HYRADIX ALPHA 4 PERFORMANCE REVIEW

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TB-03-001: HyRadix Alpha 4 Performance Review

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Integrated Enable Fuel Cell / Alpha 4 Reformer System Description

Enable Fuel Cell Corporation (Enable) supplied HARC with an integrated fuel cell – reformer system. This system consisted of a 5 kW Enable fuel cell and associated power conditioning equipment coupled to a HyRadix Alpha 4 fuel processor (reformer).

In the design of the fuel cell, Enable was sensitive to problems in providing surge capacity with battery technology due to limited cycle life, corrosiveness, and end of life disposal issues. Enable made the decision to explore the capability of an alternative system employing super capacitors (super caps) and supplemental hydrogen. The super caps substitute for batteries to provide surge capacity during power transients. However, because the energy density of super capacitors is significantly less than batteries of the same size, supplemental hydrogen fed directly to the fuel cells was needed to augment the power supplied by the super caps during load transients. After initial operations made clear the difficulty of rapid control on the supplemental hydrogen system, the team determined that maintaining a small, constant flow of supplemental hydrogen, even during steady state operation, would provide for a more stable system (see Figure 1).

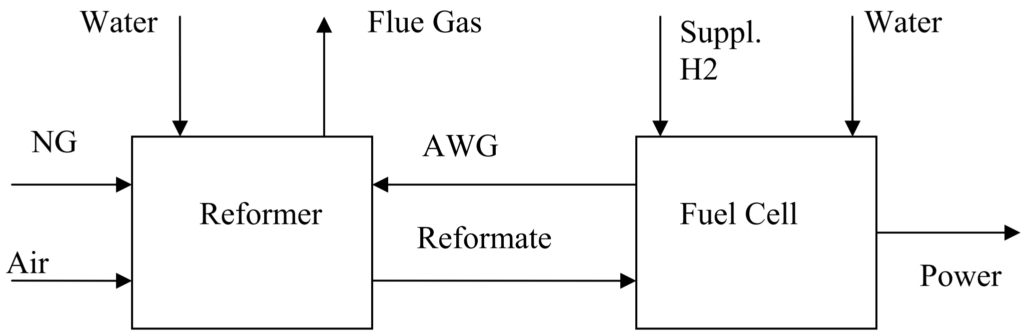


Figure 1 – Integrated Fuel Cell System

The HyRadix Alpha 4 system is a pre-commercial, stand-alone natural gas reformer sized to provide sufficient hydrogen-rich reformate to power a residential or small-commercial fuel cell system up to 5 kW in capacity. The Alpha 4 system is supplied with two modules – the reformer section and an operator interface control system as shown in the photo below. Detailed systems engineering must be undertaken to integrate the unit with a fuel cell to allow it to operate with and respond to the fuel demands of the integrated system. The Alpha 4 system as tested by HARC was not designed for co-generation heat recovery. In order to provide the necessary 25 psig inlet natural gas pressure to the Alpha 4 unit, HARC installed a natural gas booster compressor.

The Alpha 4 system (shown at left) is comprised of five primary process steps including:

1. Feed Desulfurization
2. Auto-thermal Reforming (ATR)
3. Water Gas Shift
4. Preferential Oxidation
5. Anode Waste Gas (AWG) Burner

After hydrogen production is achieved in the ATR reactor, the amount of carbon monoxide present in the synthesis gas is reduced through water gas shift and preferential oxidation reactions. Waste gas emerging from the fuel cell anode is combusted with air in the catalytic AWG burner and a portion of the resulting heat of combustion is used in the process.

Test Description

The Alpha 4 reformer was supplied to HARC by Enable as part of an integrated fuel cell system. The function of the reformer is to provide a continuous stream of hydrogen-rich reformate to be consumed by the fuel cell. At the onset of the program, the objective was to evaluate the performance of the integrated system and no independent testing of the reformer was contemplated or planned.

However, due to severe financial problems and later the bankruptcy of Enable, the company was unable to provide HARC with either technical support or spare parts to allow continued operation of the fuel cell unit. As a result, HARC decided to discontinue operating the fuel cell, but to continue independent operation of the reformer. After extended operation of the reformer in the stand-alone mode, the Alpha 4 was decommissioned in January 2003.

System engineering to integrate the two units was completed by HyRadix, Inc. and Enable prior to shipping either system to HARC. Of particular importance was to establish the communications protocols to allow the fuel cell to control the output of the reformer. To improve the transient response of the integrated system, the fuel cell was engineered to allow use of HARC's bulk hydrogen gas as a supplemental hydrogen source. This approach is an alternative to using batteries as an energy buffer. However, appropriate control of the bulk hydrogen input proved difficult to master in this system.

