Development of an External Fuel Processor for a Solid Oxide Fuel Cell

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Abstract

A 250 kW External Fuel Processor was developed and tested that will supply the gases needed by a pipeline natural gas fueled, solid oxide fuel cell during all modes of operation. The fuel processor consists of three major subsystems – a desulfurizer to remove fuel sulfur to an acceptable level, a synthesis gas generator to support plant heat-up and low load fuel cell operations, and a start gas generator to supply a non-flammable, reducing gas to the fuel cell during startup and shutdown operations. The desulfurization subsystem uses a selective catalytic sulfur oxidation process that was developed for operation at elevated pressure and removes the fuel sulfur to a total sulfur content of less than 80 ppbv. The synthesis gas generation subsystem uses a waterless, catalytic partial oxidation reactor to produce a hydrogen-rich mixture from the natural gas and air. An operating window was defined that allows carbon-free operation while maintaining catalyst temperatures that will ensure long-life of the reactor. The start gas subsystem generates an oxygen-free, reducing gas from the pipeline natural gas using a low-temperature combustion technique. These physically and thermally integrated subsystems comprise the 250 kW External Fuel Processor.

The 250 kW External Fuel Processor was tested at the Rolls-Royce facility in North Canton, Ohio to verify process performance and for comparison with design specifications. A step wise operation of the automatic controls through the startup, normal operation and shutdown sequences allowed the control system to be tuned and verified. A fully automated system was achieved that brings the fuel processor through its startup procedure, and then await commands from the fuel cell generator module for fuel supply and shutdown. The fuel processor performance met all design specifications.

The 250 kW External Fuel Processor was shipped to an American Electric Power site where it will be tested with a Rolls-Royce solid oxide fuel cell generator module.

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Executive Summary

A 250 kW External Fuel Processor was developed to supply the gases required by a Solid Oxide Fuel Cell (SOFC) generator module over all modes of operation. The fuel processor contains three subsystems to produce the required gases, including a desulfurizer, to remove fuel sulfur to an acceptable level, a synthesis gas generator to support plant heat-up and low load fuel cell operations, and a start gas generator to supply a non-flammable, reducing gas to the fuel cell during startup and shutdown operations.

The prototype fuel processor design was based on small- and intermediate-scale component development testing and a scaled-system test. For the desulfurizer subsystem a selective catalytic sulfur oxidation process was used to convert fuel sulfur to sulfur oxides and trap them in a sorbent material. The synthesis gas subsystem uses a catalytic partial oxidation reformer to convert the pressurized pipeline natural gas to a hydrogen-rich gas. The start gas subsystem uses a low-temperature combustion technique to produce a reducing gas with specified maximum hydrogen content.

The fuel desulfurization subsystem was found to have a wide operating window to allow a 10-to-1 load range while producing a gas having total sulfur content less than 80 ppbv. An operating envelope was determined for the synthesis gas generation subsystem to ensure long catalyst life while preventing carbon formation at elevated operating pressures over a load range of 10-to-1. A start gas subsystem was developed to produce a non-flammable reducing gas. The desulfurization and start gas subsystems were built onto self-contained skids. The synthesis gas generators were built for integration into the SOFC generator module.

Controls were commissioned and tested to verify conformance with the controls requirements. A fully automated mode was achieved such that the fuel processor system automatically steps through its startup procedure then awaits commands from the SOFC generator module to supply the needed gases.

A plan was developed for demonstrating the long-term durability of the External Fuel Processor. Following the initial plant tests at an American Electric Power site the fuel processor will be returned to the Rolls-Royce facility in North Canton, Ohio for extended durability testing. The testing will address thermal cycling, the impact of fuel contaminants on catalyst and sorbent performance, and the effects of ambient temperature. The extended durability testing is expected to provide the necessary level of confidence for long-term operation of the External Fuel Processor.

The cost model identified a need to address cost reduction in several areas including scale-up of a key subsystem, process simplification to reduce part count, and process-based control options to eliminate expensive measurement hardware. Experts in manufacturing processes were also used to help introduce new approaches into our design and manufacturing process. These improvements are being implemented in our next generation 1MW fuel processor, current under construction.

Finally, several approaches were examined for the integration of a coal synthesis gas plant with the Rolls-Royce SOFC power plant. The results indicated that the coal-derived synthesis gas can yield sufficient electrical conversion efficiency in a Rolls-Royce fuel cell power plant to achieve overall electrical conversion efficiencies that exceed 45% in a combined cycle plant. Furthermore, with additional design optimization, and advancements in key areas, such as coal gasification and oxygen separation, efficiencies that reach or exceed 50% are possible.

1.0 INTRODUCTION

This report provides a summary of the activities that led to the development of a 250 kW External Fuel Processor (EFP) for a Solid Oxide Fuel Cell (SOFC). This included tasks to develop and scale-up components for fuel desulfurization and for the production of synthesis gas and start gas; a task to design and test a scaled integrated system; and a task to design, build, and test the full-scale prototype, 250 kW External Fuel Processor. Additional tasks addressed a plan for long-term durability and cost modeling of the fuel processor, and an evaluation of coal gasification concepts for the Rolls-Royce fuel cell system.

The purpose of the External Fuel Processor is to produce a suitable supply of gases for a 250 kW SOFC generator module under all operating conditions. This includes subsystems to desulfurize the pipeline natural gas to a total sulfur content less than 80 ppbv, to produce a hydrogen-rich synthesis gas during fuel cell startup and low load operation, and to produce a non-flammable reducing gas during fuel cell startup and shutdown.

A schematic showing the relationship between the External Fuel Processor and the SOFC generator module and its feed supply is shown in Figure 1.

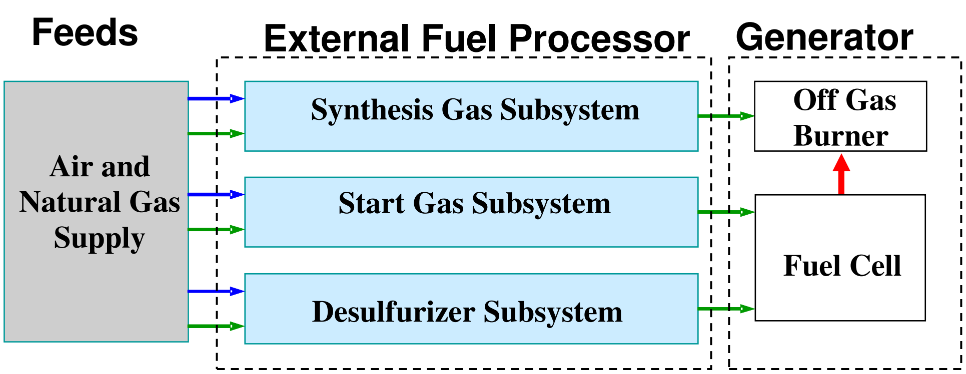

Figure 1. Relationship Between EFP and SOFC Generator

The External Fuel Processor is supplied with pressurized pipeline natural gas and pressurized air. The Synthesis Gas subsystem supplies fuel to an Off Gas Burner and the Start Gas and Desulfurizer subsystems supply fuels to the Fuel Cell.

2.0 TECHNICAL APPROACH AND RESULTS

The technical approach was to extend the Rolls-Royce Fuel Cell Systems small-scale development work on key components to an intermediate-scale that would provide scalable data for designing the full-size components, and to develop a scaled-integrated system using these components to demonstrate functionality and controllability of the fuel processor system. The data from these test programs would become the basis for the design of the 250 kW External Fuel Processor. The key components of the system include a desulfurizer, synthesis gas generator, and start gas generator.

