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1.0 ABSTRACT

The objective of 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 the option of 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 1, 2003 to December 31, 2003, under Department of Energy Cooperative Agreement DE-FC-02NT41246. This report highlights technical results of the work performed under the following tasks:

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
Task 8	Program Management
Task 9	Stack Testing with Coal-Based Reformate
Task 10	Technology Transfer from SECA CORE Technology Program

In this reporting period, unless otherwise noted Task 6 – System Fabrication and Task 7 – System Testing will be reported within Task 1 System Design and Integration.

Task 8 – Program Management, Task 9 – Stack Testing with Coal Based Reformate, and Task 10 - Technology Transfer from SECA CORE Technology Program will be reported on in the Executive Summary section of this report.

The next anticipated Technical Progress Report will be submitted July 30, 2004.

2.0 EXECUTIVE SUMMARY

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

2.1 Sytem Design and Integration (Task 1.0)

This section will now also include the information previously reported for Task 6.0 / System Fabrication and Task 7.0 / System Testing. This change was requested in the previous Technical Progress report for the period of January – June 2003.

2.1.1 Transportation Auxiliary Power Unit (APU) Design and Integration

During the period covered by this technical report, focus has been placed on Gen 3B Transportation APU system targets and component requirements to support the Gen 3B APU design effort.

The Gen 3B design level has a target capability approximately 50% of application target levels with respect to net full power electrical output and efficiency, while achieving application target package size. It is a goal of the Gen 3B APU design level to have sufficient thermal cycle durability, life, and operational reliability to begin initial evaluation in the target application.

To support the Gen 2C APU performance targets, improvements in the APU conceptual design have been made between Gen 2B and Gen 2C design levels.

To support the Gen 3B APU performance targets, improvements in the APU conceptual design have been made between Gen 2C and Gen 3B design levels.

Several changes have been made to the Gen 3B physical plant mechanization during the period covered by this technical report. They are as follows:

- Addition of anode tail gas recycle function
- Addition of fixed burner air bypass
- Separate process air and system cooling air (purge air) streams

2.1.2 Stationary Power Unit (SPU) System Design and Integration

The system development for the stationary power unit system at Delphi was advanced during the reporting period with a renewed look at our component technology status and the requirements needed for the Phase 1 deliverables for the DoE SECA program.

System engineering collected and used projections supplied from our component efforts within Delphi to better predict and manage the potential system capabilities for the 2004 – 2005 period. Several adjustments and changes to the product configuration and process mechanization were reviewed for adoption in early 2004. Design compensations were based on performance issue forecasts of the Solid Oxide Fuel Cell (SOFC) stack and reformer efforts.

The internal Delphi stationary power unit business development efforts were put on notice that an increase in advanced marketing information for the product is needed. Commercialization plans for system development and product requirements, such as overall power output sizing (electric output max) and prioritizing customer driven features (beyond SECA requirements), are being researched to set development priorities for the next two years and complete Phase 1 successfully for the DoE and Delphi. These overall system configuration decisions have impact on the fuel cell power plant sizing of the stationary power unit design.

Updates have been made to the overall system requirements as well as release of Phase 1 requirements for subsystem teams for guidance of their efforts. A system architecture block diagram has been generated to show the breakdown of the components as they pertain to the modular approach that Delphi has worked to adopt in products. Basic physical layouts have been conceived to allow a simpler unit package that will emphasize performance, durability, efficiency and cost and de-emphasize the high density, small volume target of the transportation APU designs.

2.2 Solid Oxide Fuel Cell Stack Development (Task 2.0)

Stack development was focused on transitioning from a Gen 2 design to a more manufacturable and lower cost Gen 3 design. Multiple stack fabrication, testing and fundamental development were targeted towards improving sealing, interconnects and continuous and thermal cycling durability.

The key achievements in stack development were:

- Greater than twenty Gen 2 stack sub-systems were built, and valuable lessons were learned in fabrication and testing of these stacks. The stacks produced a power density of greater than 400 mW/cm^2 at 750 ^oC with simulated reformate compositions. The stacks were successfully thermally cycled 5 times in a furnace with minimal degradation.

- Low mass (155 grams) Gen 3 cassettes (repeating unit) with anode-supported cells were fabricated successfully. The Gen 3 cassettes are only 2.1 mm in thickness. Major progress in process development of stamping, brazing and laser welding led to the fabrication of hundreds of cassettes for stack build and test.

- Durability tests on intermediate and full-sized stacks were carried out successfully for over 1000 hours. The tests underscored the degradation in power due to the interaction of chromia with the cathode in interconnect designs containing chromia forming alloys. Controlled experiments on intermediate-sized, 1-cell stacks, with non-chromia containing interconnects, showed minimal degradation in the same time periods.

- Multiple Gen 3 short stacks were fabricated and tested successfully. A 3-cell stack was thermally cycled 30 times in a furnace.

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- Multiple 15-cell Gen 3 stacks were built and tested successfully. Power density of greater than 300 mW/cm^2 was achieved with simulated reformate at 750 ^{o}C. Further optimization of cathode and anode contacts in Gen 3 stacks is underway.

- A Gen 3, 15-cell stack, was also successfully thermally cycled 10 times in a furnace with minimal degradation in power.

- Fundamental development was focused on improving cathode performance. Lanthanum Strontium Ferrite and Lanthanum Strontium Cobalt Ferrite cathodes have demonstrated good power densities in fundamental testing as well as in stacks. Key issues related to cathode degradation were studied in the presence of chromia and alumina forming alloys.

- Fundamental development of seals demonstrated improved performance from reinforced glass seals. Initial results from these seals have been very encouraging.

- Fundamental Interconnect development was focused on understanding and studying the viability of concepts that would provide an alternative to using chromia-containing alloys in the stack.

2.3 Reformer Developments (Task 3.0)

2.3.1 Reformer – Subsystem

Design developments continue with the further testing of the Tubular Gen 1.0 and Gen 1.1 designs in the areas of emissions, endothermic capability and diesel fuel reforming capability. Endothermic reforming capable designs starting with the existing “H2” design were the focus going forward in order to implement Delphi’s recycle-based reforming strategy. The “H2” reformer was subjected to an initial round of testing which highlighted several areas where improvement is needed.

Subsequently, a number of Endothermic reformer concepts have been conceived and select concepts are undergoing more detailed modeling and analysis.

2.3.2 Reformer Catalyst – Component Level

Work continues on optimizing catalyst formulations for increased activity, stability and durability while minimizing precious metal content. A new rapid aging test method designed to mimic performance features of reforming devices was introduced. Characterization of catalysts was significantly enhanced through the introduction of a novel laser Raman spectroscopy method. Methane autothermal reforming was modeled using an equilibrium approach.

2.4 Development of Balance of Plant Components (Task 4.0)

2.4.1 Combustible Gas Sensor

During this reporting period, additional development activity on the gas sensor involved further characterization of the sensor's response to hydrogen and investigating alternative sensor controller strategies.

2.4.2 Air Delivery and Process Air Subsystem

The Delphi Process Air Module, shown in **Figure 2.4.2-1**, has been redesigned to improve performance and reliability while enhancing manufacturability. A major objective of the design team was to develop an integrated package that readily mounts to the system assembly using a minimum number of electrical and mechanical connections. The Process Air Module utilizes ambient inlet air and provides four variable, measured output airflows to supply the combustor, cathode, reformer, and cathode bypass. The new Process Air Module motor is a two-pole, three-phase AC induction motor capable of 94.1 N-mm at a maximum speed of 68,000 RPM. The motor, in combination with the impeller, is capable of providing 18g/s at 68,000 RPM with 45 ºC inlet air. The motor controller utilizes sinusoidal waveform reproduction and volts/hertz controls (open loop). The system efficiency of the motor and controller is 82% at 65,000 RPM and 100% APU power. **Figure 2.4.2-2** shows a photograph of the Delphi designed Process Air Module motor.

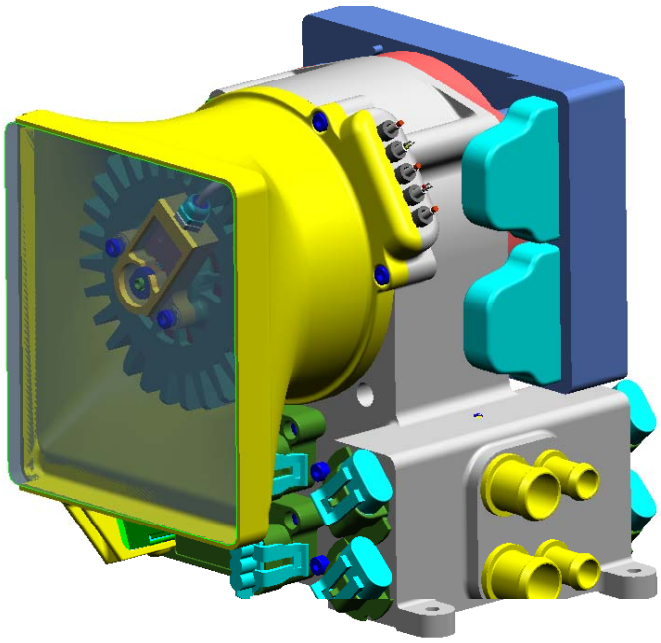


Figure 2.4.2-1 Delphi Process Air Module

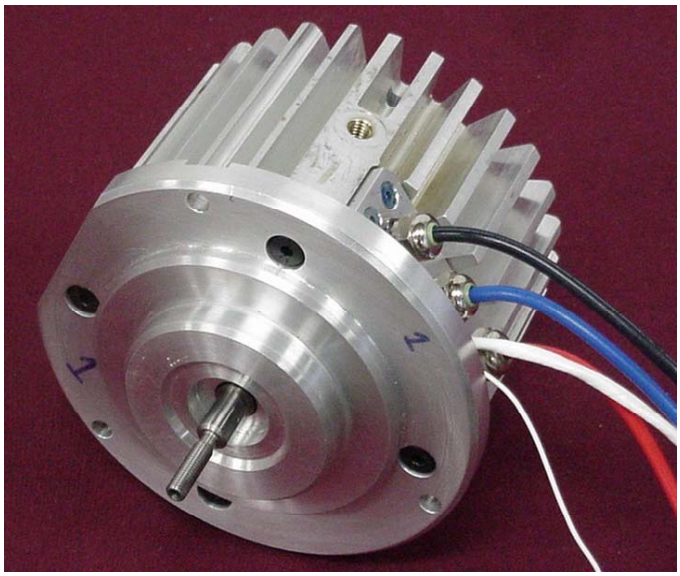


Figure 2.4.2-2 Delphi Process Air Motor

2.4.3 Hot Zone Components

During this reporting period, there was development activity on the following Hot Zone Components: Gaskets, Integrated Component Manifolds, Cathode Heat Exchangers, and Igniters. Specific activities centered around prototype part fabrication, and process development for each of the components. The result of which yielded successes in producing prototype parts for system level testing.

2.4.4 Re-cycle Pump

In order to increase overall net system efficiency of the APU, a strategy that involved taking a portion of the anode tail gas from the stacks and re-cycling it back into the reformer was developed. A system mechanization for the approach has been developed. Analysis and optimization of re-cycle parameters is currently in process by the system team. Balance of Plant efforts on Re-cycle during this reporting period included writing component specifications, conducting a technology down-select and selecting the supplier. Prototype pumps were ordered and received. Initial testing confirmed significant pump capacity.

2.5 Manufacturing Development (Privately Funded) – (Task 5.0)

Developments for manufacturing developments are reported as part of each subsection for the solid oxide fuel cell system.

2.6 System Fabrication (Task 6.0)

2.6.1 Transportation APU System Fabrication

During the period covered by this technical report, the following systems were fabricated and tested:

- Gen 2B Close-Coupled System

- Gen 2B APU
- Gen 2C Close-Coupled System

2.7 System Testing (Task 7.0)

2.7.1 Transportation APU System Testing

During the period covered by this technical report, significant experimental effort at the system level was conducted. System testing and experiments to support current system development was conducted at both close-coupled and full APU integration levels for Gen 2B system hardware, and at the close-coupled level of integration for the Gen 2C system hardware.

During the period covered by this technical report, the goals of system testing and development were as follows:

- Build and Test a Gen 2B APU
- Demonstrate 5 thermal cycles on an Gen 2B APU
- Deploy the Engine Control Units. (ECU) to the system and demonstrate automatic control of the system with APU08 Control Software
- Build and test a Gen 2C APU
- Demonstrate function of Gen 3 2x30 cell SOFC Stacks at the system level

Significant progress was made towards these goals during the reporting period, but current capability gaps still exist in the Gen 2B output power and thermal cycle durability.

2.8 Program Management (Task 8.0)

Program management duties as outlined in the cooperative agreement have been satisfied during this reporting period.

2.9 Stack Testing with Coal-Based Reformate (Task 9.0)

Two Gen 2, 2x15-cell Integrated Stack Modules, were tested with coal gas-based reformate at the Power Systems Development Facility site in Wilsonville, Alabama. The test ran for over 60 hours. The test demonstrated the feasibility of using SOFC with coal based reformate after cleanup of impurities that are harmful to the stack. Post-mortem analysis of the stack was completed to understand the effect of coal-based syngas on stack materials.

2.10 Technology Transfer from SECA CORE Group (Task 10.0)

The basic cell fabrication technique was developed on the Core Technology Program and transferred to the Delphi-Battelle Program at its outset. The technique involves tape casting of the ceramic powders, tape lamination, and then co-sintering of the bilayer.

The Lanthanum Strontium Ferrite cathode and associated Ceria barrier layer and associated processing were developed by the Core Technology Program and passed on to Delphi-Battelle Program at the outset. These layers are screen printed onto the sintered bilayer and then fired. A copper-doped-Lanthanum Strontium Ferrite cathode developed in the Core program has also been evaluated in the Delphi-Battelle test stands.

The three modeling tools that are used extensively on the Delphi-Battelle program were first developed by the Core Technology Program. They are:

- A Spreadsheet Model Of Cell Electrochemical Performance. This is the algorithm that calculates cell voltage as a function of current, temperature, fuel composition and cell physical characteristics.

- Electrochemical Modeling Of Stacks. This technique uses a Computational Fluid Dynamics code with the spreadsheet electrochemistry algorithm embedded to model the spatial distributions of electrochemical activity, temperature and fuel depletion for multi-cell stacks.

- Thermal Cycle Modeling. This technique uses Computational Fluid Dynamics and Finite Element Analysis codes to model the heat transfer and resulting temperature and stress distributions in stacks during thermal cycles. The Core Technology Program developed these modeling tools over a two-year period starting in mid FY 2000. Transfer to and use by the Delphi-Battelle Program started in mid FY 2001. Refinements continue on the models under the Core Technology Program.

The G-18 glass being used by the Delphi-Battelle team was first developed in the Fossil Energy AR&TD (DOE) project at PNNL.

The silver-copper braze being used by the Delphi-Battelle team was first developed in the Fossil Energy AR&TD (DOE) project at PNNL.

3.0 EXPERIMENTAL APPROACH

Currently Delphi APU development is focused in Rochester, New York, at the Technical Center Rochester. The facilities and floor space required for development testing began to exceed the building capabilities in 2001, and a decision was made to move into additional facilities located 5 miles north of the engineering center at 285 Metro Park Boulevard in the Town of Brighton. Building modification began in December of 2001, and our first test began in December of 2002.

At this time, the original engineering center houses balance of plant hardware testing labs and thirty percent of the fundamental stack development labs.

The Metro Park facility is a 2220 square meter facility, currently using 500 square meters for development labs and 450 square meters for system/subsystem build capability, with 220 square meters of office space. All labs have access to gasoline and diesel fuels as well as any mixture of H_2, CO, CO_2, N and reducing gases under Class I Div I safety standards. Currently stack, reformer, APU system, as well as catalyst extended durability labs, are operational. The building also houses an electronics development lab with emulation capabilities for system/subsystem controls and hardware development.

3.1 System Design and Integration (Task 1.0)

This section will now also include the information previously reported for Task 6.0 / System Fabrication and Task 7.0 / System Testing. This change was requested in the previous Technical Progress report for the period of January – June 2003.

3.1.1 Transportation APU System Design and Integration

The system integration levels are reviewed in **Figure 3.1.1-1**. Level I integration represents the individual testing and development of the major subsystems and components. The major system modules are: the Application Interface Module, Plant Support Module and Hot Zone Module. Level I integration represents the close coupling of the major system modules such that all major system functions are represented and functional during the test. In the close-coupled, Level I integration level, the Hot Zone Module plant is supported fully by the main-blower, valves, sensors, and electronics contained in the Plant Support Module. Typically, a stand to support instrumentation is employed at this level, but no product outer enclosure is used. This allows for easy access to critical subsystems, easy deployment of development instrumentation, and reduced thermal issues that may be introduced when the product enclosure and intended integration is deployed.

Level II integration represents the application target (product) package, integration, and function for the SOFC power plant, or APU. In the laboratory, a stand is employed to hold the product and facilitate fuel, air, electrical, and exhaust connections, but the intended construction and function of the system should be representative of product intent at this integration level.

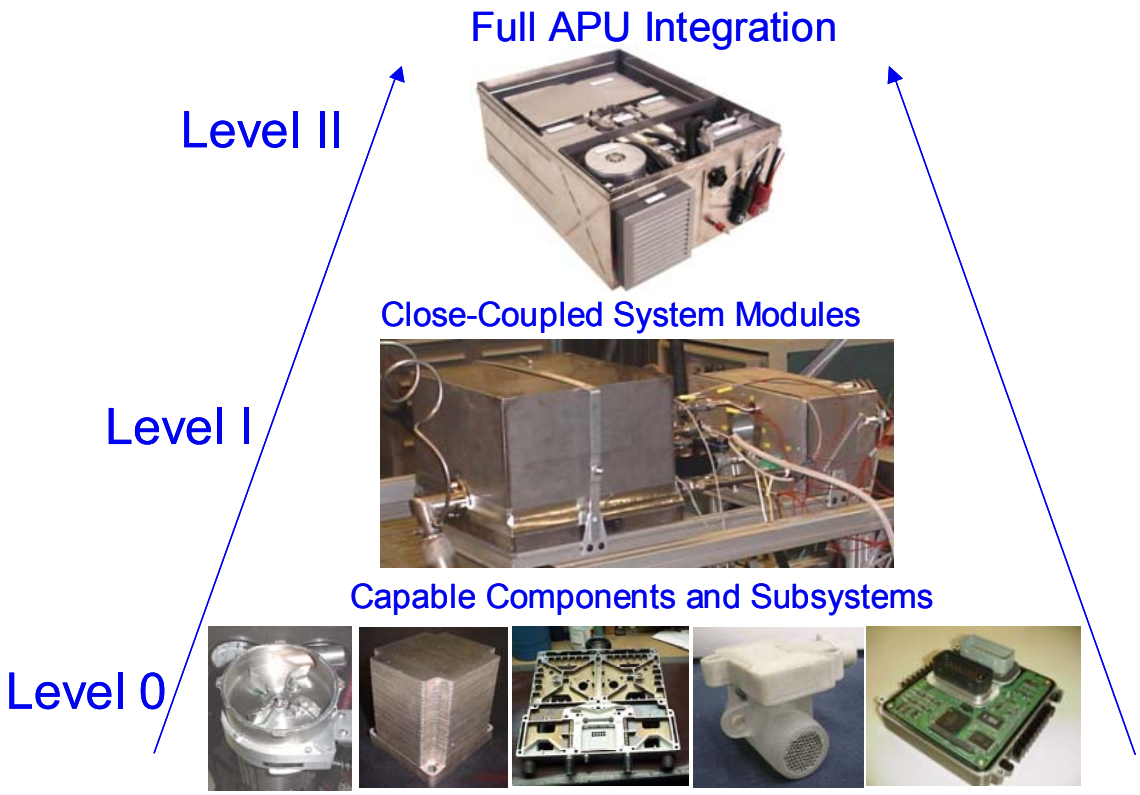


Figure 3.1.1-1 Transportation SOFC APU – System Integration Levels

In the System Laboratory there are currently, two complete test stands operational. Stand I supports Level I system integration testing (close-coupled system). Stand II supports Level II system integration testing (APU). These two stands are supported by an AeroVironment® dual-channel load bank / power supply, an electronics interface with a dSPACE® and Control Desk® control system interface to monitor and operate all APU functions for development with LabVIEW® data acquisition. The lab is also equipped a Horiba® emissions analyzer, an Orbital® mass spectrometer and an AVL® fuel supply cart. Two additional APU durability stands will be operational by the second or third quarter 2004. The SOFC System Laboratory is shown in **Figure 3.1.1-2**.

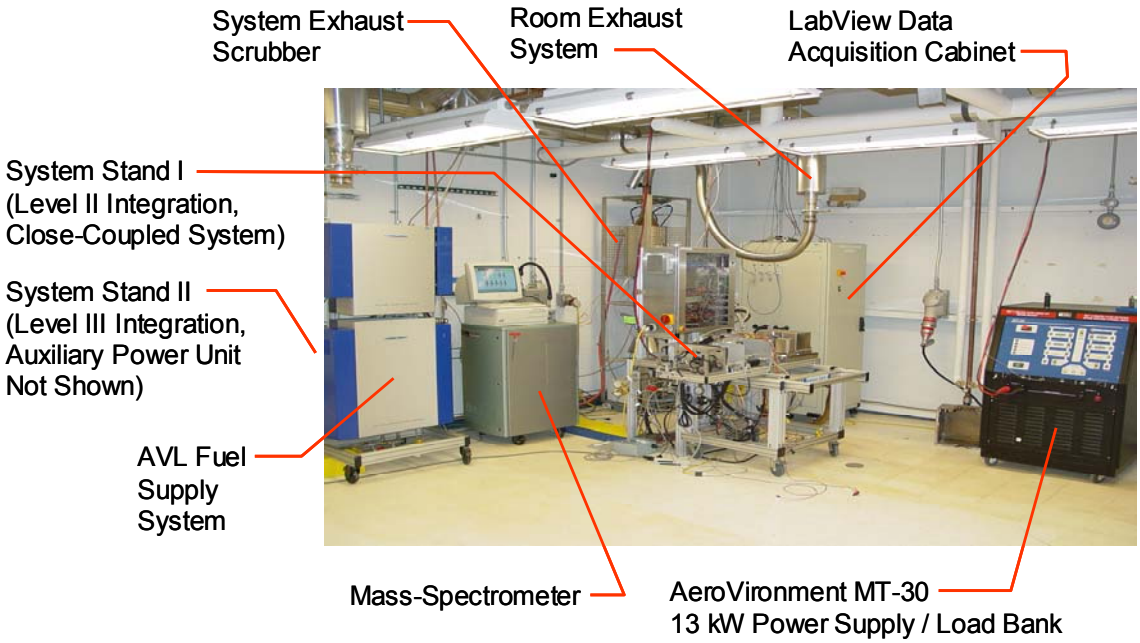
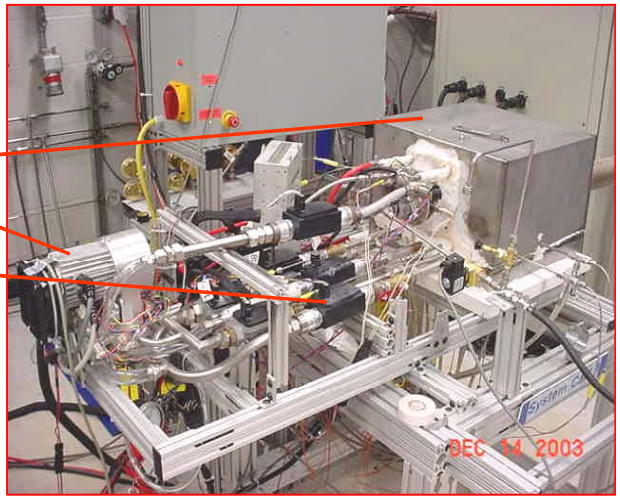


Figure 3.1.1-2 Transportation SOFC APU – System Test Laboratory

During the period covered by this technical report, system integration and development was conducted on both System Stand I (Level I) and System Stand II (Level II) to support Gen 2B and Gen 2C system hardware design levels. Details of Gen 2B and 2C results will be given in Section 4.1. For reference, system hardware on test on their respective test stands is shown in **Figures 3.1.1-3 and 3.1.1-4**.

System Stand 1
(Close-Coupled System)
Transportation-Gasoline
SOFC APU[1] Gen 2C

Hot Zone Module (Insulated)
Process Air Module
Massflow Meter Instrumentation



Process Air Module
Stack to 42V DC Converter
System Controller
Motor Controller

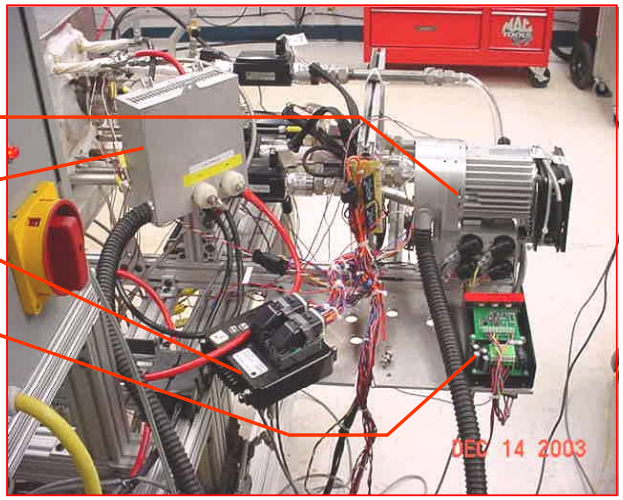


Figure 3.1.1-3 Transportation SOFC APU - System Test Stand 1

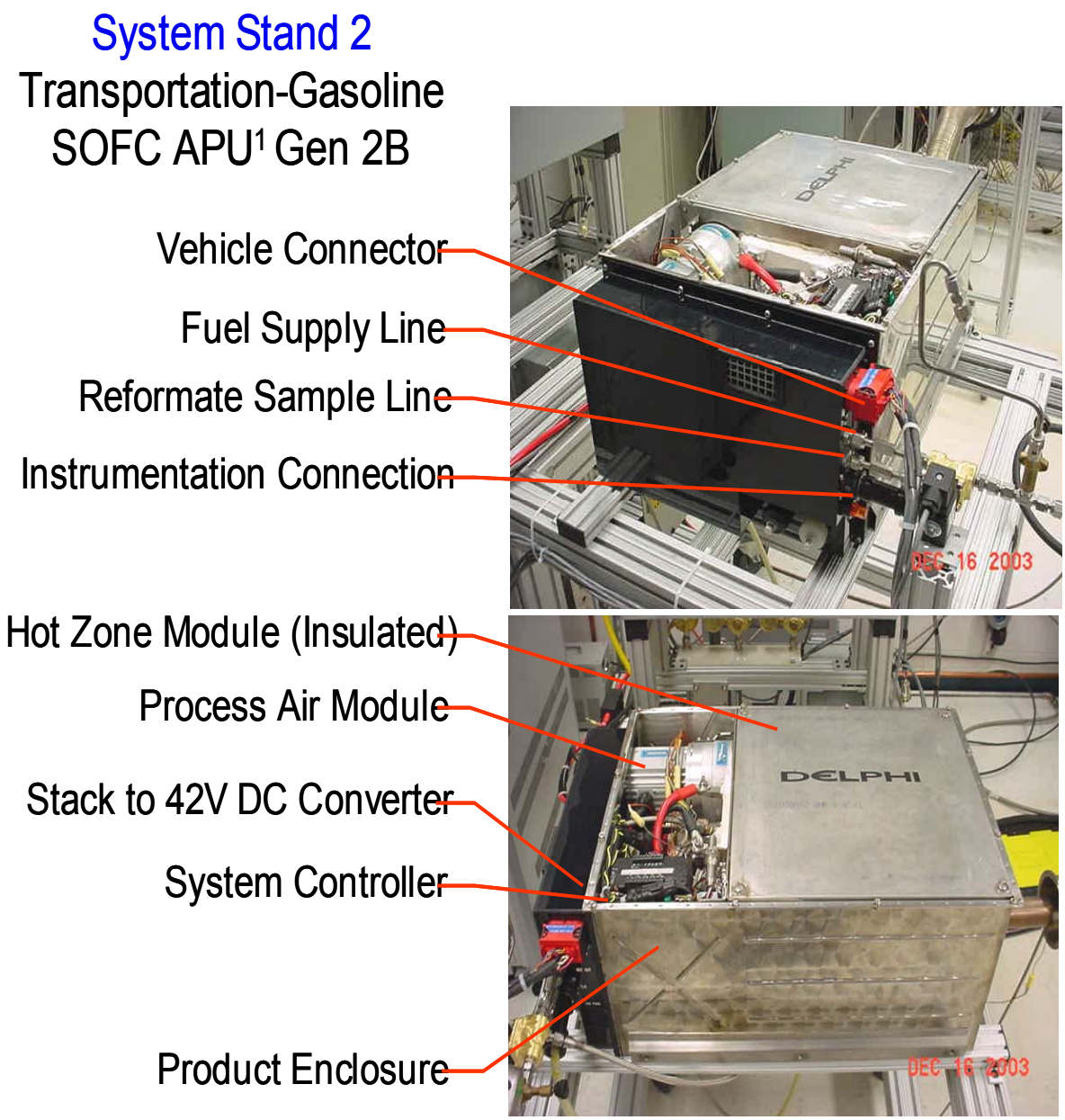


Figure 3.1.1-4 Transportation SOFC APU - System Test Stand 2

3.1.2 SPU System Design and Integration

The experimental approach, or development plan, for this period was to begin a marked increase in the focus and efforts leading to the completed Demonstration System A deliverable for the end of Phase 1. The previous reporting periods have stated that the primary strategy and objective have been the development of base technologies with a focus towards the transportation auxiliary power unit. This strategy is based on the technical challenges and requirements being similar to many of the stationary power unit's requirements. Development would adopt both sets of requirements. Due to better

understanding and forecasting of the expected component performance in the balance of Phase 1, new stationary system configurations have been considered and will be adopted for 2004 and 2005.

