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TABLE OF CONTENTS

1.0	ABSTRACT	8
2.0	EXECUTIVE SUMMARY	9
2.1	System Design and Integration	9
2.2	Solid Oxide Fuel Cell Stack Development	9
2.3	Reformer Developments	10
2.4	Development of Balance of Plant Components	10
2.4.1	Develop Energy Recovery Unit	10
2.4.2	Develop Hydrogen Sensors for High and Low Concentration Measurement	10
2.4.3	Develop Water Recovery Unit	10
2.4.4	Develop Air Delivery and Process Air Sub-System	10
2.4.5	Develop Hot Zone Components	10
2.4.6	Develop Fuel Delivery and Fuel Metering	10
2.5	Manufacturing Development (Privately Funded)	11
2.6	System Fabrication	11
2.7	System Testing	11
3.0	EXPERIMENTAL APPROACH	13
3.1	System Design and Integration	13
3.2	Solid Oxide Fuel Cell Stack Development	13
3.3	Reformer Development	13
3.3.1	H2 Planar / Gen 1 Tubular Testing Setup	13
3.3.1.1	Mass Spectrometer	13
3.3.1.2	Emissions Bench	13
3.3.1.3	Δ Gas Chromatograph	14
3.3.2	Controls and Data Acquisition	14
3.3.2.1	Dspace	14
3.3.2.2	ADAM (Advantech Data Acquisition and Control Module)	14
3.3.2.3	Labview	14
3.3.2.4	Lab Fuel / Gas Controls	14
3.3.3	Vaporizer Characterization	14
3.3.4	Catalyst Testing	15
3.4	Development of Balance of Plant Components	15
3.4.1	Develop Hydrogen Sensors for High & Low Concentration Measurement	15
3.4.1.1	Project Objectives	15
3.4.1.2	Tasks and Deliverables	15
3.4.2	Develop Air Delivery and Process Air Sub-System	15
3.4.3	Develop Hot Zone Components	16
3.4.3.1	Gasket Development	16
3.4.3.1.1	Background	16
3.4.3.1.2	Approach	16
3.4.3.2	Integrated Component Manifold (ICM)	16
3.4.3.2.1	Background	16
3.4.3.2.2	Present Approach	17
3.4.3.3	Cathode Heat Exchangers	17
3.4.3.3.1	Background	17

3.4.3.3.2	Approach	17
3.4.4	Develop Fuel Delivery and Fuel Metering	17
3.5	Manufacturing Development (Privately Funded)	18
3.6	System Fabrication	18
3.7	System Testing	18
4.0	RESULTS AND DISCUSSION	19
4.1	System Design and Integration (Task 1.0)	19
4.1.1	Define System Requirements	19
4.1.2	Develop Conceptual System Design	19
4.1.2.1	Update on Conceptual System Design	19
4.1.2.2	System Development Strategy (Plant Support Module and Hot Zone Module)	19
4.1.3	Develop System Mechanization (schematic)	20
4.1.4	Establish System Thermal Insulation Requirements	20
4.1.5	Provide System Design Support for the Fuel and Air Delivery Systems	20
4.1.6	Provide System Design Support for the Systems Control Development	20
4.1.7	Develop and Verify System Models	23
4.1.8	Perform Design Optimization	29
4.1.9	Perform System Integration	29
4.1.9.1	Three Level System Integration Process	29
4.1.9.2	System Integration Status	31
4.1.10	Prepare Detailed System Cost Estimate	33
4.2	Solid Oxide Fuel Cell Stack Development (Task 2.0)	33
4.2.1	Design Stack	33
4.2.2	Model Stack Under Steady-State Conditions	35
4.2.3	Model Stack Under Transient Condition	39
4.2.4	Develop High-Performance Cathode	42
4.2.5	Develop High-Performance Anode	43
4.2.6	Develop Cell Fabrication Techniques	43
4.2.7	Develop Separator and Support Components	46
4.2.8	Develop Gas Distribution Meshes	46
4.2.9	Develop Mesh/Electrode Interface Materials	47
4.2.10	Develop Glass and Glass-Ceramic Seals	47
4.2.11	Develop Alternative Seals	48
4.2.12	Develop Gas Headers and Manifolds	49
4.2.13	Fabricate Developmental Stacks	49
4.2.14	Evaluate Stack Performance	52
4.3	Reformer Development (Task 3.0)	58
4.3.1	Develop Steam Reformer for Natural Gas	58
4.3.2	Develop Catalytic Partial Oxidation Reformer	58
4.3.2.1	Develop Catalytic Partial Oxidation Reformer – H1 Reactor	58
4.3.2.1.1	Burn-Off Study	58
4.3.2.1.2	O ₂ Getter Study	62
4.3.2.1.3	External Mixing / Mixing Inserts	64
4.3.2.1.4	Ethylene Climb Issue	64
4.3.2.2	Develop Catalytic Partial Oxidation Reformer – H2 Reactor	66
4.3.2.2.1	Fabrication Issues	66

4.3.2.2.2	Performance Evaluation of H2 Hardware	75
4.3.2.2.2.1	Initial Testing	75
4.3.2.2.2.2	Start-Up Controls Testing	76
4.3.2.2.2.3	Gas Phase Combustor Highflow Evaluation	78
4.3.2.2.2.4	Systems Testing of H2 (Gas Phase Combustor function only)	79
4.3.2.3	Develop Catalytic Partial Oxidation Reformer – Gen1 Tubular	81
4.3.3	Develop Catalysts	87
4.3.3.1	Improvements to Catalyst Durability	87
4.3.3.2	Durability Test Stands	88
4.3.3.3	Understanding of Deactivation and Aging Mechanisms	88
4.3.3.4	Rapid Aging Test Development	89
4.3.3.5	Improved Catalyst Formulations	89
4.3.3.6	Washcoat Metallic Substrates	90
4.3.3.7	Developing Metallic Part Reactor Test	90
4.3.3.8	Diesel Fuel Processing Demonstration	90
4.3.4	Develop a Desulfurization System	90
4.3.5	Develop Reformer and System - General	90
4.3.5.1	Labview	90
4.3.5.2	Lab Test System Development	91
4.3.6	Investigate Integration of Reformer and Energy Recovery Unit Functions	91
4.3.7	Fabricate Developmental Reformers.	91
4.4	Development of Balance-of-Plant Components	91
4.4.1	Develop Energy Recovery Unit	91
4.4.2	Develop Hydrogen Sensors for High & Low Concentration Measurement	92
4.4.3	Develop Water Recovery Unit	93
4.4.4	Develop Air Delivery and Process Air Sub-System	93
4.4.5	Develop Hot Zone Components	94
4.4.5.1	Gasket Development	95
4.4.5.2	Integrated Component Manifold	95
4.4.5.3	Cathode Heat Exchangers	96
4.4.6	Develop Fuel Delivery and Fuel Metering	98
4.5	Manufacturing Development (Privately Funded).	100
4.6	System Fabrication	100
4.6.1	Provide System Design Analysis and Steering Support	100
4.6.2	Fabricate Thermal Enclosure	100
4.6.3	Fabricate Air Delivery System	100
4.6.4	Fabricate Fuel Delivery System	100
4.6.5	Fabricate Internal Gas Manifolding	101
4.6.6	Fabricate Cathode Air Heat Exchangers	101
4.6.7	Fabricate Exhaust System	101
4.6.8	Fabricate Electrical Signal and Power Harnessing System	101
4.6.9	Assemble the Solid Oxide Fuel Cell Systems	102
4.7	System Testing	102
4.7.1	Develop Test Plan for Phase I	102
4.7.2	Determine Facility Requirements for Testing	102
4.7.3	Establish Remote Link to National Energy Technology Laboratory	104

4.7.4	Conduct Testing on Full Scale Development System	104
4.7.5	Conduct Testing on Demonstration System A	104
4.7.6	Reduce and Document Data	104
5.0	CONCLUSIONS	105
5.1	System Design and Integration	105
5.2	Solid Oxide Fuel Cell Stack Development	105
5.3	Reformer Developments	105
5.4	Develop Balance of Plant Components	106
5.4.2	Develop Hydrogen Sensors for High & Low Concentration Measurement	106
5.4.4	Develop Air Delivery and Process Air Sub-System	106
5.4.5	Develop Hot Zone Components	106
5.4.5.1	Gasket Development	106
5.4.5.2	Integrated Component Manifold	106
5.4.5.3	Cathode Heat Exchangers	107
5.4.6	Develop Fuel Delivery and Fuel Metering	107
5.5	Manufacturing Development (Privately Funded)	108
5.6	System Fabrication	108
5.7	System Testing	108
6.0	ATTACHMENT 1	109
7.0	LIST OF GRAPHICAL MATERIALS	113
8.0	REFERENCES	115
9.0	BIBLIOGRAPHY	116
10.0	LIST OF ACRONYMS AND ABBREVIATIONS	117
11.0	APPENDICES	118

1.0 ABSTRACT

The objective of Phase I under this project is to develop a 5 kW Solid Oxide Fuel Cell power system for a range of fuels and applications. During Phase I, the following will be accomplished:

- Develop and demonstrate technology transfer efforts on a 5 kW stationary distributed power generation system that incorporates steam reforming of natural gas with piped-in water (Demonstration System A).
- Initiate development of a 5 kW system for later mass-market automotive auxiliary power unit application, which will incorporate Catalytic Partial Oxidation (CPO) reforming of gasoline, with anode exhaust gas injected into an ultra-lean burn internal combustion engine.

This technical progress report covers work performed by Delphi from July through December 2002 under Department of Energy Cooperative Agreement DE-FC-02NT41246 for the 5 kW mass-market automotive (gasoline) auxiliary power unit. This report highlights technical results of the work performed under the following tasks for the automotive 5 kW system:

- Task 1 System Design and Integration
- Task 2 Solid Oxide Fuel Cell Stack Developments
- Task 3 Reformer Developments
- Task 4 Development of Balance of Plant (BOP) Components
- Task 5 Manufacturing Development (Privately Funded)
- Task 6 System Fabrication
- Task 7 System Testing

The next anticipated Technical Progress Report will be submitted July 31, 2003 and will include tasks contained within the cooperative agreement including development work on the Demonstration System A, if available.

2.0 EXECUTIVE SUMMARY

The subject effort includes development of the Solid Oxide Fuel Cell (SOFC) stack and reformers. Also included are system design and integration, fabrication of demonstration systems, testing of demonstration systems, and reporting of results. Development of other balance-of-plant components (e.g., the air delivery system, fuel delivery system, sensors and controls, control algorithms and software, safety systems, insulation, enclosure and packaging, exhaust system, electrical signal and power conditioning) will be privately funded by Delphi and is considered outside the scope of this program. However, Delphi will report on the general status of the privately funded effort at the same time it is reporting on the sold State Energy Conversion Alliance (SECA) program effort.

The following accomplishments were achieved under the following tasks for this reporting period.

2.1 System Design and Integration

During the period covered by this report, the initial system design for the gasoline 5kW mobile Auxiliary Power Unit was completed, and first-design-iteration hardware was fabricated for the sub-systems. The system was evaluated using a three-tier system integration strategy whereby system sub-modules are built, tested, and verified for function before up-integration into the Auxiliary Power Unit. The highlight of this period's activity is that Delphi has been successful in combining the major elements of the Solid Oxide Fuel Cell Auxiliary Power Unit system together to produce electricity with gasoline from a cold-start. However, it is clear that much development is required of the subsystems before greater-than-break-even power levels are achieved and reliable service as a power plant is enabled.

2.2 Solid Oxide Fuel Cell Stack Development

In this report, we discuss our progress in the development of the Generation 2 stack and the fundamental characteristics of the Gen 3 stack design. Development of Generation 2 multi-cell stack and Integrated Stack Modules is addressed. Data from 1-cell to 26-cell stacks is discussed. Multiple 2x 15-cell Integrated Stack Modules were built, tested, and integrated into the Auxiliary Power Unit. Fundamental development and progress related to stack components is also discussed in detail.

The Generation 3 stack has been designed to be a lower mass volume stack that uses manufacturable processes for production.

2.3 Reformer Developments

Reformer:

Development efforts were focused on the fabrication and testing of the latest generation integrated planar reformer (H₂). Significant problems were encountered with the braze process, and several material issues were identified. With the absence of viable planar hardware to test, efforts were shifted to a POx capable tubular design. This design allowed for up-level system work to continue and demonstrated best of class performance for specific requirements.

Catalyst:

Additional improvements to performance and durability of reforming catalysts were obtained, with the assistance of a newly developed oxidative rapid aging test method. The ability of current catalyst formulations to reform diesel fuel was demonstrated. Work has begun to improve adhesion between catalyst washcoat and metallic substrates, as well as testing metallic substrates using a tubular configuration. Several degradation mechanisms, due to thermal effects and sulfur impurities, were identified – H₂ performance is impacted significantly while CO performance only marginally. Durability test stands were delivered and installed.

2.4 Development of Balance of Plant Components

The Balance of Plant Components are defined as parts that support the function of the Reformer and Stack and make up the balance of the System.

2.4.1 Develop Energy Recovery Unit is part of the Reformer development activity and will not be reported under Balance of Plant at the present time.

2.4.2 Develop Hydrogen Sensors for High and Low Concentration Measurement is part of Balance of Plant and will be reported on within the Balance of Plant section.

2.4.3 Develop Water Recovery Unit (WRU) is an activity that will be addressed in Phase two of the program and has no activity at this time.

The following development activities (new Tasks 4.4 – 4.6) will also be reported within the Balance of Plant section.

2.4.4 Develop Air Delivery and Process Air Sub-System includes the Air Filter, Blower, Hoses, Manifold, Control Valves and Air Flow Sensors.

2.4.5 Develop Hot Zone Components include the Integrated Component Manifold (ICM), the Cathode Heat Exchangers (CHX) and High Temperature Gaskets.

2.4.6 Develop Fuel Delivery and Fuel Metering includes the Fuel pump, Pressure regulator, Hoses and Injector.

The following disciplines are not part of Delphi's Balance of Plant group but are groups of their own: Power Distribution & Electronics; System Analysis & Controls.

2.5 Manufacturing Development (Privately Funded)

The Manufacturing Development for Solid Oxide Fuel Cell falls into two major categories. These are time based rather than technology based. The two major categories are the short-term and long-term time frames.

The short-term time frame focuses on the processes and process improvements required for fabrication of the prototype designs using the current materials. These developments are extremely narrow and allow for the highest quality, best performance, and quickest turn around possible. While cost is of consideration, needs placed on the prototype hardware emphasizes time and performance.

The long-term time frame efforts are placed on the cost and durability needs. The success of Solid Oxide Fuel Cell will be very dependant on cost and durability. These development efforts aim to reduce the needs for exotic materials, high cost, and low through put processes. While these developments cover all parts of the Solid Oxide Fuel Cell system, particular emphasis is placed on the areas with currently identified high-cost components and multiples of the same component.

2.6 System Fabrication

During the period covered by this topical report, many subsystems have been fabricated in their first design iteration to support early system integration efforts. The system has been assembled and evaluated using a three-tier integration strategy. The first tier, or level, represents the natural division of the system into its hot side, or Hot Zone Module, which represents the "core" of the Solid Oxide Fuel Cell plant, and the cold side, or Plant Support Module, which contains mostly Balance-Of-Plant and electronics modules that drive the plant. These sub-modules were built as independent units and tested separately for function. The second tier represents the close coupling of the sub-modules and the cooperative function of the Hot Zone Module and the Plant Support Module. Lastly, the third level of integration represents the final Auxiliary Power Unit package of highly integrated subsystems. This system fabrication and integration strategy has allowed for rapid testing and evaluation of critical system functions without the complication and commitment of full Auxiliary Power Unit integration. It should be noted that the system fabrication activity pertains to a gasoline 5 kW Auxiliary Power Unit, not Demonstration System A.

2.7 System Testing

Delphi has performed initial evaluation tests at all three levels of system integration on a 5 kW Gasoline Auxiliary Power Unit using the first iteration of subsystem hardware. It should be noted that while basic function and control have been demonstrated, the state of development for both subsystems and controls does not allow for robust operation of the Auxiliary Power Unit power plant, nor power output above break-even levels. Given

the current state of the subsystem hardware, progression past the first level of integration would not normally be warranted; however, the exercise of proceeding in the system integration has been valuable to the project by raising critical system interface, software, and laboratory issues early in the development cycle.

3.0 EXPERIMENTAL APPROACH

The following sections describe and reference experimental methods, materials, and equipment being used for the research described below.

3.1 *System Design and Integration*

For the Solid Oxide Fuel Cell Auxiliary Power Unit, much effort has been focused on the integration of system models and controls. Towards this end, a plant model with integrated controls has been developed to jointly support system analysis and concurrent control strategy development. The system model has been used to run many simulations of the 5 kW Auxiliary Power Unit featuring both straight POx reformer operation and anode tail gas recycling.

3.2 *Solid Oxide Fuel Cell Stack Development*

Typical stack testing is carried out using a test stand that has a hot furnace, electrical load bank, and gas mixing cabinet (Lynntech Inc.). Metallic cassettes for building stacks are fabricated by standard brazing procedures and are creep flattened before use. Cells are fabricated internally or bought from suppliers. A typical experiment involves measurement of standard polarization curves and power densities at constant voltages for performance evaluation.

The seal rupture strength test unit is used for quantitative comparison of seal joint strengths. A metal washer with the sample is clamped into the fixture and air pressure is increased until the seal breaks and the ceramic bilayer disk pops off.

3.3 *Reformer Development*

3.3.1 *H2 Planar / Gen 1 Tubular Testing Setup*

Reformer testing in this period largely included testing of actual product hardware. With the exception that reformer testing is done removed from the parent system, provisions in the reformer lab test system must be made to approximate the parent system environment. Toward this end, the combustor is typically supplied fuel via bottled reformat (nominally 21% H₂, 24% CO, bal N₂). The thermal enclosure is simulated via use of a zircar-insulated enclosure with packed alumina insulation. Lastly, air supplies are provided, where needed, via mass flow controller rather than actual product blower and air control valves. Other than these changes above and where noted below with the prefix “Δ” the Lab system remains as last reported and is as follows:

3.3.1.1 *Mass Spectrometer*

A gas analysis system was utilized to quantify as many as 9 compounds on a real time basis for both the reformer outlet and combustor outlet streams.

3.3.1.2 *Emissions Bench*

An Emissions bench capable of measurement in the typical Engine out range, was utilized to supplement mass spectrometer data with independent measures of total HCs

(propane equivalent), CO, No_x and O₂. Δ Note: This emissions bench was removed for upgrades during of latter half of the reporting period.

3.3.1.3 Δ Gas Chromatograph

A Gas Chromatograph has been added to provide more resolute measures and speciation of Hydrocarbons in particular.

3.3.2 Controls and Data Acquisition

3.3.2.1 Dspace

A flexible I/O component driver and controller (Dspace) were utilized for all reformer testing. The use of Dspace allows any control algorithm to be shared between the lab environment and vehicle or systems environment so that system control strategies can be exercised in the lab with virtual transparency.

3.3.2.2 ADAM (Advantech Data Acquisition and Control Module)

All non-system mechanized I/O or devices (those not on the product intent mechanization but present for enhanced lab data or control (i.e., additional thermocouples) are handled by this controller. This allows the lab environment to have supplemental I/O and devices beyond those on the mechanization. As testing progressed we gradually have begun to rely more on the Dspace I/O and less so those supported by the ADAM controller.

3.3.2.3 Labview

Labview now serves as the “umbrella” controller and provides 2 key functions: 1. Integration of data acquisition of all other (non product) devices for lab / facility control. 2. Emulation of system components not present in the test via Lab devices (i.e., makes lab environment transparent to Dspace controller). Δ This system matured to the point where data acquisition was to a common file, including all variables from Dspace, Mass Spectrometer and ADAM.

3.3.2.4 Lab Fuel / Gas Controls

A gas blending cabinet was frequently used to simulate anode tail gas representative of what might leave the stack at various fuel utilizations. This was particularly important in understanding combustor behavior. An AVL-735 unit provided accurate fuel measurement and conditioning. This provided a measure of safety given that actual injector hardware was subject to a harsh operating environment and could be subject to flow shifts.

3.3.3 Vaporizer Characterization

In addition to conventional flow visualization, two other Laser-based techniques have been employed to help evaluate and improve A/F delivery performance. Mie Scattering techniques provide visual evaluation of the distribution of liquid droplets of an injected spray while Planar Laser Induced Fluorescence (PLIF) is used as a subsequent step

and provides a visual evaluation of liquid and vapor distribution. PLIF essentially is an evaluation of fuel mass (in liquid or vapor form) distribution in the flowstream.

3.3.4 Catalyst Testing

Reforming catalysts were prepared using methods and materials currently employed for the commercial manufacturing of automobile exhaust catalysts. Catalysts were tested using a fully instrumented tubular reactor equipped with gas and mass flow controllers and gas chromatography for product analysis. Sufficient process information can be collected for completing of mass balances.

3.4 Development of Balance of Plant Components

3.4.1 Develop Hydrogen Sensors for High and Low Concentration Measurement

3.4.1.1 Project Objectives

Research and develop gas species sensors for Solid Oxide Fuel Cell program of Propulsion and Fuel Cell Center at Rochester. Supply gas species sensors to support Rochester's Solid Oxide Fuel Cell program for internal and external R&D/Technology Demonstration purposes. The sensor control and drive electronics are included in the sensor R&D efforts.

3.4.1.2 Tasks and Deliverables

Work together with engineers of Solid Oxide Fuel Cell program at Rochester to supply Delphi proprietary species gas sensors to Rochester to support Rochester's Solid Oxide Fuel Cell program for internal and external R&D/Technology Demonstration purposes. The initial sensors deliverable to Rochester are the species gas sensors for:

- Air combustible gas leak detection (gas species involved: air, CO, H₂, CH₄).
- Exhaust burner control R&D effort will be carried out on Technology Development Process advance species sensors for 1) reformer catalyst diagnosis (gas species involved: H₂, CO, CH₄), 2) exhaust converter catalyst diagnosis (gas species involved: HC, CO, NO_x), and 3) anode efficiency detection. We will also help Rochester to access commercially available sensor technologies whenever needed.

3.4.2 Develop Air Delivery and Process Air Sub-System

Development of the Process Air Sub-System included:

- Blower requirements, selection and qualification
- Mass Air Flow Sensor selection and testing
- Air control valve selection and testing
- Air hose and hose connection selection and testing

3.4.3 Develop Hot Zone Components

3.4.3.1 Gasket Development

3.4.3.1.1 Background

With the Solid Oxide Fuel Cell development, a need exists to develop high temperature gaskets. These gaskets must be capable of sealing under elevated temperatures and low system pressures while being exposed to both steady state and transient thermal cycling.

3.4.3.1.2 Approach

Various gasket materials have been investigated, designed, manufactured and tested. These materials include the following:

- Carbon Graphite
- Fluorophlogopite Mica
- Copper
- Nickel
- Hastelloy X
- Inconel 718 with plated surfaces of Silver or Nickel

These materials are rated for operation at elevated temperatures from 600 °C to 1000 °C.

The sealing ability of each material as a gasket varies with temperature, application and compressive seating load.

Gaskets have been developed to match the sealing requirements of the Cross-flow Stack, Plate Reformer and Plate Heat Exchangers. These components require various temperature limits, individual gas sealing capabilities and mounting constraints.

A test stand has been developed which offers a uniform platform for comparison of sealing characteristics at elevated temperature of the various materials and geometries. In addition various gasket-sealing techniques have been developed to optimize compressive seal loading.

3.4.3.2 Integrated Component Manifold

3.4.3.2.1 Background

With the Solid Oxide Fuel Cell development, a need exists to develop a high temperature manifold incorporating a common platform for hot zone component mounting. These components consist of one Integrated Stack Module, two Cathode Air Heat Exchangers and one Reformer. The mounting plane must be horizontal with hot zone components mounted in such a manner allowing bolting to be accessible from above. Internal ducting of the Integrated Component Manifold allows communication of working gases between components while each duct remains individually pressure tight.

3.4.3.2.2 Present Approach

Two specific materials have been investigated, designed, manufactured and tested. These materials include the following:

- Haynes 230 plates; top, middle and bottom plate
- Inconel 625 plates; upper and lower flow plates

3.4.3.3 Cathode Air Heat Exchangers

3.4.3.3.1 Background

The Cathode Air Heat Exchanger elevates the incoming air temperature for stack temperature control. It must be a gas-gas type exchanger efficient within a given allowable volume in the Hot Zone Module and have minimal internal pressure drop. Materials of composition must maintain structural integrity at elevated operating temperatures, cycling and fabrication even when using very thin stock material. The Auxiliary Power Unit and Integrated Component Manifold dictate the relative shape, maximum size and attachment mechanisms of the Cathode Air Heat Exchanger.

3.4.3.3.2 Approach

A conventional flat plate counter flow gas-gas design was fabricated. Materials of choice include Inconel 600 and Inconel 625. A simple, easily repeatable assembly and fixturing process is desired. A minimum heat radiation to the Hot Zone Module is an advantage.

A testing fixture has been designed to measure heat exchanger efficiency and internal pressure of assembled heat exchangers.

3.4.4 Develop Fuel Delivery and Fuel Metering

There has been no activity on development of the fuel pump, pressure regulator or high-pressure hoses and fittings. Testing of the Auxiliary Power Unit system to date has been strictly in a laboratory setting with commercially available fuel delivery and measurement systems. Activity has been focused primarily on development of the fuel metering device and the quality of the fuel spray that is produced. The approach has been to create a fuel spray consisting of the smallest fuel particles possible and combine them with air at an elevated velocity and temperature to create a vapor. The vapor would be created without contacting any mechanical surface and would remain a vapor as long as the temperature remained elevated. Through simple geometric measurements of diameter and distance downstream of the injector, an injector with a spray cone angle of between 60 and 80 degrees was determined adequate to avoid contact. The injector combined with the air swirling and heating devices made up the Vaporizer detailed in the Reformer section of this report. The results of the injector development will be discussed in the Reformer section.

3.5 Manufacturing Development (Privately Funded)

The short-term manufacturing development needs have led us to special brazing techniques and leak check testing. The fabrication of components for the reformer from high temperature alloys such as Haynes and Inconel present their own problems. Different designs used brazing while others used welding. The need to plate the base material or not complicates the matter. Various techniques were tried throughout the prototype build process. Each had varying degrees of success. At various points, the process and materials that were available drove the prototype design. There are currently two reformer designs based on different processes with both continuing development.

The stack components have similar issues. The creation of the anode material, cathode material, interlayer material, and assemblies have throughput and quality issues. There are several projects underway to address these from a low volume standpoint. This will provide more understanding of the longer-term, high volume development needs.

3.6 System Fabrication

Subsystem parts were fabricated and up-integrated into system sub-modules for evaluation. These system sub-modules allow for easier assembly, service access, troubleshooting, and instrumentation deployment over full Auxiliary Power Unit level system hardware. Details of this development strategy are given in Section 4.1.

3.7 System Testing

Dedicated test stands have been built to support Hot Zone Module and Plant Support Module development. These test stands feature (Brooks) mass-flow controllers, bottled gas supplies, controls interface, pressure, temperature, and gas sample instrumentation interfaces.

The test stands are installed into a facility that includes gas safety sensor and ventilation systems to protect against CO, H₂, and hydrocarbon contamination, and O₂ depletion. It features a 30 kW (AeroVironment MT-30) programmable load center, (Labview) data acquisition system, mass spectrometer, and exhaust scrubber. Emissions measurement capability is planned for implementation.

4.0 RESULTS AND DISCUSSION

This section will summarize all relevant data, and interpret how results relate to developing the overall 5 kW Solid Oxide Fuel Cell system.

4.1 *System Design and Integration (Task 1.0)*

4.1.1 Define System Requirements

No new activity for the period covered by this technical report.

4.1.2 Develop Conceptual System Design

4.1.2.1 Update on Conceptual System Design

The requirements for a conceptual system, as well as a conceptual system design, were outlined in Section 4.1.2 of the previous Topical Report (Reference Delphi, Topical Report – January through June, 2002 DE-FC26-02NT41246 Revised 02/18/03). During the period covered by this report, subsystem component parts have been further detailed, and the system design concept has been enhanced.

4.1.2.2 System Development Strategy (Plant Support Module and Hot Zone Module)

As indicated in the previous topical report, Delphi has adopted a modular system development strategy. **Figure 4.1.2.1-1** reviews the basic two-zone construction of the Auxiliary Power Unit concept. The system is naturally segregated by operation temperature.

The low-temperature zone, or Plant Support Module (PSM) houses most of the Balance-of-Plant components, and has an anticipated temperature range of -40 to 105 °C. This is the common temperature range for components that are used in under-hood locations in mobile applications. While the requirements of this zone demand rugged, durable subsystems, the devices and subsystems located in this area are adapted from conventional automotive technology.

The high-temperature zone, or Hot Zone Module houses the “core” of the Solid Oxide Fuel Cell plant including Solid Oxide Fuel Cell stacks, Energy Recovery Unit heat exchangers, fuel reformer, gas burner, and manifolding. The expected temperature range for this zone is -40 to 800 °C (950 °C in some locations). This zone must be highly insulated from the Plant Support Module. The subsystems and components located in this zone are not considered conventional automotive technology and require unique materials, processes, and development activity.

Our system development strategy allows for development of each system module, Plant Support Module and Hot Zone Module, as independent entities. This allows for a “divide and conquer” approach to development. In addition, it serves as an aid to system integration in that subsystems can rapidly be integrated into the system for “pull-

ahead” evaluation without requiring full functionality of the entire system. The system integration process will be further discussed in Section 4.1.9.

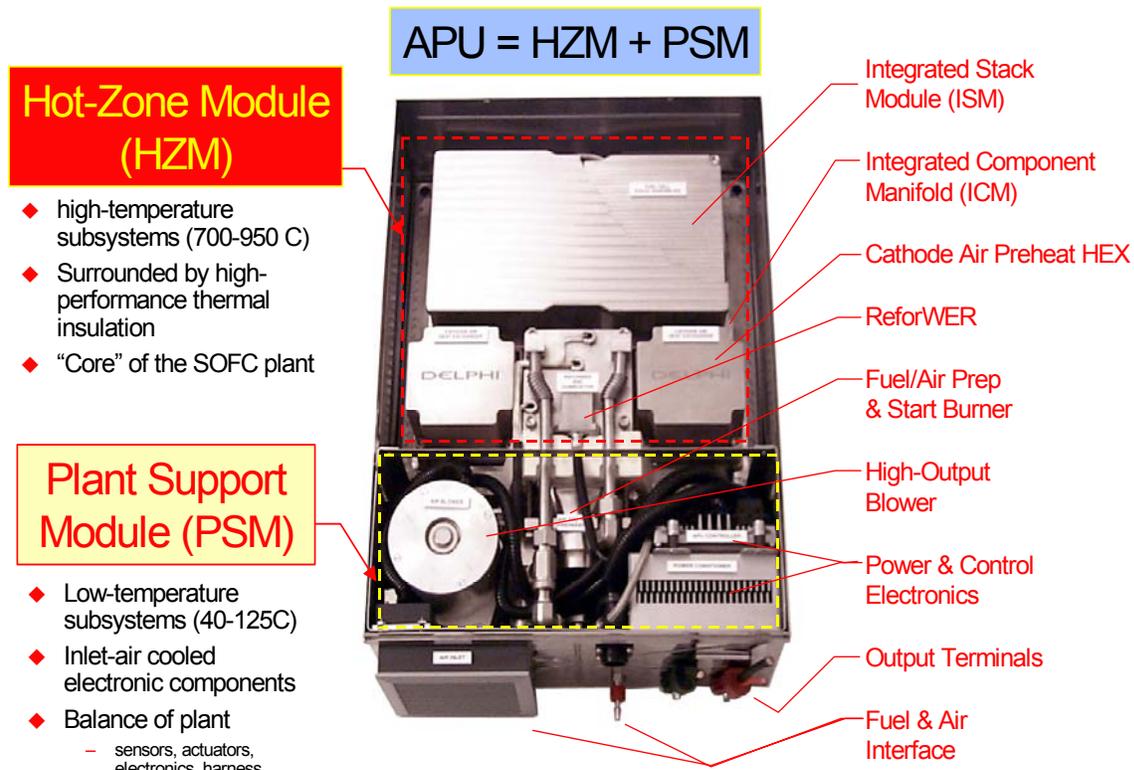


Figure 4.1.2.1-1: Auxiliary Power Unit Development Strategy

4.1.3 Develop System Mechanization (schematic)

No new activity for the period covered by this technical report.

4.1.4 Establish System Thermal Insulation Requirements

No new activity for the period covered by this technical report.

4.15 Provide System Design Support for the Fuel and Air Delivery Systems

See Section 4.6 (Balance of Plant)

4.16 Provide System Design Support for the Systems Control Development

The Solid Oxide Fuel Cell control system has been developed to a level that has enabled multiple automatic start/run cycles of complete Solid Oxide Fuel Cell Auxiliary Power Unit systems with minimal operator involvement. Automatic start / run sequence of the reformer, Gas Phase Combustor, and process air system including blower and valving is undertaken under control system direction.

The system control architecture is one of distributed control responsibility with a central coordination point. The control environment is MATLAB/ Simulink™ within a Dspace micro-autobox™ hardware platform and Control Desk™ operator interface. The control definition is documented in MSWord™ documents maintained in a locally on-line documentation folder set. Additionally, the regularly updated released control environment is similarly available on a local server.

