage efficiency
- voltage regulation and other factors for grid independent operation
- disconnect parameters for grid parallel operation
- conducted line noise at inverter switching frequencies
- individual and total harmonic voltage distortion
- conducted and radiated RFI if any
- acoustic noise
- surge protection using programmed voltage pulse tests
- ambient temperature impacts and operability
- etc.

Thus a number of other factors can influence the suitability of various residential fuel cell power plant designs in typical uses. A sample of a set of potential testing standards is shown in Table C-4, Sample Residential Fuel Cell Power Plant Test Procedure.

Other Application and Installation Standards

In addition several other standards potentially exist for residential fuel cells testing and actual site application. One of these is an ANSI Z21.83-98 equipment testing standard originally developed for the ONSI 200 kW fuel cell power plants. This AGA-UL type testing standard applies to "packaged, self-contained or factory matched" packages of integrated fuel cell power plants sized less than 1000 kW. Thus, this standard could conceptually be used for testing of residential fuel cell power plants. However, Z21.83 is not a building code standard and does not speak to the integration of the fuel cells with a site or customer's building.

DoE has developed a National Evaluation Service protocol for residential fuel cells to assist this site code implementation progress. Such national code protocol reports, while voluntary and advisory, are used by over 15,000 building regulation authorities throughout the U.S. to verify compliance with building codes.

Section D: Fuel Cell Water Supply and Interconnect

Fuel Processing

Water Need

A fuel cell operates much like a battery in that an electrochemical reaction produces direct current power. However, unlike a conventional battery, a fuel cell does not run down or need recharging. This is because additional chemical "fuel" is being continuously supplied to the cell stack in the form of hydrogen.

The hydrogen is supplied by a reformer that reacts the power plant's inlet hydrocarbon fuel with steam over a bed of catalyst pellets in the range of 1400 to 1600 °F. In addition to the energy to heat the water and fuel feedstock to that temperature, the conversion itself into hydrogen consumes heat. This heat is supplied by burning either additional fuel or the unreacted spent fuel from the cell stack, and then transferring the heat into the reformer's catalyst bed to maintain its needed operating temperature.

Reactions within the reformer are:

Reformer Reactions:

$$CH_4\text{ (methane)} + H_2O \longrightarrow 3H_2 + CO$$
$$CO + H_2O \longrightarrow H_2 + CO_2$$
$$\overline{CH_4\text{ (methane)} + 2H_2O \longrightarrow 4H_2 + CO_2}$$

net heat requirement at ~1600 °F is about 25 percent of input fuel.

As the formula illustrates, two molecules of water (H_2O) are required for each molecule of methane (CH_4) in the natural gas reformer feedstock. Although this example is for natural gas, similar conversions exist for propane (C_3H_8) and for methanol (CH_3OH) which are other common feedstocks for fuel cell power plants.

In actual practice, the carbon in the above reactions will not go all the way to completion to carbon dioxide (CO_2) and various percentages of carbon monoxide (CO) will be formed. This creates a real concern since CO levels as low as 0.001 percent can reduce the cell stack activity, either temporarily or permanently. This is because CO tends to preferentially occupy the reactive sites on the platinum catalyst treated cell stack electrodes that the hydrogen (H_2) needs to make the fuel cell's electrical production occur. As a result, various techniques are used to complete the reaction including lower temperature postprocessing or even porous metal membranes that allow hydrogen, but not CO, to pass into the cell stack.

This final reformer product is then sent to the cell stack where the hydrogen portion is converted into electricity and byproduct heat:

Cell Stack Reactions:

Anode $$4H_2 \longrightarrow 8H^+ + 8e^-$$
Cathode $$2O_2 + 8H^+ + 8e^- \longrightarrow 4H_2O$$
$$\overline{2O_2 + 4H_2 \longrightarrow 4H_2O}$$

About 50 percent conversion to DC power with balance of output as heat at ~170 °F

The anode is the fuel side of the cells; the cathode is the air side where the oxygen is supplied by an air blower to the stack. The end result from a water balance viewpoint is that two molecules of steam ($2H_2O$) needed by the reformer combine with the hydrogen atoms in the methane (CH_4) to ultimately produce four molecules of water ($4H_2O$) at the cell stack's exhaust. As a result, the fuel cell is a net water generator because the oxygen in the cathode air combines with hydrogen from the methane fuel.

Sources and Requirements

Water can be recovered from the cell stack exhaust for recycling to the reformer. The required equipment would include: a condenser, water storage tank, feed pump, pretreatment cylinder, possibly a degasifier to remove the CO_2 present in the system, and perhaps a boiler blowdown. Many, if not most, of the demonstration residential fuel cells have, or at some point are planning to have, a water recovery system. Even so, a water connection has been specified by most of the demonstration units to provide water for at least maintenance needs or during low water recovery periods such as unusually hot ambient temperatures.

Manufacturer specifications are still being defined but should be available in the future. In the interim in instances where water recovery is not practiced or not yet available, site water use can be estimated by using the fuel cell's imbedded thermochemical reactions. This calculation is based on 25 percent of the natural gas input being used directly or indirectly to supply needed heat to the reformer with the balance of the natural gas converted with steam in the reformer to make hydrogen consumed by the cell stack. These calculations assume a 50 percent extra steam ratio to drive the reformer and post-reformer fuel processing reactions further to completion. This is to minimize CO feed to the fuel cell since even moderate levels can "poison" the cell stack.

Gallons per Day = 3.14 x kW average output

Example: A fuel cell has an average load of 3 kW during overall day-night operation and has none, or an inactive, water recovery system. Thus, the resulting water use by the fuel cell power plant for that entire 24-hour day would be 9.42 gallons.

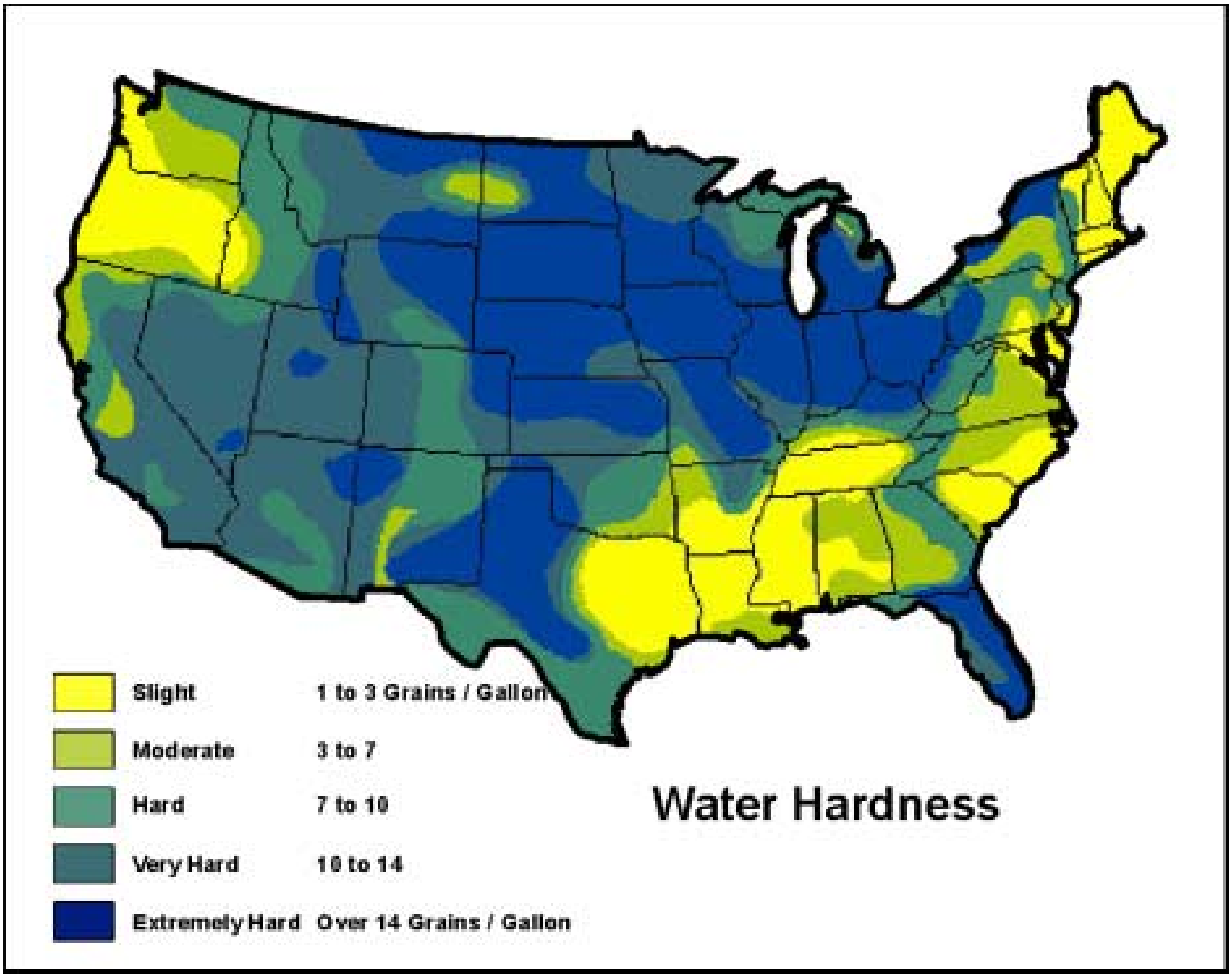
Even where water recovery is not used in a power plant, these results indicate that fuel cell water use is small compared to the normal water use of a residence. A typical estimate for residential water use is 80 to 100 gallons per day per person. Thus, a residence could be expected to consume around 160 to 400 gallons of water per day. Therefore, even if a fuel cell power plant does not utilize water recovery, fuel cell use would represent a relatively small, one or two percent increase in water use.