2.1 Desulfurizer Development

Rolls-Royce Fuel Cell Systems previously conducted small-scale development work on a Selective Catalytic Sulfur Oxidation (SCSO) desulfurization process for pipeline natural gas and showed its feasibility at the planned operating pressure. The objective of this work was to extend the process to a scalable size, such that design data could be developed for a 250 kW prototype desulfurizer, and to test the desulfurizer for an extended period to characterize performance. An intermediate-scale desulfurizer with an 18 kW capacity was selected.

In this desulfurization process a small amount of air is used to oxidize the sulfur compounds to sulfur oxides. The sulfur oxides are then trapped in a downstream absorber. The components used for the intermediate-scale tests are illustrated in Figure 2.

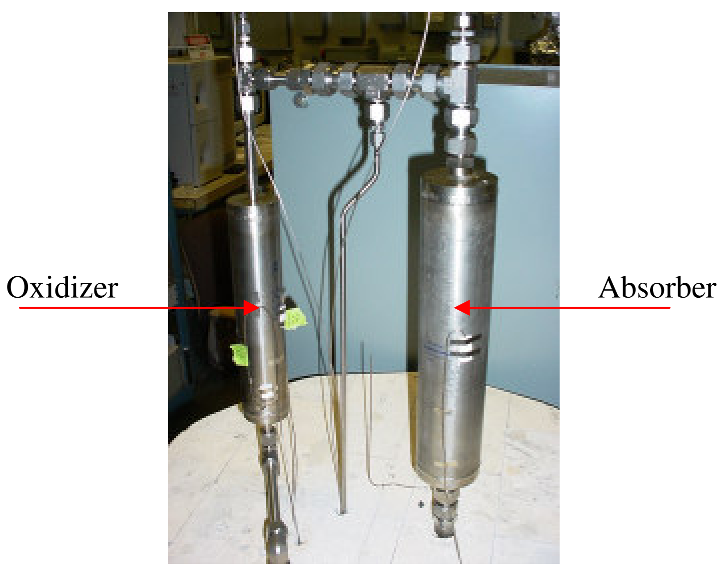

Figure 2. Intermediate-Scale Desulfurizer Test Components

The desulfurizer components were mounted inside a furnace to maintain the thermal environment. The feed streams to the oxidizer were metered and the inlet temperature was controlled. Control loops, alarms and safety trips were implemented to allow unattended operation. The process inlet and outlet gas samples were collected in cylinders and shipped to a laboratory for accurate sulfur analyses.

The test fuel for the intermediate-scale tests was pipeline natural gas. Analyses for two natural gas samples taken at the test stand in Alliance, Ohio are given in Table 1.

Table 1
Pipeline Natural Gas Properties

Component	Mole%	Mole%
Hydrogen	0.03	0.06
Helium	0.04	0.08
Oxygen	0.01	0.01
Nitrogen	1.37	2.38
Carbon dioxide	0.58	0.08
Carbon Monoxide	<0.01	<0.01
Methane	93.19	91.42
Ethane	3.50	4.22
Propane	0.77	0.94
Butanes	0.32	0.45
Pentanes	0.06	0.18
C_6+	0.07	0.18
Total Sulfur, ppmv	2.60	2.25
Higher Heating Value, BTU/Ft^3	1,044	1,058
Lower Heating Value, BTU/Ft^3	943	952

Intermediate-scale desulfurizer testing[1] confirmed the sulfur removal efficiency from earlier work and provided scalable design data over a wide range of process conditions including space velocity, inlet temperature, air/fuel ratio and pressure. A 10:1 flow turndown with acceptable sulfur reduction performance was found.

Long-term desulfurizer system performance was conducted in three operating segments - Process Parametrics between 0-650 hour run-time; Thermal Cycling between 650-840 hour run time; and Durability between 840-1750 hour run-time. These test durations are indicated by the dotted vertical lines in Figure 3.

[1] "Desulfurization of Pressurized Natural Gas - Intermediate Scale and Durability Testing", M.V. Kantak, January 2007

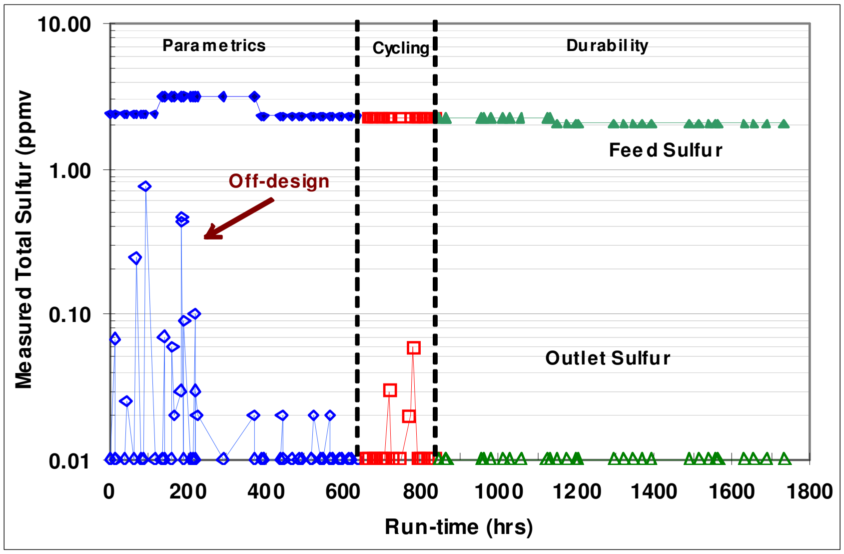

Figure 3. Long-term Sulfur Reduction Performance

During the first 650 hours of the test (Parametrics) the operating load, temperature, pressure, and feed composition were varied. The measured total sulfur in the process inlet and outlet streams are plotted in Figure 3. The inlet pipeline natural gas feed total sulfur ranged between 2-5 ppmv and was made up of linear-chain mercaptan and sulfide odorants. The treated natural gas sulfur was well below 0.1 ppmv (or 100 ppbv) except for a few off-normal conditions. At optimum operating conditions, the outlet sulfur was at or below the minimum detection limit of the instrument (≤ 0.01 ppmv).

Between 650 and 850 hours (Cycling) thirteen thermal cycle tests were carried out at one operating condition. Each cycle included 8 hours of normal operation followed by a period of "zero-flow". Gas samples were taken before and after each thermal cycle, and analyzed for total sulfur and other constituents to investigate performance differences. The collected data showed no performance loss, thus, implying the robustness of the process. For the inlet fuel-sulfur of 2 ppmv, the measured outlet sulfur was below 0.1 ppmv (100 ppbv).

During the Durability phase of the test the system logged an additional 900 hours with approximately thirty successful startups and shutdowns. Nearly 100% sulfur reduction was measured for the nominal natural gas feed rate with the outlet sulfur at or below the minimum detectable level of 10 ppbv.

Overall, the desulfurization process met or exceeded the required fuel-sulfur removal target. The process robustness and stable operation were experimentally verified at intermediate scale. The effects of several process parameters were investigated and a flow turndown of 10:1 was established for the desulfurizer components. The intermediate-scale desulfurizer data provided a good design basis and confidence in the process scale-up to a 250 kW natural gas desulfurizer. The intermediate-scale test data along with the process control know-how was used to design a full-scale desulfurization system for integration into the External Fuel Processor.

