**ORNL/TM-2004/233**

# Oak Ridge National Laboratory

# Fuel Cell Demonstration Project

# 200 kW – Phosphoric Acid Fuel Cell Power Plant
# Located at the
# National Transportation Research Center
# 2360 Cherahala Blvd,
# Knoxville, Tennessee

FINAL REPORT

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# Disclaimer

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# Abstract

Oak Ridge National Laboratory (ORNL) researches and develops distributed generation technology for the Department of Energy, Energy Efficiency and Renewable Energy Distributed Energy Program. This report describes installation and operation of one such distributed generation system, a United Technology Corporation fuel cell located at the National Transportation Research Center in Knoxville, Tennessee. Data collected from June 2003 to June of 2004, provides valuable insight regarding fuel cell-grid compatibility and the cost-benefit of the fuel cell operation. The NTRC fuel cell included a high-heat recovery option so that use of thermal energy improves project economics and improves system efficiency to 59% year round. During the year the fuel cell supplied a total of 834MWh to the NTRC and provided 300MBtu of hot water. Installation of the NTRC fuel cell was funded by the Distributed Energy Program with partial funding from the Department of Defense's Climate Change Fuel Cell Buy Down Program, administered by the National Energy Technology Laboratory. On-going operational expenses are funded by ORNL's utility budget and are paid from operational cost savings. Technical information and the benefit-cost of the fuel cell are both evaluated in this report and sister reports.

# Executive Summary

Oak Ridge National Laboratory (ORNL) is a multi-program science and technology laboratory managed for the U.S. Department of Energy (DOE) by UT-Battelle, LLC located near Oak Ridge, Tennessee. ORNL's Energy Efficiency and Renewable Energy Program conducts research and development on transportation, buildings, industry, renewable energy, and distributed energy. The DOE Distributed Energy Program co-sponsored the fuel cell installation project that is the topic of this report.

The National Transportation Research Center (NTRC) is a conduit to transportation research programs at ORNL and the University of Tennessee (UT). It offers one of the most diverse concentrations of transportation researchers in the United States. The NTRC houses an alliance among ORNL, UT, the U.S. Department of Energy, UT-Battelle, LLC, NTRC, Inc., and the Development Corporation of Knox County. UT has one of the oldest university-based transportation R&D centers in the country, and ORNL has one of the largest collections of multidisciplinary transportation researchers among the DOE national laboratories.

A 200-kW United Technology Corporation (UTC) phosphoric acid fuel cell was installed to supply electricity for about one-third of the building's electricity load. The project is one of only three fuel cells installed in the southeastern United States, and the only fuel cell installed in Tennessee.[1] The project overcame and analyzed barriers to grid inter-connection—an in-depth analysis of the compatibility of the fuel cell with the utility grid resulting in recommendations that have broad applicability to installation of any distributed generation system.[2, 3]

Thermal energy generated by operation of the fuel cell is used to supplement building heating. A central chiller conditions air that is reheated to achieve a comfortable temperature. The amount of energy required to reheat conditioned air in the summer is close to the amount of thermal energy produced by the fuel cell. Therefore, fuel cell operation increases fuel use efficiency to 59% year round.

The total capital allocated for this project was approximately $1.17 million. The project was funded by DOE's Distributed Energy Program and by the Department of Defense Climate Change Buy Down Program, administered by the National Energy Technology Laboratory (NETL). On-going operational expenses are funded with other ORNL utilities and are paid from savings. The PC25C fuel cell operated for 6,626 hours during the first year of service, reaching an availability of more than 75%. For this year of operation, the total electricity output was 834MWhrs and the total thermal output was 300MBtu.

The benefit to cost analysis shows the installation of the PC25C is not economically viable because of the initial high capital cost of the fuel cell. Project barriers had to be overcome such as installation in a commercial business park, connecting to the local utility, inability to track building electric loads, negotiating lower rates for natural gas, and difficulty in placing the maintenance contract. The project also analyzed and overcame issues regarding compatibility between the fuel cell output and the utility grid.

Fuel cell installations have several benefits in that they are a reliable and efficient form of power generation. Fuel cell technology has very minimal NOx and SOx emissions, which make the fuel cell an environmentally friendly form of power generation. However, until capital costs are reduced and interconnection with the grid becomes routine, the average commercial building will not be able to adopt fuel cell technology.  The results of this project add to the body of data used to the evaluate fuel cell technology—this technical and commercial data can further development of fuel cell technology, specifically, and further distributed generation technology, in general.

# Oak Ridge National Laboratory
# Fuel Cell Demonstration Project

## Introduction

Oak Ridge National Laboratory (ORNL) is a multi-program science and technology laboratory managed for the U.S. Department of Energy (DOE) by UT-Battelle, LLC located near Oak Ridge, Tennessee. Scientists and engineers at ORNL conduct basic and applied research and development and form partnerships with industry in order to promote technical innovation and solutions, and create scientific knowledge that strengthens the nation's leadership in key areas of science; increase the availability of clean, abundant energy; restore and protect the environment; and contribute to national security. ORNL's Energy Efficiency and Renewable Energy Program (EERE) conducts research and development on transportation, buildings, industry, renewable energy, and distributed energy.

The National Transportation Research Center (NTRC) officially opened on May 6, 2002 to house multidisciplinary transportation researchers. Along with other advanced technology, researchers test engines at the NTRC facility. Dynamometers absorb excess power produced during engine research—an important fact because this research affected the compatibility of the fuel cell with the utility grid. The center is located at 2360 Cherahala Blvd, Knoxville, Tennessee, about halfway between ORNL and University of Tennessee (UT) -Knoxville. Approximately 200 staff from ORNL and UT are located at the NTRC facility. The NTRC building contains about 83,000 sq. ft. of space, about two-thirds of it dedicated to research laboratories that support some of the most advanced transportation research in the world.