Water Quality Impact

A shown in Figure D-1 on the next page water hardness varies significantly across the country. Moreover, even a moderate hardness of 3 grains of weight of $CaCO_3$ per gallon leaves behind substantial amounts of irremovable scale in a teakettle over time. There are 7,000 grains in a pound and a gallon of water weighs 8.33 pounds. Thus, a fuel cell running at 3 kW for a year using untreated external water would contain an unworkable 1.5 pounds of solids inside the power plant at the end of the first operating year.

In contrast, recycled recovered water within the power plant would have about 0.4 grains of hardness prior to being run through any internal water demineralizer cylinder. This would be from dissolved CO_2 from the power plant exhaust and from contaminants in the air. A demineralizer captures positive and

Figure D-1
Water Hardness Map of the United States



negative dissolved elements in the water by binding them in active zeolite resins. When the resin is "full" it is either replaced or can be regenerated with caustic and acid in large industrial systems. Another option is to use a residential-type reverse osmosis system which uses a permeable membrane to separate the inlet water into treated and "solids rich" effluent streams.

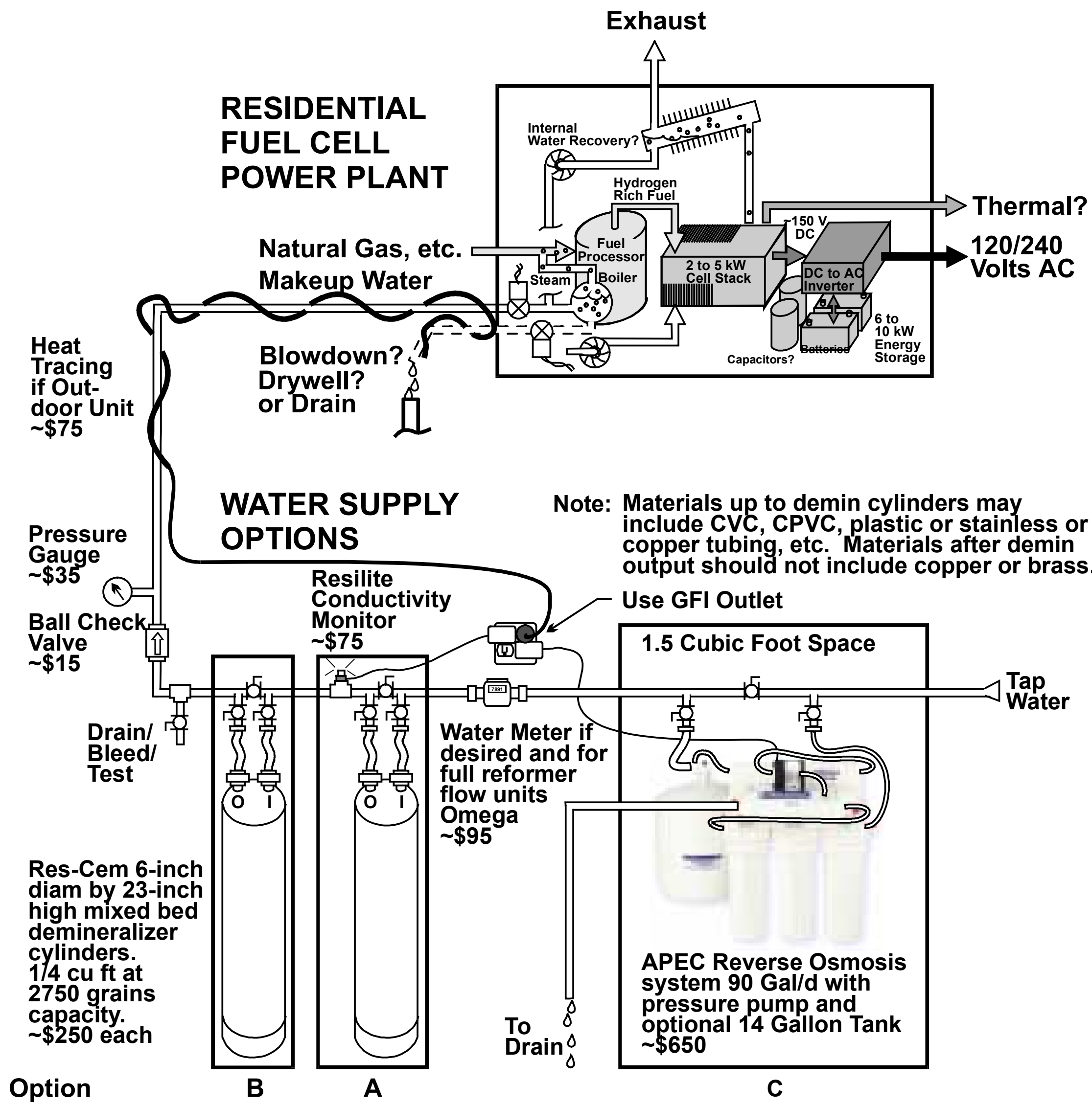
After demineralization of the recovered internal water, or pretreatment of tap water supplied to the power plant, the water feed to the reformer would be 1000 times cleaner than tap water and about 0.003 grains per gallon. Thus, either demineralized recovered water or similarly treated tap water is important in maintaining long term operation of the power plant.

Fuel Cell Water Interconnect and Options

As shown in the Figure D-2's illustration of Power Plant Water Supply and Treatment Options, various site water treatment options exist. The choice of which to use for the demonstration depends greatly on whether or not the demonstration power plant recovers water produced in the cell stack for reuse. A

Figure D-2
Power Plant Water Supply and Treatment Options

Water Supply and Treatment



Cases	Use the Following Options
Power Plant design has internal Reverse Osmosis to treat external water supplied to unit	Tap Water
No Water Recovery inside Power Plant; High Hardness or Silicates in tap water	Option A plus Option B with Option C Suggested
No Water Recovery inside Power Plant	Option A plus Option B
Partial Water Recovery inside Power Plant	Option A Suggested
Substantial Water Recovery inside Power Plant	Tap Water; But Option A Suggested

second factor is the water quality at the proposed demonstration site. A relatively inexpensive $300 water test should be a final confirming element of the site selection process as this information is useful as demonstration data even if a water test is not part of the manufacturer's suggested installation planning.

The amount of actual water use at a residential fuel cell demonstration site depends on several factors:

- whether or not the power plant recovers cell stack water product for internal reuse,
- the amount of water being recovered relative to the amount that is required by the power plant reformer, and
- whether or not a reverse osmosis system is part of the water treatment process either at the site installation or inside the power plant.

The last area impacts site water use because reverse osmosis works by feeding tap water against one side of a permeable membrane. About 25 to 33 percent of the water passes through the membrane as treated water; the balance which then contains the more concentrated solids is discharged to the sewer or ground. Thus, although such a system has a number of advantages including a reduced cost because of the longer life of any downstream demineralizer cylinders, a reverse osmosis system will multiply the fuel cell water requirements by a factor of 3 to 4 over that calculated earlier.

