

## Final Technical Report

### Integrated Fuel Cell Energy Systems for Modern Buildings

September 2001

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List of Acronyms		
Acronym	Definition	
AGO	Anode-Off Gas Oxidizer	
ATR	Autothermal Reformer	
CO	Carbon Monoxide	
CO <sub>2</sub>	Carbon Dioxide	
DOE	Department Of Energy	
F3P	Fuel-Flexible, Fuel Processor (Ing)	
FPS	Fuel Processing (Or) Subsystem	
H <sub>2</sub>	Hydrogen	
H <sub>2</sub> O	Water	
H <sub>2</sub> S	Hydrogen Sulfide	
HbT	Hydrogen Burner Technology	
HLTS	Humidified Low Temperature Shift	
HRSG	Heat Recovery Steam Generator	
HTS	High Temperature Shift	
IBACOS	Integrated Building And Construction Solutions	
LANL	Los Alamos National Laboratories	
LTS	Low Temperature Shift	
kW <sub>e</sub>	Kilowatts Electric	
NG	Natural Gas	
O&M	Operation and Maintenance	
P&IDs	Piping And Instrumentation Diagrams	
PEM	Polymer Electrolyte Membrane	
PFD	Process Flow Diagram	
ppm	Parts Per Million	
PROX	Preferential CO Oxidation	
S/C	Steam To Carbon	
SN	Serial Number	
SR	Stoichiometric Ratio	
UOB™	Underoxidized Burner	
WGS	Water Gas Shift	
ZnO	Zinc Oxide	
ZnS	Zinc Sulfide	

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## **Final Technical Report -- Integrated Fuel Cell Energy Systems For Modern Buildings**

### **1 Executive Summary**

The changing electricity marketplace is encouraging continued development of distributed generation products. Fuel cells systems for modern buildings provide a viable generation option for distributed sources of electricity. The availability of fuel processor products developed by third parties is enabling fuel cell integrators to focus on their stack, system and application issues. HbT has selected to focus its business on providing fuel processors for various applications.

Fuel processing subsystems that use natural gas are an enabling technology critical to the success of these fuel cell systems in modern building. Reformer products using autothermal technology have advantages with respect to response rate, ease of integration, efficiency, and cost. Ultimately, the fuel-processing product selected by fuel cell integrators will be based on price, performance, and availability. HbT has established business approaches, strategic alliances, and product development paths to enable the introduction of fuel cell systems.

HbT has successfully developed an integrated natural gas fueled, fuel processing subsystem and is actively moving this product toward a commercial product. This cooperative agreement with the Department of Energy building systems programs in parallel with a cooperative agreement on integrated fuel processing subsystems for transportation and two HbT internal programs were critical in establishing the technology basis for a commercially viable stationary fuel processing product. The initial model of this technology is currently being integrated with fuel cell systems for validation of product performance.

After detailed market analysis during Phase I and series of design decisions and technology validations, HbT has selected the autothermal reforming technology as the basis for this product line. A 10kW<sub>e</sub> FPS fueled by natural gas provides high efficiency, reliable performance, and quality anode ready gas for integration with the fuel cell system. The unit design was based on both customer application requirements and market study results for commercial office buildings. A manufacturing agreement was established with Visteon to support mass production and focused cost reduction activities. An initial lot of units were manufactured under the HbT internal programs and this cooperative agreement helped support some of the operational and reliability testing. Test results indicate the unit operates to specification and initial reliability is acceptable.

## 2 Introduction

The focus of this project was the development of a natural gas (NG) fueled, fuel processing subsystem (FPS) for polymer electrolyte membrane (PEM) fuel cell systems in modern buildings applications. This cooperative development program was coordinated with several parallel programs that were related to integrated fuel processor developments for fuel cell systems. The most significant were the development of an integrated fuel-flexible, fuel processing subsystem (DE-FC02-97EE0482) and internal HbT programs to develop autothermal reforming (ATR) technologies and to develop a commercially viable stationary subsystem.

### 2.1 NG Fuel Processing Subsystem Project

The purpose of the program was to advance reforming and fuel-processing technologies for PEM fuel cells in stationary applications. The program objectives were to assess alternate hardware configurations; develop a multi-kilowatt, NG FPS unit; map its performance characteristics; and assess reliability characteristics.

The project was divided into two phases. Phase I focused on the effort to assess alternative hardware and system configurations based on market analysis. Phase II focused on the fabrication and testing of a NG Fuel Processing Subsystem.

### 2.2 HbT's Fuel Cell Product Line Technology Base Objective

In addition to the objectives above HbT also participated in this program to advance its overall fuel processing technology and to establish a product line directed at fuel cell system applications. After market considerations HbT determined that the stationary fuel cell market was a near-term business opportunity in comparison to the transportation markets. In late 1999 HbT shifted a majority of its internal activities toward this stationary market opportunity.

### 2.3 Project History

The project began in October of 1997 and continued for three and a half years. The first 12 months was dedicated to Phase I, and Phase II covered the remaining period. Several issues arose during the project that caused several aspects of the original scope to be modified. The technical details of these are discussed below in the appropriate technical sections. The Phase II project was being conducted prior to, but generally in parallel with, internal development programs focused on commercial products for fuel cell developers. Originally, this project was based on non-catalyzed partial oxidation reforming equipment, but commercial interactions with a fuel cell developer indicated the need for increased H<sub>2</sub> concentrations and improved process efficiencies. As a result HbT initiated a parallel effort to develop ATR technologies for reforming to meet this and other customer requirements. At that point this project and its non-catalyzed hardware configuration was placed on hold.

HbT spent from the summer of 1999 to the end of the year assessing ATR technology retrofits in the fuel-flexible, fuel processing hardware ("Alpha Series



Hardware") that was originally developed under a parallel cooperative agreement. The success of these efforts greatly improved the subsystem performance. At this point due to the commercial potential for stationary applications HbT initiated the development of its "Beta Series" hardware for PEM fuel cells. With the concurrence of the DOE project manager the remaining scope of this effort was used to partially support testing activities focused on reliability and characterization testing of the "Beta Series" hardware.

#### 2.4 Report Organization

This final technical report is organized to provide a description of the project. Section 3 reviews the Phase I project market studies; Section 4 provides the a discussion of the Phase II hardware concepts; Section 5 assesses the Phase II test results; Section 6 identifies a follow-on activity; and Section 7 outlines the project summary.

### 3 Phase I Building System Analysis

In the Phase I effort HBT and its subcontractors Integrated Building and Construction Solutions (IBACOS) and Arcadis (formally Accurex) addressed the benefits and opportunities of various natural gas (NG) fuel processing subsystem (FPS). The variations included pressurized and ambient subsystems along with optional approaches to carbon monoxide (CO) control. IBACOS provided a linkage to the commercial building sector and equipment manufacturers while Arcadis conducted environmental assessments and system performance modeling.

#### 3.1 Market Analysis

HBT and IBACOS identified three market segments – Offices, Schools, and Retail Stores – to be evaluated during the Phase I effort. These segments were selected because they represent over 50% of the commercial sector buildings in the United States. In addition these segments are not known as priority cogeneration markets because they tend to have little if any thermal use especially on a year round basis. This was important because the non-catalyzed partial oxidation or underoxidized burner (UOB™) reformer technology is generally characterized as a lower efficiency, lower cost approach to fuel processing. These inefficiencies can be recovered as useful product heat, but over-dependence on heat recovery and utilization has fooled many developers of cogeneration systems in the past. In fact if one assumes the overall efficiency (electrical plus thermal efficiency) is equal to the building's boiler efficiency, the effect of electrical efficiency disappears from the economic analysis. This requires that all of the product heat can be used, but past experience has shown that 100% heat utilization is not practical in real world applications. Some times the cost of thermally interconnecting the cogeneration system with the building does not justify the energy value of the recovered heat.

