II.D.1 Startech Hydrogen Production*

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*Congressionally directed project

Objectives

The purpose of this project is to evaluate the viability of integrated hydrogen production from waste materials using a plasma converter and a StarCell™ multistage ceramic membrane hydrogen separation system. Specifically, this project will achieve the following:

- Field test integrated hydrogen production on a pilot scale using plasma gasification and ceramic membrane hydrogen separation.
- Evaluate commercial viability and scalability through extended operation under representative conditions.
- Characterize the performance of the integrated plasma converter and StarCell™ Systems for hydrogen production and purification from abundant and inexpensive feedstocks.
- Compare integrated hydrogen production performance to conventional technologies and DOE benchmarks.
- Run pressure and temperature testing to baseline StarCell™'s performance.
- Determine the effect of process contaminants on the StarCell™ system.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section (3.1.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan Published February 2005:

(C) Operation and Maintenance (O&M)
(D) Feedstock Issues
(F) Control and Safety
(M) Impurities
(R) Testing and Analysis
(V) Feedstock Cost and Availability
(W) Capital Cost and Efficiency of Biomass Gasification/Pyrolysis Technology

Technical Targets

The Startech Hydrogen Production project includes both hydrogen production through advanced gasification and separation of hydrogen through microporous membrane separation. This research is advancing the state of the art in both of these technology areas.

Startech Membrane Module Data: Data obtained while purifying a 50% H_2, 50% CO Gas Blend, Co-current flow, no sweep gas

Performance Criteria	Units	2003 Status	2005 Target	2005 December	2010 Target
Flux Rate	scfh/ft^2	100	100	0.64[1]	200
Membrane Material and All Module Costs	\$/ft^2 of Membrane	450-600	400	TBD	200
Durability	hr	<8,760e	8,760	TBD[2]	26,280
ΔP Operating Capability	psi	100	200	TBD[3]	400
Hydrogen Recovery	% of total gas	60	>70	80%	>80
Hydrogen Quality	% of total (dry) gas	>90	95	96%[4]	99.5

[1] Flux was determined at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 1.2 psi, and 60°C. Flux is expected to increase logarithmically with increased operating temperature.
[2] The durability of the membranes has not been determined in terms of total hours. The membranes can be regenerated once poisoned using a high temperature gas flush. The period between flush cycles will vary based on contaminant concentrations, the type of contaminant, and operating temperature.
[3] Delta P was tested between 100 and 150 psi. The membrane modules were outfitted with 150 lb ANSI flanges. The membranes themselves were not tested to failure to determine the operating capability.
[4] Hydrogen quality is expected to increase with better selectivity which will be obtained at higher temperatures and will also be improved with higher initial concentration of hydrogen. Hydrogen purity of 98% to >99% can likely be obtained with current modules with a hydrogen input purity of 80%. The composition of the non-hydrogen balance of the gas will also have a significant effect on the membrane performance.

Accomplishments

- Generated a hydrogen-rich synthesis gas from municipal solid waste (MSW) surrogate waste material with a net hydrogen concentration of 45–55% by volume. Rate of gas generation was ~150 scfm.
- Tested multiple modules of membranes on both laboratory gases and on synthesis gas generated from the MSW surrogate material.
- Purified CO and H_2 blend gas from 50% H_2 to 96% H_2. Synthesis gas was purified from 35% H_2 to ~80% H_2.
- Synthesis gas produced from MSW was shown to be low in contaminants and suitable for many subsequent processes including direct hydrogen purification through carbon coated ceramic membranes.

Future Directions

Membrane Work

- Incorporate and prove-out next generation membrane materials and module configuration.
- Water-gas-shift (WGS) evaluation: potential to incorporate WGS into the membrane.
- Process control, analysis, and optimization.
- Counter-current membrane flow.
- Temperature optimization.

Optimization of Hydrogen Production

- Challenge loading the Hydrogen Production System: identify contaminants and evaluate performance on challenge loads.
- Establish a broad feedstock specification to expand the applicability of the process to many more materials.
- Gas clean-up (specifically for catalyst preservation).
- Carbon sequestration evaluation.
- Energy optimization.

Introduction

In Startech's Plasma Converter System (PCS), organic wastes and other feedstocks are dissociated and reformed to create a synthesis gas of predominantly hydrogen and carbon monoxide. The synthesis gas produced in the dissociation process of these materials, particularly the hydrogen component, has an expanding commercial demand. Single-step gasification and reforming of feedstocks utilizing the PCS is one potential answer to both distributed and large-scale hydrogen production. The economics of the gasification process are especially favorable when gasifying organic waste including pesticides, tires, medical waste, and municipal solid waste into high purity hydrogen fuel.

To enhance the hydrogen production capability of the Plasma Converter System, Startech has invested considerable resources into the development of StarCell™, a ceramic membrane technology for the isolation and purification of hydrogen from a mixed gas stream. This technology has far reaching applications in the emerging hydrogen economy for virtually any hydrogen purification application. Inherent advantages of the ceramic membrane technology over other hydrogen purification technologies include the following:

- Excellent material temperature and chemical stability/flexibility.
- Microporous material yields higher throughputs versus nonporous polymeric membranes.
- Cost efficient gas separation can be achieved at low pressures, i.e. 50 to 100 psi.