The control environment has the following features:

- Modular for fast / distributed development and ease of configuration modification.
- Includes plant model in parallel with control model for development with incomplete, reduced capability, or unavailable Auxiliary Power Unit system hardware. Various parts of the model can be quickly substituted via simple configuration bit change.
- An “operator interface” block provides hooks for operator override of automatic set points during development of base control algorithms – allows “human in the loop” control where needed. Also allows advanced algorithm support for research labs without “cutting into” the base control code.
- Use of configurable sub-systems feature of Simulink™ – allows easy trial of different approaches to control or substitution of different models of physical hardware.

By the nature of the control system development, it is necessary to make many trials of the control system to develop the algorithm and calibration. Since this is in general relatively difficult when hardware and lab resources are limited, we have developed the capability to “run” the control system in multiple environments some of which are virtual:

- Desktop: PC platform run of the control system and virtual plant – faster than real time
- Desktop/ Micro-autobox™ / control desk: Micro-autobox™ run in a desktop environment with the full virtual plant – no system hardware – runs in real time.
- Electric emulation bench: Micro-autobox™ based control of real physical hardware on the power electronics and communication side, with the heat release and temperature part of the plant model used for driving a complete start / run cycle.
- Lab system: Full system hardware driven by micro-autobox™ or production controller.

Diagnostic algorithms will be developed and reported on during the next reporting period.

Table 4.1.6-1 summarizes these environments.

Environment Name	Controller Hardware	Operator Interface	Sensors	Plant Support Module	Hot zone Module	Stack, Dc/Dc Converter, Power Conditioner, Battery
Desktop	PC	Simulink [™] scopes or Control desk	virtual	virtual	virtual	virtual
Desktop / micro-autobox [™]	Micro - autobox [™]	Control desk	virtual	virtual	virtual	virtual
PSM development bench.	“	“	Real air meters and pressure sensors	Real blower and valves	virtual	virtual
Electric emulation bench	“	“	virtual	virtual	virtual	Emulated or real devices
Full Lab System	Micro - autobox [™]	Control desk	Real hardware	Real hardware	Real hardware	Real devices
Production Controller	DE controller	Canape	Real hardware	Real hardware	Real hardware	Real devices

Table 4.1.6-1: Control System Environments

Each of these environments is now fully functional, and being applied to continued development of Auxiliary Power Unit system control.

4.1.7 Develop and Verify System models

There are three major system models that have been developed and are being maintained for overall system design and system control development. These models compliment each other in that each has relative strengths and weaknesses. In addition, these models are compared with each other as well as with experimental data for purpose of model verification.

- MATLAB/ Simulink™: This model was reported on in the last report. Since that report the following upgrades have been made to the model:
 - All continuous integrators have been replaced with discrete integrators to make the model compatible with the digital control environment.
 - All plant model sub-systems have been re-cast with pneumatic input and output connections to allow future pneumatic network solution (currently the model is mass based rather than pressure based)
 - All solvers have been removed – the result being more than a 10x increase speed of run as compared with the model reported in the last topical report.
 - A high fidelity Solid Oxide Fuel Cell stack performance model has been introduced – models stack voltage versus stack current, temperature, and reformat flow level and composition.
 - Sensor dynamics have been included
 - Multiple structure and calibration upgrades and corrections.
 - Addition of power electronics models (in progress)

The following graph compares results from a run in the desktop environment against a recent (one of only a few) experimental run and demonstrates control performance on the virtual plant model against real hardware. The model compares reasonably with the experiment on the overall start time of about 90 minutes.

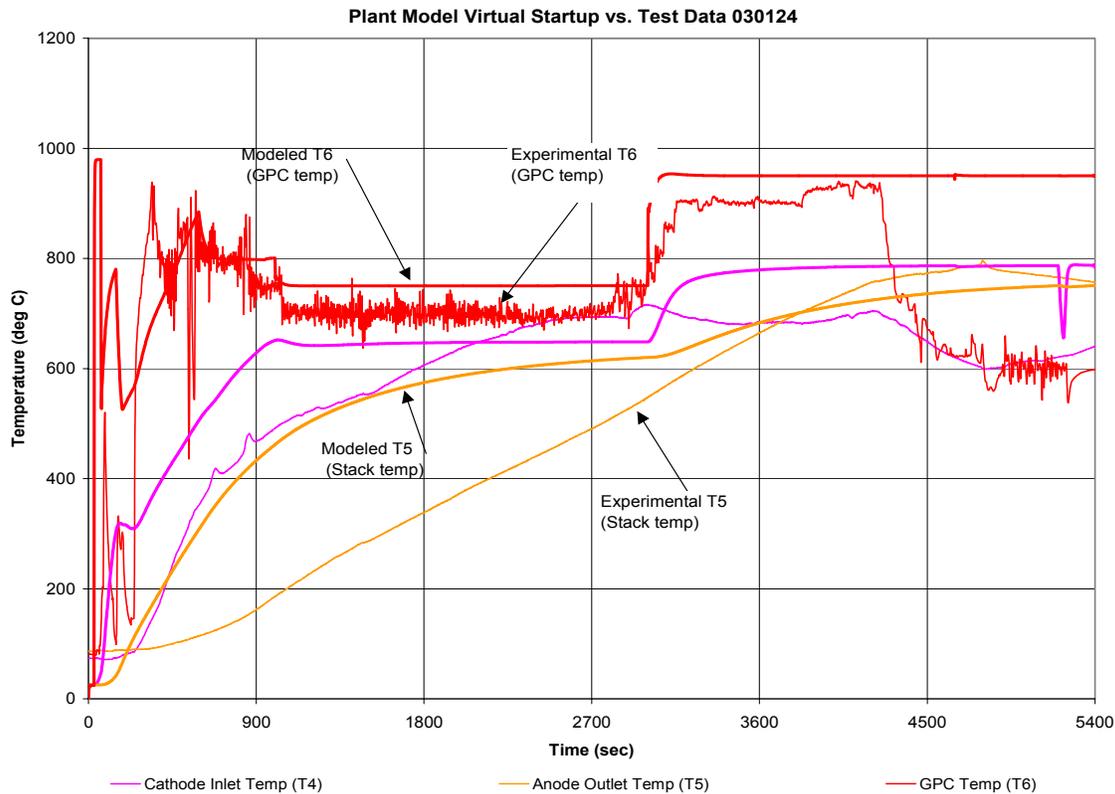


Figure 4.1.7-1: Control Performance

However, one will observe the relatively poor agreement between the stack temperature trajectory (T5) in the model and the experiment. We are investigating the causes of this. Two contributing factors are: first, the overly simple representation of the Integrated Component Manifold heat transfer, and overall mass – we believe this is a key reason the model temperature rise is initially faster than the real hardware. Secondly, during the run depicted below, we believe the stack was experiencing leaks – creating internal heating and a steeper temperature rise trajectory near the end of the test. These discrepancies are being investigated and we are confident ultimately good agreement between the model and experiment will be obtained.

It should also be pointed out that the current start up times of approximately 90 minutes are significantly longer than those projected in the last topical report. This difference can be attributed to the following factors:

- Increased mass in the real system as compared to the projected mass used in the previous runs.
- Also contributing was a higher projected possible burner temperature of 1000 °C. The particular run compared here utilized a lower burner temperature of 750 °C in an attempt to mitigate the internal stack heating attributed to leaks.

- The projected (modeled) start time is very sensitive to the assumed threshold at which power can be taken from the stack since the projected temperature trajectory is quite asymptotic near the end of the warm up. Earlier projections were less conservative with an assumed warm-up to run transition of 725 °C rather than the 750 °C represented here.

As mentioned above, the Simulink™ system model now includes a high-fidelity stack performance model originally developed at PNNL. Shown below is a plot of the measured versus predicted performance of this stack model. Good agreement is shown between predicted and measured performance.

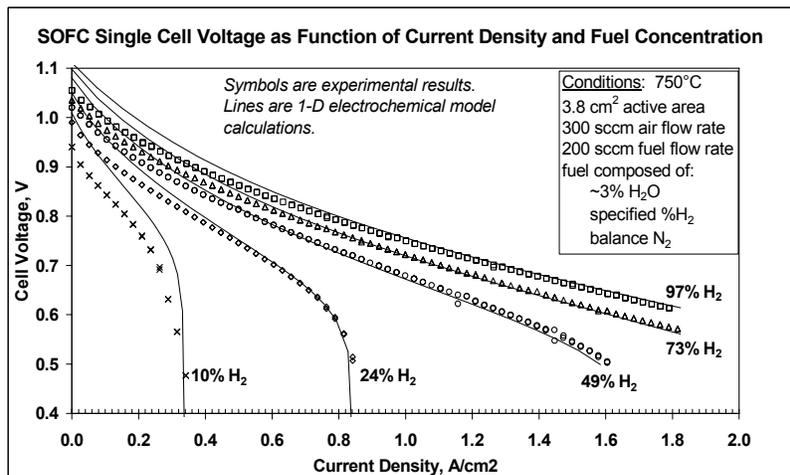


Figure 4.1.7-2: Measured vs. Predicted Performance of Stack Model

- Aspen/Hysys system plant model: This model is a steady state plant model used for system design. It contains heat release, heat exchange, mass transfer, thermodynamically determined composition at reactors (reformer, gas phase combustor), parasitic power consumption, and overall system efficiency determination. It is different from the Simulink™ and Excel models in that it determines composition of reformat and exhaust products as a function of input reactant composition and reaction temperature by minimizing Gibbs free energy. In addition, the model also represents the closed loops inherent in the control system, so that as heat release changes with different operating loads, the needed amounts of air for temperature control respond accordingly. Below are some plots of some of the system outputs computed by the Aspen/Hysys model.

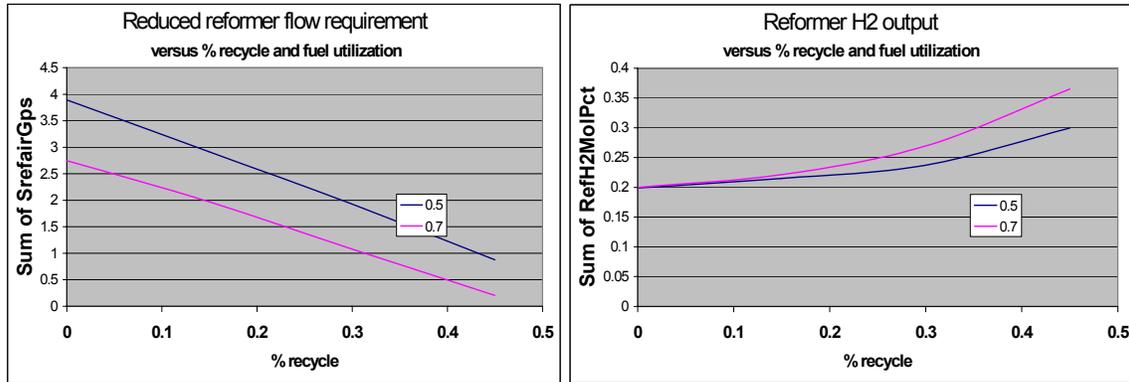


Figure 4.1.7-3: Aspen/Hysys Model Output

Aspen has been used to determine the optimum operating point of fuel and air for best reformate quality. The plot below shows projected and measured H₂ and CO production versus equivalence ratio.

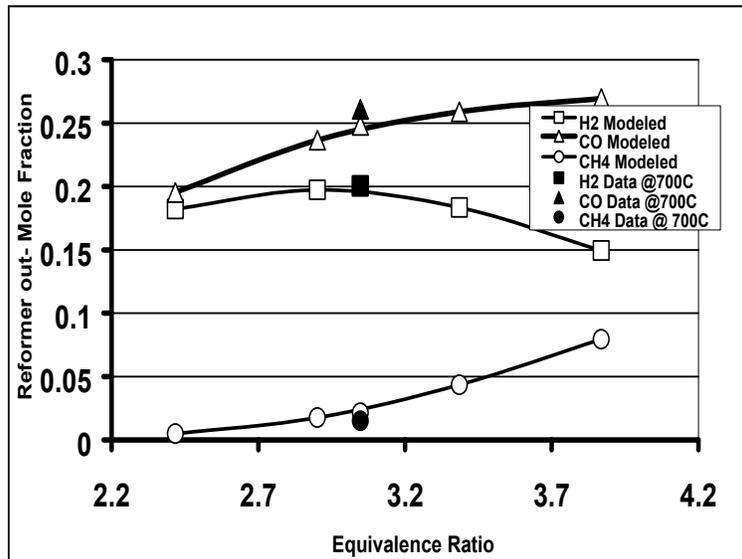


Figure 4.1.7-4: Predicted and Measured H2 and CO Production

The model is currently being transferred from Aspen to Hysys for improved ease of use.

- Excel-based system model: This model computes heat transfer, heat release, and overall system efficiency. This model is also used for system design, and crystal ball project management. It allows for more flexibility with design parameters than either of the other two models and is compatible with other tools such as Crystal Balltm. However, it requires more manual interaction than the other two to reset operating points as operating point changes. Enhancements are in progress in this model, which will include some capability for reformat composition determination, and some automated operating point determination.

All of these models have been used for various different aspects of system design. They have been and continue to be compared against each other with good agreement.

A summary of these models is contained in table 4.1.7-1.

	Simulink [™] / Matlab [™] Model	Aspen / Hysys Model	Excel System Model
Heat release	From LHV	From composition	From LHV
Heat transfer	Multi-element	Yes	Lumped parameter
Product composition	Assumed (gibbs planned)	Computed – gibbs minimization	Assumed (gibbs planned)
Dynamic?	Yes	No/Yes	No
Controls	Actual	Simulated	Simplified
Integration with control model	Yes	No	No
Stack Model	Design, temperature, reformat flow / composition sensitive	Design, temperature, reformat flow / composition sensitive	Single voltage point assumed
Process air / Plant support module	Individual valves modeled	Simple	Simple
Carbon prediction	No	Yes	No
Power electronics models included	Yes	No	No
Overall System efficiency calculations	Yes - based on cycle efficiency	Yes – steady state	Yes – steady state
Ease of design iteration / model integration	Weak	Weak	Good – use for Crystal Ball
Hardware in loop emulation possible?	Yes	No	No

Table 4.1.7-1: Model Summary Table

4.1.7 Perform Design Optimization

No new activity for the period covered by this technical report.

4.1.8 Perform System Integration

4.1.9.1 Three Level System Integration Process

To facilitate the system integration process, we have adopted a three level system integration strategy. This allows for “pull-ahead” evaluation of initial subsystem hardware, functional “shakedown” of basic system operation, and software and controls development. The three-level approach is shown in **Figure 4.1.9.1-1**.

Level I: In keeping with the system development strategy outlined in Section 4.1.2, the Hot Zone Module and Plant Support Module may be developed independently. This allows for the evaluation and optimization of each module’s function without the added complexity, and requirements of function of the next level of integration. In addition, this level of integration allows for a high implementation of instrumentation (thermocouples, pressure taps, gas sample ports, etc.) that becomes more intrusive and difficult to package at higher levels of integration.

Level II: This level represents the close coupling of the Hot Zone Module and Plant Support Module sub-modules developed at Level I. Full Auxiliary Power Unit functionality is represented at this level. This level allows for the full evaluation of system performance issues, while still allowing for a high implementation of instrumentation, but avoiding complications caused by thermal management (heat leakage, high local temperatures etc.). This level of integration has the added benefit of improved accessibility over the next level of integration.

Level III: While the previous level of integration represents full Auxiliary Power Unit function, this level of integration represents full Auxiliary Power Unit function and packaging. At this level, implementation of instrumentation is necessarily reduced, accessibility is limited, and thermal management issues become very significant.

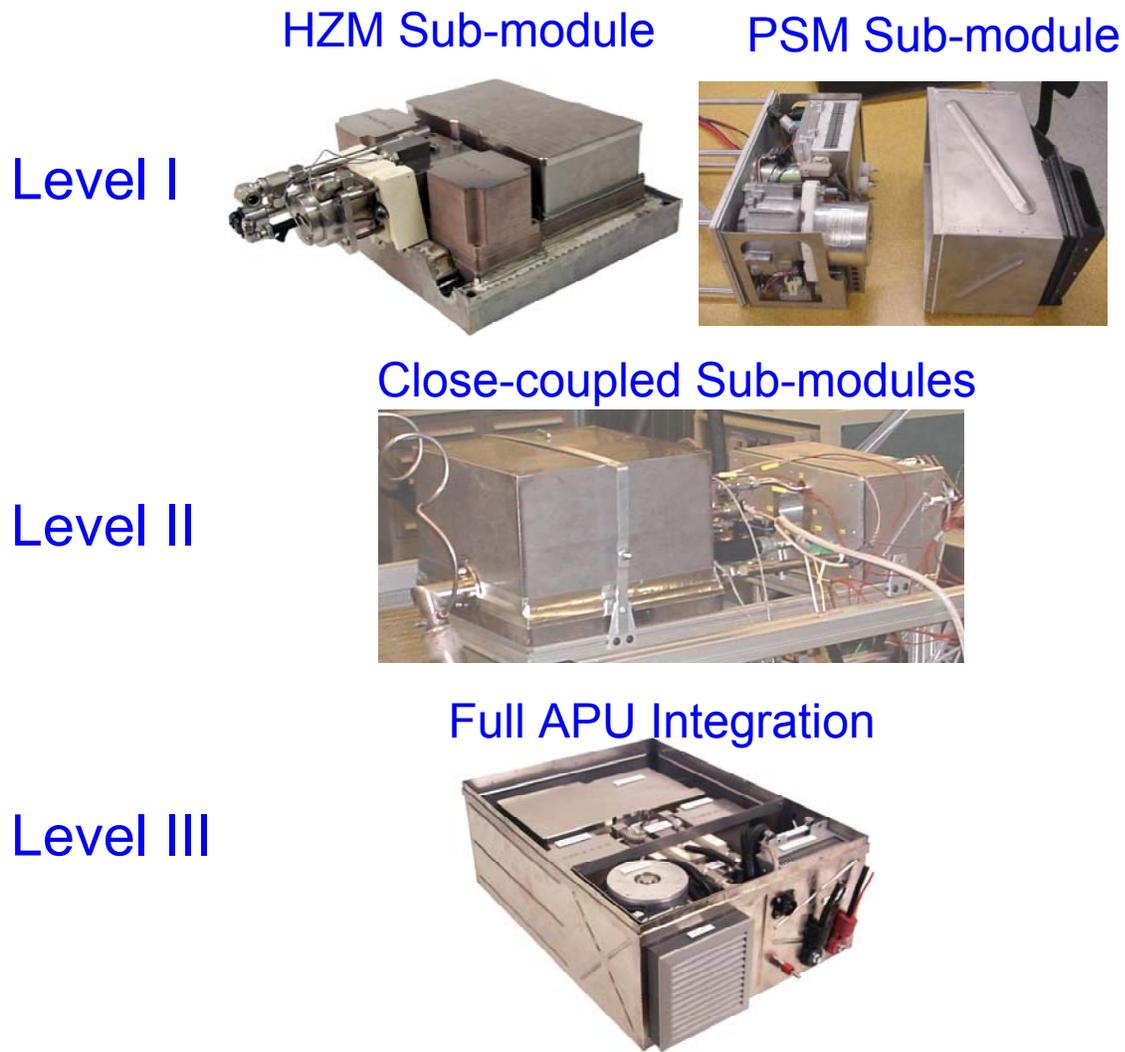


Figure 4.1.9.1-1: System Integration Levels

4.1.9.2 System Integration Status

During the time period covered by this technical report, Delphi has progressed through all three levels of integration on a 5 kW Gasoline Auxiliary Power Unit using the first iteration of subsystem hardware. It should be noted that while basic function and control have been demonstrated, the state of development for both subsystems and controls does not allow for robust operation of the Auxiliary Power Unit power plant, nor power output above break-even levels. Given the current state of the subsystem hardware, progression past the first level of integration would not normally be warranted; however, the exercise of proceeding in the system integration has been valuable to the project by raising critical system interface, software, and laboratory issues early in the development cycle.

A summary of the integration milestones is given in **Figure 4.1.9.2-1** and a list of resulting issues is presented in **Figure 4.1.9.2-2**. Summary detail of the system fabrication and testing will be given in Section 4.6 and 4.7, respectively.



◆ 10.07.02 HZM Start-Up (Bottled Reformat):

- » Beta 1 Level Control Software w/microauto box
- » Lab massflow controllers
- » RTD temperature feedback
- » Fuel: Blended POx Reformat (22%H₂, 24%CO, 56%N₂)
- » Stacks: Non electro-chemical “thermal” stacks for start tests only
- » Reformer: ReforWER H₂ design with Tailgas Combustor (GPC) only (no gasoline reforming catalyst)
- » 2 hr 20 to 650 C running GPC combustor at 2/3 capacity



◆ 11.21.02 HZM Power (Hydrogen):

- » 2 x 15 Cell Integrated Stack Module (ISM)
- » 1.5 hrs to 745 C stack temp / 29 V OCV
- » 20.0 A @ 14.3 V = 286 W



◆ 11.26.02 HZM Power (Gasoline):

- » Cold start on gasoline
- » Tubular reformer, 2 x 15 ISM
- » 1st cycle: 2 hrs, 10min to 700° C (2/3 start power)
 - ◆ 750 C Stack Temp / 30.8 V OCV / 32 A @ 15.2 V = 486 W
- » 2nd cycle: 1.5 hrs to 745°C (2/3 start power)
 - ◆ 745 C Stack Temp / 29.95 V OCV
 - ◆ 18 A @ 15.0 V = 270 W



◆ 12.20.02 Level II Integration:

- » Cold reformer start on gasoline
- » Tubular reformer, 2 x 15 ISM
- » 700 C / Approximately 4 A @ 25 V = 100 W
- » Stacks developed internal short-circuit



◆ 12.14.02 Level III Integration (APU):

- » Outer enclosure not used
- » Cold reformer start on gasoline
- » Tubular reformer, 2 x 15 ISM
- » 1hr, 20min to 700 C / 29.0 V - 135 W

Figure 4.1.9.2-1: System Integration Milestones

◆ **Level I: HZM**

- Improve seal gasket technology, difficult to seal stacks to ICM surface
- Improve start-up time by reducing heat capacity and component/control optimization
- Improve cycle durability and power density of SOFC stack (ISM)
- Improve control software for reformer and burner
- Eliminate carbon formation in reformer
- Validate anode oxidation countermeasures
- Development towards high reliability of temperature (RTD) and Igniter Components
- Development of reformer outlet gas composition sensor
- Improve cathode air heat exchanger characteristics at low flow rates

◆ **Level II: Close-coupled HZM + PSM**

- Further development of automatic control software (turn-key operation)
- Reduction of parasitic electrical loads
- Reduce blower noise
- Common calibration characteristic within sensor families
- Full deployment of product controller
- Deployment/development of power conditioning (DC to application) electronics
- Full deployment of safety and diagnostic software & hardware

◆ **Level III: APU**

- Need to reduce heat losses/leaks and adequately cool internal components
- Packaging and assembly improvement
- Improved component interfaces and seals
- Development of safety sensor (combustible gas leaks)
- Improvement of wiring harness routing and construction

Figure 4.1.9.2-2: System Issues and Needs

4.1.10 Prepare Detailed System Cost Estimate

No activity on this task during the period covered by this technical report.

4.2 Solid Oxide Fuel Cell Stack Development (Task 2.0)

This task focuses on the development, fabrication, and demonstration of Solid Oxide Fuel Cell stacks.

4.2.1 Design Stack.

The Delphi-Battelle Generation 2 stack has been designed with anode-supported cells and metallic interconnects. This design consists of a cassette configuration as the repeating unit of the stack. The cassette involves a cell to cassette (ceramic to metal) bond that is pre-fabricated before the cassettes are assembled into a stack (see **Figure 4.2.1-1** below).

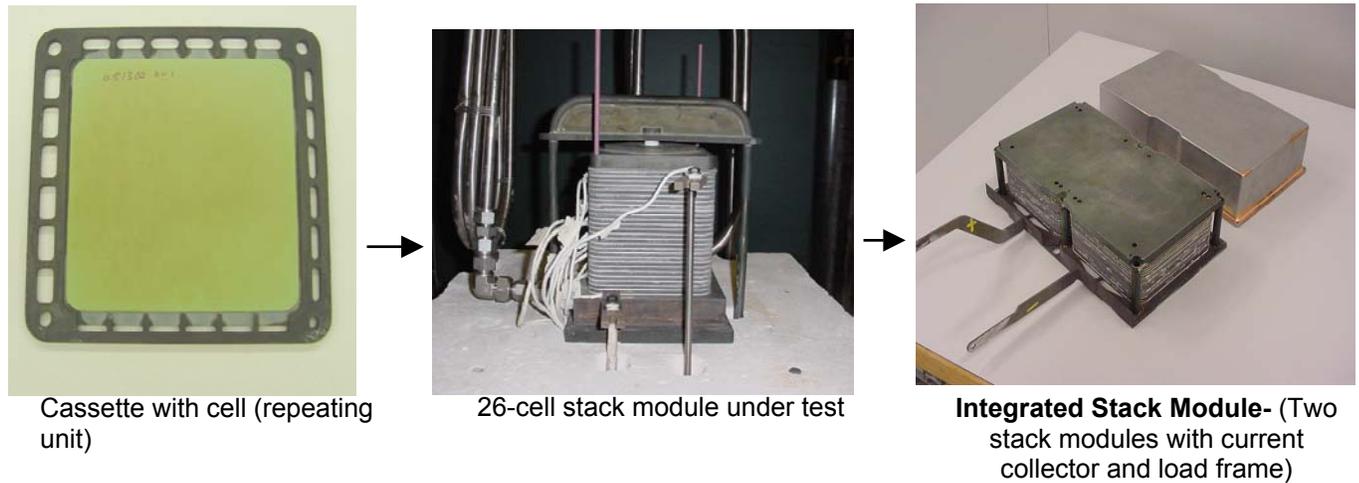


Figure 4.2.1-1: Gen 2 Cassette

Figure 4.2.1-1: Gen 2 Cassette as a repeating unit (left); 26-cell Gen 2 stack under test (center); and Integrated Stack Module consisting of two multi-cell stacks in electrical series (right).

The Gen 2 cassettes were successfully assembled into multi-cell stacks and tested. **Figure 4.2.1-1** (center) shows a picture of a 26-cell stack being tested in a furnace. Integrated Stack Modules have also been designed, built and tested. An Integrated Stack Module consists of two stack modules in electrical series on a common base plate. It has integrated manifolding, load frame and current collectors. The Integrated Stack Module is a “stand alone” stack sub-system unit that can be mounted on the base manifold (Integrated Component Manifold) of the Auxiliary Power Unit and operated.

Gen 3 Stack

The Delphi-Battelle team has designed a Gen 3 cassette that has a lower mass and volume than a Gen 2 cassette (50% reduction in mass of cassette and thickness of cassette). It is made of metal components and uses processes that are more conducive to high volume production. It consists mainly of two stamped metal components and the cassette is bonded together by laser welding. An anode-supported cell is brazed to the picture frame of the cassette before the cassette is assembled and bonded together. Development, fabrication and testing of Gen 3 cassettes are ongoing.

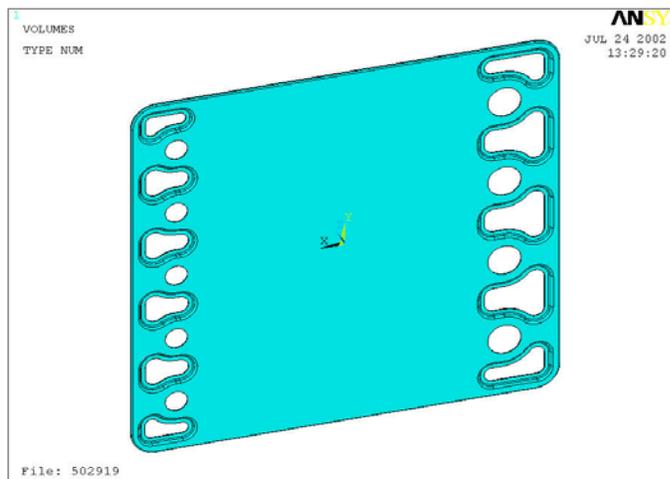


Figure 4.2.1-2: Gen 3 Cassette

4.2.2 Model Stack Under Steady-State Conditions.

The steady state flow characteristics of the Delphi-Battelle Generation 2 stack were assessed by Computational Fluid Dynamics (CFD) modeling of various combinations of fuel and air flow. These analyses make use of the electrochemistry module developed by Battelle in the Core Technical Program. The 16-cell stack model demonstrated relative uniformity in average cell temperature, ± 7 °C, but the thermal gradient across each cell varied significantly through the height of the stack. The stack stress is a function of the thermal gradients as well as the average cell temperature. Accordingly, it is advantageous to reduce the thermal gradients. The modeling demonstrated a reduction in gradient of 40 °C could be achieved with high fuel utilization. **Figure 4.2.2-1** shows the movement of the location of peak temperature toward the fuel exit with high fuel flow. Finite Element (FE) structural modeling demonstrated a corresponding 19% improvement in the safety factor at high fuel utilization.

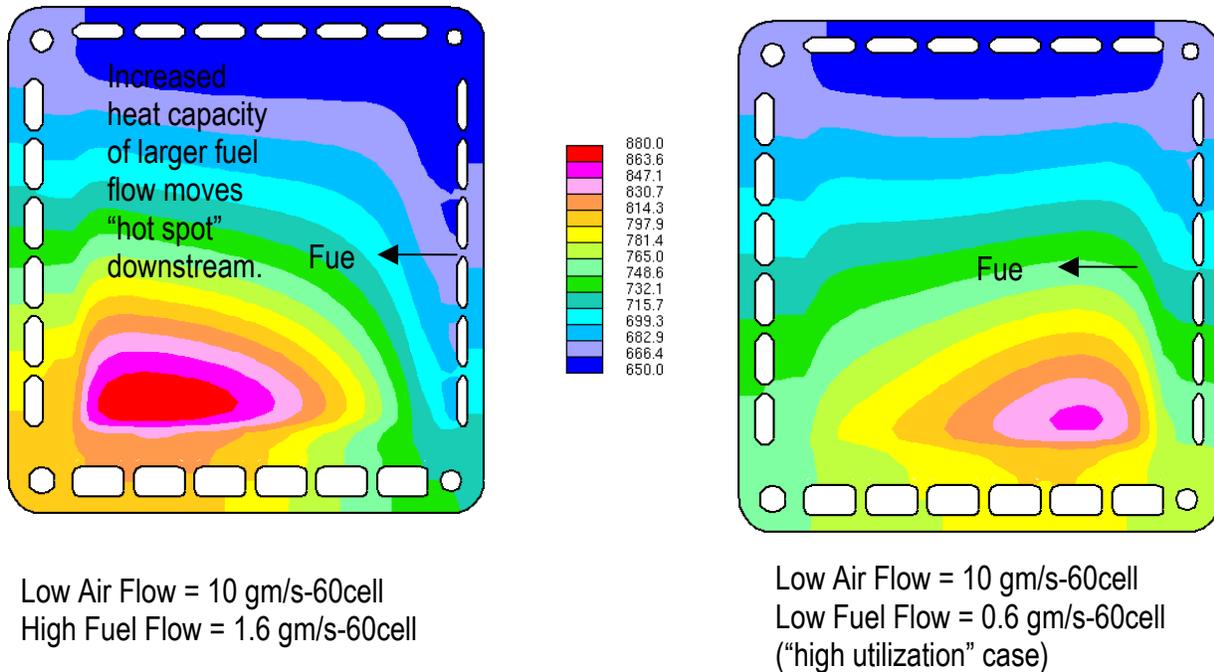


Figure 4.2.2-1: Effect Of High Fuel Flow On Cell Temperature

Computational Fluid Dynamics steady state modeling of the preliminary Delphi-Battelle Generation 3 stack was also conducted. The results indicated the flow channel height needed to be increased to minimize the pressure drop across the cell. **Figure 4.2.2-2** shows the cathode air velocity with the peak in the restricted region, which gave rise to an undesirable 7 MPa pressure drop. The analysis also showed that good flow distribution could be achieved on the anode side with a 2 KPa pressure drop.

Figure 4.2.2-3 shows the typical temperature distribution under high and low fuel utilization cases in a redesigned Generation 3 cassette with increased cathode flow channel height. The low fuel utilization case results in higher temperatures and a higher gradient, with a peak temperature of 855 °C and a gradient of 200 °C across the cell. The power density (current density) also decreases with increasing fuel utilization as shown in **Figure 4.2.2-4**.