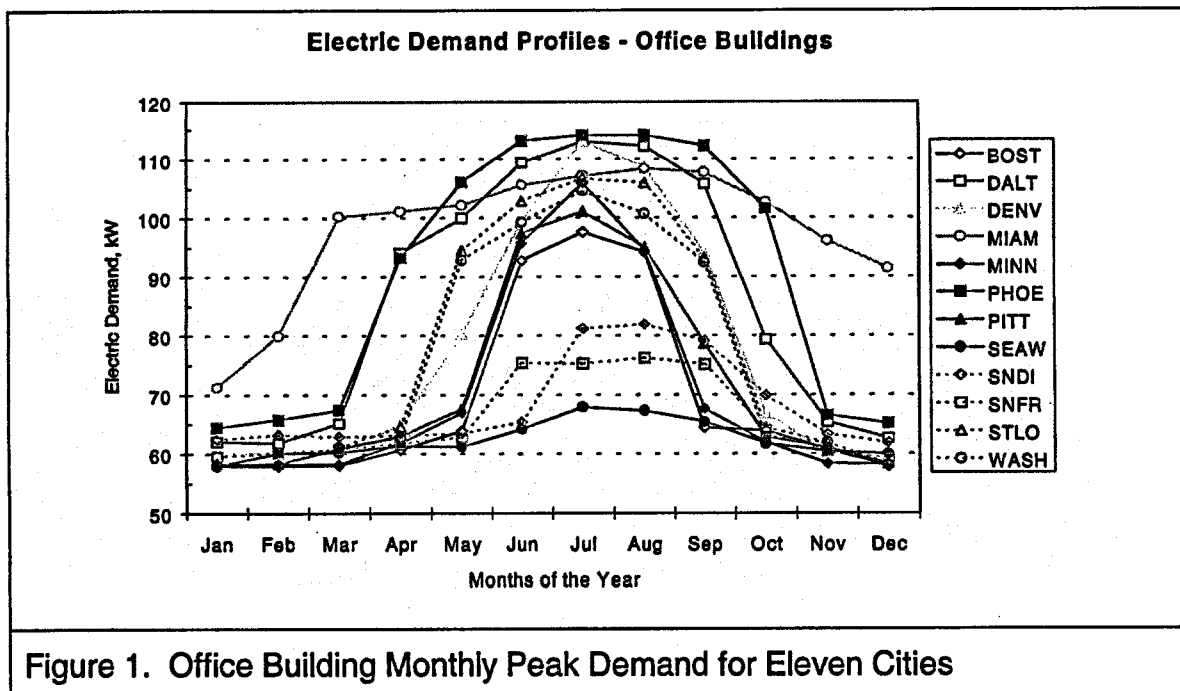
The Phase I study addressed seven alternate systems. The best overall approach was an integrated UOB™ fuel processor based on the hardware configuration being developed and verified for automotive applications. This hardware integrates the UOB™ process preheat exchangers, reaction chamber, product gas quench, ZnO absorbent, high temperature shift (HTS), heat recovery steam generator (HRSG), low temperature shift (LTS), final CO polisher and heat recovery exchanger into a single hardware package. This was believed at the end of Phase I to minimize the capital cost of the NG FPS package while benefiting from the low volume and high power density goals of the system developed for the automotive applications. At the end of Phase I the selected CO polishing technology is a dual-bed adsorption CO clean-up package being evaluated by HBT and our automotive fuel cell manufacturing partner. This UOB™ NG FPS package is described in more detail later.

The primary driver for the specific subsystem's selection was its ability to achieve a low capital cost in low production volumes. Capital cost of the systems evaluated appears to control the economics of the various systems analyzed. During Phase II activities alternate configurations driven by automotive catalytic converter style hardware seemed to achieve the least cost approach.

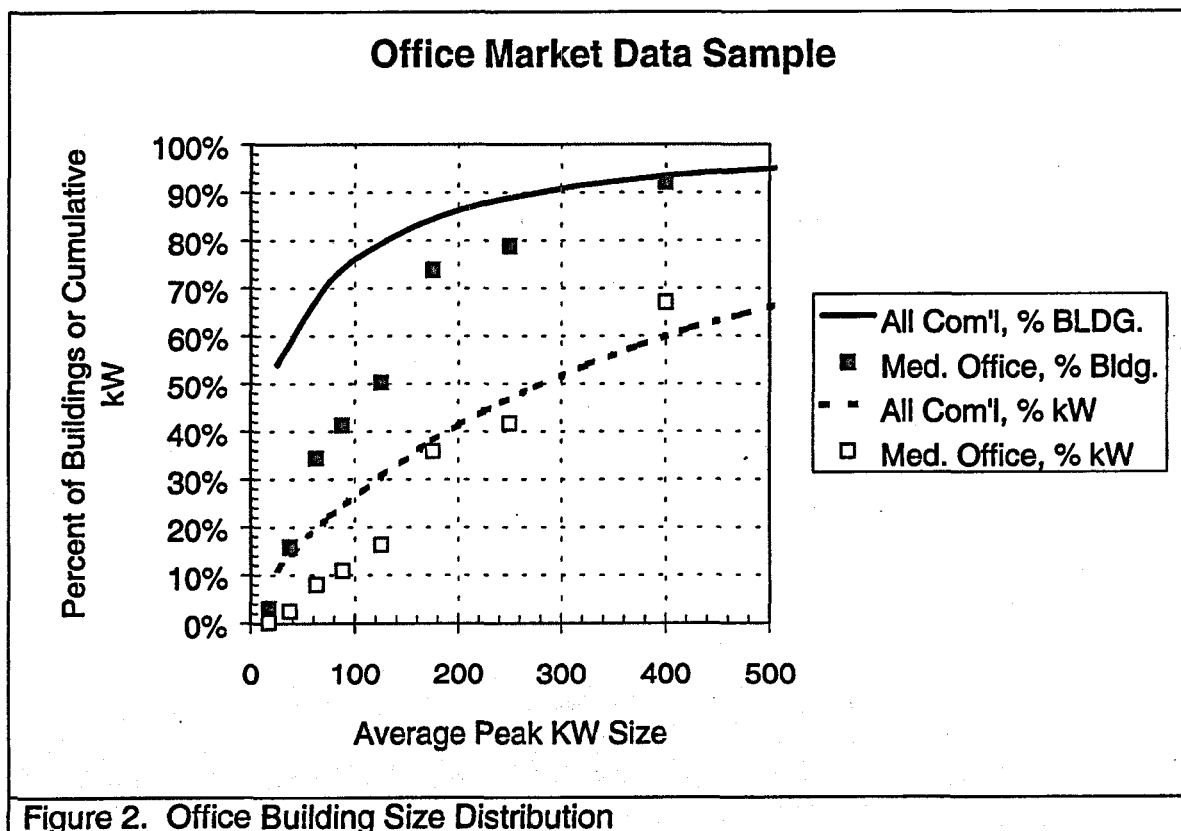
During Phase I HBT was assisted by IBACOS and Arcadis in evaluating seven alternative subsystem and system options. This effort was performed to identify the critical trade-off analysis that would drive the product development effort and ensure the highest probability of a commercially successful product. IBACOS provided detailed commercial building system design and population data plus an understanding of the criteria used by different building owners and equipment manufactures to assess worthwhile investments. Arcadis provided some environmental evaluations and conducted system level modeling to identify system cost and performance characteristics. HBT processed this data and information and conducted extensive statistical and probabilistic type market analysis utilizing an existing economic analysis and forecasting model.