The Delphi stationary power unit design for the 2004 and 2005 period (completion of Phase 1) will be thoroughly detailed in the next reporting period. The July - December 2003 period was a focusing time for the basic commercial planning and commonization of core technologies within the SOFC program towards the SPU product. The period within January to June 2004 is planned to be used to complete updated system requirements, system modeling and system designs. The commonization of the core componentry will be addressed in this period also for the APU and SPU programs. Using a selected amount of common design, development time and componentry addresses the strategy of lower system costs through high volume usage of common hardware.

The planned testing for the Delphi Demonstration System A SPU will be following successful test demonstrations to DOE personnel at our Technical Center Rochester labs. The current timing forecasts the Demonstration System A tests concluding internally in November 2005 and a planned demo to the DOE by Dec. 9, 2005. Upon approval and sign off in Rochester, NY, Delphi would require approx. 1 week to pack and ship the unit for arrival to the DOE NETL site in late December 2005. The operation of the system at the DOE site (assuming all lab connections are coordinated appropriately) would begin approximately 2-3 days from arrival and checkout at NETL.

The following areas were addressed during this period:

- Product configuration and process mechanization
- Commercialization plan (connection and sizing)
- System architecture block diagram
- Basic physical layouts and packaging

The primary configuration change is the increase in the overall package volume away from the conceptual final APU volume of 50 liters. The ideal development volume does not require the development teams to invest a disproportionate amount of time in packaging and allows more development focus into the specific performance requirements that are important to commercialization. The basic package for development system and demonstration system A will be a larger volume system that utilizes 4 stack modules. This differs from the auxiliary power unit configuration using 2 stack modules arranged in a small high-density package for vehicle mounting.

Focusing on the deliverables for Phase 1, the system configuration will also be laid out to improve development access and maintenance. This configuration allows for a higher level of instrumentation for development. The trade-off recognized in such a configuration is the thermal management aspects of a small volume product. This will be addressed at a later phase based on acceptable physical volume feedback from actual market analysis.

The modular approach that is a cornerstone of the transportation APU integration plan will be retained with the SPU system. These modular sections were defined by the names Hot Zone Module, Plant Support Module, Application Interface Module and Product Enclosure. The largest difference from APU plans to SPU plans is the product enclosure for a stationary system. This enclosure is impacted by the product configuration decisions as part of the market studies for Delphi. For purposes of the Phase 1 SECA program, systems engineering will be developing around an exterior pad mounted power unit design that is integrated with a residences primary gas and electricity supply feeds. Prototype focus is on approx. 5 KW net power SPU for initial prototypes in 2004-05. Larger systems (up to 10 kW) may be a better commercial output level but studies will need to support this sizing.

The following issues were identified as significant between transportation and stationary power systems:

- Supply gas pressure is limited to low pressure (<35 kPa) in residential homes.
- Higher power is available for start-up (AC and/or DC power to start system).
- Thermal cycle / start frequency is much lower (100s of hours between cycles).
- Acceptable cold start times could be much longer (cost / durability sensitive).
- Stack oxidation protection could be by replaceable bottled gas or self-generating.
- Power output is expected to be AC (120/230/240 50/60 Hz) for North America/ European markets.
- Grid connection strategies affect the power electronics / battery pack designs.
- Operational vibration limited to typical earth and residential vibrations. Highest vibration levels will be during delivery and manufacturing.
- Safety codes are completely different and numerous at local and federal levels.

In order to focus Delphi efforts on a product that is acceptable for both our commercial interests and DoE SECA Phase 1 deliverables, the following high-level plan was submitted:

- A full product has both a fuel cell power plant and a product power configuration
- Focus on the fuel cell power plant for a 6000 watt DC gross power output
- Performance, durability, efficiency and manufactured cost at highest focus
- Secondary focus on power electronics and refined package issues
- Ultimate product configuration (i.e., grid connection) will be a business team decision with input from engineering
- Exterior installed unidirectional grid connected residential power system appears to be best initial system direction

Delphi will approach this stationary system development in 3 distinct steps to final product integration and operation. The initial SOFC small-scale system will use a 30-cell stack module that will allow lower cost and smaller space for more prototypes in test and faster development turns for design changes. A planned second quarter 2004 launch of this cart-

based system is expected. A full-scale development system (6000 watts desired) with 4 stack modules would be designed and moved to "build" phase with good results from subsystem and the small-scale system progress. The plan would be to have a third through fourth quarter run date at Delphi. Demonstration System A (6000 watt) system would begin design in late 2004 for a build release in February 2005. Testing would begin in late April 2005 of this system involving the 1500-hour tests as part of the SECA contract.

- **Items to Clarify:**
  - Grid-Power Connection strategy assumed to be grid-parallel where end-user would use high-efficiency fuel cell system power for the majority of daily electrical demand
  - Combined Heat and Power systems would be integrated into second generation releases

- **Grid Connection Strategy / Business Case Determines Designs:**
  - Grid Connect Parallel Unidirectional
  - Grid to start and support high-load peaks in home only (load transients)
  - Grid Connect Parallel Bi-directional
  - Grid to start, support high-load peaks in home and out on grid
  - No Grid / Stand Alone: Battery to start and level power demands (No Grid)
  - Grid Connect / Back-Up: Reacts to loss of grid power only / battery start
  - Battery capacity for transients
- **Needs Definition:**
  - Length of transient (milliseconds to hours)
  - Typical usage cycle and maximum power user cycle

3.2 Solid Oxide Fuel Cell Stack Development (Task 2.0)

Typical stack testing is carried out using a test stand that has a hot furnace, electrical load bank and gas mixing cabinet (Lynntech Inc). Cells are fabricated at Delphi. A typical experiment involves measurement of standard polarization curves and power densities at constant voltages for durability using simulated reformate.

The Interconnect Resistance Unit is a device that is used to characterize the electronic conductivity of the interconnects at operating temperatures. A current at a density of 0.5 A/cm^2 is run through a double cathode "sandwich" as the specimen is heated at stack operating temperature in air. Various material combinations and configurations for separator plate, mesh, bonding paste and current collector grid can be conveniently tested in the Interconnect Resistance Unit. The Area Specific Resistance (ASR, $ohm\text{-}cm^2$) is calculated as ½ the measured resistance multiplied by the surface area.

The seal rupture strength test unit is used for quantitative comparison of seal joint strengths. A metal washer with the sample attached, 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 (Task 3.0)

3.3.1 Tubular Reformer Testing Setup

3.3.1.1 Mass Spectrometer

A third mass spectrometer has been added for use in the Reformer Lab. This third unit is an older unit that was rebuilt to the same specifications as the other two newer units.

3.3.1.2 Controls and Data Acquisition

3.3.1.2.1 dSPACE®

The control strategy used on the APU system with the dSPACE® controller has now been implemented in the Reformer Lab. This will allow the reformer development team to analyze the control strategy effect on the performance of the reformer.

3.3.1.2.2 ADAM (Advantech Data Acquisition and Control Module)

No activity in this period.

3.3.1.2.3 Labview®

The Labview® data acquisition system now has the ability to take “averaged” test data, recording an average reading over a specified time interval and its standard deviation. This was implemented to ensure accurate and statistically sound data collection.

3.3.1.2.4 Lab Fuel / Gas Controls

A gas blend cabinet has been installed for blending customized mixtures of simulated stack anode tail gas for both recycle feedstream to the reformer inlet as well as combustor fueling. This cabinet interfaces with the Labview control system to determine desired mixtures and flowrates.

Two micromotion coriolis gas meters were purchased for use with the recycle pump. These meters read mass flow measurements that account for changing densities of the fluid, so they are ideal for varying anode tail gas compositions and flowrates. They will help characterize the performance of the recycle pump.

3.3.2 Reforming Catalyst Development

3.3.2.1 Catalyst Preparation

The same catalyst preparation methods and procedures that were described in prior reports were employed during this reporting period.

3.3.2.2 Catalyst Testing

The same catalyst testing methods and procedures that were described in prior reports were employed during this reporting period. In addition, a new rapid aging method was developed.

3.4 Development of Balance of Plant Components (Task 4.0)

3.4.1 Combustible Gas Sensor

Testing was conducted to further characterize the sensor's response to hydrogen and investigating alternative sensor controller strategies. Additionally, packaging studies were set up and conducted at the system level.

3.4.2 Air Delivery and Process Air Subsystem

3.4.2.1 Process Air Blower Motor

Significant analysis was performed to determine the optimal machine and controller technology for the Delphi Process Air Module Blower Motor. Results are shown in Section 4.4.

3.4.2.2 Process Air Manifold

A test manifold is being fabricated from high strength, high temperature stable material using a stereo-lithography process so that the air control valves can be integrated and tested on a flow bench to determine their performance characteristics. See section 4.4 for a complete description.

The test manifold will consist of the air control valve, a stepper-motor actuator, an existing high-volume production automotive component, while the mass airflow sensor is a repackaged version of the standard Delphi high-volume production automotive air meter. Each of the four mass airflow sensors will be the same part so that only one part needs to be designed. Accurate, repeatable calibration of the Delphi sensors for the APU has been an issue in the past. This was most likely a result of the airflow bench used for calibration not accurately representing the flow characteristics of the APU. Using physical models of the APU components in the airflow calibration bench should vastly improve the calibration of the sensors in the future.

3.4.3 Hot Zone Components

3.4.3.1 Gaskets

Delphi has set up and tested multiple variations of metal gaskets. Experimental tests were made on each gasket examined. Results of this testing are shown in Section 4.4.

3.4.3.2 Integrated Component Manifold

Design, fabrication and initial system testing with these Integrated Component Manifolds were completed during this period. Results of system testing are presented in Section 4.4.

3.4.3.3 Cathode Heat Exchangers

Design, specification, and vendor selections for the dedicated Cathode Heat Exchanger Test stand has been completed, and components have been ordered. This test stand is expected to be operational the first quarter of 2004.

3.4.3.4 Igniters

As previously reported, failures of the ceramic igniters resulted in the procurement of new prototype igniters being fabricated with a higher temperature braze alloy and higher temperature wire insulation. Additionally, in order to better understand potential failure mechanisms resulting from igniter location in the application, it was decided to equip some test igniters with thermocouples. The thermocouples are located in close proximity to the igniter tip and will be used to indicate igniter tip temperatures. Successful use of thermocouple equipped igniters could eliminate the separate thermocouple installation located next to the igniter, and will provide more accurate temperature feedback.

3.4.4 Re-cycle Pump

Set up and initial testing of prototype pumps for re-cycle of anode tail gas was completed. Details of this analysis are shown in Section 4.4.

3.5 Manufacturing Development (Privately Funded) – (Task 5.0)

Developments for manufacturing developments are reported as part of each subsection for the solid oxide fuel cell system.

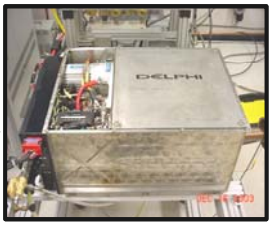
3.6 System Fabrication (Task 6.0)

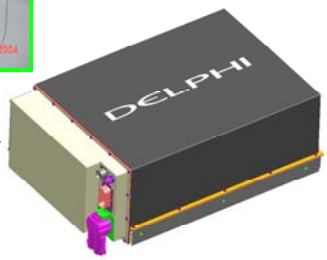
A design level summary of the SOFC APU is shown in **Figure 3.6-1**. Systems that have been fabricated during the period covered by this technical report are:

- Gen 2B: Up to the APU (Level II) Integration
- Gen 2C: Up to the Close-coupled System (Level I) Integration

The Gen 3A/3B design level is currently in the design phase. Details supporting this design level will be given in Section 4.0.

- Proof-Of-Concept (POC)- 12/2000
  - First demonstration of gasoline-fueled SOFC APU[1]
- Gen 2A – 12/2002
  - Revised package, integrated design.
  - First cold-start, warm-up, and power from a system (<200W Gross)
- Gen 2B – 11/2003
  - Improved reliability, controls, and assembly (integration) from 2A
  - First Net Power in APU System (186 W Net, 660 W Gross, 2x15 cell stacks)
  - First APU[1] run in full enclosure
  - Most full thermal cycles in a system with a stack (3) – Gen 2 stacks
- Gen 2C – 03/2003
  - Gen 2B APU[1] modified to use Gen 3 stacks (2 x 30 cell)
  - Highest net power achieved in system (423 W Net, 2x30 cell stacks)
- Gen 3A/3B – 6/2004
  - APU redesign - 200mm tall APU package target
  - Gen 3 Stacks
  - Gen 3A – CPOx Reformer, no Anode Recycle
  - Gen 3B – Anode Tail Gas Recycle (TGR) deployed





3.6-1 Transportation SOFC APU - System Progression Summary

3.7 System Testing (Task 7.0)

During the period covered by this technical report, the goals of system testing and development were as follows:

- Build and Test a Gen 2B APU
- Demonstrate 5 thermal cycles on an Gen 2B APU
- Deploy the ECU to the system and demonstrate automatic control of the system with APU 08 Control Software
  - The product intent ECU replaces the large control cabinet and Micro-Autobox® controller used for earlier system testing and development
- Build and test a Gen 2C APU
  - Demonstrate function of Gen 3.0 2x30 cell SOFC Stacks at the system level

Details of these system hardware design levels and subsequent results will be given in Section 4.0.

4.0 RESULTS AND DISCUSSION

4.1 System Design and Integration (Task 1.0)

4.1.1 Define System Requirements

4.1.1.1 Transportation APU System Requirements

During the period covered by this technical report, focus has been placed on Gen 3B Transportation APU system targets and component requirements to support the Gen 3B APU design effort.

The Gen 3B design level has a target capability approximately 50% of commercial application target levels with respect to net full power electrical output and efficiency, while achieving application target package size. It is a goal of the Gen 3B APU design level to have sufficient thermal cycle durability, life, and operational reliability to begin initial trial evaluation in the target application.

To close these capability gaps, significant advancements in reformer and SOFC stack capacity, efficiency, and durability need to be made. To support the target of 3.2 kW gross stack output, which will result in approximately 2.2 kW net electrical output (at a regulated 42V), the Gen 3 SOFC stack must be capable of 500 mW/cm^2 at a cell operating voltage of 0.7 V/cell. Stack cell integration at the 60-cell level (2 x 30 cell stacks, series electrical connection) will also be required to meet the target. The total parasitic load for the electrical support of the APU should be kept to 590 W maximum.

4.1.1.2 SPU System Design and Integration

These issues were identified as significant between transportation and stationary power systems:

- Supply gas pressure is limited to low pressure (<35 kPa) in residential homes
- Higher power is available for start-up (AC and/or DC power to start system)
- Thermal cycle and start frequency is much lower (100s of hours between cycles)
- Acceptable cold start times could be much longer (cost / durability sensitive)
- Stack oxidation protection could be by replaceable bottled gas or self-generating
- Power output is expected to be AC (120/230/240 50/60 Hz) for NA / Euro markets
- Grid connection strategies effect the power electronics / battery pack designs
- Operational vibration limited to typical earth and residential vibrations. Highest vibration levels will be during delivery and manufacturing.
- Safety codes are completely different and numerous at local and federal levels

In analyzing our hardware from APU to SPU, we separated components of the final product into three levels of components. This will assist our efforts to support our co-development strategy between the two markets:

- Level 1: Design changes limited or not allowed / High investment and risk
- Level 2: Design changes allowed / Use same technology and process techniques
- Level 3: Low investment / low technology or commodity item

Level 1 components identified are such items as the 30-cell SOFC stack module, the process air module, the fuel cell controller module, and the recycle pump and motor driver. Level 2 and Level 3 items will be assessed in early 2004 for level status using lab test data and modeling output. Design changes should be justify by impact and/or cost-reduction potential based on reasonable commercial targets. SPU configurations will look at best re-using of hardware and technologies from the APU programs.

The basic system configuration layout that will be the foundation for the Phase 1 system at Delphi will be a vertical 400-liter enclosure. The volume will be adjusted according to the system development possible and the components performance and design progress that is completed in 2004. Having stated that the priority is not on package volume, an adjustment may be needed in late 2004. The final configuration for the Demonstration System A system is most affected by the power output and durability trade-offs that will be needed for the stack modules and the final size of our natural gas reformer and desulfurization method.

Basic requirements have been established and have been used for preliminary subsystem and system work to date. A refinement of these documents (to reflect the Phase 1 development plan in 2004 and 2005) will be issued in February 2004 to Delphi teams.

4.1.2 Develop Conceptual System Design

4.1.2.1 Transportation APU Conceptual Design

To support the Gen 2C APU performance targets, improvements in the APU conceptual design have been made between Gen 2B and Gen 2C. These include the following:

SOFC Stack:
The Gen 2C APU will use the Gen 3, 2x15 Cell SOFC Stacks featuring:

- Improved system gasket interface design for improved connection reliability
- Improved internal seals for improved thermal cycle durability

Balance of Plant:

Integrated Component Manifold:

- To support the installation of Gen 3 SOFC Stacks, the Integrated Component Manifold has been redesigned. In addition to improved gasket seal geometry and fastening, the burner exhaust is routed directly in the manifold instead of an external “can” manifold around the stacks. This both improves system start-up time and reduces exhaust gas leakage from the Hot Zone Module.

To support the Gen 3B APU performance targets, improvements in the APU conceptual design have been made between Gen 2C and Gen 3B. These include:

System Design:

Single Path Combustor (Burner) Exhaust Routing:

Current Gen 2B hardware has a symmetric design around reformer and burner. Burner exhaust splits to the right and left side of the system to feed two separate Cathode Air Heat Exchangers. During development testing, it has proved difficult to balance left and right side exhaust temperatures. Since the cathode air to each SOFC stack is individually preheated from the split stream, left-to-right exhaust temperature imbalance has caused a general temperature imbalance in the system that may persist throughout operation. Elimination of the burner exhaust path split not only eliminates this problem, but also has the added benefit of eliminating one of the two cathode air heat exchangers.

Improved Thermal Management within System Enclosure

Current system hardware suffers from high air temperatures due to heat leakage from the Hot Zone Module to the Plant Support Module. To improve this condition, the Gen 3 conceptual design has increased insulation allocation between Hot Zone Module and Plant Support Module and a reduced number and size of high-to-low temperature pass-throughs.

Additionally, a low-power cooling fan is employed in the system to circulate cool ambient air through the Plant-Support-Module to both cool the zone and subsequently cool the power electronics.

Reduced Package Size:

The Gen 3B APU features a reduced 200mm package height to be consistent with Transportation application targets. The Gen 2B APU had a 275mm package height.

Improved Enclosure / Support Frame Design For Improved System Assembly:

Improvements continue to be made to the enclosure and support frame for the Transportation APU. The Gen 2B APU required lifting the Hot Zone Module and Plant Support Module within a support frame into the outer product enclosure. This assembly and disassembly process is required whenever significant hardware changes are required in either area. For Gen 3B, the package has been inverted such that no lifting of the assembly frame is required for assembly. The assembly frame forms the bottom structural member of the enclosure subsystem. Once Hot Zone Module and Plant Support Module and Application Interface Module are assembled together, the outer enclosure cover is assembled to the unit. This completes the full product assembly process.

Balance of Plant:

Integrated Component Manifold:

Special emphasis has been placed on high-reliability, high-temperature interfaces between components and manifolds. For Gen 3B, an enhanced interface geometry and gasket seal technology will be employed. Additionally, heat transfer breaks and thermal isolation will be provided for in the design to reduce influence of high temperature gradients on sensitive subsystems and components.

Anode Tail Gas Recycle Pump:

To support high efficiency reformer operation, an anode tail gas recycle pump and anode tail gas heat exchanger (cooler) will be employed in the Gen 3B APU.

Reformer
High-Efficiency (Endothermic) Reformer Design:

To improve overall system efficiency, the Gen 3B APU will utilize a new reformer design featuring:

- Integrated burner assembly (Gas Phase Combustor) within main reformer
- New low-mass, improved air temperature distribution non-contact fuel vaporizer assembly
- Increased thermal resistance in reformer body insulation pass-through

SOFC Stack:
The Gen 3B APU will use the Gen 3.1, 2x30 Cell SOFC Stacks featuring:

- Improved power connection terminal lead routing (eliminate short-circuits)
- Performance: Improved power density and reduced degradation
- Improved system gasket interface design for improved connection reliability
- Improved internal seals for improved thermal cycle durability

4.1.2.2 SPU Conceptual Design

Conceptual system design for the revised mechanizations for the SPU will be completed following mechanization approval and modeling support and confirmation.

4.1.3 Develop System Mechanization

4.1.3.1 Develop Transportation APU System Mechanization

Several changes have been made to the Gen 3B physical plant mechanization during the period covered by this technical report. They are as follows:

- **Addition Of Anode Tail Gas Recycle Function:**
  The Anode Tail Gas Recycle Pump will provide the necessary circulation of stack anode tail gas to the reformer air/fuel vaporizer

  The Recycle Cooler Heat Exchanger will reduce the anode tail gas temperature from 750 ºC to approximately 100 ºC. This will allow the Anode Tail Gas Recycle Pump to be realized with conventional pump technology, and prevent fuel pre-ignition in the reformer fuel vaporizer.

- **Addition Of Fixed Burner Air Bypass:**
  When moderate SOFC stack fuel utilization and anode tail gas recycle is employed in the system, the anode tail gas routed to the burner is both depleted in Heating Value and reduced in mass-flow rate. When large cathode air mass-flow is used to manage stack temperature under high electrical loads, burner temperature may drop below target due to too much excess air in the combustion process. One solution is to eliminate the cathode air tail gas linkage back to the Gas Phase Combustor (GPC) and provide all combustor air directly from the process air system. To support high-

efficiency operation of the reformer, this is undesirable in that the sensible heat contained in the cathode tail gas is not used effectively in the burner and subsequently in the reformer reactor. Another solution is to add a high-temperature valve to the system that allows for control over cathode tail gas bypass around the burner. This solution has significant cost, control, and reliability implications. The solution employed in the Gen 3B system mechanization is a hybrid of these two solutions. A fixed (un-actuated) valve will be employed to bypass a fixed percentage of cathode air tail gas around the burner. The bypass percentage will typically be above 75% for most operating points of interest.

- **Separate Process Air And System Cooling Air (Purge Air) Streams**
  In the current Gen 2B and Gen 2C APUs, process air inlet air is used to cool the system airspace as well as provide cooling for the power electronics. The heat added to this air stream has proved to impact the blower efficiency, blower operational envelope, and blower capacity. The solution employed in the Gen 3B mechanization is to split the highly filtered, high flow and pressure process air stream from the lightly filtered, high flow and low pressure cooling air stream. This allows for significant cool airflow to be provided to critical electronics systems within the APU with a very low power air source (<15W), and heat rejected into this cooling stream is exhausted from the APU, instead of being directed into the process air blower subsystem. This change has the additional benefits of completely isolating the interior spaces of the APU from the process air stream (reduced contaminant risk), and having low power, reliable cooling air independent of process air flow rates.

4.1.3.2 Electrical and Electronics System

4.1.3.2.1 Power Conditioner for Stationary APU

A Magnetek DC/AC power inverter is the unit designed to convert DC fuel cell stack output power to usable 120 VAC power **(Figure 4.1.3.2.1-1)**. The inverter has 2 standard wall sockets for output power. The units use simple digital signal lines for control that can be connected to the system controller for configuring user output based on the fuel cell auxiliary power unit's state. The stationary power conditioner's efficiency is greater than 91% for the majority of operating points **(Figure 4.1.3.2.1-2)**. This unit has been fully bench tested and the performance has been verified.

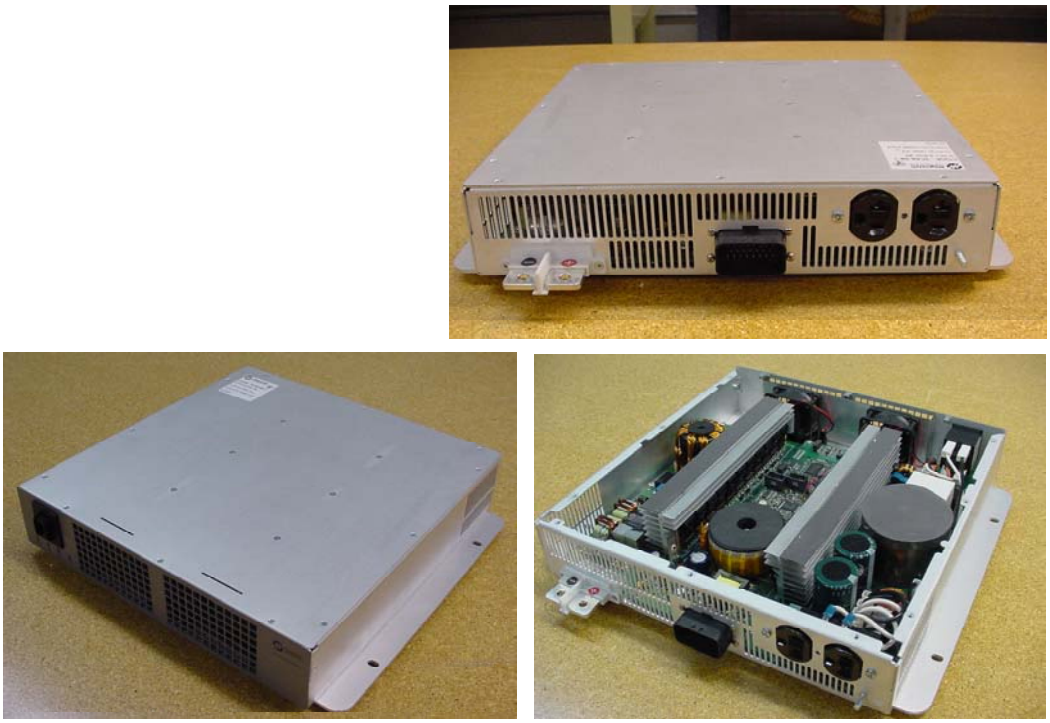


Figure 4.1.3.2.1-1 DC/AC Stationary Power Conditioner

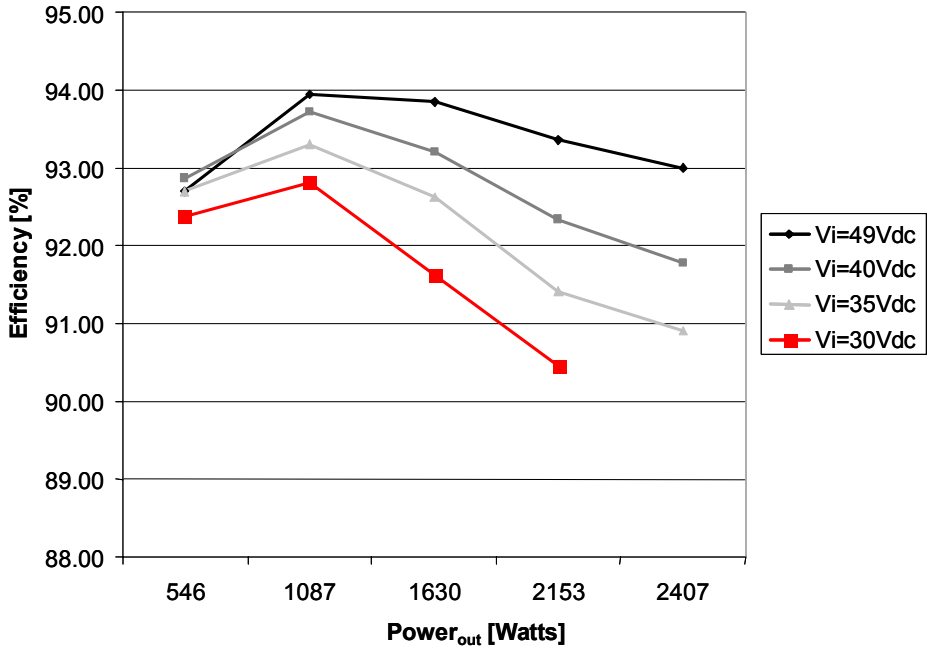


Figure 4.1.3.2.1-2 DC/AC Power Conditioner Efficiency versus Output Power

4.1.3.2.2 Power Conditioner for Transportation APU

A Solectria DC/DC power converter is designed to regulate 42-volt power to the user of the SOFC APU **(Figure 4.1.3.2.2-1)**. There are several configurations of power conditioners to allow development for various applications. This generation of hardware has two power levels: There is a 1.8-kilowatt DC/DC converter and a 3-kilowatt converter. The power conditioners' efficiencies are greater than 85% for the majority of operating points **(Figure 4.1.3.2.2-2)**. These are each also configurable as 100 kilobaud Low Speed Fault Tolerant Controller Area Network (CAN) or 500 kilobaud High Speed CAN. These units have been bench tested and verified in the system. All software and hardware interaction has been tested and the unit functions appropriately under fully automatic control of the power management software.