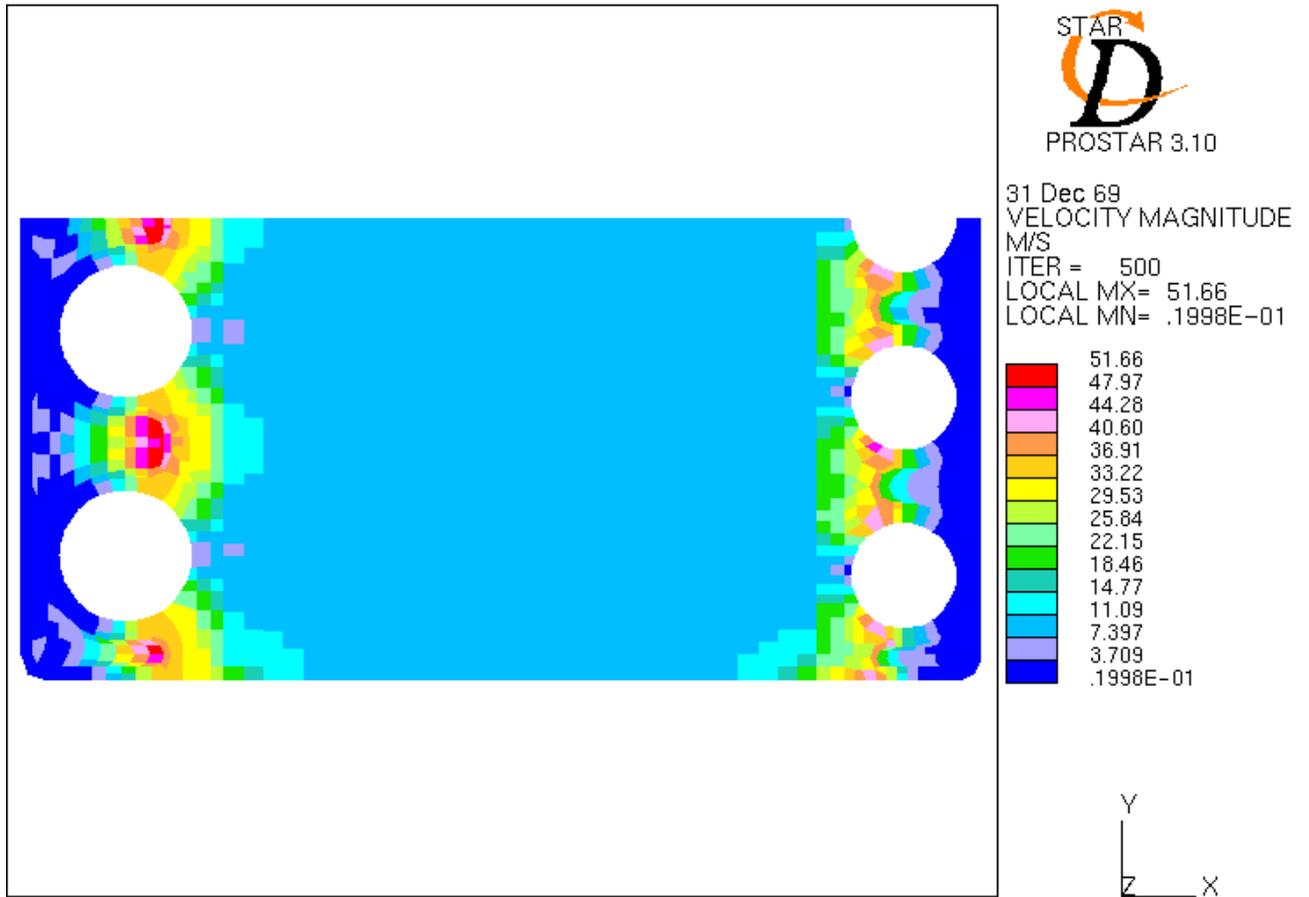


Figure 4.2.2-2: Cathode Air Flow Velocity

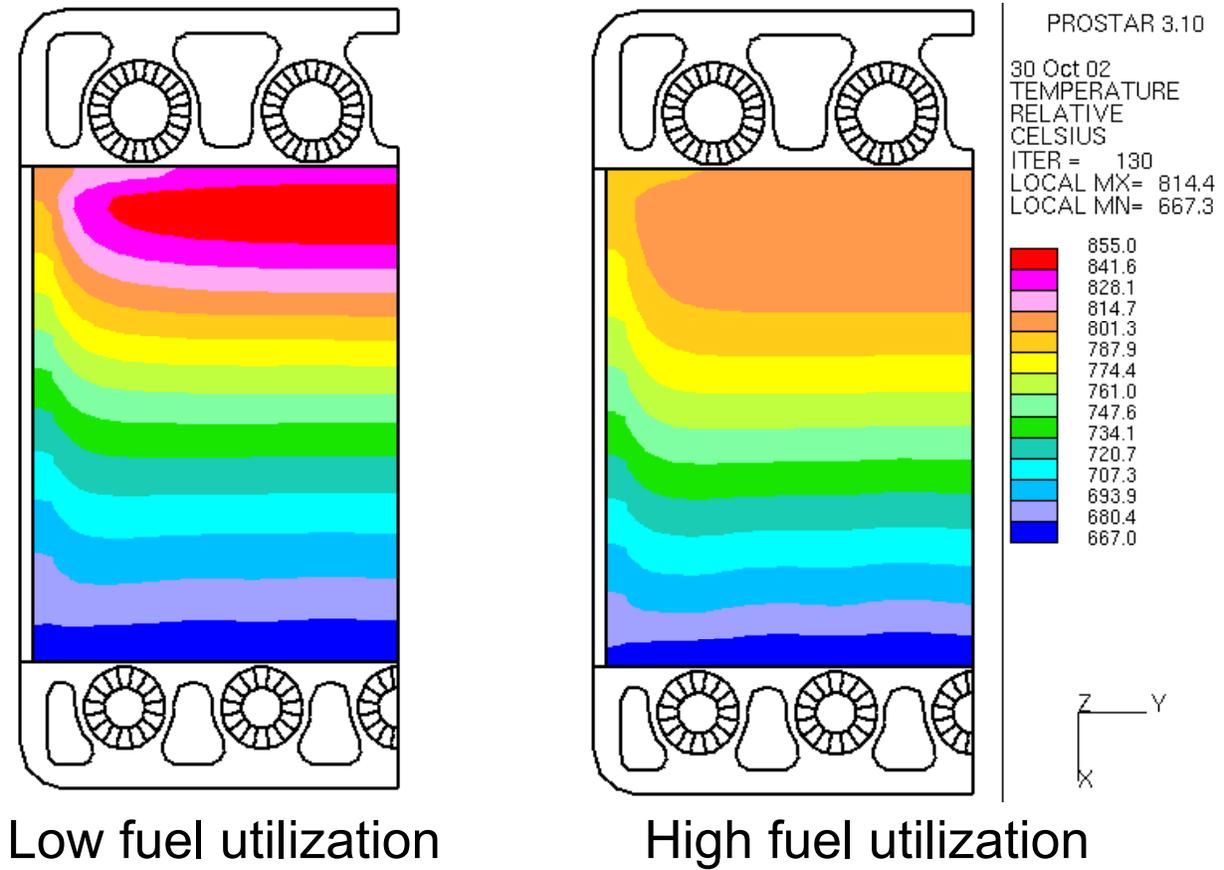


Figure 4.2.2-3: Steady State Temperature Distribution

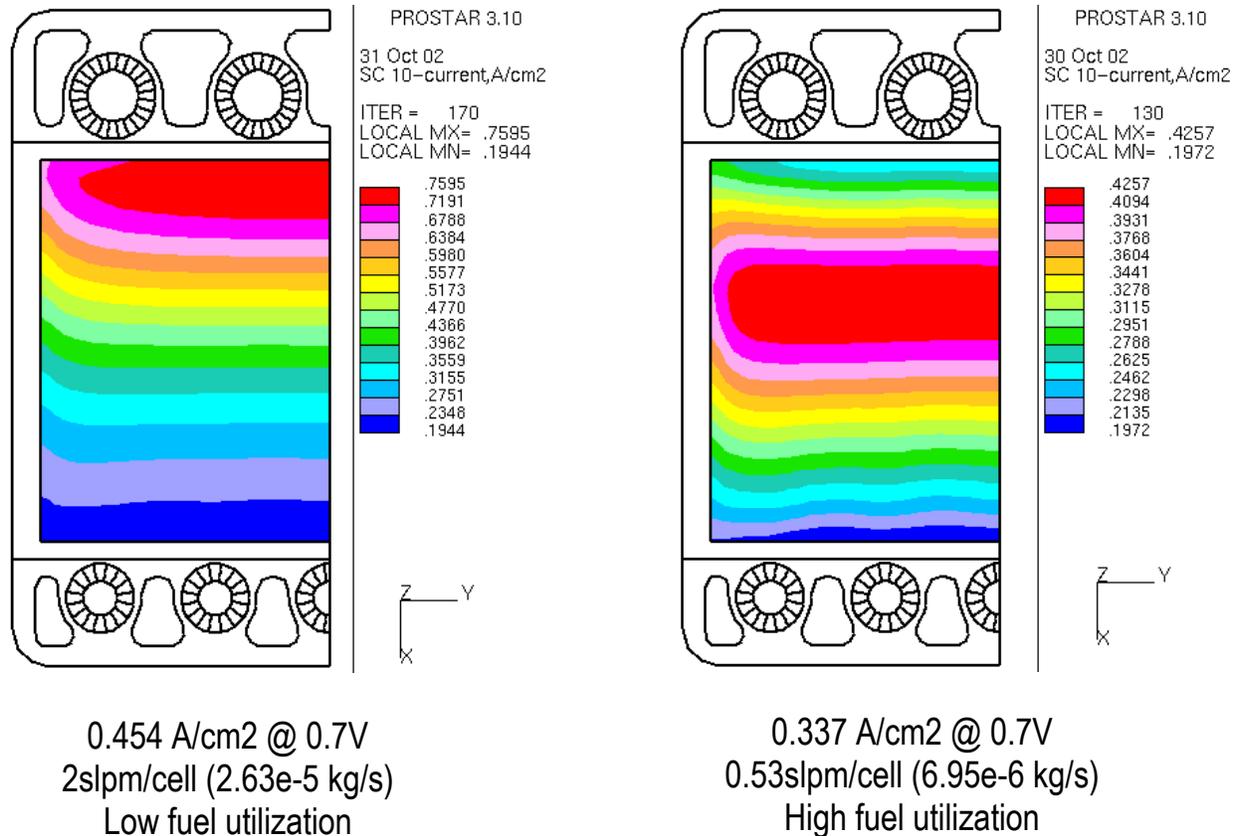


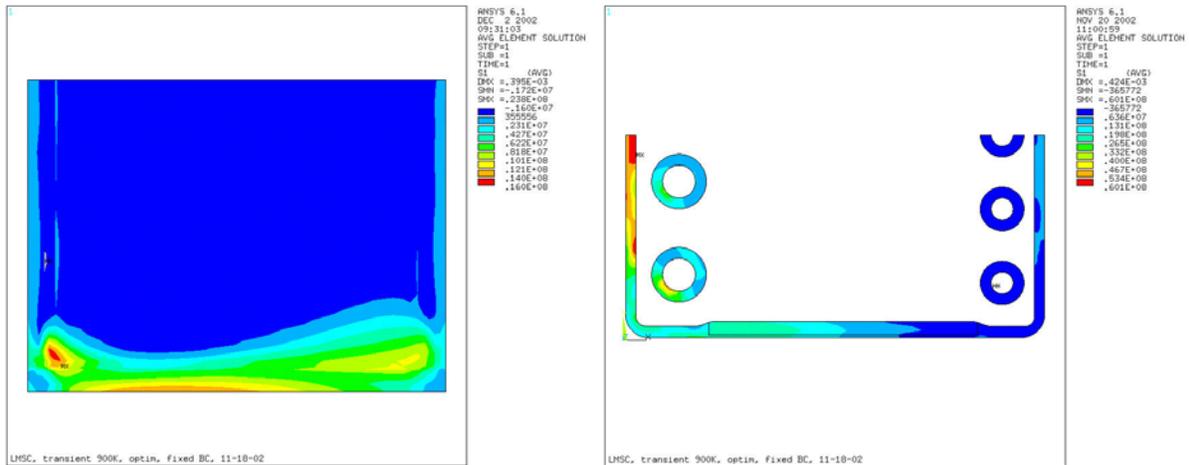
Figure 4.2.2-4: Effect Of Fuel Utilization On Current Density

4.2.3 Model Stack Under Transient Condition.

Computational Fluid Dynamics and Finite Element modeling of the Generation 3 design were conducted to determine the thermal stress distribution generated during the start-up transient. The stack heating is achieved by blowing hot (1000 °C) air through the cathode passages and hot reformat on the anode side. The transient thermal analysis begins at a uniform temperature of -40 °C. The stack reached an average temperature of 700° C in 17 minutes. Typical stress distributions for the anode and glass seals are shown in **Figure 4.2.3-1**. The peak anode stress of 38 MPa occurred at an average cell temperature of 230 °C, while the peak seal stress of 68 MPa occurred at an average cell temperature of 530 °C. Regions of the stainless steel separator plate that exceed the yield strength and will plastically deform can be observed by plotting the inverse safety as shown in **Figure 4.2.3-2**.

Auxiliary Power Unit system limitations, along with stack thermal stress limits, preclude the immediate application of the 1000 °C air. An inlet air temperature controller was developed to maintain an optimum temperature gradient across the stack while maintaining the stack stress at an acceptable level. Start up time without the optimized controller was predicted to be 60 minutes for the Generation 2 design.

Variation in the frame-to-frame glass seal stress as a function of vertical thermal gradient was examined with Finite Element models. **Figure 4.2.3-3** illustrates the tensile stress that develops at the outside edge of the glass seal at the connection between cell frames. The edge stress dissipates in each interface higher up the stack. Modeling of the braze seal was also conducted. The braze stress was nominal, peaking at ambient room temperature.



Anode stress

Glass seal stress

Figure 4.2.3-1: Stress During Start-Up Transient

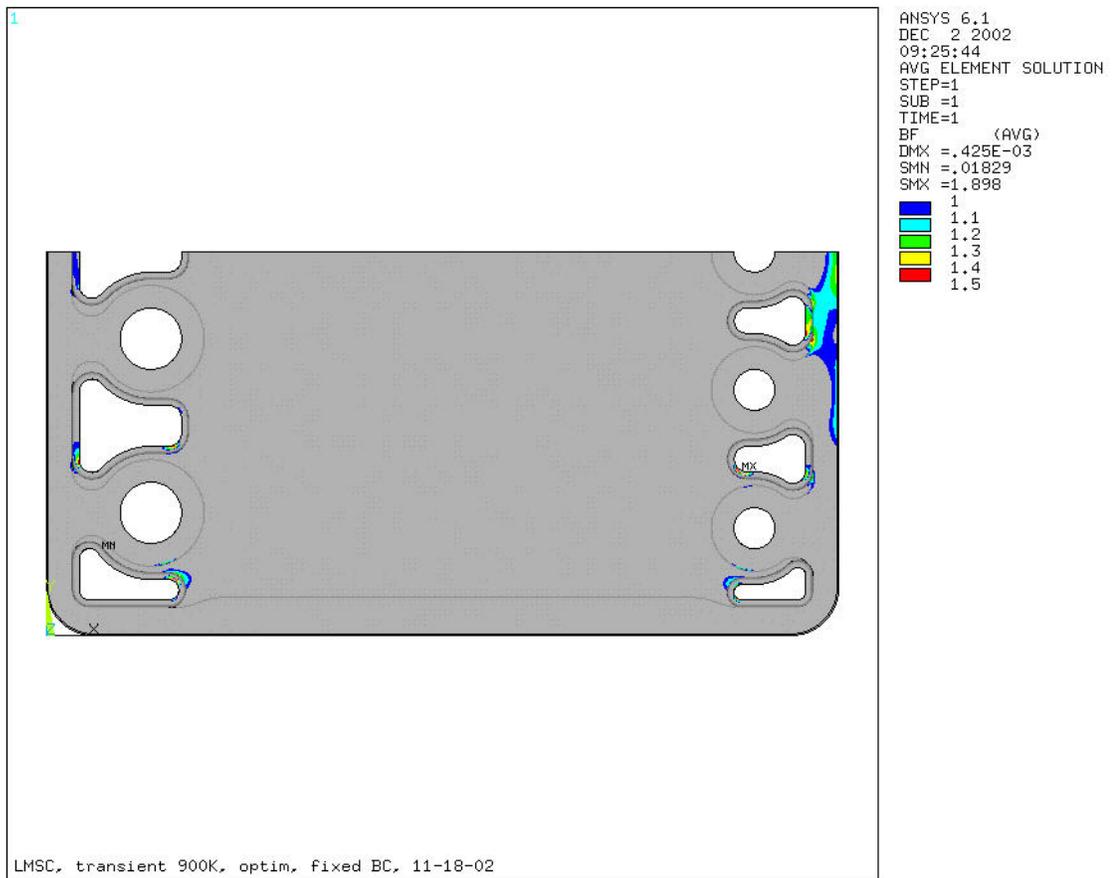


Figure 4.2.3-2: Separator Plate Inverse Safety Factor

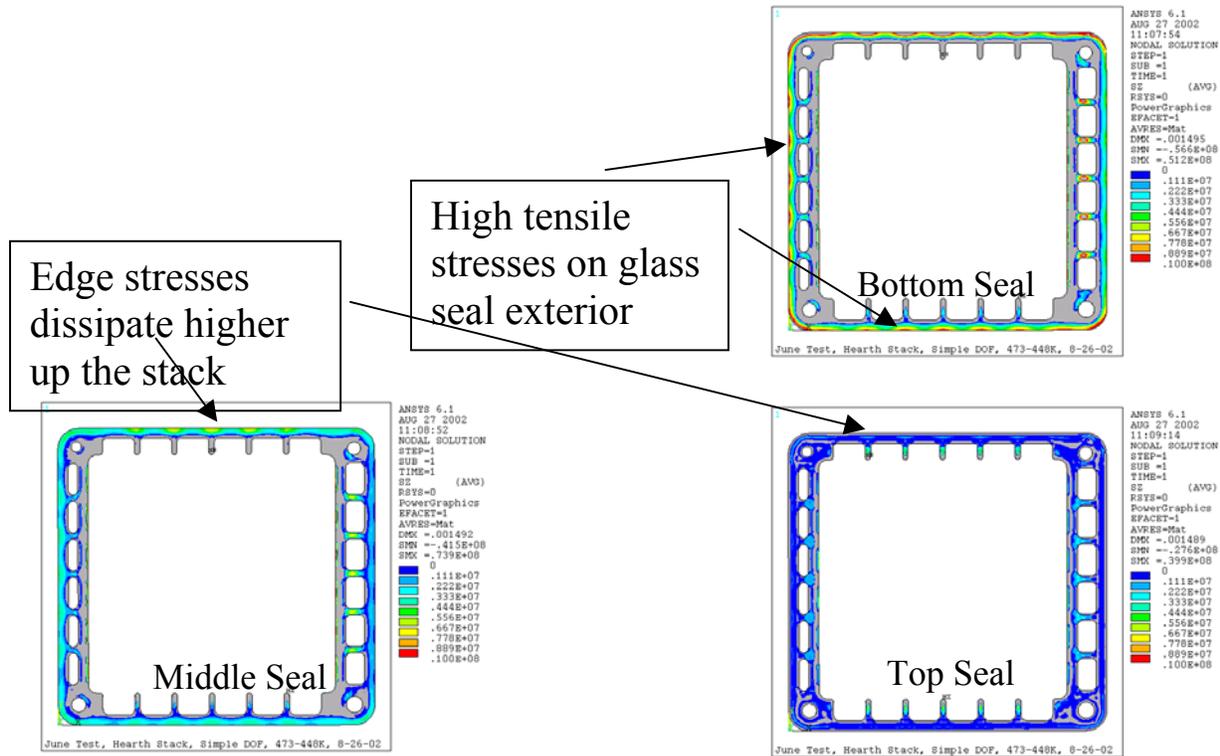


Figure 4.2.3-3: Seal Stress

4.2.4 Develop High-Performance Cathode.

Cathode development has focused on bringing 8 cathode test stands online. Initial testing of the stands, shown in **Figure 4.2.4-1**, has focused on optimization of assembly procedures and variance testing with standardized materials sets. Future development will focus on reduction of the cathode over potential by optimization of both the stoichiometry and microstructure of (La, Sr) FeO₃ based cathodes. These optimization studies will be used to assist commercial ceramic powder vendors in the production of reliable high power density cathode powder.



Figure 4.2.4-1: Cathode Test Stands

4.2.5 Develop High-Performance Anode

Included in 4.2.6.

4.2.6 Develop Cell Fabrication Techniques

The Anode Development and Cell Fabrication efforts focused on three major thrust areas; Camber reduction in anode supported cells, improved manufacturing techniques, and aqueous based production processes.

Camber Reduction in Anode-Supported Cells. In anode-supported cells, the thermal expansion differential between the thin, $8\mu\text{m}$ electrolyte (Thermal Expansion Coefficient $10.5\text{ ppm}/^\circ\text{C}$) and the bulk NiO-Yttria-stabilized zirconia anode ($12.5\text{ ppm}/^\circ\text{C}$) creates a positive camber towards the electrolyte. In addition to making the subsequent processing operations on the bilayer more difficult, the camber of the ceramic part will dictate the flatness of cell assemblies when the metal becomes sufficiently thin ($300\text{--}500\ \mu\text{m}$). In order to reduce this camber, several materials were investigated which could lower the Thermal Expansion Coefficient of the bulk anode without deleteriously impacting cell performance. An additive was found that successfully controlled camber. **Figure 4.2.6-1** shows the result of the additive on the camber induced into a GEN 3 cell assembly. Initial electrochemical validation testing was done on 1" diameter "button" cells containing the additive, which showed no performance degradation over 1000 hrs of operation, **Figure 4.2.6-2**. In addition to the increased flatness, the cells also exhibit an increased flexural strength when compared to the base anode composition (**Figure 4.2.6-3**).

Improved Manufacturing Techniques. During the co-sintering operation, stresses created due to the difference in sintering kinetics of the anode and electrolyte layers result in warpage of the bilayer structure. Removing this warpage has required a secondary “creep flattening” operation in which the part is weighted during a heat treatment. In order to improve yield and reduce the number of high temperature firing operations, a constraining system was developed which enable the desired part flatness to be achieved during the initial sintering operation. Microstructural analysis of these parts indicates no adverse reactions with the reusable constraint material. In addition to improving yield, the process has increased the temperature-processing conditions under which the anode-supported cells can be fabricated.

Aqueous-Based Production Processes. Most ceramic processing techniques utilize organic solvents in order to prevent the formation of hydroxyl groups on the ceramic powder. However, the flammability and exposure limits of these organic solvents often prohibit safe and economic scale-up of these processes. Recent developments have focused on: the replacement of the 2-propanol used in our anode milling operation with an aqueous based slurry; and developing an aqueous tape casting technique for the bulk anode composition to eliminate the MEK/Ethanol solvent system currently used. Under the correct milling conditions, the aqueous milled anode powder can be used in either an aqueous or organic tape cast formulation with minimal changes to the resulting anode microstructure.

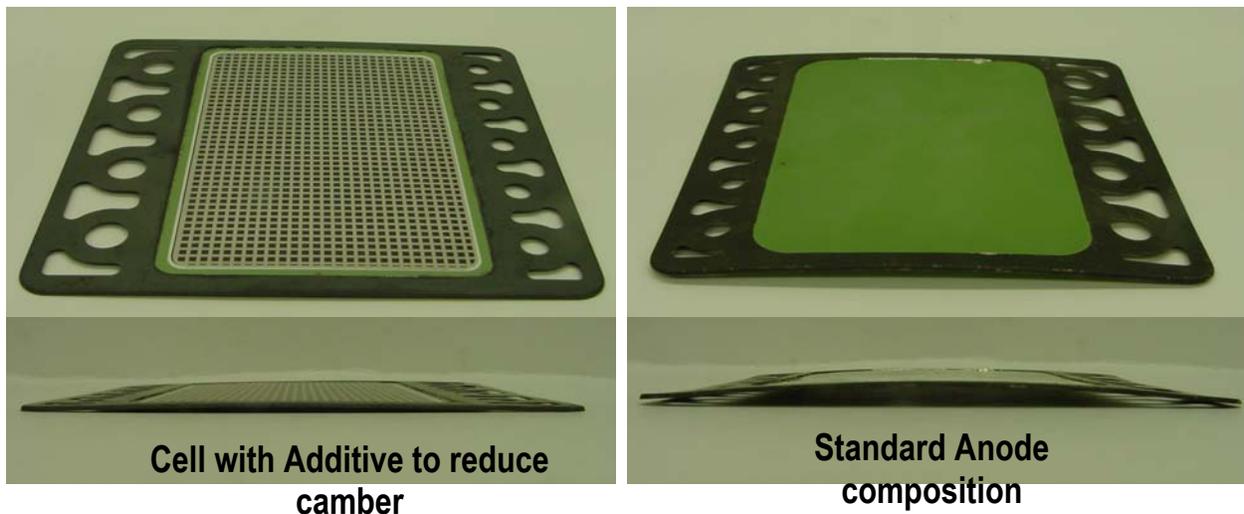


Figure 4.2.6-1: Effect of Additive on Cell Curvature

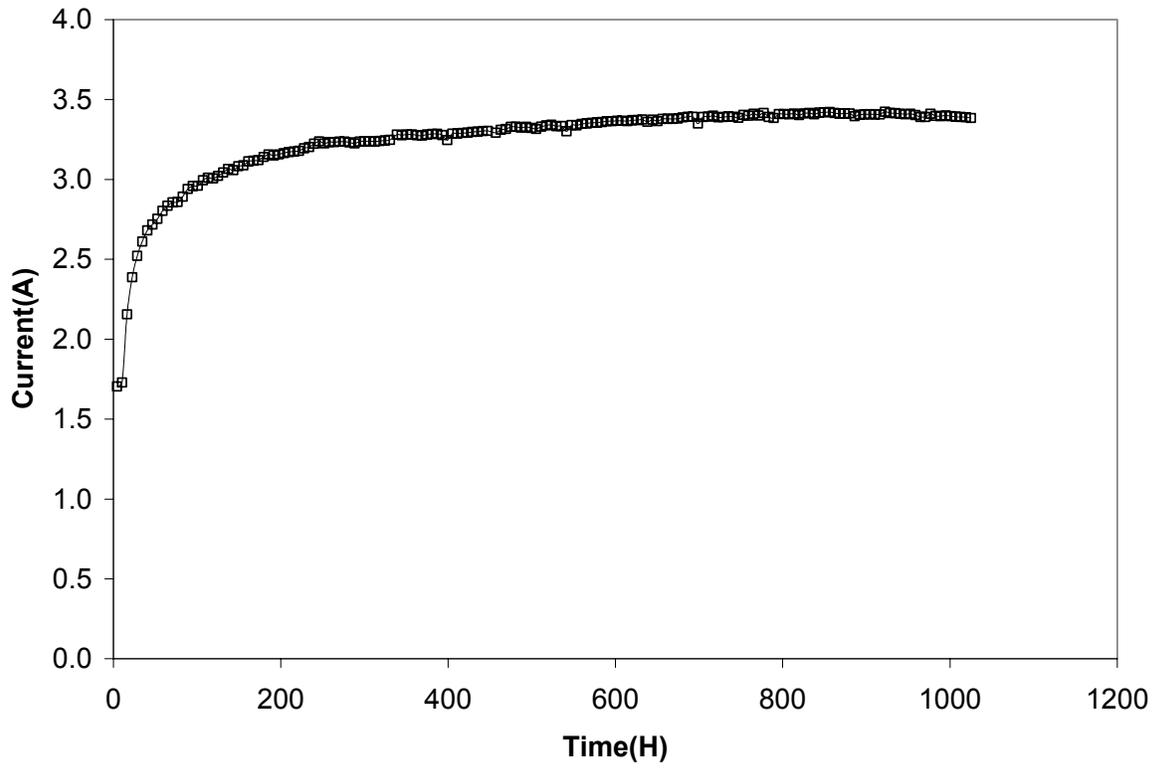


Figure 4.2.6-2: 1000 hr Test of Cell with Anode Containing Anti-Camber Additive

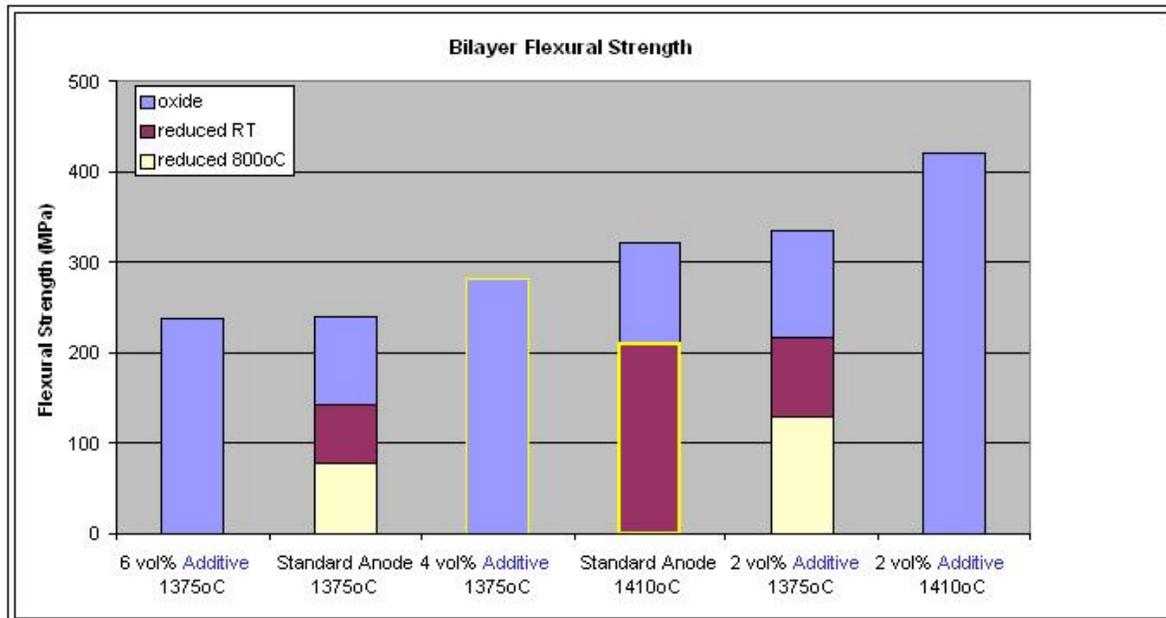


Figure 4.2.6-3: Bilayer Flexural Strength, As Oxide, Reduced and at 800 °C

4.2.7 Develop Separator and Support Components

Ferritic steel is the material of choice for separator plate development. A slurry coating applied to the metal surface and fired near 1000 °C has been employed to improve glass seal strengths. A creep-flattening heat treatment of this component following the firing process has proved critical to successful stack assembly and sealing.

4.2.8 Develop Gas Distribution Meshes

Discussed in the previous report was the feather mesh interconnect design, a series of parallel mesh strips welded to either side of the separator plate that simultaneously make electrical contact with the anode and cathode from adjacent cells. Several other contact concepts have been considered and investigated not only in terms of their electrical resistance at operating temperature, but also with respect to the pressure drop incurred due to gas flow across the interconnect.

Figure 4.2.10-□ Develop Mesh/Electrode Interface Materials

There are several factors to consider in the design of the interconnect, including: (1) resistance through the entire electrical pathway, including any oxide scale; (2) chemical stability of the interconnect material, particularly with respect to oxidation and reactivity at the interfaces with the cell electrodes and separator plate, (3) appropriate mechanical design for good electrical contact and structural support of the ceramic cell under dynamic loading or vibration (e.g. of the type experienced in an automotive application); and (4) pressure drop, which was discussed in Section 4.2.8.

Figure 4.2.10-□ Develop Glass and Glass-Ceramic Seals

Discussed in the previous report were several concerns with thermal expansion stability of the glass-ceramic seal employed in the cell-to-window frame and cassette-to-cassette seals. It is imperative in a static seal design that the two sealing surfaces and the joining material either (1) all display matching coefficients of thermal expansion (CTE) or (2) exhibit the propensity to undergo substantial elastic or plastic deformation to minimize the generation of thermal mismatch stresses in the joint during thermal cycling and subsequently avoid component warpage and cell fracture. In our work on the barium aluminosilicate G-18 glass, we have observed that when at operating temperature as crystalline phases form in the glass over time (**Figure 4.2.10-1 a**), the CTE of the material decreases measurably (**Figure 4.2.10-1 b**). This not only occurs in the bulk glass, but at the interface with the stainless steel used in the window frame. A two-prong approach was taken to correct this problem: (1) reformulation of the glass composition to improve long-term CTE stability in the bulk glass and (2) development of surface coatings on the stainless steel components in an effort to eliminate the formation of deleterious phases at the metal/glass interface.