As shown in Figure 2 below, HARC received and tested two HyRadix reformers between January 2002 and January 2003. During system commissioning, the initial system was inadvertently flooded with water. The system was repaired and successfully integrated with the Enable fuel cell. Once integrated, the combined system was tested in the fuel cell laboratory for about 400 hours over a period of about 3 weeks. This unit was replaced by HyRadix due to performance concerns related to the water flooding.

A second unit was shipped to HARC and commissioned in mid-April 2002. This unit was integrated with the Enable fuel cell and was operated for about 120 hours, at which time Enable fuel cell system encountered technical difficulties and ceased operating. Consequently, testing of the integrated fuel cell - reformer system was terminated.

Although HARC laboratory was not configured to monitor the independent operation of the Alpha 4 unit in detail, HARC continued to operate the reformer in idle mode through January 2003 to gather reliability information. Idle mode entails producing reformate with the system under minimal load conditions. In this case, the system consumed a constant flow of natural gas of about 8 slpm with all reformate combusted within the reformer by the AWG burner. Reformate hydrogen purity and CO concentrations were monitored by HARC during this testing.

Figure 2: HyRadix System Timeline 2002-2003

First Reformer	J	F	M	A	M	J	J	A	S	O	N	D	J
Setup and Commissioning	■												
Integrated System Testing		■	■	■									
Reliability Testing													
System Decommissioned				■									
Second Reformer	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**J**
Setup and Commissioning				■									
Integrated System Testing				■	■								
Reliability Testing						■	■	■	■	■	■	■	
System Decommissioned													■

Start Up Performance

During system start up, the Alpha 4 system exhibited a lack of stability which required substantial operator intervention to avoid system shutdowns. The Alpha 4 system stability problems, which adversely impacted transient operation, resulted from control issues encountered in operation of the integrated fuel cell/reformer system. During normal and typical operations, start up of the reformer from a cold start took 4-5 hours.

Variable Power Test

The specified transient response for the Alpha 4 reformer was 2% of design flow per minute, which is the hydrogen equivalent of a 100 W/min electrical load change. As mentioned above, supplemental hydrogen was provided to the fuel cell to make up for the difference between the energy provided by the fuel processor and the super caps during a load change. The AWG burner in the fuel process was designed to accommodate the unreacted hydrogen present in the AWG during a transient.

Throughout the transient testing, the fuel processor transient response was consistent with manufacturer specifications. However, degradation of the fuel cell resulted in overall efficiency with an attendant increased slip of supplemental hydrogen to the AWG burner. The increased hydrogen overloaded the AWG burner and caused several shutdowns due to high temperature. Unstable flow control of the supplemental hydrogen exacerbated the problem.

In order to maintain stable burner temperatures, the maximum load change was reduced to 100 W per minute. This minimized the addition of supplemental hydrogen and the impact of the unstable control. Attempts to fix the flow control problems and the cell efficiency problems were underway when Enable encountered their financial difficulties and ceased providing technical support.

To avoid the AWG burner temperature shutdowns, the system operator could intervene to adjust and control the AWG burner temperature. By watching the AWG burner temperature on the control screen, the operator could manually adjust the air bypass valve to maintain the desired temperatures in the AWG burner. This became a critical aspect of successful system start up and operation, but required significant operator attention. As a result, the system could not be started and run independently of the operator.

Constant Power Test

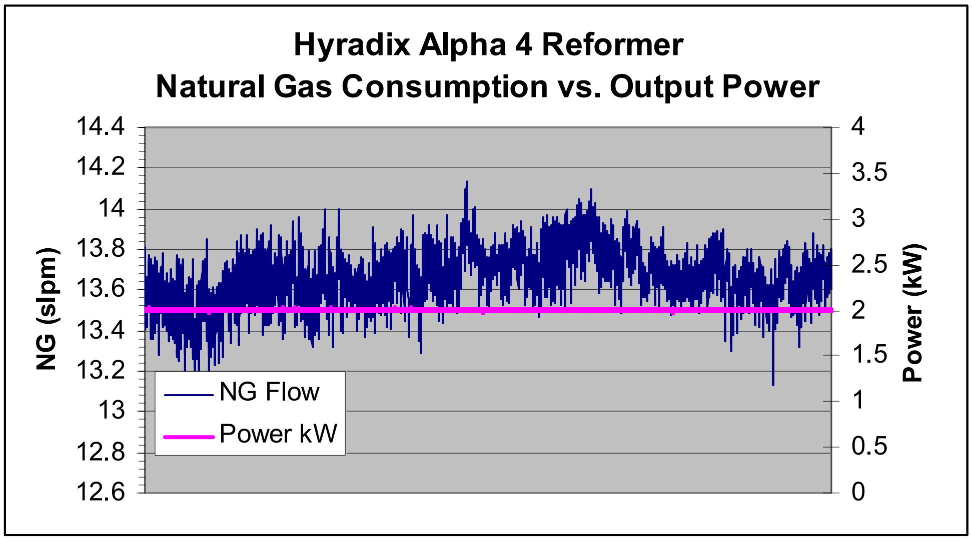
The integrated system was capable of reaching and maintaining a constant power set point. Once the reformer was started and the desired output level was reached, successful steady state operation could be maintained. The Alpha 4 reformer was initially tested at 500 Watts constant power, and then brought up to 2000 watts in 100 watt per minute increments. The longest run of the integrated system was for 140 hours at 2000 Watts. As shown in Figure 3, the Alpha 4 reformer consumed about 13.6 slpm of natural gas to maintain an electrical output power of 2000 W from the Enable fuel cell, implying a 22-25% efficiency for the combined fuel cell/reformer system.