A 200-kW United Technology Corporation (UTC) phosphoric acid fuel cell was installed to supply electricity for about one-third of the building's electricity load. The project is one of only three fuel cells installed in the southeastern United States, and the only fuel cell installed in Tennessee and adjacent states (see Figure 1).[1] Since this distributed generation installation is the first of its kind in the Lenoir City Utility Board (LCUB) district, coordination with the local utility was extremely important and resulted in the requirement to install and use a reverse power relay to prevent fuel cell-generated electricity output to the utility grid. This strict control of reverse power coupled with the inability of the fuel cell to track building loads resulted in numerous events that placed the fuel cell in 'idle mode.' The project included an in-depth analysis of the compatibility of the fuel cell with the utility grid that developed recommendations with broad applicability to installation of any distributed generation system.[2, 3]

Thermal energy generated by operation of the fuel cell is used as supplemental heating. Seven gas-fired boilers (2,070 MBtu/hr each) produce hot water to heat the building. The NTRC building is built with discrete variable-air-volume (VAV) air-handling units and ductwork that serves sections of the building. Since this is a new building, the percentage of outside air is relatively high (20-80%) in accordance with ASHRAE standards. A central chiller produces 55$^{o}$F air that is reheated to achieve the proper temperature.

Temperatures are controlled with terminal reheat by groups of offices and conference rooms. The amount of energy required to reheat conditioned air in the summer is close to the 450,000 Btu/hr at 250°F or 3,000-3,300 therms/month produced by the fuel cell. The fuel cell project increased fuel use efficiency from ~33% (for centrally generated electricity) to 59% efficiency year round by using the 250°F water, generated with the high-grade heat recovery unit, for temperature control and heating.

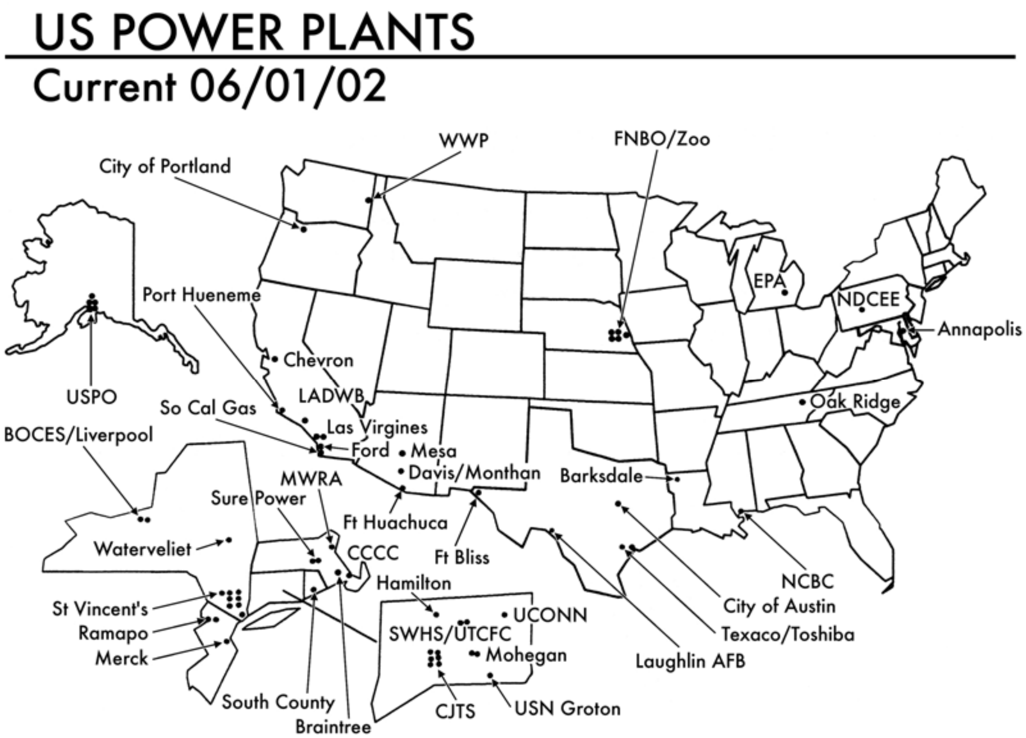


Figure 1. The NTRC fuel cell, shown as located in Oak Ridge, Tennessee is unique in the southeastern United States.

The cooling system for the fuel cell also produces low-temperature hot water (450,000 Btu/hr at 140°F). In typical installations, 140°F hot water can be used for laundry, showers, pools, etc. However, the NTRC has minimal use for hot water because it is primarily an office building. The project team evaluated using this low-grade heat to warm the near-by high bay area during winter months. The team also evaluated replacing the existing emergency diesel generator with the fuel cell power output. However, the capital costs for each of these project initiatives exceeded the project budget. If the fuel cell were installed during building construction, these efficiency enhancements would be more cost effective.

Information on fuel cell emissions was shared with Knox County and Tennessee State air permitting authorities. Minimal NOx and SOx emissions made the fuel cell acceptable to local air quality regulators; Tennessee State Air Permitting Knox approved the fuel cell installation with no permit on August 13, 2001. The fuel cell is installed near the rear of the NRTC building (see Figure 2). Covenants and restrictions for the professional business park, where the NTRC is located, required that the architectural control committee review installation plans for the fuel cell. The Development Corporation of Knox County committee required written documentation and a presentation on the fuel cell installation. On April 9, 2002 this committee established requirements for a fence to screen the fuel cell from the street with a hedge of Leather Leaf Viburnum along the fence line. The Knox County Code Administration and Inspection Department required this approval before issuing the building permit.

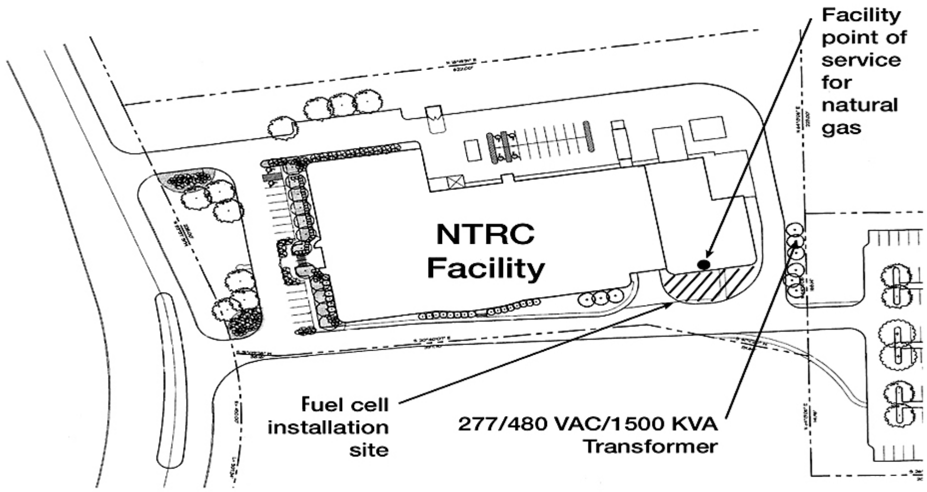


Figure 2. Location of Fuel Cell at NTRC.