One reason for using a site reverse osmosis system, shown as Option C in Figure D-2, where an external supply is required is that it can significantly extend demineralizer life where the tap water is extremely hard. Also, a reverse osmosis unit is a good way to remove large quantities of silicates as might be found in the Southwest. Unremoved silicates can cause very serious boiler problems. A 1/4-cubic foot demineralizer cylinder would cost on the order of $90 to refill with new resin after it reaches it's capacity to absorb water impurities. This Figure D-2 on the previous page describes these various options and when they might be best utilized.

The life of the resin in the demineralizer cylinder can be estimated as follows:

$$\text{Days of Life} = \frac{\text{2,750 Grains Capacity per 1/4 cubic foot resin fill}}{\text{Gallons per Day Water Use} \times \text{Grains per Gallon Hardness}}$$

Example: A fuel cell has an average load of 3 kW during overall day-night operation and has none, or an inactive, water recovery system. As calculated in the earlier equation , the resulting water use by the fuel cell power plant for that entire 24-hour day would be 9.42 gallons. Assuming a water hardness of 8.5 grains per gallon, the resulting life per resin cylinder would be [2750/(9.42 x 8.5)] or 34.3 days. Based on $90 of labor and material to refill the cylinder, the resulting annual cost would be $958 a year.

Under these conditions, the Option C reverse osmosis unit in the illustration would make sense in both dollars and minimizing site labor. If the reverse osmosis unit improves the tap water by a conservative factor of twenty, then the life per cylinder would increase to well over two years and the annual cost for resin refills would decrease to $45, a savings of $913 per year. This would rapidly pay for the $650 purchase price for a site's reverse osmosis unit. Of course, a tradeoff is that the water consumption of the system would be around 38 gallons per day, on the order of four times larger, due to the reverse osmosis discharge.

Water Quality Testing

As indicated earlier, a water test should be part of the final site selection process for any fuel cell power plant having a site water connection line. This is particularly important where the power plant does not recover all of its needed water supply and, in such instances, is crucial for sites using their own water well. One option for this testing is to use a specially developed $355 sampling kit using protocol developed for this CRN demonstration program. These details may be found as part of the Site Selection Letter Report. Of course, this test source is developed for the convenience of the co-op participants and similar tests may be secured through various local sources, or perhaps even from local county or state agencies. If the site supply is from a local water company, most if not all of this test data should already be available.

This type of water testing is recommended because a number of additional water factors can impact fuel cell power plants that rely on some type of intermittent or continuous site water supply, particularly from water wells. For example, silicates can leave troublesome deposits inside the fuel cell and, without special prefiltering, can also plug any reverse osmosis membranes involved in power plant or in site water pretreatment. Iron compounds may cause problems and the related bacteria sometimes found with iron-rich well water can actually plug various pretreatments like reverse osmosis, softeners, and demineralizer resins. It also potentially possible to introduce sulfur-containing compounds with the water that could damage reformer or cell stack catalysts.

Some of these water factors should be well recognized by the fuel cell powerplant suppliers; others may be less well known. Even if troublesome compounds are identified, front end well water filtering or some type of demineralizer and/or reverse osmosis pretreatment is relatively simple and straightforward as shown in Figure B-2. The water test results should be forwarded to the manufacturer for a fuel cell connected to site water supply and the manufacturer specifically charged with developing pretreatment recommendations, if any.

Section E: Fuel Cell Metering and Instrumentation

Introduction

The residential fuel cell's input, output, efficiency and power quality need to be verified as part of the demonstration program. The related metering also provides a valuable cross-check on information collected by the power plant itself and can serve as a useful troubleshooting supplement. Fortunately, the related metering and the data collection will be unintrusive and a relatively small part of the overall demonstration cost.

Site Reporting

Site Service Logbook or Diary

Before discussing more high-tech portions of the data collection concepts imbedded in the demonstration program, the most important data collection device will actually be a simple logbook or site diary. A bound logbook or diary should be purchased and placed in a permanent spot at the site near the fuel cell when installation begins. This can also be an invaluable help with any future field troubleshooting.

Monthly Meter Readings

Monthly Meter Reading forms will be provided to each participant for the collection of standard data such as fuel consumption, electric output, hours operated, availability, and related data. This spreadsheet will have a simple one-time setup to incorporate meter calibration factors, index rollovers, fuel heating values and similar factors. Upon posting monthly data, the spreadsheet will automatically calculate monthly heat rates, imputed availabilities, and the like.

Service Reports

Service Report forms will also be provided for reporting: interconnect issues, scheduled or unscheduled maintenance, shutdown causes, service hours worked, evaluating manufacturer response and parts availability, and related site call information. In addition to being a useful site log and troubleshooting reference, this straightforward form provides a low-effort means to collect key reliability and service incident data.

Upon forwarding of a copy of this Residential Fuel Cell Service Report to EnSig, the information will be put into a searchable data base like MS Access. In addition to searching for types of incidents and user assessments of manufacturer or equipment performance, the data base will automatically calculate key demonstration results such as raw or corrected Mean Time Between Forced Outage, Mean Time to Repair, and availabilities.

Data Collection Systems

Instrumentation Equipment Selection

In developing the supporting CRN demonstration metering and data collection program, the criteria were moderate cost, good reliability, reasonable accuracy, and easy implementation. The resulting major components are highlighted in Table E-1. As shown on the next page, the system basically starts with normal utility meters plus a Btu meter for thermal recovery. Pulse outputs add energy logging and an automated Power Quality monitor adds interconnect and customer interface monitoring. Outdoor ambient temperature will also be logged by the unit.

Table E-1
Demonstration Metering, Instrumentation, and Functions

Meter or Equipment	Function
Gas or Fuel Meter w pulse output Electric Meter w pulse output Btu Meter if thermal recovery used	Measure energy input to fuel cell Measure power output from fuel cell Measure any usable thermal energy from fuel cell
UltraLite 1T/3P Logger with three pulse inputs plus outdoor temperature ~$715	Log above pulse readings on an n-minute basis so as to: -measure power plant efficiency -understand power plant operating pattern (stack vs bat) -record the site's electric load profile and the fuel cell power plant's response
PowerTronics PQR1010 power quality reporter 2 ch volt, 1 ch amps, temp, etc sag/surge/impulse/freq/etc automatic report by type, etc 1500 event storage per channel ~$1800	Log power quality interaction between fuel cell and dwelling using standard or user set triggers. Download at site with laptop serial port or plug-in external modem can be added for remote download. Software will categorize events and report by pie charts, graphs, text, tables, etc. Win95 based with cut and paste to conventional windows software including spreadsheets.
Fuel Cell Output Bus, etc. - 110 VAC Hour and Tenths Meter - 110 VAC Counter Self-pwrd - Since-installation Clock Timer ~$160	Accumulate power plant operating hours, shutdown or interrupt counts, and shutdown lengths. Self-powered timer duration since installation enables convenient availability calculations on site. All of these timers are inexpensive and stocked by Grainger.
Fuel Cell Output Bus, etc. - Periodic harmonic measurements at commissioning, 2,000 hours and every 4,000 hours thereafter.	Planning is for participants to use their own existing instrument. If none generally available, CRN will purchase or lease suitable instrument which can be loaned from site to site during the program.

Energy Use Logging

The resulting meter pulse logs can be easily downloaded into the serial port of a laptop in a few minutes at the site. This would be once each month when the fuel cell's gas and electric meters are read. These downloaded logs are readily importable into an Excel spreadsheet for analysis and review. The 1T/3P UltraLite Logger is a moderate cost $715-unit that is ready to go including download cable, temperature sensor, etc. It is self-powered with a three-year life battery that also wets the pulse contacts. Thus, no additional wiring is needed other than simple twisted-pairs to the meter pulse outputs.

Telephone modems have not been included in the base systems because they add cost and complexity. Also, such modems would need to share a line with the fuel cell and other equipment thereby requiring something like an added $170 Viking PDF telephone line director for multiple on-site modems to share a single telephone line.