Figure 4.1.3.2.2-1 DC/DC Mobile Power Conditioner

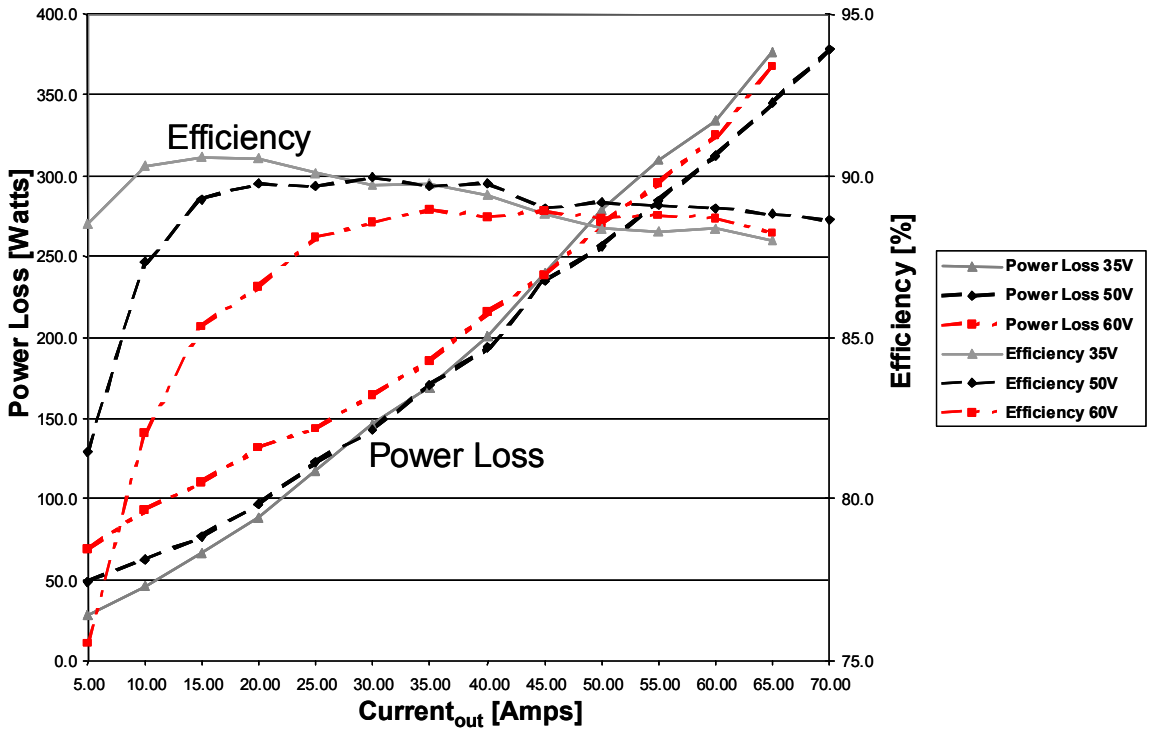


Figure 4.1.3.2.2-2 DC/DC Power Conditioner Efficiency and Power Loss versus Output Current

4.1.4 Establish System Thermal Insulation Requirements

4.1.4.1 Transportation APU Thermal Insulation Requirements

Current generation APU hardware suffers from high heat leakage from the Hot Zone Module to the Plant Support Module. The heat transfer results in very high ambient temperatures in the Plant Support Module (90-100 ºC). The causes of the excessive heat transfer include:

- Proximity of the Gas-Phase-Combustor to the insulation bulkhead In the Gen 2B/2C APU hardware. The GPC is located in the Hot-Zone-Module in close proximity to the opposite side of the insulation bulkhead. The local temperature at this point far exceeds the 750 ºC target temperature for the design of the insulation.

- Large Low-Performance Reformer Pass-Through. The reformer air/fuel mix feed duct passes through the insulation into the Hot Zone Module where the reformer catalyst is located. The geometry of this duct is difficult to seal with thermal insulation. In addition, there is a large amount of heat conduction along the duct walls.

- Large Number Of Air Tube (Feed), And Sensor Pass-Throughs With Low Performance Seals. Current generation APU hardware has approximately 5 air feeds, 2 igniters, and 6 thermocouples passing through the insulation. The relief of the high performance insulation is generous in the areas of pass-throughs, and filler insulation material is low in performance.

- Exhaust Gas Leakage In The Hot Zone Module. The Gen 2B APU has an external exhaust gas manifold around the SOFC stacks that has proved difficult to seal even at very low pressures. Any exhaust leakage from this duct will migrate into the Plant Support Module airspace. At operating temperature, every 1 g/s of exhaust gas leakage could account for up to 1000W of heat load on the Plant Support Module airspace.

For the Gen 3B APU, adjustments have been made in all of the above areas to address heat leakage. Air- feed pass-throughs have been reduced to 3 from 5. Reformer pass-through geometry will be simplified with special attention placed to thermal breaks in the duct. External exhaust manifolds have been eliminated from around the stacks (also in Gen 2C). While the GPC is still in close proximity to the insulation bulkhead, additional insulation has been allocated to the bulkhead to improve its performance.

4.1.4.2 Stationary APU Thermal Insulation Requirements

Thermal insulation cost and volume allotment will be adjusted in early 2004 to reflect the focus on system cost. Economies of scale studies between the APU and the SPU may also help with shared insulation techniques.

4.1.5 Provide System Design Support for the Fuel and Delivery Systems

Delphi has begun to better understand the natural gas distribution pressure issues in residential markets. The issue is the available gas pressure versus the operating pressure for gas inlet to the SOFC system. Residential gas safety, National Fire Protection Agency, and gas industry codes limit pressure access at various points. Delphi may propose an alternative pressure concept in 2004 that may require review by DoE, safety and gas industry experts. The basic idea for this alternative concept is a utility gas and electric control center that allows high-pressure input to an exterior Stationary Power Unit. The concept may also allow for the remote metering of gas and electricity for the utility company and would be integrated a single package for installation.

During the ramp up of Stationary Power Unit engineering in Q3/Q4 of 2004, the issue of existing regulation and safety compliance programs was noted as needing communications. The development of the SOFC products may be effected by existing codes that could require the SOFC systems to adopt old or outdated regulations. In order to take advantage of energy efficient techniques and new methodologies, a certain amount of resource should be focused on reviewing such standards as fire codes, industrial safety codes, residential safety codes and distribution regulations that may be obsolete or rendered obsolete by such an emerging technology.

The primary example that can be used is in the area of natural gas supply and safety codes for residential distribution. The pressures that are used typical to a gas appliance in home in the US are 3 to 5 inches of water pressure. An SOFC power system would need to boost this pressure up to a metering pressure for introduction into the fuel reformer since the system we are considering run at elevated pressures (10 to 30 KPa).

The pump required might consume power, which adds to the parasitic power losses, system efficiency, and added cost and complexity to the overall product. The supply pressure to a residence (pre-regulator) is higher and a change in regulator location and plumbing may support a fuel cell power system without the need of auxiliary pumping systems.

The codes followed by the NFPA (National Fire Protection Agency) the NEC (National Electric Code) and several international agencies have had activity underway for several years to address the expected arrival of fuel cell based home power systems. The regulations and codes may not, however, be abreast of impact re-use of certain dated policies have on the cost and roll-out of new products such as fuel cells.

4.1.6 System Control Development

Since issuance of the last report, system control development has continued to progress. Advances have been primarily focused on introduction and maturation of the code to make it compatible with the engineering development ECU controller, a production-like controller which replaces the dSPACE® micro-autobox development controller. Further advances in the control algorithm itself have been made – however the pace of changes has decreased as the performance control algorithm is now becoming more mature.

4.1.6.1 Control System Development Stage

Control Algorithm Modifications:
As mentioned above, fewer improvements were made in the last reporting period. However, there were some.

Power Management:
The power management algorithm is now mature. Changes were made to improve communication robustness between the power management algorithm and the external power requesting process. Additionally, numerous electronic communication modifications were made to allow the power management algorithm to correctly "mode" the power conditioner and the DC-to-DC converter.

Stack Control:
The stack control algorithm was improved to fix the calculations involved with executing a minimum reformate flow through the stack. The fuel cell stack is currently not capable of high utilization, especially at lower power levels. The control algorithm, therefore, now adjusts target utilization at low powers such that a minimum reformate flow is maintained through the stack at all times, even when no power is being drawn. Additionally, the stack model is now incorporated in control directly for polarization curve projection. Previously the (large) polarization curves were installed via table lookups. The new method allows for simple re-calibration of the stack projections (for control purposes) when the stack is replaced or degrades.

Process Air Control:
Upgraded control of the stack cathode inlet and anode outlet temperatures has been accomplished. Previous control of anode outlet temperature via adjustment of cathode airflow level assumed (incorrectly) that the incoming cathode air would always be cooling the stack. Under conditions of no power draw, it has been shown that the stack may need to be "kept warm" by reverting to a heating mode like the stack warm up mode. Stack cooling and heating have now been unified in one algorithm that is employed in all modes. Additionally, modifications to the reformer vaporizer air temperature control, which previously involved separate electric heating and air cooling sections, have unified this control in a single control effort variable (heating watts).

Communications:
Communications of control messages interfacing with the Labview® lab control and data acquisition system have been upgraded to allow block-by-block enable of these messages under calibration control. This change makes the control system communication "configurable" for use in the reformer lab versus the system lab.

4.1.6.2 Control Development Environment

The control development environment developed by Delphi, with help from an outside consultant, continued to be effective for advancement of the system control during the reporting period. Well organized control system definition, documented in multiple word processing documents and organized in a folder structure reflecting the hierarchy of the

control system and sub-systems continues to be utilized. A multi-sheet, shared action items list in a Microsoft Excel® spreadsheet, documents the changes requested. The calibration environment contained within Microsoft Excel® spreadsheet has been further developed; employing multiple calibration workbooks for the macro hierarchy of the control system, each with multiple calibration worksheets reflecting the sub-system hierarchy in each of the three major blocks of the system (operator interface, plant model, and control system). We continue to utilize the "overlay" approach. Released calibrations are "executed" first during control system code build, with controller and site-specific calibration overlays executed last. The overlay calibration sheets override the default calibration for purposes like controller specific hardware calibrations (e.g. amplifier gain corrections) and temporary tries at new calibrations.

4.1.6.3 Controller Hardware Development

The SOFC engineering development ECU is a functional controller of a Fuel Cell Management System, which combines microprocessor, Fuel Cell APU component interfaces, vehicle component interfaces and software control algorithms **(Figure 4.1.6.3-1)**. It is intended for rapid prototype development and is designed for flexible configuration and modification for controller based development systems. The SOFC ECU is suited for use in multiple development applications. This controller conditions and reads inputs of up to 64 volts, supplies processing capability, and provides output drivers to control actuators as directed by software and calibration. This controller takes the place of the dSPACE® Micro-Autobox® development controller and associated supporting circuitry **(Figure 4.1.6.3-2)**.

Battery	4
Switched Ignition	1
Power Ground	4
Flatpack Mot. Ground	4
VREF1 @100mA1	
VREF2 @100mA1	
VREF3 @ 75mA	1
VREF RTN	3
RX_TX RTN	1
Discrete Input 1	1
Discrete Input 2	1
Discrete Input 3	1
Discrete Input 4	1
Discrete Input 5	1
Discrete Input 6	1
Input Capture 1	1
Input Capture 2	1
5V Temp. Inputs	12
5V Pressure Inputs	7
5V PTC Inputs	2
5V EHC Inputs	2
5V EGR Inputs	4
5V Sensor Inputs	4
*10V Sensor Inputs	4
5V Flatpack Pos. Fdbk	4
5V Current Sense Inputs	4
*64V Analog Inputs	2
*32V Analog Input	1
*14V Analog Input	1
*5V Analog Input	1
*Config. Analog Input	3

*** Configurable Scaling**

****Diagnostics Available**

Features:

32 Bit 40 MHz
448KB Internal FLASH
26KB Internal FAST RAM
6KB TPU Microcode RAM
2MB External FLASH
256KB External RAM
2 CAN Ports
TX/RX Serial Port
CAN Wakeup
IGN Wakeup
Internal Wakeup

Functions:

6 Digital Inputs
2 Freq. Input Capture
3 Analog Ref Voltages
(100mA, 100mA, 75mA)
51 Analog Inputs
Ref Volt Measurement
Internal Temp. Monitor
4 8-Bit ADC Channels
10 HSD Outputs
10 LSD Outputs
2 EST Outputs
2 Injector Drivers
6 Stepper Motor Drivers
4 Flatpack Motor Drivers
(w / Position Feedback)

Mechanical:

Supply 8V. – 16V.
Op. Temp -40°C - 105°C
St. Temp -40°C - 105°C
(2) 173 Pin Connectors

1 HSD, 300mA**
9 HSD, 30mA **DK197007**
8 HSD, 30mA **DK208052**

2 EST 5V source/sink**

2 Injector Driver, 1A**

1 LSD, DOUT11, 0.5A**
1 LSD, DOUT12, 0.5A**
1 LSD, OUT13, 1.0A**
1 LSD, DOUT14, 1.0A**
1 LSD, DOUT15, 0.5A**
1 LSD, DOUT16, 3.0A**
1 LSD, DOUT17, 3.0A**
1 LSD, DOUT18, 1.0A**
1 LSD, DOUT19A, 6.0A**
1 LSD, DOUT19B, ----
1 LSD, DOUT20A, 6.0A**
1 LSD, DOUT20B, ----

24 IAC Motor Driver Signals**
4 Flatpack Motor Drivers**

4 0-5V, 10mA DAC Channel

1 K_CAN_HI (500Kb)
1 K_CAN_LO (500Kb)

1 DIAG_CAN_HI (500Kb)
1 DIAG_CAN_LO (500Kb)

1 K_CAN_HI (125Kb)
1 K_CAN_LO (125Kb)

1 DIAG_CAN_HI (125Kb)
1 DIAG_CAN_LO (125Kb)

1 RX
1 TX

Figure 4.1.6.3-1 SOFC ECU Mechanization

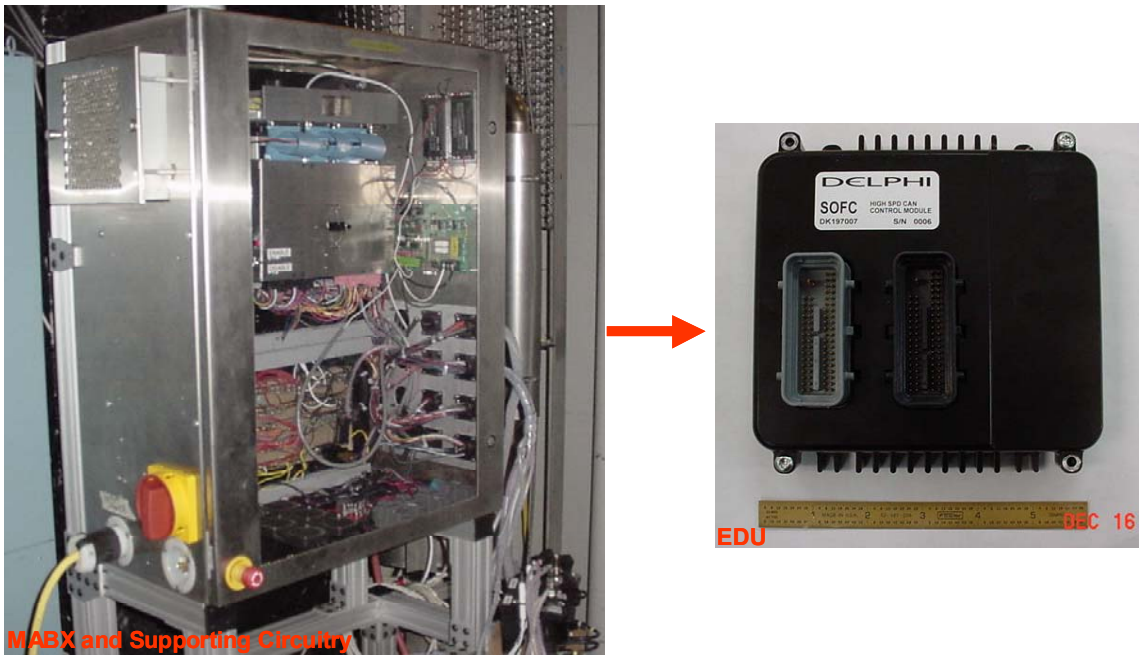


Figure 4.1.6.3-2 SOFC APU Controller – Micro-Autobox ® versus ECU

The ECU is a production intent controller that is based on Delphi's production Engine Control Units. Migration to a production intent controller is advantageous for several reasons: 1) size; 2) testability; 3) durability and, 4) cost. The size of the ECU is much smaller than the Micro-Autobox®, but it also integrates all the supporting circuitry for reading and conditioning signals as well as driving actuators into the controller package. The controller is portable and fits in the intended APU system packaging. In addition, the controller allows for system testing of the actual enclosed APU with a production like controller. Since the ECU is based on proven Delphi production controllers, it is robust and the signal conditioning and driver components are verified and well tested. Debugging hardware and tracing component failures has been minimized since migration from the complex Micro-Autobox® control system configuration. Finally, the cost of each ECU is cheaper than the Micro-Autobox® development controller hardware, software and support since it is internally designed, built and supported.

4.1.6.4 Controller Software Development

There are several advances to the controller software development toolset since the last reporting period. Controller software is still developed using The Mathworks/Matlab/ Simulink/Stateflow® modeling and simulation software, but implementation/integration of the software into the controller has advanced significantly. A fully integrated system plant model, operator interface and control algorithm is implemented in Simulink®. This model is then configured for automatic code generation using the Mathworks® Embedded Coder toolset. Embedded Coder automatically generates real-time C-code that is used to create an executable file that is directly loaded into the ECU's memory. The controller runs the executable code to automatically control the SOFC auxiliary power unit. This represents a great advancement in control algorithm development. It takes approximately 30 minutes to

implement a code change, rebuild the software set, download it to the controller and run real-time in the system. This process is extremely optimized since it generally requires hand modification of the C-code software set to make a change. This is time consuming and expensive for small changes. Migration to the new process required several upgrades and modifications to the software set and the supporting tools to make the process seamless.

Since the ECU is a production intent controller, it does not have all the advanced features available in the Micro-Autobox® solution. Memory space and throughput are limited in the ECU; and therefore, model size, organization, configuration and modeling method are very important. In order to optimize memory usage, all signals and parameters used in the model were converted to single precision values. The original model used all double precision values for more accurate calculation. This is fine in the Micro-Autobox® where memory and throughput are not limited, but in the ECU storage, space is downsized. This conversion cut storage space in half for calibration and signal values. In addition, the processor in the ECU is less capable than the dual-processor configuration of the Micro-Autobox®, so scheduling of tasks becomes very important so the model can run in a slower microprocessor. Work was completed to optimize the scheduling of various tasks such that the most important tasks run more often than ancillary tasks, such as measuring ambient temperature, which does not need to be updated as often as air flow for instance. Configuration of the model and its components is very important so calculations occur properly and without exception. It was determined that one must be very selective in their coding methods. Certain blocks produce inefficient code and certain configurations of blocks cause run time errors. Verification of the modeling methods used proved to make the software development process smoother. Finally, the model must be configured to generate an Association for Standardization of Automation, measuring system interface, database to create a CAN interface for communicating with the controller. This allows the use of a CAN interface for calibration, diagnostics and data logging while using the ECU to control the system.

4.1.6.5 Automatic Code Gen

The automatic code generation process is a very powerful tool. It is fast and reliable. Code changes can be made in an object based modeling environment, Matlab /Simulink/Stateflow®, and then real-time code is generated and an executable is created that is loaded onto the production intent controller **(Figure 4.1.6.5-1)**. The process takes minutes as opposed to the previous process which takes weeks to hand code and test the software. The Delphi implementation was created internally and with the help of an outside consultant. As mentioned previously, the tool used to generate C-code is The Mathworks® Embedded Coder, which creates real-time code from an object-based model, then an internally developed software set links the code and creates an executable file. This executable file is then configured and downloaded into the Electronic Controller Unit's internal memory where it runs. The linking and downloading process uses WindRiver's Tornado® toolset and VisionProbel® hardware to load the software into the Electronic Controller Unit through the Background Debug Mode port. This process takes less than thirty minutes.

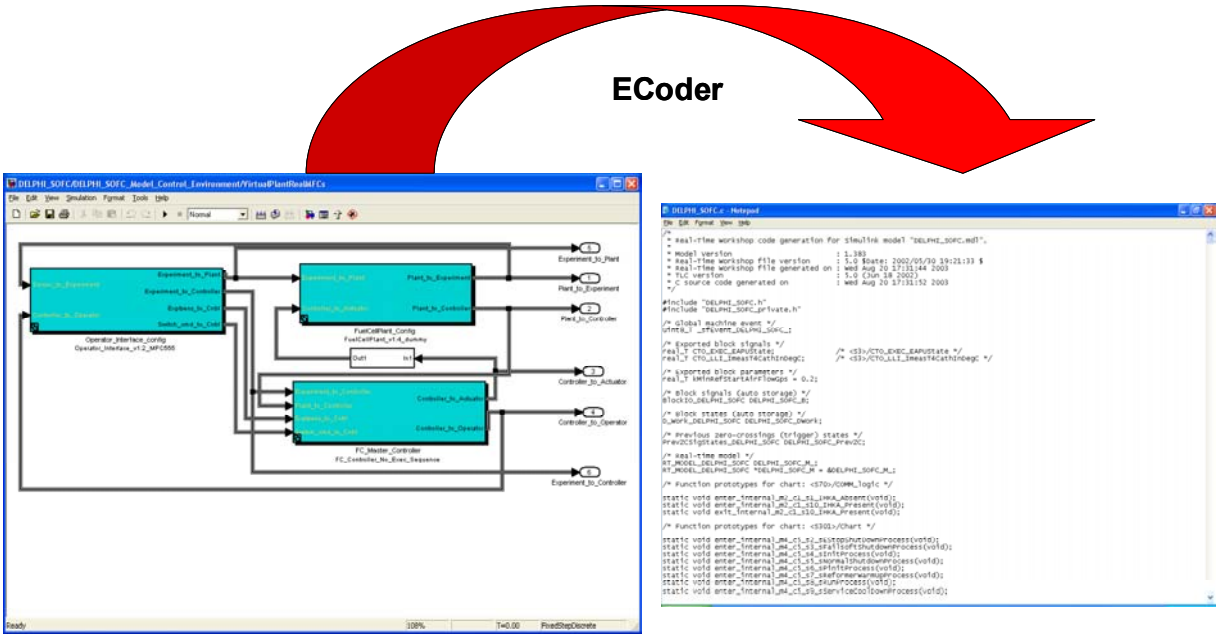


Figure 4.1.6.5-1 Automatic Code Gen - Model Based Algorithm Development to Real-Time Code

4.1.6.6 Debug and Instrumentation Tools

Implementing the production intent controller created the need for new debug and instrumentation tools. WindRiver's SingleStep® debugger is used for real-time software debugging while the control code is running in the ECU **(Figure 4.1.6.6-1)**. SingleStep® is a very powerful tool that allows access to variables and processor states real-time via the ECU's Background Debug Mode port. A new tool for instrumentation has also been implemented. Vector's CANape® allows calibration, instrumentation and diagnosis of the auxiliary power unit control algorithm real-time **(Figure 4.1.6.6-2)**. CANape® is the window into the controller while the system is running. In addition, it allows for data logging of any signal in the algorithm. This tool communicates with the ECU over the CAN bus using CAN Calibration Protocol.

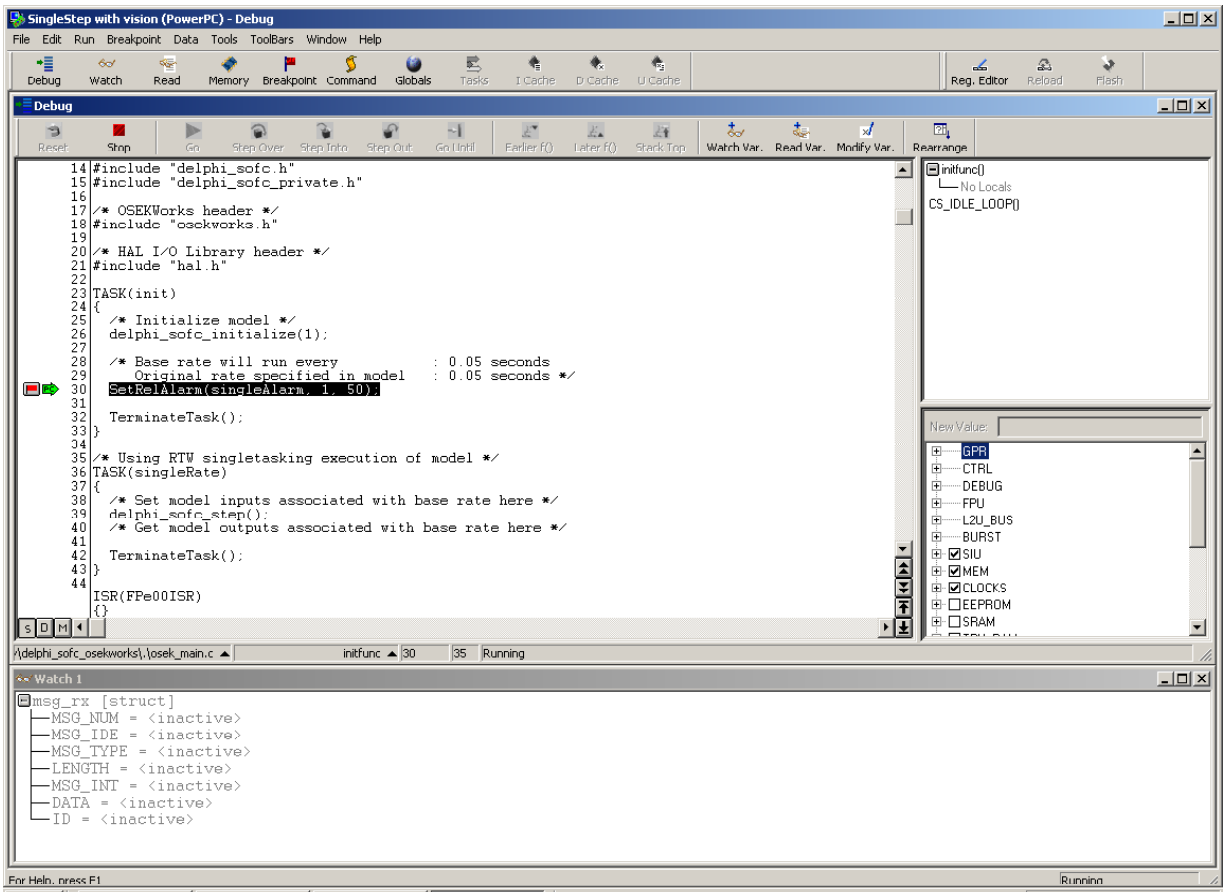


Figure 4.1.6.6-1 SOFC ECU Controller Software Instrumentation/Debug Tool (Single Step®)

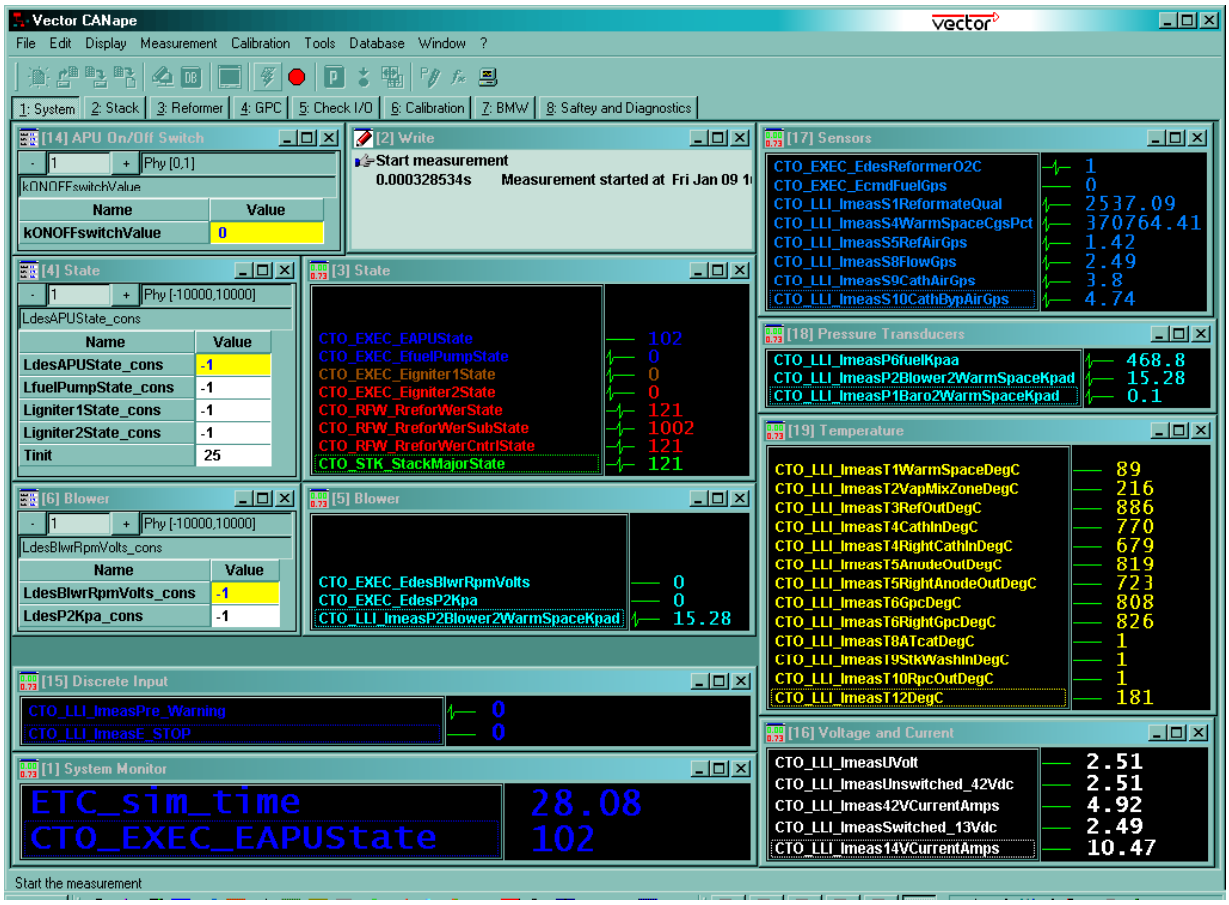


Figure 4.1.6.6-2 SOFC ECU Controller Interface and Data Logging Software (CANape®)

4.1.6.7 Electronics Emulation Test Bench and Plant Simulator

In order to verify and test the software/hardware interaction of the control system, plant hardware emulation tools were developed. An electronics emulation bench was created to verify the ECU's operation with real sensor and actuator hardware **(Figure 4.1.6.7-1)**. The setup contains all sensors, actuators and electrical hardware in the system except for the fuel cell stack. Through CAN, a user can read sensors and actuate the blower, valves, combustors, etc., to verify functionality and calibration. A portable SOFC plant simulator was also created to checkout control hardware and debug software/hardware interactions **(Figure 4.1.6.7-2)**. The plant simulator allows the user to input signals to the ECU to determine the reaction of the control algorithm and to verify it's hardware or software response. These tools have proven invaluable in developing and debugging the control system.