Capital allocated for this project was approximately $1.17 million. The project was funded by DOE's Distributed Energy Program and by the Department of Defense Climate Change Buy Down Program, administered by the National Energy Technology Laboratory (NETL). On-going operational expenses are funded along with other ORNL utilities and are paid from savings. The fuel cell operated for 6,626 hours during its first year of service, reaching an availability of more than 75%, with a total electricity output of 834MWhrs and a total thermal output of 300MBtu. The NTRC fuel cell plant reverted to idle mode when reverse power or grid fault protection situations occurred. The power plant operated in idle mode or was shut down for 2,134 hours. During these forced outages, the fuel cell was not producing usable power.

ORNL visitors have expressed interest in the fuel cell and several tours have been conducted including representatives of DOE's EERE Program Office, Gas Technology Institute (GTI), Construction Engineering Research Laboratory (CERL), Tennessee Valley Authority (TVA), and Southern Company. However, it is unlikely that an average commercial building would adopt fuel cell technology because the initial high capital cost of the fuel cell make installation and operation economically unviable. Further, project barriers must be overcome including interconnection requirements, which increase the cost and complexity of the project.

## Results and Discussion

The following section describes the fuel cell installation and presents data on the first year of operation at NTRC in Knoxville, Tennessee. Data are provided regarding power plant reliability, costs, expenses, efficiency and on operation and maintenance issues.

**Installation**

Project implementation began with a signed copy of a subcontract between UT-Battelle, LLC and International Fuel Cells, Inc. (now United Technology Corporation) documenting that ORNL purchased a 200kW/235kVA PC25 Phosphoric Acid Fuel Cell Power Plant (see letter from Jan Berry, Project Manager, ORNL, to Michael P. Nolan, NETL, dated July 26, 2001). The fuel cell and cooling tower were delivered in September 2001 and stored (see section entitled, ‘Photo Gallery’) until the project design and building interfaces were specified by an architecture/engineer firm, I.C. Thomasson, Nashville, Tennessee. The unit was ordered with grid-independent capability and the high-grade heat recovery option.

System design was initiated on September 4, 2001 with a subcontract between ORNL and I.C. Thomasson (Design Contract to Install PC25 Fuel Cell Power Plant Sub-Contract #: 4000008705). Design considerations included an assessment of the location for the fuel cell taking into account the Distributed Energy Program’s interest in exploring grid compatibility issues. The team selected a site based on specific findings: (1) the electric load for this building transformer periodically falls below the 200 kW output of the fuel cell enabling the team to evaluate the load tracking feature of the fuel cell; (2) the building thermal load matches the heating output of the fuel cell and the location is within close proximity reducing the cost of piping.

After design was completed on April 17, 2002, the best value to the government was obtained by issuing a competitive procurement for the fuel cell installation project. This competition resulted in estimates ranging from $280,000 to $490,000. I.C. Thomasson was selected to manage the project construction. Detailed review of cost estimates resulted in a reduction in scope. The following options were deleted: (1) use of low-grade heat to warm the near-by high bay area during winter months that would have increased fuel efficiency to 76% with a capital cost estimate of $48,879; (2) replace the existing emergency diesel generator with the fuel cell power output with a capital cost estimate of $14,000.[i] The final construction costs were $238,061. The construction kick-off meeting was held on July 18, 2002.

Construction was completed with several barriers having been overcome such as resolution of the appropriate grid-interconnection device. A reverse power relay was installed and start-up was scheduled for January 2003. In February 2003, two building engineers were trained on the fuel cell operation at UTC’s facilities in South Windsor, Connecticut. However, issues regarding liability of the UTC maintenance contractor required senior management resolution resulting in a startup date of May 15, 2003.

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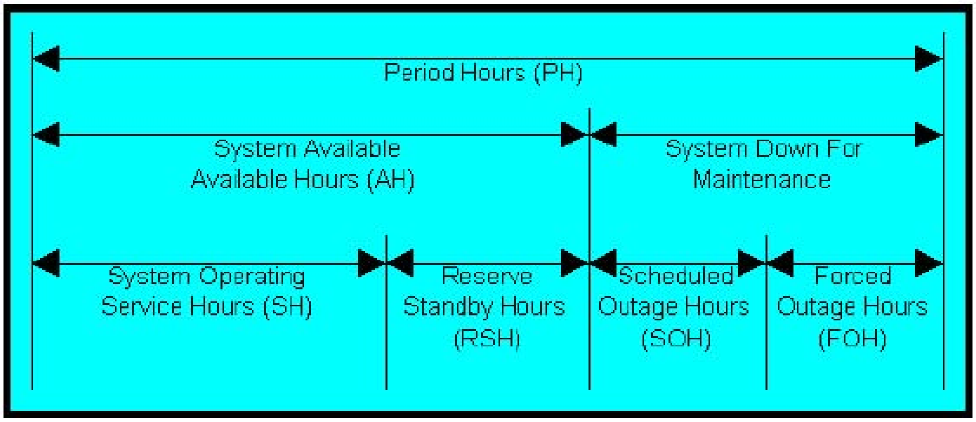
[i] Installation of the fuel cell and its use as emergency power supply was reviewed with Knox County Deputy Fire Marshall Brown.

**Commissioning**
The PC25C Fuel Cell power plant was commissioned on May 15, 2003 and commenced regular operation on June 17, 2003.