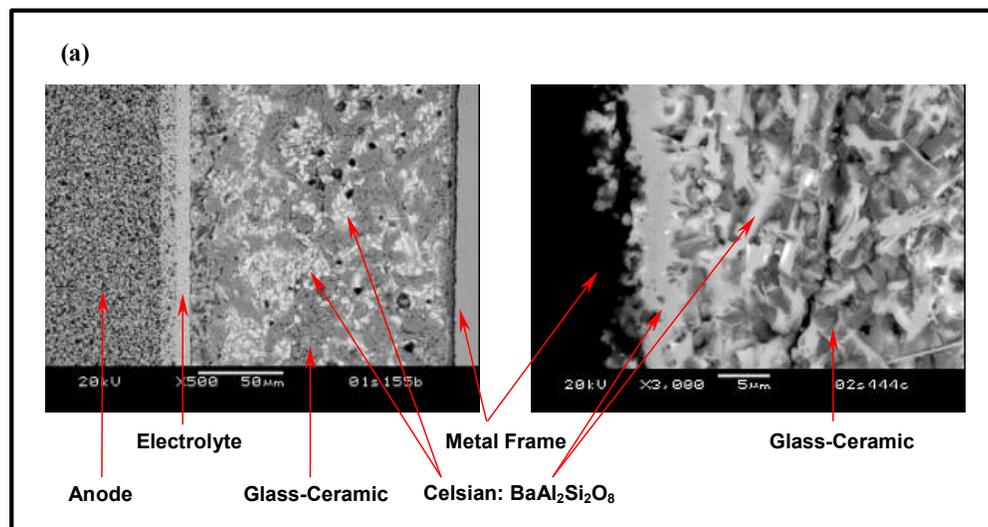


Figure 4.2.10-1 (a) Celsian Phase Formation

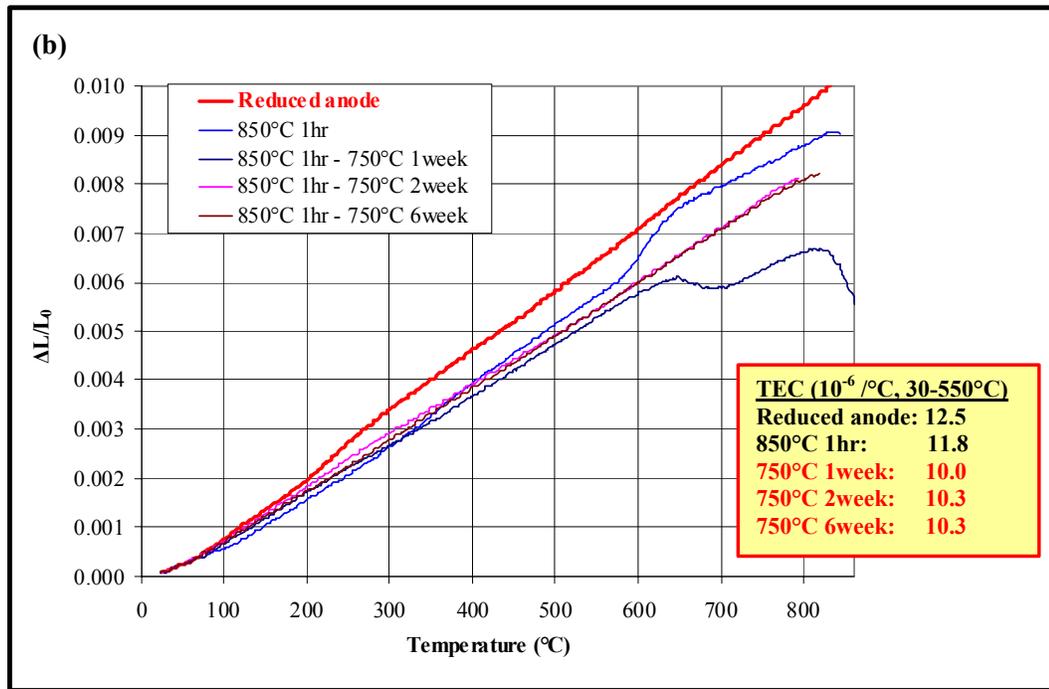


Figure 4.2.10-1 (b): CTE Effects

4.2.11 Develop Alternative Seals

The silver-based braze under development has performed quite well in rupture testing and has been scaled up for use in stack testing. A commercial vendor currently supplies foils of the appropriate composition, which are being used to seal full-size cells to the ferritic stainless steel window frames, as shown in **Figures 4.2.11-1 (a) and (b)**.

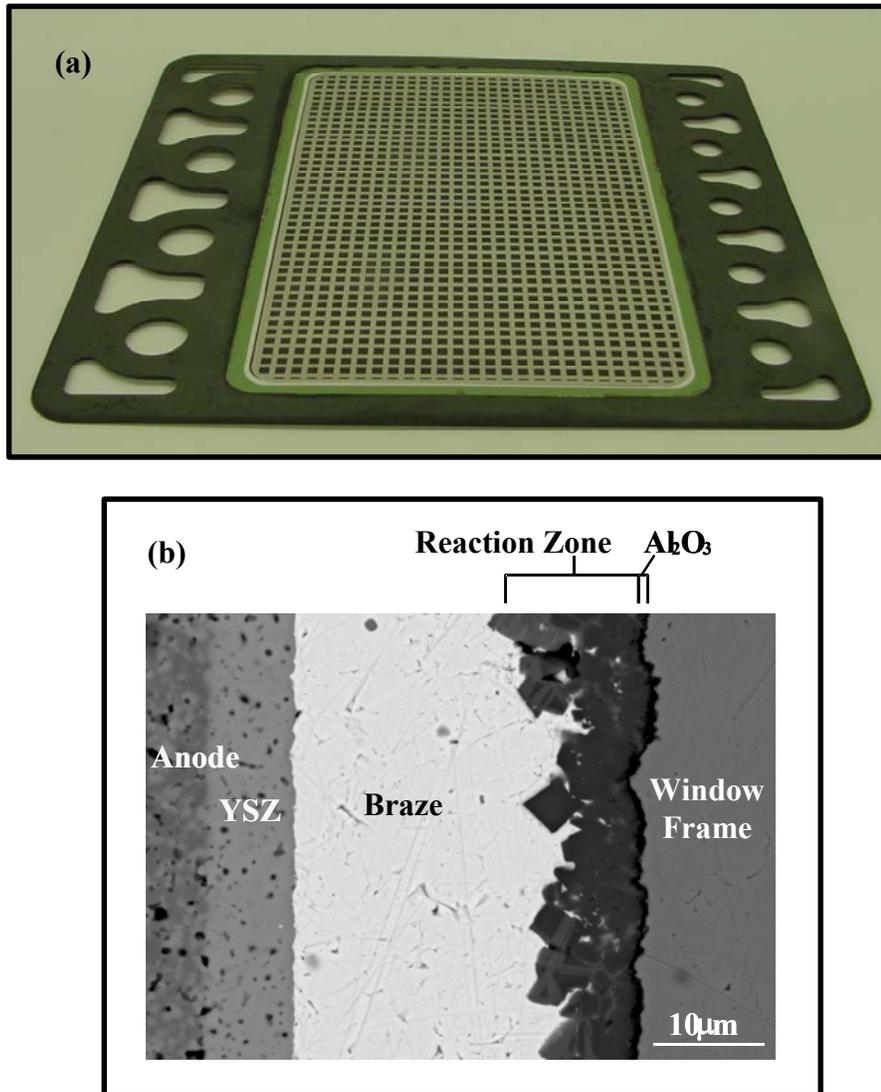


Figure 4.2.11-1 (a) Cell brazed & (b) SEM micrograph of frame joint.

Figure 4.2.11-1 (a) Cell brazed to a window frame component. (b) SEM micrograph of frame joint.

4.2.12 Develop Gas Headers and Manifolds

Discussed in section 4.2.1.

4.2.13 Fabricate Developmental Stacks

A variety of stacks have been built and tested to understand and improve performance of the stack. The stack tests can be classified into two main categories:

- Stack tests with intermediate-sized active area cells (7 cm x 7 cm)
- Stack tests with full-sized cells (11.5cm x 11.5cm).

Stack test with intermediate-size active area cells: Extensive experience has been gained in the fabrication and testing of these stacks with cell dimensions of 7cm X 7cm. The intermediate-sized tests are used to evaluate novel cell materials, cell processing parameters, new interconnect materials and designs, and alternate sealing techniques. Screening tests and performance evaluations can readily be performed using single-cell, intermediate-size tests.

Test data is presented (in **Figure 4.2.13-1**) for a single-cell intermediate-size stack test (I-16) that shows performance durability after four thermal cycles. The OCV after each thermal cycle was near the theoretical value of 1.09 V, indicating good performance by the glass seals. The initial power density for this stack was 0.43 W/cm² during the initial cycle. After four thermal cycles, the power density was 0.41 W/cm², a net loss of 3% in power from the initial performance.

A demonstration of high-power density from an intermediate-size stack test is shown in **Figure 4.2.13-2**. With similar stack materials to test I-16, this test reached 0.65 W/cm² at 0.7 V and 750 °C with 5 lpm air and 2 lpm of fuel (50/50 H₂/N₂). The stack components for test I-16 and I-17 did include Pt for the cathode current collector grid, paste and mesh.

Stack test with full-size active area cells: In addition, experience is also being gained in the fabrication and testing of these stacks with cell dimensions of 11.5 cm x 11.5 cm dimension. Full-size stack testing has consistently produced performance results which are ~25% lower than similar test conditions at the intermediate-size components. The differences in performance between the two geometries will be the subject of future investigation.

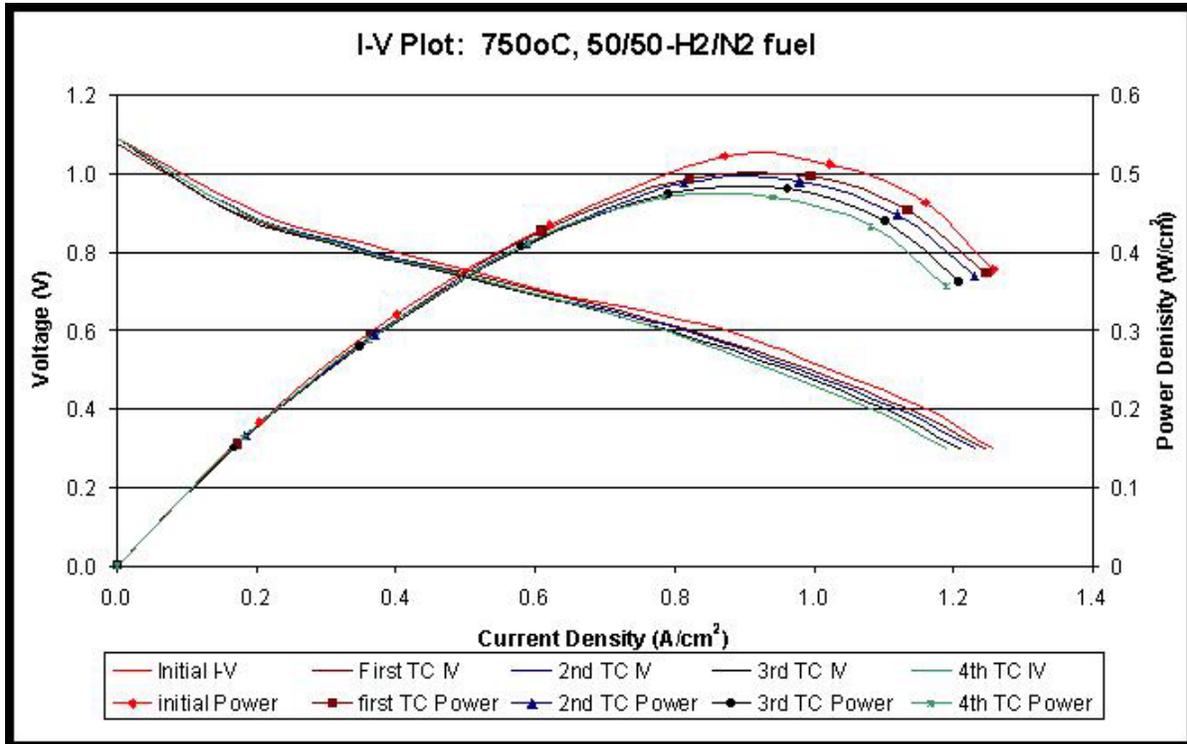


Figure 4.2.13-1: Intermediate-Size Stack Test w/ 5 Thermal Cycles

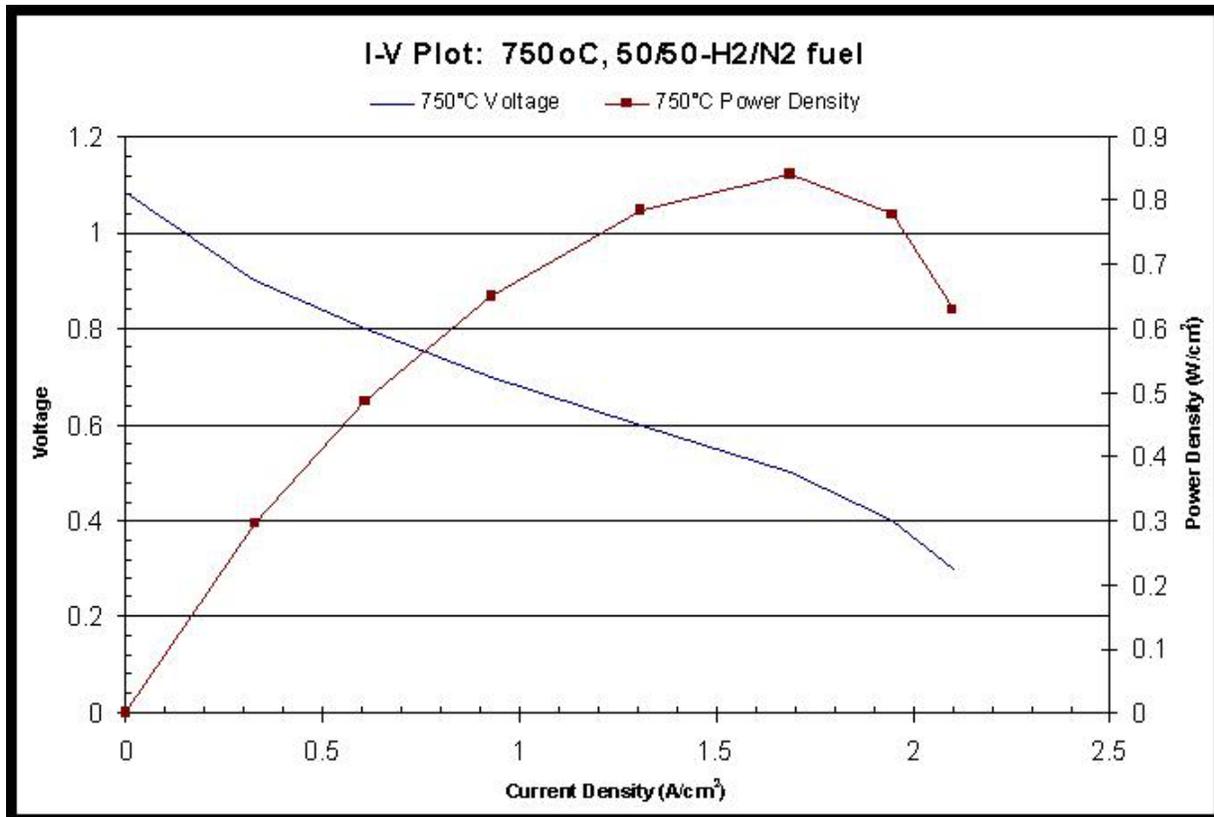


Figure 4.2.13-2: Intermediate-Size Stack Test w/High Power Density

4.2.14 Evaluate Stack Performance

Stack testing with Full-Sized Cells

Evaluation of performance with full sized Gen 2 single-cell stacks to multi-cell stacks (with ~11.5 x 11.5 cm cells) has been carried out to validate the design and understand the performance characteristics. Multiple stack modules have been built and tested. Multiple Integrated Stack Modules, stack sub-system consisting of two stack modules in electrical series and manifolded parallelly) have also been built, tested and integrated into the Auxiliary Power Unit system.

1-Cell Cassette Stack

Full-size single cell stacks have been tested to evaluate performance under different conditions. The IV curve in **Figure 4.2.14-1** shows the performance at 750 °C with different reformate compositions. A maximum of 350 mW/cm² is achieved with hydrogen.

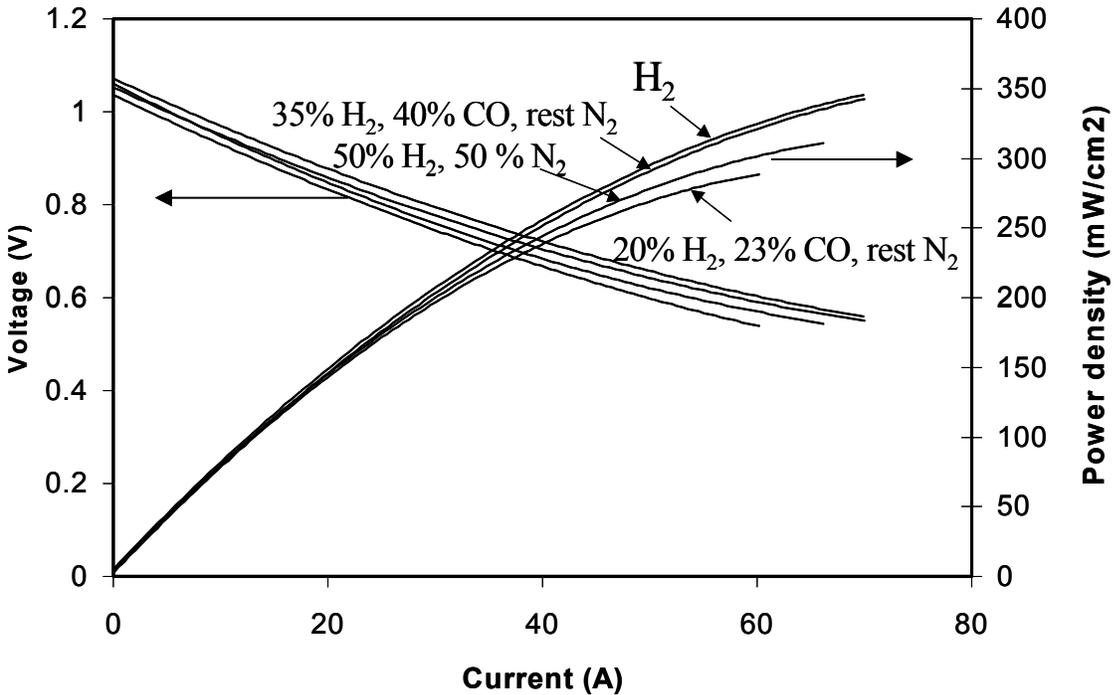


Figure 4.2.14-1: I-V curve from a 1-cell stack test at 750 °C

Further, thermal cycling tests are being performed on a full-size, single-cell stack test. **Figure 4.2.14** shows data on a stack being thermally cycled in a furnace from ambient to operating temperature. The temperature ramp rate was 3 °C per minute. Leak rates were measured by pressurizing the stack to 3kPa with all outlets blocked. Open circuit voltages and power density at 0.5 V was measured in each cycle. The open circuit voltage and the power densities show stable and encouraging performance. While the leak rate at room temperature seems to increase over time, the leak rates at operating temperature are observed to be low throughout the test.

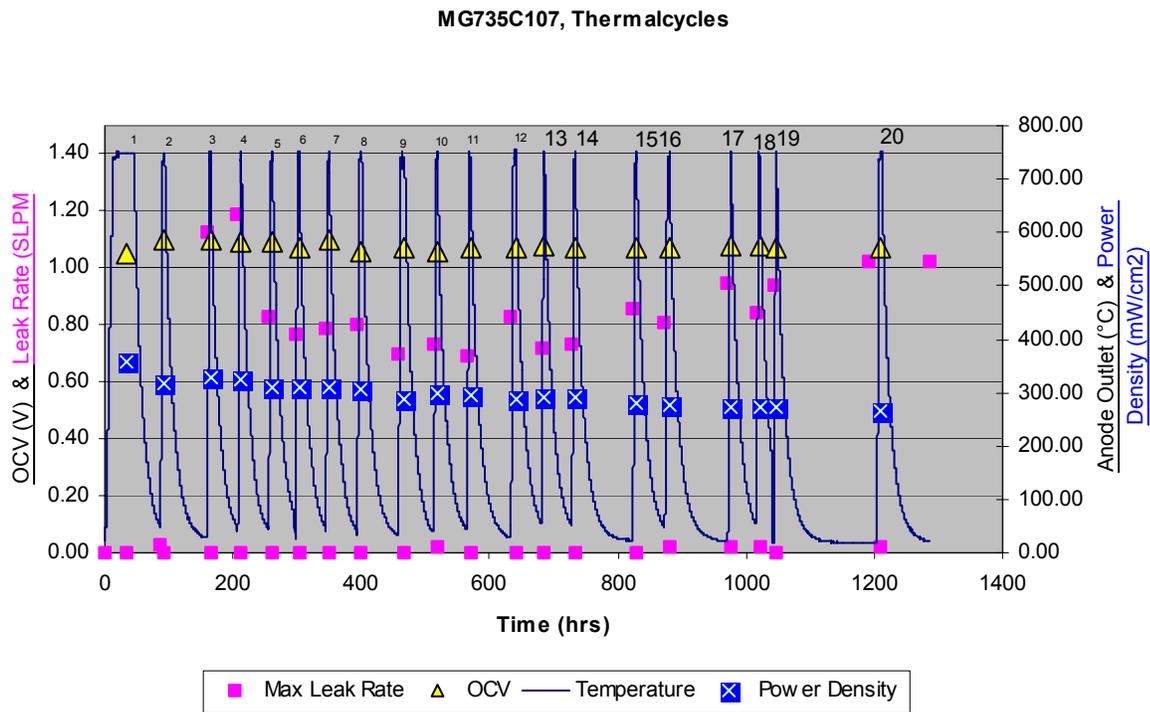


Figure 4.2.14-2: Thermal Cycling Test on Gen 2 Single-Cell Stack

26-Cell Cassette Stack

Multi-cell stacks have also been built and tested. A 26-cell cassette stack was built and tested. The cassettes were pre-fabricated with the cells sealed in them and leak tested before assembly into a stack. The stack was then assembled with glass seal between the repeating units. The cells were reduced in-situ once the glass sealing process was complete and polarization curves were measured (see **Figure 4.2.14-3**). Hydrogen was used as a fuel (52 LPM) and Air (52 LPM) was used on the cathode side.

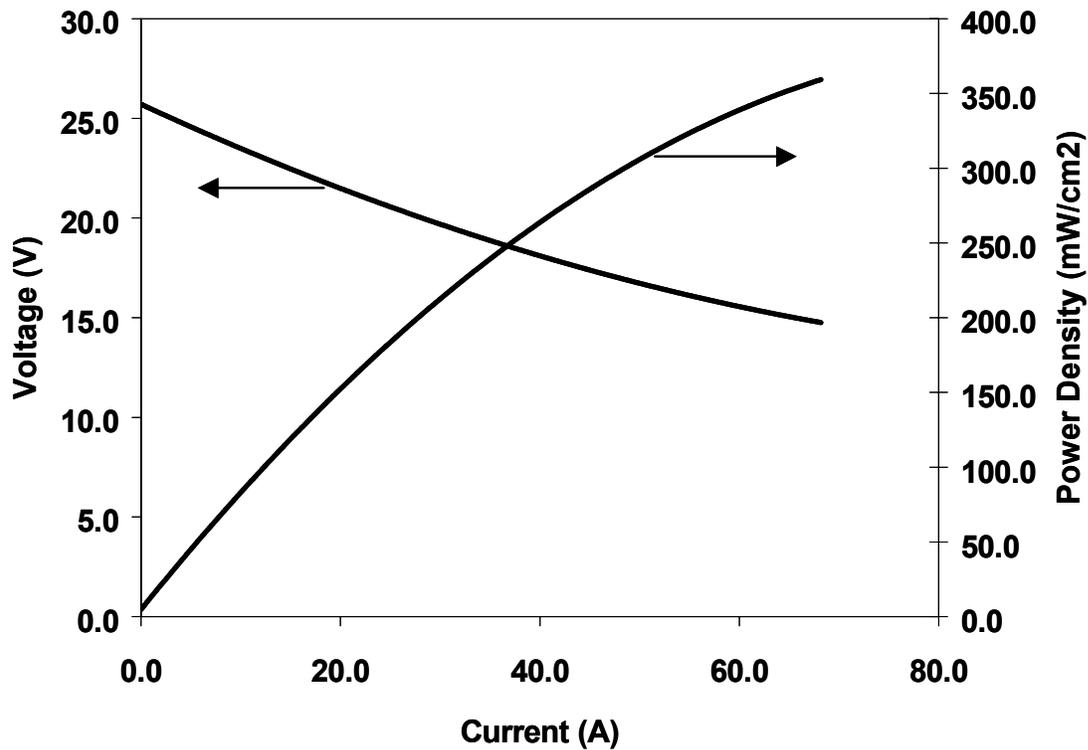


Figure 4.2.14-3: IV Curve of 26-Cell Stack With Hydrogen at 750 °C.

Maximum power density of 350mW/cm² @ 15V (H₂) at 750 °C was achieved. Further optimization of Gen 2 stacks is ongoing.

Integrated Stack Module

Multiple Integrated Stack Modules (two stack modules in electrical series) were built and tested. **Figure 4.2.14-4** shows a picture of a 2x15-cell Integrated Stack Module with load frame and current collectors integrated in the sub-system. The Integrated Stack Module is ready to be integrated into the system.

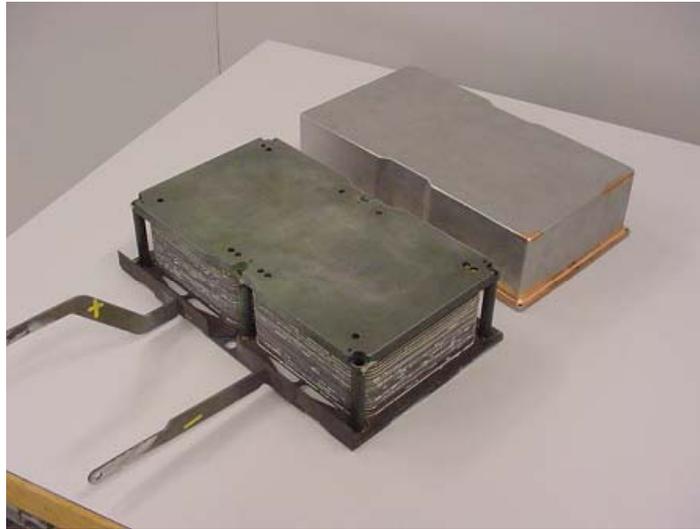


Figure 4.2.14-4: Integrated Stack Module

30 Cell ISM #2 MG735C103 10/21/02

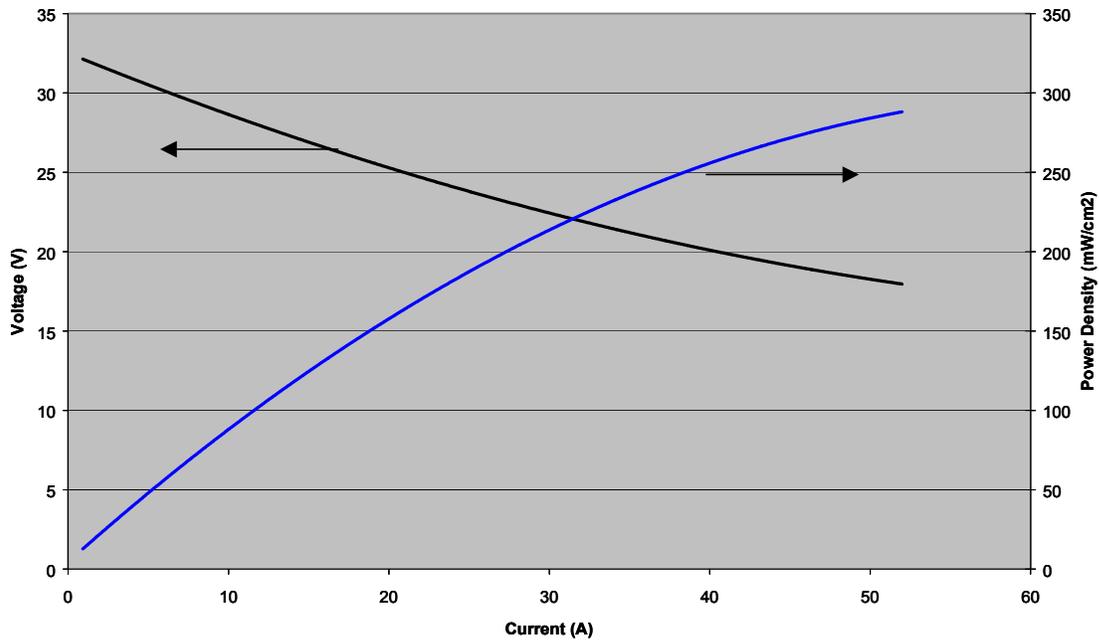


Figure 4.2.14-5: IV curve of a 2x15-cell Integrated Stack Module with Hydrogen at 750 °C.

Figure 4.2.14-5 is a polarization curve from a 2 x 15-cell Integrated Stack Module test. A maximum power density of 288 mW/cm^2 @ 17.6V was achieved (H_2 , 750°C). The amount of fuel flow was 60 LPM on the anode side and 60 LPM on the cathode side.

The Integrated Stack Module has also been integrated and operated in the Auxiliary Power Unit. This was a significant milestone in demonstrating the integrated functioning of an Auxiliary Power Unit. **Figure 4.2.14** shows the picture of the hot zone module in an Auxiliary Power Unit with integrated POx reformer and heat exchangers.

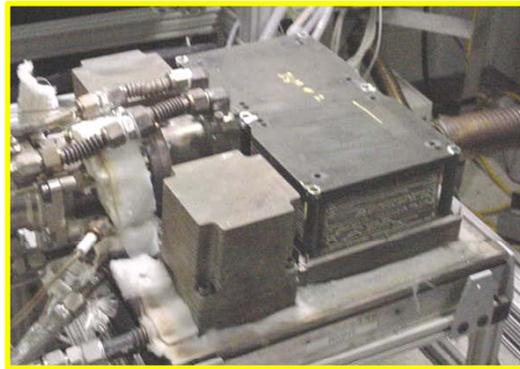


Figure 4.2.14-5: Integrated Stack Module Integrated in the Hot Zone of an Auxiliary Power Unit

For the first time, the Integrated Stack Module was heated by cathode air pre-heated in the system using the combustor and reformat from the reformer. The stacks were heated to $\sim 750^\circ\text{C}$. Open Circuit Voltages (OCV) came up to 30.8 V. POx reformat (from gasoline) flowing into the stack consisted of 21% H_2 , 20% CO, 3% H_2O . Polarization curves were measured and shown in **Figure 4.2.14-6**. The stack produced 486 Watts @ 15.2V. This was the first result from a Gen-2 Auxiliary Power Unit producing power from gasoline. Further testing of Integrated Stack Modules in Auxiliary Power Unit and optimization of the startup and steady state operation is continuing.

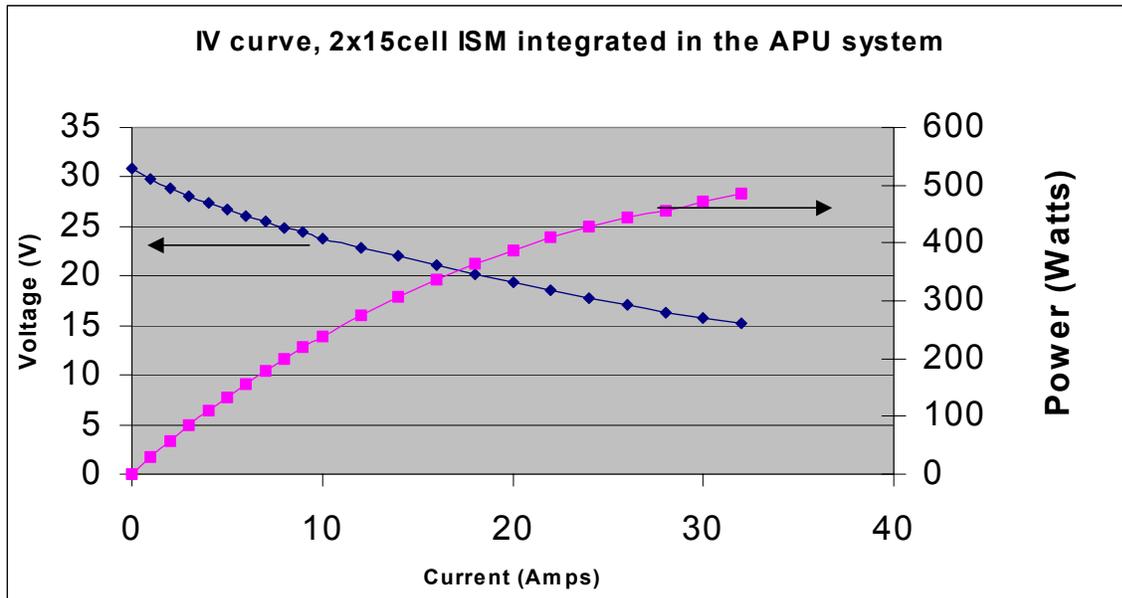


Figure 4.2.14-6: IV Curve from Integrated Stack Module Integrated in the Auxiliary Power Unit (Hot Zone Module)

4.3 Reformer Development (Task 3.0)

4.3.1 Develop Steam Reformer for Natural Gas

No work complete under this subtask.

4.3.2 Develop Catalytic Partial Oxidation Reformer

Several reformer designs were involved in development during this reporting period and will be discussed in chronological order.

4.3.2.1 Develop Catalytic Partial Oxidation Reformer – H1 Reactor

The H1 reactor discussed in the 1st topical report continued as a platform for reformer testing. Primarily serial numbers 4 and 5 (only 5 assemblies were ultimately built) saw testing during this reporting period and were involved in testing as follows:

4.3.2.1.1 Burn-Off Study

During the testing of serial number 4 for the purposes of determining maximum Gas Hourly Space Velocity (GHSV) for good conversion (see **Topical Report 1**), we periodically encountered instances where repeat runs at the same conditions would not produce the same results in reformat quality. Suspecting carbon formation as the cause we embarked upon a series of runs in hopes of clarifying the relative merits of several burn-off methods as well as more clearly determining which data sets were impacted by carbon accumulation. Three particular burn-off methods were employed. The three methods are referred to as:

1. Dry Burn-Off (Dry BO)
2. Lean of Syngas with water (LOsyn/water)
3. Lean of Stoichiometric with water (LOstoich/water).

Dry Burn-off had been a technique used earlier in our development with some success, but the benefits of water addition had yet to be evaluated. Both methods employing water required that catalyst temperature (particularly the front edge) be maintained within limits via the test operator slewing in phi and steam/carbon ratios accordingly.