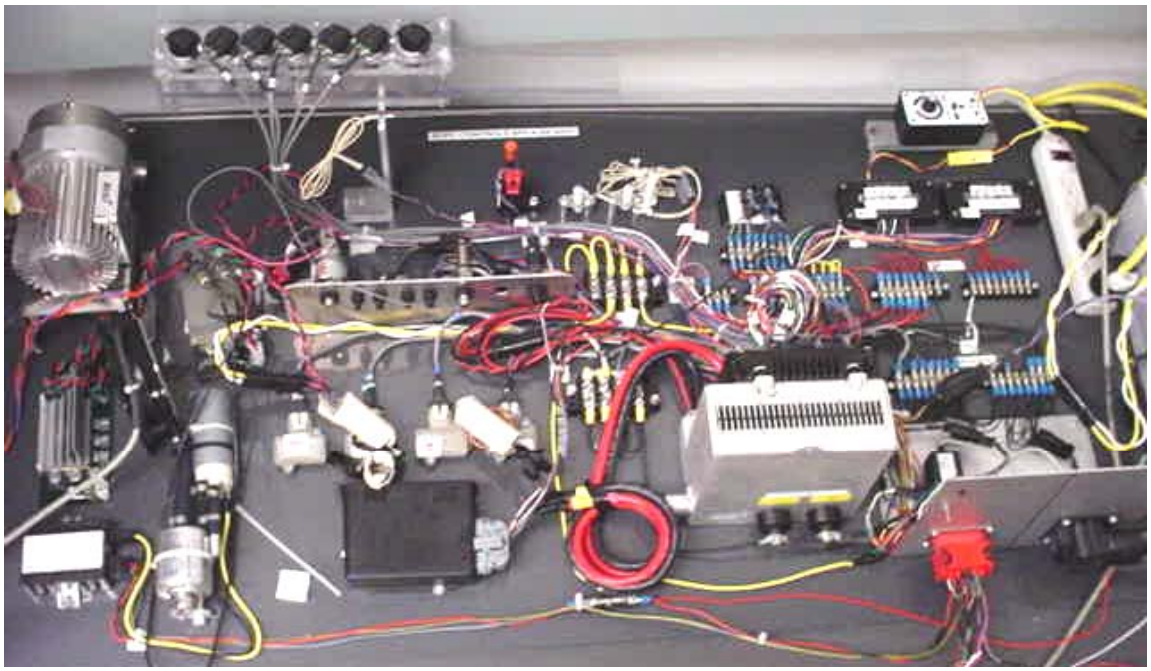


Figure 4.1.6.7-1 SOFC Electronics Emulation Test Bench

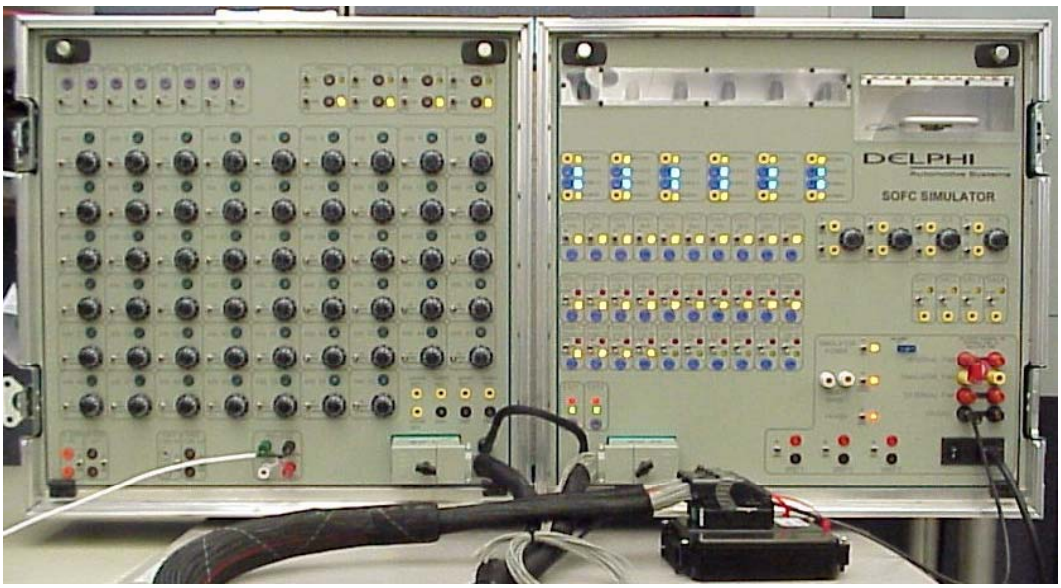


Figure 4.1.6.7-2 SOFC Plant Simulator

4.1.6.8 Integrated Dynamic Simulink®

The interface between the embedded plant model and control algorithm has been upgraded to make the system more compatible with future plans for Hardware In the Loop systems. For example, whereas in the past, the control signal “desired V7 flow” would be “lagged” and become actual V7 flow in the model, now the control communicates to the plant model via

stepper motor step position. In the future, the actual electric signals that drive the air control valves will be presented to a real time version of the plant model in the HIL system.

4.1.7 System Analysis

4.1.7.1 Dynamic Simulink® System Model

During the reporting period, it was determined that the Simulink® plant model did not correctly account for some of the mass of the system in the start-up prediction. This problem is being corrected as of the writing of this report. This modification would normally result in longer predicted start times. However, the actual and predicted start times were agreeing for previous comparisons of the model with experimental data. Further investigation and comparison of experimental results with model predictions indicated that we were not predicting correctly intermediate temperatures. This has led to the observation that the heat transfer within the model was not completely correct. As a result of these two changes, the model is now (still) predicting similar overall start times, however it is now additionally predicting intermediate temperatures better. Complete validated results are expected shortly.

4.1.7.2 Steady State Hysys® Model

During the reporting period, the Hysys® system model has been employed to make further predictions about the performance of the system at specific operating points. Multiple additional mechanization options were explored and, a target mechanization was selected for the next generation system. It is interesting to note that the election (of a mechanization, and target flows, temperatures, etc.) is highly dependant on the expected ultimate performance of components in the system. For example, the temperature at which the reformer will run has strong implications for heat transfer design, and ultimate efficiency of the system.

4.1.7.2.1 Updated Stack Model

The Battelle/PNNL model has not yet been incorporated into the Hysys® system model, primarily because the current design focus has been on evaluating a maximum power point. Since the maximum power point is currently defined at a fixed voltage, the prediction of this voltage is not necessary. As the focus shifts toward “turn down” evaluations, the PNNL stack model will be employed to determine what the expected stack voltage and resultant internal heating will be for conditions other than max power.

4.1.8 Perform Design Optimization

See section 4.1.1.

4.1.9 System Integration Status

See Section 4.1.1.

4.1.10 System Cost Estimate

After completion of the Gen 3B APU design, the System Cost Model will be updated. This will occur during the second quarter of 2004.

4.2 Solid Oxide Fuel Cell Stack Development (Task 2.0)

4.2.1 Design Stack

The 2x15-cell, Gen 2 stack subsystems called Integrated Stack Modules continued to be successfully fabricated and tested. Greater than 20 Gen 2 Integrated Stack Modules were fabricated. This design demonstrated the viability of building a stack subsystem that could be integrated into the system. The transition to the more manufacturable Gen 3 design with lower mass and volume was successfully carried out.

Multiple Gen 3 cassettes (repeating units for stack) were successfully fabricated and tested. The Gen 3 cassettes are only 2.1 mm thick and weigh 155 grams (50% reduction compared to Gen 2). The cassettes are fabricated using high volume manufacturing processes like stamping, brazing and laser welding.

The cassettes were successfully assembled into multiple 15-cell stack modules **(Figure 4.2.1-1)**. Test results are discussed in the latter sections. The Gen 3 modules were also successfully integrated into the system and tested with very encouraging results. The results from the tests are discussed in the Systems section.

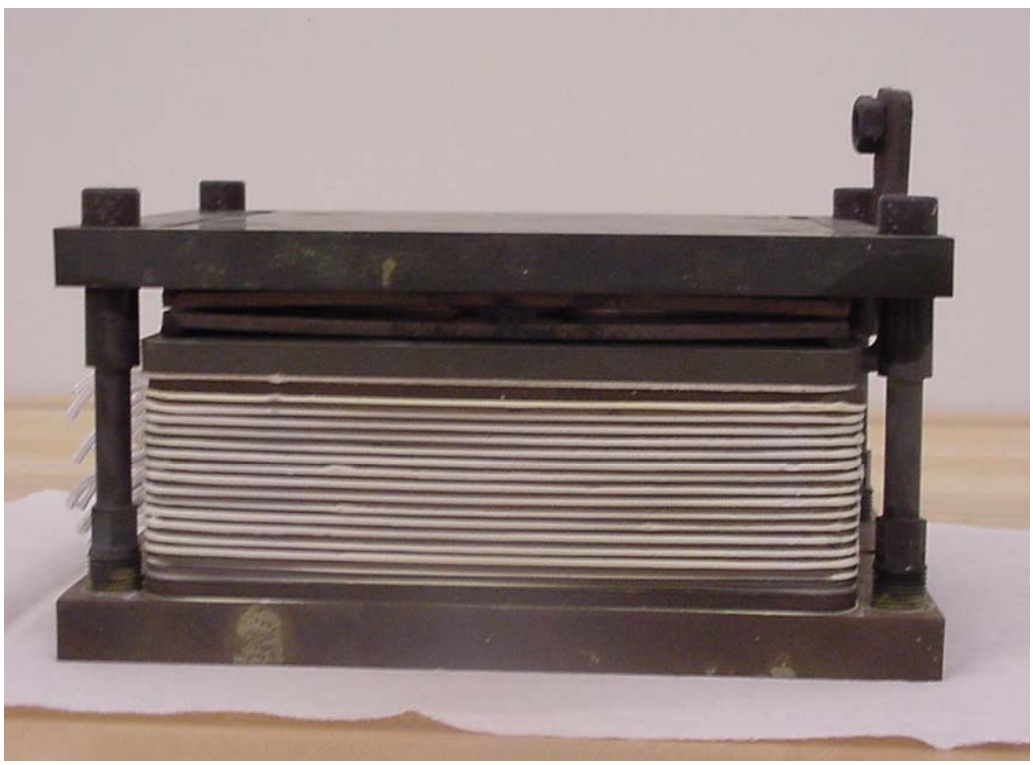


Figure 4.2.1-1 15-Cell Gen 3 Stack

4.2.2 Model Stack Under Steady-State Conditions

No work was performed under this subtask during the reporting period.

4.2.3 Model Stack Under Transient Condition

No work was performed under this subtask during the reporting period.

4.2.4 Develop High Performance Cathode

Cathode development efforts have focused on improving the stability and power density of selected cathode materials. As shown in **Figure 4.2.4-1**, these efforts have demonstrated that selected cathodes have the fundamental potential to meet the power density and degradation goals to achieve the SECA targets.

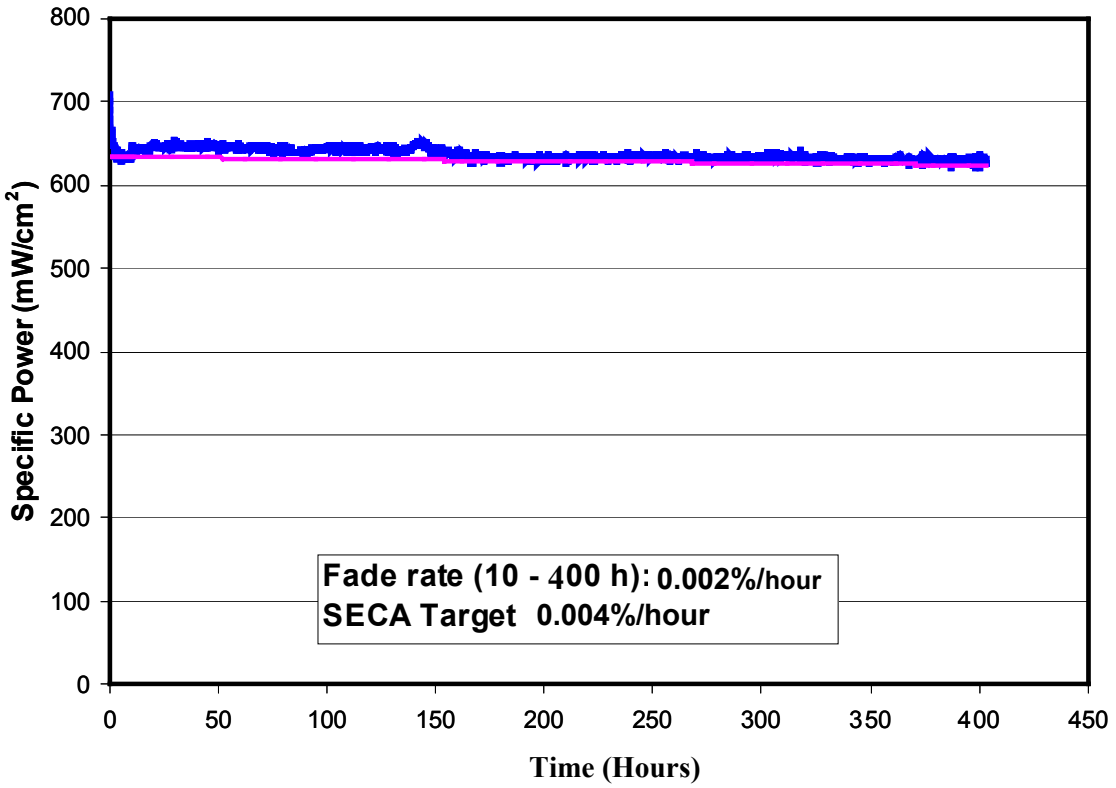


Figure 4.2.4-1 Long-Term Stability of Cathode Material

4.2.5 Develop High-Performance Anode

The cell fabrication effort has focused on improving the robustness of the cell manufacturing process through a variety of designed experiments. These efforts have successfully identified a wide processing window for the cell fabrication in which the final cell properties are insensitive to small variations in batch compositions.

Previous efforts focused on improving the quality of the electrolyte tape in order to reduce pinholes while improving the density and consistency of the sintered electrolyte. Successful implementation of these new electrolyte formulations has focused the current development efforts on improving the robustness of the bulk anode composition in order to improve the overall manufacturing process. Initial screening test were conducted in order to narrow the optimal working range for the tape cast compositions. After these initial screening tests, an

L9 designed experiment was setup in order to establish the robustness of the resulting compositions.

4.2.6 Develop Cell Fabrication Techniques

This section is combined with section 4.2.5.

4.2.7 Develop Separator and Support Components

As discussed in previous reports, ferritic stainless steel is the material of choice for separator development. It has been well established that the largest contributor to resistance in the interconnect train electrical pathway is the oxide scale formed on the mesh and the separator. Multiple stacks have been fabricated using the ferritic steel/mesh based interconnect pathway and extensively tested.

Based on the lessons learned, a next-generation interconnect design is being developed which fundamentally improves the interconnect train and the role of the separator plate, potentially eliminating the oxide scale from the interconnect conduction pathway.

4.2.8 Develop Gas Distribution Meshes

As discussed in previous reports, the anode and cathode gas distribution meshes are two key components of the interconnect train. These components must provide a low-resistance electrical connection between the separator plate and the corresponding electrodes and allow access of air and fuel gas to the electrodes. A study of mesh welding parameters is underway to ensure that joining of the mesh to the separator is optimized for strength and also to ensure that the spot weld provides a minimum contribution to the total electrical resistance of the interconnect train.

4.2.9 Develop Mesh/Electrode Interface Materials

No work was performed under this subtask during the reporting period.

4.2.10 Develop Glass and Glass-Ceramic Seals

As discussed in the previous report, a reinforced glass seal has been used to overcome the problems of oxide scale formation between the glass and the metal structural components. “Pop-gun” samples produced using this seal have undergone thermal cycling (heated at 75 °C/min in a quartz lamp furnace, held for 10 minutes, then cooled to ~100 °C within 40 minutes) up to 20 times without any degradation in seal strength. Several test stacks were produced using dummy cassettes joined with reinforced glass seals. Dummy cassettes contain a metal sheet in place of the ceramic-metal cell. This allows testing of the cassette-to-cassette seals without the possibility of leaks developing in cell-to-frame seals. These dummy stacks have so far undergone up to 50 thermal cycles while remaining hermetically sealed.

The reinforced glass seals are a composite structure, referred to as the Glass-Fiber-Mesh.

4.2.11 Develop Alternative Seals

A braze seal is being used for sealing between the ceramic cell and the cassette. Hundreds of cassettes have been fabricated and tested using this process.

4.2.12 Develop Gas Headers and Manifolds

The Gen 3 stack sub-system was fabricated which included the load system and the base plate.

4.2.13 Fabrication Developmental Stacks

Extensive experience has been gained in the fabrication and testing of intermediate scale, single cell stacks, with cell dimensions of 7 cm X 7 cm. 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.

Extensive experience has also been gained in the testing of short stacks to evaluate durability and thermal cycling. Initial results show degradation primarily due to reaction of chromia with the cathode in the presence of chromia formers. Thermal cycling evaluation has demonstrated more than 20 cycles in short stacks with minimal degradation in sealing and power. Further development and evaluation is ongoing to improve durability performance of the stacks.

4.2.14 Evaluate Stack Performance

Over twenty Gen 2 stack sub-system were built and tested. They were successfully integrated into the system. Power densities of 420 mW/cm^2 at 0.7V/cell at 750 ^{o}C were achieved in the stack laboratory with simulated recycle reformate. Thermal cycling tests in a furnace with 60 minutes heat-up from room temperature to 750 ^{o}C demonstrated five thermal cycles with minimal degradation.

The transition to a more manufacturable and lower cost stack design (Gen 3) was successfully made. New parts were developed and fabricated. The Gen 3 stack has a 50% improvement in lowering the mass and the volume of the stack.

Greater than seven Gen 3, 15-cell stacks, were fabricated and tested. Results from the sealing of these stacks were very encouraging. This is a major step towards demonstrating the ability of a thin metallic cassette based design to seal well as an assembled stack. Power densities of 305 mW/cm^2 at 0.7 Volts/cell at 750 ^{o}C, with simulated recycle reformate, were achieved. Current efforts are focused on building 30-cell stacks and further improving power density and robustness in these stacks.

4.3 Reformer Development (Task 3.0)

4.3.1 Develop Steam Reformer for Natural Gas

Endothermic reformer concepts were investigated that are related to the development of the Steam Reformer for Natural Gas.

4.3.1.1 Demonstration of Methane Steam Reforming

Endothermic reformer concepts were investigated that are related to the development of the Methane Steam Reforming.

4.3.1.2 Steam Reformer Concept Study and Evaluation – Analysis

- **Concept Study:** Endothermic reformer concepts have been generated. Conceptual ideas include tubular and flat plate designs, as well as integration of heat transfer function and flow field.

- **Concepts Evaluation and Analysis:** Endothermic reformer concepts have been evaluated using computational analysis. Current results remain preliminary and do not yield a full picture.

4.3.1.3 Natural Gas Mixer Concepts Study

Both analysis and test of Natural Gas Mixer concepts will be reported upon their completion.

4.3.2 Develop CPO Reformer

4.3.2.1 H2 Reformer w/ Recycle

Background

The CPO characteristics of the H2 reformer had been evaluated preliminarily in the fourth quarter of 2002. Testing was limited due to leaks and part availability. Having resolved the manufacturing issues with brazing an H2 reformer, the endothermic performance remained to be tested. The H2 is a second-generation planar design, the details of which have been reported previously (Quarters 3 & 4 SECA Technical Report 2002). **Figure 4.3.2.1-1** shows the H2 concept mated to a fuel vaporizer, which is essentially a cross-flow heat exchanger with central combustor, and an open face to admit the fuel/air mixture.

Endothermic operation in Delphi's system is achieved by way of recycling anode tail gas from the SOFC stack to the reformer. In this way, unused hydrogen and carbon monoxide can be reused, and water and carbon dioxide re-reformed, resulting in higher overall system efficiencies.

This section reports the results of a test that was performed to characterize the endothermic capabilities of the H2 design. An intermediate system objective was to attain gross reforming efficiencies of 110% at fueling rates of about 0.3 grams per second of gasoline. The gross reforming efficiency is defined as the ratio of the lower heating value of the reformate to the lower heating value of the fuel fed to the reformer. Although the heating value of recycled anode tail gas contributes to the lower heating value of the reformate, it is not considered in the calculation which can result in reforming efficiencies greater than 100%. The net reforming efficiency subtracts out the heating value of the recycled hydrogen and carbon monoxide. Each efficiency can be reported with or without the heating value of

methane in the reformate. This section of the report will only consider the reforming efficiency without the heating value of the methane (or other hydrocarbons) content of the reformate.

At this stage of endothermic reformer development, reformer operation is currently tested as a stand-alone subsystem. Hence, there is no tail gas from a fuel cell available for recycle. Therefore, recycle is accomplished via blending of a synthetic gas mixture that simulates tail gas. The composition of the recycle is predicted by way of a thermodynamic model of the reformer-fuel cell system for a given operating point. This model is also used to determine the amount and composition of tail gas available for the GPC that provides heat to sustain the endothermic reforming reaction.

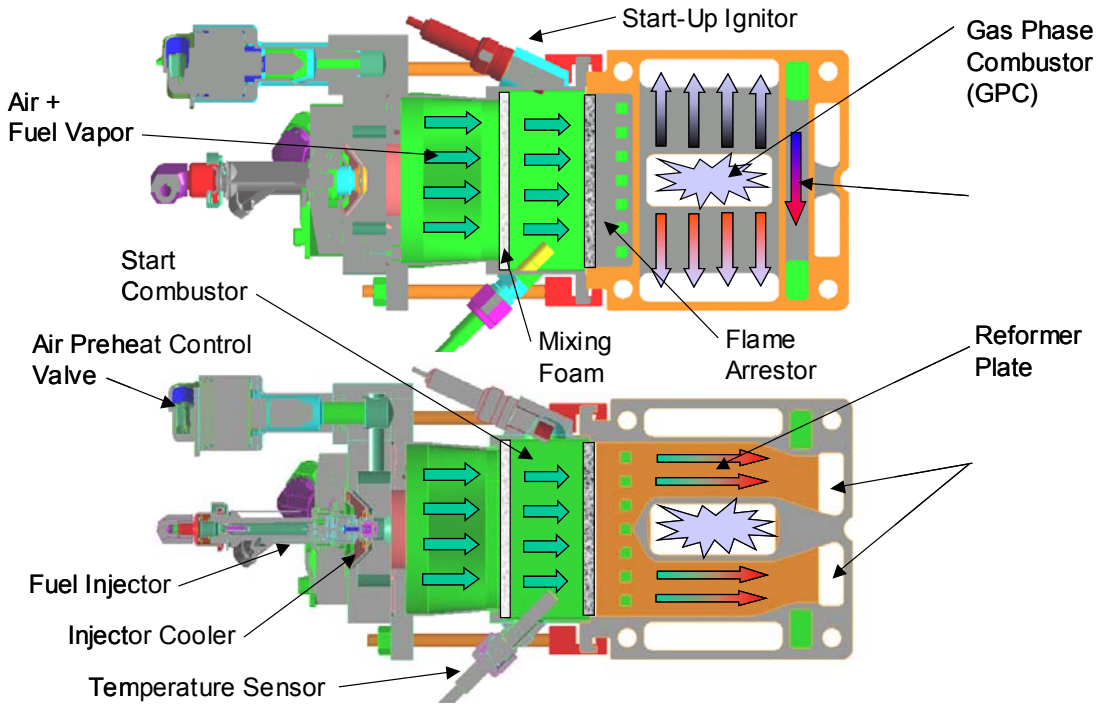


Figure 4.3.2.1-1 Schematic of H2 Endothermic Reformer

4.3.2.1.1 Description of Test

The H2 reformer is evaluated in the reformer lab on one of the development stands with complete gas analysis and reformer control capabilities. The reformer is bolted to a manifold fixture, which holds the reformer in place, and distributes and collects, the reformer and combustor gases. The Non-Contact Vaporizer is bolted to the front of the reformer to deliver the vaporized fuel/air mixture to the reforming layers. Recycled anode tail gas is also introduced to the air stream in the Non-Contact Vaporizer ahead of the mix point with the gasoline. The recycle stream was humidified and heated to 100 ºC, though it would be available from the SOFC anode at 750 ºC. For this test, the recycle flow rate and composition were fixed at an anticipated operating point from the thermodynamic model.

Simulated SOFC anode and cathode exhaust gases were also fed to the gas phase combustor. The anode stream was simulated using a bottled mixture of gases, necessitating a fixed composition, though the flow rate was varied to supply more heat to the reformer. Heated air was used to simulate the cathode exhaust. The air/fuel mixture (or phi) was varied to control the temperature of the combustor. Phi is defined as 100/(%Excess Air + 100).

The reformer was started in CPO mode and operated for approximately 4 hours to achieve a thermal steady state condition. The last operating point in CPO mode is shown in **Table 4.3.2.1.1-1** as Test Condition Number 1. Endothermic mode commenced with Test Condition Number 2, and the introduction of recycle gas. The reformer and GPC control variables were then changed in an evolutionary optimization-style progression to maximize reformer efficiency. The primary control variables being:

- Reformer Air Flow
- Reformer Fuel Flow
- GPC Air Flow
- GPC Fuel Flow

These variables affect reaction temperatures; reactant stoichiometry, space velocities and heat transfer rates. The responses to changes in these variables are measured primarily by process thermocouples and product gas composition via real-time instrumentation.

Test	Reformer			GPC		
Condition	Fuel	Air	O/C	Fuel	Air	
Number	gps	gps	ratio	gps	gps	Changes to Operation
1	0.15	0.85	1.18	0.91	7.97	CPO mode
2	0.15	0.85	1.37	0.91	7.97	Started recycle-Endothermic mode
3	0.15	0.80	1.32	0.91	7.97	Decreased reformer air flow
4	0.15	0.74	1.25	0.98	7.97	Decr. Ref. air flow & increased GPC fuel flow
5	0.10	0.57	1.45	0.98	7.97	Decr. reformer fuel & air flow
6	0.10	0.48	1.31	0.98	7.97	Decr. reformer air flow
7	0.10	0.48	1.31	0.98	6.48	Decr. GPC air flow
8	0.10	0.48	1.31	0.98	5.98	Decr. GPC air flow
9	0.10	0.48	1.31	0.98	5.78	Decr. GPC air flow
10	0.10	0.48	1.31	1.01	5.98	Incr. GPC fuel & air flow
11	0.10	0.48	1.31	1.04	5.98	Incr. GPC fuel flow
12	0.10	0.46	1.27	1.04	5.98	Decr. reformer air flow
13	0.10	0.44	1.24	1.04	5.98	Decr. reformer air flow

Table 4.3.2.1.1-1 Endothermic Reforming Test Conditions Matrix

4.3.2.1.2 Results

The results of this test series are summarized in **Figure 4.3.2.1.2-1**, which shows the steady progression of reformer efficiency as the control variables were changed. Each point on the graph represents an average of 5 minutes of data (5 second scan rate) once a thermal steady state was achieved at the desired condition.