2.2 Synthesis Gas Generator Development

Earlier small-scale tests of the synthesis gas generator performed at operating pressures up to 12 Bar absolute (Bara) confirmed that pressure had a positive impact on the reformer performance by enabling higher throughput per unit volume of catalyst. The tests also confirmed that carbon will form at elevated pressures when proper operating conditions are not maintained. The process uses a Catalytic Partial Oxidation (CPOX) reformer to partially oxidize the fuel with a sub-stoichiometric quantity of air to produce a synthesis gas containing H_2, CO, CO_2, and water.

The objective of this work was to extend the process to a scalable size such that design data could be developed for the prototype synthesis gas generators required by the 250 kW External Fuel Processor. Additional objectives included definition of operating conditions that avoid carbon formation while maintaining catalyst temperatures that will ensure long-life, and to confirm that a 10-to-1 turndown for the reformer could be achieved. An intermediate-scale reformer with a 17 kW capacity was selected. The hardware used for the intermediate-scale test is illustrated in Figure 4.

17 kW CPOX Reformer

Test Stand for Synthesis Gas Generator

Figure 4. Intermediate-scale Synthesis Gas Generator Hardware

Intermediate-scale synthesis gas tests[2] characterized the performance of a CPOX reformer as a function of throughput (load) and air-to-fuel ratio (O_2/C ratio) at elevated pressures. Testing was performed to define operating conditions that avoid carbon formation while maintaining catalyst temperatures that will ensure long-life. Additionally, test data was generated to confirm that a 10-to-1 turndown for the CPOX reactor could be achieved. The high pressure test stand is illustrated in Figure 5.

Figure 5. High-Pressure CPOX Test Stand

The CPOX reactor performance was characterized by performing 18 steady-state tests. All tests were performed with pipeline natural gas (See Table 1 for gas composition). Each steady-state test was an average of at least three test measurements (each with complete gas analysis) at the given steady-state condition.

Test results indicated that the reactor operated at an average efficiency of 77%. This was near the expected value based on thermodynamic equilibrium. The efficiency was slightly sensitive to operating load. Results, illustrated in Figure 6, showed that efficiency was lowest at the lowest load levels. This was most likely a result of a higher fractional heat loss at the low-load

[2] "Test Report for Intermediate-scale (17kW) Pressurized Catalytic Partial Oxidation (CPOX) Reformer", M.A. Perna, January 2007

condition that caused a lower reactor temperature, and a correspondingly lower conversion of the natural gas.

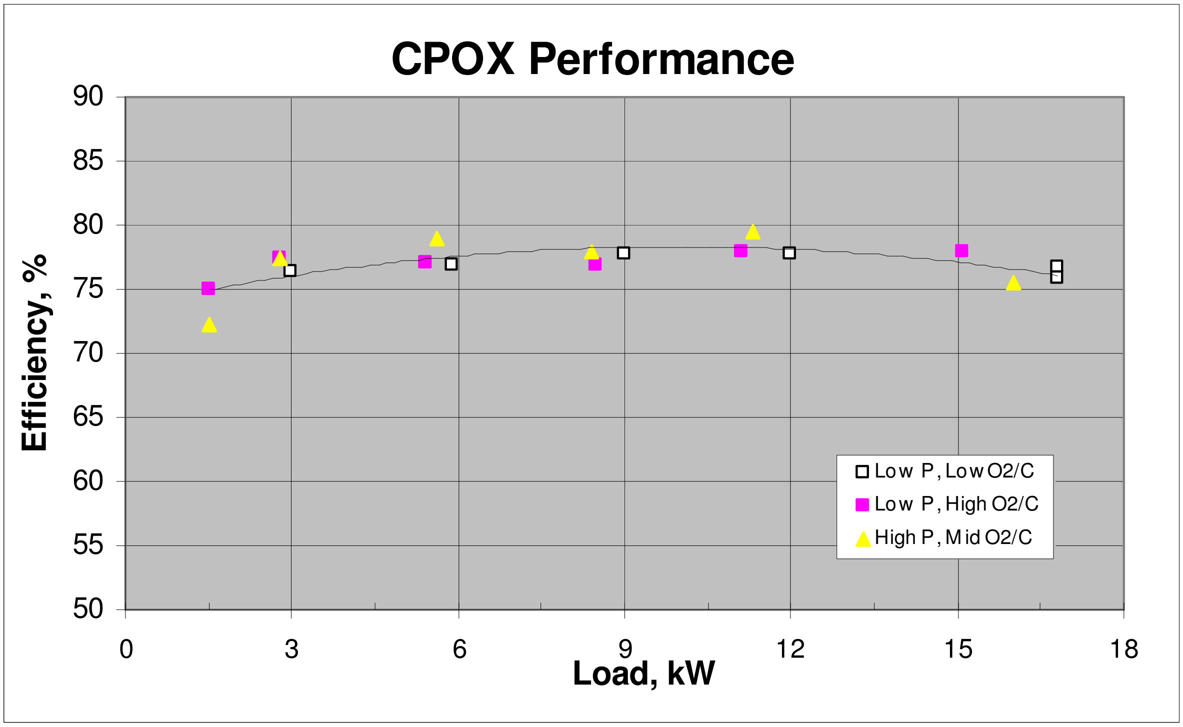

Figure 6. Impact of Load on Fuel Processor Efficiency

Test results also showed the outlet temperature was sensitive to load and increased with increasing load level. The minimum catalyst outlet temperature was achieved at the low-load condition. The results indicated that hydrocarbon slip (as C_2+) was sensitive to load and similar results were observed at both low and elevated pressures.

Results for catalyst outlet temperature showed that it was significantly impacted by the O_2/C ratio. The tests at the highest O_2/C ratios for each load level had the highest catalyst outlet temperatures. No carbon deposits were observed in the CPOX reactor or on the CPOX catalyst. A sufficiently high catalyst outlet temperature is believed to have prevented carbon formation.

The intermediate-scale test data provided a basis for scale-up to larger, pressurized CPOX reactors. Operating conditions were developed that define parameters for achieving a minimum temperature to prevent carbon formation and a maximum temperature that will ensure long catalyst life while operating at elevated pressure over a 10-to-1 load range.

2.3 Start Gas Generator Development

The Start Gas subsystem produces a relatively low-temperature reducing gas to the SOFC generator module during startup and shutdown operations. A component was developed to produce the desired gas composition. Initial testing with a small-scale component confirmed the feasibility of the design and provided the basis for an intermediate-scale component. From the intermediate-scale component tests the relationship between feed conditions and outlet composition was developed. Conditions under which unstable operation and an out-of spec outlet composition may result were also developed. The start gas reactor used for the intermediate-scale component tests is shown in Figure 7. The intermediate-scale component tests provided the basis for the reactor design for the full-size component.

Figure 7. Intermediate-scale start gas reactor

A start gas reactor was developed to generate an oxygen-free, reducing gas from pipeline natural gas. Small-scale tests were performed to select a catalyst that achieved reactor light-off at an acceptable temperature and produced the desired gas composition. Intermediate-scale component tests then developed the relationship between feed conditions and outlet composition.