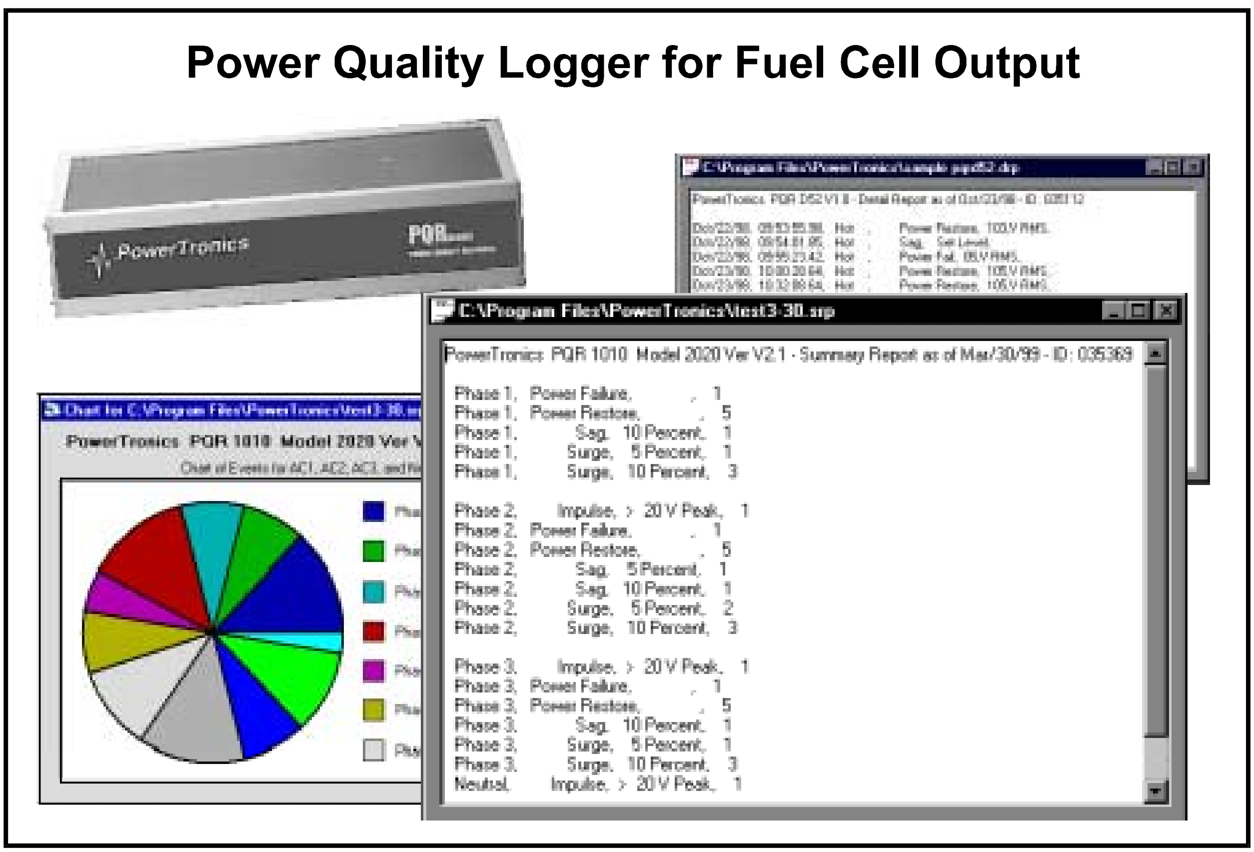
Power Quality Logging

Until recently a major difficulty in power quality (PQ) analysis at ordinary customer sites was the cost and complexity of conventional Digital Fault Recording equipment. Furthermore, this was significantly magnified by the extensive technical labor to pull-up each individual event record and then analyze its waveform trace. In addition, the results from such a record analysis approach were not particularly repeatable since they depend on individual interpretation as to what is a sag, swell, flicker, etc.

As a result of increased interest in power quality by both electric suppliers and customers, significantly less expensive systems with automated analysis are now available. The selected $1,800 PowerTronics unit is an automated, line-powered system for installation at the customer's main circuit breaker panel on the fuel cell's bus before the automatic transfer switch.

The PowerTronics logger detailed above in Figure E-1 has preset limits for recording events such as: impulse voltages, sags, surges, dropouts, power failures, high frequency noise, and line frequency events. Included is an AC/DC current probe which should be used on the line likely having the largest dwelling load or loads. Since the logger has a built-in temperature channel, an indoor ambient temperature can also be logged by the unit. Monthly PowerTronics records can be easily loaded into the serial port of a laptop in a few minutes.

Figure E-1
Power Quality Monitor and Sample Output



Section F: Residential Fuel Cell Application and Markets

Introduction

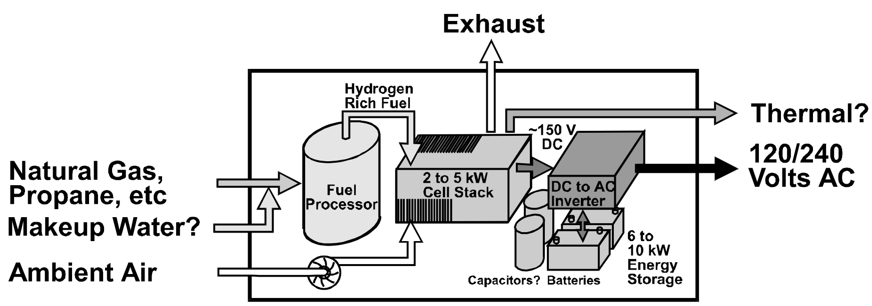
Technical Issues

Two basic types of risks are inherent in any residential fuel cell endeavor. One portion of the issues associated with residential fuel cells are *technical*, and can therefore be readily assessed by gas and electric meters and by calculations of reliability and availability. These risks are principally associated with the cell stack, a high value component having both life and potential catastrophic failure risks. For example, 40,000 hours or more is considered necessary for an economic cell stack life. However other equally important elements are fuel processor design and life, inverter operation, and battery life, among others.

This section addresses equally important, but harder to define, elements such as residential fuel cell application and markets. These *application-price-market-business* issues will be just as, if not, more important in assessing residential fuel cell technology and its future.

Figure F-1
Key Residential Fuel Cell Issues

Components and Issues of Residential Fuel Cells . . .



Issue is Not will RFC's work but how long will they work . . . and . . . Price / Markets?

- Life and aging of cell stack
- Reformer life and response
- Reformer load following
- Reliability and maintainability
  - MTBFO
  - Duration of repairs
  - Quality of Mfgr support
  - Availability of ordinary personnel to service
  - Likely cost of service for a mature product
- Can Mfgr's deliver on production-cost curve
- Application economics vs typical customer size
- Market profile
  - Customer types and prospects
  - Early entrance markets?
  - Can early applications transition to mature markets and costs?

Application and Market Risks

Residential applications pose difficult challenges. The resulting 4 to 10 kW fuel cell power plant equipment is much smaller in capacity and higher in unit cost than that required for commercial building or transportation applications, which are in the 50 to 200 kW size range. Thus, the capital cost of the equipment is relatively high; plus, the ratio of average to peak use of a typical residential consumer connected to the power plant is low.

Because of their relatively small 2 to 5 kW cell stacks, residential fuel cells can not achieve reasonable costs by the traditional economy-of-scale associated with industrial applications. For example each time the size of a piece of equipment is doubled, the cost per unit output, such as dollars per kW of capacity, typically decreases by about 20 percent. Since residential fuel cells cannot be large, the manufacturers' plans are typically to build a lot of units and thereby drive the price down by "economies-of-production" rather than by "economies-of-equipment size".

Thus, a key component of fuel cell application risk is whether or not the manufacturer can achieve projected targets for sales versus price. To achieve commercial market pricing, hundreds, if not thousands, of units will need to be produced and sold by a manufacturer. Misassessed customer needs or cost sensitivities, under-implemented market plans, and/or missed production cost goals can have a major impact on technology viability. So to can reliability (MTBFO) and service repair costs, as well as customer acceptance issues.

Residential Fuel Cell Economics

Table F-1
Typical Mature Market Customer Cost Estimate by Manufacturer

- **$4,000 installed cost**
- **ten year life**
- **9 percent cost of capital**
- **33 percent efficiency HHV = 36.6% LHV**
- **99.9 percent availability = 8.8 hours per year**
- **1 service call per year @ $200 = 1.1 ¢/kWhr.**
- **$5.00 natural gas**
- **25 percent of water heating thermal recovery**
- **2 kW average load = 17,502 kWhr per year**

RESULTS...

Annual Capital Cost	**$623**	
Fuel Cost	**905**	
Maintenance Cost	**200**	
Thermal Recovery Credit	**-130**	
Total	**$1599**	**= 9.1 cents per kWhr**

. . . but . . .