Gross CPO reforming efficiency (without methane) was established at 65%, at a fueling rate of 0.15 grams per second of gasoline. Introducing recycle at 0.26 grams per second (or approximately 13% of the predicted available steady-state anode tail gas) increased the gross reformer efficiency slightly (from the hydrogen and carbon monoxide content of the recycle). The net efficiency, however, decreases due to the higher space velocity in the reforming channels. Test conditions #3 and #4 show further reductions in reformer airflow to decrease space velocity. Reducing airflow on the reformer side also decreases the enthalpy of the reforming reaction however. To compensate, more fuel is added to the GPC in test condition #4. None of these actions increased the net reformer efficiency.

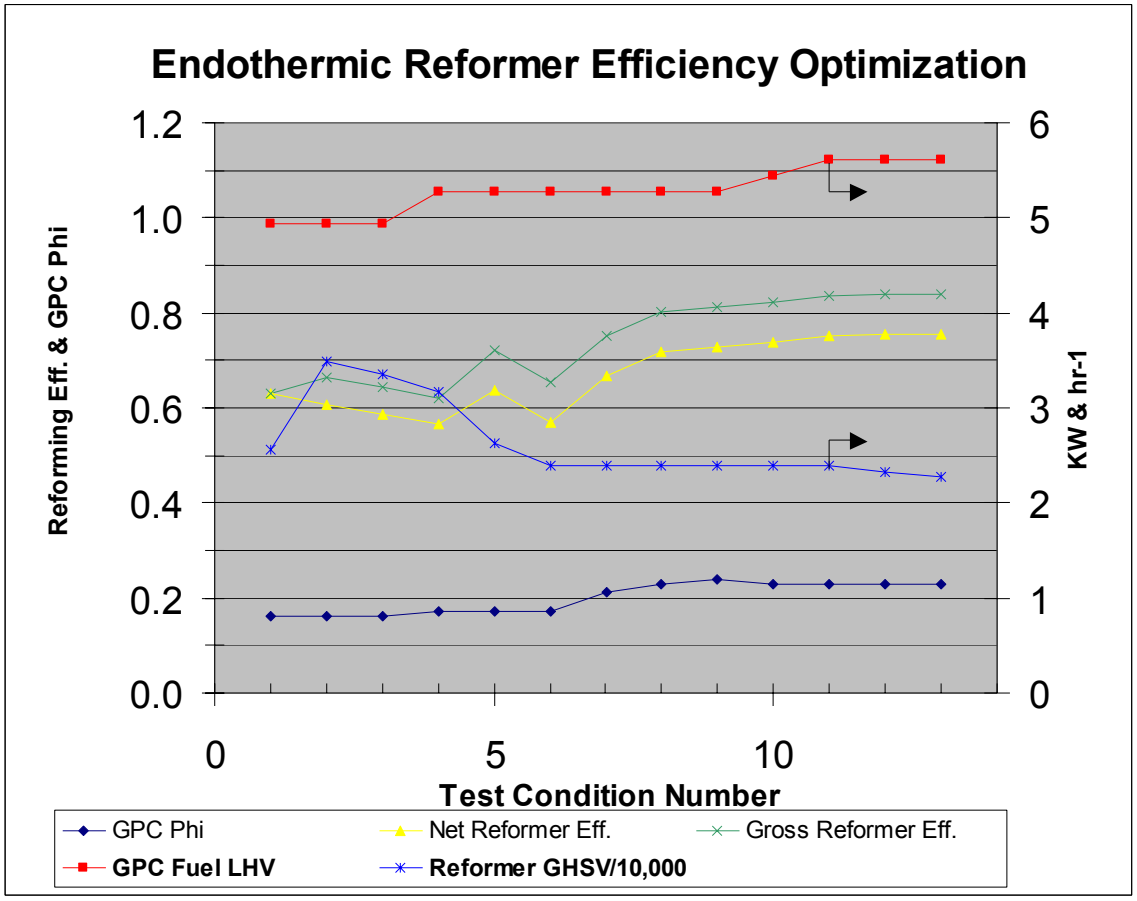


Figure 4.3.2.1.2-1 H2 Reformer Efficiency with Recycle - Summary

A significant increase in net reformer efficiency was not achieved until the space velocity of the reformer was reduced by cutting the fuel rate from 0.15 to 0.10 grams per second of gasoline in test condition #5. There was also an increase in O/C ratio. This fueling rate was maintained for the balance of the test. Backing out some air from the reformer in condition #6 resulted in reduced reforming efficiency due to a slight drop in temperature. Hence, the temperature of the Gas Phase Combustor (GPC) was driven up in the next condition by increasing the combustor phi (decreasing GPC air). This change resulted in a small

increase in combustor temperature (see **Figure 4.3.2.1.2-2**), but increased reforming temperature by 35 ºC and reforming efficiencies by 10%. The next several test conditions continued in this direction, increasing the temperature of the combustor via GPC fuel and phi adjustments, until diminishing returns set in, with a maximum gross efficiency of 83.6% at test condition #11. Further increases in reforming temperature through higher GPC temperature were discontinued, as the GPC was getting too hot relative to the materials of construction. The relationship between GPC temperature and reforming temperatures is best seen on **Figure 4.3.2.1.2-3**.

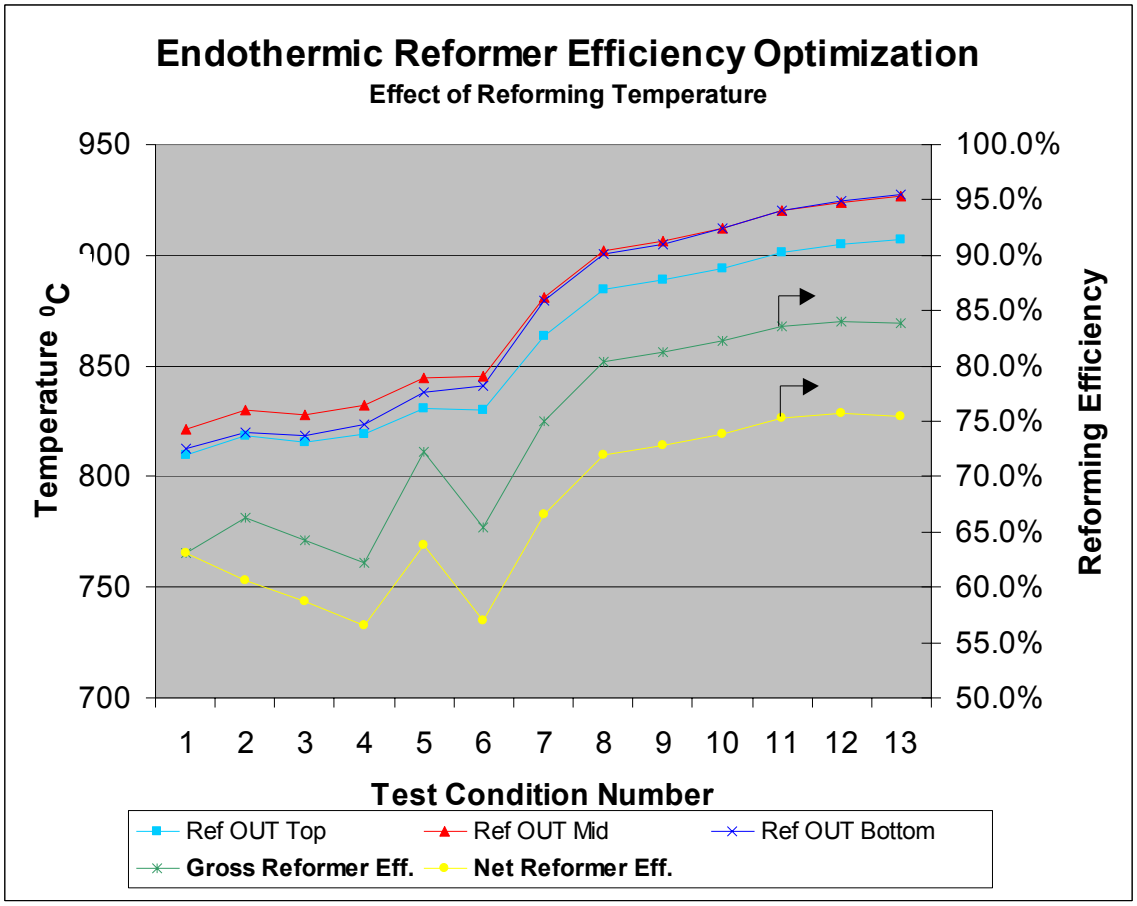


Figure 4.3.2.1.2-2 H2 Reformer Efficiency with Recycle - Reforming Temperature Effect

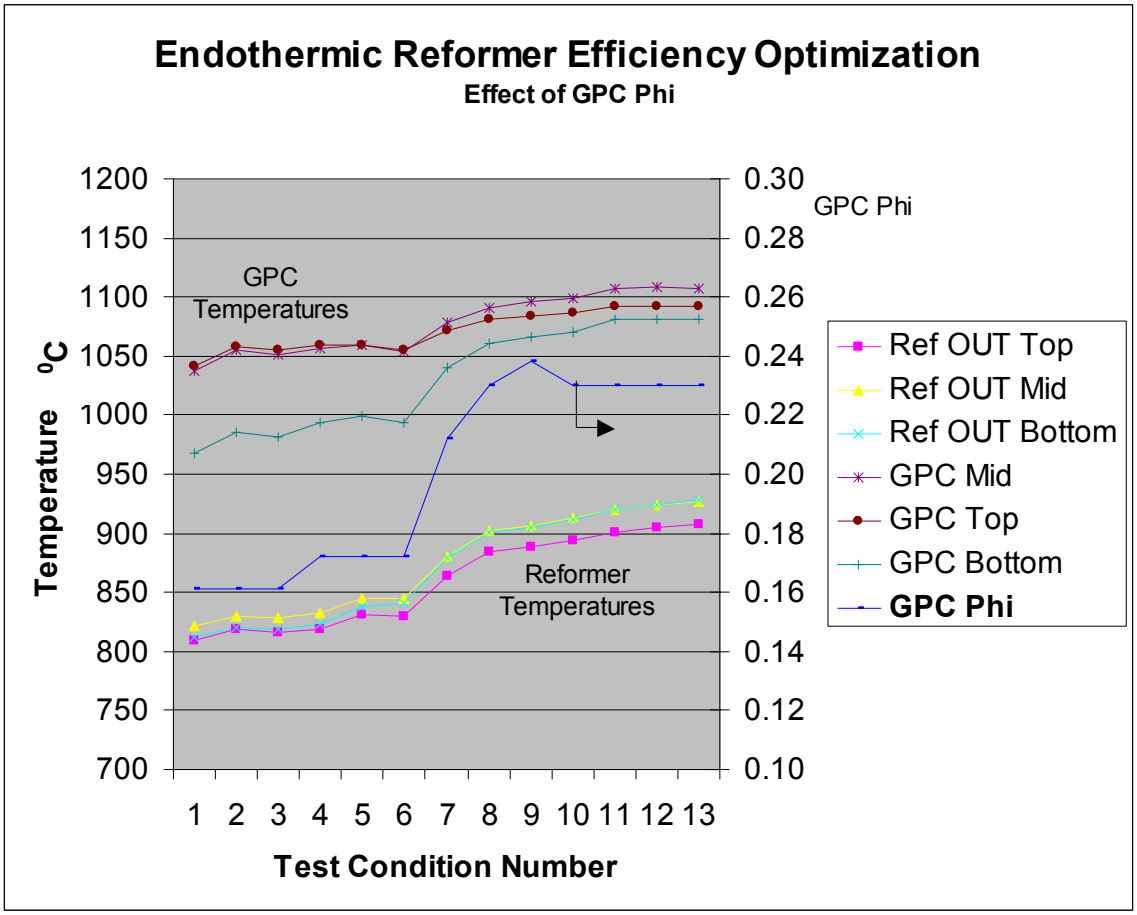


Figure 4.3.2.1.2-3 H2 Reformer Efficiency with Recycle - GPC Phi Effect

A very slight increase in reformer efficiency (to 84.1%) was attained by reducing reformer airflow in test condition #12. Although another reduction of reformer airflow increased reformer temperature slightly (condition #13), no corresponding increase in efficiency was observed.

Reformate quality for this experimental run is summarized on **Figure 4.3.2.1.2-4**. The quality, particularly at greater than 80% gross efficiency, is good with the exception of the high ethylene concentration. The 0.35% to 0.45% ethylene concentration is considerably higher than that observed from foam supported catalysts, and is of a concern with respect to carbon formation in the SOFC stack downstream of the reformer.

Mechanically, the H2 reformer performed very well, as no distortion or damage was observed following the test. It also appears that the catalyst coating was undamaged.

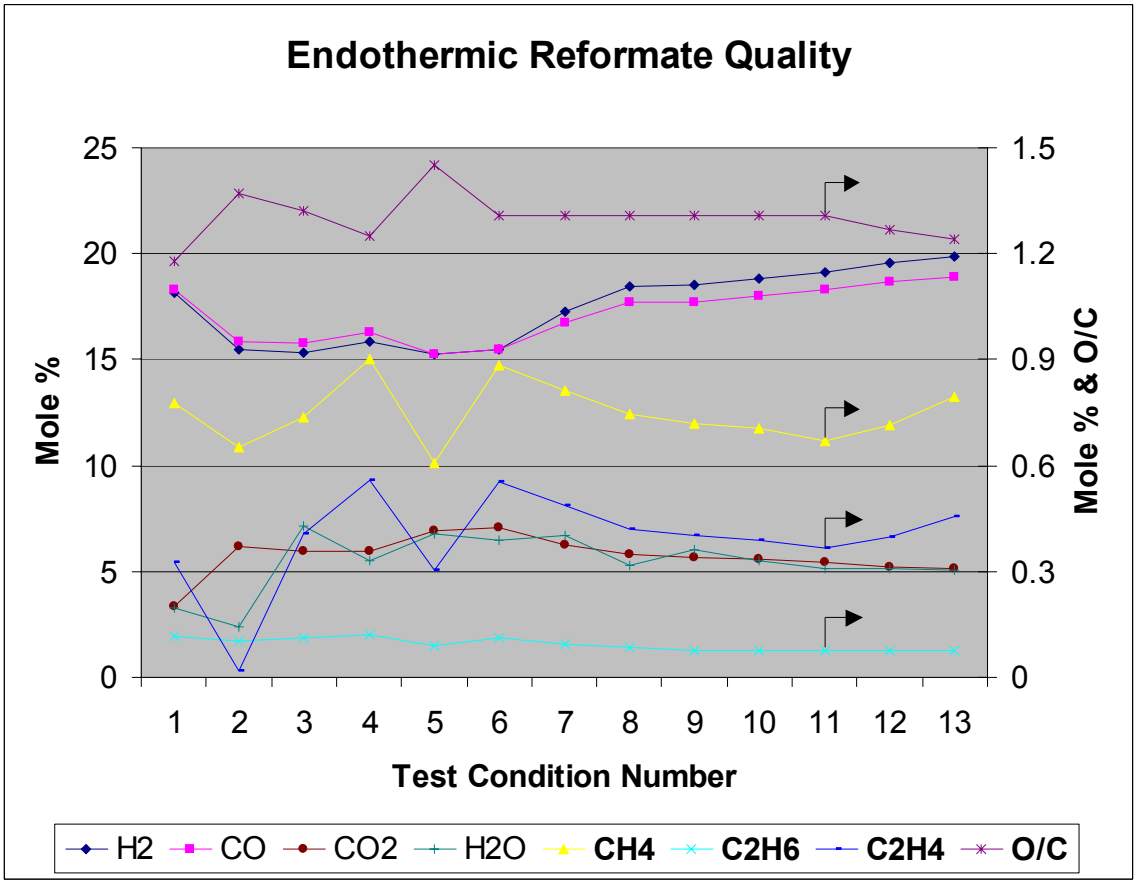


Figure 4.3.2.1.2-4 H2 Reformer Efficiency with Recycle - Reformate Quality

4.3.2.1.3 Conclusions

Although the performance objectives were not achieved, considerable information was garnered regarding the H2 reformer design.

- The maximum reforming efficiency (gross) was limited to 85% by an upper reforming temperature limit of 925 ºC. The reforming temperature was limited by an upper limit on the GPC temperature of 1100 ºC imposed due to materials limitations.
- The large temperature delta observed between the reformer and combustor indicates deficiencies in the heat transfer capabilities of this design.
- The energy input to the GPC to achieve a 925 ºC reforming temperature is about double what is available for the combustor operation.
- Energy input to the reformer is high partially due to high heat losses to the environment in the test environment. Heat loss from the reformer at peak efficiency for this test series was approximately 2 kilowatts, which in relation to the product reformate lower heating value of 4.2 KW is unacceptably high.

- The combination of catalyzed surface area and volume for reaction that are characteristic of the H2 design limit the capacity of the reformer to about one forth or one fifth of what is eventually needed for a $5KW_e$ APU.

Based on this analysis, future endothermic reformer designs will focus on the following:

- Focus on attaining much higher heat transfer rates between the GPC and reformer layers
- Allow for greatly improved thermal isolation of the reformer from the environment
- Provide for several times more catalyzed reaction area than available with the H2 reformer
- Eliminate mass for improved startup response

In addition, future testing needs to be conducted to understand the relatively high production of ethylene from this design and to evaluate the impact on carbon formation.

4.3.2.2 H2 Combustor Evaluation

Tests were conducted on the H2 combustor design to evaluate the temperature uniformity across the flow area using two different mixing geometries. For purposes of preserving catalyst and substrate integrity, a 1000 °C limit was imposed. Hydrogen and CO conversion was also measured.

Figure 4.3.2.2-1 shows the two insert geometries (“house” and “hole”) tested. **Figures 4.3.2.2-2 and 4.3.2.2-3** show the thermocouple placement used for this testing. **Figure 4.3.2.2-4** shows the temperature distribution using the house insert. This geometry yielded a 250 °C or greater temperature spread across the thermocouples in the Gas Phase Combustor. This distribution was not sensitive to mixture variation. As the mixture was leaned to stay below 1000 °C, there was insufficient response in temperature, indicating that mixing was poor. This is also supported by the poor H_2 and CO conversion. Due to these reasons, this geometry was not favored for this application, even though the pressure drop was associated with this geometry was less.

"House" Insert

"Hole" Insert

Figure 4.3.2.2-1 Insert Geometries

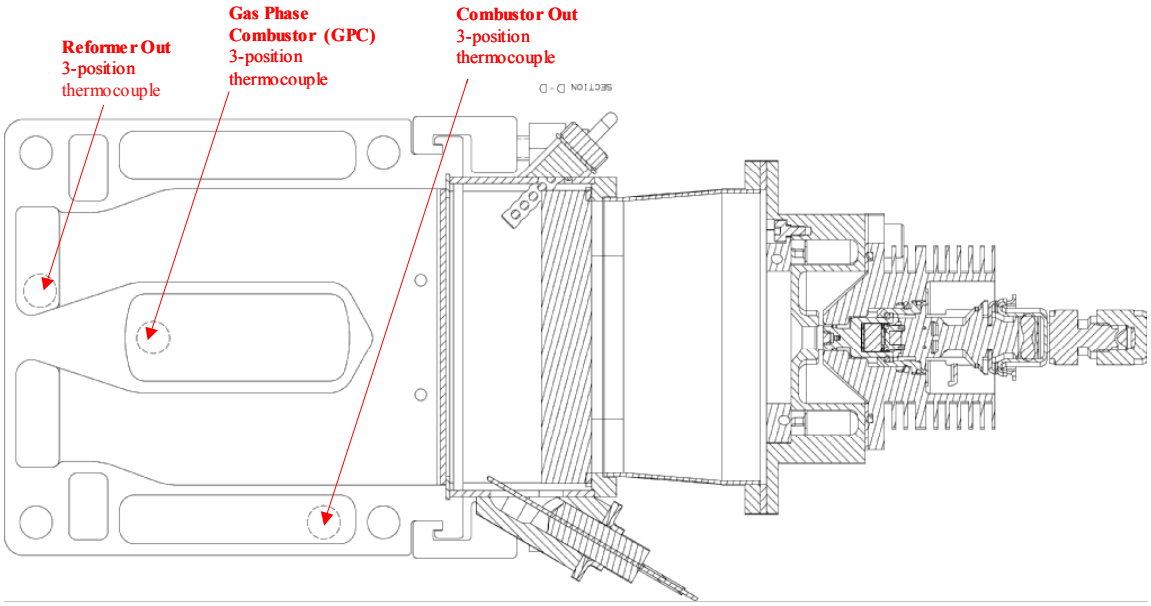


Figure 4.3.2.2-2 Thermocouple Placement – Top View

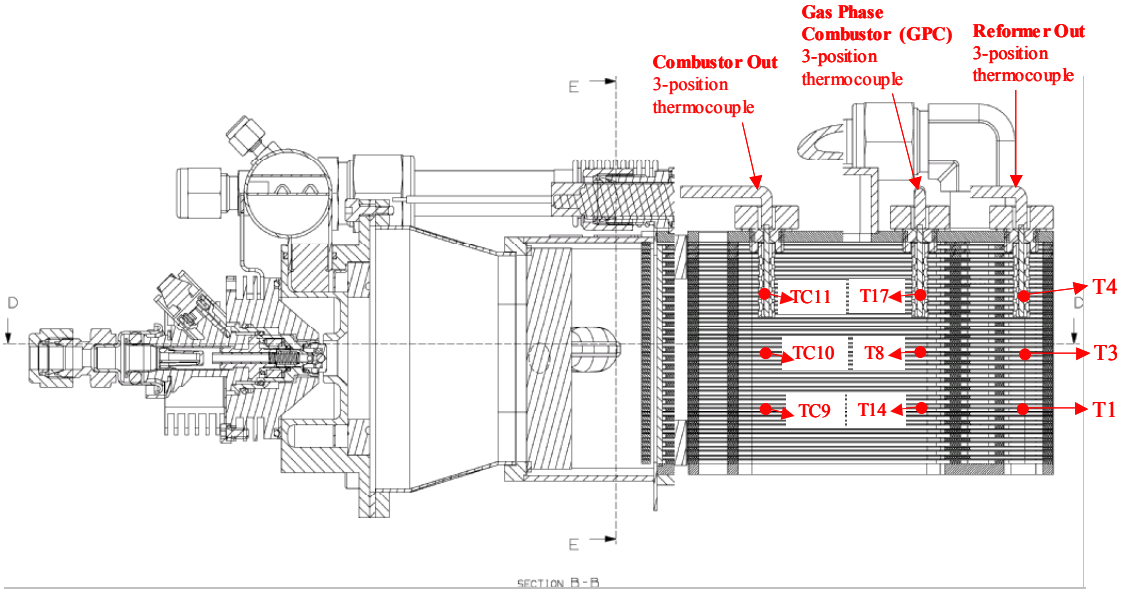


Figure 4.3.2.2-3 Thermocouple Placement – Side View

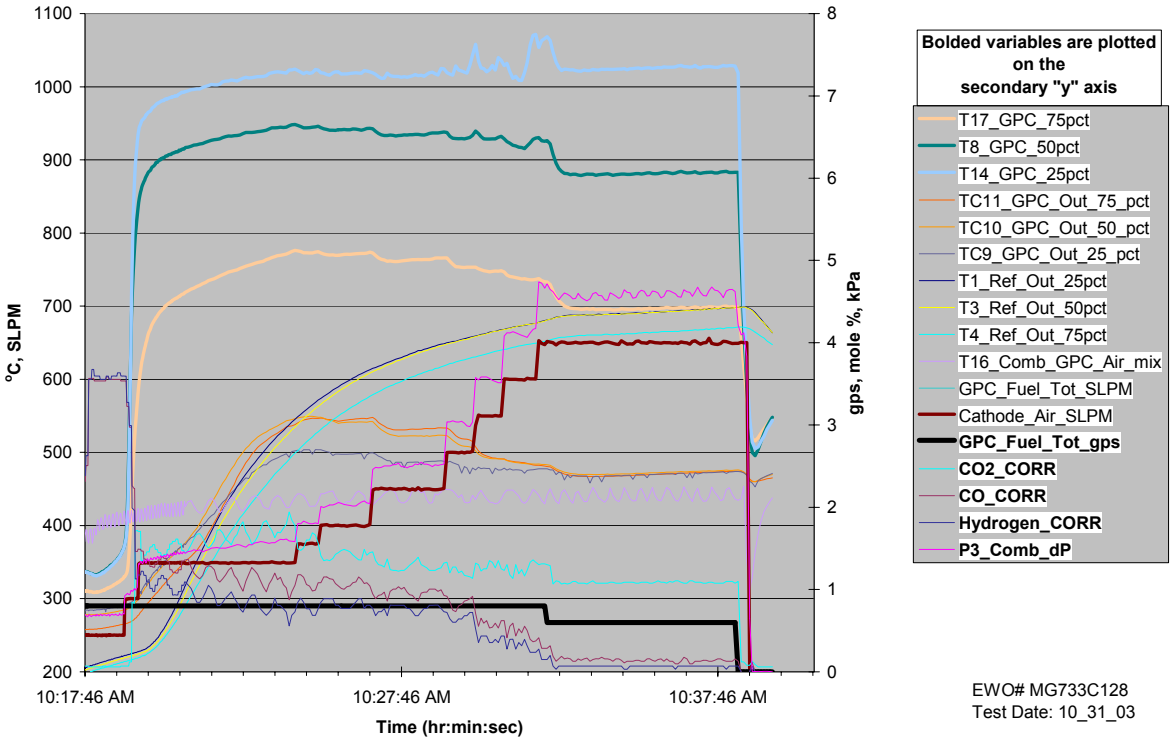


Figure 4.3.2.2-4 Performance Data – House Insert

Figure 4.3.2.2-5 gives the temperature, conversion, and pressure profiles using the hole insert. The temperature distribution is reduced to ~60 °C, while the CO and H_2 conversion is

significantly improved. Pressure drop across the part suffers, however, to achieve this performance.

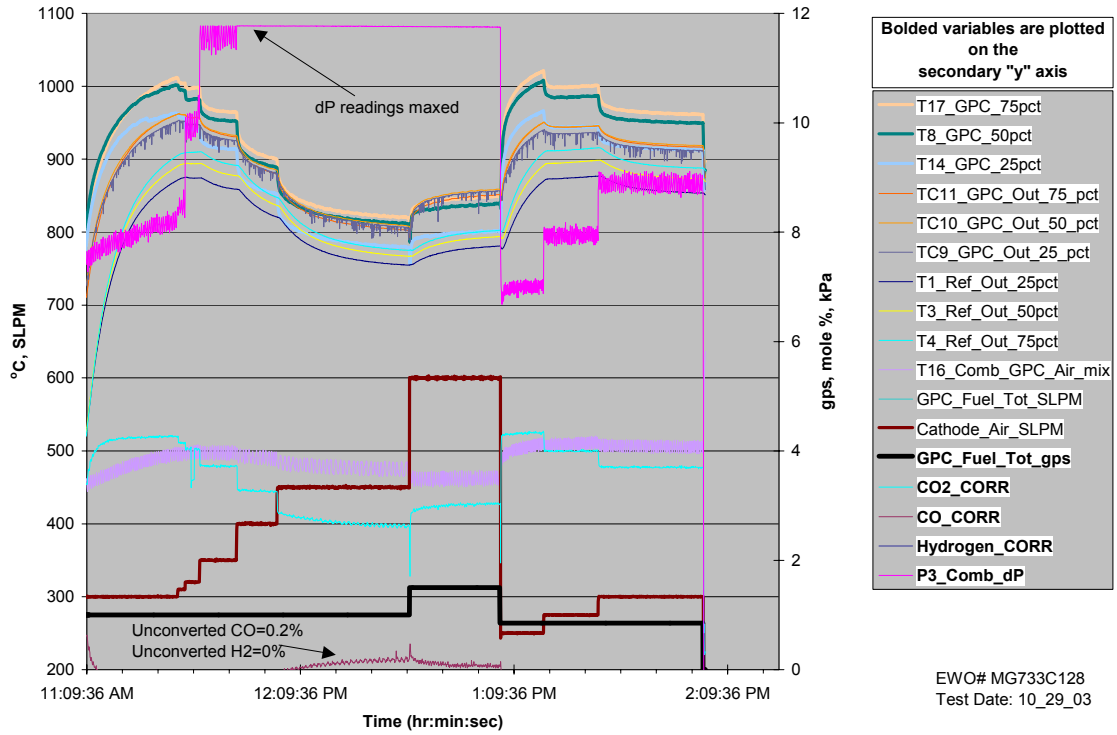


Figure 4.3.2.2-5 Performance Data – Hole Insert

4.3.2.3 H2 Heat Exchange Evaluation

Background

The previous section of this report explains that the heat transfer capacity of the H2 reformer is insufficient. To enhance our understanding of this limitation on this design, and support the next iteration, a test was performed in an attempt to quantify the heat transfer characteristics of the actual H2 reformer, independent of any reforming reactions.