IBACOS collected and processed commercial building data on three market segments – Offices, Retail Stores, and Schools. This data included energy use profiles, building population estimates, building size distribution estimates, up-to-date energy rate structures, and regional representations. Eleven cities in four regions were selected to reflect the normal variation of climate and building use characteristics typical within the United States.

This data was summarized and processed to provide the required format needed by the economic analysis model. As an illustration, the electric energy monthly peak demands for a typical, medium-size office building is shown in Figure 1. Similar data was prepared for the typical building electric load factors, and thermal energy use expressed as a thermal to electric energy ratio.



IBACOS also developed sample building population and distribution data for input into the economic model. This data allowed the economic program to assess the optimum size or preferred capacity for the fuel cell system. Figure 2 illustrates the sample office building data provided and compares it to data for the entire commercial building sector. The sample included over 500 individual buildings in the eleven cities and related suburban areas. A larger sample would help to create a more uniform distribution, but the focus of this effort was on providing indications of trends not extensive market modeling. Another observation from this data was that the office segment represents a class of buildings that tend to be larger than the typical commercial building. The more gradual rise for the offices (solid squares) in comparison to the more rapid raise for all commercial buildings (solid line) demonstrates this characteristic.

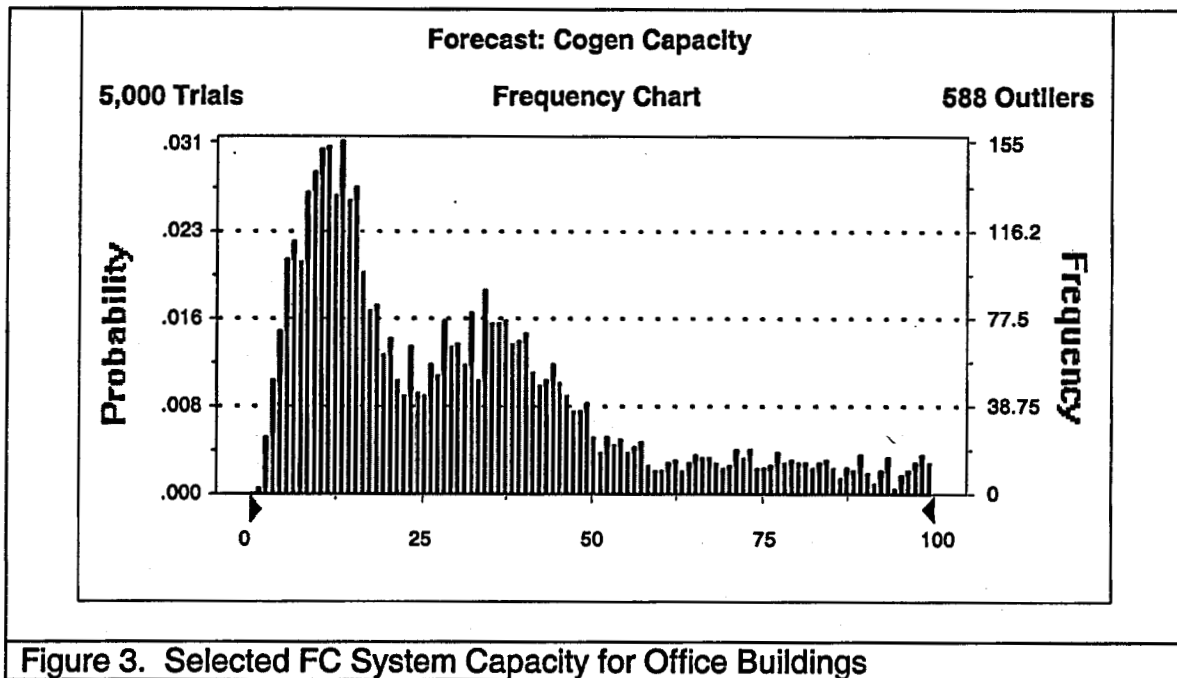


### 3.2 Unit Capacity Selection

This data was important to the overall design activity and selection of the proper product capacity. Everyone realizes that ultimately a complete family of fuel cell products will be needed to serve the commercial sector. Incrementally units as small as 5 to 10 kW, followed by a 20 to 25 kW product, a 50 kW product, up to the 200 to 250 kW class product will be needed. Today, fuel cells are being introduced at the 200 kW and 250 kW. Small capacity units will have broader market applications, but also drive the estimated operations and

maintenance (O&M) costs higher because the O&M will tend to be driven by the number of visits to the site and not the actual cost of the hardware serviced.

This size distribution data on office buildings was used to select the nominal/peak size of the UOB™ NG FPS package. During the modeling runs HBT selected an option that varied the system capacity based on the building energy loads and characteristics. Figure 3 illustrates the results from one of these runs.



This Figure 3 data indicates that a majority of the systems that were sized below 50 kW capacity when the economic sizing filter was utilized. The median of this data is at 30 kW although the data ranged from as small as 2 kW to as large as 465 kW. Two obvious peaks exist, which are driven by the office building size distribution and the economics of under sizing with respect to the building peak load. Based on this type of analysis, HBT has selected the nominal 25 kW NG FPS unit as the optimum design capacity for the initial product configuration at the end of Phase II for prototype package development and verification. A unit size of 10 kW<sub>e</sub> would also make sense from this data.

### 3.3 System Configuration & Technology Selection

Several system and NG FPS package options were evaluated as part of the Phase I activities. These ranged from units without heat recovery, systems based on ambient pressure operations, and systems operating at two to three atmosphere pressure. Other trade-off analysis included CO polishing hardware and process options. Likewise the CO polishing unit was eliminated and the stack are was increase to compensate for the decreased cell performance.

Some of these results are illustrated in Figure 4. In this chart all the system's data points illustrate the range of results with one set of probabilistic assumptions. The data shows the break-even cost of electricity generated by the fuel cell system versus the system's estimated installed capital cost in \$/kW. This data represents the office building segment and all eleven cities or climate effects. Fuel prices range from 3 to 8 \$/mcf based on rate data collected by IBACOS.