Component Reliability

The HyRadix reformer system exhibited several recurring problems that adversely affected system reliability. The majority of equipment failures are related to design flaws, some of which HyRadix claims to have resolved in the Alpha 5 design. For example, the failure of the FT 400 air flow meter was replaced some 10 to 15 times throughout the test period. The repeated failure of this device has been attributed to constant back flow of heated air. In addition, HARC noted the following component failures:

- Partial oxidation air compressor– replaced 3 times
- ATO air compressor – replaced 3 times

Figure 3: Natural Gas Consumption at 2000W



Reformate Quality

The quality of the reformate gas stream produced by the Alpha 4 is shown in Figures 4 and 5 below. As shown in Figure 4, the Alpha 4 consistently produced reformate with a hydrogen concentration in the 45-48% range. In addition, carbon monoxide concentrations were consistently found to be less than 5 vppm (dry basis) with the unit operating in idle mode. Typical performance is shown in Figure 5.[1]

Software Issues

Throughout the test period, the HyRadix reformer design, including the software revision, was in a constant state of upgrade. The software had three major upgrades in the one year test period. The most significant software problem related to a virtual memory leakage. As the data being created became larger than 2 gigabytes, the reformer CPU would shut down. While a temporary solution (cutting, pasting, and saving the file under a different name) allowed the system to be operated, a long-term solution was not implemented before the end of the test period.

[1] HARC did not have CO detection capabilities when the Alpha 4 and the Enable fuel cell were operating as an integrated system.

Figure 4: Typical Hydrogen Percentage in Reformate

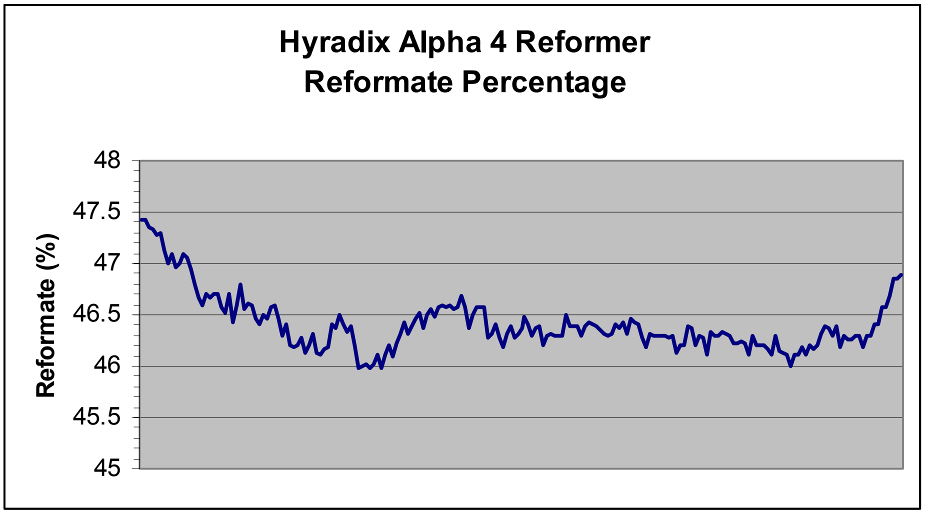
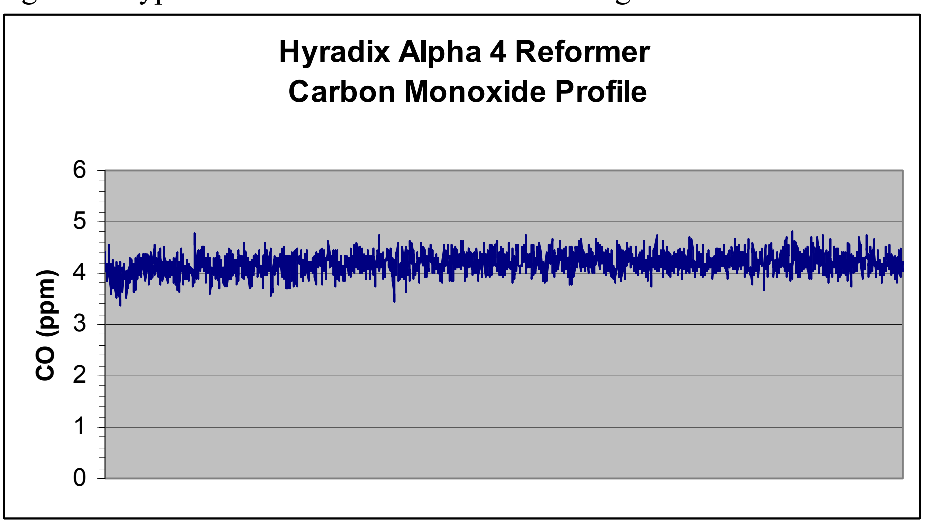