4.3.2.3.1 Description of Test

The H2 reformer was configured as it would be for a reforming run, bolted to a manifold and insulated from the environment. However, an inert reducing gas was presented to the reforming section of the reformer in place of a fuel/air mixture. Heat was supplied to the reformer via combustion of simulated SOFC anode and cathode gases in the GPC chamber. Under steady state conditions, a heat balance could then be completed using measurements of mass flow rates and the entrance and exit temperatures of the different streams. The heat transfer characteristics of the reformer can be estimated from this heat balance.

4.3.2.3.2 Results

The heat balance results from this test are summarized on **Figure 4.3.2.3.2-1**. For this first test, the points shown on the graph represent average conditions (5 minutes) taken after

temperatures leveled off, but before a true steady state was attained. As it turns out, this was not an important consideration. Heat balances conducted around the points taken showed that a significant amount of heat could not be accounted for in the process streams. This is attributed to heat loss to the environment, which would include to the manifold and insulation surrounding the reformer.

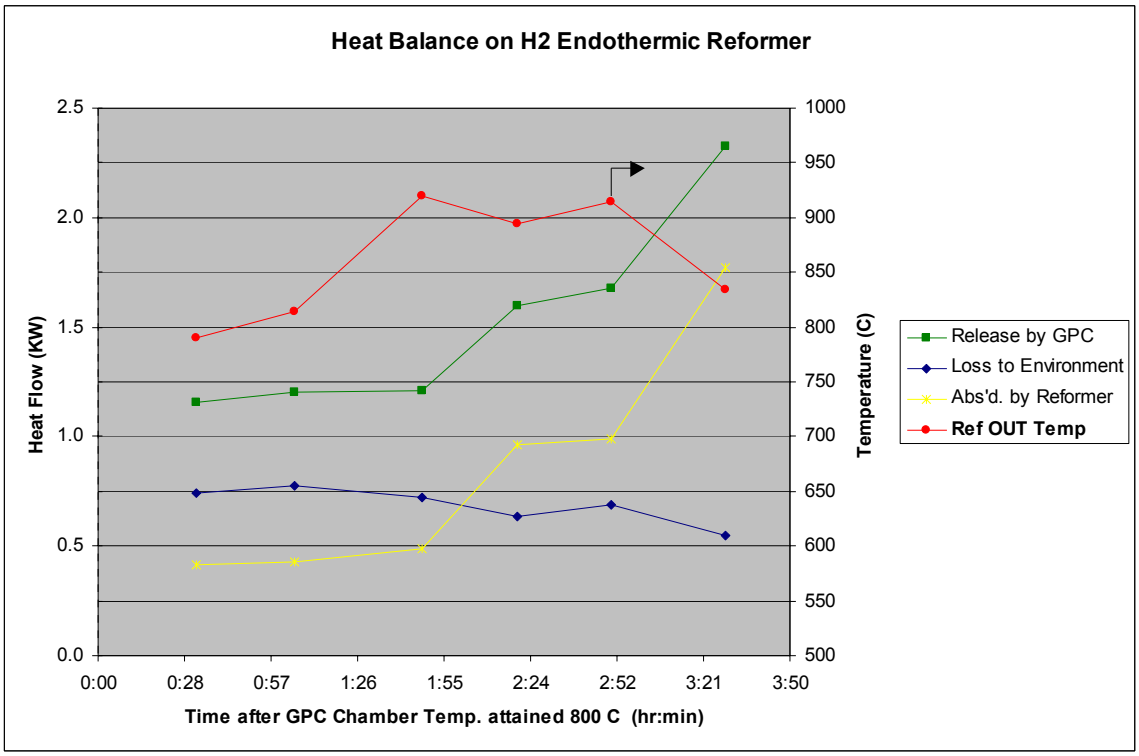


Figure 4.3.2.3.2-1 Heat Balance on H2 Endothermic Reformer

Despite temperatures being somewhat low early in the test, heat losses are higher for the first two test points. This is attributed to higher heat losses to the manifold, as it comes up to temperature. However, even after approximately 4 hours of run time, heat losses on the order of 50% of the exchanged heat are too high for these results to be used for estimating heat transfer parameters.

4.3.2.3.3 Conclusion

Heat losses from the H2 reformer are too large a proportion of the supplied heat from the combustor, making estimates of heat transfer characteristics of the reformer rather meaningless. These results further emphasize the need to isolate an endothermic reformer from the balance of an APU.

4.3.2.4 Recycle Pump Testing

Recycle Pump testing “in-situ” began in November 2003 in the reformer lab after initial performance tests were conducted by the Balance of Plant team on stand-alone units. Preliminary tests were done in the reformer lab to characterize flow stability with

temperature, and temperature profiles of the pump exterior and outlet gas. Results will be reported in subsequent reports.

4.3.2.5 Tubular Start-up Emissions Data

In previous testing, a common trend of hydrocarbon conversion, over the start sequence of the reformer, was identified. The analysis of this trend is used to evaluate improvements of the air heat exchange function, the fuel vaporization function, and the air/fuel mixture and distribution.

A generic trend for this Non-Contact Vaporizer hardware coupled to a reformer is shown in **Figure 4.3.2.5-1**. During the combustion portion of the start-up, the hydrocarbons will spike in accordance with initial air and fuel temperatures and flow rates, fuel particle size, and initial mixture quality. Upon quenching the flame with air, hydrocarbons emissions drop. When reforming (rich fueling) begins, portions of the catalyst are still too cold to generate a reaction, and a high degree of hydrocarbon break-through is seen. As the reaction in the catalyst propagates and bulk catalyst temperature elevates, hydrocarbons drop. Insufficient fuel vaporization, due to low air temperature, is occurring in tandem with the catalyst temperature generation. This indicates that some fuel is condensing on surrounding surfaces, and the catalyst, therefore runs lean. This lean operation causes the dip in hydrocarbons. As the inlet air temperature rises to a level sufficient for full vaporization, the collected fuel upstream of the catalyst boils off and mixes with incoming air/fuel mixture, creating a rich condition in the catalyst and higher hydrocarbon emissions. Once this excess fuel is purged, the catalyst operates at the desired air/fuel ratio, and hydrocarbon emissions reach equilibrium.

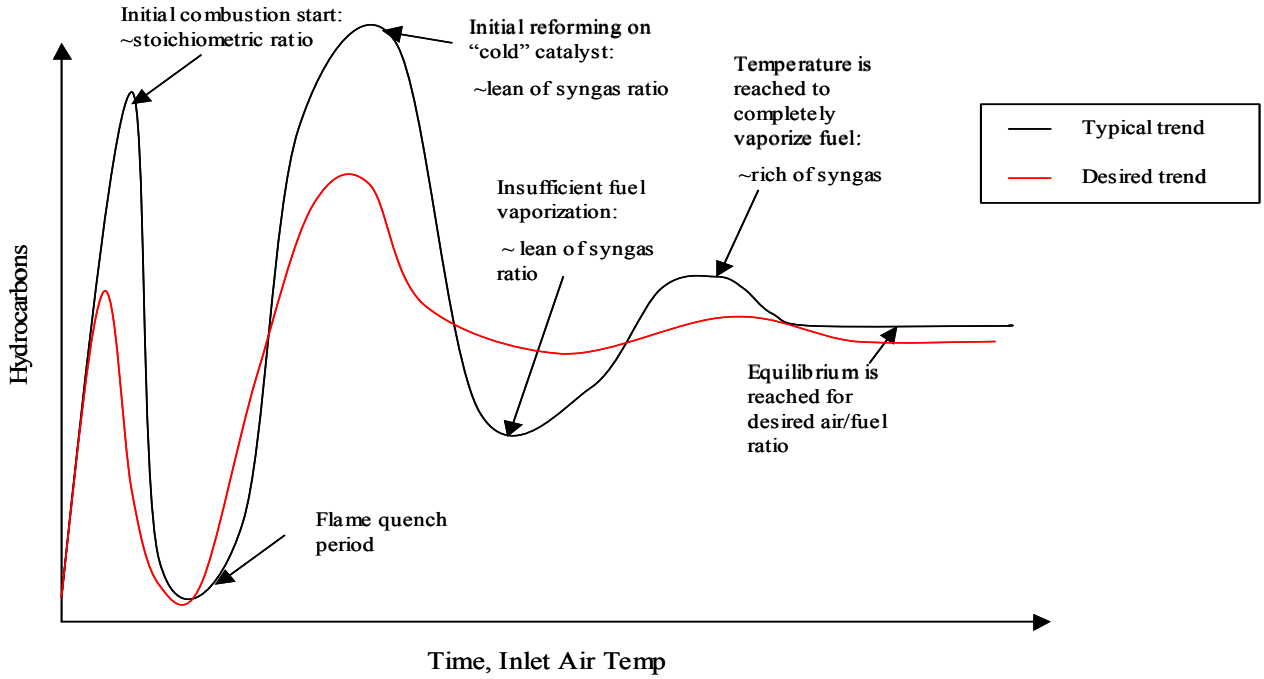


Figure 4.3.2.5-1 Start Performance – Gen 1.1 Tubular with/without Preheat

Using the explanation above, the goal is to achieve better vaporization sooner, and facilitate a fast catalytic reaction during cold starts. This effectively lessens the peaks and valleys of the start-up trend, and lessens stress on the catalyst and risk of carbon formation. This desired trend is shown on **Figure 4.3.2.5-1**. This target is used as the measurement for emissions testing, along with achieving low hydrocarbon emissions during steady state operation.

The Gen1.1 Tubular Reformer design introduced a lower mass Non-Contact Vaporizer with higher thermal conductivity. There were also enhancements to the air/fuel mixing geometry within the Non-Contact Vaporizer. These improvements were expected to show better start-up emissions on Gen 1.1 versus Gen1.0 due to more efficient air heating and better mixture preparation.

The two tests plotted in **Figure 4.3.2.5-2** use a Hot Flame Ionization Detector Methane Hydrocarbon Analyzer to measure emissions from the reformer during start and run, with a maximum measurement range of 30,000 ppm of methane-equivalent hydrocarbons. This method of measurement is faster than the mass spectrometer normally used. Gen1.1 shows improvement of emissions during start-up. The hydrocarbons produced in the first 10 minutes of reforming show significant reduction. This reduction could be caused by increased heat exchange to the Non-Contact Vaporizer, indicated by the "Non-Contact Vaporizer_air_In" temperatures, as well as enhanced mixing.

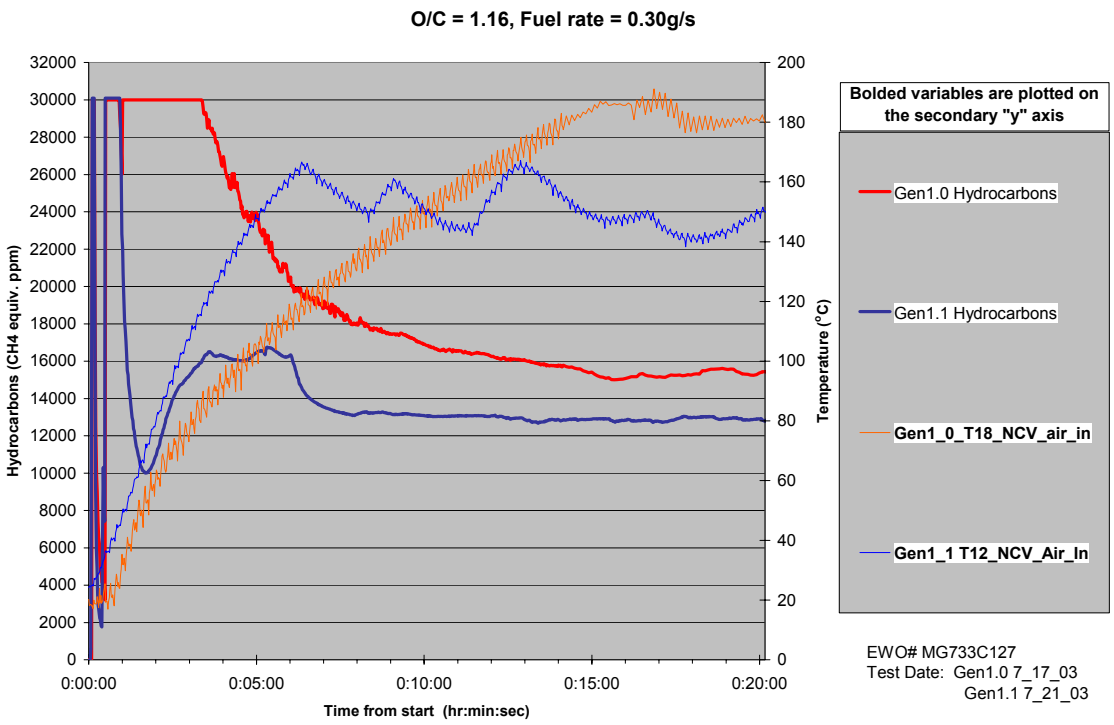


Figure 4.3.2.5-2 Start/Run Emissions – Gen 1.0 vs. Gen 1.1 Tubular

The Gen1.1 and Gen1.0 designs use a 42-volt, 300-Watt in-line cable heater to assist the reformer air heat exchanger during start-up. The contribution of this heater to start-up emissions was evaluated. **Figure 4.3.2.5-3** shows heat-up and performance profiles on Gen1.1 with and without the assistance of the heater.

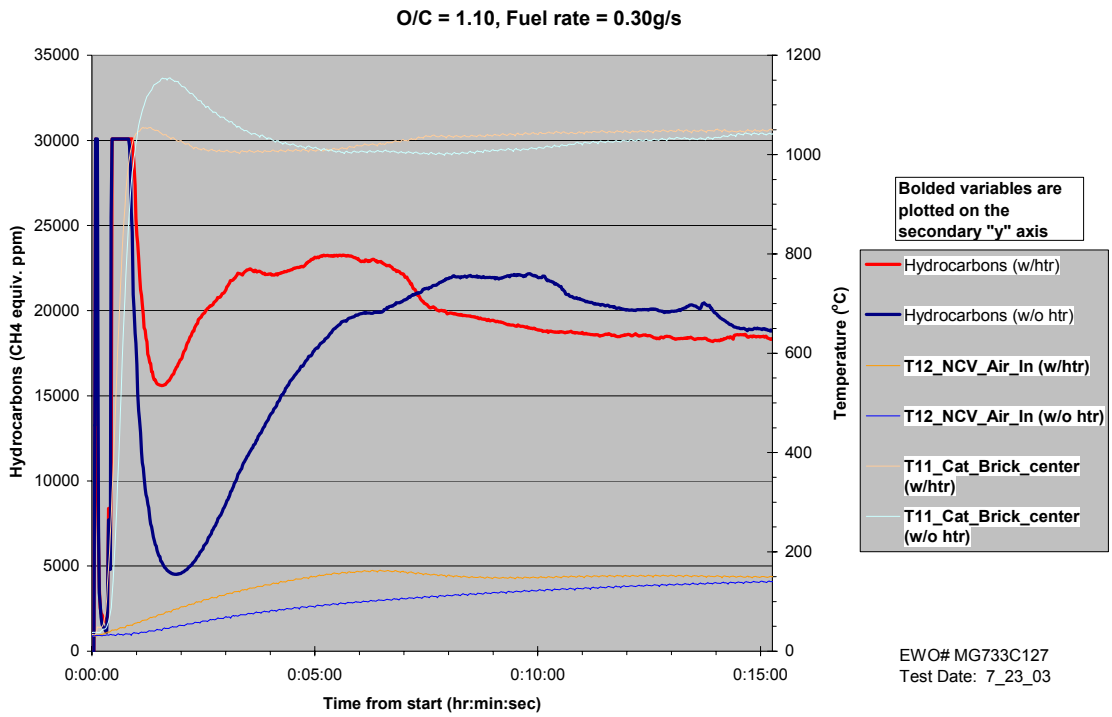


Figure 4.3.2.5-3 Start Performance –Gen 1.1 Tubular with/without Preheat

Integrating over the 15-minute test period would result in less emissions accumulation for the run when the heater is not used.

It is speculated that when the heater is not in use, fuel condenses on the walls upstream of the catalyst face creating a lean condition within the catalyst. While this may be beneficial from an emissions standpoint, catalyst durability may be compromised as a result of the higher temperatures.

The heated run shows a smoother profile of hydrocarbon emissions and catalyst temperature, indicating less risk of catalyst degradation and carbon formation.

4.3.2.6 Tubular Diesel Testing

As preparation for future work, preliminary testing was conducted on Gen 1.0 hardware to evaluate catalyst and vaporizer performance under two grades of diesel fuel. The first diesel blend is a Swedish City Diesel Fuel, which is a low sulfur, low aromatic blend with a distillation curve similar to military JP8 fuel. With these qualities, this blend serves as a baseline fuel for testing. **Figure 4.3.2.6-1** shows the thermocouple placement during diesel

testing. **Figure 4.3.2.6-2** and **Figure 4.3.2.6-3** shows this design's performance using this fuel. Conversion data on **Figure 4.3.2.6-2** looks similar to most runs on gasoline, and indicates this design may be acceptable with this fuel. Likewise, the temperature profile on **Figure 4.3.2.6-3** is typical to those seen with gasoline. Post-run teardown examination showed minimal carbon formation after this brief run period.

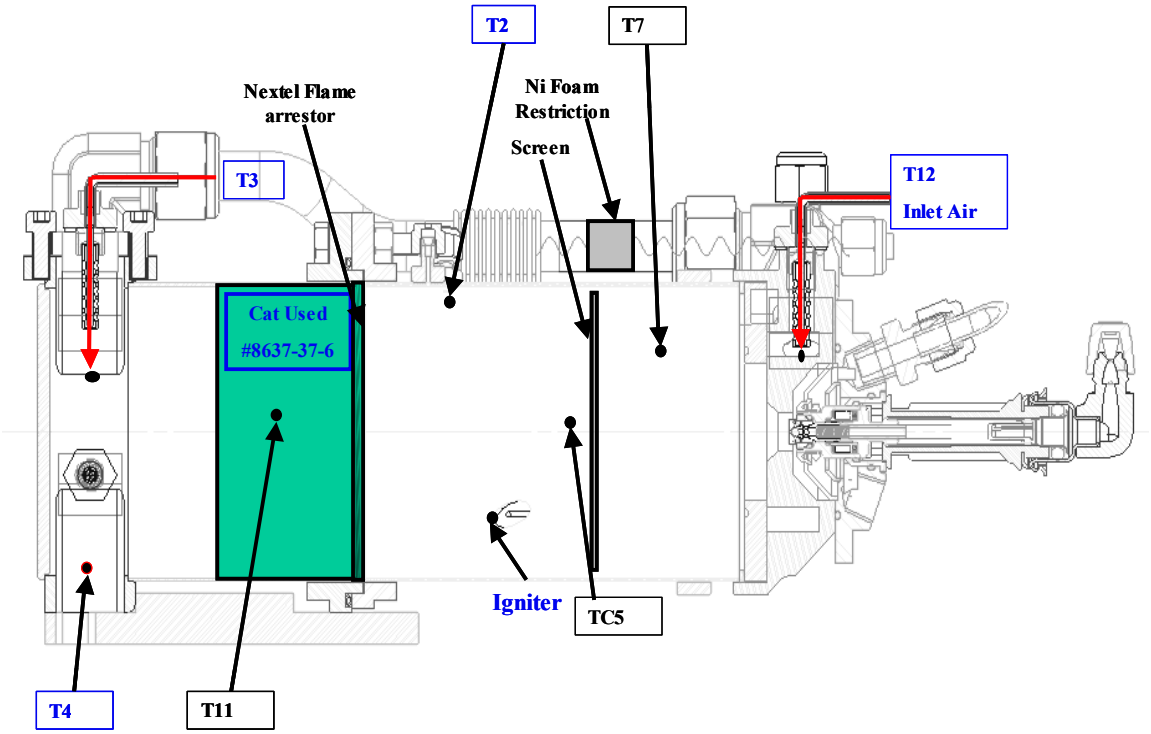


Figure 4.3.2.6-1 Thermocouple Placement – Gen 1.0 Tubular Diesel Testing

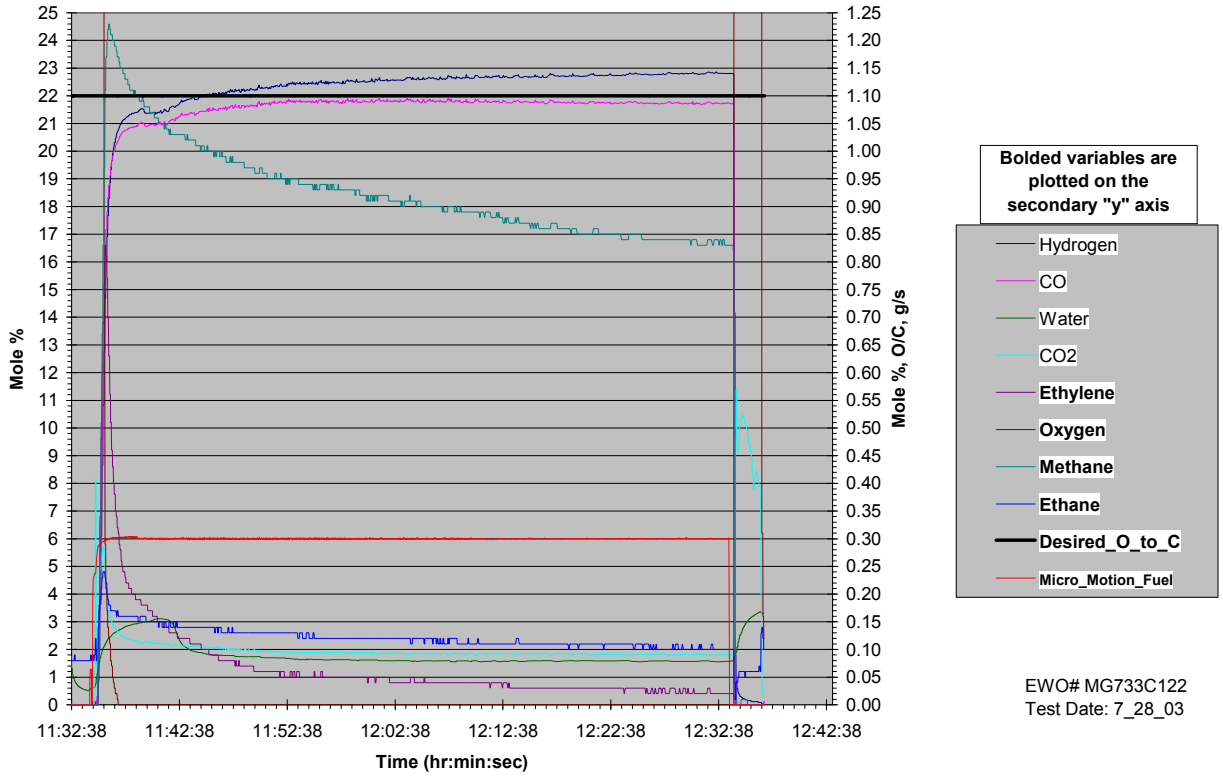


Figure 4.3.2.6-2 Conversion Profile – Gen 1.0 Tubular on Swedish Diesel Fuel

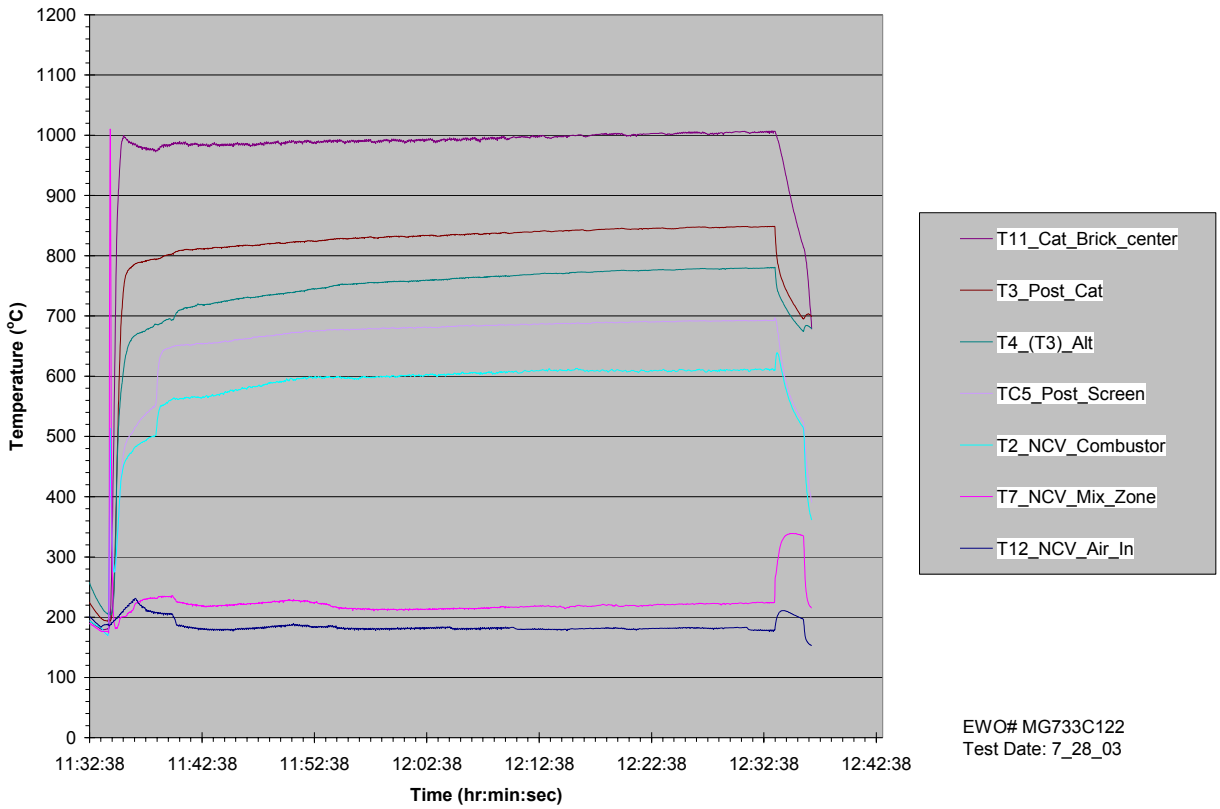


Figure 4.3.2.6-3 Temperature Profile – Gen 1.0 Tubular on Swedish Diesel Fuel

To stress this design to a greater degree, road diesel from a local pump was tested. This fuel's aromatic and sulfur content is much higher than the Swedish blend's, and consequently is more difficult to vaporize and reform. **Figure 4.3.2.6-4** shows poor conversion of hydrocarbons indicative of possible poor vaporization and/or mixing of the fuel, and/or insufficient catalytic reaction. **Figure 4.3.2.6-5** indicates a different temperature profile from the Swedish blend, in that mix zone temperatures (T7) are lower despite a higher incoming air temperature (T12) probably resulting from the differences in heats of vaporization. Additionally, the catalyst temperature (T11) is higher. Pre-combustion was also a problem during this testing, as the mixture seemed very sensitive to incoming air temperature. Post-run teardown examination after the road diesel runs showed significant carbon formation after this test. These preliminary tests show the critical role of the vaporizer/mixing strategy and strong variation in performance with different diesel blends. Extensive testing is still required for further design evaluation.