Results presented in **Figure 4.3.2.1.1-1** and **Figure 4.3.2.1.1-2** raised several points regarding repeatability and effectiveness.

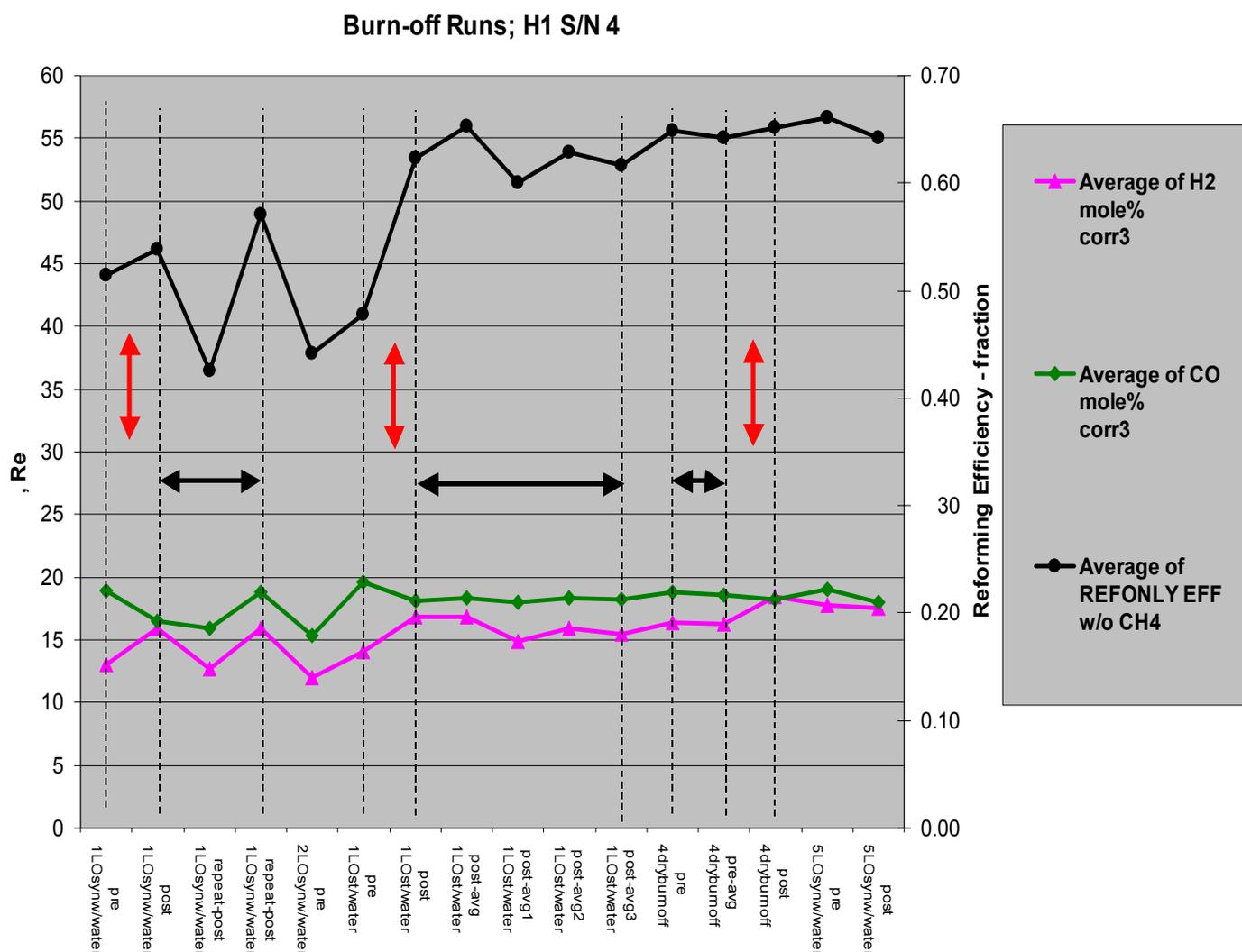


Figure 4.3.2.1-1: Burn-Off Evaluation: H2, CO, Reformer Efficiency

Figure 4.3.2.1-1 shows the chronology of burn-off data. Black arrows indicate spans in data that should be consistent as they represent repeat data points and/or averaging of many points. Red arrows indicate where a burn-off event occurred and changes in plotted variables in this span represent the potential effect of the burn-off event. The variability in the LOsynwater and LOstoichwater repeat data spans are a concern. **NOTE:** The suffix “corr3” refers to 3 levels of correction applied to raw data. Raw mole % data is first corrected for the water knockout that occurs prior to sample gas entering the Mass Spectrometer. The water mole% is estimated prior to the water knockout via a Dew Point sensor. The second correction is for misread between CO and N₂. Due to their identical molecular weights, the type of Mass Spectrometer employed for this testing can misread CO as N₂ and vice versa. Through mass balance on N₂ an expected N₂ mole % can be calculated and thus CO can be adjusted closer to its true value. The third correction is to back out the dilution effect of non-air N₂ that is frequently needed by the reformer to control lead edge temperatures.

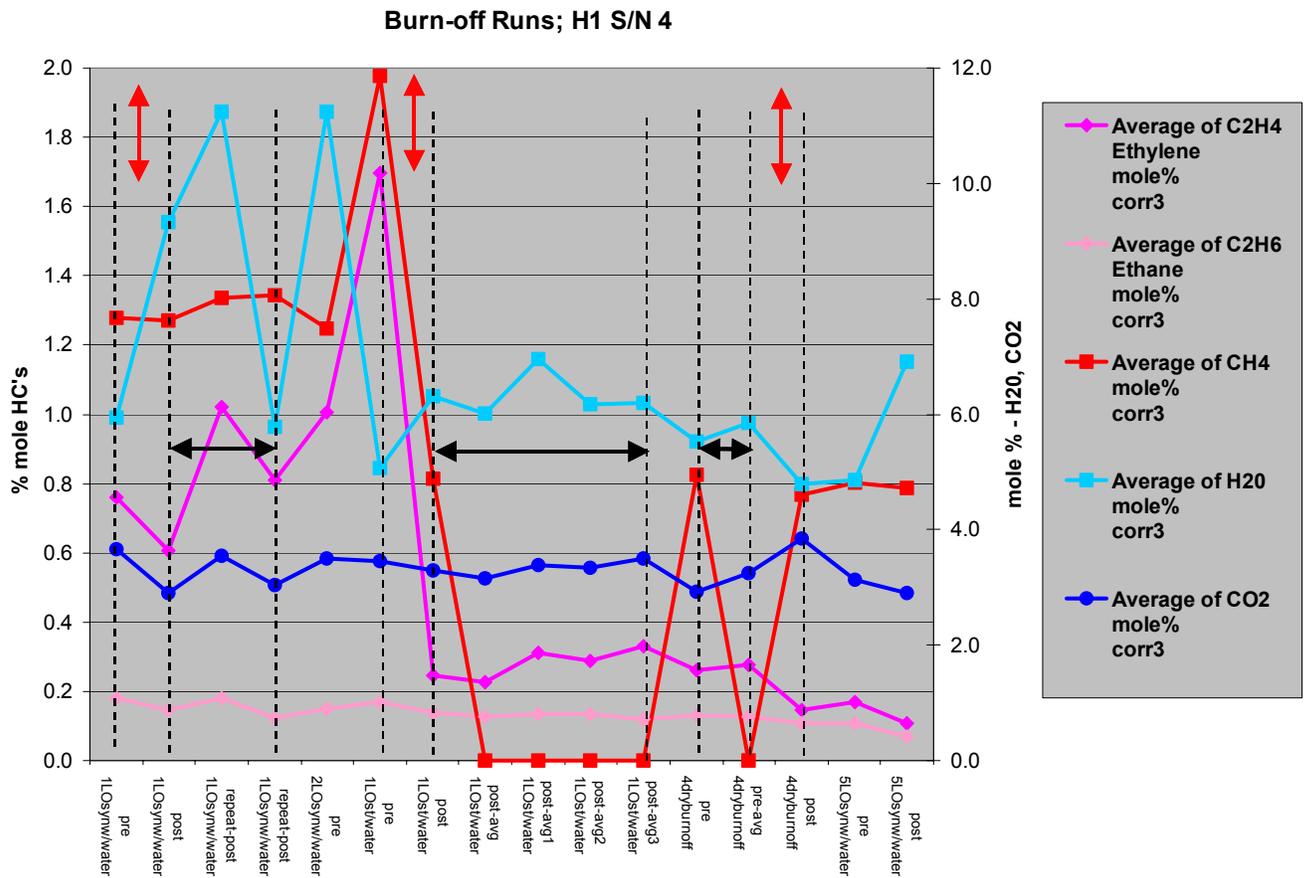


Figure 4.3.2.1.1-2: Burn-off Evaluation: HC, H₂O, CO₂

Figure 4.3.2.1.1-2 shows the chronology of burn-off data. Black arrows indicate spans in data that should be consistent as they represent repeat data points and/or averaging of many points. Red arrows indicate where a burn-off event occurred and changes in plotted variables in this span represent the potential effect of the burn-off event.

NOTE: Methane values were taken from a mass spectrometer with a calibration offset. The values are not accurate but still have resolution.

Both the 1Losyn/water post burn-off repeats and the 1Lostoich/water post burn-off repeats were not consistent. Data collecting at the time of this testing required periodic manual capture of Mass Spec and specific control variables. As a way to minimize the impact of short-term fluctuations in response variables, data averaging of many minutes was employed and is indicated by ending with the 'avg' label. While this helped, variation was still unsatisfactory. Explanations for this are not complete but factors include:

- Variation in reforming temperatures due to variation in the mass of Nitrogen added to the reformer feed stream as a way to manage lead edge catalyst temperatures. (This issue will be discussed more fully later in the report.)
- Variable temperature at the rear of the reformer due to difficulties controlling combustor temperatures.

With respect to effectiveness, only the Lostoich/water showed significant impact. However, past experience had also shown the Dry Burn-off to be effective. This raised the possibility that the reformer states prior to burn-off were not consistent, such that a burn-off may or may not show the marked improvement indicative of it removing soot.

Unfortunately these issues were not brought to closure before all viable H1 parts were consumed. Further carbon formation and detection work is now underway

4.3.2.1.2 O₂ Getter Study

A requirement of the reformat is that O₂ content be extremely low due to the damage that would result due to stack anode oxidation prior to the stack coming up to operating temperature. The system mechanization includes an 'oxygen getter' material that will remove limited amounts of oxygen present in the anode stream.

While it could be assumed that a reformation reaction should consume all the available oxygen and reformer out Mass Spectrometer shows indicated Oxygen at 0%, the resolution on the Mass Spectrometer cannot detect the low levels of O₂ that would be harmful to the stack. Because of this, it was decided it would be worthwhile to conduct a test to indirectly measure O₂ levels in the reformat using both Oxygen getter material (nickel foam for this round of testing) and actual stack anode material.

Table 4.3.2.1.2-1 shows the conditions and results for 4 tests in this sequence. The first 2 tests employed actual H1 reformer hardware where the oxygen getter material was placed in the reformer outlet tubing. Tests 3 & 4 were conducted using a tube furnace with the oxygen getter material again located inside a tube but with heat provided via the furnace. Test 1 showed no evidence of oxidation. It did however show appreciable coke. Given that precautions were taken to expose this material to only steady state quality reformat (i.e., start-up was done off-line) it was necessary to find an explanation for the carbon deposition.

Test #	1	2	3	4
TEST NAME	Preliminary	Lean correction	CO ₂ , no HC's	CO ₂ + HC's
HARDWARE	H1 SN5	H1 SN5	Tube in furnace	Tube in furnace
O/C	O/C=1.05	O/C=1.20	NA	NA
DATE	08/13/2002	08/23/2002	09/18/2002	10/01/2002
H ₂ O mol%	4.14	5.05	4.25	4.03
H ₂ mol%	20.87	19.22	19.12	11.36
CO mol%	19.86	19.25	22.62	11.47
CH ₄ mol%	0.82	0.68	0.00	1.09
Ethane mol%	0.05	0.02	0.00	0.00
Ethylene mol%	0.20	0.13	0.00	0.02
Propane mol%	0.00	0.00	0.00	0.008
Propylene mol%	0.00	0.00	0.00	0.008
CO ₂ mol%	2.35	2.45	2.32	0.76
N ₂ mol%	51.72	53.20	51.89	51.82
He mol%	0.00	0.00	0.00	19.44
Total mol%	100.01	100.00	100.00	100.00
Total Reformate Flow - slpm	32.8	27.0	18.0	19.0
Run Time	2hrs	3hrs	1hr 15min	1hr
Temp at "getters"	830 nom. 600 start	overtemp	770	770
Temp excursion?	possible (fuel oscill)	definite	None	None
Oxidation exposure	minimal / none	high degree	O ₂ flowback from vol. change due to HVAC shutdown	O ₂ flowback from vol. change due to HVAC shutdown
Upstream "getter"	coke, no oxide	NA	no coke	no coke
Fuel Cell mat	NA	NA	no coke, reduced	no coke, reduced
Downstream "getter"	NA	NA	NA	no coke
Filter	NA	NA	NA	no coke

Table 4.3.2.1.2-1: Oxygen 'getter' Summary

Test 2 was conducted in which O/C was increased to 1.2 as 1.05 was thought to be too aggressively rich. Due to a flow controller malfunction an overtemp condition was created and results were not useable.

Test 3 was conducted as a means of answering the question of whether the coke detected in Test 1 was a result of in-stream reformate soot and soot pre-cursors or a result of CO reacting to form C and CO₂. Results indicate that the CO reaction was not a contributing factor.

Test 4 was conducted in an attempt to better simulate reformate by adding controlled amounts of Hydrocarbons (HC's) to the reacting stream. Although no coke formed, it was felt that the test did not reasonably represent reformer outstream conditions in that:

- Actual reformation is likely to create Poly Nuclear Aromatics not present in simulated reformate.
- HC's present in simulated reformate are not the same species and levels (note: 0.2% ethylene in Test 1 as compared to 0.02% in Test 4).
- Temperatures of reaction are considerably more variable (i.e., gradients with reactor) than those of the furnace and therefore, more likely to promote carbon forming reactions.

4.3.2.1.3 External Mixing / Mixing Inserts

There were frequent concerns that combustor heat release was not uniform over the adjacent reforming layer contributing to increase in temperature gradients. Poor mixing is evident by the fact that the combustor outstream contained combustibles (H_2 and CO), which with good mixing should to be consumed given the temperature and excess O_2 . Two techniques were employed to improve this situation.

The first attempt to improve mixing involved pre-mixing the two flow streams (air and simulated anode tail gas) into a manifold external to the actual part and including a flame arrestor element. This method worked well and was used extensively from this point forward.

In parallel mixing inserts that fit inside the Gas Phase Combustor combustion manifold were designed and fabricated. Their design was intended to route air and anode tail gas in a way that would promote mixing by folding the two streams onto one another several times before entering into the plate combustor inlets. Limited testing of these inserts showed some improvement and by the time these improvements were realized it was concluded that the next generation reformer (H_2) would need a redesign of the combustor features.

4.3.2.1.4 Ethylene Climb Issue

A parameter of significant concern is the level of ethylene in the reformat. Ethylene is thought by many to be a key pre-cursor and intermediary in Poly Nuclear Aromatics / soot formation. **Figure 4.3.2.1.4-1** is data from 8/13/02 indicating an interesting Ethylene rise over the course of several hours of testing. Initial supposition was that $O/C=1.05$ is too rich and that ethylene formation could be a gradual result of carbon deposition.

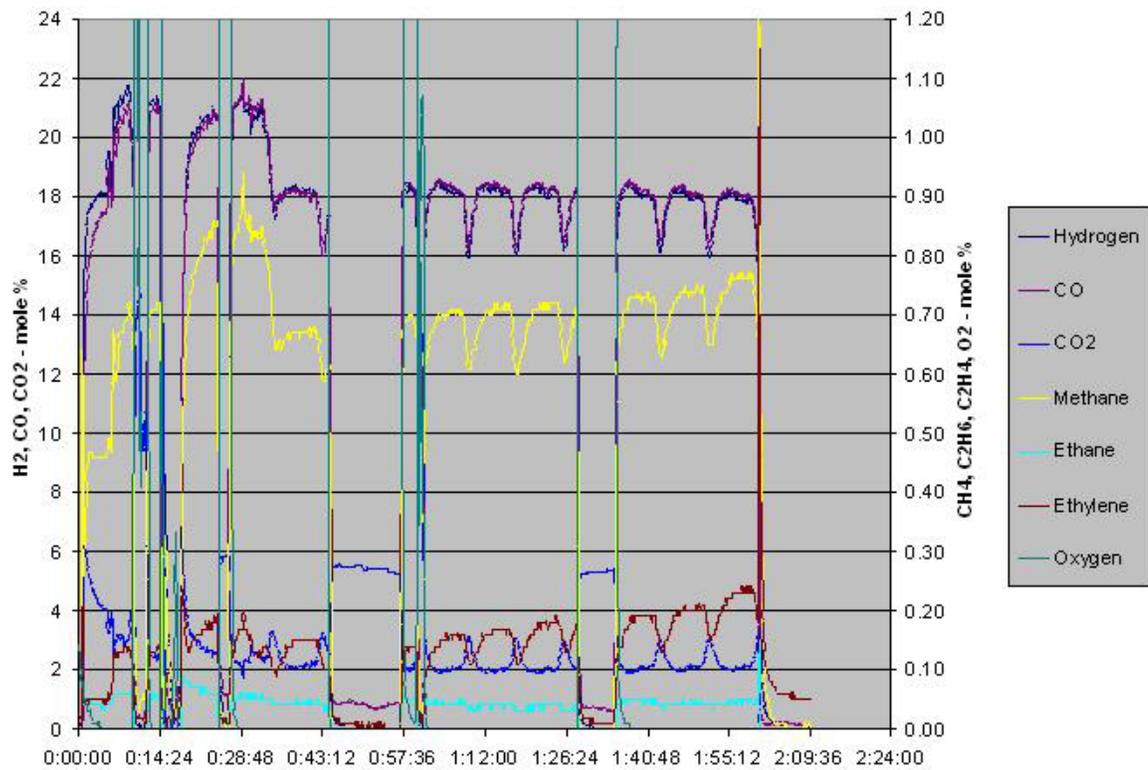


Figure 4.3.2.1.4-1: Ethylene Climb at O/C = 1.05

A follow-up test using O/C of 1.2 indicated Ethylene level stable at ~.13 mole %. See **Figure 4.3.2.1.4-2**. More comprehensive testing to map the effect of O/C and other control variables, particularly in relation to carbon formation, is planned for the future.

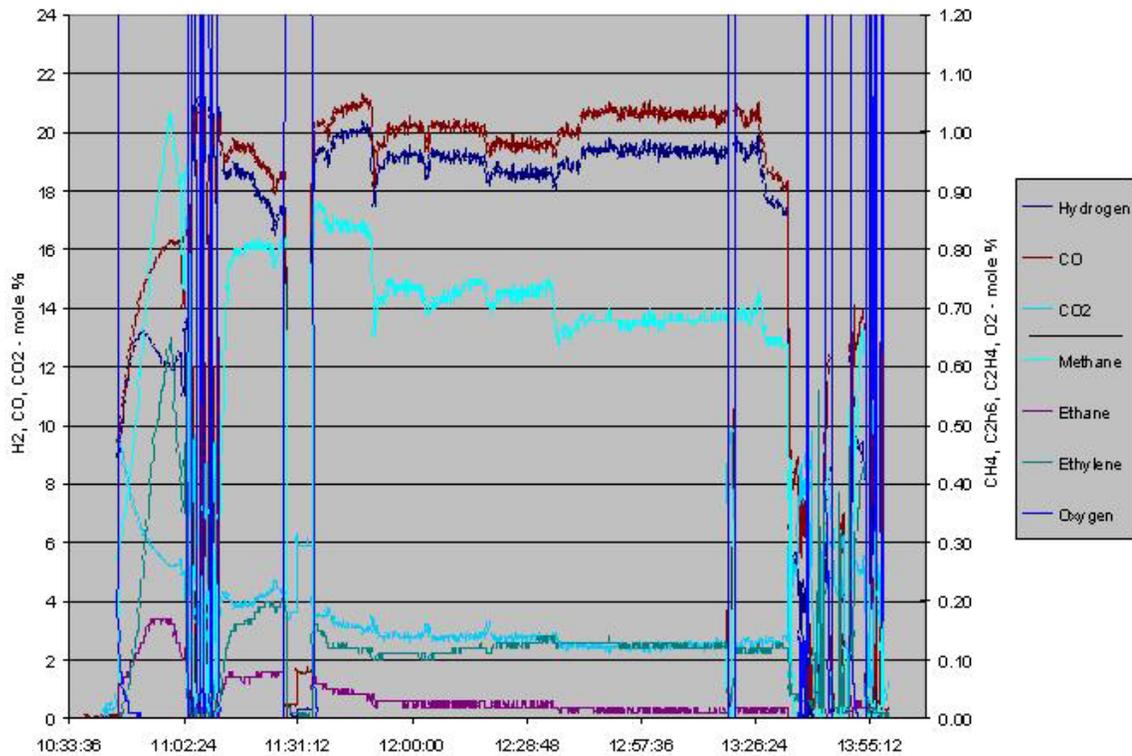


Figure 4.3.2.1.4-2: Ethylene Climb at O/C = 1.20

4.3.2.2 Develop Catalytic Partial Oxidation Reformer – H₂ Reactor

The H₂ reactor discussion will be divided into all the fabrication related activities and problems, followed by the performance testing of the samples that underwent testing.

4.3.2.2.1 Fabrication Issues

Multi-plate planar reformer fabrication has presented many problems most of which have been braze related.

A Successfully Brazed assembly is defined by:

- **Final Height** being within specifications, the vaporizer has a fixed seal interface height and width that must seal to the H₂ reformer face.
- **Seal Integrity** between each of 3 flow passages (reformer, combustor, air pre-heat) and seal to ambient.
- **Un-Restricted Flow Area** of each of the 3 flow passages.
- **Structural squareness** allowing the ability to bolt the reformer assembly to manifold without significant enlargement to bolt holes to accommodate out-of-squareness.

For each assembly both pre-braze and post-braze heights were recorded in an attempt to better predict the degree of braze settling. Predictability was moderate at best and was sensitive to specifics of braze alloy, braze alloy application, braze cycle and burr conditions of the assembled parts (which impacts pre-braze height data collection). Despite this poor predictability, this was perhaps the easiest of the four criteria to meet.

Table 4.3.2.2.1-1 through 4.3.2.2.1-4 contain assembly / braze information on all braze attempts. Each table is a 'snapshot' of the master spreadsheet used to document what configurations were attempted and the results that followed. The tables have been divided at chronological points based on the material used for reformer fabrication during that period of braze development. These periods of specific material usage were a result of either material availability or concerns about the impact of material on braze success.

Brazing Controls	H2 Reformer	H2 Reformer	H2 Reformer
Chronology Index	6	7	8
Identifier / Serial No.	B1 config	Braze Trial 0	B3 config (aka sn B2)
Date Sent to Brazer	?		?
Unsupported Shim Dimension (mm)	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.7	60.2/104.7 23.6/97.5 76.2/15.8
Channel Height; Ref / Comb	.75 / .94 (0.030" / 0.037")	.94 / .94 (0.037" / 0.037")	.94 / .94 (0.037" / 0.037")
Number of A/B etched Plates			
Number of Combustion Plates	25	5	24
Number of Combustion Shims			
Number of Reforming Plates	25	5	24 (w/ fingers)
Number of Reforming Shims			
Number of Generic Shims	49	11	47
Part Material	Inconel 600	Inconel 600	Inconel 600
Shim Thickness (mm)	0.010"	0.010"	0.010"
Braze Alloy 1st Braze	Nicrobraz 150 (BNi-9)	Nicrobraz 150 (BNi-9)	Nicrobraz 150 (BNi-9)
Braze Alloy 2nd Braze (Fittings)	N/A	N/A	Nicrobraz 150 (BNi-9)
Weight Applied During Braze Process (lb)	32?	32?	
Dimples in Shims (Yes/No)	No	No	Yes
Grafoil Shims Installed (Yes/No)	No	No	No
Shims Tack welded in place	No	No	No
Inconel tube inserts for squareness of assembly during braze	No	No	No
Wire EDM of locating bolt holes to 8.6 mm	No	No	No
Braze Application Method (Spray, Slather, Foil)	Spray Frames Only	Spray Frames Only	Spray Frames Only
Results (Good, Acceptable, Poor)	Poor (see .ppt file for photos)	Poor; still collapsing	OK after 1st braze; some collapsing after 2nd fitting braze; part in use

Table 4.3.2.2.1-1: H2 Inconel 600 Braze Configs: Index 6-8

Table 4.3.2.2.1-1 covers the initial fabrication and braze of Inconel 600 H2 reformers. Inconel 600 was the first material used primarily due to its availability.

Haynes 214 was the preferred material, but as initial orders for H2 hardware were placed it became evident that lead times for Haynes 214 in the dimensions we desired would be longer than desirable. It was accepted that the Inconel 600 material did not have the properties to meet durability requirements but would allow more rapid testing of prototype geometry. The choice of Inconel did have some trade-offs. It was advantageous in that it is slightly easier to machine than the Haynes 214 but more importantly, because it is a chromia former (forms chromium oxides when heated in an oxidizing environment) it can be brazed without any special treatments. While this is advantageous to the braze process, the alumina based washcoat does not adhere as well to a chromia former as it does to an alumina former. Haynes 214 on the other hand is an alumina former and as a result would have good washcoat adhesion performance but unfortunately requires Nickel plating in order to braze properly.

While the need for Nickel plating with Haynes 214 is generally accepted, we are working with various braze methods to see if Haynes 214 can be brazed without this treatment. **Table 4.3.2.2.1-1** shows braze trial #6 (following the relatively successful brazing of H1 serial numbers 1 thru 5) had a poor result. Sectioning of the sample showed that significant shim collapsing had resulted. Braze trial #7 tried thicker reforming plates will similar results. Several theories were put forth on why this was occurring. One suggested that the reformer inlet edge of the shims which had a long unsupported length was the initiation point for the surface tension of accumulated braze to ‘zipper’ the shim together.

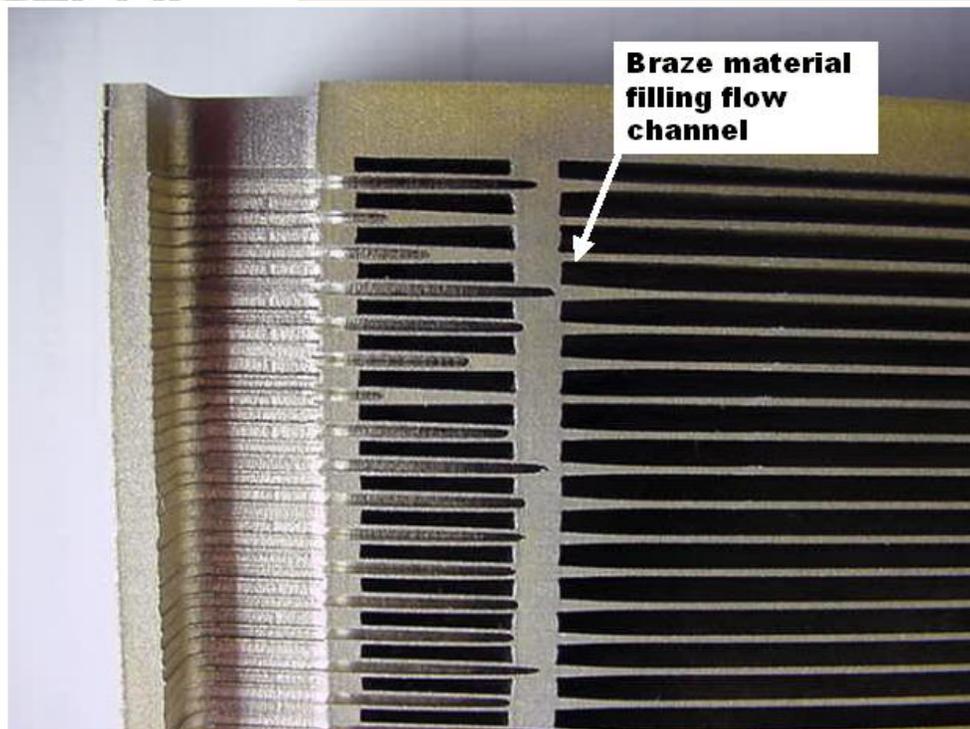


Figure 4.3.2.2.1-1: Collapsed Channels

Another theory suggested was that the braze alloy was alloying with the base metal to further weaken the shims when at temperature. In general the notion of insufficient strength at temperature was a concern. The fact that Haynes 214 has substantially more strength at braze temperatures than does Inconel 600 was thought to improve the situation but the same phenomena was experienced with Haynes trials as well. Trials with both Bni3 and Bni9 brazes also experienced this problem.

The next trial used ‘fingers’ on the combustor plates that served to separate shims at the combustor level and hopefully provide a surface for braze to wick and attract the shim to prevent the reforming layer from collapsing. This proved marginally successful

as Braze trial #8 yielded virtually no visible collapsed shims through the first braze. The subsequent braze cycle for attachment of top plate fittings resulted in some collapsing of shims but managed to yield the first viable part (serial number B2).

Table 4.3.2.2.1-2 covers braze trials using Haynes 214. This material change was accelerated by the fact that the washcoat adhesion with the untreated Inconel 600 was not at all good. Serial Number B2 saw only ~5 hrs of time at temperature testing before evidence of significant washcoat spallation occurred,

SEE SECTION 6.0, PAGE 110 FOR TABLE 4.3.2.2.1-2: H2 HAYNES 214 BRAZE CONFIGS: INDEX 9-16

During this period, problems with the adhesion of the Nickel plating to the Haynes 214 is believed to be responsible for several assemblies failing leak check. This triggered work with several plating suppliers in order to produce parts capable of undergoing the braze environment without blistering. At one point, existing parts were screened based on the presence / absence of blisters after having been run through the braze cycle.

Table 4.3.2.2.1-3 covers braze trials using a combination of Haynes 214 and Inconel 600 parts. This was a direct result of our discovery that the plating process of Nickel onto Haynes 214 was not yet reliable. Because plates (either reformer or combustor) could be bulk plated and more easily processed, they were more readily available. Shims however required masking (so as not to plate over the alumina forming base metal where washcoat was expected to adhere). As a result, we attempted brazing assemblies with Haynes 214 Nickel plated reformer and combustor plates combined with Inconel 600 shims. In an attempt to bolster adhesion of the washcoat, the Inconel shims were etched. During this period an internally guided braze fixture was being tried as a way to achieve acceptable part squareness (low skew) but as the results indicate, there were many instances where parts became hung-up (did not settle) which results in gross leak failures.

SEE SECTION 6.0, PAGE 111 FOR TABLE 4.3.2.2.1-3: H2 HYBRID (HAYNES 214/INCONEL 600) BRAZE CONFIGS: INDEX 18-23

By this time we had adopted a shim design that had strategically located dimples that when assembled rested on the adjacent shim below it. The stagger in the dimples allowed them to effectively create a column within the part that prevented shim collapsing in these areas. While helping the shim collapsing problem, it did not eliminate it. Additionally a problem of shim lifting became more evident.

Table 4.3.2.2.1-4 covers the braze trials using Haynes 214 parts after successful development of the Haynes / Nickel- plating process.

SEE SECTION 6.0, PAGE 112 FOR TABLE 4.3.2.2.1-4: H2 INCONEL 600 BRAZE CONFIGS: INDEX 24-28, H2 HAYNES BRAZE CONFIGS: INDEX 29

Despite the grouping by material, there were a number of other variables included in the many braze trials. Skew and Hang-up were two problems that were primarily felt to be the result of fixturing.

In order to provide low skew assemblies an internally guided braze fixture was employed (**Figure 4.3.2.2.1-2**). This involved 4 posts that were fixed to the fixture base plate. Over these posts were 4 loose fitting sleeves. Location of the posts and sleeves were on the centers of the 4 existing bolt holes found in each plate and shim. Parts were then placed over these sleeves allowing parts to slide on the OD of the sleeve during the braze process. The sleeves were sized such that the brazed assembly could be lifted off the fixture after braze and the sleeve could be machined away to return to the intended bolt hole diameter.

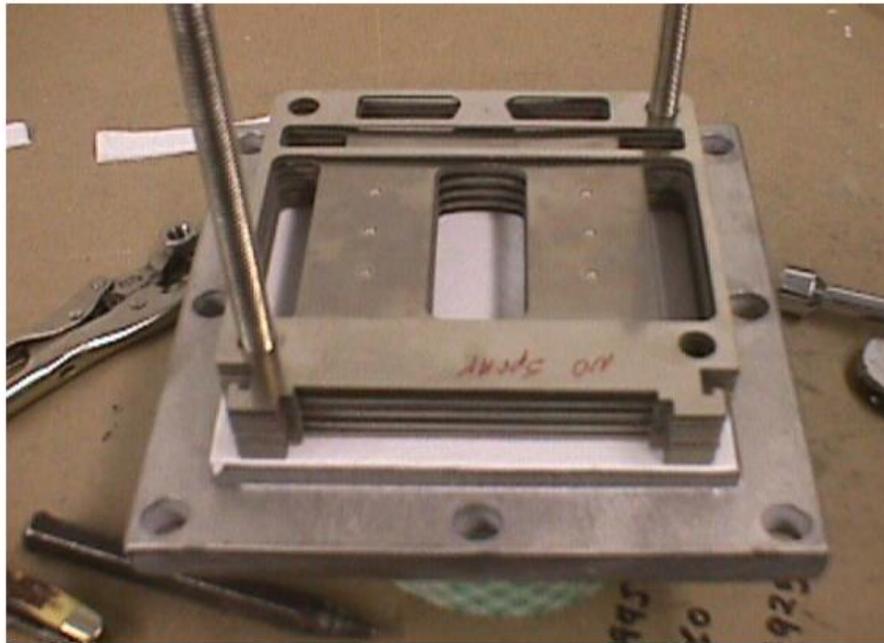


Figure 4.3.2.2.1-2: Initial Braze Fixture (no sleeves shown)

During the many trials of this fixture, it was determined that this approach was simply too constrained to allow completely free and unbinding movement of the parts downward as the braze liquefied. We had a number of trials that resulted in “hang ups”

of portions of the braze stack. A number of increases in clearance and material changes were never completely successful and so a new fixture approach was adopted.