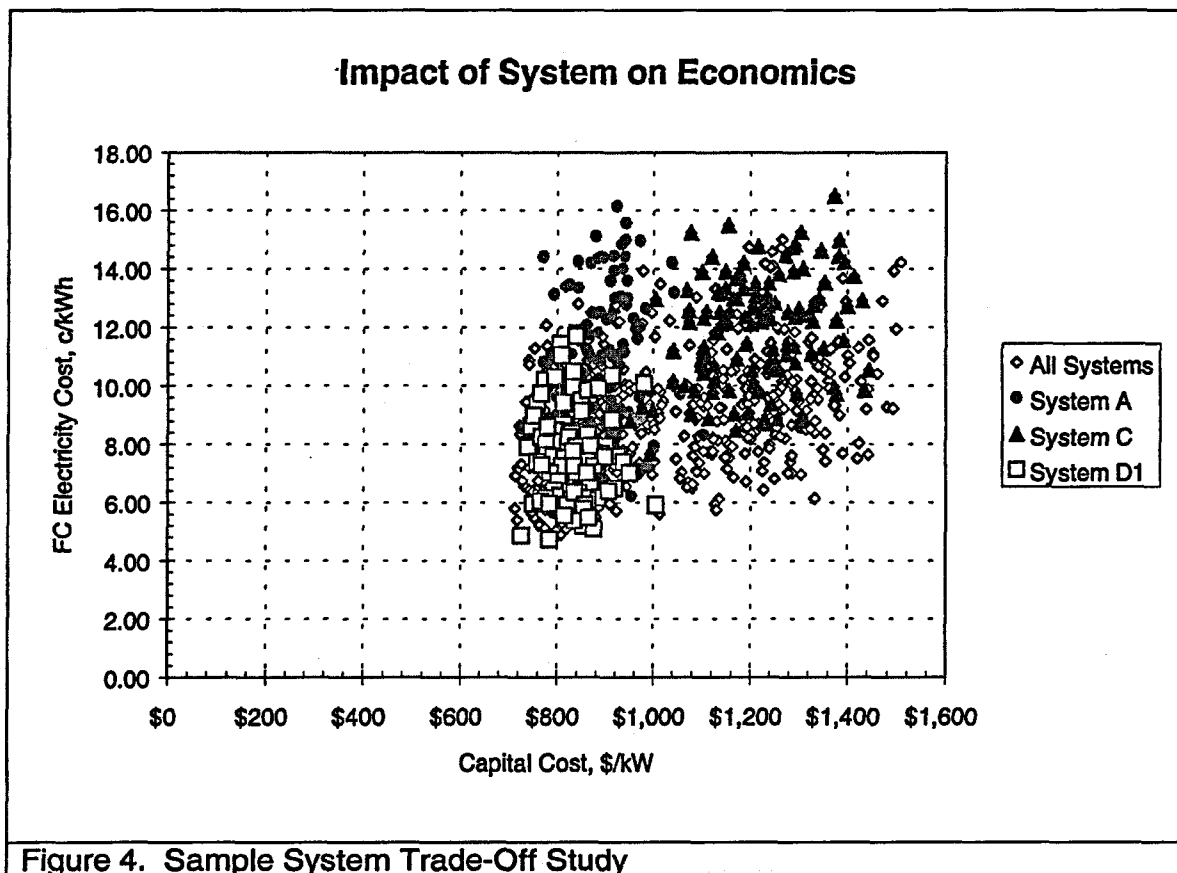
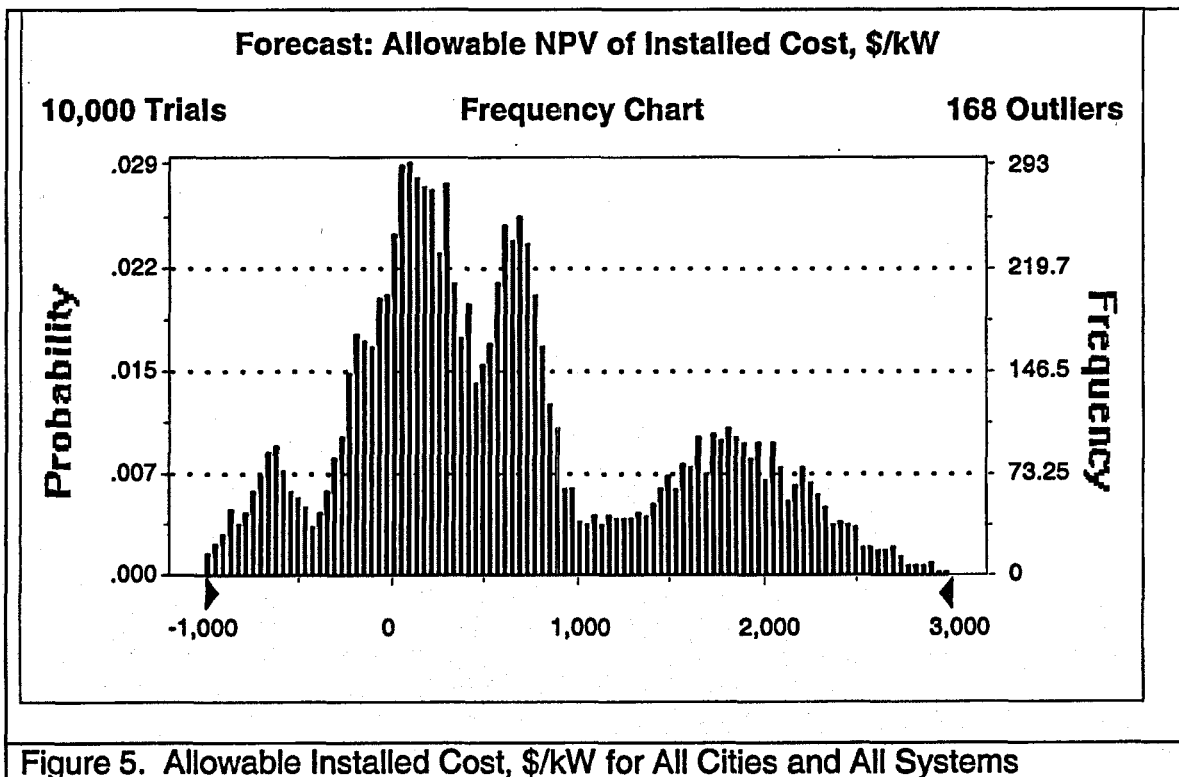


Figure 4. Sample System Trade-Off Study

The system capital cost was estimated in relatively high production volumes. Cost was estimated for the fuel cell stack, the NG FP subsystem, process feed pumps, air supply system, electrical including controls and power conditioning, and heat exchanger equipment. Approximately three quarters of the costs were split evenly between the fuel cell, NG FPS, and the electrical components. These costs were then increased by 100% to reflect manufacturer mark-ups and distribution costs, finally 7% sales tax was assumed. Installation costs were probabilistically handled but ranged between \$100 to \$350/kW. The no-heat-recovery case was discounted by 50% due to absence of thermal interconnect requirements. Three cases are illustrated in Figure 4. Case A is the blower-driven process that has a low electrical efficiency at high load factors because of the increased parasitic loads. Case C is the no-heat-recovery case but includes a higher price fuel cell stack. Case D1 is the system that represents the selected NG FPS package. Although the no-CO polishing case had similar

economic performance as the selected case when the fuel cell costs are low, early market considerations caused this system not to be selected. When the cost of the fuel cell hardware is high the CO polishing system is preferred. Probably the most critical observation of these data is that the variation between the various systems was from 5 to 15 c/kWh and the variation within selected system was 5 to 12 c/kWh. What this states is that the market variation covered within the analysis had a greater impact on economic performance than the system configuration variations. Therefore, the best system is the system driven by customer decision criteria than economic criteria.

Another method of evaluating economics is to assess the allowable installed cost of the systems based on the customer's economic criteria. Figure 5 illustrates a typical example of the results achieved from the eleven cities and multiple system model run. Multiple peaks in this chart are driven by the various electric and gas rate schedules versus the fuel cell system characteristics. As prior experience has indicated, the market for onsite or building energy systems providing electricity is very regionally sensitive.