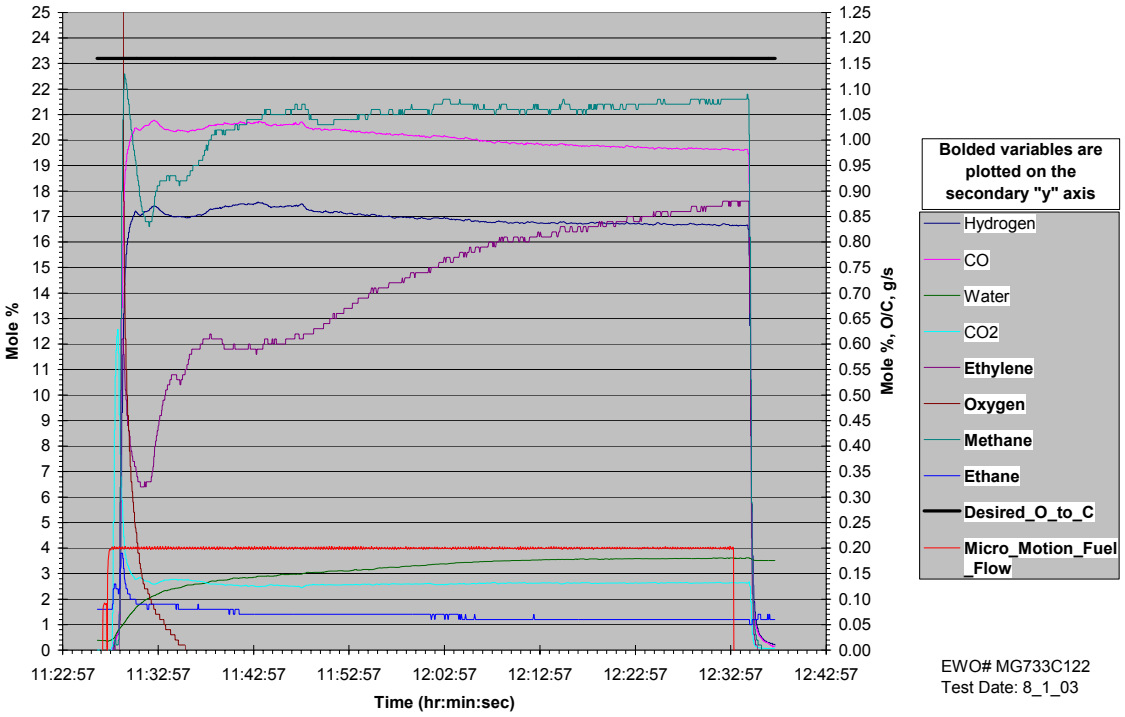


Figure 4.3.2.6-4 Conversion Profile – Gen 1.0 Tubular on Road Diesel Fuel

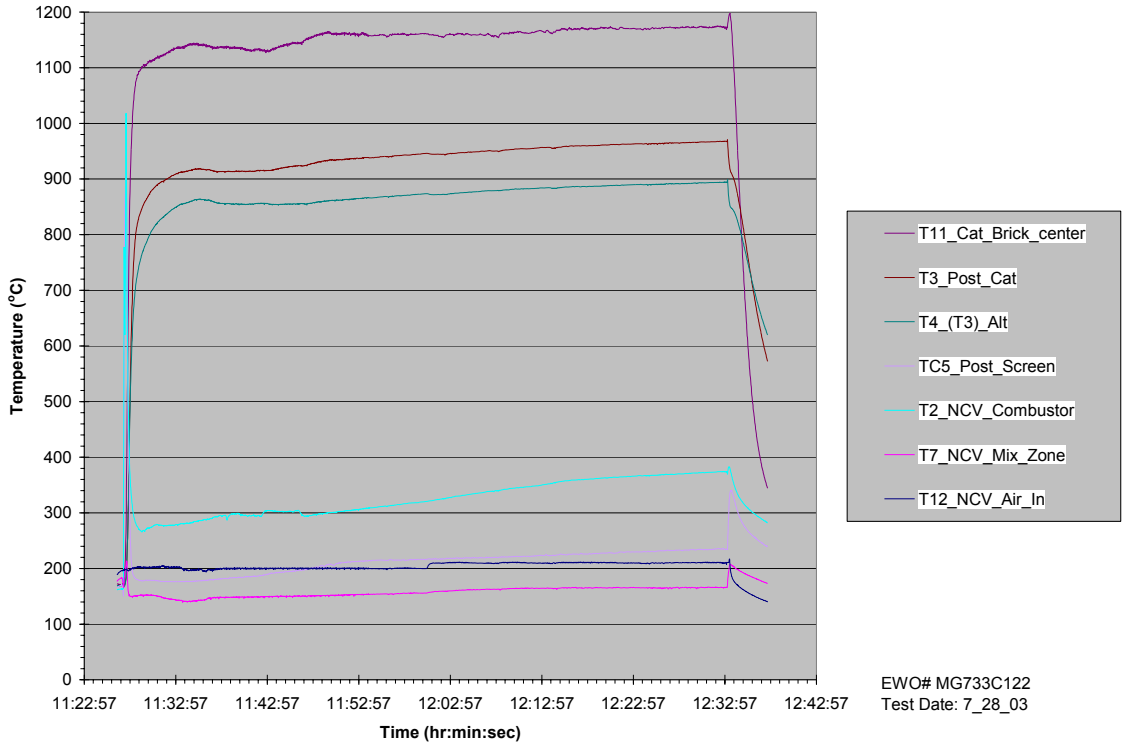


Figure 4.3.2.6-5 Temperature Profile – Gen 1.0 Tubular on Road Diesel Fuel

4.3.3 Develop Catalysts

Catalyst work is discussed in terms of activity areas. These include the following:

- Catalyst Formulation - for optimizing the chemical nature of the catalyst and washcoat
- Catalyst Product Development - for optimizing the catalyst substrate and catalyst loadings on the washcoat and substrate
- Catalyst Manufacturing Process Development - for methods and techniques related to commercial scale manufacturing of the catalyst
- Catalyst Testing - related to measuring the performance of the catalysts in either a fresh or aged state, and developing rapid aging test methods
- Catalyst Applications - related to improving processes employing the catalysts and modeling to understand and predict catalyst performance
- Characterization of Catalysts - related to understanding underlying structure-activity relationships in reforming catalysts

4.3.3.1 Catalyst Formulation

Catalyst formulations continue to be improved, with the focus remaining on modifying washcoat chemistry for improved thermal stability and active metal durability.

4.3.3.2 Catalyst Product Development

4.3.3.2.1 Washcoat - Substrate Adhesion

No new work conducted during this reporting period.

4.3.3.2.2 Substrate Development

Zirconia-Toughened Alumina substrates have been used exclusively as catalyst washcoat supports, rather than cordierite, Silicon Carbide, or metallic monoliths commonly used in the automotive exhaust catalyst industry. We have found that the cordierite melts under partial oxidation reaction conditions, Silicon Carbide decomposes, and readily available metallic monoliths have poor durability. While good performance has been obtained on the Zirconia-Toughened Alumina foams, a monolithic substrate should allow for some additional performance benefits, including lower mass, decreased pressure drop, and improved utilization of washcoat.

4.3.3.2.3 Washcoat Formulation Development

Work continues on optimizing the concentration of active metal in the catalyst washcoat and on the density of active metal on the substrate.

4.3.3.3 Catalyst Process Development

No work directed as catalyst manufacturing development was initiated during this reporting period.

4.3.3.4 Catalyst Testing

The effects of startup method and shutdown atmosphere on catalyst degradation rates were evaluated during this reporting period.

4.3.3.5 Catalyst Application Development

4.3.3.5.1 Carbon Detection Method Development

An optical detection system for detecting poly-aromatic hydrocarbons and carbon formation on the downstream side of a catalyst was used under catalyst application development.

4.3.3.5.2 Methane Reforming Modeling

<u>Methane Steam Reforming Modeling</u>

The impact of steam-to-carbon ratio on coke formation at various operating temperatures was determined by performing a series of equilibrium analysis on methane (CH_4) steam reforming. A free-energy minimization procedure is accomplished with the EQUIL software, which uses a CHEMKIN-3.7 interface to STANJAN. STANJAN provides an efficient algorithm for minimizing the free energy of a mixture to find the equilibrium state. The gas-phase species that are considered when determining the equilibrium conditions are specified in the gas-phase kinetics input data file, while the bulk-phase liquid and solid species are specified in the surface kinetics input file. For this case, the bulk species included are liquid water and solid carbon. The calculations were constrained to allow only the following species and phases to be present at equilibrium: CO, CO_2, H_2O (vapor), H_2O (liquid), H_2, O_2, N_2, C (solid), and CH_4.

Figure 4.3.3.5.2-1 shows the product distribution obtained by equilibrium modeling of methane-steam reforming at a steam-to-carbon ratio of 1.0 and at 1 atmosphere total pressure. At low temperatures, below 450 °C, H_2 and CO_2 are the most stable products. Noticeable CO concentrations begin to be observed at about 400 °C. A stability pocket of solid carbon exists between 425 and 825 °C. Consequently, operating in this temperature range should be avoided. The concentration of carbon diminishes at above 825 °C. Above this temperature, the desired products, H_2 and CO, are the most stable species, with a H_2/CO ratio of 3. To prevent carbon formation, operating temperatures must be higher than the limiting temperatures as indicated in Figure 4.3.3.5.2-1, which means that more energy will be required. At the feed ratio of H_2O/CH_4 = 1.0, the best operating temperature is above 825 °C.

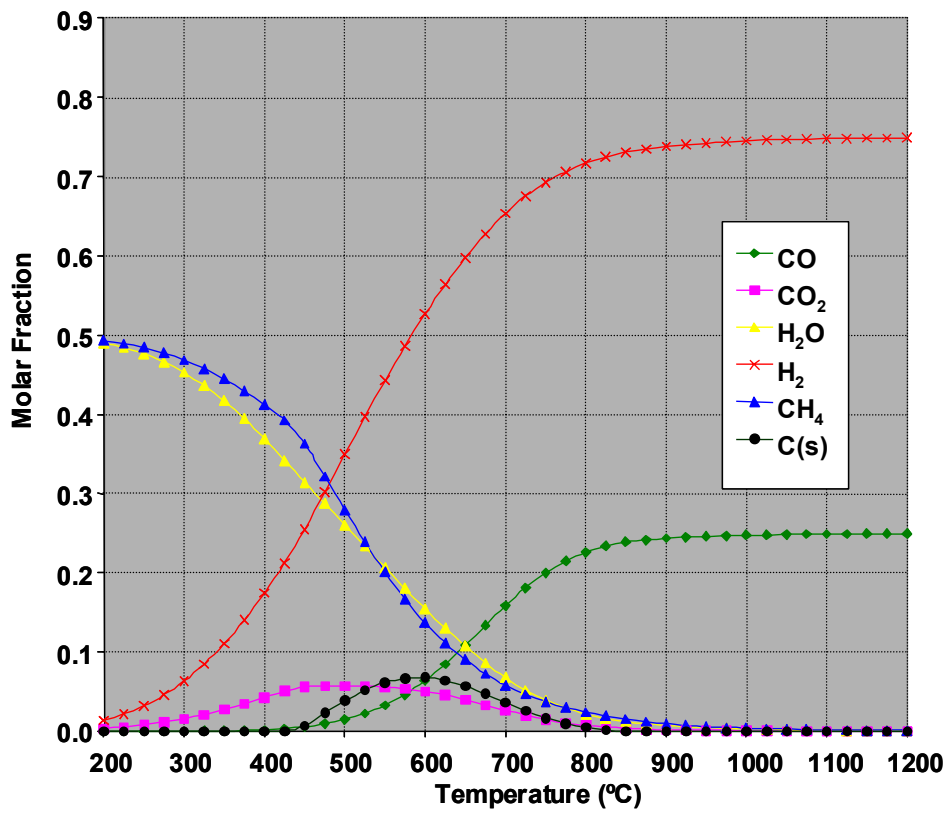


Figure 4.3.3.5.2-1 Product Distribution Obtained Through Equilibrium Modeling of CH_4 Steam Reforming at H_2O/C = 1.0 and P = 1 atm

Figure 4.3.3.5.2-2 shows the product distribution obtained during equilibrium modeling of methane-steam reforming at steam-to-carbon ratio of 4.0 and 1 atmosphere total pressure. Comparison of **Figure 4.3.3.5.1** and **Figure 4.3.3.5.2** reveals that the carbon stability pocket is not present for the case with H_2O/CH_4 of 4.0 in the feed. In fact, carbon formation is not thermodynamically favored, at measurable concentrations, throughout the temperature range of 200 to 1200 °C.

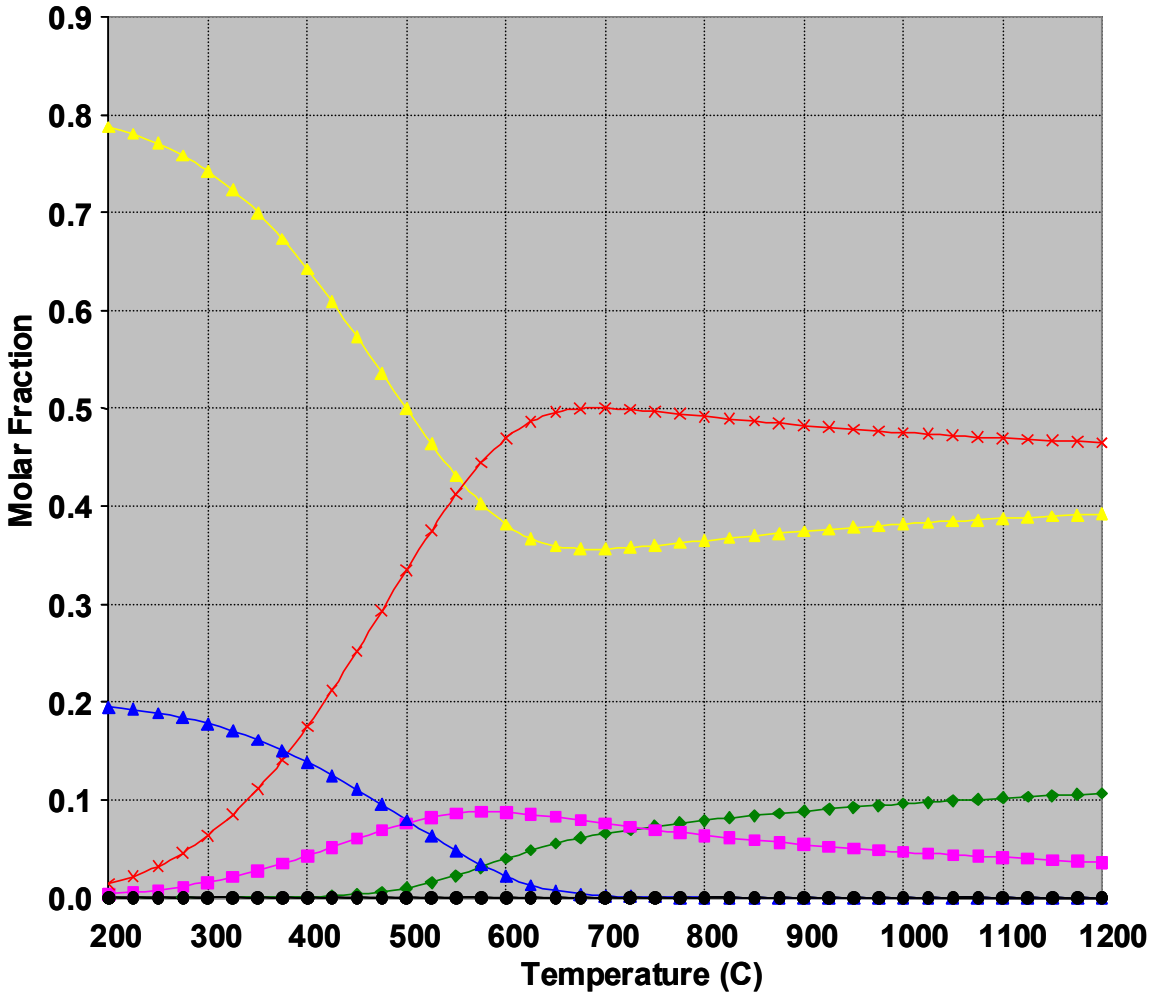


Figure 4.3.3.5.2-2 Product Distribution Obtained Through Equilibrium Modeling of CH_4 Steam Reforming at H_2O/C = 4.0 and P = 1 atm

Figure 4.3.3.5.2-3 shows the concentration of solid carbon in the combined gas and solid product, as a function of temperature and H_2O/CH_4 ratio. Clearly, carbon deposition is thermodynamically possible for a H_2O/CH_4 reforming feed ratio of ≤ 1.0 at atmospheric pressure. Using excess H_2O in the feed may avoid carbon formation at lower temperatures. As evidenced in **Figure 4.3.3.5.2-3**, equilibrium modeling predicts that no measurable carbon will form when H_2O/CH_4 is greater than 2.0.

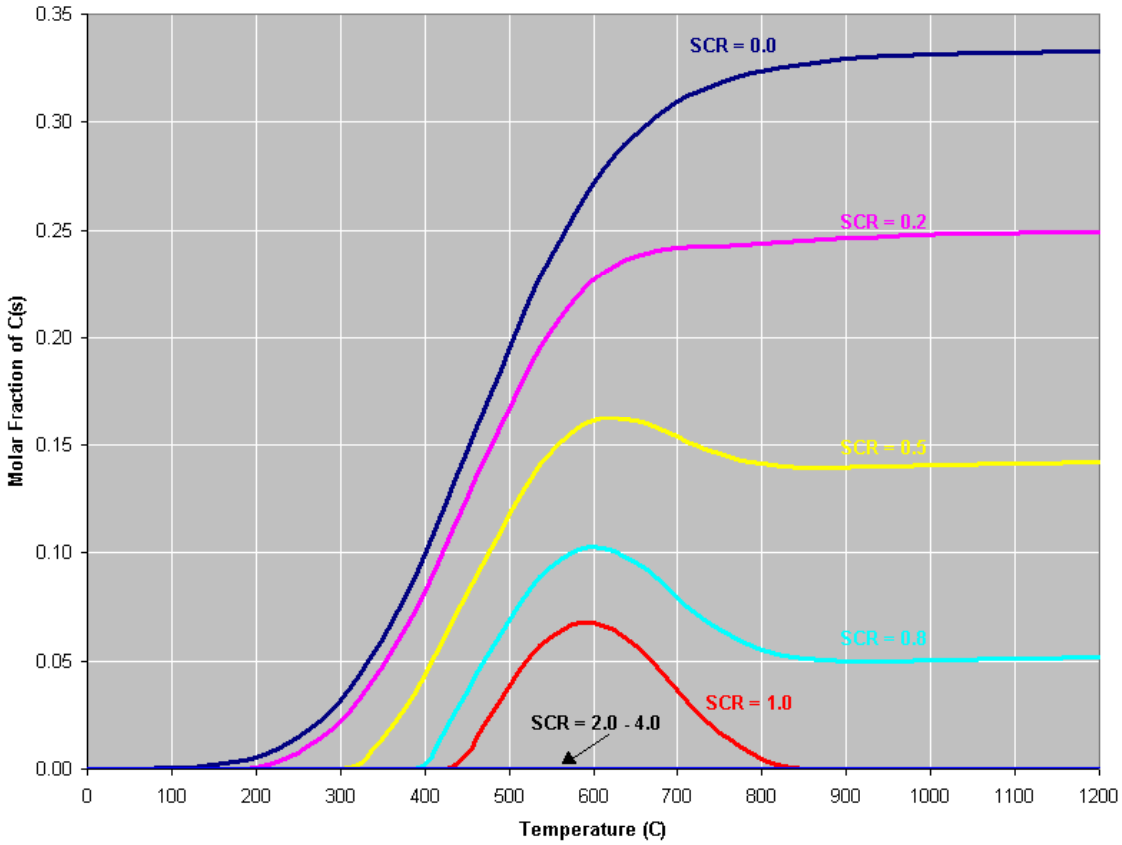


Figure 4.3.3.5.2-3 Equilibrium Modeling of Carbon Formation as a Function of Temperature

4.3.4 Desulfurization of Gasoline and Natural Gas

No new work was completed during this reporting period.

4.3.5 Develop Reformer and System – General

New equipment procurement is outlined in Section 3 above relating to new developments for this reporting period.

4.3.6 Investigate Integration of Reformer and ERU Functions.

This subject covered under "Develop CPO Reformer" Section

4.3.7 Fabricate Developmental Reformers.

See related discussion under "Develop CPO Reformer"

4.4 Development of Balance of Plant Components (Task 4.0)

4.4.1 Combustible Gas Sensor

During this reporting period, additional development activity on the gas sensor involved further characterization of the sensor's response to Hydrogen and investigating alternative

sensor controller strategies. Additionally, packaging studies carried out at the system level, highlighted a need for not only reducing the overall size of the sensor itself, but more importantly, the controller box. The sensor was characterized using hydrogen from 0 to 45,000 ppm, as the test gas. Shop air was used to purge the test enclosure.

Figure 4.4.1-1 shows the relationship between hydrogen concentration and sensor output voltage.

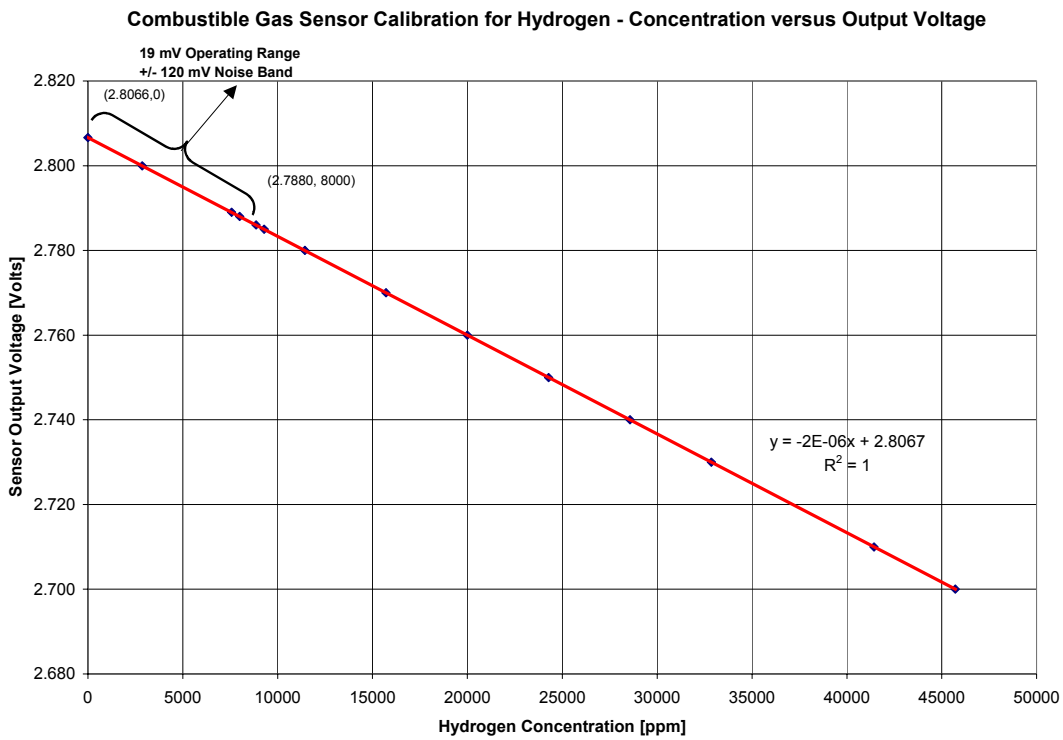


Figure 4.4.1-1 Combustible Gas Sensor Calibration

Figure 4.4.1-2 shows an oscilloscope trace plot of the sensor output signal. At 2.78 volts, the noise in the sensor signal as indicated from the oscilloscope is +/- 120 mV. Although the sensor detects concentrations of 0 to 45,000 ppm of hydrogen, the noise of +/- 120mV on the signal is greater than the entire operating range of the sensor, 2.700 to 2.8066 volts or 110mV. This means that the sensor could falsely indicate due to noise and as currently calibrated does not have adequate sensitivity.

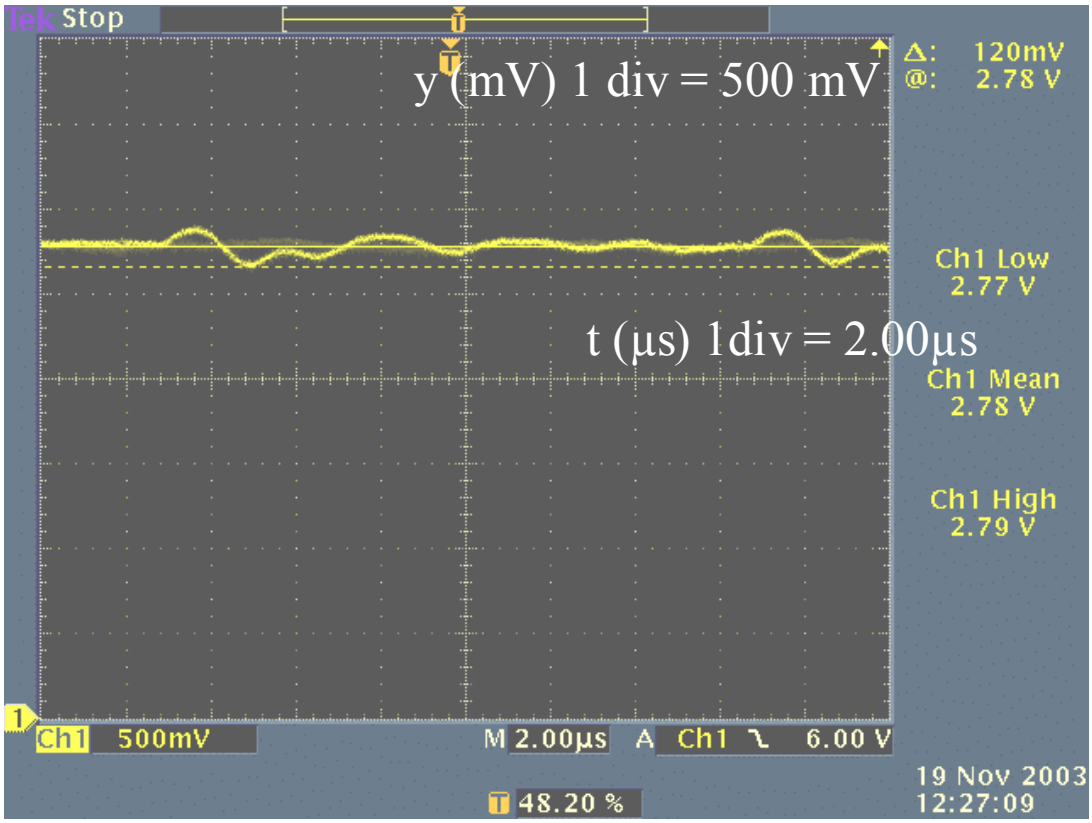


Figure 4.4.1-2 Gas Sensor Signal Trace

4.4.2 Develop Air Delivery and Process Air Sub-System

4.4.2.1 Process Air Blower Motor

The Delphi Process Air Module Blower Motor is a two-pole, three-phase AC Induction Motor capable of 94.1 N-mm at a maximum speed of 68,000 RPM. The motor in combination with the compressor is capable of providing 18g/s at 68,000 RPM with 45 ^{0}C inlet air. The machine controller utilizes sinusoidal waveform reproduction, V/Hz controls (Open Loop). The system efficiency (motor and controller) is 82% at 65,000 RPM and 100% APU power. **Figure 4.4.2.1-3** shows the Delphi designed Process Air Module motor.

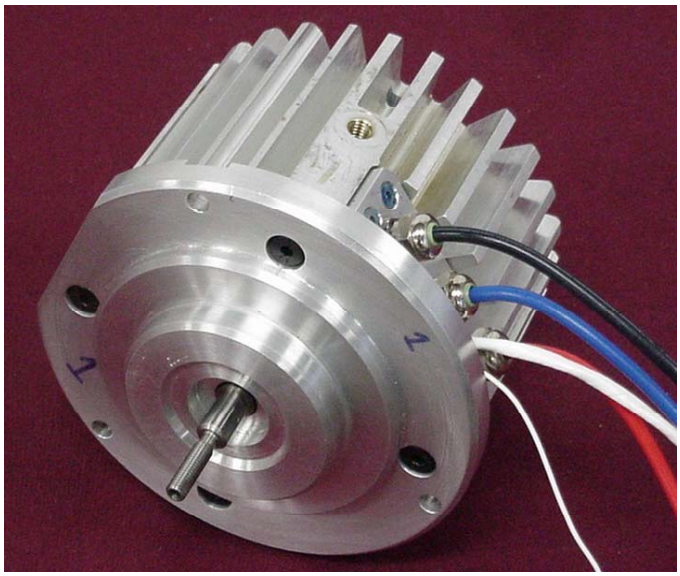


Figure 4.4.2.1-3 Delphi Process Air Motor

Significant analysis was performed to determine the optimal machine and controller technology for this application. Variations of Permanent Magnet and Induction Machine technologies were evaluated to determine the best fit for the application. The following machine and control technologies were evaluated: Induction Machine Sine, Permanent Magnet Square Wave, Permanent Magnet Sine Wave, and Permanent Magnet Six Step. System efficiency was determined at various speeds, inlet air temperatures, and APU power levels for each of the technologies mentioned, to be used for the technology down select. Analytical tools SPEED PC-BDC® software and ANSOFT® Software were used for permanent magnet technology evaluation. Custom Delphi software, which includes statistical machine optimization capability, was used for induction machine technology evaluation.

Thermal analysis was performed using ANSYS® on both the motor and controller to verify satisfactory operating temperatures. Analysis was performed using 30 cfm at 45 °C inlet air condition and 85 °C ambient temperature in PSM.

Structural Finite Element Analysis was performed on several motor components using ANSYS® to verify structural and material design decisions. The following components were analyzed: Rotor Core and End Ring structural analysis, rotor shaft to core interference fit analysis, motor housing structural analysis, complete rotor dynamic analysis with critical speed identification, and various additional analyses on component interfaces.

Induction machine and permanent magnet six-step technologies were found to be the best selections for the current APU application based on efficiency, technical risk, fabrication, and projected cost. Induction machine technology was ultimately chosen due to high efficiency across the entire operating speed range, even though it is slightly less efficient than

Permanent Magnet at higher speed. **Figure 4.4.2.1-4** shows machine speed vs. efficiency for the above mentioned machine technologies.