Some Alternate Sensitivity Estimates if Projections Not Achieved

• **$4,000 installed cost and ten year life = Above Case**	**+0.0 cents per kWhr**
• **$7,000 installed cost and six year life**	**+5.4**
• **$7,000 installed cost and six year life and 15% cost of cap**	**+7.0**
• **with 1.4 kW average load instead = 12,251 kWhr per year**	**+1.7 to 13.7**
• **Propane at $10.00 per million Btu**	**+4.5**
• **Two service calls per year at $300 each**	**+2.3**
• **No thermal recovery**	**+0.8**
• **99 percent availability = 3.6 days down per year**	

Overall residential fuel cell customer economics are shown in Table F-1 on the preceding page. Because of the magnitudes and sensitivities of the above costs, an understanding of market applications and the related user's needs are critical.

Customer Application

Customer Economics

The customer's average annual load is a key element in determining comparative fuel cell economics. Results are shown below as a function of customer electric load. This assumes a $4,000 installed cost, a 10-year life, and a 9 percent cost of capital. The fuel is assumed to be natural gas at $5.00 per million Btu.

Table F-2
Customer Economics as a Function of Average Annual kW Use

Customer Annual Cost	**=**	**$623**	**Annual Capital Cost**
		+ 200	**Maintenance Cost**
		-??	**Thermal Recovery Credit**
		$823	**+ Fuel Cost**
	=	**$823**	**+ ($0.052 x kWavg x Operating Hours per year)**

Thus, at $5.00 gas:

$$\text{¢/kWh} = \frac{\$823}{\text{kWavg} \times 8760 \times \text{Availability}} + 5.2$$

$$= \frac{9.4}{\text{kWavg}} + 5.2$$

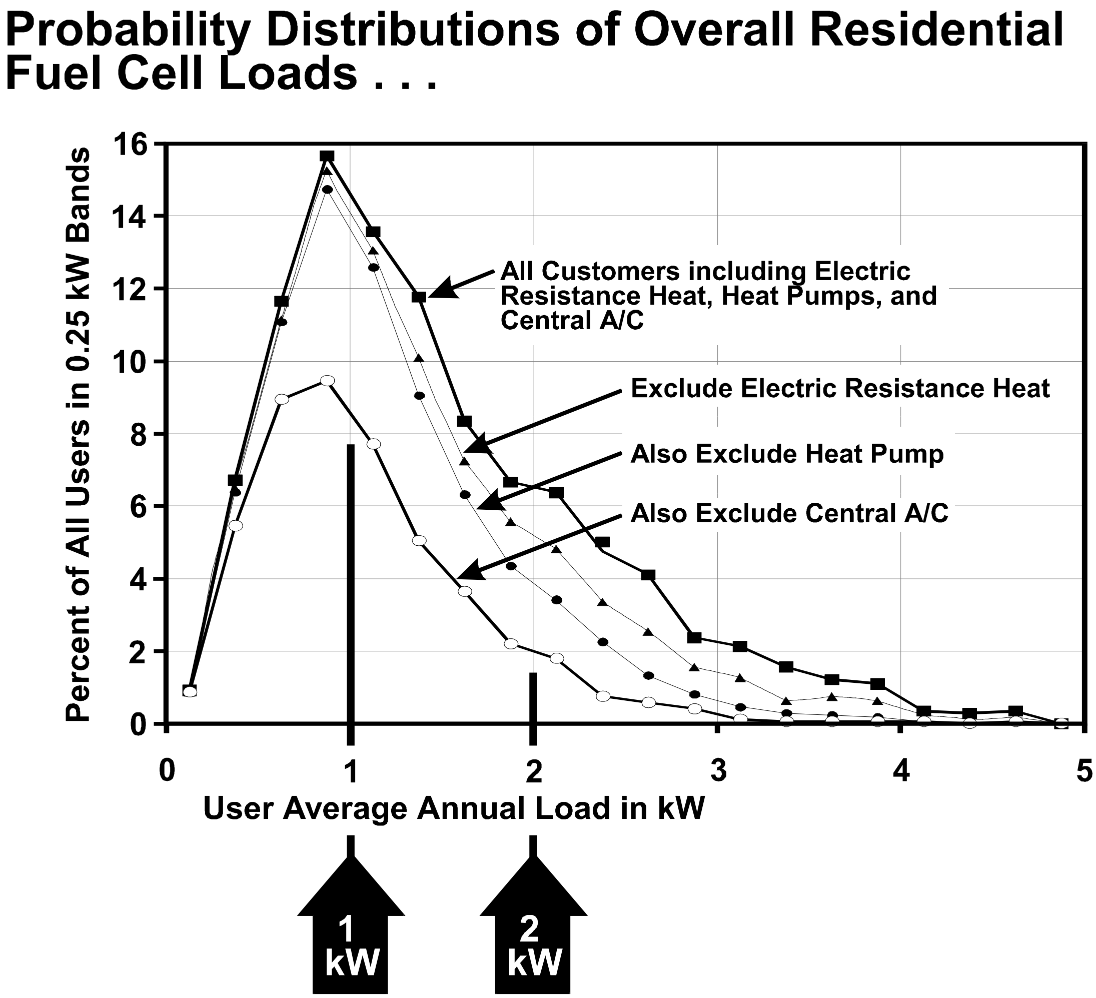
In reviewing this formula and its impact, two factors stand out. First, the customer's per kilowatt-hour cost is very sensitive to the size of the annual load. Second, the relative slope of electric cost reductions due to increased load are likely to be greater for the fuel cell than for conventional grid rates. Thus, fuel cell application economics tend to favor larger sized dwellings with greater electric loads. The end result is that customer annual loads, their causes, and their distributions are a major factor in understanding residential fuel cell potential markets and applications.

Distribution Load Profiles

A key source of customer size and profiles will be the co-op's own metering records when it comes to analyzing the suitability of a specific site. Indeed, the most valuable records will be those containing both monthly use and electric demand. However, those customer-by-customer records are unlikely to contain information on the specific types and saturations of electric uses necessary to gain conceptual market understandings useful in assessing the basic fit, if any, of residential fuel cell technology to overall markets.

Fortunately, some guidance is available from the Department of Energy's Energy Information Administration. This agency conducts periodic energy surveys of residential energy use and markets. The 1993 survey collected data from over 7,000 residential consumers across the country in the ten census divisions. These census areas are actually subsampled in city, suburban, town, and rural locations. Since anonymized data files are available for each interview, it is possible to use data base software to construct a picture of related dwelling characteristics by geographic region and within

Figure F-2
Residential Load Distribution Profiles



Source: EnSig proprietary analysis of 1732 actual customer's measured use in single family attached and detached dwellings in town and rural areas from raw 1993 EIA Census Data.

various urban to rural environments. This survey also collects actual annual electric use when possible and includes a detailed appliance and space conditioning survey.

The results from the 1732 samples in the survey where detailed consumptions were available from actual utility bills is reported above in Figure F-2. The data is only for single family or one-family detached dwellings. The information has been processed to show the percent of the users that had various average annual average electric loads in kW. In effect, the data is calculated by dividing the total annual kilowatt-hour use by 8,760 hours per year.