The objective of the Startech Hydrogen Production Project is to further development in two hydrogen infrastructure technology areas. Single-step plasma gasification of the various feedstocks into a hydrogen-rich synthesis gas furthers the DOE goal of distributed hydrogen production. Using StarCell™, a systemized ceramic membrane technology, to separate the hydrogen from the gas generated by the gasifier and subsequently purifying the hydrogen component will also yield performance data that will be crucial to the future scale-up and commercialization of this technology. Test results obtained during this testing will be compared with DOE cost targets.

Approach

A key element to this research is the characterization of plasma conversion and StarCell™ hydrogen purification through real time operation on a pilot scale rather than theoretical projections of laboratory or bench-scale testing. Very little modification was done to the PCS as it will first be characterized in light of DOE's objectives to identify the strengths and weaknesses of the technology. While the PCS has demonstrated that it does produce suitable gas for hydrogen purification from coal and MSW, differences between the current PCS configuration and a PCS optimized for hydrogen production were such that meaningful cost metrics were not obtainable.

The technical approach of the project was to get the systems interfaced and operational and then to operate the systems to obtain analytical data to establish a performance baseline. It is recognized that significant progress continues to be made in membrane development and we continue to find and conquer new impediments in the incorporation of the membranes into pilot-size modules. Establishment of a performance baseline is an essential step in measuring technical improvements under representative conditions.

To characterize the PCS, the synthesis gas produced will be analyzed to verify its suitability for downstream processing such as hydrogen purification and WGS for additional hydrogen production. A significant portion of the research effort will be focused on laboratory analysis of the plasma converted gas. This portion of the research is especially critical as the majority of gasification technologies, especially those linked with separation technologies, have performed their testing on low contaminant feedstocks (i.e. low sulfur coal, and clean natural gas) that are not viable solutions for fossil fuel independence. It is important to identify contaminants in diverse feedstocks and understand their effects on downstream components.

StarCell™ system construction was a major accomplishment of this research effort as it is a very flexible tool for pilot-scale membrane characterization in general. Instrumentation on the StarCell™ provides continuous data logging of process temperatures, pressures, flows, and gas composition at points of interest in the purification system. StarCell™ was constructed to accommodate tubular membranes bundled together in modules, though planar stacks and other configurations could easily be incorporated.

It also has two stages of compression to evaluate various multistage module configurations. Some of the operational configurations are as follows:

- Single stage compression cascading through multiple stages of modules.
- Dual compression for instances where Stage 1 permeate pressure is too low to drive Stage 2 separation.
- Stage 1 to Stage 2 switching to allow Stage 1 to Stage 2 configurations of 6 and 2, 5 and 3, or 4 and 4 as conditions and membrane performance require.

After the first round of testing, the temperature capability of the StarCell™ system will be upgraded using an induction heating system to yield maximum temperature flexibility. Q3 and Q4 2006 testing will further characterize membrane module performance under wider temperature ranges, with various gas mixtures and with plasma converted gas generated from MSW surrogate material.

Results

Detailed results of the initial testing were reported in the Phase 1 Technical Report submitted in January, 2006. The design, assembly, and integration of the StarCell™ system is evolving to expand its test capability. We have included photo documentation of the system as it has evolved (Figures 1-6).