Figure 5: Typical Carbon Monoxide Level during Idle Mode



Technical Support

HARC found the technical support team at HyRadix to be very responsive and knowledgeable. The response time between equipment failure and a return phone call was usually prompt, although technical support was only available Monday thru Friday between 8:00 AM and 5:00 PM Central time. A HyRadix technician was present at

HARC when the system was commissioned. Furthermore, on several occasions HyRadix personnel came to the HARC facility to support the system as necessary.

Manuals and Training

The operations manual provided by HyRadix covered the basic process description and theory of operation. The manual strongly emphasized safe operation and pointed out potential sources of danger. However, the manual lacked detailed and specific instructions needed to operate the system proficiently. For example, the complexity and the stringent limits of the burner temperatures required substantial operator involvement to start the system, but the details were not sufficiently documented in the manual. During system commissioning, HyRadix did provide about four days of on-site training.

Technology Update – HyRadix Agilon

HyRadix has developed a new generation of fuel processor named the Agilon™. The unit is shown in the photo below. While the unit is based on the same process principles as Alpha 4, the unit reportedly includes many improvements that address some of the shortcomings identified in the Alpha 4 through the experiences at HARC and other demonstration sites. One of the key enhancements in the unit is that it has been extended to enable processing of LPG.

According to HyRadix, the Agilon unit benefits from significant improvements in balance of plant component selection and testing, catalyst and reactor design and optimization, controls hardware component selection, and automation and operator interface. The following paragraphs describe some of these improvements.

Installation and Size - As noted in this report, the Alpha 4 unit was delivered with a separate panel housing the control hardware and interface, which required interconnecting wiring and installation of multiple items upon delivery. In the Agilon unit, the control system and interface are integrated into a single unit. Also, the total volume of the Agilon unit is ~18 ft^3, which is a less than fifty percent of the Alpha 4 unit volume. This provides for an easier installation and significantly reduced footprint.

Balance of Plant - The Agilon unit is a complete fuel processor designed to operate in a stand-alone mode (including all balance of plant components and controls). Where appropriate, the balance of plant components have been bench tested to prove the reliability and performance capability. Based on this testing, more robust and reliable flow metering solutions were chosen which are expected to eliminate repeat failures, such as those experienced on the air flow meter. The Agilon system also has upgraded natural gas compressors that allow the unit to be hooked up directly to pipeline pressure natural gas with no need for a booster compressor.

Automation and Startup - The Agilon also includes the significant automation enhancements. While the Alpha 4 required substantial operator intervention to startup the system, new automation in the Agilon permits true pushbutton startup. After pressing the startup button, the operator may go about other business and return about an hour later to find the Agilon unit ready to deliver hydrogen to a fuel cell. As reported by HyRadix, the startup time of the Agilon unit is about seventy five percent less than that of the Alpha 4. This improvement is the result of reconfiguring the process design and startup sequence to maximize the use of heat available. HyRadix claims that the startup time improvement was accomplished without compromising the efficiency of the unit during normal operations.

HyRadix has delivered an Agilon reformer to the Texas Department of Transportation's Transguide facility in January 2004. The unit is processing LPG (commercial propane) for use with an integrated fuel cell to provide power to traffic monitoring equipment at the Transguide site.

End of Report