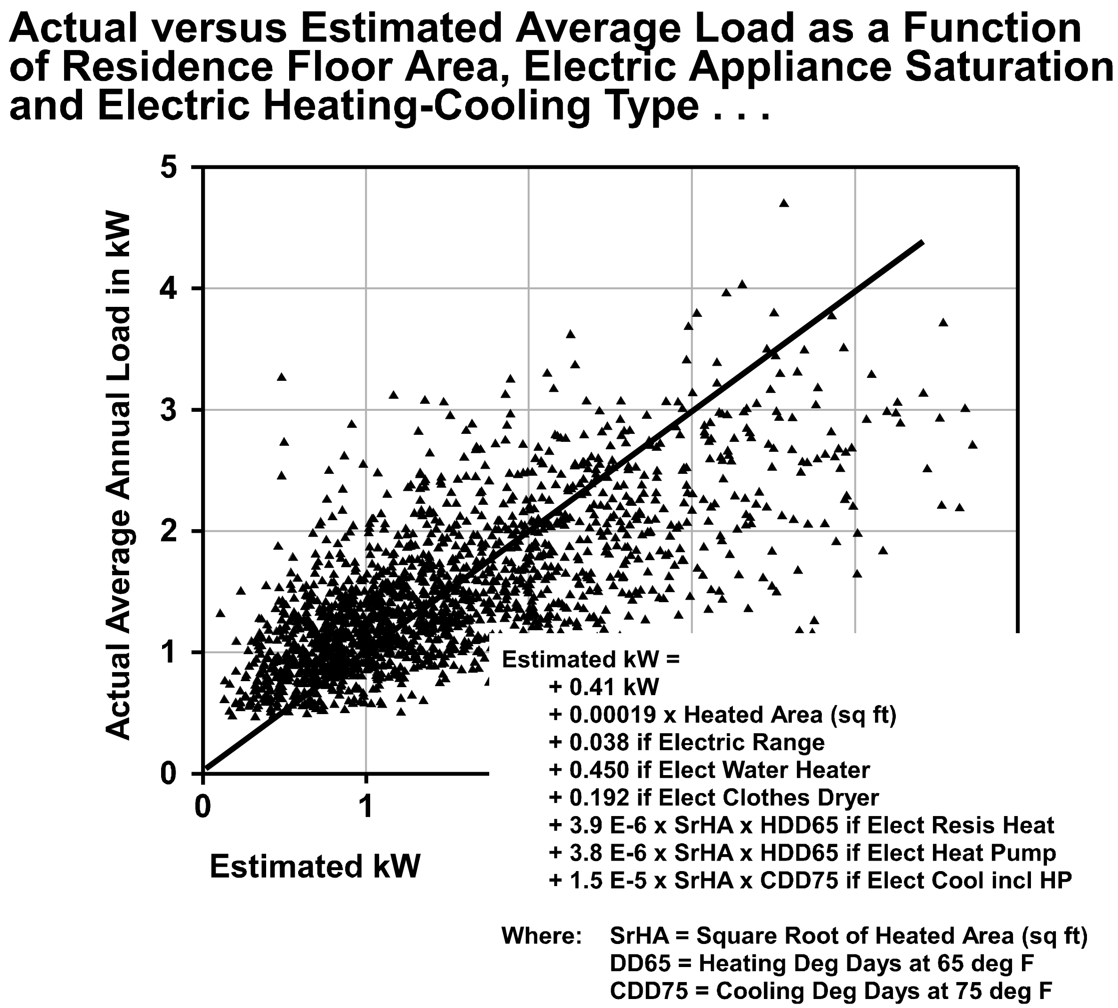
The outer, tallest curve is for all dwellings regardless of whether electric heating of any type or central electric cooling are used. The first inner curve backs out electric resistance heat. The next inner curve backs out both electric resistance heat and heat pumps, but retains those dwellings that have central air conditioning. The innermost curve excludes all of the above and reports only those dwelling that have no type of electric heating and do not have central air conditioning.

The curves decline in height since they are all referenced to the total sample of all 1,732 dwellings where data was available. The number of dwellings represented by the inner curves are 1480, 1284, and 815 respectively. This means, for example, that 47 percent of the dwellings did not have any form of electric heat or central air conditioning.

Of particular interest is the fact that the composite market distribution peaks at around a 1 kW average annual use. About 60 percent of the market is greater than 1 kW and 24 percent is over 2 kW on an average annual basis. Thus, the data suggests that only about one-fourth of the potential market will be able to take advantage of the improved fuel cell economics that occur with an average annual use in excess of 2 kW.

Projection from Customer Profile

Figure F-3
Residential Annual Load Projection



Source: EnSig proprietary analysis of 1732 actual customer's measured use from raw 1993 EIA Census Data. Resulting r^2 is 49 percent accuracy.

Of particular help in assessing prospective residential fuel cell markets would be the likely profile of these larger customers where a residential fuel cell is potentially more economically attractive. Figure F-3's analysis uses the previous segments dwelling data to develop prediction correlations of average annual use. The methodology, termed a multiple regression analysis, analyzes the differences between each of the 1,732 lines of data to see what correlations exist between average annual electric use and various energy survey components. In addition to the obvious items, such as individual electric appliances, heat pumps, resistance heat, central A/C, and the like, this analysis incorporates additional survey parameters including the dwelling square footage and local heating-cooling degree days.

The results shown in Figure F-3 project, for example, that heating and cooling loads should be a function of degree days below 65°F and above 75°F respectively. The analysis setup also uses the square root of the dwelling area since that approximates the perimeter wall length where most heat losses and heat gains would occur. The statistical analysis then starts through all the variables and calculates the overall set of individual variables that best predict the overall load.

The calculated predictors are overlaid on Figure F-3 and indicate, for example, that the non-appliance-heating-cooling base load is 0.41 kW plus 0.00019 times the heated area in square feet. The results for a 2,000 square foot all-electric home in the East North Central region with 5,905 heating degree days and 654 cooling degree days would yield the following loads:

	Annual Electric Use	
Item	Average Annual kW	Kilowatt-Hours
Base Load (lights, etc.)	0.790	6,920
Electric Range	0.038	333
Electric Water Heater	0.450	3,942
Electric Clothes Dryer	0.192	1,681
Electric Heat Pump on Heating Cycle	1.003	8,762
Electric Heat Pump on Cooling Cycle	0.439	3,845
Total	2.912	25,483

As the chart scatter epitomizes, predicting average annual loads is not easy, even if the types of appliances and heating-cooling equipment in the dwelling are known.

Market Connected Loads

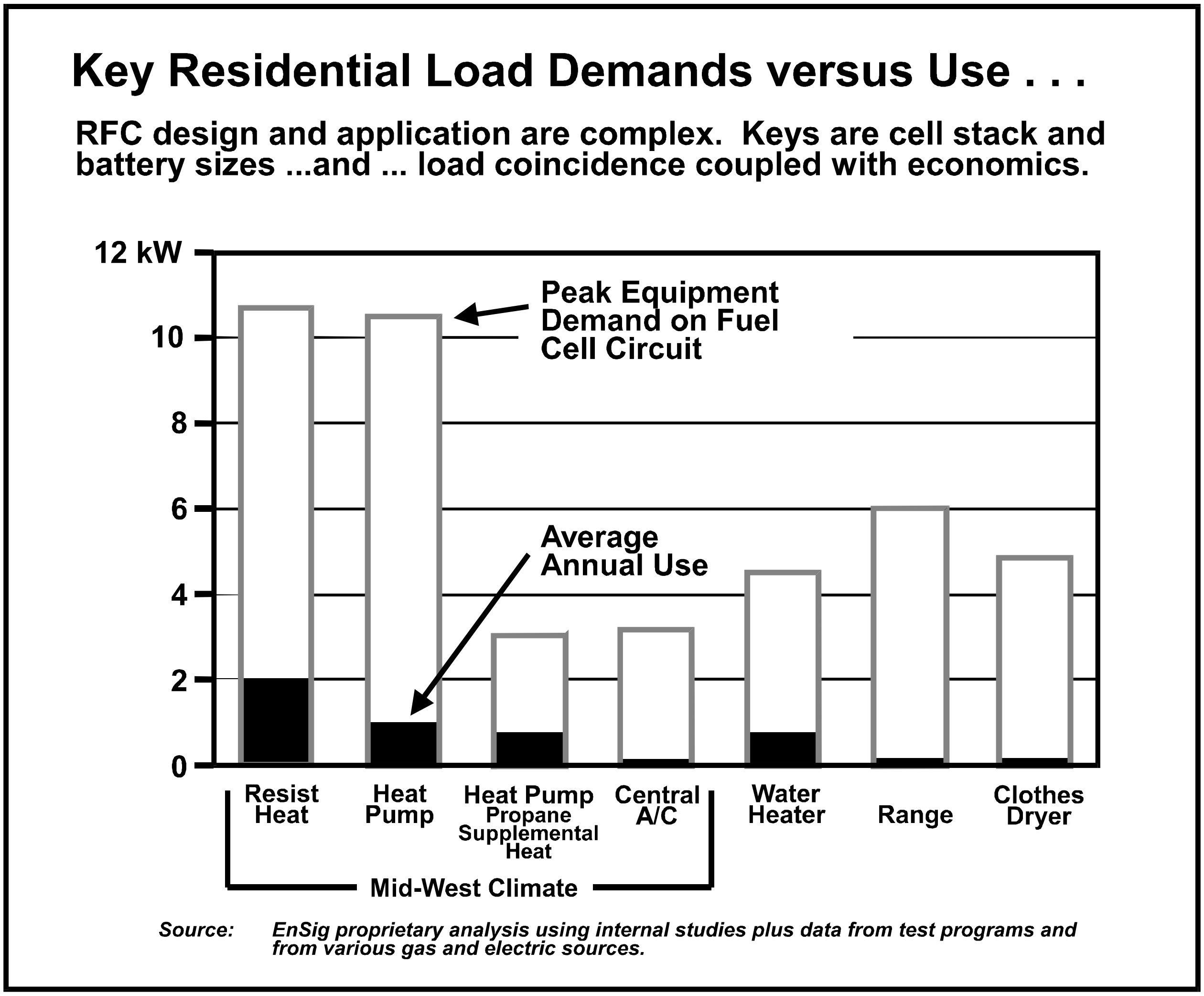
Importance

Customer peak loads are also crucial in analyzing potential applications and markets. Here the factor is not so much the overall cents per kWh economics, but rather assessing whether customer peak loads will fit within the size of the fuel cell power plant's overall capacity.