### 3.4 Economic Sensitivity

The sensitivity of the fuel cell system economics is driven by many parameters. The five most sensitive parameters, when economics were assessed as the system's average cost of electricity, were the stack or NG FPS

package cost uncertainty, the customer acceptance criteria (discount rate), the city and related fuel price, number of maintenance visits per year, and the system cost and performance variations. The relative sensitivities of major parameters are as follows (greatest sensitivity to least):

- Uncertainty in the stack and NG FPS package costs had a sensitivity of 6.
- Customer discount rate had a sensitivity of 3;
- Selected city had a sensitivity of 2;
- Number of maintenance visits had a sensitivity of 1.2; and
- System type had a sensitivity of 1.

These results indicate that HBT's approach to focusing on durable and low cost fuel processing technology is proper. Minimizing subsystem complexity and cost are important. For these reasons at the end of Phase I the dual-bed adsorbent, CO polishing technology was selected because it appeared to have less risk and fewer control issues when compared to active air bleeds system such as the preferential oxidation (PROX) reactors. From a cost stand point, all of these systems had similar costs in high production, but the dual-bed adsorbent and methanation approach had lower costs in low production. The methanation unit was not selected because it had a higher parasitic hydrogen loss, and therefore, lower system efficiencies.

By the conclusion of Phase II this decision was reversed and HbT adopted the PROX hardware concepts due improved performance during transient and the ability to consistently achieve lower CO concentrations. These criteria became more important customer criteria as commercial discussion identified specific needs.



## 4 Hardware Selection

At the end of Phase I, HBT selected the UOB™ NG FPS package to be developed for Phase II activities. This system is a direct derivative of the automotive system being developed under a parallel DOE sponsored program. Again, as commercial discussion progressed and improved operational characteristics were being requested by the fuel cell developers, HbT placed on hold the Alpha Series fabrication and adopted autothermal reforming technology and an advanced Beta Series package. This Beta Series package was the hardware actually used for verification testing.

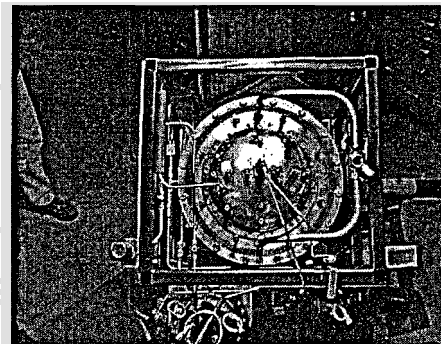
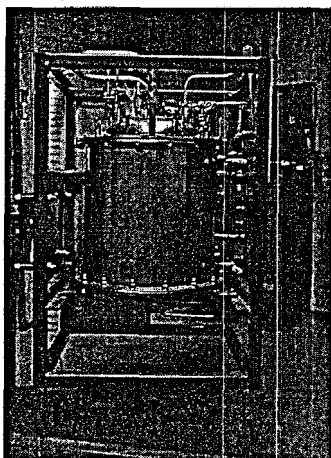
### 4.1 Alpha Series Hardware

An illustration of the Alpha Series hardware is provided in Figure 6. The capacity of the shift reactors has been increased to extend the operation maintenance interval. The unit is easily maintained and compact in configuration, but relatively high cost in low production volumes. The primary interfaces are inlet process air, inlet process fuel, and demineralized water. The output is a mixed gas, hydrogen rich stream. The stream is near saturation and at PEM fuel cell operating temperatures. The CO level was projected to be between 10 and 20-ppm. The Hydrogen concentration is approximately 35 to 40% on a dry basis depending on operating load condition. The design stoichiometric ratio for the pre-commercial hardware is 0.35 to 0.40 depending on the operation point. The modeling effort assumed increasing SR levels with lower loads to maintain reactor temperatures. This relates to a NG FPS package efficiency of 70 to 75% based on the lower heating value of natural gas.

The primary unit integrates all of the functional process components into a single integrated package. The core of this unit is the partial oxidation combustion chamber, which is fed by a proprietary HbT process gas injector at one end. The patented chamber design and recuperative heat exchanger configuration central to HbT's UOB™ technology is utilized. A shell-in-shell configuration, with its co-flow/counter-flow process orientation is used. After exiting the heat exchanger section the UOB™ product gas flows through a water quench and sulfur absorbent cartridge then enters the high temperature shift (HTS) section. Following the HTS is a heat recovery steam generator (HRSG) and finally the low temperature shift (LTS) reactor section.

The HTS and LTS are located in annular chambers surrounding the combustion chamber. By-product heat from the HTS reaction is used to pre-heat the inlet process air prior to entering the recuperative heat exchanger section of the NG FPS package assembly. The temperature of this final process is controlled to minimize CO concentrations and properly condition it for the CO polishing process. The NG FPS is designed for pressurized operation to minimize face velocities in the catalyst beds and to maximize system performance.

## Top and Side View of F3P Assembly



September 01

Hydrogen Burner Technology



Figure 6. Top and Side View of Alpha Series Hardware in Test Fixture Frame

### 4.2 Beta Series Hardware

With the development of the Beta Series hardware under HbT internal program activities, different hardware decisions were made based on improved technology and expanded cost estimates. This hardware design was sized to be 10kW<sub>e</sub> peak capacity with 7kW<sub>e</sub> high normal operation and 2kW<sub>e</sub> low normal operation. This capacity was consistent with the analysis and our customer needs, although half the size originally selected. ATR technology was selected because it enhanced system efficiencies achieving values of 80 to 85% (LHV of H<sub>2</sub> generated / fuel consumed). The water gas shift reactor was selected to be a single temperature based on conventional LTS catalyst and a three-stage PROX reactor was developed.

Several hardware configurations were tested and alternate integration and manufacturing approaches were assessed during the prototype development step. These efforts led to the "Beta Series" hardware platform, which is shown in Figure 7. This figure also identifies the six major components or groups comprising the fuel processor. The process hardware includes four vessels – ATR Reactor, WGS Reactor, PROX Reactor, and the AGO Combustor. The fifth group consists of the blowers, valves, sensors, and other components needed for measuring and managing the process fluids as they are feed into the reactors. The major items are the process air blower, natural gas compressor, and combustion air blower. The final group is the process controls, which include

both hardware and software. All of these components are packaged into a single frame intended to meet customer volume and configuration requirements. The unit is 50 cm wide by 75 cm long and 109 cm tall and weights slightly over 180kg.