A reactor light-off test was performed at the planned operating pressure using oxygen-depleted air and natural gas. With a preheated catalyst, natural gas flow was initiated and the catalyst inlet temperature began to rise after a short lag time until a maximum catalyst temperature was reached. The observed rate of temperature rise was a considerably slower rate than for a CPOX reactor.

A number of tests were conducted to establish the operating conditions of space velocity, air/fuel ratio, and preheat needed for provide stable operation for producing the desired outlet composition and outlet temperature. The feasibility tests established these conditions which provided the basis for reactor scale-up.

The measured H_2+CO concentration from the reactor feasibility tests was in excellent agreement with the expected equilibrium values. All test conditions had good agreement between the measured and the equilibrium values except one test at high space velocity. The plot in Figure 8 shows the relationship between the measured and predicted values.

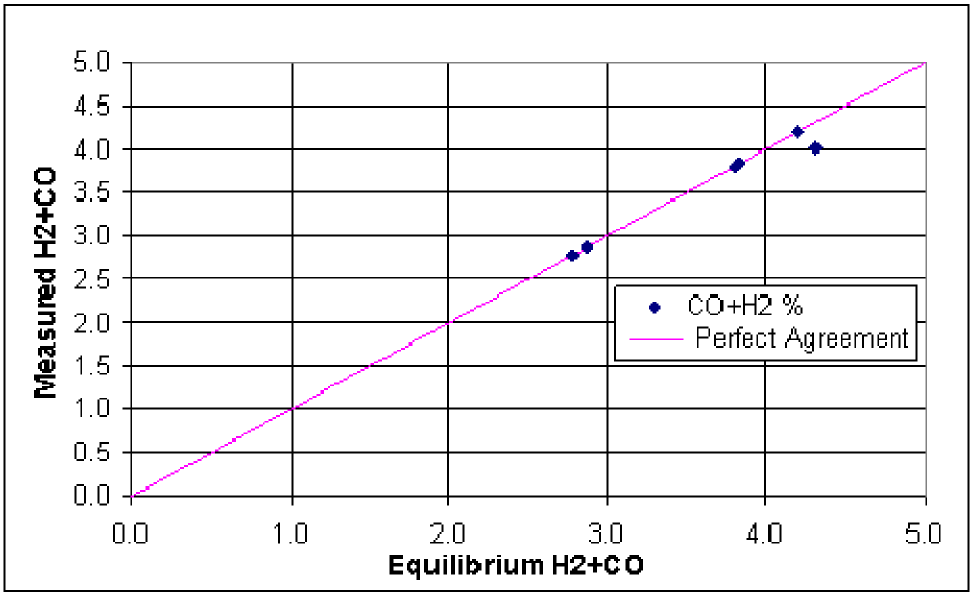

Figure 8. Measured vs. Equilibrium Values for H_2 + CO Concentration

After the small-scale feasibility tests were completed a larger reactor (75% of full-scale) was tested to provide an initial estimate of the reactor size for the full-scale prototype system while satisfying various constraints on outlet composition and temperature. The test hardware for the intermediate-scale start gas reactor is illustrated in Figure 9.

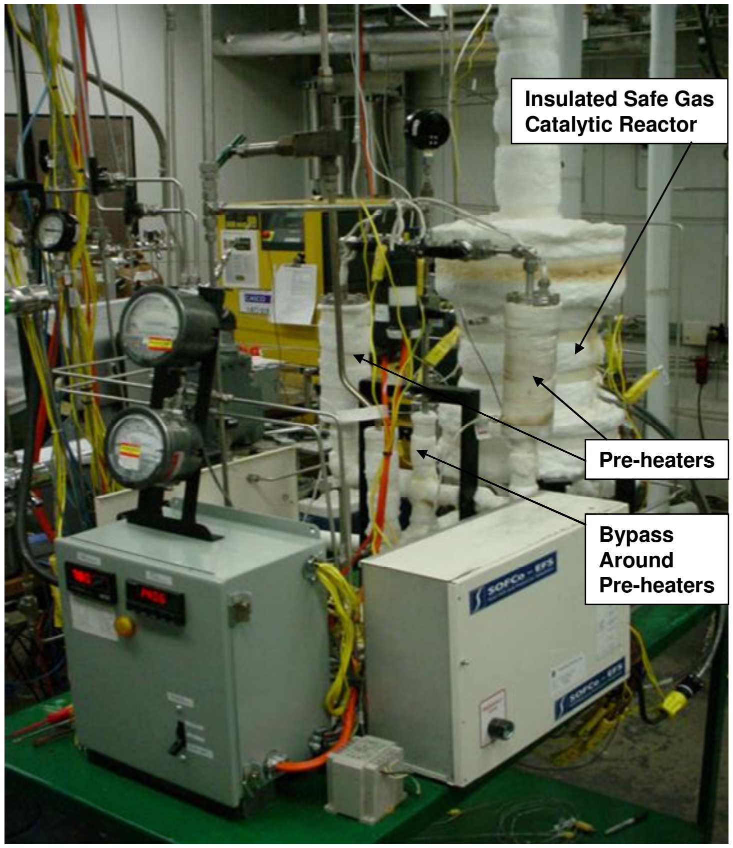

Figure 9. Intermediate-Scale Start Gas Test Hardware

From the intermediate-scale component tests the required full-scale reactor size was determined and the relationship between feed conditions and outlet composition was developed. The operating envelope was also developed to define regions for unstable operation or an out-of spec outlet composition.

2.4 Intermediate-scale Integrated System

The Intermediate-scale Integrated System included a full-scale synthesis gas generator, a near-full-scale start gas generator, and a sub-scale (18 kW) desulfurizer system. The objective for the test was to verify operation of each subsystem over its various modes of operation. Modes of operation included start up, load range, hot idle, restart, and shutdown.

The scaled-system was characterized in both open loop and closed loop configurations. The open loop configuration allowed functional testing of each subsystem while closed loop testing (not part of this project) allowed the scaled system to be tested with a SOFC at the Rolls-Royce facility in Derby UK. Figure 10 shows the Intermediate-scale Integrated System fuel and air supply (left cabinet) and test hardware (right cabinet).

