VII.F.7 CHARM - Cost-Effective, High-Efficiency Advanced Reforming Module

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Objectives

Develop an advanced reforming module for stationary applications

- Develop a 1,000 scfh (2.4 kg/hr) fuel processor with low product life-cycle cost; minimize capital, operating and maintenance costs over a five year product life
- Develop a scaleable technology from 500 to 2,000 scfh (1.2 to 4.7 kg/hr)
- Achieve a cost-effective balance between efficiency and manufacturability
- Demonstrate a lifetime assessment through accelerated aging
- Demonstrate performance of a 1,000 scfh fuel processor at Argonne National Laboratory

Technical Barriers

This project addresses the following technical barriers from the Fuel Cell section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. This activity addresses the fuel processor sub-section to address the challenge of developing a natural gas or LPG fueled fuel processing system

- A. Durability
- B. Cost
- F. Fuel Cell Power Integration
- I. Hydrogen Purification/Carbon Monoxide Cleanup
- J. Startup Time/Transient Operation

Technical Targets

Status versus the DOE technical targets for fuel processors as outlined in the March 2005 version of the HFCIT Multi-Year RD&D Plan, Table 3.4.7, is presented below (http://www.eere.energy.gov/hydrogenandfuelcells/mypp/).

Nuvera Progress Toward Meeting DOE Stationary Fuel Processor Targets

Characteristic	Units	2005 Target	CHARM Status
Cold startup time to rated power	min	< 60	120
Transient response time (10 to 90% power)	min	< 4	15
Durability (catalyst and major component lifetime)	hours	20,000	Designed for 40,000 hours, validation required
Survivability	°C	-30/+40	Designed for -20/+40, validation required
CO content in product stream	ppm		
Steady state		5	< 0.5
Transient		50	< 6
H_2S content in product stream	ppm	< 5	TBD
Ammonia content in product stream	ppm	< 0.1	TBD

<u>CHARM Targets:</u>

The goals of this project are to develop a cost-effect, high-efficiency advanced reforming module. Specific technical targets include:

- Cost: $10,000 for a 1,000 scfh system, at quantity of 50 units
- Efficiency: > 75% lower heating value (LHV)
- Lifetime: 40,000 hours, 1,000 cycles
- Scalability: 500 to 2,000 scfh

Approach

- <u>System Definition</u>: Use system modeling to determine the proper balance of fuel processor integration. Define specifications and operating conditions.
- <u>Design & Analysis</u>: Conduct subscale testing and select a fuel processor concept to achieve the performance, cost and durability specifications.
- <u>Prototyping & Testing</u>: Demonstrate full-scale performance of the fuel processor subsystem. Assess temperature profiles, heat flux, reaction equilibrium, and burner emissions.
- <u>System Demonstration</u>: Validate performance with system level testing, demonstrate durability via accelerated aging, and complete a fuel processor subsystem demonstration at Argonne National Laboratory.

Accomplishments

- Developed a system model and conducted a parametric sensitivity analysis to define the fuel processor subsystem specifications and tolerances.
- Completed subscale testing of multiple fuel processing concepts. Selected a design that best satisfies the performance specifications and enables scalability of the technology to support the widest range of product applications.
- Completed testing of three iterations of the fuel processor (FP) design (FP1, FP1A and FP1B) to improve thermal profiles and maximize the reforming reaction rate, while minimizing peak operating temperatures.
- Achieved full power on the FP1B fuel processor subsystem, generating 1,000 scfh of hydrogen at 72% efficiency (LHV).
- Achieved excellent hydrogen purity in the product stream with CO levels < 0.5 ppm.

- Achieved excellent burner emissions (NOx < 15 ppm, CO < 50 ppm @ 3% O_2) that satisfy requirements from the California South Coast Air Quality Management District and the Environmental Protection Agency Best Available Control Technologies.
- Demonstrated stable fuel processor subsystem performance when integrating FP1A with a pressure swing adsorption (PSA) hydrogen purification subsystem. The fuel processor design was very tolerant of pulsations in fuel mass flow rate and composition to the burner.

Future Directions

- Evaluate the FP1B fuel processor in a system level context. Optimize performance for efficiency, product stream purity (CO, H_2S, NH_4), burner emissions, cold startup and transient response times, while minimizing peak metal temperatures. Prepare detailed design documentation of the fuel processor subsystem. Develop a roadmap for continued technology development to achieve efficiency > 80% LHV [Q3'05].
- Conduct a detailed DFMA® with a third party to refine the design and assess true manufacturing costs. [Q4'05].
- Conduct accelerated aging of the fuel processor to demonstrate durability and survivability [Q1'06].