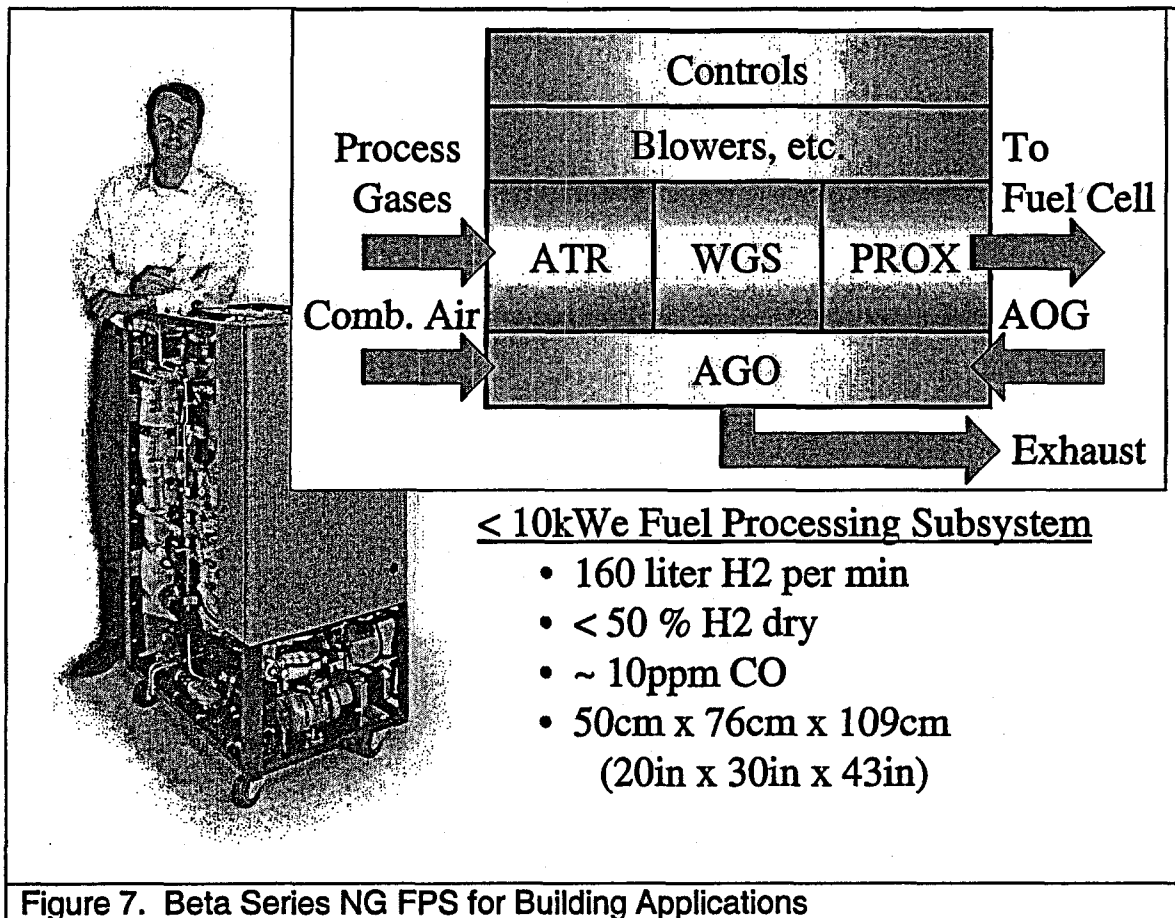


Figure 7. Beta Series NG FPS for Building Applications

The Beta Series hardware is a fully integrated, fuel processing subsystem. Direct current electricity consistent with the unregulated power from a 10kW<sub>e</sub> fuel cell stack powers the controller, blowers, and other ancillary components. Pipeline quality natural gas and air are pressurized sufficiently to overcome internal unit pressure drops and meet product gas delivery pressure requirements up to 0.3atm (5psig). The current design philosophy anticipates that a source of treated and pressurized water is available from the fuel cell's balance of plant. This water is used both to cool internal reactors and to generate steam for use within the process. During start-up the product gas is used internally to drive the reaction, and once all the reactors achieve normal operation, the unit automatically sends the product gas to the fuel cell stack. The ATR reactor is the primary unit that converts the fuel into H<sub>2</sub>, CO, and CO<sub>2</sub>. The WGS reactor functions to convert the CO in the ATR outlet gas into CO<sub>2</sub> and additional H<sub>2</sub>. The PROX reactor selectively oxidizes any remaining CO to achieve the fuel cell requirement of 10ppm. The final reactor group, the AOG combustor is responsible for thermal management. The AOG combusts

hydrogen and methane remaining in the anode off gas stream after the fuel cell and uses the heat for steam generation and reactant preheat.

Although HbT's product roots are in industrial on-site hydrogen generation systems, the company has recently focused on bringing to market a fuel processing subsystem for stationary distributed power. This product is designed to enable PEM fuel cell system integrators to evaluate HbT's technology and establish business relationships for specific products that meet their customer's needs. Since technological maturity and market applications differ between individual fuel cell integrators, the fuel processing subsystem requirements also vary among applications and integrators. HbT's approach to addressing these various needs is to develop a generalized product capable of meeting all the requirement of a few select customers. The product requirements and specification for this unit are defined in Table 1.

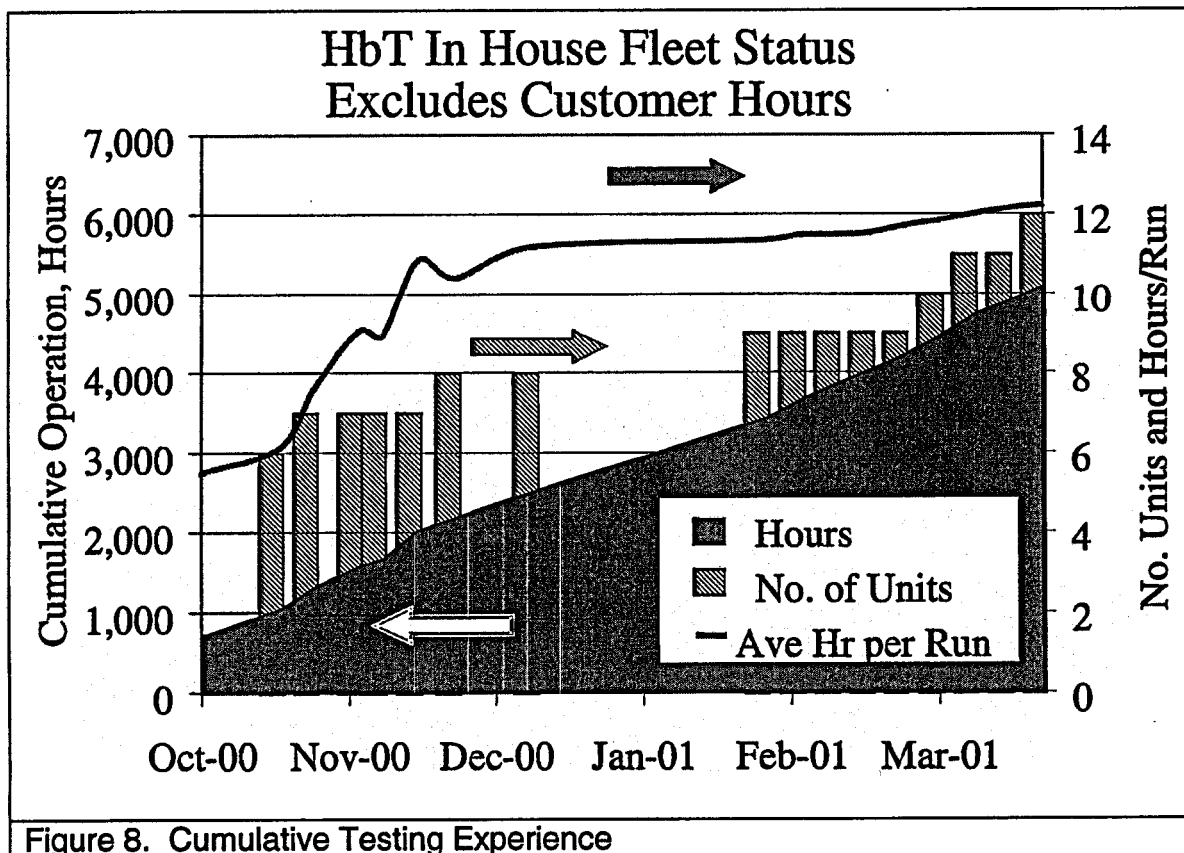
Table 1. Summary Specification for Beta Series Hardware				
Category	Units	Product Development		
		Pre-Production	Production	Commercial
H2 Production Capacity	Normal Liters per minute	30 to 160	13 to 160	Tailored to Customer
Power	kW <sub>e</sub> net	2 to 10	1 to 10	---
Inlet Fuel Source		Natural Gas Propane HD-5	Natural Gas Propane HD-5	Natural Gas Propane Diesel
Outlet Product				
H2 Concentration	% dry	~45%	> 50%	> 50 %
CO Upper Limit	ppm vol	30	10	10
Sulfur Upper Limit	ppb vol	500	<500	200
Start-up Time	Minutes	60 to 120	< 30	< 15
Reliability Estimate	MTBF, Hours	~ 20,000	~ 40,000	~ 60,000
Life Expectancy	Years	< 1	< 4	8 to 20
Full Load Parasitic Power	Watts/kW <sub>e</sub>	60	25	14
Product Selling Price	\$ US/kWe	\$3k to \$5k	\$500 to \$1k	under \$200