The 2nd fixture (see **Figure 4.3.2.2.1-3**) was flexible in that several approaches could be tried. One approach involved guiding on a single part bolt hole diameter and using external guide rods on each of the 2 adjacent sides. This 3-point guiding was presumed to allow the part to grow thermally without significant binding. Another approach used only external guiding in that 2 guide pins along each of 2 adjacent sides would be used. This idea would, if brazed perfectly horizontally potentially allow the part to skew in a direction away from either of the guided sides. To prevent this, canted graphite blocks were made to tilt the fixture ~5 degrees in each of the 2 guided directions. Additionally, canted blocks were used to support the braze weight as well. For this fixture, rods were polished ceramic to minimize friction (and potential hang up) with precision fits to the mating base fixture holes to minimize skew.

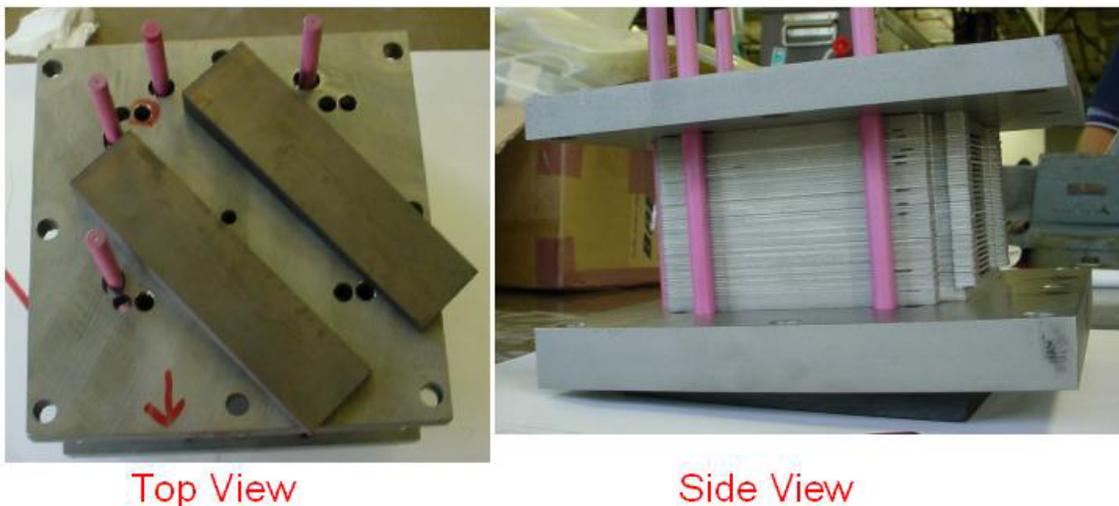


Figure 4.3.2.2.1-3: 2nd Braze w/ External Guides

While the tilted fixture approach did produce low skew assemblies, it had the unfortunate effect of directing excess braze alloy to collect at the rear of the reformer outlet passages as shown in **Figure 4.3.2.2.1-4**.

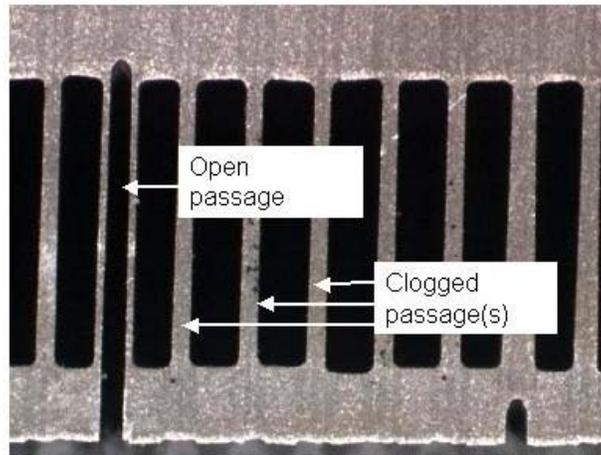


Figure 4.3.2.2.1-4: H2 Reformer A9 – Reformer Outlet

This was felt to ultimately be a result of excessive braze and is a result of the spray application process. An evaluation to determine the mass of braze applied and its variability based on differing numbers of spray passes was conducted. See **Figure 4.3.2.2.1-5**.

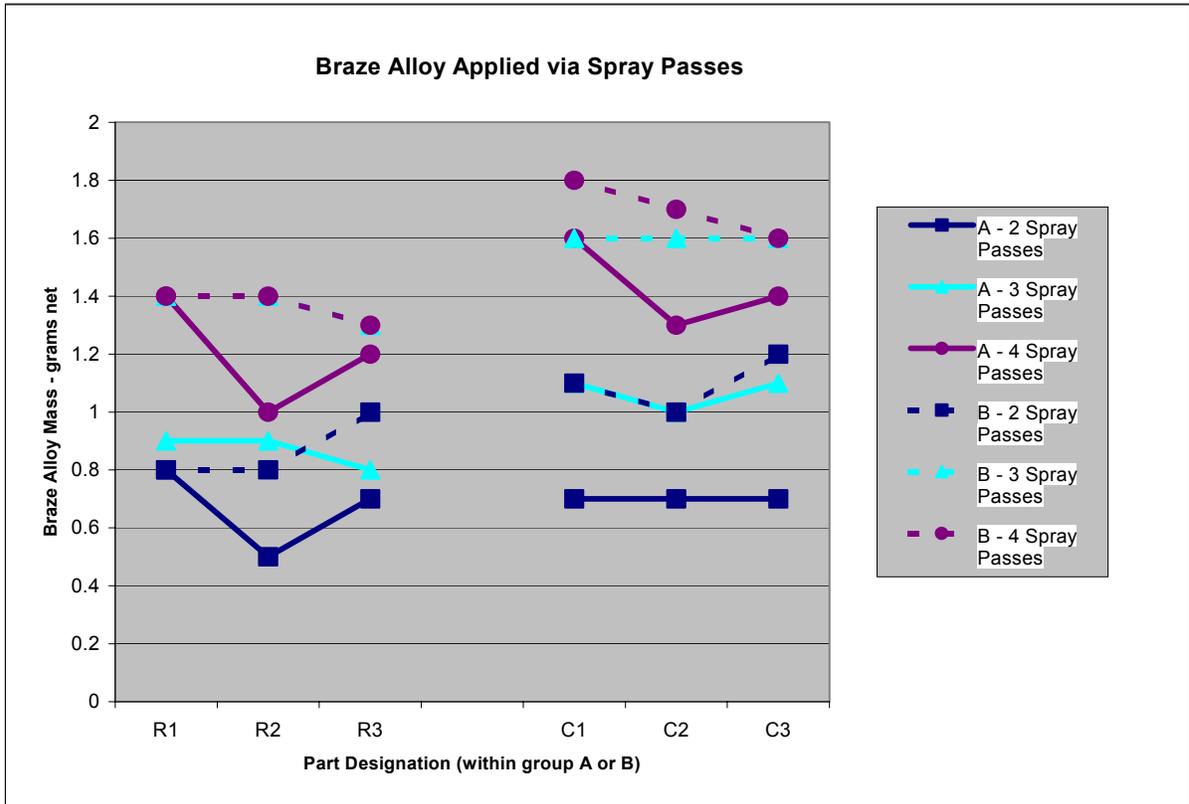


Figure 4.3.2.2.1-5: Spray Braze Evaluation

This graphic describes the variation pattern in grams of sprayed on braze alloy deposited on both reforming plates (“R” designation) or combustion plates (“C” designation). These plates, along with shims that separate them, represent the repeating unit for constructing an H₂ planar reformer. Two groups of parts were processed. The groups differ by the date they were sprayed. In each group six plates were positioned on the spray table in alternating fashion (i.e., C-R-C-R-C-R) from left to right to help block out this effect. Parts were successively sprayed and weighed through 2, 3 and 4 passes to evaluate the weight gain after each pass. Several points are evident:

- 1) Inconsistency in weight gain per pass is evident particularly on the 4th pass where 4 of 6 parts showed insignificant gains.
- 2) Day-to-Day variation (i.e., group-to-group) variation is significant as 3 of 6 parts showed similar or greater weight gain with 1 pass as compared with the other groups weight gain at 2 passes.
- 3) Combustion “C” plates generally show greater weight gains than Reformer “R” plates

In response to these findings and other brazing concerns, a new braze house was contracted that employs a dispense method rather than spraying. Braze alloy dispensing is done using a hypodermic needle and braze alloy is applied only in certain fillet areas based on part geometry. This relies on the wicking action to distribute braze alloy evenly and does not require any part settling during the braze cycle. This has the potential to eliminate hang-up and may impact other braze failure modes, in particular clogging due to uncontrolled excess braze. At this point in the program, it was decided to focus the planar reformer efforts on resolving the manufacturing issues while in parallel producing a relatively straight forward tubular design for use in advancing our systems development efforts.

4.3.2.2.2 Performance Evaluation of H2 Hardware

As mentioned above, hardware for H2 was scarce due to continued fall-out at the braze process. The first H2 assembly arrived for testing in late July.

4.3.2.2.2.1 Initial Testing

The initial test objective was to start the reformer and verify basic functions. This involves exercising and evaluating control loops and assessing thermal management capabilities. **Figure 4.3.2.2.2.1-1** shows the test setup employed.

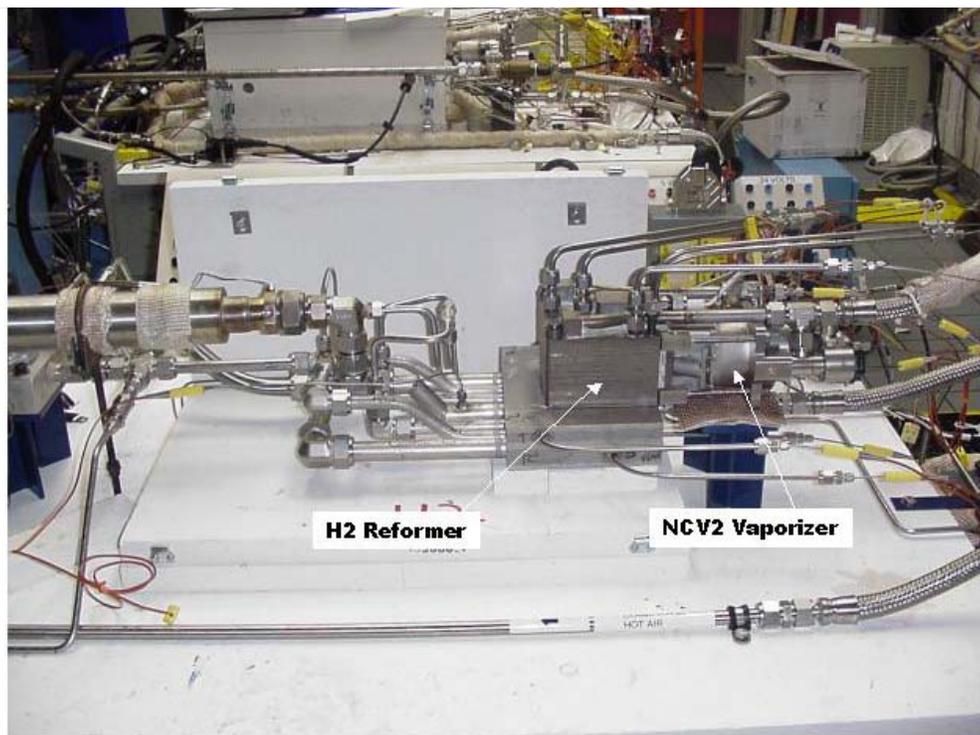


Figure 4.3.2.2.2.1-1: H2 Reformer Test Setup

Testing proceeded as follows:

- The Gas Phase Combustor was started first, rather than the reformer, in order to avoid any catalyst damage or sooting during a cold start of the reformer. This was done via a bottled reformat (21% H₂, 24% CO, balance N₂) feed to the combustor.
- When reformer plate temperatures were approximately 550 °C, rich fueling was commenced and reforming began.
- The combustor showed stable temperature control throughout the test. Run phi was ~ 0.13, with 0.12% CO emissions, which is comparable with H1 data.
- Reformer response showed fast light-off on front edge. Reformer outstream temperatures are comparable to those of H1 for the short duration of this test, indicating that temperature distribution in the reforming layer is at least as good as the H1 part.
- Reformer was ramped to a 0.3 scale factor (0.19 g/s) and N₂ was needed in comparable amounts to that of H1 to control lead edge temperature.
- Testing was terminated because the Air Control Valve (ACV) for reformer inlet air temperature control was not controlling T18 (air inlet temp to vaporizer) within range (target of 180 °C), and temperatures were getting too high and threatening gas phase combustion in the vaporizer. This problem was addressed, in addition to an intermediate leak check of reformer system, the following day.
- On 7/25/02 during the leak check, flakes of washcoat were found in the outlet of the reformer indicating that adhesion to the substrate was compromised. This was presumed to be the cause for performance degradation. Subsequent attempted starts of the reformer confirmed that catalyst performance due to washcoat loss was continuing to degrade performance.
- On 7/31/02 an investigation into Air Control Valve control showed that more restriction through the reformer heat exchanger leg was necessary in order allow the Air Control Valve to force more cool air directly into the Vaporizer. By adding restrictive foams to the heat exchanger leg the Air Control Valve then had enough authority to regulate temperature through the flow range.

4.3.2.2.2 Start-Up Controls Testing

Several Vaporizer/Combustor starts were conducted with the H2 Serial Number B2 hardware to evaluate start time, emissions, temperatures, and formulate a start and run routine that was repeatable on each cold start. Data for the starts are listed in **Table 4.3.2.2.2-1**. Of particular importance is the 'time to reform' average value that for this data set was 103 seconds. A portion of these starts was specifically aimed at determining the effects of igniter placement and is summarized in **Table 4.3.2.2.2-2**. The revised igniter placement did have the desired effect of reducing 'time to ignite' from 12 to 8.5 seconds. Due to limitations in igniter length, only a small change in location was possible and it was recognized that more work and more flexible hardware would be needed to properly optimize ignition.

Date	hardware	Start Emission Peaks (emission bench) during k_NCV_startflow fueling					Run Emissions (emission bench) during k_NCV_fuelflow fueling					time = 0 when injector turns on (DC >0%)					
		HC (ppm)	Nox (ppm)	CO2 (%)	O2 (%)	CO (%)	HC (ppm)	Nox (ppm)	CO2 (%)	O2 (%)	CO (%)	Peak TC temp @ T2 loc (C)	Peak RTD temp @ T2 loc (C)	time to light (sec) (fuel on till T2 shows rise)	time to reform (sec) (fuel on till enable _ ref _ temp)	fuel flow change (sec)	ref out temp (when T11 cat face = enable_reforming_temp)
7/31/2002 am	NCV2 H2 B2	10000	12	10.1	6.34	0.12	6737	6	5.54	10.33	0.10	884	216	8	81		
7/31/2002 pm	NCV2 H2 B2	17000	15	10.4	6.05	0.14	8130	6	5.65	10.33	0.11	901	230	11	77		
8/1/2002 pm	NCV2 H2 B2	17407	15	10.4	5.84	0.15	7677	6	6	10.33	0.13	925	273	12	75	13	36
8/2/2002 am	NCV2 H2 B2	15201	18	10.52	5.8	0.18	7755	8	6	10.41	0.15	920	265	10	78	13	36
8/2/2002 am	NCV2 H2 B2	14470	20	10.98	5.17	0.18						978	na	19	na		
8/19/2002 am	NCV2 H2 B2	11151	15	10.68	5.87	0.23	10420	6	4.17	10.33	0.11	847	138	6	129	9	41
8/20/2002 pm	NCV2 H2 B2	11325	21	11.57	4.44	0.21	9600	6	4.48	10.31	0.13	na	na	na	na		
8/21/2002 am	NCV2 H2 B2	15175	18	11.81	4.4	0.19	10177	1	4.42	10.25	0.11	883	138	11	119	14	37
8/21/2002 pm	NCV2 H2 B2											1017	166	4	51		
8/21/2002 pm	NCV2 H2 B2	6625	17	11.94	3.61	0.19	4364	6	9.46	8.83	0.18	1029	669	4	51		
8/22/2002 am	NCV2 H2 B2	20469	55	13.29	2.24	0.36	na	na	na	na	na	1107	222	38	na		
8/22/2002 am	NCV2 H2 B2	11094	17	11.35	4.55	0.22	3713	13	8.84	8.75	0.20	1014	183	7	58		
10/23/2002 pm	NCV2 H2 A8	na	na	na	na	na	na	na	na	na	na	857	475	4	313		
	NCV2 H2 AVG	13628.8	20	11.2	4.9	0.20	7619	6	6.1	10.0	0.14	947	270	11	103	12	38

Table 4.3.2.2.2-1: H2 Start Evaluation

Date	hardware	inj S/N	notes	time = 0 when injector turns on (DC >0%)					
				Peak TC temp @ T2 loc (C)	Peak RTD temp @ T2 loc (C)	time to light (sec) (fuel on till T2 shows rise)	time to reform (sec) (fuel on till enable _ ref _ temp)	fuel flow change (sec)	ref out temp (when T11 cat face = enable_reforming_temp)
7/31/2002 am	NCV2 H2 B2		ignitor is located on edge near NCV2 wall	884	216	8	81		
7/31/2002 pm	NCV2 H2 B2		ignitor is located on edge near NCV2 wall	901	230	11	77		
8/1/2002 pm	NCV2 H2 B2		ignitor is located on edge near NCV2 wall	925	273	12	75	13	36
8/2/2002 am	NCV2 H2 B2		ignitor is located on edge near NCV2 wall	920	265	10	78	13	36
8/2/2002 am	NCV2 H2 B2		ignitor is located on edge near NCV2 wall	978	na	19	na		
				922	246	12.0	78	13	36
8/19/2002 am	NCV2 H2 B2		ignitor angle is increased by about 5 degrees (correct design)	847	138	6	129	9	41
8/20/2002 pm	NCV2 H2 B2		ignitor angle is increased by about 5 degrees (correct design)	na	na	na	na		
8/21/2002 am	NCV2 H2 B2		ignitor angle is increased by about 5 degrees (correct design)	883	138	11	119	14	37
				865	138	8.5	124	12	39

Table 4.3.2.2.2-2: H2 Starts – Effect of Igniter Location

4.3.2.2.3 Gas Phase Combustor Highflow Evaluation

Given that reformer function was lost on this sample, testing turned to evaluation of the Gas Phase Combustor behavior.

The primary objective was to run with bottled reformat (nominally 21% H₂, 24% CO, balance N₂) at high flow rates to simulate actual system start-up conditions and evaluate Gas Phase Combustor temperature management. See **Figure 4.3.2.2.3-1**.

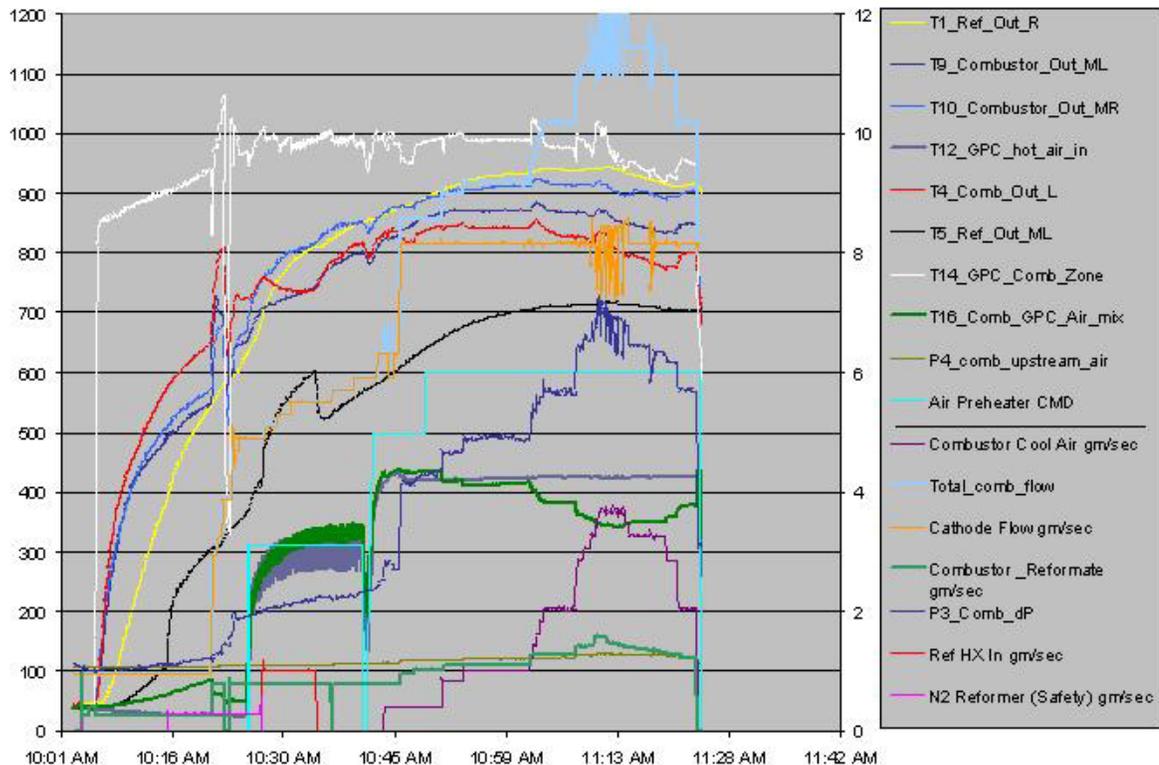


Figure 4.3.2.2.3-1: H2 B2 Gas Phase Combustor Temps/Flows 8/21/02 Testing

Conclusions from this test are as follows:

- During the test, air was commanded to 11.4 gm/sec (Total_comb_flow) and bottled reformat at 1.4 gm/sec (Combustor_Reformat gm/sec) yielding phi between 0.086 and 0.096. Temperature (T14_Gas Phase Combustor_Comb_Zone) remained in control at ~950 °C to this point.
- Airflow rate for the Auxiliary Power Unit system is about 15 gm/sec for start-up but during this test was limited to 11.4 gm/sec due to supply pressure limitations to the air mass flow controller.
- Pressure drop across the combustion chamber, represented by P3_Comb_dP ran very high at 6.7 kPa.

- Emissions were low considering exhaust catalyst condition was probably poor at this point (loss of washcoat adhesion similar to reformer side). **See Figure 4.3.2.2.3-2.**

CO	0.15% (on the Mass Spectrometer)
CO	0.0 % (on emissions bench)
NO _x	0-1 ppm
HC's	None expected due to bottled reformat.

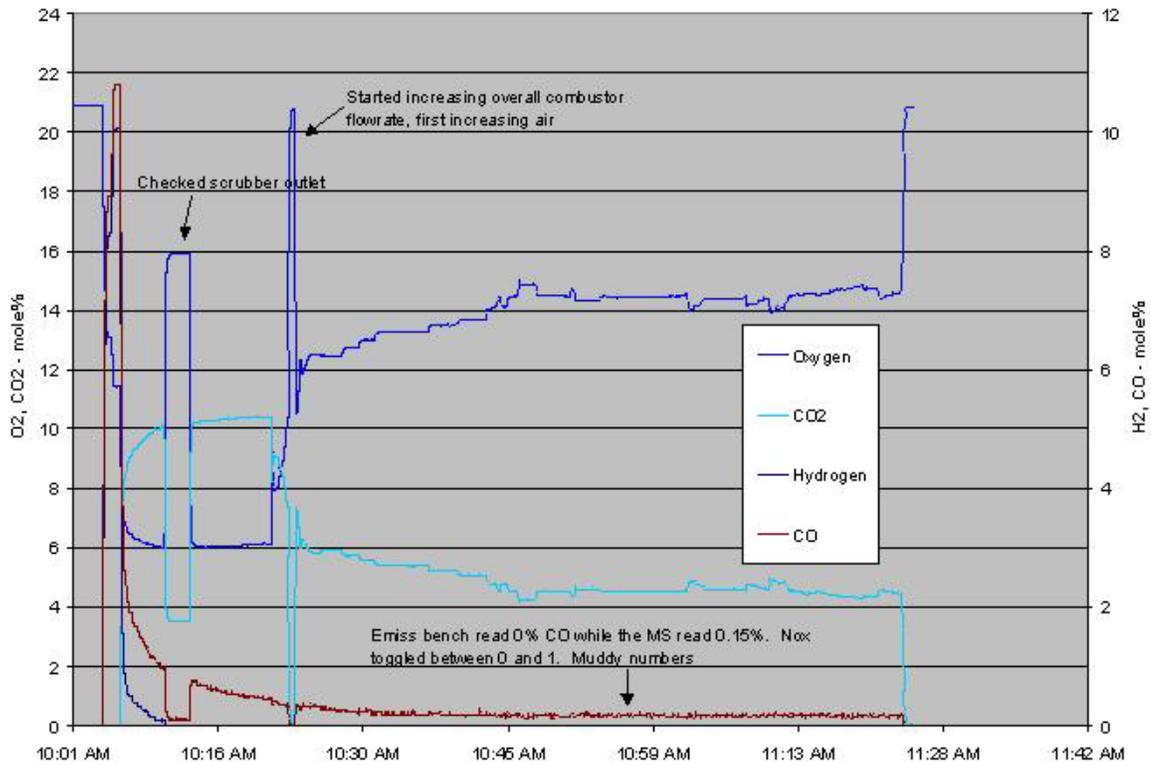


Figure 4.3.2.2.3-2: H₂ Serial Number B2 Gas Phase Combustor Emissions 8/21/02 Testing

4.3.2.2.2.4 Systems Testing of H₂ (Gas Phase Combustor function only)

The several samples of H₂ produced were, after their reforming catalysts had degraded, used in systems tests to provide the Gas Phase Combustor function. This allowed system startup testing to proceed. This testing, as well as that done by the reformer group, led to observations of severe distortion inside the Gas Phase Combustor cavity, see **Figure 4.3.2.2.4-1**. Specifically the entrance to the combustor plate appears misshapen, apparently the result of over temping, and globules of either molten metal or molten braze are evident.

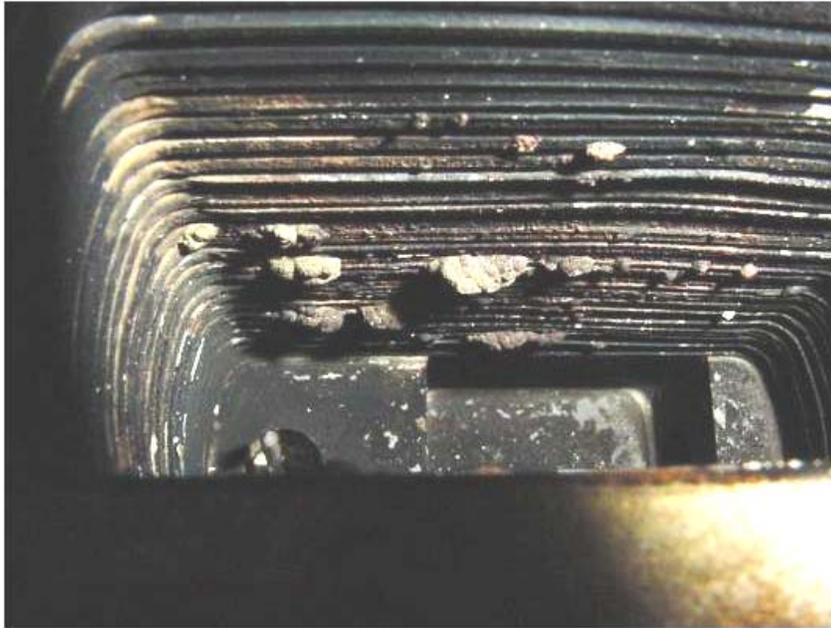


Figure 4.3.2.4-1: H2 Serial Number B2 Gas Phase Combustor

Figure 4.3.2.4-2 shows adiabatic flame temperature that could have been experienced during test relative to braze melt temperature. Due to limitations on number and placement of thermocouples, it is highly likely that areas within the Gas Phase Combustor exceeded recorded values. Concerns about the material appropriateness were again raised, and this stressed the importance to produce a viable H2 reformer using Haynes 214. In the interim, a burner insert was developed to prevent direct impingement of the flame front onto the lower level combustor plate inlets where distortion was greatest.

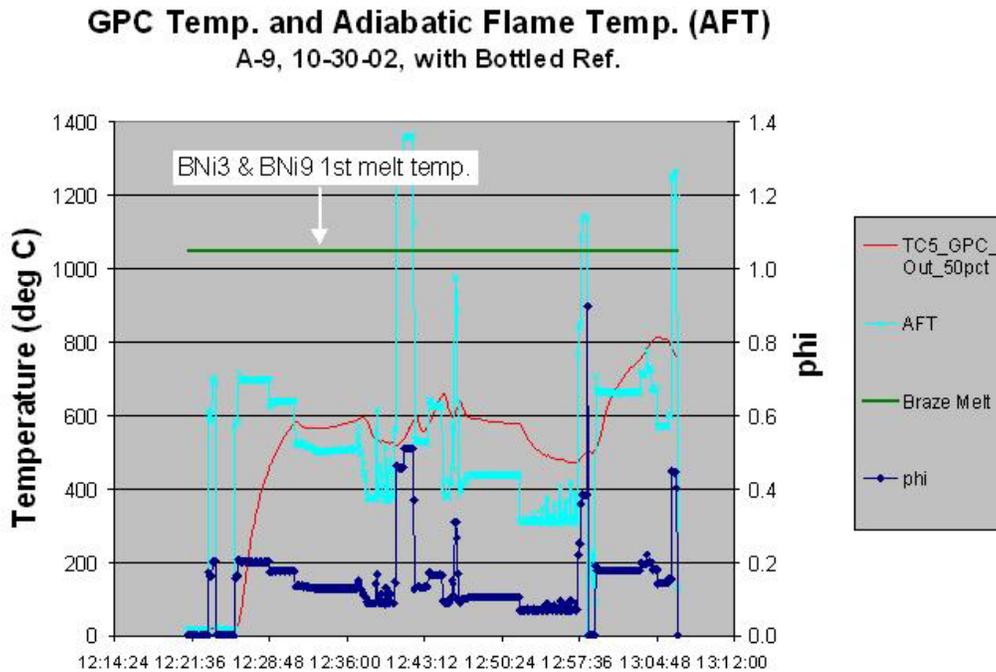


Figure 4.3.2.2.4-2: Gas Phase Combustor and Adiabatic Flame Temperatures

4.3.2.3 Develop Catalytic Partial Oxidation Reformer – Gen1 Tubular

Due to the difficulties in producing the H₂ planar hardware and the success of previous (as well as parallel) programs using tubular reformers, we decided to adapt a tubular design that could be fit within the current Auxiliary Power Unit packaging and allow the continuation of systems level development, see **Figure 4.3.2.3-1**. Development, with respect to fabrication and performance, was rather rapid but resulted in very favorable performance. The first test effort, once initial hardware was available, was to develop start calibrations specific to this new geometry.

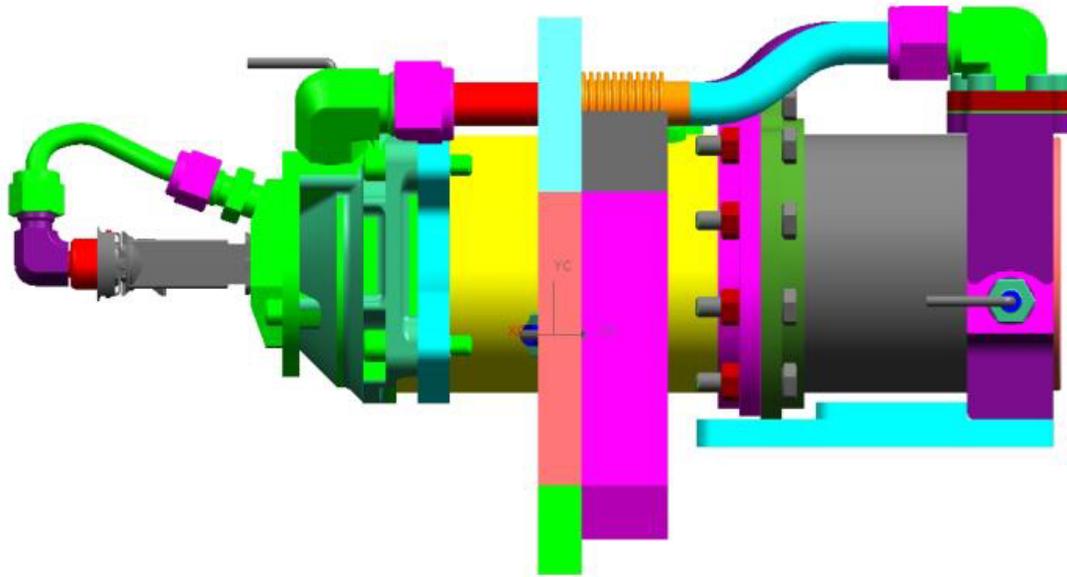


Figure 4.3.2.3-1: Tubular Reformer Assembly (side view)

A consequence of this simple construction was the deletion of the gas phase combustor function. The initial configuration utilized a ceramic mixing foam to separate combustion and mixing zones. Using a small quartz tube inserted in this area allowed for rough determination of start calibrations and visualization of the start combustor process. Subsequent to this, the quartz tube was removed and final start calibrations were evaluated. Several configuration variants involving the use of different elements to separate mix and combustion zones were evaluated.