**Reliability Analysis (MTBF)**
To determine the reliability statistics, performance indices are used that are published by the GTI in Des Plaines, Illinois.




| ***Reliability Performance Indices*** | ***Formula*** |
|---|---|
| ***Period of Demand (POD):*** *Measures the time the unit was planned to operate.* | $POD = PH - RSH - SOH$ |
| ***Availability Factor (AF, %):*** *Measures, on a percent basis, the unit's "could run" capability. Impacted by planned and unplanned maintenance.* | $AF = \frac{(PH - SOH - FOH) \times 100}{PH}$ |
| ***Forced Outage Rate (FOR, %):*** *Measures portion of downtime due to unplanned factors.* | $FOR = \frac{FOH \times 100}{SH + FOH}$ |
| ***Scheduled Outage Factor (SOF, %):*** *Measures percent of time set aside for planned maintenance.* | $SOF = \frac{SOH \times 100}{PH}$ |
| ***Service Factor (SF, %):*** *Percent of total period hours the unit is on-line – varies due to site-related or economic factors.* | $SF = \frac{SH \times 100}{PH}$ |
| ***Mean Time Between Forced Outages (MTBFO):*** *Measures the nominal time between unscheduled forced outages.* | $MTBFO = \frac{SH}{\# ForcedOutages}$ |
| ***Mean Down Time (MDT):*** *Measures the nominal duration the unit is down during maintenance events.* | $MDT = \frac{SOH + FOH}{\# ForcedOutages + \# PlannedOutages}$ |

(Source: http://www.gri.org/pub/solutions/dg/rel_metrics.html)

**Operating Hours / Availability**

Reliability performance indices shown in Table 1 were calculated based on the shutdown event log (see Table 2.) The NTRC fuel cell operated with an availability factor of 75.6% during the one-year period. The fuel cell load time clock reflects 8,523 hours when the power plant was warm and ready to produce power. However, the system was operating in idle mode for 338 hours and shut down for 1,796 hours resulting in a total of 2,134 hours when the system was not providing electricity to the grid. The system produced energy for 6,626 hours (see Table 2).

Table 1. Reliability Performance Indices

| | |
|---|---|
| Period Hours, PH | 8,760hr |
| Scheduled Outage Hours, SOH | 0 |
| Forced Outage Hours, FOH | 2,134hr |
| Reserve Standby Hours, RSH | 0 |
| System Available – Available Hours, AH | 6,626hr |
| System Operating Service Hours, SH | 6,626hr |
| Period of Demand, POD | 8,760hr |
| Availability Factor, AF | 75.6% |
| Forced Outage Rate, FOR | 24.4 % |
| Scheduled Outage Factor, SOF | 0 |
| Service Factor, SF | 75.6% |
| Mean Down Time, MDT | 93hr |
| Mean Time Between Failure (MTBF) | 288hr |
| System Total Use (MWh) | 834 |
| System Peak Use (kW) | 0 |
| Total Fuel Cell Plant Capacity (kW) | 200 |
| Heat Rate Ave Yr (BTU/kWh) | 9,810 |
| Capacity Factor (% of Nameplate Rating) | 47.6% |
| Thermal Output (Btu/yr), if byproduct used | 300 |

## Shutdown Summary

UTC Fuel Cell's Model PC25C model fuel cell was delivered to the NTRC Site in September 2001 and installed by IC Thomasson. The construction contract was managed by Pellissippi Investors, the NTRC building owner, under a lease agreement with ORNL. Fuel cell start up was May 15, 2003. During startup maintenance, fan motors on the cooling towers were replaced due to a manufacturers defect. The fuel cell began producing net power to the grid in June 2003 and immediately encountered problems with reverse power situations, grid current imbalance, and poor power factors which caused the fuel cell to revert to idle mode. Events that are the basis of this study are recorded beginning June 16, 2003 (see Table 2). These events were analyzed in detail in the following reports:

"Compatibility Study of Protective Relaying in a Grid-Connected Fuel Cell," ORNL/TM-2004/12 by R.H. Staunton, and

"Compatibility Study of Fuel Cell Protective Relaying and the Local Distribution System," *IEEE Power Delivery,* TPWRD-00213-2004.R1 by R. Staunton, J.B. Berry, C. Dunn.

The inability of the fuel cell to track the building load was the primary cause of the reverse power situations coupled with a narrow setting for controlling reverse power. Each time a reverse power situation occurred, a representative of the local utility, LCUB, had to manually reset the relay before the fuel cell could output power to the grid. Notifying LCUB and scheduling this manual reset resulted in significant fuel cell down time.

Early in the first year of operation, team members communicated with UTC regarding the ramp down rate of the fuel cell and increased this internal setting. However, it was later determined that the Square D® power monitor that would provide a 4-20 ma signal data on the building load had been destroyed during the electrical storm of June 16, 2003. The building owners were unwilling to replace the device because they felt the electrical system's poor power quality might harm it. The load-tracking feature of the fuel cell was not tested.

Parallel monitors were installed to determine fluctuations in the building load and interactions between the building, fuel cell and grid electrical systems. Throughout June-September, the team worked to identify the root cause of the events understanding that valuable information was being obtained. The team was reluctant to reduce the fuel cell's power output. Based on the emerging understanding of the building power quality, TVA was asked to study the building electrical system. TVA concluded that, "When the dynamometers are running the power factor drops to 0.52 . . . there is a very large fifth harmonic component when the dynamometers are running."[4]

In October, the power output of the fuel cell was reduced to 125kW resulting in a reduction in the number of reverse power events. However, the reverse power relay settings were still narrow. On November 4, 2003, the UPS internal to the fuel cell failed causing the controller to reboot and a complete system shutdown. In December the fuel cell output was reduced to 110kW and the reverse power relay setting was widened. These system parameter changes resulted in less down-time for the fuel cell system. During the first year of operation, the fuel cell plant generated 834 MWh for use at the NTRC. To ensure proper operation, UTC, in South Windsor, Connecticut monitored the fuel cell plant through a secure data line and provided technical expertise.

## Grid Compatibility Analysis Results

Oak Ridge National Laboratory analyzed the compatibility of the fuel cell protective relaying and the local distribution system that was funded equally by DOE's Distributed Energy Program and the Distributed Generation Technologies program of TVA.

The goal of this study was to characterize the compatibility between the protective relaying system of a 200-kW fuel cell and the local electric power system. This study was motivated by the fact that distribution utility engineers are uncomfortable with the synthesized protective relaying and hardware that is generally provided in distributed generation systems. Power grid disturbance electrical data and event-related, building-load electrical data were collected for 6 months during which a larger-than-expected number of interruptions to grid-connect power generation occurred. There were 7 grid-interaction events that have potential global applicability to other distributed generation sites. Other events were due either to NTRC's unique dynamometer power dumping operations (in the engine laboratories) or unique difficulties in establishing load tracking in the fuel cell. Problems related primarily to load tracking and to low power factor, complex load balance dynamics, and possible harmonic-distortion-induced instrumentation error as noted in Table 2.

Table 2. Shutdown Event Log

| Date | Time[1] | Response | Initiating event | Fuel Cell event log information[2] | Load Time | Run Hours | System Down Hours |
|---|---|---|---|---|---|---|---|
| *10-Jun-03* | *10:27* | | *Not part of study--provided for information only* | | *299* | *92* | |
| *14-Jun-03* | *6:40* | *Reverse power* | *Not part of study--provided for information only* | *No grid anomaly* | *391* | *23* | *31* |
| 16-Jun-03 | 13:26☼ | Reverse power | Electrical storm, Feeder 254 reclosure | Grid unbalanced, grid undervoltage | 445 | 435 | 265 |
| 15-Jul-03 | 16:12☼ | Reverse power; severe current step and unbalance | Not apparent | No grid anomaly; system in idle mode during outage | 1145 | 149 | 165 |
| 28-Jul-03 | 18:25 | Reverse power; severe current unbalance with a drop in current | Electrical storm | Grid unbalanced, grid undervoltage; system idle | 1459 | 294 | 86 |
| 13-Aug-03 | 14:43☼ | Reverse power; current unbalance, very high current | Not apparent | No grid anomaly; system in idle mode during outage | 1839 | 198 | 168 |
| 28-Aug-03 | 20:09 | Reverse power; slight current unbalance and distortion | Unknown | No grid anomaly; system in idle mode during outage | 2205 | 55 | 16 |
| 31-Aug-03 | 19:22 | Fuel cell trip; “excessive disconnect count” permissive | Severe electrical storm | 3 interrupts for unbalanced grid voltage for >0.5 sec | 2276 | 23 | 43 |
| 3-Sep-03 | 13:51☼ | Reverse power; slight current unbalance | Minor storm system | No grid anomaly; system in idle mode during outage | 2342 | 32 | 142 |
| 10-Sep-03 | 19:23 | Reverse power; moderate current unbalance | Unknown | No grid anomaly; system in idle mode during outage | 2516 | 5 | 180 |
| 18-Sep-03 | 15:07☼ | Reverse power; Normal waveform plot | Load change due to chiller trip—no load tracking | No grid anomaly; system in idle mode during outage | 2701 | 58 | 93 |
| 24-Sep-03 | 19:19 | Reverse power; Normal waveform plot | Low building load—no load tracking | No grid anomaly; system in idle mode during outage | 2852 | 42 | 44 |
| 28-Sep-03 | 10:01 (weekend) | Fuel cell event data for this event lost due to a “controller reboot.” | Uninterruptible power source (UPS) failed | Grid voltage sag; | 2938 | 0 | 121 |
| 3-Oct-03 | 13:35 | Fuel cell in idle mode | Testing and fixing laptop communications | Operator selected idle mode | 2959 | 266 | 1 |
| 14-Oct-03 | 16:25☼ | Fuel cell entered the idle mode | Voltage sag in grid (possibly weather related) | Grid under voltage and voltage unbalance lasting longer than allowed; system in idle mode | 3226 | 399 | 16 |

Table 1. Shutdown Event Log (continued)

| Date | Time[1] | Response | Initiating event | Fuel Cell event log information[2] | Load Time | Run Hours | System Down Hours |
|---|---|---|---|---|---|---|---|
| 1-Nov-03 | 2:11 | Reverse power; current unbalance with a drop in current | Low building load—no load tracking | No grid anomaly; system in idle mode during outage | 3641 | 0 | 72 |
| 4-Nov-03 | 2:10 | Reverse power; large drop in current and unbalance | Low building load—no load tracking | No grid anomaly | 3713 | 0 | 17 |
| 4-Nov-03 | 16:30☼ | Controller reboot and total fuel cell shutdown. | Unknown UPS anomaly | Not available | 3713 | 0 | 8 |
| 5-Nov-03 | 0:07 | Reverse power | Low building load—no load tracking | No grid anomaly; system in idle mode during outage | 3721 | 106 | 134 |
| 14-Nov-03 | 23:18 | Reverse power | Low building load—no load tracking | No grid anomaly | 3961 | 235 | 83 |
| 28-Nov-03 | 5:25 | Fuel cell trip | First voltage unbalance lasting >0.5 sec | Interrupt >0.5 sec followed by unbalanced grid voltage transients | 4279 | 318 | 76 |
| 14-Dec-03 | 15:36 | Fuel cell trip | Voltage unbalance lasting >0.5 sec | Grid voltage unbalance >0.5 sec | 4673 | 2452 | 17 |
| 26-Mar-04 | 12:56 | System shut down | Resin bottle change out | Not available | 7142 | 87 | 173 |
| 13-Apr-04 | not available | System trip to idle mode | Reverse power | System in idle mode while disconnected from grid | 7402 | 1091 | 30 |
| 30-May-04 | 7:35 | Systen trip to idle mode | Reverse power | System in idle mode while disconnected from grid | 8523 | 381 | 64 |
| 12-Jun-04 | not available | System placed in idle mode | Fuel cell pump filter clogged; maintenance required; no contract | System in idle mode while waiting for maintenance contract to be approved | 8968 | 0 | 120 (estimate) |
| 17-Jun-04 | not available | End of study period | | | 8968 | | |
| **June 2003 through June 2004** | | | | | **8523** | **6626** | **2134** |

☼ Daytime operation that may have coincided with poor power factor due to operation of dynomometers.

As long as the utility grid is energized, fuel cell interruptions do not cause the building occupants to suffer a loss of power, aside from possibly the brief grid voltage variation itself. This is an important advantage of parallel operation in the grid-connected operating mode. If the grid returns to normal after the fuel cell is forced into the idle mode, resynchronization and reconnection takes place based on a user-selected protocol plan.

The effectiveness of the fuel cell's synthesized relay protection scheme was evaluated relative to the IEEE 1547-2003 interconnection standard.[5] Although the full implications of the new standard will only be understood over time, the relay protection scheme for this system cannot help but fully satisfy its intents since it designed to very rapidly place the fuel cell in the idle mode when utility grid anomalies are detected. The conservative design approach makes the fuel cell transparent to the grid during grid anomalies by quickly placing the fuel cell in idle mode.

The fuel cell protective relaying system does not provide fault current protection other than over current and timed over current protection that are designed primarily to protect the fuel cell inverter. The protective relaying system of the fuel cell would not be able to detect a fault current unless major modifications were made including the installation of sensors on grid lines well removed from the fuel cell system. This lack of fault current protection is the reason why the local utility insisted on the use of a reverse power relay system. For the installation at NTRC, when the reverse power relay needed to be reset a representative of the utility physically visited the site and manually reset the relay resulting in significant system down time.

The state of fuel-cell-to-grid compatibility based on the results of this study is considered to be good. There are valuable lessons learned that should be helpful to any organization that is contemplating the operation of grid-connected distributed generation. The following are the primary recommendations of this study.

1. If possible, choose a distributed generation system that has operated for years and proved itself. Speak with technical representatives at the company to: (a) assess the apparent level of cooperativeness, and (b) learn of any operational issues that are not yet resolved.
2. If the distributed generation system is not well proven in the field, a comprehensive service contract should be sought from the vendor/manufacturer.
3. Talk to a representative of the local utility to determine whether and what type of reverse power relay is a required including reset setting. Assess the level of cooperativeness and ensure that utility-provided manual resets will be prompt.
4. Discuss with the local utility representative the type of reverse power protection that will be used, and review what settings may be involved. If reverse power is defined by a window of lagging current phase angles, request a reverse power window of 120º (or 110º) to 270º, rather than 90º to 270º. Generally, ~50 kVA coincident with this 120º - 270º window should be permitted since such a power level should not significantly jeopardize the safety of power grid protective

relaying systems. In this installation, high levels of reverse power had to be tolerated for at least 5 sec to give the load tracking system time to compensate for large load drops.[ii]

5. Do not underestimate the need for reliable load tracking even if projections for power demand far exceed the generation capacity. A downward variation in load need last only seconds for an RPR trip to occur; and sudden, deep drops in load do occur. Thoroughly check out the load tracking system at startup. Install adequate surge protection on the system electronics that produce the control signal.
6. Ensure that distributed generation system operators have ownership and management of the load tracking system including the source of the control signal.
7. Verify that the power ramp-down rate of the power generation system is consistent with the reverse power time interval permitted by the reverse power protection system.
8. Know the distributed generation system control software and all the features and functions that it may control.
9. In installations where the power factor is poor, avoid selecting a distributed generation system with a real power output that will routinely come close to matching the load demand. Otherwise, the power grid will be supplying high levels of reactive power and little real power. This situation may create high current levels and result in high PF charge penalties from the utility. (Note: This recommendation does not apply if the distributed generation system is able to supply adequate levels of reactive power for power factor correction.)
10. At least initially, consider installing a data logger with continuous data sampling of the building load. The data may prove useful in assessing performance of the distributed generation system during interrupt events. If the distributed generation system has an event log, arrange for access to those data also. Review data soon after events to minimize the learning curve.

If these recommendations are followed, the fuel-cell-to-grid compatibility experience should be good to excellent, rather than “assessed as good” or “theoretically good” as has been the experience at the NTRC.[2, 3]

[ii] This is in apparent conflict with IEEE Standard 1547-2003, which requires island detection in 2 sec. However, the load tracking system needs 5 sec to reduce generation by 100 kW based on the maximum rate of 20 kW/sec for this fuel cell system design.

## Cost Parameters

Economic data from the first year of operation follows:

| | |
|---|---|
| Total Fuel Cell Capital Cost ($) | $1,171,780 |
| Fixed Operating Cost | 15-58 mills/kWh |
| Variable Operating Costs | 67 mills/kWh |
| Local Area Electricity Price (cents/kWh) | 8.6cents/kWh |
| *Fuel Price ($/MBTU) | $6.88/MBTU |

*Year Average from June 2003 to June 2004

Fixed operating costs are based on the maintenance contract. A startup contract was placed with UTC for $13,000 resulting in a 15 mills/kWh fixed cost. ORNL and UTC worked throughout the year to place an operations maintenance contract. However, the two companies did not reach agreement on the terms and conditions of the contract until August 2004, after the study period. Had the $35,000/yr contract been in place, the fixed operating cost would have been 58 mills/kWh.

## Capital Cost Summary

The $1.17M project was funded by DOE's Distributed Energy Program and by the Department of Defense Climate Change Buy Down Program, administered by the NETL. The equipment costs were $830,700 including the fuel cell power plant with the high grade heat recovery option. An architect-engineer completed the design for $36,852. Construction management was performed by the building owner, Pellissippi Investors, at a cost of $38,123 and construction cost $199,938. Costs are summarized in Table 3.

Table 3. Fuel Cell Capital Cost

| Activity | Cost ($) |
|---|---|
| <u>Investment</u> | |
| Total Fuel Cell Plant Cost | 810,700 |
| High Grade Heat | 20,000 |
| Shipping | 0 |
| Sales Tax (6.0%) | 49,200 |
| Roane County Tax | 44 |
| Overhead | 16,923 |
| Installation design | 36,852 |
| Construction management | 38,123 |
| Installation Cost | 199,938 |
| **Total Investment** | 1,171,780 |
| <u>Funding</u> | |
| DoD/DOE Climate Change | 200,000 |
| DOE Distributed Energy | 971,780 |
| **Total Funding** | 1,171,780 |

## Natural Gas Consumption of the National Transportation Research Center (NTRC)

Natural gas fuel consumption increased after the fuel cell began operating by 80,000 therms for June 2003-June 2004. Because of this anticipated increase in gas use, the local gas utility authorized an interruptible gas rate for the entire site. Meetings with gas utility representatives early in the project resulted in the favorable rate and resulted in improved project economics. The average fuel cost under the previous rate was $1.0596/therm. Compare this rate with the average interruptible rate of $0.6880/therm (see Table 4). This is an important approach given that the price of natural gas is generally increasing.

Table 4. NTRC Natural Gas Consumption and Cost Before and After Fuel Cell Operation

**NTRC Before Installation**

| Date | Site Gas Use (therms) | Maximum Site Fuel Use (Demand) | Site Cost ($) |
|---|---|---|---|
| Jun-02 | 2,245 | 546 | 2,474.45 |
| Jul-02 | 1,964 | 546 | 2,101.87 |
| Aug-02 | 1,305 | 546 | 1,714.60 |
| Sep-02 | 1,137 | 546 | 1,721.82 |
| Oct-02 | 1,662 | 546 | 2,035.66 |
| Nov-02 | 3,301 | 546 | 3,078.70 |
| Dec-02 | 4,149 | 541 | 3,721.83 |
| Jan-03 | 7,705 | 291 | 5,913.07 |
| Feb-03 | 6,108 | 383 | 4,769.54 |
| Mar-03 | 3,034 | 383 | 3,508.98 |
| Apr-03 | 6,028 | 383 | 5,138.36 |
| May-03 | 3,417 | 383 | 3,508.98 |
| | | | |
| Total | 42,055 | | 39,687.86 |
| Average fuel cost ($/therm) | | | 1.0596 |

**NTRC During Fuel Cell Operation**

| Date | Site Gas Use (therms) | Maximum Site Fuel Use | Fuel Cell Gas Use (therms)* | Fuel Cell Cost ($) | Site Cost ($) |
|---|---|---|---|---|---|
| Jun-03 | 2,189 | 383 | 1,753 | 1,146.46 | 2,252.84 |
| Jul-03 | 8,013 | unknown** | 9,767 | 6,387.62 | 6,923.20 |
| Aug-03 | 6,219 | unknown | 10,138 | 6,659.65 | 5,413.28 |
| Sep-03 | 1,706 | 291 | 5,152 | 3,457.51 | 1,904.19 |
| Oct-03 | 12,636 | 624 | 7,520 | 5,054.19 | 10,224.45 |
| Nov-03 | 11,742 | 749 | 5,460 | 3,621.62 | 9,460.36 |
| Dec-03 | 20,467 | 770 | 6,844 | 4,669.66 | 16,102.67 |
| Jan-04 | 17,836 | 770 | 6,943 | 4,935.78 | 14,822.50 |
| Feb-04 | 17,021 | 714 | 6,512 | 4,551.24 | 13,964.45 |
| Mar-04 | 3,434 | 557 | 5,746 | 4,079.66 | 3,599.12 |
| Apr-04 | 2,101 | 557 | 4,995 | 3,493.00 | 2,622.10 |
| May-04 | 500 | unknown | 5,162 | 3,894.21 | 1,037.90 |
| Jun-04 | 10,227 | 410 | 4,995 | 3,768.23 | 9,293.22 |
| Total | 111,901 | | 79,234 | 54,572.37 | 95,367.44 |
| Average fuel cost ($/therm) | | | | 0.6880 | 0.8522 |

*Data from internal fuel cell gas monitor. Does not match billing meter.
**Changed billing method to include interruptible rate because of fuel cell installation.

## Electrical Consumption of the National Transportation Research Center (NTRC)

Although electric consumption at the NTRC decreased after installation of the fuel cell, as expected, the cost of electricity per kW-hr increased. This increase in electricity rate is due to: (1) poor power factor because of the engine research using dynamometers to absorb excess power; and (2) increase in peak demand. These changes offset the reduction in electricity costs resulting from operating the fuel cell (see Table 5).

Table 5. NTRC Electrical Use and Cost Before and After Fuel Cell Operation

**NTRC Before Installation**

| Date | Electrical Use (kW-hr) | Peak Demand (kW) | Cost ($) |
|---|---|---|---|
| Jun-02 | 170,520 | 450 | 10,548.86 |
| Jul-02 | 190,040 | 450 | 11,355.58 |
| Aug-02 | 182,040 | 461 | 11,161.15 |
| Sep-02 | 185,120 | 450 | 10,462.26 |
| Oct-02 | 157,800 | 456 | 10,275.01 |
| Nov-02 | 135,480 | 658 | 11,639.71 |
| Dec-02 | 145,200 | 450 | 9,775.72 |
| Jan-03 | 81,480 | 450 | 7,579.63 |
| Feb-03 | 139,440 | 637 | 11,580.31 |
| Mar-03 | 117,000 | 480 | 9,125.73 |
| Apr-03 | 142,440 | 468 | 9,870.84 |
| May-03 | 157,920 | 573 | 11,513.96 |
| Jun-03 | 182,120 | 487 | 10,747.69 |
| Yearly Total | 1,986,600 | | 135,636 |
| Average cost ($/kW-hr) | | | 0.0683 |

**NTRC During Fuel Cell Operation**

| Date | Electrical Use (kW-hr) | Peak Demand (kW) | Cost ($) |
|---|---|---|---|
| Jun-03 | 182,120 | 487 | 10,747.69 |
| Jul-03 | 157,680 | 606 | 11,861.89 |
| Aug-03 | 144,240 | 871 | 14,191.71 |
| Sep-03 | 213,600 | 731 | 15,107.11 |
| Oct-03 | 141,120 | 741 | 13,534.43 |
| Nov-03 | 134,880 | 590 | 11,711.02 |
| Dec-03 | 127,440 | 541 | 10,879.41 |
| Jan-04 | 49,560 | 600 | 8,668.43 |
| Feb-04 | 68,760 | 651 | 9,980.05 |
| Mar-04 | 98,160 | 789 | 12,601.36 |
| Apr-04 | 157,440 | 780 | 14,691.96 |
| May-04 | 178,440 | 655 | 14,056.23 |
| Jun-04 | 276,840 | 702 | 18,223.03 |
| Yearly Total | 1,930,280 | | 166,254 |
| Average cost ($/kW-hr) | | | 0.0861 |

## NTRC Fuel Cell Electric Output

Electric output generated by the fuel cell varied by month depending on the number of shutdown events which govern the operating hours. Because the fuel cell output exceeded the building load, especially during night-time hours, and the system was unable to track the building load, the fuel cell output was reduced to 110 kW. This reduction in output reduced the total MWh produced, but also reduced the shutdown events. The total electric output of the fuel cell for the year was 834MWh (see Table 6).

Table 6. Monthly Fuel Cell Electric Output

| Month | Energy Output (MWh) | Maximum Power Output (kW) |
|---|---|---|
| June-03 | 16.4 | 200 |
| July-03 | 100.3 | 200 |
| August-03 | 109.5 | 200 |
| September-03 | 31.6 | 200 |
| October-03 | 83.6 | 125 |
| November-03 | 42.2 | 150 |
| December-03 | 78.9 | 110 |
| January-04 | 81.7 | 110 |
| February-04 | 76.5 | 110 |
| March-04 | 67.4 | 110 |
| April-04 | 29.0 | 110 |
| May-04 | 77.4 | 110 |
| June-04 | 39.6 | 110 |
| **Total** | **834.1** | |

## Emissions

The air quality is poor in the Tennessee Valley, where ORNL is located. Emission reduction because of distributed generation technology is a key benefit promoted by the Distributed Energy Program. By installing and operating the fuel cell, emission of harmful air pollutants such as $NO_x$ or $SO_x$ is reduced when compared with central generation of power. By selecting and operating the high-grade heat recovery option offered with the fuel cell, the thermal output is beneficially used to heat the NTRC building, year round, reducing the need to fire the building's boilers and resulting in a system efficiency of 59%. This recycle of thermal energy is highly efficient use of the natural gas fuel—an excellent method for reducing air emissions.

$NO_x$ and other harmful emissions produced during operation of the fuel cell are negligible. The steam reformer portion of the system produces a hydrogen-rich gas from the natural gas supply, producing $CO_2$ and water. Since there is no combustion, minimal amount of $NO_x$ is produced (see Figure 3). And since natural gas does not contain significant amount of sulfur (unlike coal), minimal $SO_x$ is produced (see Table 7). Fuel cell technology offers the promise of dramatically reducing air pollution while generating electric and thermal energy.

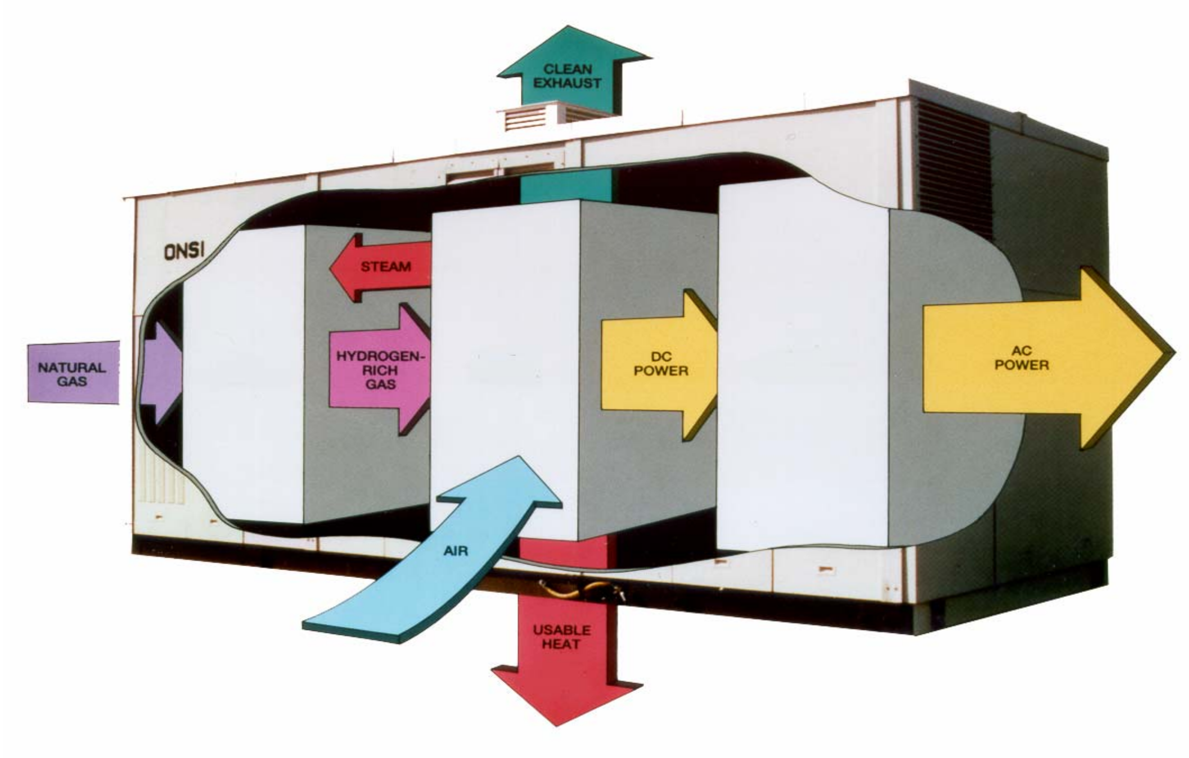



Figure 3. UTC Fuel Cell has three sections: steam reforming; fuel cell; DC to AC inverter.

Table 7. Fuel Cell Emissions

| **Emissions** | **Fuel Cell Emissions (15% O2)*** |
|---|---|
| NOx | <1ppmV |
| SOx | Negligible |
| $NO_2$ | Negligible |
| $SO_2$ | Negligible |
| CO | <2 ppmV |
| Particulates | Negligible |
| Smoke | None |
| Hydrocarbons | Negligible |

* UTC literature

## Conclusions

The UTC Model PC25 fuel cell power plant at the NTRC in Knoxville, Tennessee, successfully completed its first year of operation. Operating data show that the power plant had an availability of 75.6%. The NTRC fuel cell included a high-heat recovery option so that use of thermal energy improves project economics and improves system efficiency to 59% year round. During the year the PC25C supplied a total of 834MWh to the NTRC and provided 300MBtu of hot water. On-going operational expenses are funded by ORNL's utility budget and are paid from savings. ORNL also analyzed valuable technical and operational data, on the fuel cell-grid compatibility, collected during this year of operation. This information is applicable not only to future fuel cell installations, but also to distributed generation that use other prime movers such as microturbines, gas turbines, and reciprocating engines.

With the purchase, installation and operation of the PC25C, ORNL provided electricity to NTRC while decreasing power used from the grid—reducing the amount of harmful pollutants in the air such as NOx and SOx and improving air quality in Knoxville, which recently was designated non-compliant with ozone standards.

With the Department of Energy's help to fund the purchase of the PC25C fuel cell, ORNL was able to develop a better understanding of fuel cell operation that may facilitate installation of fuel cells and further promote the maturing concept of distributed generation.

## Photo Gallery

Figure 4. National Transportation Research Center Site Overview


Figure 5. NTRC Fuel Cell Operating

Figure 6. Fuel Cell Cooling Module and Fence

Figure 7. Fuel Cell Underground Piping


Figure 8.  Fuel Cell Being Unloaded

Figure 9.  Fuel Cell Being Stored During Project Design

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