## 5 Test Results

During the initial manufacturing and developmental stage 25 units have been fabricated. To date, 18 have been built, 13 by HbT and 5 by Visteon. We have shipped 5 of these units to customers for their evaluation and have scheduled another five for shipment. HbT and Visteon are using the other units for evaluation and reliability testing and for technology development.

### 5.1 Pre-Production Unit Test Experience

The ATR reactor demonstrated that 85 to 95% of the fuel is converted into  $H_2$ ,  $CO$ , and  $CO_2$ . Internal heat recovery achieved S/C ratio in the range of 2 to 3 without supplemental fuel consumption. Over 5,000 hours of testing experience has been logged on the beta test units. This has been limited primarily by availability of test facilities. Figure 8 provides a summary of the HbT in-house fleet status for these units through April 2001. Currently, with a mix of unit development and endurance testing this experience is achieving on average of approximately 12 hours per run. The maximum operational experience on any one unit is over 1,500 hours and the longest continuous test was just under 300 hours.



## 5.2 Characterization Test Results

Figure 9 demonstrates some of the operational characteristics of these units. The figure illustrates a six-hour portion of the acceptance testing on one unit. The product  $H_2$  concentration was approximately 52-53%, which is well above the target of <45% and meets our commercial targets. The product gas CO level was also below 10ppm, also meeting performance targets. Also shown is the transient performance behavior. During this run an up transient from 2.5kW<sub>e</sub> to 4.5kW<sub>e</sub> was completed, followed by four small down transient steps back to 2.5kW<sub>e</sub>. The important characteristic to note is the stability of the CO level, which remained below 20ppm. Operation similar to this should be acceptable to any fuel cell system integrator.

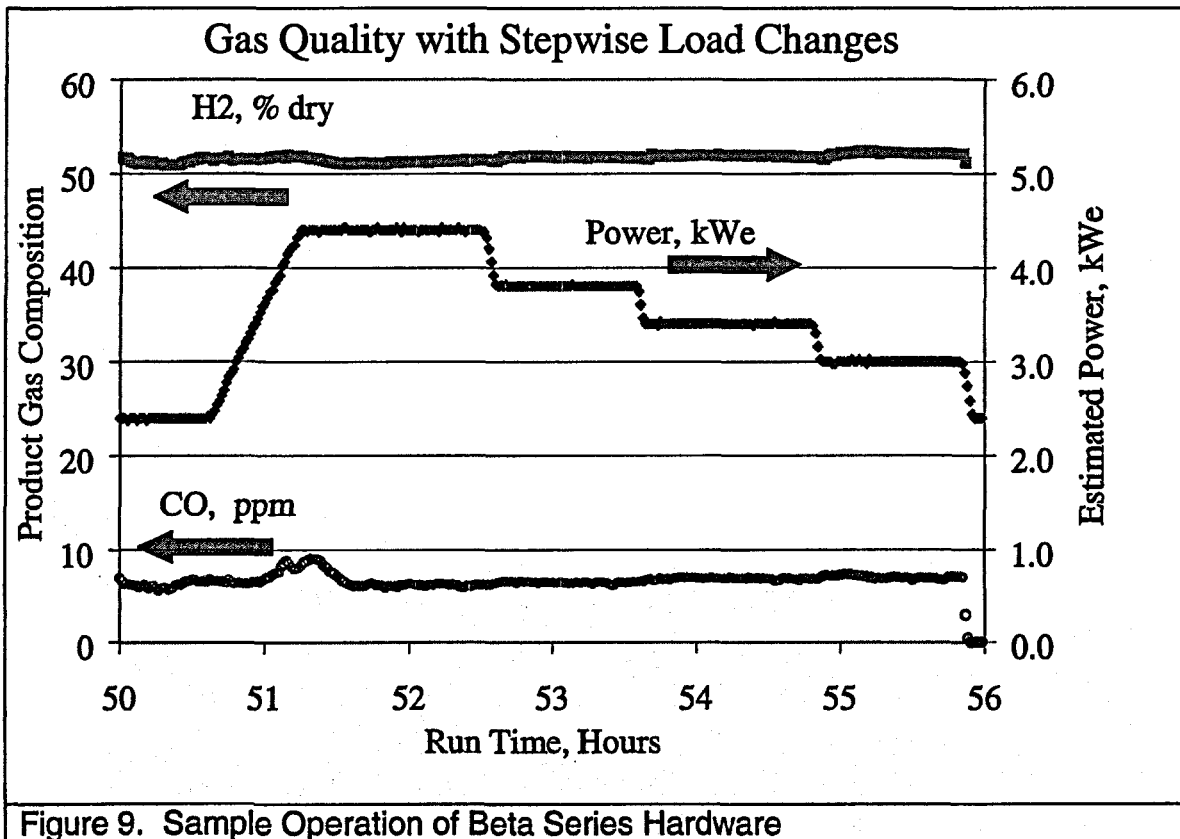
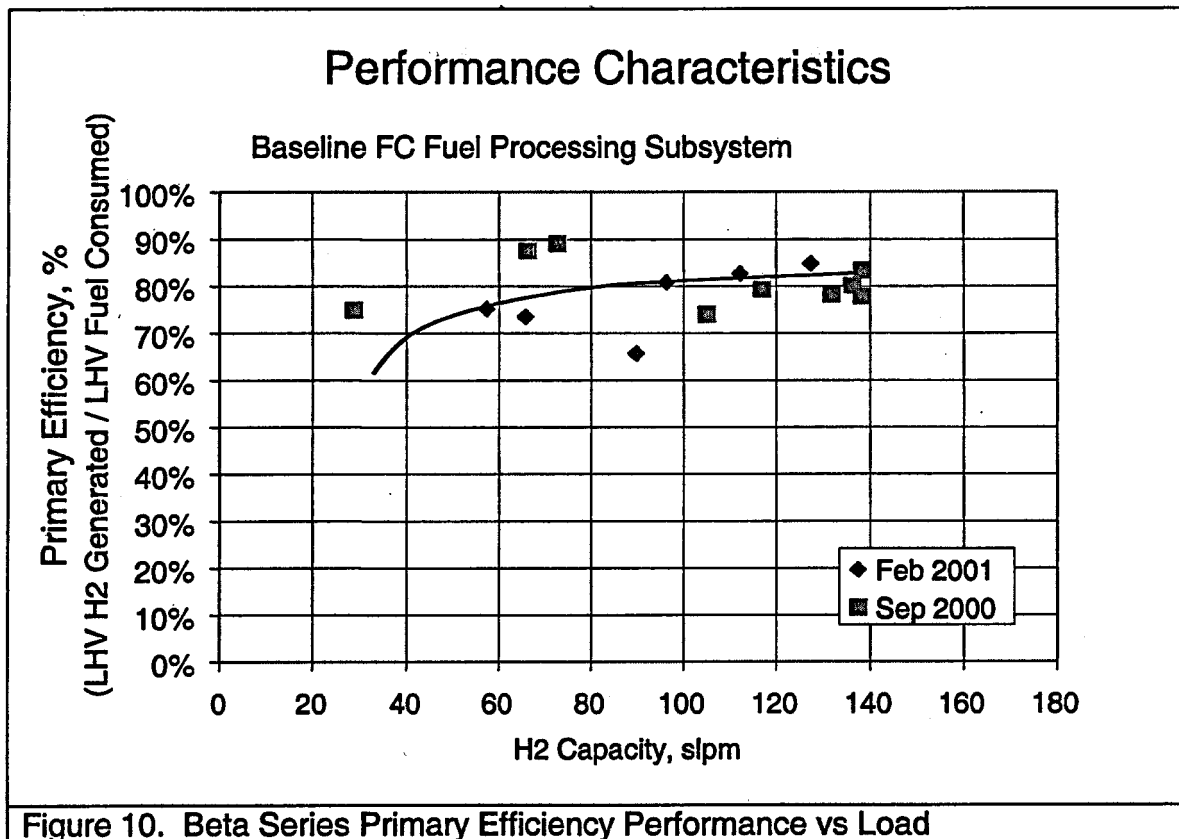


Figure 9. Sample Operation of Beta Series Hardware

The improved performance characteristic was also demonstrated over the full range of the unit's capacity. Figure 10 shows the primary efficiency of the units at various part load conditions. Two sets of data are illustrated to indicate typical performance of the units. First, the September 2000 time frame shows performance when the units were undergoing initial characterization testing. Also shown is data for units in the February 2001 time period after process changes for improved controls and operations had been implemented.

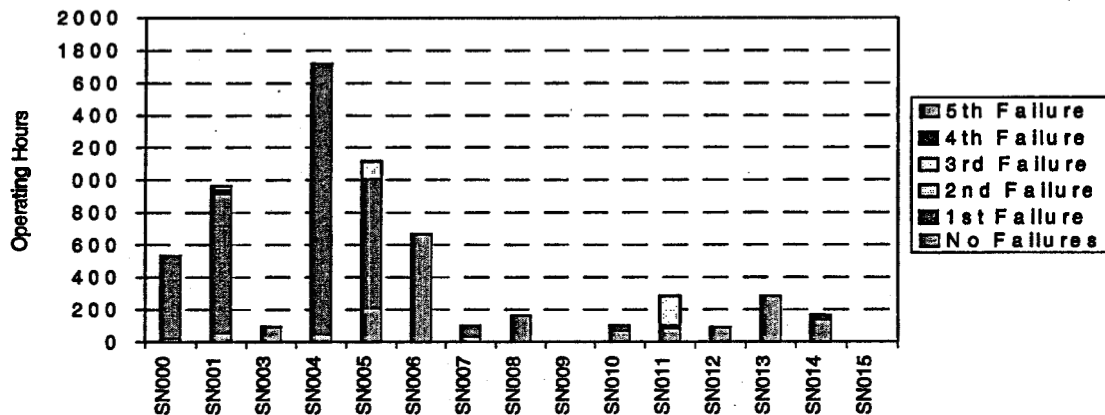


### 5.3 Reliability Test Results

This project supported a period of testing of the Beta Series hardware to assess the potential reliability of the units. A summary of the initial time frame of testing is provided in Figure 11. The initial 6000 hours of operational experience is represented in this figure. The majority of the in-house testing occurred on units with serial numbers 0,1,4,5 and 6, which were the research departments developmental units. The other units were operated for acceptance only before being shipped to customers. The early failures were caused by component deficiencies and were corrected with component improvements. Only unit SN001 had more than three failures during this period. The best unit operated over 1600 hours between its first and second failure. Most of the failures result for process control and monitoring components, which have been applied wrong or operated outside their nominal specification. This data is limited and additional reliability growth testing is required to validate commercial viability. HbT's internal development program is continuing this effort.

## Fleet Status — Update through 6/15/01

Model 39 & 40 Time Between Failures



- Early failures on units 1 - 5 were fixed by major component improvements.
- Units 0, 1, 4, 5, and 6 are being run in-house, showing improved reliability.
- The other units were run for about 100 hours each before shipment to customers.
- Some units show failure after 5 - 10 hours, typically due to assembly errors or faulty components. These faults are caught prior to shipment and will not affect the customer.
- The ongoing reliability growth testing program is generating further reliability improvement.

Figure 11. Fleet Reliability Beta Series Hardware



## 6 Phase III Proposed Activity

Continued support of HbT building system program was coordinated with a leading fuel cell system integrator, Plug Power Corporation, through a subcontract under their DOE cooperative agreement (DEFC01-99EE27569). The initial phase of this study built on the design basis of the Beta Series hardware. Improved process designs were evaluated under this effort. Capacity of the FPS package was scaled up to 50kW<sub>e</sub> and conceptual layout designs developed. Hardware fabrication and implementation was planned for the continuation of this cooperative agreement. This effort has not been initiated to date.

## 7 Summary and Conclusions

Fuel cells systems for modern buildings provide a viable generation option for distributed sources of electricity. Fuel processing subsystems that use natural gas are an enabling technology critical to the success of these fuel cell systems. HbT has successfully developed an integrated natural gas fueled, fuel-processing subsystem and is actively moving this product toward a commercial product. This building system cooperative agreement in parallel with a cooperative agreement on integrated fuel processing subsystems for transportation and two HbT internal programs were critical in establishing the technology basis for this commercially viable stationary fuel processing product. The initial model of this technology is currently being integrated with fuel cell systems for validation of product performance.

After detailed market analysis during Phase I and series of design decisions and technology validations, HbT has selected the autothermal reforming technology as the basis for this product line. This was selected after assessing customer requirements for process efficiency. In addition, the CO polishing technology selected was preferential CO oxidation, due to its ability to consistently reduce CO levels below customer requirements of 10ppm. The FPS fueled by natural gas provides high efficiency, reliable performance, and quality anode ready gas for integration with the fuel cell system. The capacity of the unit was based on both customer application requirements and market study results for commercial office buildings.

This 10kW<sub>e</sub> hardware design is identified as the Beta Series. A manufacturing agreement was established with Visteon to support mass production and focused cost reduction activities. An initial lot of units were manufactured under HbT's internal programs and this cooperative agreement helped support some of the operational and reliability testing. Test results indicate the unit operates to specification and initial reliability is acceptable. Extended validation is required to verify the commercial acceptability of this product.

The changing electricity marketplace is encouraging continued development of distributed generation products, including fuel cell systems. The availability of fuel processor products developed by third parties is enabling fuel cell integrators to focus on their stack, system and application issues. Products using autothermal technology appear to have advantages with respect to response rate, ease of integration, performance, and cost. Ultimately, the fuel processing product selection by fuel cell integrators will be based on price, performance, and availability. HbT has established business approaches, strategic alliances, and product development paths to enable the company to offer a winning combination of these factors. Having completed the second step along the product development path, HbT has resolved many of the technical problems while maintaining cost-effective product designs. The success in meeting performance characteristics and packaging constraints provide a foundation to assess the commercial potential of fuel processing products, which are needed for fuel cell systems to be successful in the market.