During this effort an oscillation in the control of inlet air temperature (T12) was observed. A modification to the vaporizer air manifold air routing was made that involved bringing pre-heated air from the reformer pre-heat loop together with un-heated air prior to their entering into the donut shaped manifold supplying air to the director. T12 senses air from this donut manifold and were too closely coupled (via proximity) to the pre-heat air feed.

Table 4.3.2.3-1 shows the results of preliminary evaluation of start-up. Notice that “time to reform” is 9 seconds as compared to 103 seconds for the H2 Planar reformer. Given relatively stable start up behavior, reformers were released to the Systems group for inclusion into the Auxiliary Power Unit system test plans. While the degree of integration varied relative to which sub-systems were present and functional, in all cases the reformer was mounted to an Integrated Component Manifold that had been modified to provide the Gas Phase Combustor function now absent from the reformer.

Date	hardware			time = 0 when injector turns on (DC >0%)				
				Peak TC temp @ T2 loc (C)	Peak RTD temp @ T2 loc (C)	time to ignite (sec) (fuel on till T2 shows rise)	time to reform (sec) (fr fuel on till T2 shows fuel flow change (sec) ref temp)	ref out temp (when T11 cat face = enable_reforming_temp)
11/16/2002	Tubular Reformer sn1		613	n/a	19	10	3	
11/16/2002	Tubular Reformer sn1		391	n/a	3	12	7	
11/18/2002	Tubular Reformer sn1: Start and Run on video		333	n/a	2	9	6	
11/19/2002am	Tubular Reformer sn1		410	n/a	6	9	none	
11/19/2002am	Tubular Reformer sn1		484	n/a	3	6	5	
11/19/2002pm	Tubular Reformer sn1		501	n/a	2	6	5	
11/21/2002	Tubular Reformer sn1		420	n/a	2	9	5	
	TUBULAR GEN1 AVG		450		5	9	5	

Table 4.3.2.3-1: Gen 1 Tubular Start Evaluation

During several of the system level runs in which both reformer and Gas Phase Combustor were functioning, increases in system pressure readings indicated an increased reformer pressure drop and subsequent teardowns revealed varying degrees of inlet and/or catalyst coking. After ruling out any lab / control based differences, tests were conducted that isolated the use of the Gas Phase Combustor (as integrated into the Integrated Component Manifold passages) as the primary cause for the inlet / catalyst coking. The use of this combustor is thought to both radiate and conduct heat to the reformer (the combustor is located within the area of the Integrated Component Manifold directly beneath the reformer rear tube section).

The current reformer lab test fixture was then replumbed so that a Gas Phase Combustor function would be possible. While not identical to the physical modifications made to the Integrated Component Manifold, it did prove adequate in helping to recreate the carbon forming conditions.

Once the thermal conditions experienced in the systems lab were recreated and verified through the witnessing of catalyst and inlet coking we proceeded to alter inlet and catalyst configurations to control key temperatures.

Table 4.3.2.3-2 provides a listing of inlet / catalyst configurations tested. Data from 12/13/02 represents a condition where the reformer coked. Analysis of the gas temperature grade line through the inlet and into the catalyst suggests that if temperatures are kept below critical values (less than 600 °C near the center of the combustor and less than 450 °C at the exit of the mixing element separating the mixing and combustion zones), pre-combustion can be avoided. Each configuration that was tested did a good job of limiting these 2 temperatures. Past experience with 1” tubular reactors suggests that a steep rise in temperature as reactants enter the catalyst is more desirable. This goal competes with the need to have rapid vaporization in the mix zone, which is greatly assisted by radiation from the catalyst face. This trade-off will be investigated more fully in future reporting periods.

Col#	1	3	4	5	6	7	8	9
Temps are from:	SS before pre-comb event	SS	SS	SS	SS	not as SS as other runs	SS	SS
Internal Inserts	None	rad shield	mix foam	monolith	rad shield	rad shield w/ spikes	rad shield w/ spikes	rad shield w/ spikes
Catalyst Position (Flush, recess, beyond)	flush	flush	beyond	beyond	recessed	recessed	recessed	recessed
Catalyst Size	1.75"	1.75 "	1"	1"	1"	1"	1"	1"
GPC or No GPC	GPC	GPC	GPC	GPC	GPC	GPC	GPC	No GPC
O/C	1.04	1.10 / 1.04	1.04	1.04	1.04	1.04	1.04	1.04
Day of Week	Fri	Tues	Wed	Thur	Thur	Fri	Tues	Wed
Date & Time of Run	12/13/02	12/17/02	12/18/02	12/19/02	1/2/03	1/3/03	1/7/03	1/8/03
Catalyst delp change during test?	Yes	No	No	No	No	No	No	No
Reformer Out Filter Status	very black	clean	very black	some carbon	some carbon	Black	very black	some carbon

Table 4.3.2.3-2: Catalyst/Inlet Configurations vs. Carbon/Filter Results

Additional developments were made to the air pre-heat heat exchanger. The initial design used a single loop of tubing. This was awkward to fabricate and did not provide sufficient heat exchange. The subsequent design utilized stainless steel bellows to form a U-shaped loop. This design, while superior to the full loop tube, still could not provide rapid heat for vaporization during start-up. To provide this a 42V coiled rod heater was added to the reformer pre-heat return tube. This provided rapid and clean start up heat. Full evaluation of this approach is underway to understand the power consumed vs. benefits to start quality at various heated air temperatures.

In general the performance of the tubular reformer (in partial oxidation mode) has been exceptional. Data in **Figure 4.3.2.3-2 and 4.3.2.3-3** shows mass spectrometer and temperature data respectively for a typical tubular reformer. Six reactors were built and all underwent performance validation testing before being offered for Auxiliary Power Unit testing. Reformate quality was very good and remarkably consistent.

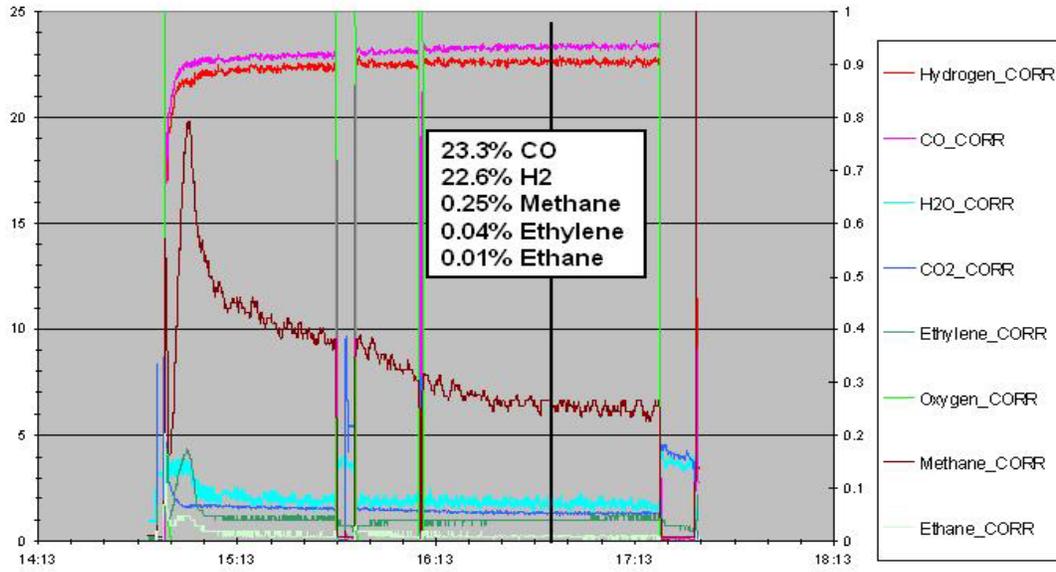


Figure 4.3.2.3-2: Tubular Data: Mass Spec

Note: The "CORR" suffix refers to a water knockout correction only

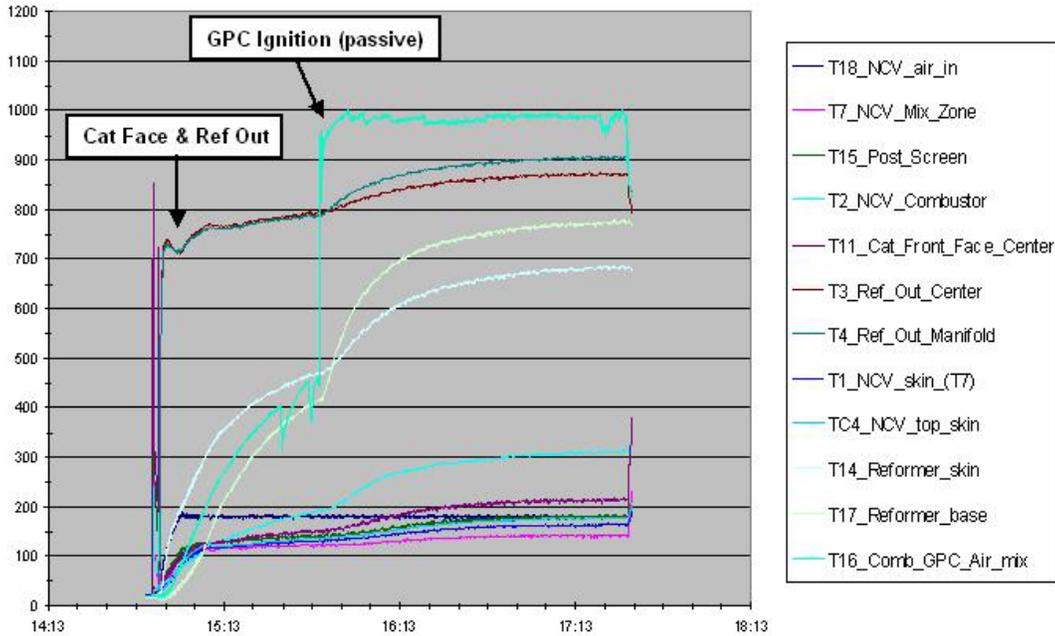


Figure 4.3.2.3-3: Tubular Data: Temperature Data

Gas Chromatograph data (**Table 4.3.2.3-3**) confirmed what had been observed via Mass Spectrometer data, that reformat quality was very good, and in fact, met our current preliminary requirements ($\Sigma\text{HC's} \geq \text{C}_2 < 0.1$ mole%, $\text{CH}_4 < 1$ mole % and $\text{H}_2\text{O}/\text{CH}_4$ ratio ≥ 3) with the exception of brief periods during start up.

GC Data	Average
% H2	0.0000
% CO	21.5589
% Methane CH4	0.0000
% Methane CH4 (Mass Spec)	0.6665
% Ethane C2H6	0.0158
% Ethylene C2H4	0.0405
% Propane C3H8	0.0008
% Propylene C3H6	0.0212
% Butane C4H10	0.0002
% Iso-Butane C4H10	0.0006
% Butene C4H8	0.0033
% N2	48.8873
% CO2	1.4267
Sum of All C2 (%)	0.0563
Sum of All C3 (%)	0.0220
Sum of All C4 (%)	0.0040
Sum of C2 and Greater (%)	0.0822
Sum of C3 and Greater (%)	0.0260

Table 4.3.2.3-3: GC Data

NOTE: % H2 is shown as 0 due to initial setup problem with this GC

4.3.3 Develop Catalysts

4.3.3.1 Improvements to Catalyst Durability

Catalyst formulations are developed using highly consistent, controllable, and well instrumented test stands. These test stands hold a 1” diameter tubular reactor, operated in a downflow mode, and configured with a fuel vaporizer, a mixing and heat retaining reticulated foam in front of the catalyst, separated from the catalyst by a flame arrester, 1” length of catalyst, and then a post-catalyst heat retainer. The goal of the testing is to eliminate or minimize all variables except for catalyst composition. Catalysts consist of active metal bearing washcoats held on ceramic substrates. Typical compositions are rhodium on alumina over zirconia-toughened alumina (ZTA) reticulated foam substrates. The major assumption of the catalyst testing is that catalyst rankings and performances determined from these development test stands are directly transferable to differing hardware configurations. Evidence to date indicated that this assumption is true.

Determination of optimum catalyst compositions currently relies on testing the performance of these catalysts, for gasoline partial oxidation, using an aggressive testing protocol. Testing is conducted by establishing total space velocities and air-fuel ratios such that catalyst center temperatures exceed 1050 °C. Under these conditions, only the best catalysts maintain good performance during the relatively short duration of the tests. Good performance is the observation of at least 20 mole % hydrogen in the total product gas over the duration of the testing. Testing typically proceeds for 50 to 70 hours.

Even after this testing, we have found a number of catalyst compositions that have nearly identical performance at the end of the test. While testing to significantly longer time periods may ultimately discriminate between the compositions, durability testing consumes significant resources and limits the number of catalysts that can be evaluated. This shortcoming is currently being addressed by several activities, including installation of durability test stands, understanding of catalyst deactivation and aging mechanisms, and development of rapid aging tests. We have identified several improved catalyst formulation that meet the most rigorous durability tests to date.

4.3.3.2 Durability Test Stands

Greenlight Power Technologies, of British Columbia, Canada, has been contracted to provide modular durability test equipment. These units feature a control module, capable of independently operating up to six test modules, and designed for continuous unattended operation. The control module is equipped with data collection, continuous process monitoring, and process control features, and contains process gas analysis, waste-gas combustion, and primary gas and liquid feed sources.

The test modules are configured for up-flow tubular reactors, and contain all controllers and instrumentation for each reactor. Each test module can be independently configured with a variety of fuels, including gasoline, diesel fuel, or natural gas, as well as air and water. A control module and two test stands have been delivered and installed, and are currently undergoing performance certification. They will be used for continuous long-term testing of catalysts to prove durability performance in both steady or start/stop modes. Additional control and test modules will be installed in the upcoming reporting periods.

4.3.3.3 Understanding of Deactivation and Aging Mechanisms

Work in this area focused on the effects of fuel impurities on catalyst performance. Testing is performed in a reactor configured as described previously, except that the reactor diameter is 7/8". Exposing the catalyst to SO₂ during reforming resulted in a product containing significantly lowered concentrations of H₂, and elevated levels of H₂O and CH₄; CO and CO₂ followed similar trends but to a much lesser extent.

A different behavior was observed from different classes of organic components contained in fuel. Reforming with a single component, such as iso-octane, results in repeatable light-off behavior. However, exposing the catalyst to gasoline, such as CARB Phase II, produces a delay in H₂ light-off, which is not restored upon switching back to iso-octane.

4.3.3.4 Rapid Aging Test Development

An oxidative aging method was demonstrated, taking advantage of the observation that heating catalyst samples in hydrogen had little to no effect on performance, while heating in air had a significant impact. We speculate that under reducing conditions, a high degree of metal dispersion is obtained, overcoming any effects of washcoat morphology changes due to the temperatures of heat treating. In an oxidative environment, metal particles are assumed to exhibit significant sintering.

Various catalysts were exposed to air at 1200°C for six hours. These were then tested for gasoline partial oxidation, according to the usual procedures, and the performances compared to tests of similar catalysts not pre-aged in air. The washcoat formulation used, generation 1, referred to as alumina-NC, exhibits deactivation after about 2000-3000 minutes of testing. Use of the oxidative aging test reproduced this same behavior after only 300 minutes of testing, although the test was extended to 1000 minutes for behavior confirmation.

Selectivity to H₂ and CO was found to respond to aging differently. For example, frequently the amount of hydrogen a catalyst can produce deteriorates much more rapidly than the amount of carbon monoxide produced. This behavior was mirrored in the aged catalysts. Aging was able to reproduce the hydrogen (and water) performance that a fresh catalyst exhibits after 1000 minutes of testing, CH₄ and C₂'s performance after 2000 minutes, and minimal changes in CO and CO₂ performance. These results suggest that catalyst properties responsible for H₂ formation are most sensitive to thermal degradation mechanisms, while those responsible for CO formation are relatively stable, aligning with the results from the SO₂ deactivation studies.

Evaluation of this oxidative aging method was repeated on a more advanced washcoat, designated alumina-TG, and the results of testing aged and fresh catalysts indicated no difference could be observed between the aged and fresh catalysts. The aged catalysts, tested for 300 minutes, have the same performance as the fresh catalysts after a test of 3500 minutes. Compared to the findings with the NC washcoat, this suggests that alumina stability play a key role in determining catalyst performance during the first 60 hours of testing. We will be continuing to develop more sophisticated aging tests and further understandings of catalyst deactivation mechanisms in future work.

4.3.3.5 Improved Catalyst Formulations

The rapid aging test described above was used to evaluate a series of modified Rh/alumina-TG catalyst compositions. Simultaneously, a different Rh addition method was tested. Adding Rh by chemisorption instead of equilibrium adsorption results in a catalyst with lower initial activity and very poor stability. However, preparing a catalyst with modifier and by rhodium chemisorption results in very stable performance, even after aging, equivalent to or better than the standard equilibrium adsorption method. Future work will focus on optimizing and understanding these differences.

4.3.3.6 Washcoat Metallic Substrates

Of particular concern is the adhesion of washcoats to metallic substrates, as will be used in the intended final reformer design. A multi-factor design-of-experiments approach will be taken to identify possible issues; factors to be examined include metal composition, pretreatment, use of barrier and protective coatings on the metal, oxidative or etching pretreatment, and washcoat composition, pH, and aging will be evaluated. These materials will be exposed to air at from 850 to 1000 °C for up to 500 eight-hour hot/cold thermal cycles. Materials are currently being collected for this project, involving 18 different metal substrate materials and 54 unique samples. Samples will be periodically examined for washcoat retention

Some preliminary work indicates that best retention of washcoat, after only 5 thermal cycles, occurred for metallic substrates heated to 800 or 1095 °C.

4.3.3.7 Developing Metallic Part Reactor Test

While thermal cycling in air will determine the most likely candidates, testing metallic substrates under reaction conditions is paramount to selecting the best metal / treatment / washcoat composition. However, testing of planar configurations in a high throughput mode can be difficult and time-consuming, due to the need to fabricate rectangular cross-section reactors with narrow channels with a high leak-integrity. A novel tubular design has been fabricated and tested, wherein a rod or hollow tube, with the lead-end sealed, of the metal to be evaluated is placed into a quartz tube, so that the gap between quartz inner surface and metal outer surface is the same as the gap between plates in a planar assembly. Results are comparable to what can be obtained with conventional tubular reactors using a monolithic or reticulated foam substrate. Additional work will be required to solve some processing problems, the most notable of which was the tendency of the feed to pre-combust due to excessive furnace heating at the inlet. We anticipate that this configuration will be invaluable in studying the performance of metal substrates / washcoat systems.

4.3.3.8 Diesel Fuel Processing Demonstration

An expansion into reforming of diesel fuel will occur during the next reporting period.

4.3.4 Develop a Desulfurization System

No work completed under this subtask.

4.3.5 Develop Reformer and System - General

4.3.5.1 Labview

As mentioned previously, the labview system was enhanced to the point where all data was available on a single file. In addition preliminary real time calculations were enabled. Currently these are limited to Mass Spectrometer corrections for water knockout but plans are moving forward to have labview do most common data compilations (i.e., calculate reformer efficiency, space velocity, etc.).

In addition, variable passing was greatly simplified by allowing Labview to determine how variables are ultimately logged and labeled.

4.3.5.2 Lab Test System Development

Two Gas Chromatographs were added to our lab equipment. One is used for reformer development, and the other is dedicated to the Catalyst durability stands. Additionally, a 3rd Mass Spectrometer was received.

This equipment will ultimately reside in a new facility that recently opened. The facility has both Reformer Development Lab (equipped with 3 development stands) and Reformer/Catalyst Durability Lab (currently equipped with 3 stands with plans for 11 total).

4.3.6 Investigate Integration of Reformer and Energy Recovery Unit Functions

This subject covered under “Develop Catalytic Partial Oxidation Reformer” Section.

4.3.7 Fabricate Developmental Reformers.

No work completed under this subtask; see related discussion under “Develop Catalytic Partial Oxidation Reformer”.

4.4 *Development of Balance-of-Plant Components*

4.4.1 Develop Energy Recovery Unit

The Energy Recovery Unit is part of the Reformer development activity (traditionally referred to as the WER – Waste Energy Recovery) and will not be reported on under Balance of Plant at the present time.

4.4.2 Develop Hydrogen Sensors for High and Low Concentration Measurement

A Full Range O₂ sensor developed by Delphi (Flint) was tested as a High Concentration Hydrogen sensor used to monitor the health and performance of the reformer. Preliminary results (shown in **Figure 4.4.2-1**) indicated that the response of the sensor follows the combined levels of H₂, CO and CH₄ as measured by a Mass Spectrometer. However, CH₄ is considered to be a dysfunctional output of the reformer and its exact influence on the sensors output is unknown at this time. A technique for independently measuring the levels of CH₄ has been devised and testing is planned.

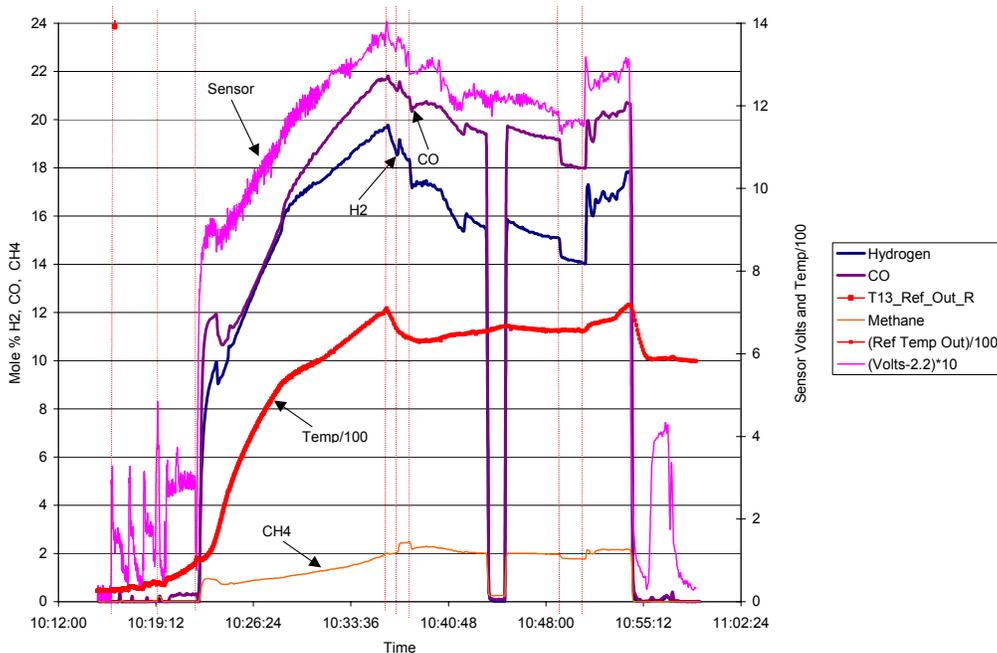


Figure 4.4.2-1: Preliminary Reformer Sensor Results

A similar sensor technology was used in the development of a combustible gas sensor. The results of testing are included in **Figure 4.4.2-2**.

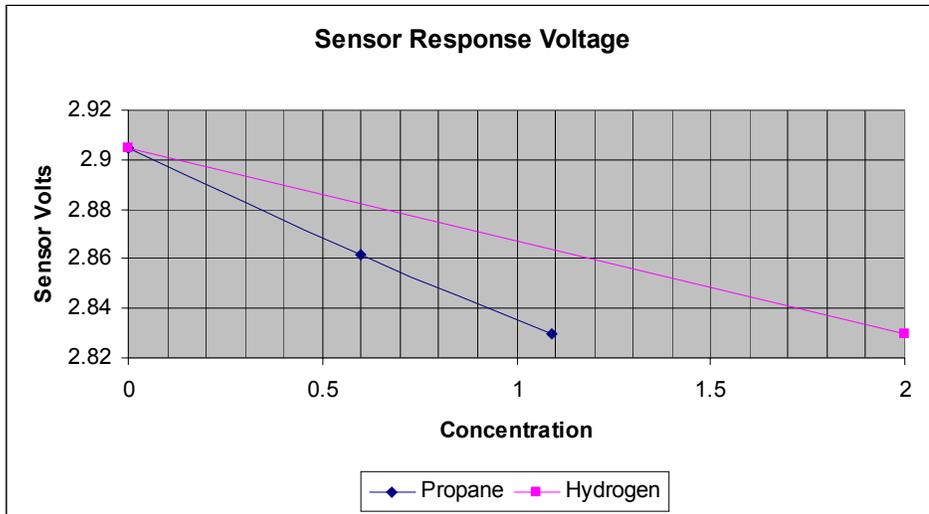


Figure 4.4.2-2: Combustible Gas Sensor Output

4.4.3 Develop Water Recovery Unit

The Water Recovery Unit is an activity that will be addressed in Phase two of the program and has no activity at this time.

4.4.4 Develop Air Delivery and Process Air Sub-System

Blower selection was limited to what was commercially available within the system development time frame. Two types of air moving devices were purchased and tested. Type-1 was a positive-displacement compressor and Type-2 was a high-speed dynamic machine using radial compressor technology. Limited testing was done on the Type-1 compressor because of noise, size, power consumption, cleanliness and durability issues.

The Type-2 compressor was deemed more appropriate for the Auxiliary Power Unit requirements. As a result of size limitations, extensive development of inlet housing design and air turning vanes resulted in a compact and efficient blower assembly (see **Figure 4.4.4-1**).



Figure 4.4.4-1(a): Type 2 Blower



Figure 4.4.4-1 (b): Blower Inlet Housing And Curved Inlet Guide Vanes

Curved Inlet Guide Vanes as well as pre-swirling flow in the direction of the wheels rotation, as shown in **Figure 4.4.4-1 (b)**, improved ingestion of air into the inlet of the compressor and greatly improved the performance of the blower.

A study was initiated that would compare the size, weight, cost, reliability and efficiency of several electric motor types.

4.4.5 Develop Hot Zone Components

The Hot Zone Components are contained within the Hot Zone Module. With the exception of the Stack, they are developed within the Balance of Plant team. Included are the Integrated Component Manifold, the Cathode Heat Exchangers and High Temperature Gaskets. They are detailed in the sections below.

4.4.5.1 Gasket Development

Due to the restriction on bolt loading, creep conditions effecting bolt stresses over time, a limit is placed on bolt torques of 5 ft-lbsf. This guarantees the bolt stresses will remain below the 100-hour creep life. This applies to Reformer and the Heat Exchangers.

A separate problem exists with the Stack. Sensitivity to compressive loading of the glass seal at the base of the Stack limits the maximum amount of compressive load. This value is a nominal 100 lbsf per Stack or 2 lbsf per linear inch for sealing contact length.

This restriction has lead to the development of unique beaded gaskets. These gaskets use minimum surface areas for sealing which maximizes the available seating pressures. The uniqueness comes from the shape and location of the bead, aligning the narrow beads such that compressive loads are equal against two parallel surfaces. These beads are formed such that they are in alignment while circumventing a given flow field.

Ongoing development has lead also to the design of gasket with a gas-actuated spring that follows Boyle's Law for a gas filled volume under temperature and pressure.

Test fixtures have been designed, manufactured and are presently in use for gasket seal evaluation. The fixtures match surface quality, pressure differentials, temperature ranges and compressive loading to system conditions. In addition numerous tests with gaskets have been performed using system components, sub-systems and actual Auxiliary Power Unit system assemblies.

4.4.5.2 Integrated Component Manifold

The manufacturing approach used allows 5 plates to be processed to unique geometries by water-jet cutting then brazing together, forming a solid manifold. In addition several minor components are attached to complete the brazement.

Six units of the current 5 piece design have been incorporated into successful Auxiliary Power Unit builds.

Studies are presently underway to investigate alternate methods with the goal of reducing manufacturing costs and increasing manifold reliability.

As a separate study, one model of an Integrated Component Manifold was produced using epoxy resin by the Stereo Lithography process. This model incorporates the first design attempt at simplifying the present manufacturing method by reducing the number of plates from five to three. To use three plates, the two flow plates and center partition plate are combined into one unit.

Using this approach, many new options for manufacture are available. These include, but are not limited to:

- Inconel 625 Casting
- Ceramic flow plate
- Inter-metallic materials such as Nickel-Aluminide
- Machined from solid plates

Flow tests are being performed to evaluate pressure drops throughout the internal ducting of the Integrated Component Manifold. These experiments will lead to a better understanding of overall system pressure drop and ways to improve these losses through more efficient fluid flow design practices.

4.4.5.3 Cathode Heat Exchangers

A stacked flat-plate heat exchanger design was built with Inconel 600 sheet stock and tested. Testing of the assembly showed acceptable internal pressure drop, high heat exchange efficiency within an acceptable volume and simple assembly to the Integrated Component Manifold. Noticeable properties were: pressure drops (4.5 KPa “hot side” and 3.75 Kpa “cold side”), effectiveness (0.72), and weight (2.2 Kg).



Figure 4.4.5.3-1: Flat Plate Cathode Heat Exchangers

Next generation heat exchangers were designed to increase efficiency, reduce weight, reduce assembly overhead (number of parts and fixturing). One alternative was a four pass tube-shell design. This had a slightly complex assembly fixturing technique, required 25% fewer parts, targeted similar heat exchange efficiency and required an equivalent volume in the Hot Zone Module but had a higher internal pressure drop. Two modifications of this tube-shell were built to work toward requirements. Both were two pass systems: One with increased manifold headroom for reduced pressure drop and one with turbulators in the tubes to increase heat efficiency.



Figure 4.4.5.3-2: Tube-Shell Cathode Heat Exchangers

An alternative design utilizing internal fins in a modified plate style exchanger was designed. This would increase the heat transfer in a given air flow which would reduce the overall volume of the exchanger. This design builds on the simplified fabrication technique developed for the flat plate but increases piece count. The advantage will be in reduction of overall volume the exchanger component. This is currently being fabricated.

4.4.6 Develop Fuel Delivery and Fuel Metering

A single fuel injector performs the fuel metering and fuel spray preparation for the Auxiliary Power Unit. The injector is based on Delphi's Multec 2 design with the exception of the spray tip, which was originally developed for Direct Injection (DI) applications (**Figure 4.4.6-1**).

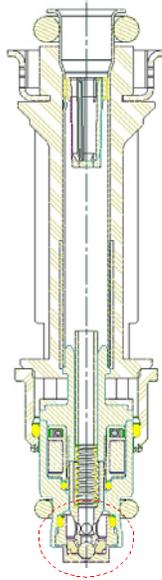


Figure 4.4.6-1: Multec 2 Injector with Swirl Spray Tip Cutaway

The traditional Multec 2 injector employs a director plate at the tip of the injector with holes that direct the streams of fuel forming the fuel spray. The Direct Injection spray tip has a single exit orifice at the tip of the injector with an upstream swirler plate that imparts a tangential component to the fuel leaving the exit orifice. This creates a swirling spray that results in smaller fuel particles and a wider spray pattern than that which can be achieved with the traditional director plate. Both injectors still utilize an inward opening armature and ball that, when de-energized, seals on a conical seat. The guide for the ball also has slots and a lower annulus on the outside diameter that allows fuel to flow to the outer "hockey stick shaped" passages in the swirler plate. Fuel is then accelerated through the swirler slots and toward the ball before exiting at the orifice.

Since the same injector is used to supply "start fuel" to the start combustor and "run fuel" to the Reformer, a dynamic range of fuel metering is required. The fuel metering function of the injector is accomplished by modulating the pulse width (or on time) to the injector. Typical fuel flow (g/sec) vs. pulse width (msec) data, taken on a Hartridge flow stand with Stoddard solvent, for various exit orifice and swirler combinations. The data shows that the injectors have a linear flow rate increase with pulse width and that as exit orifice size increases, so does the flow rate. Also for a given exit orifice, a swirl slot with a larger cross-sectional area (less swirl) results in a slightly higher flow. The static (full

on) flow rate is always non-linear with respect to the dynamic (pulsed) flow rate due to the lack of opening and closing response effects.