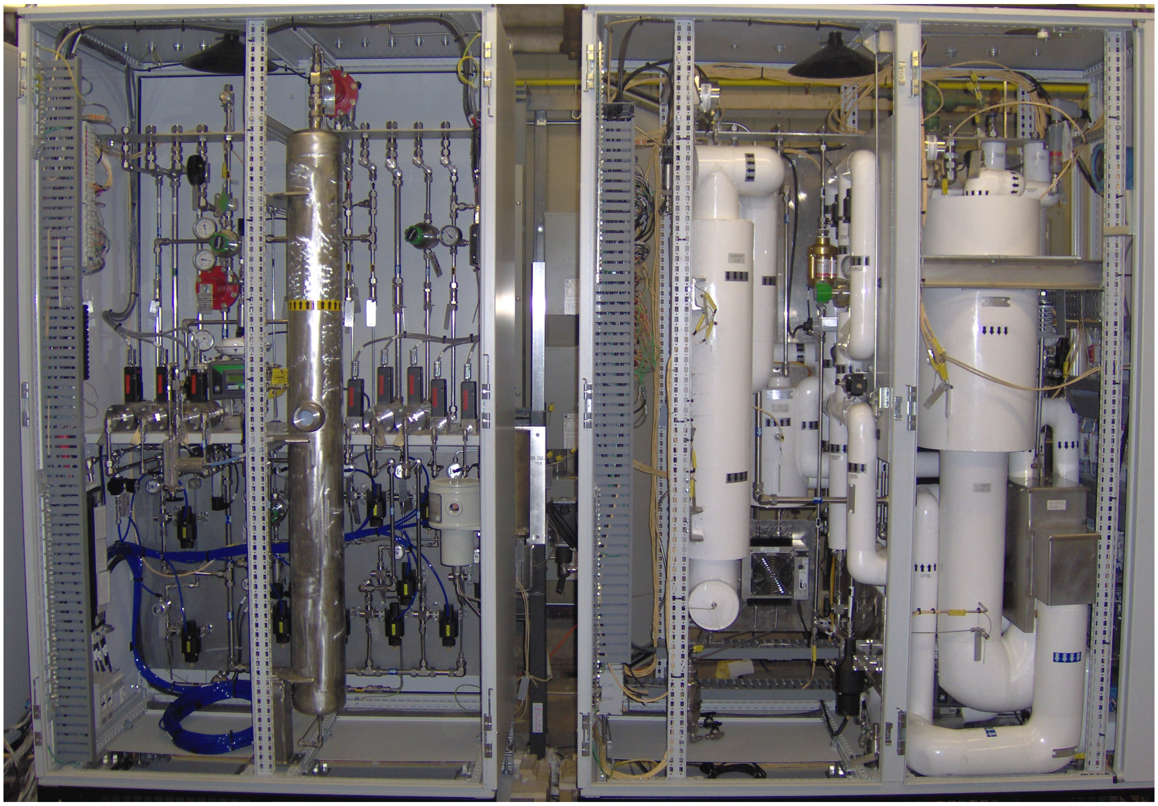

Figure 10. Intermediate-scale Integrated System Hardware

Testing started with the desulfurizer subsystem including start up, normal operation and shutdown. Figure 11 shows the sulfur removal levels as a function of load for this test and for the small-scale development unit. The desulfurizer was effective over the full load range and produced a gas with total sulfur content well below the target specification.

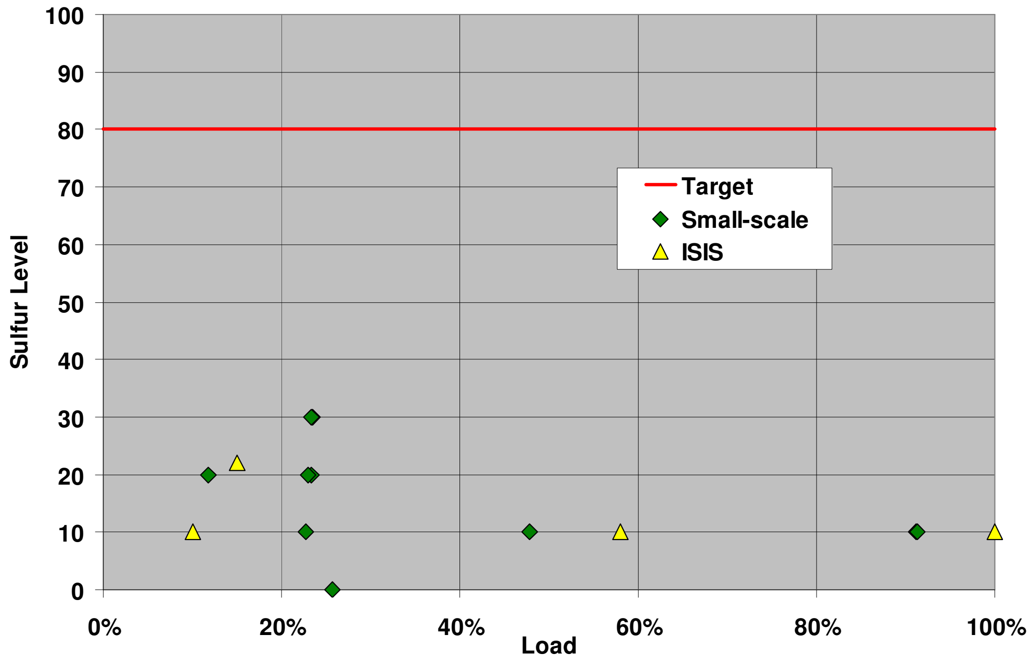

Figure 11. Desulfurizer Performance Comparison

The hydrogen concentration in the synthesis gas as a function of load is shown in Figure 12. These data are consistent with expectations and meet the requirements of the design specifications. Test data from the small scale developmental tests are also shown for reference.

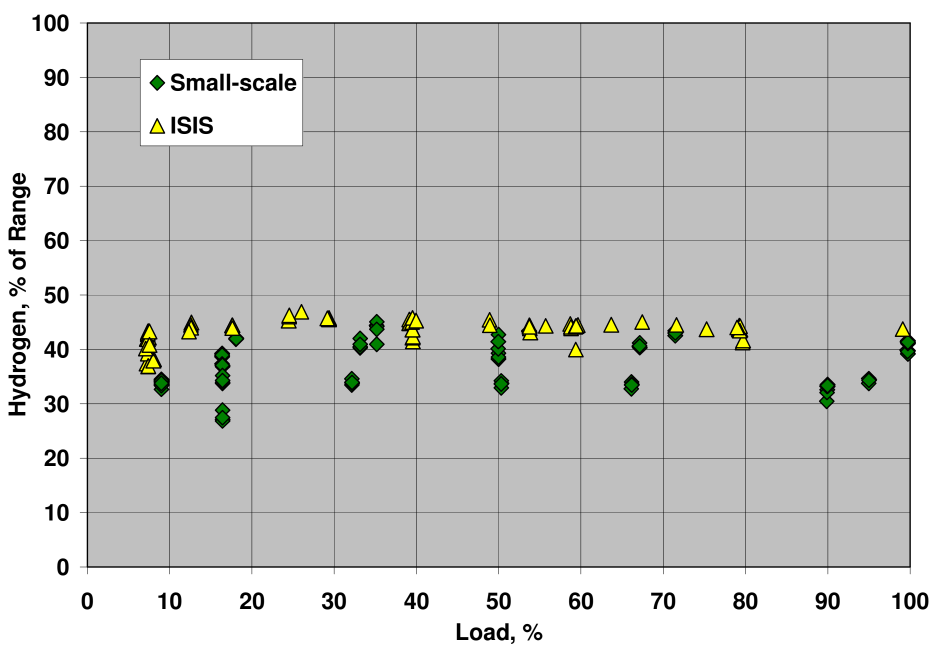

Figure 12. CPOX Reformer Performance Comparison

Figure 13 shows a comparison of hydrogen concentration in the start-gas as a percent of its full-range using three independent techniques. The results show a favorable comparison.

The Intermediate-scale Integrated System was successfully run over all operating states including startup, normal operations and shutdown. The desulfurization subsystem process met the required fuel-sulfur removal targets. The effects of process conditions were investigated and the specified load turndown was demonstrated. The synthesis gas and start gas subsystems successfully produced there target gas compositions. Startup and operating conditions were developed and the specified turn-down ratio was demonstrated. Overall results demonstrated important features in performance, hardware design and controls that were used for development of the 250 kW External Fuel Processor.