Introduction

Over the past several years, Nuvera Fuel Cells, Inc. has developed steam reformer technology for incorporation into stationary fuel cell power systems. Recent analyses have indicated that significant cost reductions and durability improvements are required in order to make the commercialization of stationary fuel cell systems a reality. Therefore, Nuvera intends to develop a modular stationary reformer with a key emphasis on cost reduction via optimization of the burner/reformer assembly. The design modifications proposed here are a direct result of our key learning's from previous designs.

During the previous year, the specifications of the fuel processor subsystem were defined in Task-1 (System Definition) in order to achieve the DOE fuel processor targets. Multiple fuel processor concepts were designed and evaluated via subscale testing in Task-2 (Design & Analysis). A concept was selected that offered the best balance of efficiency, cost, durability, scalability, and stability for the widest range of product applications. Task-3 (Prototyping & Testing) work commenced with the fabrication of the test stand and development of the full-scale fuel processor.

Approach

Task-1 System Definition: Since the burner must efficiently combust the non-utilized hydrogen exhaust from a fuel cell or a hydrogen purification subsystem, it is important to design the fuel processor in the context of a complete system. A detailed process model was developed and a system level parametric analysis was used to assess process sensitivity and identify key design specifications to ensure performance. A key objective was to determine the optimal level of fuel processor integration to balance efficiency with cost, durability and manufacturability.

Task-2 Design & Analysis: Six fuel processor concepts were screened in a qualitative decision matrix, including different burner technologies, reforming pressures, and geometries. Concepts ranged from simple designs utilizing residential furnace burner technology and controls to Nuvera's core technology of efficient fully integrated designs. The concepts were assessed against the fuel processor specifications defined from the system model. The two highest scoring concepts were fabricated and tested in subscale fuel processor trials. The decision matrix was then repopulated with the subscale test results to facilitate a quantitative assessment and selection of the final concept.

Task-3 Prototyping & Testing: A full-scale fuel processor (FP1) was designed and fabricated. The test infrastructure to support the fuel processor evaluation was also developed. Detailed analysis of the test results enabled several iterations (FP1A, FP1B) in efforts to improve efficiency, flow distributions, and burner emissions, while reducing the peak metal temperatures. The FP1A fuel processor was evaluated in a more demanding system level context with a PSA hydrogen purification subsystem. The selection of this fuel processor design was validated as the burner demonstrated remarkable stability under extreme pulsations in fuel flow rate and composition from the PSA exhaust.

Results

Task 1 (System Definition)

The formal specifications of the fuel processor module have been defined in a system context. The Fuel Processor Module specifications include:

- Fuels: Natural gas or LPG
- Efficiency: > 75% (LHV)
- Hydrogen output: 1,000 scfh (scaleable from 500 to 2,000 scfh)
- High durability: 40,000 hours, 1,000 cycles
- Low system operating cost: (Proprietary target)
- Short development time: Prototype available in March'05
- Low technical risk: maximize flame stability and minimize fuel/air manifold complexity
- Minimize capital cost: (Proprietary target)
- Burner emissions: NOx < 15 ppm, CO < 30 ppm (3% O_2, 3 hour average)
- ASME code stamping: minimize boundary metal temperatures
- Reparability: life mitigating parts can be replaced at 1/3 to 2/3 the cost of a new fuel processor module
- Flame ignition detector controls: able to use existing in-house control module

Three fuel processor concepts were identified and evaluated in a decision matrix against each of the above specifications. Both low and high pressure reforming options were considered for each concept. The low pressure reformer concepts 1 and 2 were among the higher scoring candidates, with schedule, turndown and scalability being the most significant advantages. The high pressure reformer options were eliminated due to anticipated performance limitations in several of the most critical specifications (durability and technical risk). Since the scoring in this matrix was only qualitative, a decision was made to proceed with laboratory testing of the two highest scoring concepts.

Task 2 (Design & Analysis)

A subscale version of Concept-1 was designed and tested. This concept employed a simple burner tube design used in residential furnaces combined with a reformer shell. This burner was designed to provide a very long flame length and maximize the effective heat transfer area to the reformer. Advantages of this concept were the high efficiency design and the low peak metal temperatures (high durability). Drawbacks included the need for specific burner nozzle designs for different fuels. This makes it difficult to start the furnace on natural gas, and then transition to a non-utilized hydrogen fuel source at steady state operation.