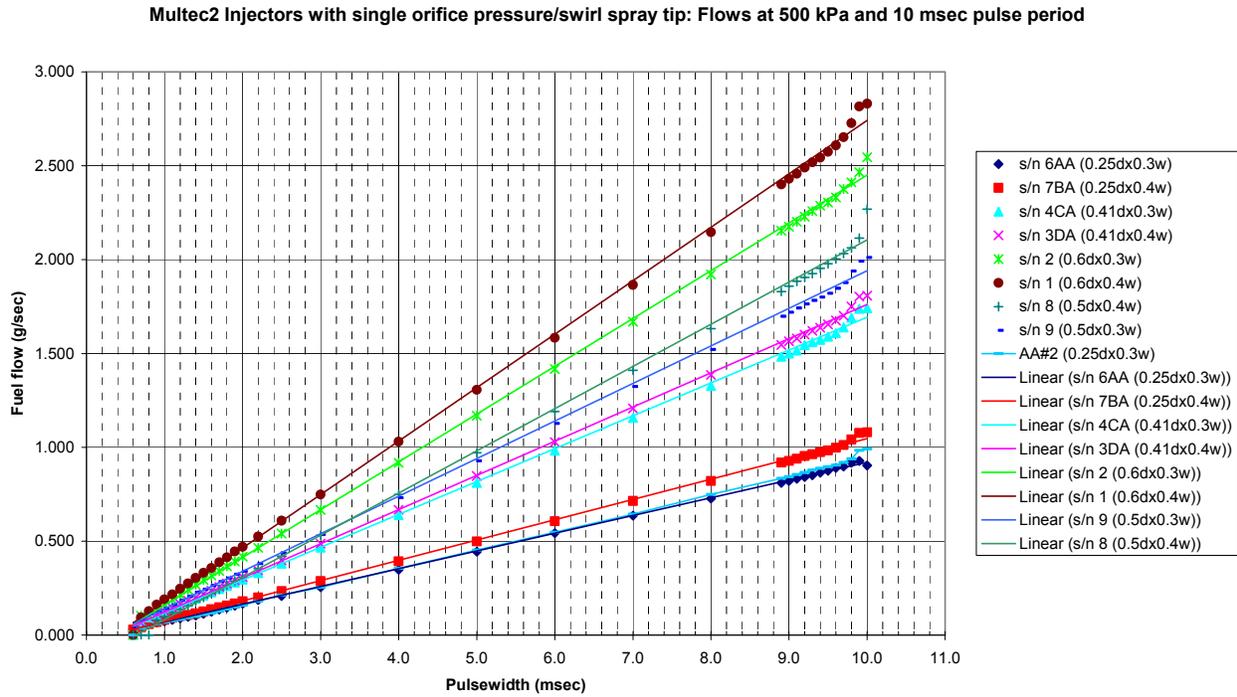


Figure 4.4.6-2: Injector Flow Data

4.5 Manufacturing Development (Privately Funded).

Results to date have indicated that functioning Solid Oxide Fuel Cell components can be built using the prototype processes available to us. The quantities required are small enough that volume throughput is rarely an issue. The welding processes for the reformer are successful as are the brazing processes. Stack component processes have been improved to where the yields are sufficient, but long-term costs are an issue. Glass dispensing has made much improvement in this area in the quality and throughput of the stack assembly process. The area still needing much work is stack component fabrication. The tape casting process through the flattening and noble metal deposition are areas where improvement is not only necessary but also very attractive. Because there are so many of these pieces used in every system, cost and throughput improvements multiply the effect.

The cost study of the system coupled with Crystal Balltm analysis software will point to areas to focus for improvement. Because the probability is part of the analysis, varying degrees of success can be examined and decisions can be made from that analysis.

4.6 System Fabrication

During the period covered by this technical report, many subsystems have been fabricated in their first design iteration to support early system integration efforts. A summary description of these parts is given in this section where appropriate. It should be noted that the system fabrication activity pertains to a gasoline 5 kW Auxiliary Power Unit, not Demonstration System A.

4.6.1 Provide System Design Analysis and Steering Support

System design analysis and steering is covered under Sub-Task 4.7.1.

4.6.2 Fabricate Thermal Enclosure

The insulating material is Wacker WDS Si-HT, and the panel thickness is nominally 30mm. The insulation material is packaged between an exterior and interior stainless steel jacket that forms a structural “clam-shell” enclosure shape. This shell structure, as discussed in the previous topical report, allows for convenient assembly and access to system components in the Hot Zone Module.

4.6.3 Fabricate Air Delivery System

The development and fabrication of the air delivery system is covered in Section 4.4.

4.6.4 Fabricate Fuel Delivery System

The development and fabrication of the fuel delivery system is covered in Section 4.6.

4.6.5 Fabricate Internal Gas Manifolding

The design and development of the Integrated Component Manifold is covered in Section 4.5.

4.6.6 Fabricate Cathode Air Heat Exchangers

The design and development of the cathode air heat exchangers is covered in section 4.5.

4.6.7 Fabricate Exhaust System

An exhaust scrubber is part of the system laboratory (Task 4.7.2).

4.6.8 Fabricate Electrical Signal and Power Harnessing System

The electrical signal and power harnessing systems employed in the Auxiliary Power Unit are conventional automotive technology/tooling employed by Delphi Packard Electric Systems.

4.6.9 Assemble the Solid Oxide Fuel Cell Systems

Per the system integration strategy outlined in Section 4.1.9, a Hot Zone Module, Plant Support Module, Close-coupled Module, and an Auxiliary Power Unit have all been assembled and tested for function. The integration milestones are covered in Section 4.1.9. It should be noted that while basic function and control have been demonstrated, the state of development for both subsystems and controls does not allow for robust operation of the Auxiliary Power Unit power plant, nor power output above break-even levels.

Per the design requirements outlined in the previous topical report, all components are mounted to the top surface of the Integrated Component Manifold for maximum accessibility and ease of assembly.

The modular construction of the Hot Zone Module allows for the evaluation of different technologies or designs for a given function within the system.

4.7 System Testing

4.7.1 Develop Test Plan for Phase I

No activity during the period covered by this report

4.7.2 Determine Facility Requirements for Testing

The current system laboratory for the Solid Oxide Fuel Cell Auxiliary Power Unit is shown in **Figure 4.7.2-1**. The facility includes gas safety sensor and ventilation systems to protect against CO, H₂, and hydrocarbon contamination, and O₂ depletion. It features a 30 kW (AeroVironment MT-30) programmable load center, Labview data acquisition system, mass spectrometer, and exhaust scrubber. Emissions measurement capability is planned for implementation.

The system test stands for Level I system integration activity is shown in **Figure 4.7.2-2**.

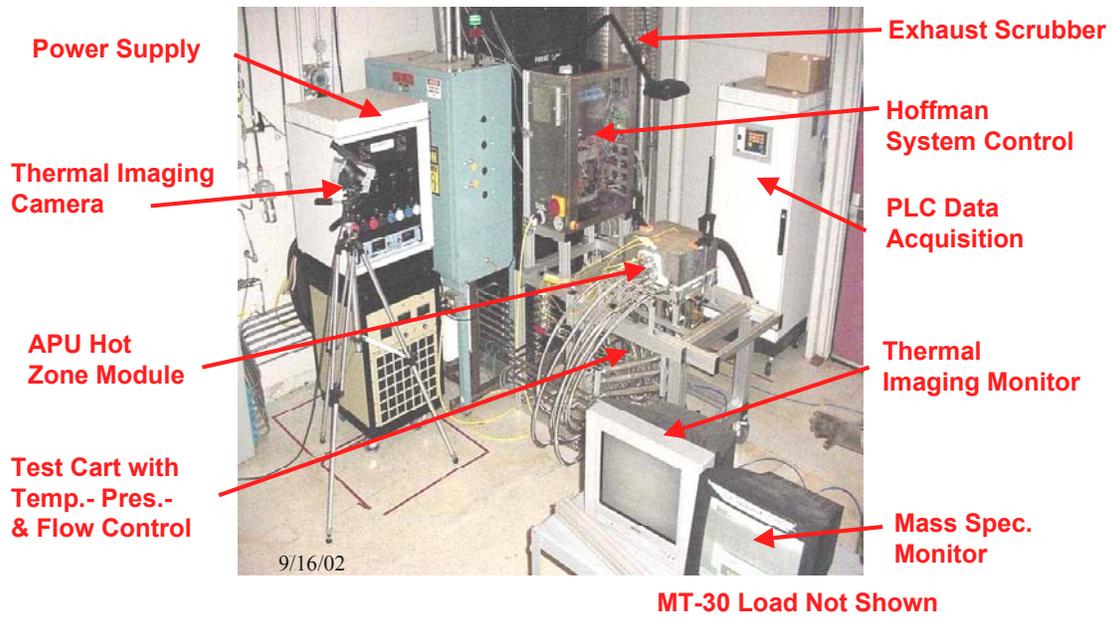


Figure 4.7.2-1: System Test Lab

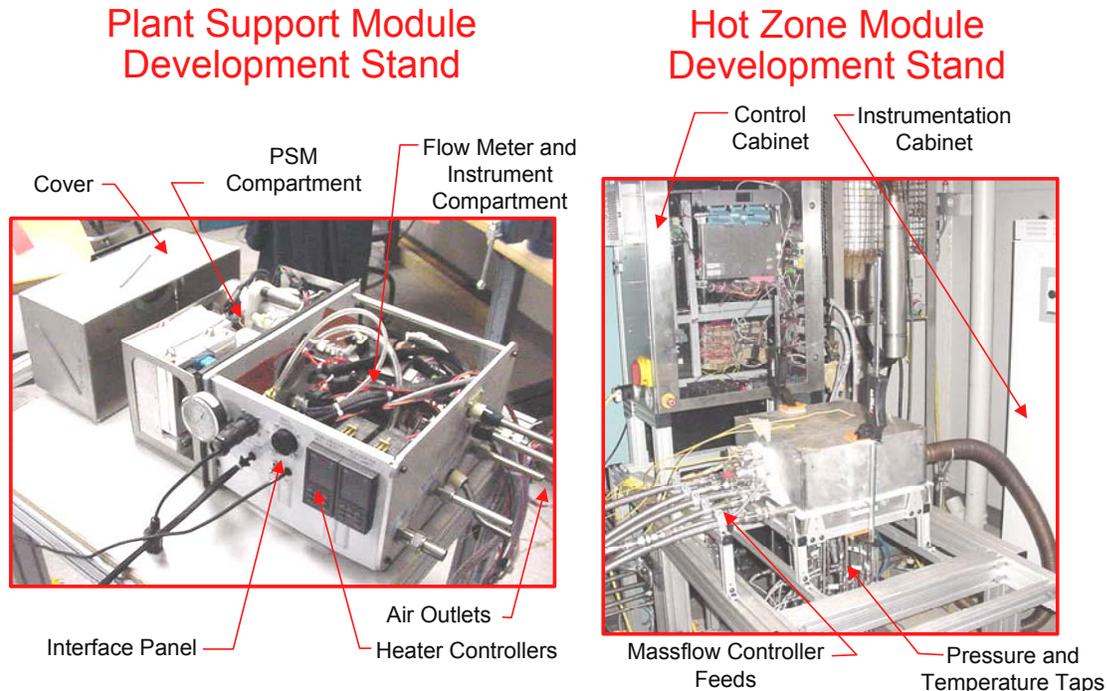


Figure 4.7.2-2: Level 1 Integration Test Stands

4.7.3 Establish Remote Link to National Energy Technology Laboratory

No activity on this task during the period covered by this report.

4.7.4 Conduct Testing on Full Scale Development System

The result of the testing during the system integration phase is summarized in **Figure 4.1.9.2-1**. It should be noted that while basic function and control have been demonstrated, the state of development for both subsystems and controls does not allow for robust operation of the Auxiliary Power Unit power plant, nor power output above break-even levels. Due to this fact, testing on a full-scale development system will be postponed until further development on the subsystems occurs and more controlled testing can be conducted.

4.7.5 Conduct Testing on Demonstration System A

No activity on this task during the period covered by this technical report.

4.7.6 Reduce and Document Data

It should be noted that while basic function and control have been demonstrated, the state of development for both subsystems and controls does not allow for robust

operation of the gasoline Auxiliary Power Unit power plant, nor power output above break-even levels. Due to this fact, formal data documentation and report out activity will be postponed until further development on the subsystems occurs and more controlled testing can be conducted.

5.0 CONCLUSIONS

5.1 System Design and Integration

During the period covered by this report, the initial system design for the gasoline 5 kW mobile Auxiliary Power Unit was completed, and first-design-iteration hardware was fabricated for the sub-systems. The system was evaluated using a three-tier system integration strategy whereby system sub-modules are built, tested, and verified for function before up-integration into the Auxiliary Power Unit. The highlight of this period's activity is that Delphi has been successful in combining the major elements of the Solid Oxide Fuel Cell Auxiliary Power Unit system together to produce electricity with gasoline from a cold-start. However, it is clear that much development is required of the subsystems before greater-than-break-even power levels are achieved and reliable service as a power plant is enabled.

5.2 Solid Oxide Fuel Cell Stack Development

During the period covered by this report, we have successfully demonstrated the fabrication, build and testing of Generation 2 stacks. The performance of the Gen 2 stack has been reported. We have also reported the design of the new Generation 3 stack. Work is focused in developing fundamental components to meet the requirements of the stack.

5.3 Reformer Developments

Reformer development proceeded despite the lack of abundant hardware. Hardware braze development which feverishly tried to produce hardware will need to take a more fundamental look at the H₂ geometry and braze process to determine viability. Additional brazing resources have already been enlisted.

Carbon formation was encountered and now needs to be addressed in a more disciplined fashion and will likely require development of methods to assess carbon formation in-situ. Operation of the integrated Gas Phase Combustor went well but identified significant material limitations. Start combustor testing provided enough information to produce reasonably stable starts but little optimization was conducted.

Lastly, the deployment of an alternate Pox reformer (Tubular) has yielded encouraging performance and will in some ways be carried forward and investigated further.

5.4 Develop Balance of Plant Components

5.4.2 Develop Hydrogen Sensors for High and Low Concentration Measurement

Current sensor technology has not developed to the point where selectivity to H₂ and CO is not coupled with cross-sensitivity to other gas species like CH₄. In the case of a safety sensor (or combustible gas sensor) this is not a particular issue, but in the case where reformer health and performance need to be monitored, the cross-sensitivity of several gas species is a real issue.

5.4.4 Develop Air Delivery and Process Air Sub-System

Development of the systems Process Air blower will continue with the investigation of at least three motor types:

- Permanent Magnet
- Inductance
- Switched Reluctance

In addition to the blower, development of reliable, robust Air Mass Flow Sensors and flow control valves have been proven to be critical to the safe and efficient operation of Solid Oxide Fuel Cells.

5.4.5 Develop Hot Zone Components

5.4.5.1 Gasket Development

Testing of gasket materials has led to the following conclusions:

- An Oxygen environment rapidly oxidizes copper at elevated temperatures.
- Uncontrolled flatness of the clamping surfaces induce large leakage paths.
- Increased clamping loads are necessary for proper Integrated Stack Module / Integrated Component Manifold sealing reliability.
- Carbon Graphite bonders break down at 800 °C or higher .
- F-mica maintains the temperature limits, however it's fibrous makeup will not seal properly.

Long-term sealing has yet to be evaluated using the thermal cycling approach. By minimizing the seal surface area maximum compressive loading will occur.

5.4.5.2 Integrated Component Manifold

Ongoing design studies, new vendor interfacing and new hot zone component designs will be incorporated into the latest Integrated Component Manifold under development. This includes the Co-flow Stacks, related mounting frame and new Reformer designs.

5.4.5.3 Cathode Heat Exchangers

Airflow temperature can be managed within the allowable space and internal pressure drops utilizing gas-gas heat exchanger technology. A stacked flat-plate design has demonstrated adequate heat exchange, internal pressure drop and size. This path has a large part count, and high weight but is a low risk assembly technology.

Alternative designs are being pursued to:

- Reduce part count
- Reduce weight
- Reduce assembly complexity
- Increase heat exchange efficiency
- Reduce outward heat radiation

This will include further refinements of tube-shell styles, incorporation of fin material into plate spaces, incorporation of corrugations into separator plates, modifications of separator plates to eliminate spacers and designs composed of ceramic and metal assemblies.

5.4.6 Develop Fuel Delivery and Fuel Metering

The injector development has resulted in a fuel vapor preparation that meets the Reformer start and run fueling requirements. Further development is needed to minimize heat transfer back to the injector during hot shutdown (hot soak) conditions of the Auxiliary Power Unit. Future Reformer development should continue to include thermal insulation between the injector tip and the face of the Reformer. The cooling jacket affixed to the outside of the injector (**Figure 5.4.6-1** below) provides the means to keep the injector at a temperature that prevents vapor lock provided that a suitable gaseous or liquid cooling fluid is circulated through it. The availability of such a fluid has not yet been confirmed at a System level.

Development of the fuel pump, regulator, hoses and fittings should also be started with the design of the Fuel Delivery System as the end goal. This activity will be discussed with the Delphi fuel pump and regulator business teams in the near future.



Figure 5.4.6-1: Injectors with Cooling Jacket

5.5 Manufacturing Development (Privately Funded)

The current status of the process development is highly slanted to the short-term process development required for prototype production. The facets of the program with multiple approaches are being pursued to determine the most feasible design from a performance and cost perspective. The potential for improvement is also part of the analysis. The areas for long-term process development are indicated by the cost study.

It identifies high cost areas of the system. The major areas of need are: the minimization of noble metals, the minimization of exotic high-temperature alloys, and the improvement in yield and cost of the stack component fabrication. These component parts with multiple firings offer much potential cost reduction. Because they are used in high count multiples, reduction in cost multiplies the savings. At this point in time, these three areas are indicated as the most pressing areas for process development.

5.6 System Fabrication

The three-level system integration strategy greatly simplified the initial system fabrication and evaluation activity. It will continue to be the model for Auxiliary Power Unit system development.

5.7 System Testing

While basic function and control have been demonstrated at the system level in the laboratory, the state of development for both the Auxiliary Power Unit subsystems and controls does not allow for robust operation of the gasoline Auxiliary Power Unit power plant, nor power output above break-even levels. More meaningful testing at the system level may be conducted with the next design level of subsystem hardware.

6.0 ATTACHMENT 1

Brazing Controls	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer
Chronology Index	9	11	12	13	14	15	16	
Identifier / Serial No.	Braze Trial 2	Braze Trial 3	Braze Trial 4	Braze Trial 5	Braze Trial 6	Braze Trial 7	Braze Trial 8/ Serial A1	
Date Sent to Brazer	6/18/02	7/11/02	7/11/02	7/15/02	7/29/02	7/29/02	8/6/02	
Unsupported Shim Dimension (mm)	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.8	60.2/104.7 23.6/97.5 76.2/15.9
Channel Height; Ref / Comb	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")
Number of A/B etched Plates								
Number of Combustion Plates	5	5	5	5	5	5	5	23
Number of Combustion Shims	5	5	5	5	5	5	5	23
Number of Reforming Plates	4	4	4	4	4	4	4	24
Number of Reforming Shims	4	4	4	4	4	4	4	23
Number of Generic Shims								
Part Material	Haynes 214	Haynes 214	Haynes 214	Haynes 214	Haynes 214	Haynes 214	Haynes 214	Haynes 214
Shim Thickness (mm)	0.010"	0.010"	0.010"	0.010"	0.010"	0.010"	0.010"	0.010"
Braze Alloy 1st Braze	Microbraz 150 (BNi-9)	Microbraz 150 (BNi-9)	Microbraz 150 (BNi-9)	Microbraz 150 (BNi-9)	Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)
Braze Alloy 2nd Braze (Fittings)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Microbraz 130 (BNi-3)
Weight Applied During Braze Process (lb)	32	32	32	32	32	32	32	24
Dimples in Shims (Yes/No)	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Grafoil Shims Installed (Yes/No)	No	Yes	Yes	No	No	No	No	No
Shims Tack welded in place	No	No	No	No	No	No	Yes	No
Inconel tube inserts for squareness of assembly during braze	No	No	No	No	No	No	No	No
Wire EDM of locating bolt holes to 8.6 mm	No	No	No	No	No	No	No	No
Braze Application Method (Spray, Slather, Foil)	Spray Frames Only	Spray Frames Only	Spray Frames Only	Spray Frames Only	Spray Frames Only	Spray Frames Only	Spray Frames Only	Spray Frames Only
Results (Good, Acceptable, Poor)	Poor	Poor, Graph Foil Spacers burned through the shims	Poor, Graph Foil Spacers burned through the shims	Acceptable, Dimples may help. Top shim collapsed	Very Good	Shims buckled and resulted in poor adhesion.	Good, Became S/N A1 for test. Sent to Jeff Weissman for wash coat 8/16/02. Failed Leak Test, bad dimples	

TABLE 4.3.2.2.1-2 H2 HAYNES 214 BRAZE CONFIGS: INDEX 9-16

Brazing Controls		H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer	H2 Reformer
Chronology Index		18	19	20	21	22	23
Identifier / Serial No.		Braze Trial 10	Braze Trial 11/ Serial # A2	Braze Trial 12/ Serial # A3	Braze Trial 13	Braze Trial 14/ Serial # A4	Braze Trial 15/ Serial # A5
Date Sent to Brazer		9/3/02	9/18/02	9/26/02	9/23/02	9/27/02	10/1/02
Unsupported Shim Dimension (mm)		60.2/104.7 23.6/97.5 76.2/15.10	60.2/104.7 23.6/97.5 76.2/15.11				
Channel Height; Ref / Comb		.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")
Number of A/B etched Plates							
Number of Combustion Plates		5	24	24	5	24	26
Number of Combustion Shims		5	24	24	5	24	26
Number of Reforming Plates		4	24	24	4	24	26
Number of Reforming Shims		4	23	23	4	23	25
Number of Generic Shims							
Part Material		Hybrid (Haynes 214 Plates & Inconel 600 Shims (Ethched)	Hybrid (Haynes 214 Plates & Inconel 600 Shims (Ethched)	Hybrid (Haynes 214 Plates & Inconel 600 Shims (Ethched)	Hybrid (Haynes 214 Plates & Inconel 600 Shims (Ethched)	Hybrid (Haynes 214 Plates & Inconel 600 Shims (Ethched)	Hybrid (Haynes 214 Top, Bottom Plates, Air Preheat Block, ansd Igniter Block. Inconel 600 Air Tubes, Reformer Plates, Combustion Plates and Etched Shims)
Shim Thickness (mm)		0.010"	0.010"	0.010"	0.010"	0.010"	0.010"
Braze Alloy 1st Braze		Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)	Microbraz 130 (BNi-3)	TBD	Microbraz 130 (BNi-3)
Braze Alloy 2nd Braze (Fittings)		N/A	TBD	N/A	N/A	TBD	Microbraz 130 (BNi-3)
Weight Applied During Braze Process (lb)		24	24	24	24	30	30
Dimples in Shims (Yes/No)		Yes	Yes	Yes	Yes	Yes	Yes
Grafoil Shims Installed (Yes/No)		No	No	No	No	No	No
Shims Tack welded in place		No	No	No	No	Yes	No
Inconel tube inserts for squareness of assembly during braze		No	Yes	Yes	No	No	Yes
Wire EDM of locating bolt holess to 8.6 mm		No	No	Yes	No	No	Yes
Braze Application Method (Spray, Slather, Foil)		Spray Frames Only	Spray Frames Only	Spray Frames Only	Dispense	Dispense	Spray Frames Only
Results (Good, Acceptable, Poor)		Failure, good braze except where stack hung up on the alignment posts.	Failed, Plates and Shims hung up on the alignment posts	Failed, Plates and Shims hung up on the alignment posts	Used for braze trials at Hi Techmetal Group	TBD	Failed, plates and shims hung up on the alignment posts.

TABLE 4.3.2.2.1-3: H2 HYBRID (HAYNES 214/INCONEL 600) BRAZE CONFIGS: INDEX 18-23

Brazing Controls			H2 Reformer	H2 Reformer				
Chronology Index			24	25	26	27	28	29
Identifier / Serial No.			Braze Trial 16/ Serial # A8	Braze Trial 17/ Serial # A9	Braze Trial 18/ Serial # A10	Braze Trial 19/ Serial # A11	Braze Trial 20/ Serial # A12	Braze Trial 21
Date Sent to Brazer			10/7/02	10/8/02	10/9/02	11/10/02	TBD	11/8/02
Unsupported Shim Dimension (mm)			60.2/104.7 23.6/97.5 76.2/15.11	60.2/104.7 23.6/97.5 76.2/15.8				
Channel Height; Ref / Comb			.74 / 1.14 (0.029" / 0.045")	.74 / 1.14 (0.029" / 0.045")				
Number of A/B etched Plates								
Number of Combustion Plates			24	24	24	25	24	5
Number of Combustion Shims			24	24	24	25	24	5
Number of Reforming Plates			25	25	25	26	25	4
Number of Reforming Shims			24	24	24	25	24	4
Number of Generic Shims								
Part Material			Entire stack is made of Inconel 600, including Air Tubes, igniter blocks, air preheat blocks. Inconel Shims were etched	Entire stack is made of Inconel 600, including Air Tubes, igniter blocks, air preheat blocks. Inconel Shims were etched	Entire stack is made of Inconel 600, including Air Tubes, igniter blocks, air preheat blocks. Inconel Shims were etched	Entire stack is made of Inconel 600, including Air Tubes, igniter blocks, air preheat blocks. Inconel Shims were etched	Entire stack is made of Inconel 600, including Air Tubes, igniter blocks, air preheat blocks. Inconel Shims were etched	Haynes 214
Shim Thickness (mm)			0.010"	0.010"	0.010"	0.010"	0.010"	0.010"
Braze Alloy 1st Braze			Nicrobraz 130 (BNI-3)	Nicrobraz 150 (BNI-9)	Nicrobraz 150 (BNI-9)	Nicrobraz 130 (BNI-3)	Nicrobraz 130 (BNI-3)	Nicrobraz 130 (BNI-3)
Braze Alloy 2nd Braze (Fittings)			Nicrobraz 130 (BNI-3)	Nicrobraz 150 (BNI-9)	Nicrobraz 150 (BNI-9)	Nicrobraz 130 (BNI-3)	Nicrobraz 130 (BNI-3)	Nicrobraz 130 (BNI-3)
Weight Applied During Braze Process (lb)			30	30	30	30	30	30
Dimples in Shims (Yes/No)			Yes	Yes	Yes	Yes	Yes	Yes
Grafoil Shims Installed (Yes/No)			No	No	No	No	No	No
Shims Tack welded in place			No	No	No	No	No	No
Inconel tube inserts for squareness of assembly during braze			No	No	No	No	No	No
Wire EDM of locating bolt holes to 8.6 mm			No	No	No	No	Yes, Back Left Hole Only	No
Braze Application Method (Spray, Slather, Foil)			Spray Frames Only	Spray Frames Only				
Results (Good, Acceptable, Poor)			Passed 2nd braze and leak test. Went to Jeff Weissman for wash coat 10/14/02.	Passed 2nd braze and leak test. Went to Jeff Weissman for wash coat 10/15/02	Looked good but failed leak test 10/17/02. Gross leak from combustion chamber to reforming chamber, not salvageable	Failed 1st braze due to shim lift. 11/15/02		Poor, The Shims did not braze to the plates in all areas.

**TABLE 4.3.2.2.1-4: H2 INCONEL 600 BRAZE CONFIGS: INDEX 24-28
 H2 HAYNES 214 BRAZE CONFIGS: INDEX 29**

7.0 LIST OF GRAPHICAL MATERIALS

Figure 4.1.2.1-1	Auxiliary Power Unit Development Strategy	20
Table 4.1.6-1	Control System Environments	22
Figure 4.1.7-1	Control Performance	24
Figure 4.1.7-2	Measured vs. Predicted Performance of Stack Model	25
Figure 4.1.7-3	Aspen/Hysys Model Output	26
Figure 4.1.7-4	Predicted and Measured H ₂ and CO Production	27
Table 4.1.7-1	Model Summary Table	28
Figure 4.1.9.1-1	System Integration Levels	30
Figure 4.1.9.2-1	System Integration Milestones	32
Figure 4.1.9.2-2	System Issues and Needs	33
Figure 4.2.1-1:	Gen 2 Cassette	34
Figure 4.2.1-2:	Gen 3 Cassette	35
Figure 4.2.2-1	Effect of High Fuel Flow On Cell Temperature	36
Figure 4.2.2-2	Cathode Air Flow Velocity	37
Figure 4.2.2-3	Steady State Temperature Distribution	38
Figure 4.2.2-4	Effect Of Fuel Utilization On Current Density	39
Figure 4.2.3-1	Stress During Start-Up Transient	40
Figure 4.2.3-2	Separator Plate Inverse Safety Factor	41
Figure 4.2.3-3	Seal Stress	42
Figure 4.2.4-1	Cathode Test Stands	43
Figure 4.2.6-1	Effect of Additive on Cell Curvature	44
Figure 4.2.6-2	1000 hr Test of Cell with Anode Containing Anti-Camber Additive	45
Figure 4.2.6-3	Bilayer Flexural Strength, As Oxide, Reduced and at 800 °C	46
Figure 4.2.10-1	(a) Celsius Phase Formation	47
Figure 4.2.10-1	(b) CTE Effects	48
Figure 4.2.11-1	(a) Cell brazed & (b) SEM micrograph of frame joint	49
Figure 4.2.13-1.	Intermediate-Size Stack Test w/ 5 Thermal Cycles	51
Figure 4.2.13-2.	Intermediate-Size Stack Test w/High Power Density	52
Figure 4.2.14-1:	IV curve from a 1-cell stack test at 750 °C	53
Figure 4.2.14-2:	Thermal Cycling Test on Gen 2 Single-Cell Stack	54
Figure 4.2.14-3:	IV Curve of 26-Cell Stack With Hydrogen at 750 °C.	55
Figure 4.2.14-4:	Integrated Stack Module	56
Figure 4.2.14-5:	IV curve of a 2x15-Cell Integrated Stack Module with Hydrogen at 750 °C.	56
Figure 4.2.14-5:	Integrated Stack Module Integrated in the Hot Zone of an Auxiliary Power Unit	57
Figure 4.2.14-6:	IV Curve from Integrated Stack Module Integrated in the Auxiliary Power Unit (Hot Zone Module)	58
Figure 4.3.2.1.1-1	Burn-off Evaluation: HC, H ₂ O, CO ₂	60
Figure 4.3.2.1.1-2	Burn-off Evaluation: HC, H ₂ O, CO ₂	61
Table 4.3.2.1.2-1	Oxygen 'getter' Summary	63
Figure 4.3.2.1.4-1	Ethylene Climb at O/C = 1.05	65
Figure 4.3.2.1.4-2	Ethylene Climb at O/C = 1.20	66

Table 4.3.2.2.1-1	H2 Inconel 600 Braze Configs: Index 6-8	68
Figure 4.3.2.2.1-1	Collapsed Channels	69
Table 4.3.2.2.1-2	H2 Haynes 214 Braze Configs: Index 9-16	70
Table 4.3.2.2.1-3	H2 Hybrid (Haynes 214/Inconel 600) Braze Config: Index 18-23	70
Table 4.3.2.2.1-4	H2 Inconel 600 Braze Configs: 24-28 H2 Haynes 214	71
Figure 4.3.2.2.1-2	Initial Braze Fixture (no sleeves shown)	71
Figure 4.3.2.2.1-3	2nd Braze w/ External Guides	72
Figure 4.3.2.2.1-4	H2 Reformer A9 – Reformer Outlet	73
Figure 4.3.2.2.1-5	Spray Braze Evaluation	74
Figure 4.3.2.2.2.1-1	H2 Reformer Test Setup	75
Table 4.3.2.2.2.2-1	H2 Start Evaluation	77
Table 4.3.2.2.2.2-2	H2 Starts – Effect of Igniter Location	77
Figure 4.3.2.2.2.3-1	H2 Serial Number B2 Gas Phase Combustor Temps/Flows 8/21/02 Testing	78
Figure 4.3.2.2.2.3-2	H2 Serial Number B2 Gas Phase Combustor Emissions 8/21/02 Testing	79
Figure 4.3.2.2.4-1	H2 Serial Number B2 Gas Phase Combustor	80
Figure 4.3.2.2.4-2	Gas Phase Combustor and Adiabatic Flame Temperatures	81
Figure 4.3.2.3-1	Tubular Reformer Assembly (side view)	82
Table 4.3.2.3-1	Gen 1 Tubular Start Evaluation	83
Table 4.3.2.3-2	Carbon/Filter Results	84
Figure 4.3.2.3-2	Tubular Data: Mass Spec	85
Figure 4.3.2.3-3	Tubular Data: Temperature Data	86
Table 4.3.2.3-3	GC Data	87
Figure 4.4.2-1	Preliminary Reformer Sensor Results	92
Figure 4.4.2-2	Combustible Gas Sensor Output	93
Figure 4.4.4-1(a)	Type 2 Blower	94
Figure 4.4.4-1 (b)	Blower Inlet Housing And Curved Inlet Guide Vanes	94
Figure 4.4.5.3-1	Flat Plate Cathode Heat Exchangers	96
Figure 4.4.5.3-2	Tube-Shell Cathode Heat Exchangers	97
Figure 4.4.6-1	Multec 2 Injector with Swirl Spray Tip Cutaway	98
Figure 4.4.6-2	Injector Flow Data	99
Figure 4.7.2-1	System Test Lab	103
Figure 4.7.2-2	Level 1 Integration Test Stands	104
Figure 5.4.6-1	Injectors with Cooling Jacket	108

8.0 REFERENCES

None required.

9.0 BIBLIOGRAPHY

None required.

10.0 LIST OF ACRONYMS AND ABBREVIATIONS

A	
APU	Auxiliary Power Unit
B	
BOP	Balance-of-Plant
C	
CFD	Computational Fluid Dynamics
CHX	Cathode Heat Exchanger
CPO	Catalytic Partial Oxidation
D	
DI	Direct Injection
DOE	Department of Energy
E	
ERU	Energy Recovery Unit
F	
FE	Finite Element
H	
HZM	Hot Zone Module
I	
ICM	Integrated Component Manifold
L	
LHV	Lower Heating Value
N	
NETL	National Energy Technology Laboratory
P	
PSM	Plant Support Module
S	
SECA	Solid State Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell
ULEV	Ultra-Low Emission Vehicle
W	
WRU	Water Recovery Unit

11.0 APPENDICES

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