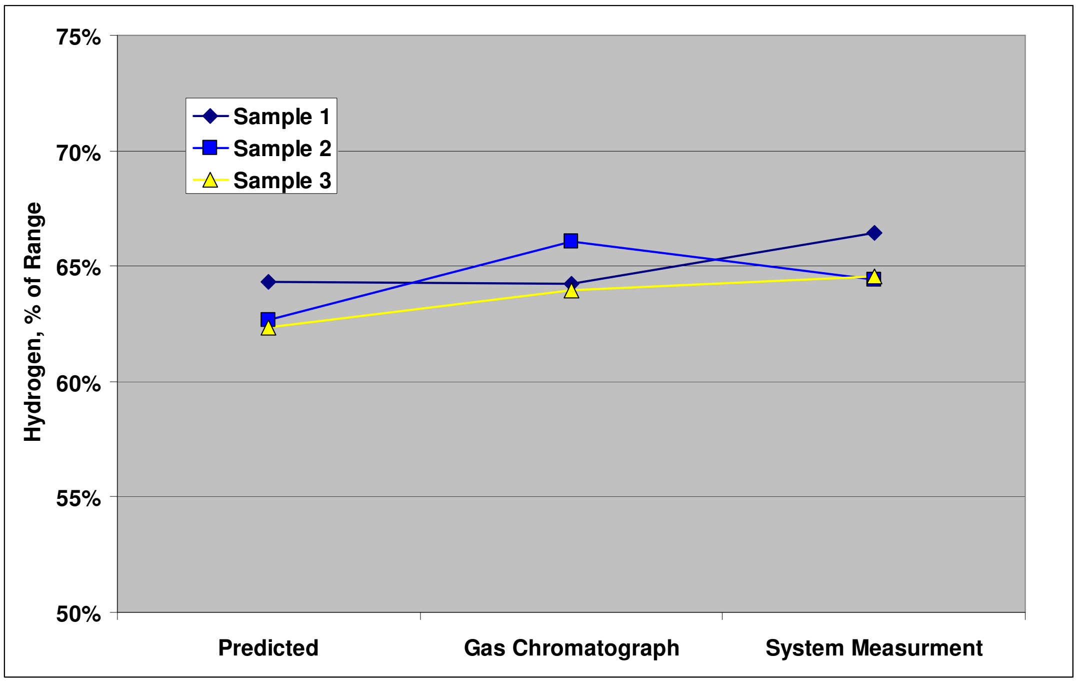

Figure 13. Start Gas System Performance

3.0 250 KW EXTERNAL FUEL PROCESSOR

The objective of this task was to design, assemble and test a fully-packaged integrated 250 kW External Fuel Processor using the major components developed in the earlier tasks.

The desulfurizer subsystem consists of a Selective Catalytic Sulfur Oxidation (SCSO) reactor and sorbent beds. Air and pipeline natural gas are supplied to the system. The natural gas flow is regulated by down stream component demand. The air flow is proportionately controlled to the natural gas flow. The SCSO has an electric preheater for the pipeline natural gas. A natural gas burner is used to preheat the sorbent bed during start up. Lastly, the treated natural gas is cooled with an air cooled heat exchanger. The desulfurizer and CPOX controls are located on the main skid as shown in Figure 14.

Figure 14. Skid with Desulfurizer Subsystem and CPOX controls

The synthesis gas subsystem consists of a preheater and CPOX reformer. Air and pipeline natural gas are supplied to the system. The air flow is proportionally controlled to the fuel flow. The CPOX reactor produces a hydrogen rich synthesis gas. A CPOX reformer and its supporting equipment was set up on a test stand and used to test the subsystem as shown in Figure 15. Two CPOX reformers were built for installation into the SOFC generator module.

Figure 15. Synthesis Gas Subsystem Test Stand

The start gas subsystem consists of hardware designed to produce a relatively low-temperature reducing gas to the SOFC generator module during startup and shutdown operations. The skid is shown in Figure 16.

Figure 16. Start Gas Subsystem

The facility used to test the 250 kW External Fuel Processor includes air and natural gas compressors, a flare to burn off the product gases, controls and a facility safety system. The control system provides manual and fully automated control of all major components and subsystems for start up, steady state operation and shutdown. The control system human machine interface is shown in Figure 17. An independent safety system provides for immediate shutdown if an unsafe condition is detected. During testing the skids and natural gas compressor are housed inside a ventilated enclosure with gas detectors to assure safe operation.

Figure 17. Control System

3.1 Experimental Results and Discussions

The External Fuel Processor skids were installed in a ventilated enclosure for testing. Gas supply, exhaust lines and power connections were made. The control system was connected to the external computed that contained the controls software. Each subsystem was commissioned separately and tested. Commissioning included verification of all electrical, instrument and pneumatic connections. Connections were checked from the source to the electrical cabinets, controls system and human machine interface. All flow control devises were checked, calibrated and setup for normal operation. Typical testing included the following.

- Verify normal operation of the subsystem with manual software controls including start up, normal and shutdown operations
- Measurement and verification of process performance and comparison with design specifications
- Step wise operation of automatic controls including start up, normal and shutdown operations
- Verification of fully automated operation

The main skid with the desulfurizer subsystem was installed in the ventilated enclosure and commissioned. Manual operation of all components was verified including valves, heaters and instrumentation. The system was operated in manual mode according to the controls statement of requirements. The statement of requirements is a detailed document that describes the sequential operation of the system. This document is used to develop the automatic controls software. Start up, normal and shutdown operations were performed. Performance data was collected to bench mark with design specifications. Figure 18 shows the sulfur removal levels as a function of load. The desulfurizer removed sulfur to below the target over the full load range. Also shown in the figure are test data from the small scale developmental unit and the Intermediate-scale Integrated System test. After performance was verified, the automatic controls were commissioned and tested. Controls testing was conducted first in a step wise mode to verify conformance with the controls statement of requirements, and then in fully automated mode. Full automation is virtually a one button operation. Push the button and the system automatically goes through the startup procedures and waits for commands from the generator module on fuel supply and shutdown. Generator module commands were simulated with software.