Residential fuel cells typically have a 3 to 7 kW cell stack supplemented by 3 to 10 kW of DC batteries. Capacitors may also be added for short-term motor starting loads. This composite DC buss feeds a DC-to-AC inverter sized for the power plant's maximum specified load. Normal operation would charge the batteries during the night when the dwelling's loads are low and the charged batteries would then assist the unit's supply of customer loads during peak, and perhaps, normal daytime operation.

Figure F-4 shows key residential loads along with their connected peak demand and probable annual use that would have to interface with the fuel cell. The largest residential loads are associated with electric resistance heat and normal heat pumps. These can reach in excess of 10 kW and are generally

Figure F-4
Key Residential Loads, Demands, and Annual Use



impractical to serve with a fuel cell. Also, it would not make energy sense to convert natural gas or propane into electricity at 33 percent efficiency only to use the resulting power in a baseboard electric resistance heater when a conventional gas or propane furnace would have an 80+ percent efficiency.

Heat Pump Market Profile

On the other hand, the compressor of an electric central heat pump or the equivalent air conditioning system can make a reasonably attractive load at the 3 kW level. Indeed one of the design criteria for a typical residential fuel cell is, or should be, that it have the capability to power a 3-ton central A/C system, and by inference, a similarly sized central heat pump. One reason is that the three-ton heat pump or central A/C market is relatively wide spread, particularly among the high income levels and larger sized dwellings that are likely to be key residential fuel cell markets and applications.

However, the ability to serve a heat pump is contingent on eliminating the heat pump's supplemental duct heaters which come on a low outdoor temperatures. These supplemental heating elements can have

Table F-3
Fuel Cell Heat Pump Key Market Data

HEAT PUMP SATURATION IN SINGLE FAMILY DETACHED DWELLINGS (HOMES)					Weighted Avg All Four	Composite of Town plus Rural
Census Division	**City**	**Suburban**	**Town**	**Rural**		
New England	0.0	3.5	0.0	1.9	1.4	0.9
Middle Atlantic	0.0	5.4	1.9	4.3	3.5	3.4
East North Central	2.0	0.0	3.7	6.7	2.7	5.5
West North Central	0.0	4.4	0.8	12.0	3.6	5.1
South Atlantic	30.9	41.7	15.1	19.0	28.1	17.5
East South Central	13.7	25.5	8.6	30.1	21.5	24.3
West South Central	5.0	14.0	3.0	11.9	6.7	6.0
Mountain	7.9	10.1	7.4	7.4	8.0	7.4
Pacific	0.9	7.4	4.6	6.5	3.5	5.5
Composite	8.0	13.6	4.9	12.7	9.7	9.1

Saturation of ELECTRIC APPLIANCES AND OTHER APPLICABLE ELEMENTS in the above TOWN PLUS RURAL locations for the above SINGLE FAMILY DWELLINGS THAT USE HEAT PUMPS:

Electric Water Heating	90%	Well Pump	39%
Electric Range	93%		
Dishwasher	69%	Utility Gas Available	17%
Electric Dryer	95%	Propane Used	7%

Note: Based on a sample of 197 installations. Saturation in individual Census Divisions is not tabulated here due to the small sample size.

Source: EnSig proprietary analysis of raw 1993 EIA Census Data

demands of 10 kW or more. Thus, the heat pump supplemental heater load would need to be eliminated! This can be by substitution of a natural gas / propane furnace for the heat pump air handler or, alternately, by the replacement of the supplemental heaters with an hydronic coil connected to the converted, thermal recovery water heater.

Central A/C Key Market Profile

Because of their widespread saturation in high-end residential markets, the fuel cell's ability to serve central A/C systems is also a key market and design criteria. However, from a load-factor point of view a central A/C system itself is not a particularly attractive load. For example, a central A/C unit might run 1,200 hours a year in a Midwest application compared to 2,500 hours a year for a heat pump compressor in the heating mode. Thus a three-ton heat pump with summer cooling use will make a far more attractive fuel cell load than would a simple three-ton central A/C only system.

Along with heat pump consumers, another key market segment is consumers using central A/C units. This is because these dwelling loads are likely to be larger than customers not having central air conditioning and will thus tend to have somewhat better fuel cell economics. As shown in the top portion of Table F-4, central A/C applications are relatively high across most sections of the country excepting New England and the Mountain plus Pacific regions. When reviewing Tables F-3 and F-4 it may be helpful to refer to Figure B-1 on Page B-3 which shows a U.S. Census Division map.

Table F-4
Fuel Cell Central A/C Key Market Data

CENTRAL A/C SATURATION that do not use Heat Pumps or Electric Resistance Heating IN SINGLE FAMILY DETACHED DWELLINGS (HOMES):

Census Division	City	Suburban	Town	Rural	Weighted Avg All Four	Composite of Town plus Rural
New England	11.2	17.7	9.2	8.6	11.7	8.9
Middle Atlantic	14.3	37.9	36.1	11.2	26.5	20.9
East North Central	39.0	59.5	24.6	33.3	40.9	30.0
West North Central	48.8	70.9	39.5	43.4	47.5	41.0
South Atlantic	28.8	37.1	31.7	22.3	29.6	25.8
East South Central	35.8	35.9	42.8	17.7	30.2	24.5
West South Central	42.4	47.7	48.8	19.7	41.7	39.2
Mountain	20.3	15.2	11.1	6.8	16.6	9.0
Pacific	27.0	22.7	16.4	4.6	21.9	10.8
Composite	31.8	40.4	32.5	21.1	31.6	26.4

Saturation of ELECTRIC APPLIANCES AND OTHER APPLICABLE ELEMENTS in the above dwellings (homes) that have Central A/C but do not use Heat Pumps or Electric Resistance Heat:
TOWN plus RURAL COMPOSITE . . . .

Census Division: Town + Rural Composite Location	Elect Water Heat	Elect Range	Dish-washer	Elect Dryer	Well Pump	Utility Gas Avail	LPG Used
New England	10	87	93	71	26	33	15
Middle Atlantic	20	59	88	34	42	40	11
East North Central	35	60	58	69	66	60	22
West North Central	47	76	61	86	25	48	27
South Atlantic	52	77	66	87	33	34	25
East South Central	62	90	57	94	8	31	28
West South Central	12	41	59	79	9	73	14
Mountain	53	77	91	100	27	61	17
Pacific	11	42	76	46	0	44	9
Composite	35	65	65	76	29	48	20

Note: Above tables are based on a total sample of 1404 A/C installations not having a heat pump or electric resistance heat. Sample count for Town is 256 and 232 for Rural. "Utility Gas Avail" and "LPG Used" are based on all 4350 single family detached dwellings to improve the accuracy in that projection.

Because of the relatively large sample size, related appliance saturations are broken down by census divisions and by town versus rural locations. These breakdowns show several interesting, but expected, characteristics. Electric water heating saturations are significantly higher in rural versus town locations. The same trends also exist for electric cooking and electric clothes dryer saturations.

Water Heating Thermal Recovery

Table F-5 shows related electric-to-gas water heater conversion economics. Electric water heating can have 4.5 kW demands lasting from three to nine or more hours per day. The range of operation is directly proportional to the customer's daily hot water use. Depending on the power plant's cell stack size and on the other loads in the dwelling, this will present a problem in most applications. Moreover, in a heat pump application where the supplemental resistance heaters in the air handler are likely to need replaced to reduce the load on the fuel cell, the simplest procedure may be to convert the electric water heater to gas and then circulate some of its hot water to a hydronic coil in the air handler to replace the heat pump's supplemental heaters.