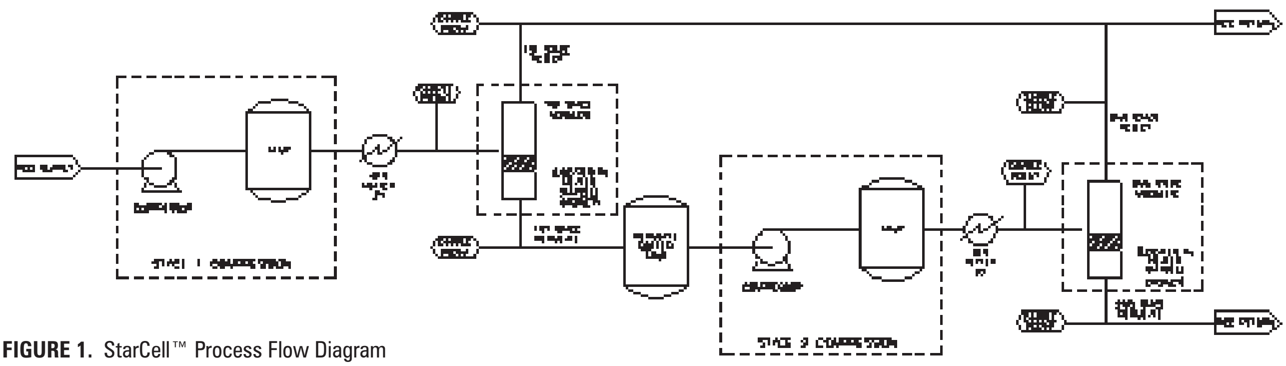

FIGURE 1. StarCell™ Process Flow Diagram

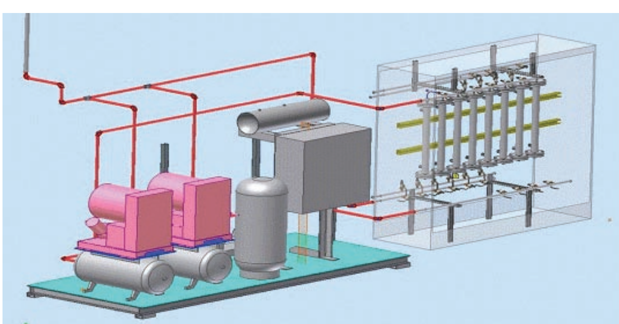

FIGURE 2. StarCell™ 3D Design, February 2005

FIGURE 3. StarCell™ Construction, April 2005

FIGURE 4. Installed StarCell™ System, July 2005

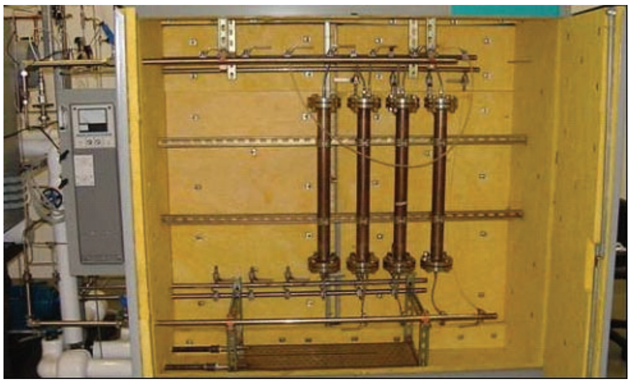

FIGURE 5. 4 Modules Installed in StarCell™ I, July 2005

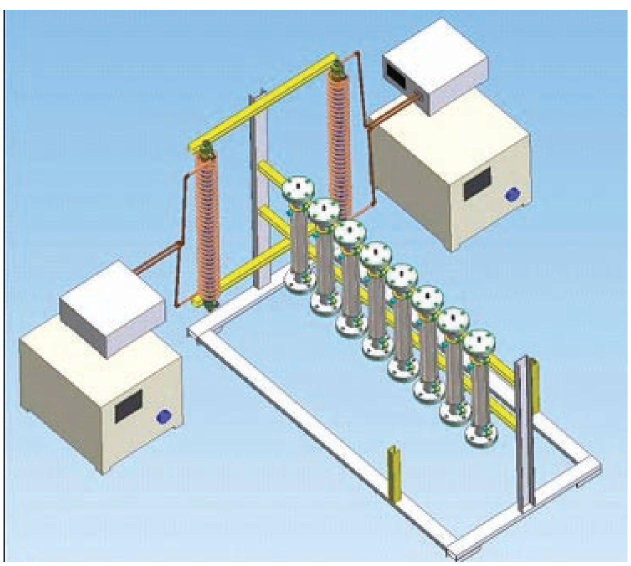

FIGURE 6. Modified StarCell™ 3D Design, June 2006 (Prototype Testing Underway)

Conclusions

The research done to date on this project has shown advancements in many technical areas in support of large-scale hydrogen production. Hydrogen-rich synthesis gas was produced from waste material on a commercial scale. This is significant as municipal solid waste was heretofore not even considered as a potential large-scale source of hydrogen. Furthermore, the PCS has the potential for application not only to waste materials, but also to abundant biomass feedstocks that are not amenable to gasification by other methods for various reasons. The results of this testing also showed that the gas produced in a PCS from municipal solid waste was very clean with 46%–55% hydrogen content before WGS. The gas produced was suitable for many applications including subsequent purification through carbon molecular sieve membranes.

The membrane data obtained during this testing was also very significant. The membranes used were actual commercial scale membrane bundles (referred to as modules) in this testing. Also, actual gasification gas was used from a non-fossil source as the feedstock for these membranes rather that clean natural gas. No sweep gases or other process aides were used that would improve performance statistics while decreasing the practical use of the gas. Even under these conditions, the StarCell™ system demonstrated gas purification from a 50% concentration to 96% purity and showed hydrogen recovery rates in excess of 86%.

Now that the performance baseline has been set for both the PCS and the StarCell™ Hydrogen purification system, next-step improvements can be made to both technologies. A significant area for improvement on the StarCell™ system is to increase the temperature capabilities to be more representative of high temperature applications. Higher separation temperatures will significantly improve membrane performance because flux is a logarithmic function of temperature. Higher temperature is also known to increase poison resistance of the membranes. Other StarCell™ research may include different types of membranes, counter-current gas flows, or the incorporation of WGS directly into the membrane module. The PCS used in this testing was designed for destruction of hazardous waste materials rather than low-cost synthesis gas generation. Changes to the PCS relative to hydrogen production should focus on three areas: reducing even the trace quantities of sulfur species that are known to poison various catalysts used in WGS systems, reducing the amount nitrogen in the gas produced, and improving the energy efficiency of the torch system used to produce the plasma.