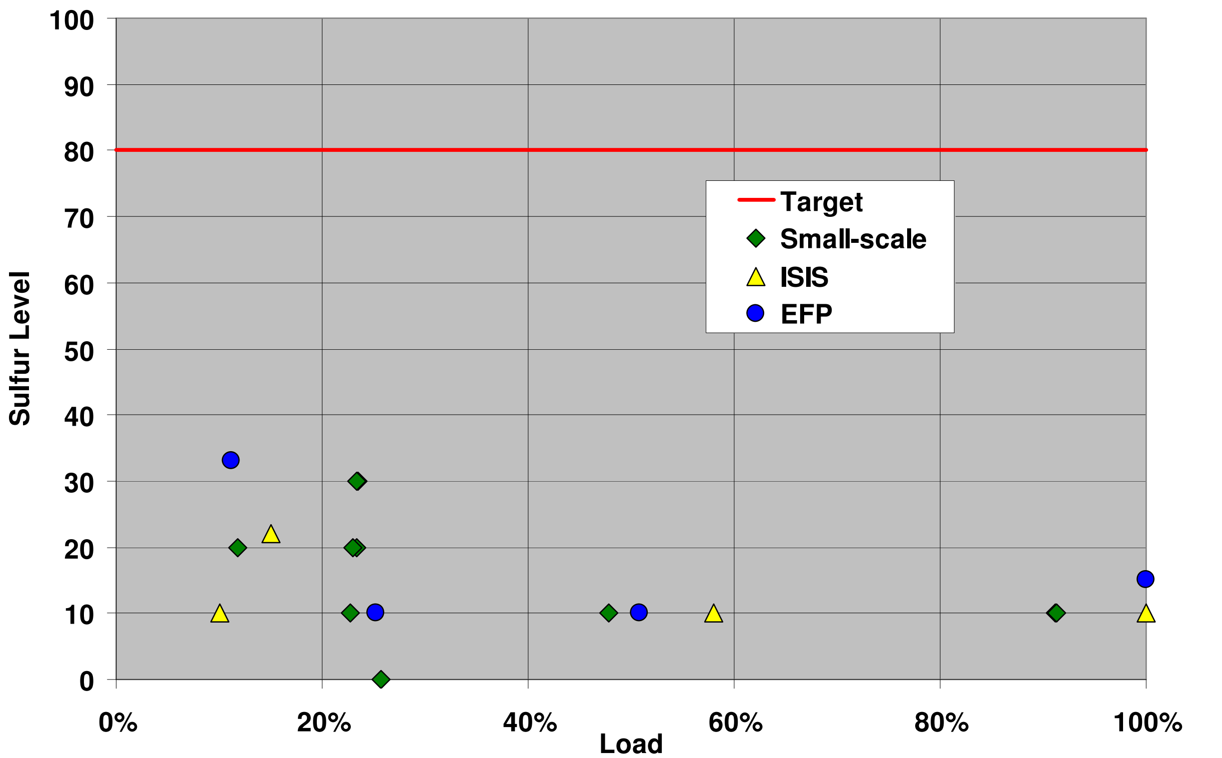

Figure 18. Desulfurizer Performance Comparison

The main skid with the CPOX reformer controls and the synthesis gas test stand were installed in the ventilated enclosure and commissioned. Manual operation of all components was verified including valves, heaters and instrumentation. The system was operated in manual mode according to the controls statement of requirements. Performance data was collected to bench mark with design specifications. Figure 19 shows a fairly constant hydrogen concentration in the synthesis gas as a function of load. Also shown in the figure are test data from the small scale developmental unit and the intermediate-scale unit. After performance was verified, the automatic controls were commissioned and tested first in step wise mode to verify conformance with the controls statement of requirements and then in fully automated mode. Full automation is virtually a one button operation. Push the button and the system automatically goes through the startup procedures and waits for commands from the generator module on fuel supply and shutdown. Generator module commands were simulated with separate software.

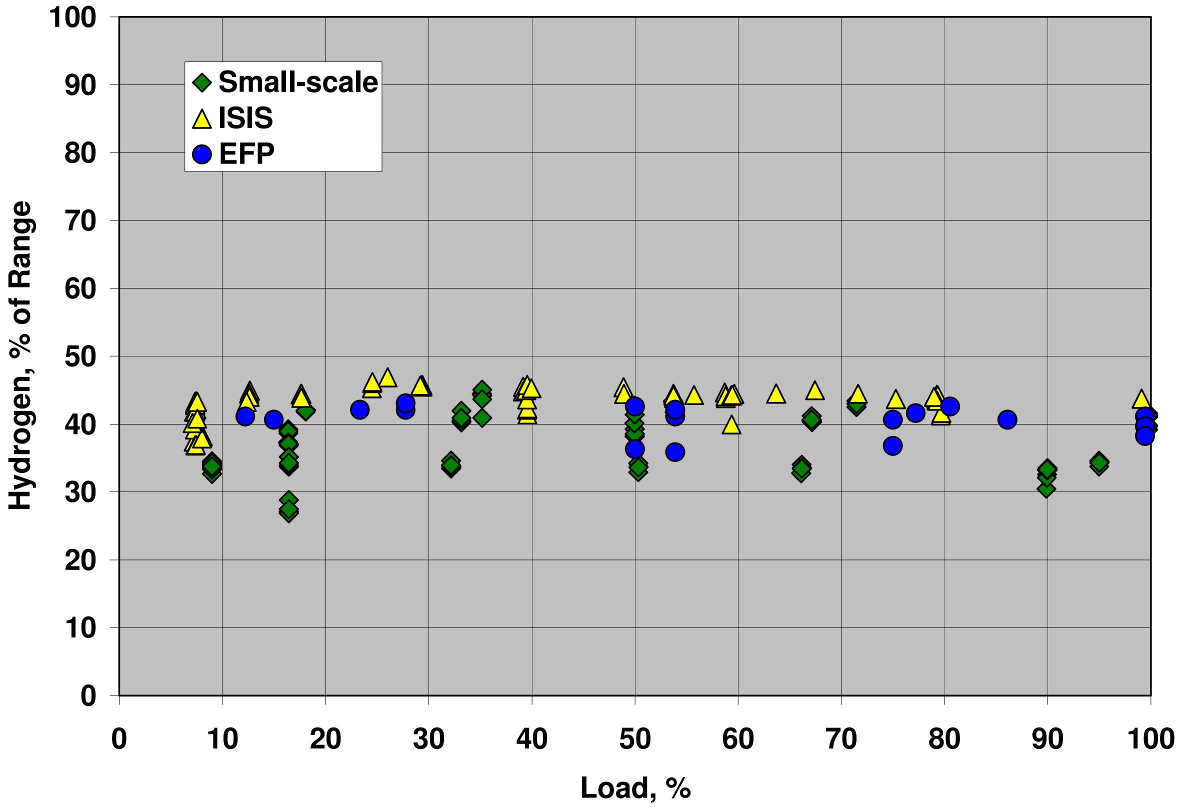

Figure 19. CPOX Reformer Performance Comparison

The start gas subsystem skid was installed in the ventilated enclosure and commissioned. Manual operation of all components was verified including valves, heaters and instrumentation. The system was operated in manual mode according to the controls statement of requirements. Performance data was collected to bench mark with design specifications. Figure 20 shows the hydrogen concentration as a function of time. The External Fuel Processor online system measurement compares favorably with the chromatographic measurement and is within the range of the specifications. After performance was verified, the automatic controls were commissioned and tested first in step wise mode to verify conformance with the controls statement of requirements and then in fully automated mode. Full automation is virtually a one button operation. Push the button and the system automatically goes through the startup procedures and waits for commands from the generator module on fuel supply and shutdown. Generator module commands were simulated with separate software.

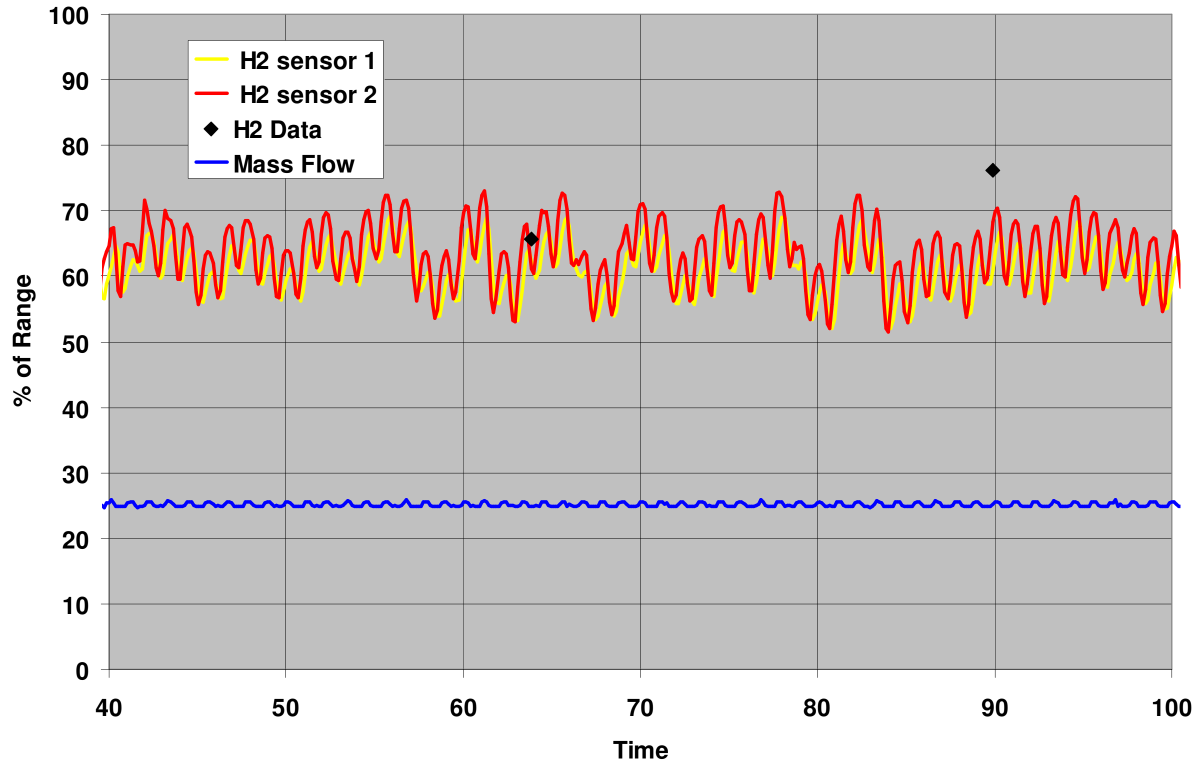

Figure 20. Start Gas System Performance

A 250 kW External Fuel Processor prototype system was designed, fabricated and tested. The design was based on subscale subsystem development and the Intermediate-scale Integrated System. The External Fuel Processor consisted of a desulfurizer subsystem, a synthesis gas subsystem and a start gas subsystem. The subsystems were integrated into a full scale prototype package that included controls hardware, safety system and computer based controller. The 250 kW External Fuel Processor was successfully run over all operating states including startup, normal operations and shutdown under manual and fully automated controls. Results demonstrated that this full scale prototype unit is ready for testing with the 250 kW SOFC system.

4.0 DURABILITY

The purpose of this task is to prepare a plan for addressing the long-term operation of the External Fuel Processor system to ensure its performance and durability during representative operation. The External Fuel Processor includes three major subsystems for desulfurization, start gas generation and synthesis gas generation. The desulfurization subsystem is designed for multiple startups and 8,000 hours of continuous operation between servicing cycles. The start gas subsystem is designed for multiple startups and service during startup and shut-down modes of operation. The synthesis gas subsystem is designed for multiple startups and service during startup and at low load conditions.

The External Fuel Processor was initially operated in the laboratory to validate the performance and controllability of each subsystem for all modes of operation. The fuel processor skids were then shipped to an American Electric Power site where it will be tested with a 250 kW SOFC Generator module. Upon completing these initial plant integration tests the fuel processor will be replaced with a larger, 1MW fuel processor and the 250 kW External Fuel Processor will be returned to the North Canton facility for extended durability testing. This durability testing will address issues such as thermal cycling, the impact of fuel contaminants on catalyst and sorbent performance, and the effects of ambient temperature.

5.0 COST MODEL

The cost model identified a need to address cost reduction in several areas including scale-up of a key subsystem, process simplification to reduce part count, and process-based control options to eliminate expensive measurement hardware. Experts in manufacturing processes were also used to help introduce new approaches into our design and manufacturing process. These improvements are being implemented in our next generation 1MW fuel processor, currently under construction.

The cost model for the 250 kW External Fuel Processor identified the need to address cost reduction in the following areas.

- Scale-up of a key fuel processing system to gain cost savings over multiple, smaller systems
- Implement a lower cost system approach to address a certain emergency plant shutdown scenario
- Functional evaluations of all aspects of the fuel processor to simplify operation and reduce component part count.
- Process-based control options to eliminate expensive measurement hardware.

Experts in manufacturing processes were also being used to help introduce new approaches into our design and manufacturing process. Design-for-manufacturing/assembly/cost measures have been identified and are being reviewed with potential suppliers to further understand cost savings potential. All the above cost reduction areas are being implemented into our next generation, 1MW fuel processor and are having a positive impact on our next generation plant configuration.

6.0 COAL GASIFICATION CONCEPT EVALUATION

Finally, several approaches were examined for the integration of a coal synthesis gas plant with the Rolls-Royce SOFC power plant. The goal of the study was to develop a concept for a near-zero emissions (including CO_2) power plant for producing electricity with a high overall efficiency (greater than 50%). The study attempted to identify a commercially viable system that does not require significant re-design of the Rolls-Royce Fuel Cell System's hybrid SOFC system being developed for pipeline natural gas. Process simulations were performed to evaluate the integration of the synthesis gas conditioning processes required by the solid oxide fuel cell with the overall plant design.

The results indicated that the coal-derived synthesis gas can yield sufficient electrical conversion efficiency in a Rolls-Royce fuel cell power plant to achieve overall electrical conversion efficiencies that exceed 45% in a combined cycle plant. Furthermore, with additional design optimization, and advancements in key areas such as coal gasification and oxygen separation, efficiencies that reach or exceed 50% are possible. The approach of using coal-derived synthesis gas in place of purified H_2 as a feed stream to the fuel cell power plant yielded significant simplifications to the overall plant design but required a significant modification to the off-gas burner within the fuel cell power plant. A Topical Report[3] provides the details of this work.

7.0 CONCLUSIONS

A 250 kW External Fuel Processor was developed to supply all the needed gases for an SOFC fueled by pipeline natural gas. The prototype fuel processor design was based on scaled component, and system development tests that confirmed earlier small-scale feasibility tests conducted by Rolls-Royce. The development tests provided scalable data for designing full-size components, and to develop an integrated system using these components.

Factory testing of the 250 kW External Fuel Processor demonstrated the functionality and controllability of the process over all operating states, including startup, normal operations and shutdown. The test results demonstrated that this full scale prototype unit is ready for integration with a 250 kW SOFC system.

A cost model identified areas for cost reduction including scale-up of a key subsystem, process simplification, and alternative control options to eliminate expensive measurement hardware. Approaches for introducing design-for manufacturing techniques were also indentified. These improvements are being implemented into our next generation fuel processor.

A plan was developed for demonstrating the long-term durability of the External Fuel Processor. This extended durability testing will commence in mid-2008 and is expected to provide the necessary level of confidence for long-term operation of the External Fuel Processor.

[3] "Preliminary Process Simulation Model Assessment of a Plant Design for Integrating a Coal Gasification and Pre-treatment Plant with a Rolls-Royce Fuel Cell", M.V. Scotto, January 2008

List of Acronyms and Abbreviations

CPOX	Catalytic Partial Oxidation Reformer
EFP	External Fuel Processor
ISIS	Intermediate-scale Integrated System
kW	Kilowatt electrical
MW	Megawatt electrical
ppbv	Parts-per-billion (volume basis)
ppmv	Parts-per-million (volume basis)
SCSO	Selective Catalytic Sulfur Oxidation