Table F- 5
Electric Water Heater Conversion Costs

Parameters and Assumptions:

GPD	=	Gallons per day of hot water use.
n	=	Efficiency of water heating; electric = 100%, gas = 65%
MilBtu/yr	=	GPD x (140°F - 60°F) x 8.33 lb/gal x 365 d/yr / (n/100 x 1000000)
$/yr	=	0.374 x GPD x $/MilBtu
...or...		
kWh/yr	=	GPD x (140°F - 60°F) x 8.33 lb/gal x 365 d/yr / (3412.6)
$/yr	=	0.713 x GPD x ¢/kWh
$/MilBtu	=	$5.00 for natural gas,
	=	0.1095 x ¢/gallon propane @ 91.3¢ = $10.00 per MilBtu
GPD	=	90

Existing Cost:

Electric Water Heating = 0.713 x GPD x ¢/kWh		
	@ 4.5¢	$289 / year
	@ 6.0¢	$385 / year

Fuel Cell Application Options:

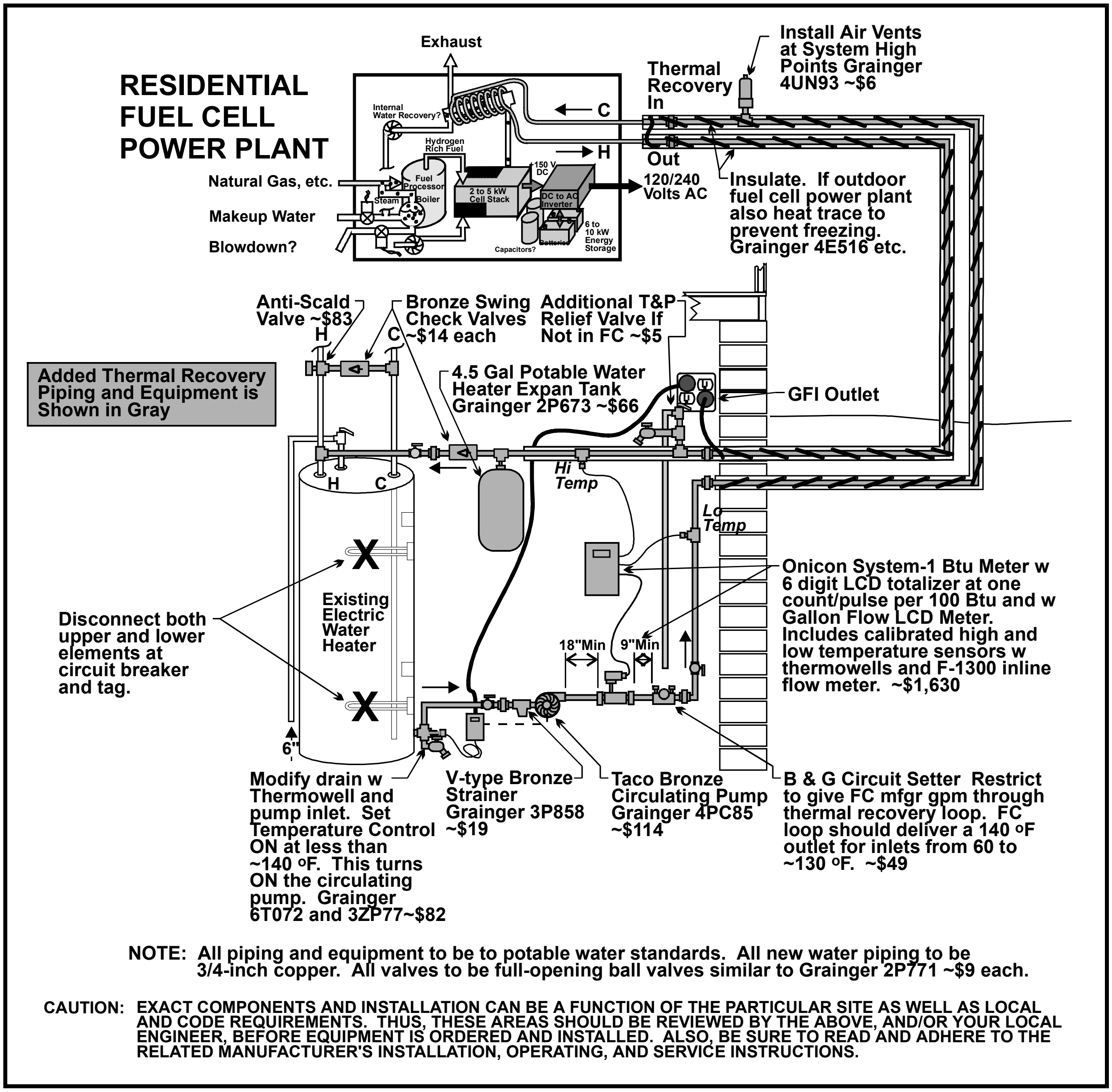
Recover Energy From Fuel Cell:*		$ 0 / year
Burn Fuel in Fuel Cell to make electricity for Electric Water Heater:	Natural Gas	$333 / year
	Propane	$666 / year
Convert Electric Water Heater to :	Natural Gas	$168 / year
	Propane	$336 / year

***NOTE: At 60 percent recovery of available thermal energy, a residential fuel cell operating at a 1 kW output would produce sufficient thermal energy to heat 150 gallons per day of hot water.**
At a 9 percent cost of capital and a 10-year life, a $1,000 thermal recovery expenditure would cost the equivalent of $156 annually.

The simplest and absolute minimum cost thermal recovery configuration that can generate any reasonable level of thermal recovery benefits is shown on the next page in Figure F-5. It converts an existing electric water heater for use as a storage tank by adding a small circulating pump with, or without, a controller. Upon a need for hot water for dwelling use, the controller sensing a reduced temperature in the bottom of the tank because of cold make-up water flowing into the heater would turn on the circulating pump to send this cool make-up water through the fuel cell thermal recovery loop.

Because the dwelling's potable water circulates through the fuel cell thermal recovery loop, it is important that the loop and fuel cell thermal recovery exchanger be constructed to potable water standards. This should be evident from the manufacturer's equipment specifications and should be discussed with any applicable code officials. Because of the system configuration, an anti-scald valve should always be included in the dwelling's domestic hot water supply line as shown.

Figure F-5
Minimum Cost Thermal Recovery Conversion of Electric Water Heating



Potential Owners Group Role

The establishment of an Owners Group under the demonstration program umbrella will significantly enhance information transfer, ideas, and assessments between participants. The Owners Group will enable participants to become more familiar with the actual field operation of the various technologies, to better assess the various manufacturers and their equipment, and to maximize feedback to the manufacturers. Moreover, the Owners Group can also provide a mechanism whereby common issues, needs, and efforts can be addressed. Examples include: early entrance market definition, overall economic quantification, service and maintenance issues, system dispatch and monitoring needs, business issues and criteria, etc.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 2002	Subcontract Deliverable

4. TITLE AND SUBTITLE
National Rural Electric Cooperative Association, Cooperative Research Network Residential Fuel Cell Demonstration Handbook, Final Report, December 27, 2000

5. FUNDING NUMBERS
CF: AAD-1-30605-12
DP02.1001

6. AUTHOR(S)
E. Torrero and R. McClelland

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cooperative Research Network
National Rural Electric Cooperative Association
Arlington, Virginia
and
Energy Signature Associates, Inc.
Pittsburgh, Pennsylvania

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-560-32455

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: Holly Thomas

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)* This report is a guide for rural electric cooperatives engaged in field testing of equipment and in assessing related application and market issues. Dispersed generation and its companion fuel cell technology have attracted increased interest by rural electric cooperatives and their customers. In addition, fuel cells are a particularly interesting source because their power quality, efficiency, and environmental benefits have now been coupled with major manufacturer development efforts. The overall effort is structured to measure the performance, durability, reliability, and maintainability of these systems, to identify promising types of applications and modes of operation, and to assess the related prospect for future use. In addition, technical successes and shortcomings will be identified by demonstration participants and manufacturers using real-world experience garnered under typical operating environments.

14. SUBJECT TERMS: PV; fuel cell; electric load; grid independent; dual operating mode; grid parallel; thermal recovery; application-price-business; peak load impacts

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL