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The Direct FuelCell™ stack engineering

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Abstract

FuelCell Energy (FCE) has developed power plants in the size range of 300 kW to 3 MW for distributed power generation. Field-testing of the sub-megawatt plants is underway. The FCE power plants are based on its Direct FuelCell™ (DFC) technology. This is so named because of its ability to generate electricity directly from a hydrocarbon fuel, such as natural gas, by reforming it inside the fuel cell stack itself. All FCE products use identical 8000 cm^2 cell design, approximately 350–400 cells per stack, external gas manifolds, and similar stack compression systems. The difference lies in the packaging of the stacks inside the stack module. The sub-megawatt system stack module contains a single horizontal stack whereas the MW-class stack module houses four identical vertical stacks. The commonality of the design, internal reforming features, and atmospheric operation simplify the system design, reduce cost, improve efficiency, increase reliability and maintainability.

The product building-block stack design has been advanced through three full-size stack operations at company's headquarters in Danbury, CT. The initial proof-of-concept of the full-size stack design was verified in 1999, followed by a 1.5 year of endurance verification in 2000–2001, and currently a value-engineered stack version is in operation. This paper discusses the design features, important engineering solutions implemented, and test results of FCE's full-size DFC stacks.

Keywords: Direct FuelCell™; Carbonate fuel cell stack; Internal reforming fuel cell; Full-size carbonate stack

1. Introduction

The carbonate fuel cell promises highly efficient, cost-effective and environmentally superior power generation from pipeline natural gas, coal gas, biogas, and other gaseous and liquid fuels. FuelCell Energy Inc., has been engaged in the development of this unique technology, focusing on the development of the Direct FuelCell (DFC®). The DFC® design incorporates the unique internal reforming feature that allows utilization of a hydrocarbon fuel directly in the fuel cell without requiring any external reforming reactor and associated heat exchange equipment. This approach upgrades waste heat to chemical energy and thereby contributes to a higher overall conversion efficiency of fuel energy to electricity with low levels of environmental emissions. Among the internal reforming options, FuelCell Energy (FCE) has selected the indirect internal reforming (IIR)–direct internal reforming (DIR) combination as its baseline design. The IIR–DIR combination allows reforming control (and thus cooling) over the entire cell area. This results in uniform cell temperature. In the IIR–DIR stack, a reforming unit cell (RU) is placed between a group of standard fuel cell packages. The hydrocarbon fuel is first fed into the RU where it is reformed partially to hydrogen and carbon monoxide fuel using heat produced by the fuel cell electrochemical reactions. The reformed gases are then fed to the DIR chamber, where the residual fuel is reformed simultaneously with the electrochemical fuel cell reactions.

FuelCell Energy plans to offer commercial DFC® power plants in various sizes, focusing on the sub-MW as well as the MW-scale units. The plan is to offer standardized, packaged DFC® power plants operating on natural gas or other hydrocarbon-containing fuels for commercial sale. The power plant design includes other fuel processing options to allow multiple fuel applications. These power plants, which can be shop-fabricated and sited near the user, are ideally suited for distributed power generation, industrial cogeneration, marine applications and uninterrupted power for military bases.

FuelCell Energy operated a 1.8 MW plant at a utility site in 1996–1997, the largest fuel cell power plant ever operated in North America. This proof-of-concept power plant demonstrated high efficiency, low emissions, reactive power control, and unattended operation capabilities. Drawing on the 1.8 MW plant proof-of-concept demonstration experience, FCE has developed its commercial DFC® power plants. FuelCell Energy is currently engaged in commercial field-testing of its DFC® power plants. Over 40,000 operational hours have been accumulated with FuelCell Energy's alpha and beta units providing valuable design and engineering data

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while providing customer training and operational experience.

2. Direct FuelCell® design features

FuelCell Energy Inc., has been engaged in developing a highly efficient, cost-effective direct carbonate fuel cell (DFC®) since the late 1970s. All FCE products use identical 8000-cm^2 cell packages, approximately 350–400 cells per stack, external gas manifolds and similar non-repeating auxiliary hardware components. The unique feature of the DFC® is its ability to accept a hydrocarbon fuel directly without the need for any external reforming. This feature reduces cost and increases overall power plant efficiency dramatically. This is accomplished within the DFC® stack design by a combination of direct and indirect internal reforming cell packages. With this concept as illustrated in Fig. 1, the anode compartment of each cell contains a reforming catalyst for DIR hydrocarbon conversion. Periodically, every 8–10 cells, a special cell containing a reforming unit is situated between cell groups for the initial IIR hydrocarbon reforming. This design approach has been adopted to optimize performance, efficiency, life and thermal management. These cell packages are stacked repetitively until the desired numbers are achieved. A stack compression system and external manifolds are subsequently assembled on the stacked cells forming the building block DFC® stack which is common to all FuelCell Energy products. As illustrated in Fig. 2, this DFC stack is either brought to a horizontal position and integrated with remaining non-repeat components and package in an insulated vessel to form the sub-MW module. Or it is left vertical and integrated with four other identical stacks into a single insulated vessel to form the MW module. This building block approach provides scalability and a standardized manufacturing product that takes advantage of cost savings through the economies of scale.

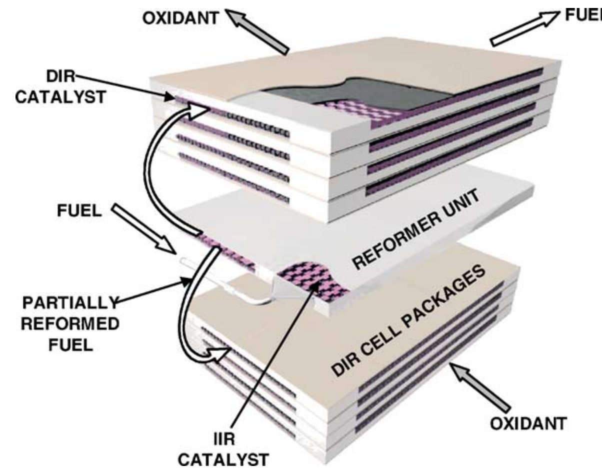


Fig. 1. DFC® stack concept: an indirect internal reforming unit (RU) placed between a group of direct internal reforming (DIR) cell packages.

3. Engineering tools and solutions

Major cell, stack and module design considerations are uniform compressive load to ensure good cell-to-cell contact, thermal uniformity and provision of uniform reactant gas flow (cell-to-cell, within a module and to each stack within a MW module). Over the past decade, several unique engineering tools have been made available for design development, engineering analysis and verification that have

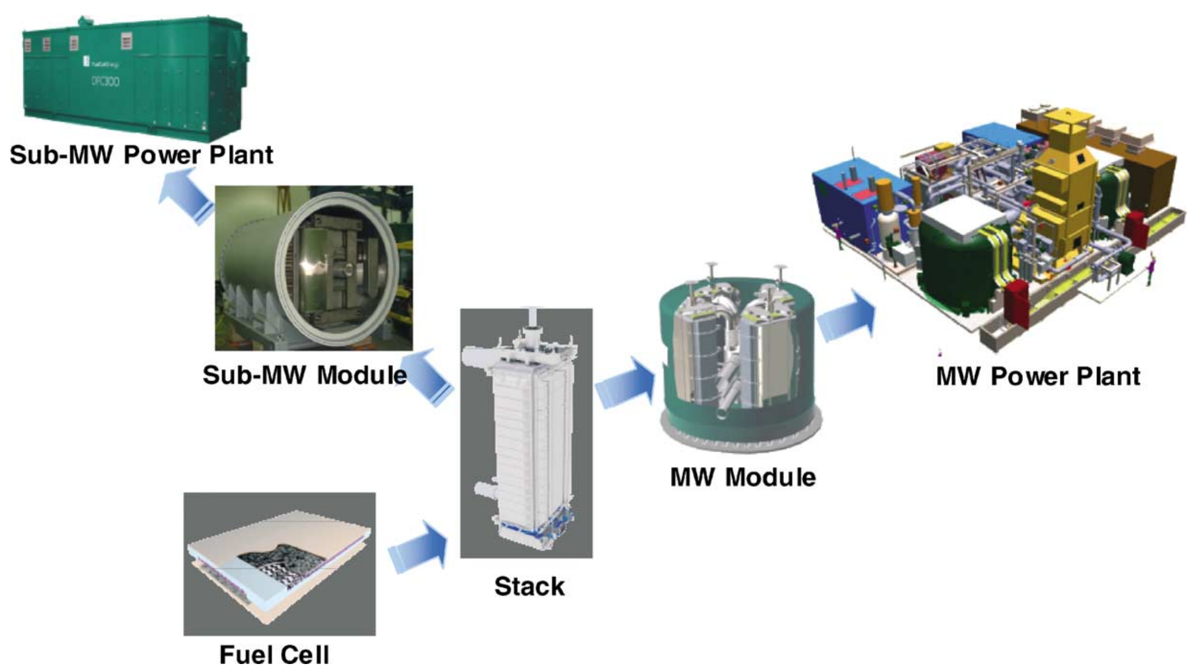


Fig. 2. The building block full-size stack: identical cell packages and common stack hardware is used in DFC® products.

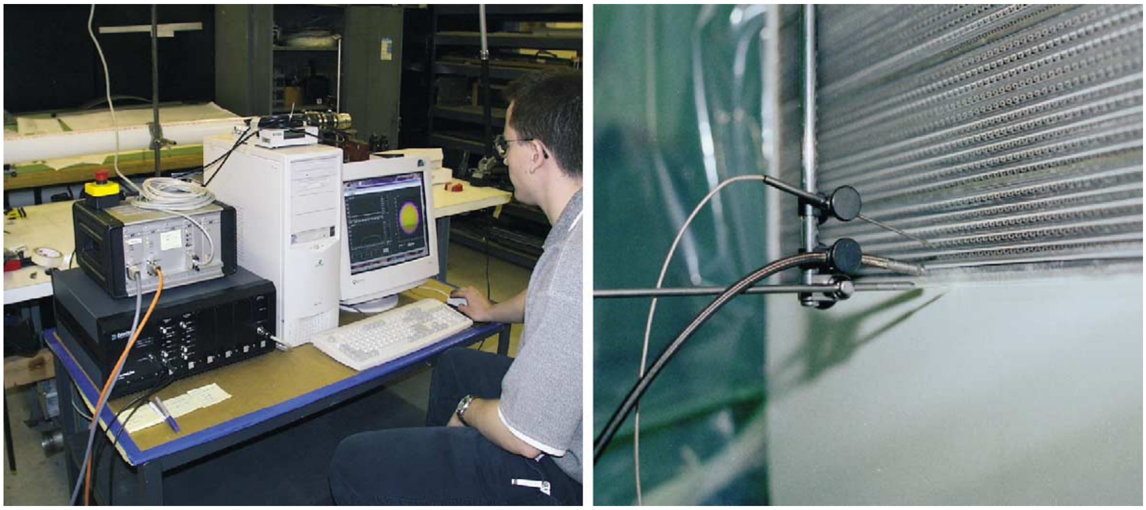


Fig. 3. Hot wire anemometer flow analysis set-up: quantifies cell-to-cell reactant gas flow uniformity within a stack.

greatly accelerated the pace for DFC® power plant development and performance improvements. The following are some of the tools utilized that will be discussed in the following sections:

- Computer aided design (CAD) three-dimensional (3-D) parametric solid modeling.
- Scale models and testing of key functional components.
- Finite element analysis (FEA) of material strengths and stresses.
- Water flow visualization.
- Hot wire anemometer flow analysis.
- 3-D computational fluid dynamics (CFD) simulation models.
- Full scale testing of key functional components.

4. Direct FuelCell® engineering tools and solutions

Techniques such as water flow visualization, hot wire anemometer flow measurement and CFD modeling have been used to enhance reactant gas cell flow uniformity and performance. Simple water visualization equipment can be inexpensively purchased or fabricated to qualitatively identify flow deficiencies. Using water as the medium, the flow can be matched to a gas flow according to appropriate Reynolds number and luminescent dies can be injected in the fluid path to elucidate flow characteristics. In this way, dead zone regions can be quickly and easily identified enabling engineers immediate feedback for corrective action. A more quantitative technique for cell flow characterization is the hot wire anemometer. Fig. 3 shows such an apparatus analyzing cell flow uniformity within a stack. The anemometer is set up to scan across each individual cell package quantitatively measuring flow and temperature. The integrated data identifies cell-to-cell flow variations with high degree of precision and accuracy. Using the hot wire anemometer as a tool, FuelCell Energy engineers have successfully improved cell-to-cell reactant gas flow uniformity six-fold with design improvements.

A comprehensive three-dimensional stack simulation model is being developed at FuelCell Energy that includes

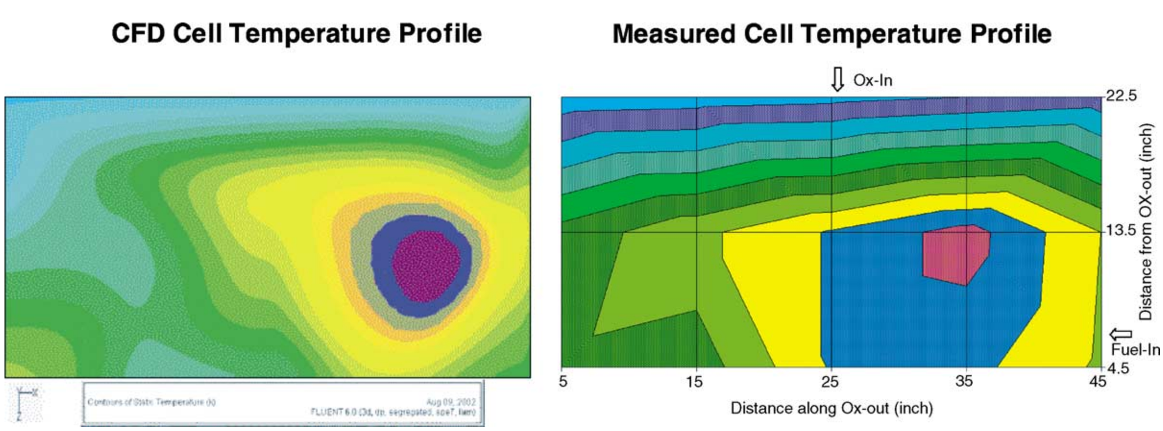


Fig. 4. Model predicted and experimental thermal profile comparisons: good correlation of CFD model with test data enabled engineers to modify design for ~30% improvement in cell thermal profile within a stack.

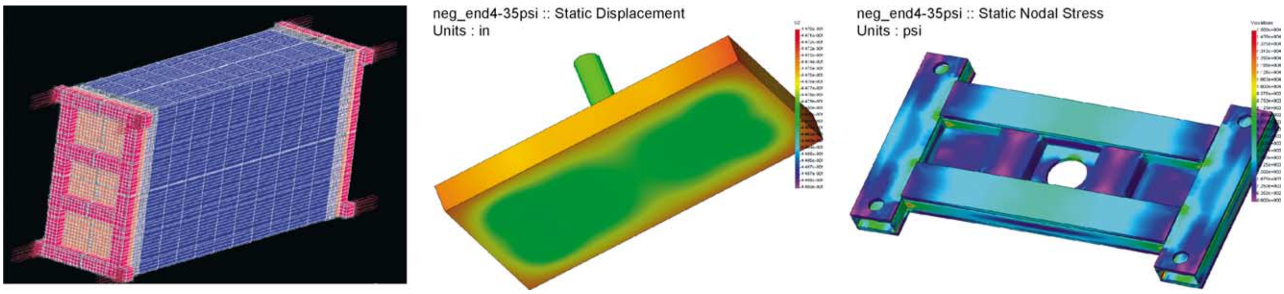


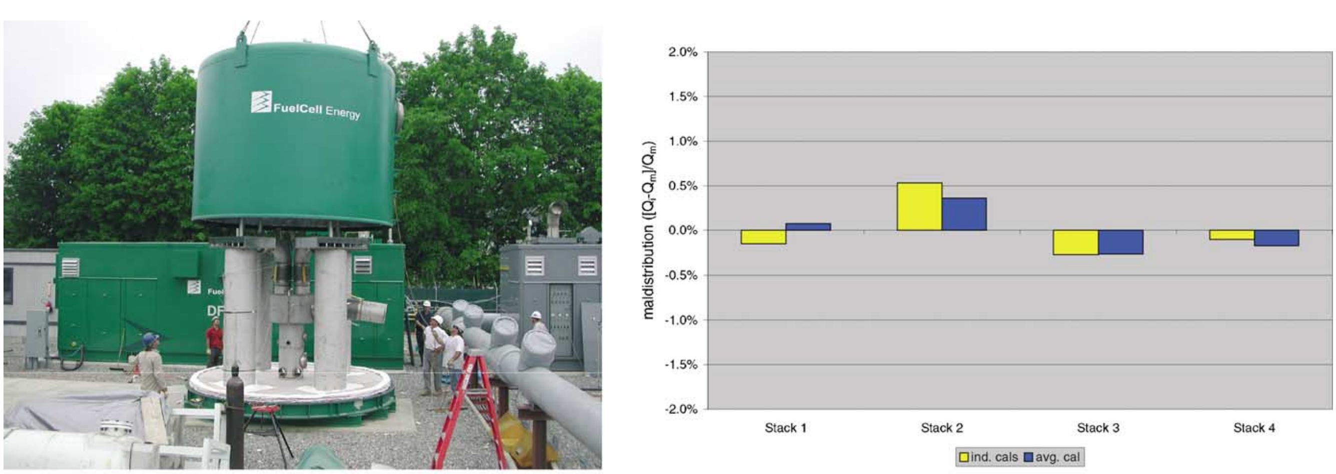
Fig. 5. Examples of computational FEA applications: computational FEA have proven a useful tool to the engineer in developing and verifying new component designs for the DFC®.

fluid flow, chemical and heat transfer processes. Initial results have already aided engineers to a better understanding of the design parameters affecting cell performance. Fig. 4 compares a model predicted temperature profile of a typical cell with results obtained empirically from a full area technology stack instrumented for temperature profiling. These results have enabled engineers to enact cell internal reforming design modifications to improve the thermal profile within a stack by approximately 30%. This advancement enables higher power density operation with improved performance and life.

5. Stack and module engineering tools and solutions

All design and engineering drawings at FuelCell Energy comply with ASME and ANSI standards to ensure quality and vendor compliance. Computer graphics are used to construct state-of-the-art CAD 3-D models enabling design verification in virtual reality to provide interference free fit during assembly. CAD solid models allow use of analysis tools for strength and stress analysis to enable quick, efficient design and materials verification. Finite element analysis modeling of material strength and stress ensures correct design and material selection to prevent failure. Fig. 5A shows that 3-D computational FEA has been used to model stack movement through various operating modes. Fig. 5B and C present FEA models of end plates and compression hardware ensuring that engineered designs meet their functional requirements for flatness, uniform stack compressive load and strength under stack operating conditions (high temperature and load). Using computational FEA as the major tool, engineers have improved compressive load uniformity to the stacked cells two-fold.

Computer aided design 3-D parametric solid modeling has also enabled fuel cell designers and engineers to construct individual components and stack assemblies in virtual reality. This efficient technique identifies design oversights and interferences in advance of component manufacture saving costs and lost assembly time at the factory. Redesign of FuelCell Energy's sub-MW power plant has been performed for improved performance, efficiency and reliability. Key functional components were engineered, designed and fabricated in this improved sub-MW product called the DFC300A in less than 1 year. This rapid design development effort was made possible through construction of a CAD 3-D solid model containing all stack components and the assembled module. This virtual model identified design



(A) (B)

Fig. 6. Full scale testing of MW power plant components: stack-to-stack reactant gas flow uniformity confirmed to be ±0.5%.

interference and provided the database for FEA and CFD engineering analysis. Once a CAD solid model has been constructed, it is likewise useful to construct a scale model to test design parameters using techniques such as water flow visualization, gas flow and pressure drop analysis. As part of design verification for the improved DFC300A, a 1/5th scale model was built using the CAD engineering drawings to ensure precision scaling. Some detailed components were fabricated using state-of-the-art stereo lithography model fabrication to ensure strict dimensional tolerance adherence.

Full scale testing of key functional non-repeating components is also performed prior to stack integration to ensure design functionality. Fig. 6A shows field-testing of key MW class non-repeating components. The actual MW module was assembled with all flow related components (end plates, flow distributors, piping, etc.) and heated to the operating temperature of 650 °C and tested for stack-to-stack flow uniformity using high capacity blowers and calibrated laminar flow elements. Results shown in Fig. 6B confirm uniform flow within ±0.5% to each of the four stacks in the module. Infrared thermal imaging analysis of the module at temperature was also performed to confirm vessel insulation design and identify any potential heat losses that may result in reduced thermal efficiencies. Results indicated some heat loss through the pipe connections that were easily corrected with minor design modifications.

As part of FuelCell Energy's quality improvement process, all major components go through an extensive engineering design failure modes and effects analysis (DFMEA) prior to release for production. Interdisciplinary DFMEA teams are formed with the mission of identifying, prioritizing and resolving potential design weaknesses or problems. DFMEA is an ongoing process minimizing the possibility of a component not functioning as designed and considers potential problems or failures that may occur during normal operation. This processes ensures probability of component success without failure prior to it being procured and installed in the fuel cell power plant.

Fig. 7. Stack FA-100-2 test in 400 kW-class power plant: DFC®/T proof-of-concept and stack design demonstration.

6. Test results of FuelCell Energy's full-size power plants

There have been several engineering improvements in FuelCell Energy's building-block stack design. All major component designs for the full-size stack have been value-engineered for improved functional performance and

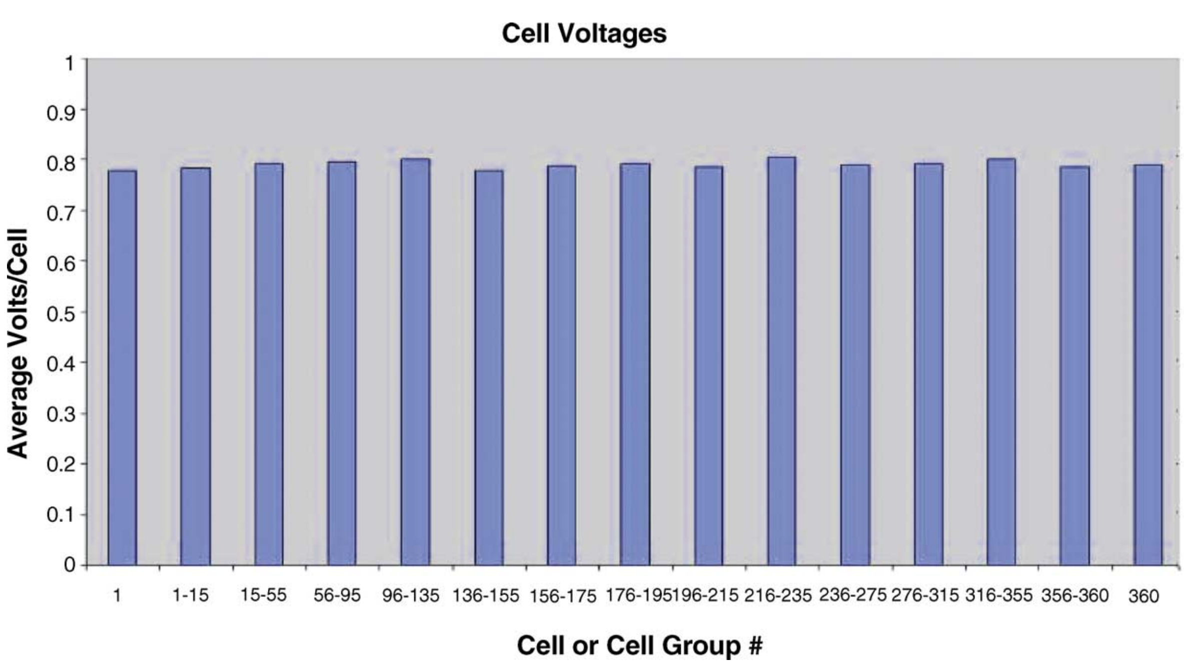


Fig. 8. Stack FA-100-2 performance uniformity at 265 kW dc: uniform performance achieved (±1.6%) in product building-block stack.

reduced cost. The full-height Stack FA-100-2 was assembled with several of these value-engineered components for verification testing. Enhanced involvement by the procurement team has led to multiple approved vendors for key stack components. The first phase of operational testing for FuelCell Energy's alpha unit was in conjunction with a micro turbine as ''proof-of-concept'' design verification. This testing performed at FuelCell Energy's state-of-the-art 400 kW test facility at its Danbury, CT headquarters is depicted in Fig. 7. Cell-to-cell performance uniformity, within $\pm$1.6%, at 265 kW power was achieved as shown in Fig. 8. The major highlights of the system operation include attaining design power level of 250 kW net (eq.) ac, and LHV based efficiency of $\sim$51% at 208 kW net (eq.) ac. The test operation was shutdown for evaluation of stack non-repeat hardware (low-cost value-engineered components) performance, to verify the design for the MW-class stack. All first time used components were examined and verified to have functioned as designed. Based on these findings, the MW-class stack module M10 design has been validated.

Several commercial field trials of FuelCell Energy's Direct FuelCell® sub-MW power plants is underway in the US and Europe. In the US, testing began in June 2001 at the Mercedes-Benz SUV manufacturing facility at Tuscaloosa, Alabama and at the Los Angeles Department of Water and Power headquarters building in downtown Los Angeles, California starting in July 2001. In Europe, Direct FuelCell® power plants supplied by FuelCell Energy's German partner, MTU have operated at the University of Bielefeld, Bielefeld, Germany for >2 years from 1999 to June 2000. Other ongoing demonstrations in Germany are at the Rhon-Klinikum Hospital in Bad Neustadt since May 2001 and at the RWE fuel cell center in Essen since April 2002. These commercial field trial beta units are providing valuable real life engineering data verifying design operability. Customer product familiarity, training and operational experience is also being developed through these successful field demonstration projects. Over 40,000 operational hours have been accumulated from testing at FuelCell Energy's facility and customer sites.

7. Conclusions

The Direct FuelCell® product building-block stack design has been successfully developed and verified for commercial market entry and field trial demonstration. Several advanced and sophisticated engineering tools have been successfully employed enabling rapid design development and verification for early market introduction. These tools have also assisted engineers to develop improved cell and stack designs for enhanced performance, efficiency, reliability and endurance. Successful redesign, from concept to operation, of FuelCell Energy's sub-MW product was completed in less than 1 year due in part to computer aided engineering tools such as CAD solid modeling, FEA and three-dimensional CFD parametric models. This improved DFC300A model being introduced into field demonstration projects is expected to provide performance, life and operational improvements for customer evaluation. In addition, FuelCell Energy's ongoing field demonstrations both abroad and in the US have accumulated over 40,000 h testing confirming the DFC® design, providing valuable engineering data and customer operational experience.

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