A full-scale version of Concept-2 was also designed and tested, using 12 reformer tubes inside of a burner shell. The advantages of this concept included reliability of the burner ignition and controls, the avoidance of an ASME pressure vessel stamp, and most importantly - excellent flame stability with a wide range of fuel flow rates and composition. The decision matrix was re-populated with actual performance data (Table 1), indicating that Concept-2 was the clear choice for satisfying the fuel processor specifications. This full-scale fuel processor was identified as FP1.

Task 3 (Prototyping & Testing)

FP1A Development

The FP1 fuel processor was modified by inverting the fuel processor to further improve ignition and reduce heat loss through the burner end plate. This change also facilitated the use of a commercially available induced draft blower. This modified reformer was renamed as FP1A. Improvements observed with FP1A include reduced heat loss and reduced NOx exhaust emissions by reducing the residence time at high temperatures. At full production capacity, the specified rate of conversion in the reformer (2% methane slip) was achieved, but at significantly higher peak metal temperatures than desired. In contrast, limiting

Table 1. Decision Matrix for Fuel Processor Concepts 1 and 2

Specification	**Importance**	**Fuel Processor Assembly Design Concepts**	
		Concept-1	**Concept-2**
FP Material cost	9	5	5
FP operating cost	9	9	5
Scaleability	9	5	5
Reliability	9	5	9
Durability	9	9	5
Steam production	5	5	5
Development schedule	5	5	9
Flame stability	5	3	9
Controls	5	5	5
Emissions	5	5	5
Turndown capability	5	5	9
Startup time	3	5	5
ASME Certification	3	5	9
Intellectual property	3	5	5
Manufacturing complexity	3	5	3
Fuel type	3	3	5
Total score		**506**	**552**

operation to a peak wall temperature of 850°C resulted in only 80% production capacity. These results are summarized in Table 2. Extensive testing combined with computational fluid dynamics (CFD) modeling identified the performance limiting aspects of the reformer design:

- Heat loss through the outer burner shell was estimated between 6-8 kW at nominal operating conditions.
- Asymmetry in the location of the burner exhaust port led to a radial gradient in the heat flux and non-uniformity in the extent of reaction between the 12 reforming tubes.

Table 2. Performance Comparison of FP1A & FP1B

	Design Spec.	**FP1A Performance**		**FP1B Performance**^{1}
H_2 product, kg/day	56.6	>56.6	44.5	>56.6
SR Input, kW_{th}	108	108	100	108
S/C	3.1	3.1	3.7	3.3
CH_4 slip, %	2	2.3	6.8	2.1
TGC Input, kW_{th}	52.5	52.5	52	52.1
Burner Phi (diluted)	0.5	0.48	0.34	0.66
Max. Wall Temp, ºC	850	1,104	850	972^2
NOx, ppmv, 3% $O_2^{(3)}$	153	~62	~14	~11
CO ppmv, 3% O_2^3	503	~10	~24	~25

(1) SR Inlet @ 450^{o}C instead of 520C

(2) CFD Predicted (150^{o}C higher than measured)

(3) FP1A & FP1B emissions projected for “humid” fuel

- The burner flames were impinging directly on the reformer tube caps resulting in excessive peak metal temperatures (>1,000°C) at the nominal operating conditions.

CFD modeling was used to enhance the understanding of air/fuel mixing and combustion in the burner. Modeling revealed a fluid flow phenomenon that was causing the four burner flames surrounding each reformer tube to merge and impinge upon the tube caps. The combustion behavior was found to vary significantly depending on air/fuel inlet hole pattern, enabling screening of several alternate inlet hole patterns for improved combustion behavior (Figure 1).

FP1B Development

Based on these findings, a third iteration (FP1B) was made in the fuel processor design.

Improvements include:

- Use of a burner end plate with an alternate air/fuel inlet hole pattern to avoid direct flame impingement on the reformer tube caps.

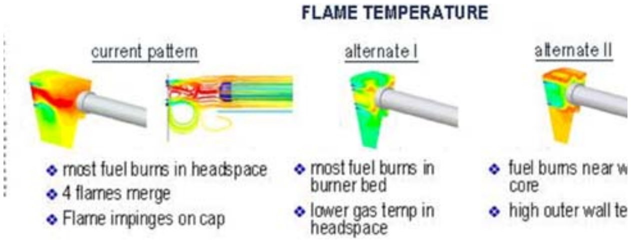

Figure 1. CFD Modeling of Burner Flame Temperature

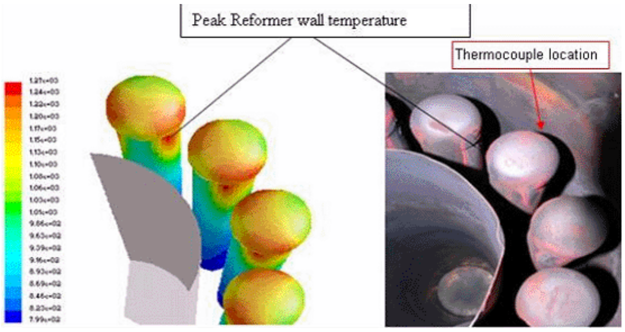

Figure 2. Peak Metal Temperature Locations in both CFD Model and Actual Photograph of Reformer Tubes

- Modifications to enable quick-change of the burner endplates to allow testing of multiple alternate designs
- Improved burner flow distribution via redesign of the exhaust port
- Reduced heat loss via improved internal insulation design
- An adjustable burner headspace distance
- A simplified reformer manifold design

The improved performance is contrasted to that of FP1A in Table 2. With FP1B, full production capacity and low methane slip were achieved with a wall temperature of 822°C. Examination of the reformer tubes indicated that the burner flames were impinging along the sides of the reformer tubes. The locations of the thermocouples did not correspond with the actual locations of the flame impingement. Detailed modeling by CFD closely matched performance of the location of the flame impingement and the wall thermocouple measurements (Figure 2). This modeling suggested actual peak temperatures about 150° higher than that recorded by the thermocouples. As a result, a peak temperature of 972° was entered in Table 2.

Figure 3. FP1A (left) and the Balance of Plant and PSA Subsystems in a System Level Evaluation

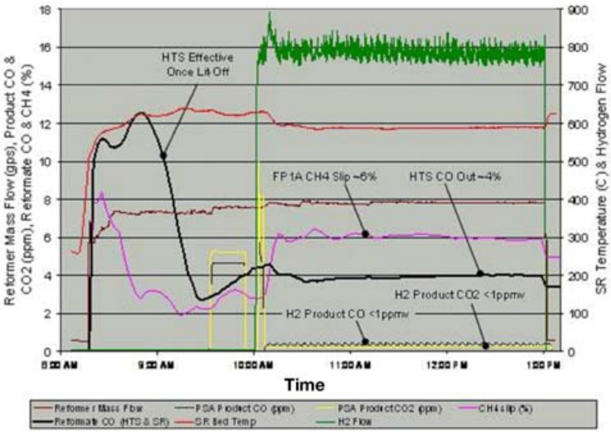

Figure 4. FP1A Profiles in a System Level Evaluation

System Level Evaluation

The FP1A version was integrated with a PSA and balance of plant subsystems for a rigorous system level evaluation. A photograph of the system is presented in Figure 3, with the insulated FP1A subsystem on the left. In order to limit the peak metal temperatures with FP1A, the system was operated at 80 percent of the production capacity. Even with the performance limitations of the earlier FP1A design, the burner demonstrated remarkable stability when combusting the PSA exhaust with large pulsations in both fuel flow and composition. Performance profiles of FP1A and the generation system are summarized in Figure 4. From a cold start, the system was producing 800 scfh of hydrogen in less than two hours. The hydrogen product stream demonstrated excellent purity levels with both CO and $CO_2 < 1$ ppm. It is expected that the assessment of FP1B at a system level evaluation will enable full production capacity to be achieved, while maintaining acceptable peak reformer wall temperatures.

Conclusions

- The specifications for the fuel processor assembly were defined in the context of a larger hydrogen generation system. System modeling suggested that the best balance of cost, efficiency, manufacturability and durability could be achieved by a low pressure steam reformer module, comprised of two separate vessels: an integrated burner/reformer, and an integrated steam generator/superheater/shift reactor.
- A burner/reformer concept was selected that demonstrated remarkable flame stability over a wide range of fuel flow rates and compositions. Combined with the ability to scale from 500 to 2,000 scfh, this design can be adapted for use in a broad range of reformer applications, while minimizing additional development costs.
- The third iteration of the full scale design achieved the target specifications for production capacity, reformer efficiency, and hydrogen purity and burner emissions.
- The reformer was evaluated in a demanding system level evaluation, demonstrating remarkable burner stability and hydrogen purity.

FY 2005 Publications/Presentations

1. "CHARM: Cost-Effective, High-Efficiency Advanced Reforming Module," Holmes et al, 2005 DOE Hydrogen Program Review, 26 May 2005.