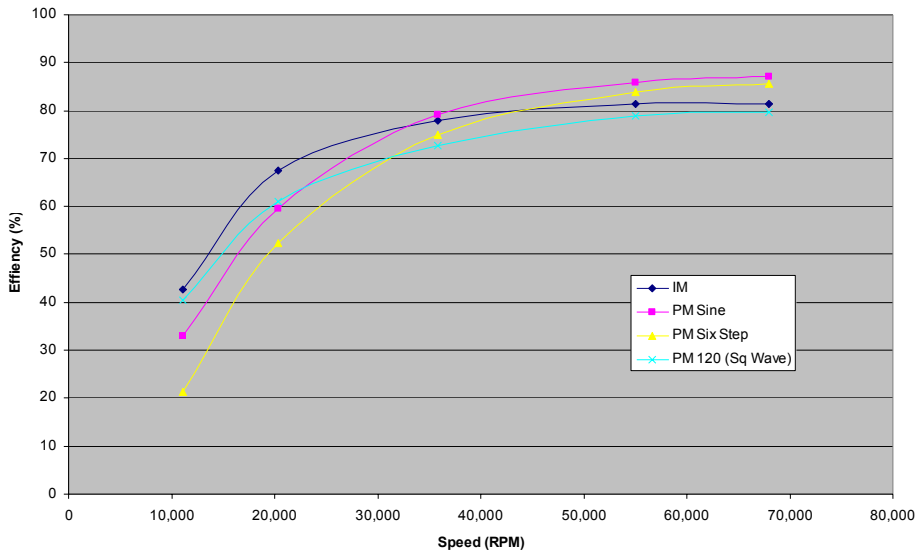


Figure 4.4.2.1-4 Machine Speed vs. Efficiency

Thermal analysis revealed that both motor and controller temperature profiles would be within the limits of component materials and sub-assembly operating capability. **Figure 4.4.2.1-5** shows results of motor thermal analysis and **Figure 4.4.2.1-6** shows results of controller thermal analysis.

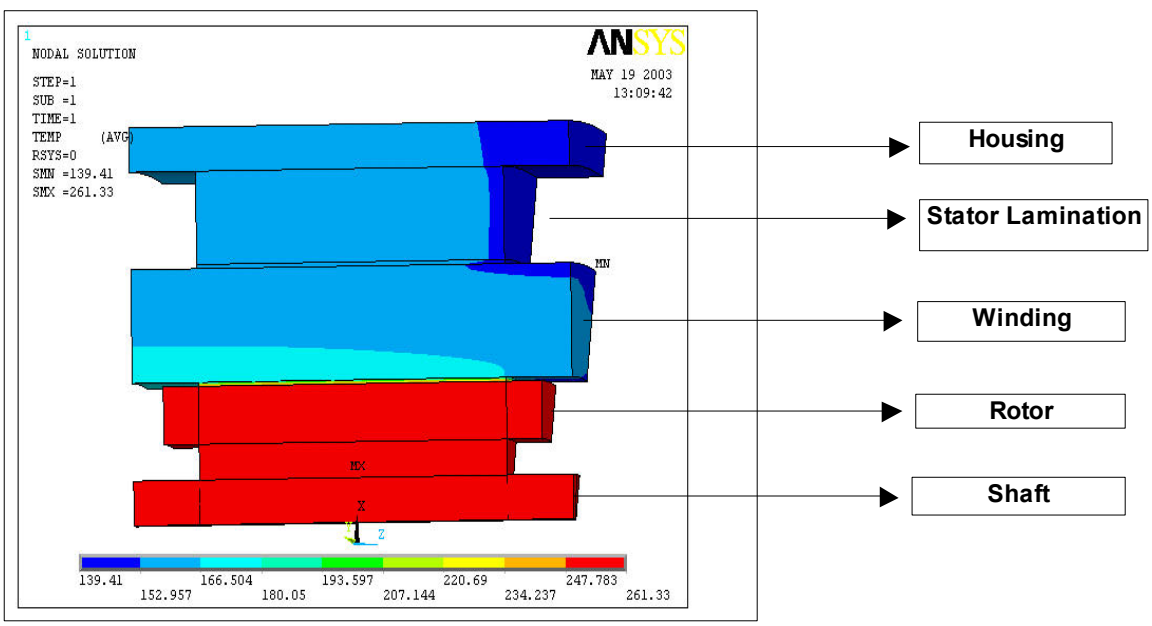


Figure 4.4.2.1-5 Motor Thermal Analysis

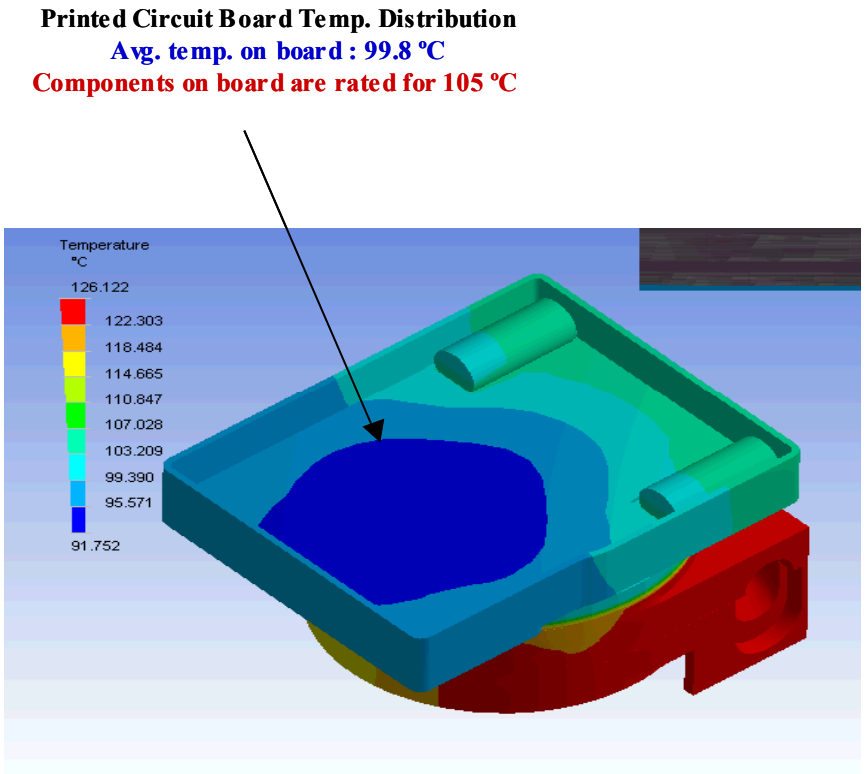


Figure 4.4.2.1-6 Controller Thermal Analysis

Finite element analysis yielded satisfactory results in all areas. The components and interfaces that were analyzed included the rotor core and end-ring structural analysis, rotor shaft to core interference fit analysis, motor housing structural analysis, rotor dynamic analysis with critical speed identification, bearing sleeve to housing interface, and various additional analyses on component interfaces.

Following is an example of an analysis performed to investigate the steel, bearing sleeve fit with the aluminum motor housing throughout the projected motor temperature range. The coupled field finite element analysis predicts the sleeve maintains contact with the housing at steady state operating temperatures. **Figure 4.4.2.1-7** shows contact pressure (MPa) at maximum operating temperature.

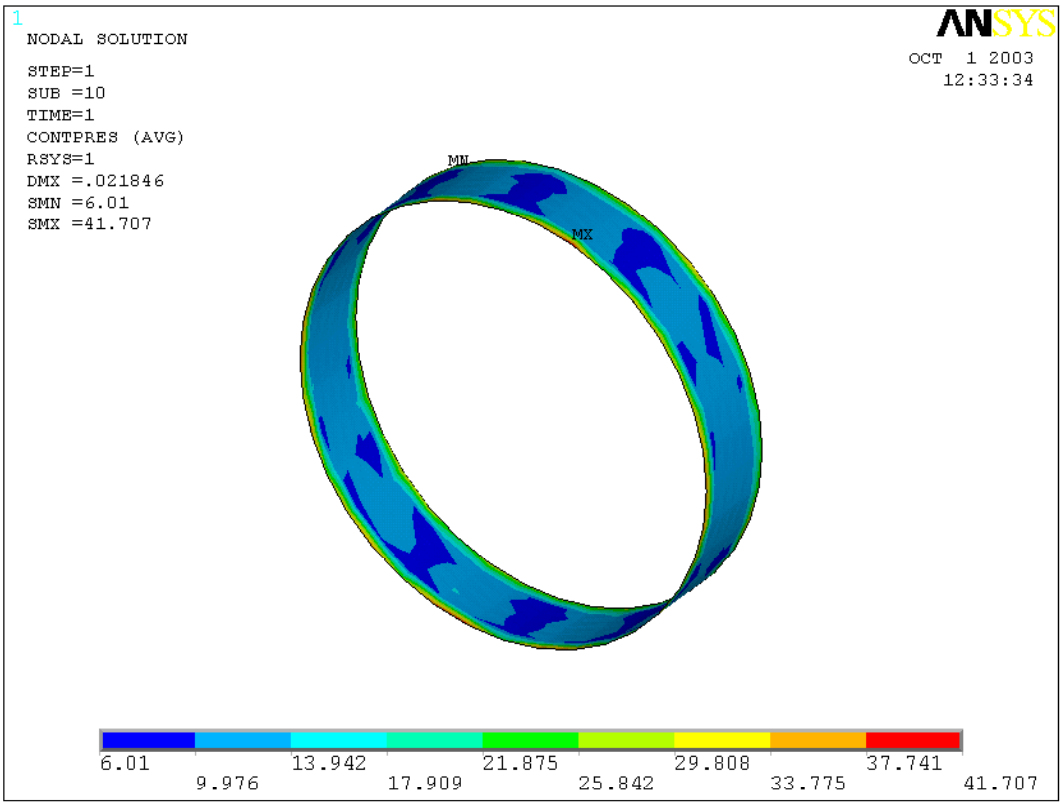


Figure 44.2.1-7 Contact Pressure at Maximum Operating Temperature

4.4.2.2 Process Air Manifold

The Delphi Process Air Module, shown in **Figure 4.4.2.2-1**, has been redesigned to improve performance and reliability while enhancing manufacturability. A major objective of the design team was to develop an integrated package that readily mounts to the APU assembly using a minimum number of electrical and mechanical connections. The Process Air Module utilizes ambient air and provides four variable, measured output airflows to supply the combustor, cathode, reformer, and cathode bypass and is comprised of four subassemblies; inlet shroud and filter, manifold, motor and impeller, and motor controller.

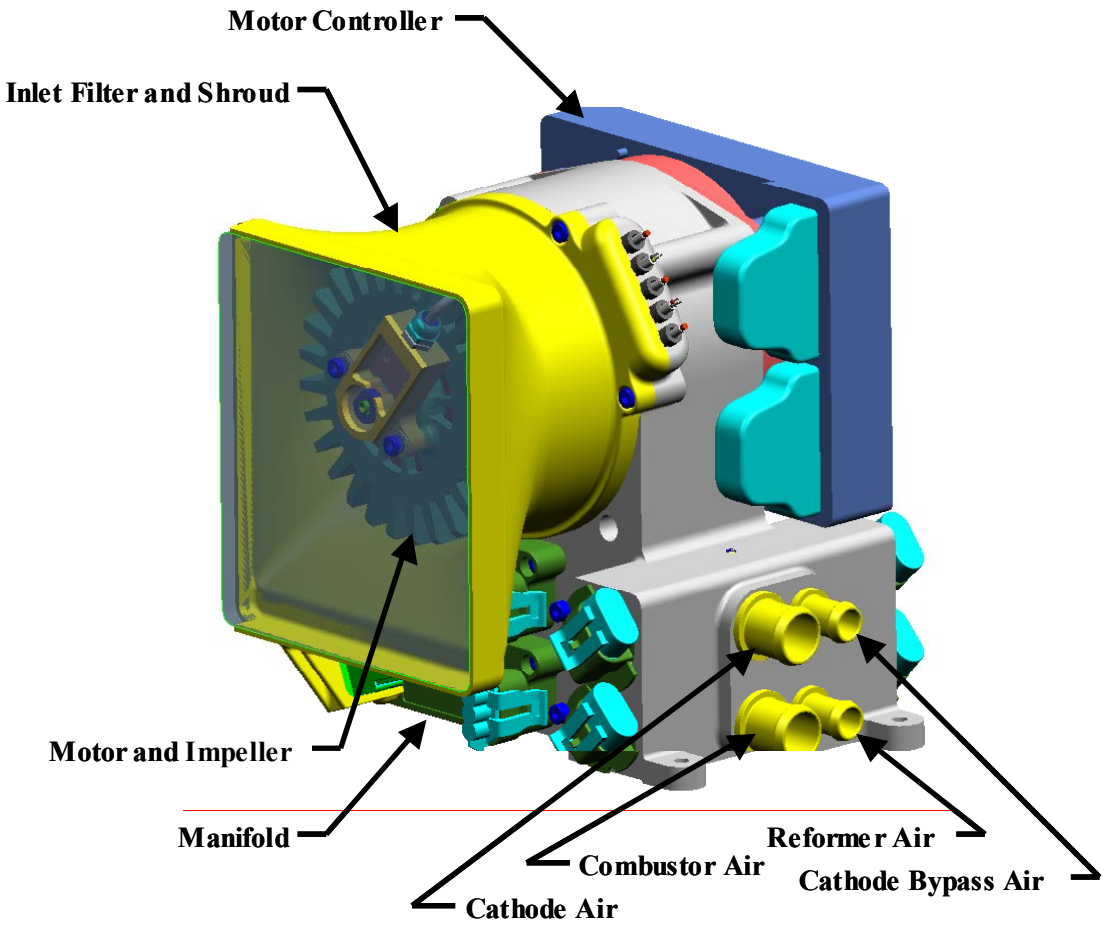


Figure 4.4.2.2-1 Delphi Process Air Module

The manifold assembly, shown in **Figure 4.4.2.2-2**, provides the inlet and outlet scroll air passages for the impeller and includes an air control valve and a mass airflow sensor for each of the four air outlets. The manifold assembly also provides the mounting structure for the motor, motor controller, and inlet air shroud. EFD® lab computational fluid dynamics software, supplied by Nika Fluid Solutions, is being used to assess the behavior of the manifold assembly. A test manifold (**Figure 4.4.2.2-3**) is being fabricated from high strength, high temperature stable material using a stereo-lithography process so that the air control valves can be integrated and tested on a flow bench to determine their performance characteristics.

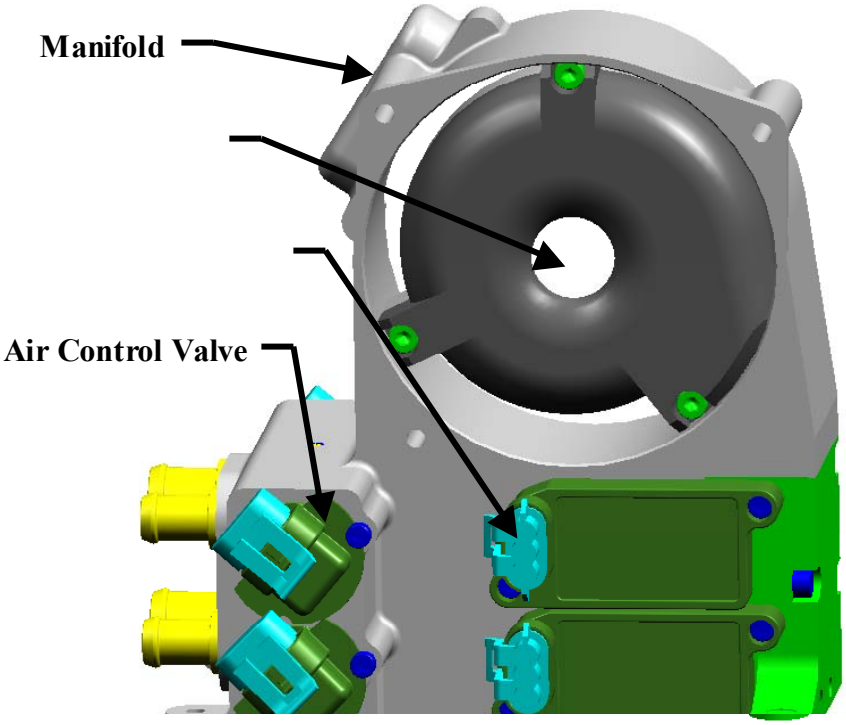


Figure 4.4.2.2-2 Manifold Assembly

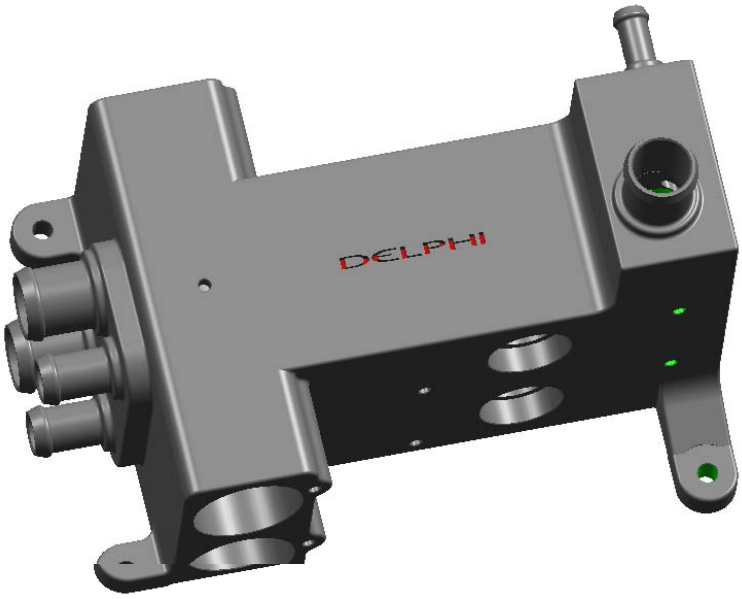


Figure 4.4.2.2-3 Test Manifold

Description of the test manifold is presented in section 3.4.

Improvements have been considered for the design of the Process Air Module impeller to increase its efficiency. These changes include replacing straight vanes with swept vanes, adding splitter vanes to prevent or minimize flow separation, and extending the leading edge of the vanes further into the throat of the impeller. A redesigned impeller was fabricated using a high strength, high temperature stable stereo-lithography material. **Figures 4.4.2.2-4** and **Figure 4.4.2.2-5** show structural finite element stress plots, as a result of centrifugal forces at 65,000 RPM, of the original and redesigned impellers fabricated with the high strength stereo-lithography material. Ignoring stress concentrations at the intersection of the vanes and inlet nozzle, the original and redesigned impellers have comparable stress levels and are equally capable of being tested across the full operating range if fabricated with the stereo-lithography material, which has tensile yield strength of 78 MPa. Performance testing of the redesigned impeller will be done on the airflow bench using an existing Process Air Module.

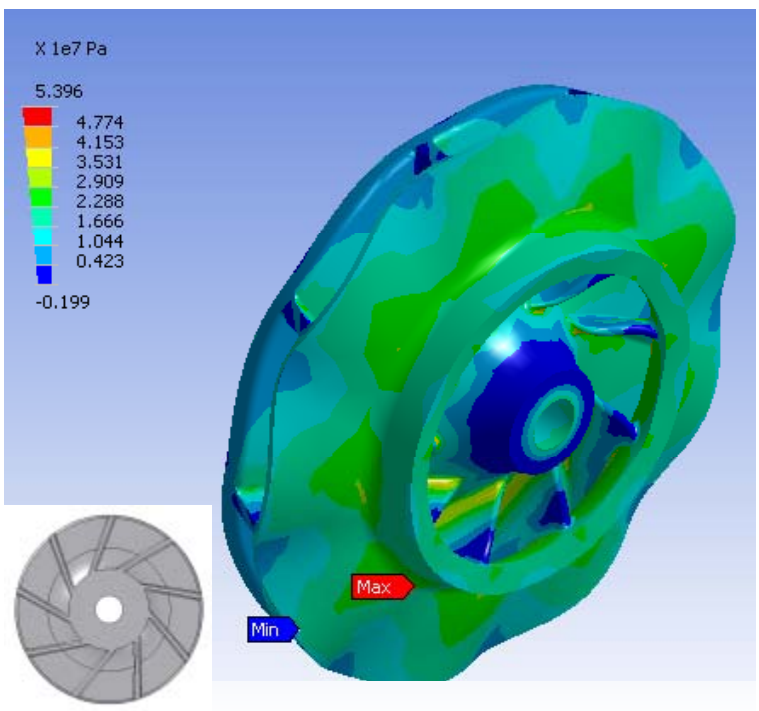


Figure 4.4.2.2-4 Stress Plots, Original Impeller

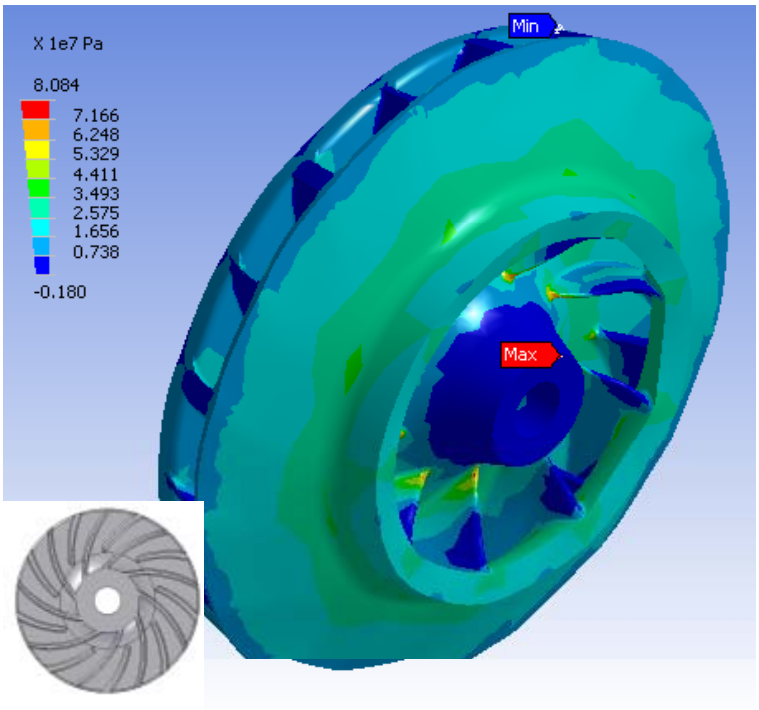


Figure 4.4.2.2-5 Stress Plots, Re-designed Impeller

4.4.3 Hot Zone Components

4.4.3.1 Gasket

Delphi has tested multiple variations of metal gaskets: Flat stock metal gaskets, chemically etched metal gaskets and water-jet flat stock metal gaskets. Mechanically processed flat stock tended to leave a jagged burr on the exit side. Attempts to remove this slight burr resulted in either machining scratches on the sealing area or in incomplete burr removal. Adding an over-plate to the gasket only enhanced the surface scratches or the burr. The metal gaskets also tended to leak along long edges of a joint due to the reduced compressive force in those areas. Increasing the number of bolts slightly increased the sealing of the gaskets, and required component design changes.

As previously reported, die cut F-mica gaskets generally have advanced sealing capability. Die cut F-mica gaskets were designed, fabricated and tested as component interface seals between the Reformer, Stack and Cathode Heat Exchangers to the Integrated Component Manifold. Reviewing the manufacturing process of 1 mm thick mica gasket cut with a steel rule die showed that the material was de-laminating, and that some would break apart with handling. Process changes resulted in eliminating the de-lamination and part breakage and significantly advanced the sealing capability of F-mica gaskets.

A new component gasket was also developed during this reporting period. In the Integrated Component Manifold design configuration number 9 (refer to section 4.4.3.2 Integrated Component Manifold), a new insertable GPC was introduced. An additional seal was required to seal the GPC to the Integrated Component Manifold. Discussions with vendors

lead to the selection of an internal pressure metal "C" –Ring gasket. The sealing concept of the metal "C"-Ring is based on elastic deformation of a metal "C" substrate that gives a contact point on each sealing surface. The base metal was plated with a deformable plating to increase the seal. The metal "C"-Ring was placed into a machined groove that restricted lateral movement of the ring when axial pressure was applied. The depth of the groove was maintained so as to not allow the Combustor base and mating surface to bottom out as the "C"-Ring was compressed. The "C" of the ring is open to the side of higher pressure so that the high pressure actually helps maintain the seal.

Figure 4.4.3.1-1 illustrates the "C"-Ring gasket design. Testing to date has shown adequate sealing of the Combustor to the Integrated Component Module with this gasket technology.

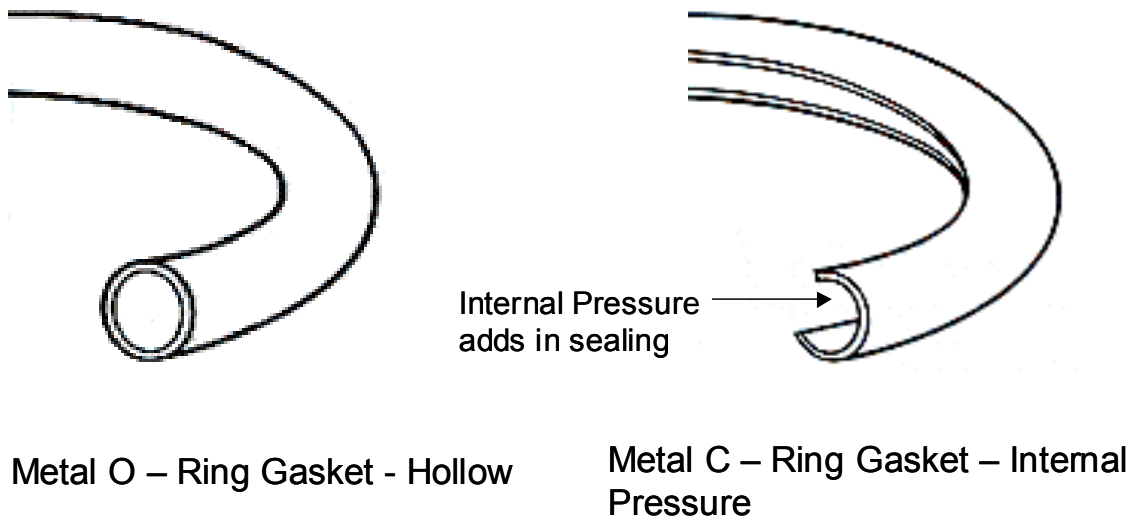
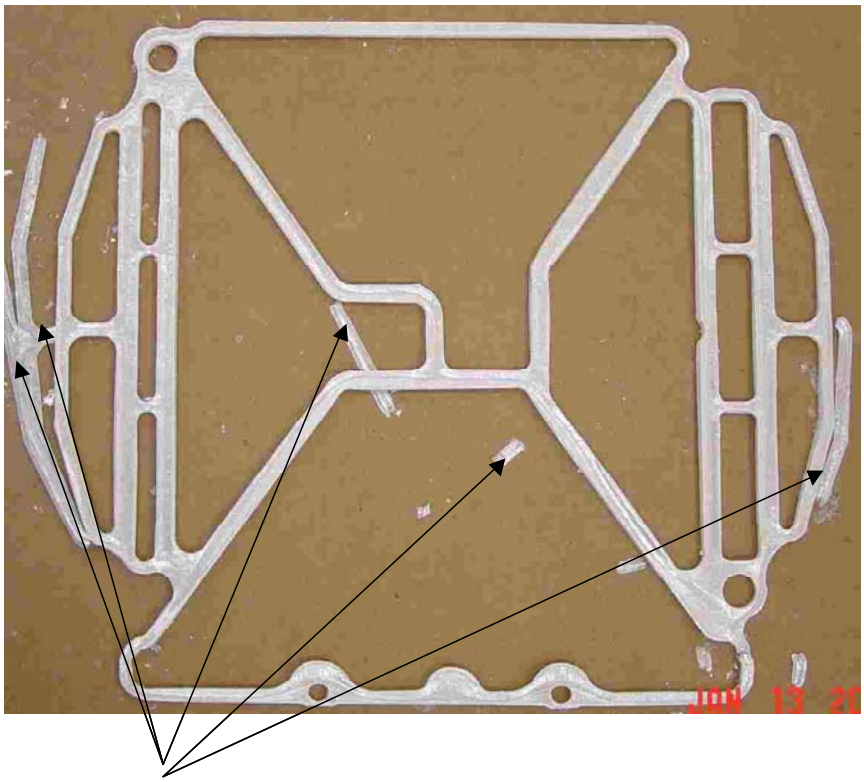


Figure 4.4.3.1-1 "C"- Ring Gasket

Figure 4.4.3.1-2 and **Figure 4.4.3.1-3** are examples of the die cut F-mica gaskets. Sometimes parts would break upon removal from the die. Others would break apart during handling. Gaskets that didn't break apart all had some amount of de-lamination on the edge.



Rib areas breaking off due to weakening from pinching by die cut operation

Figure 4.4.3.1-2 Die-Cut Gasket

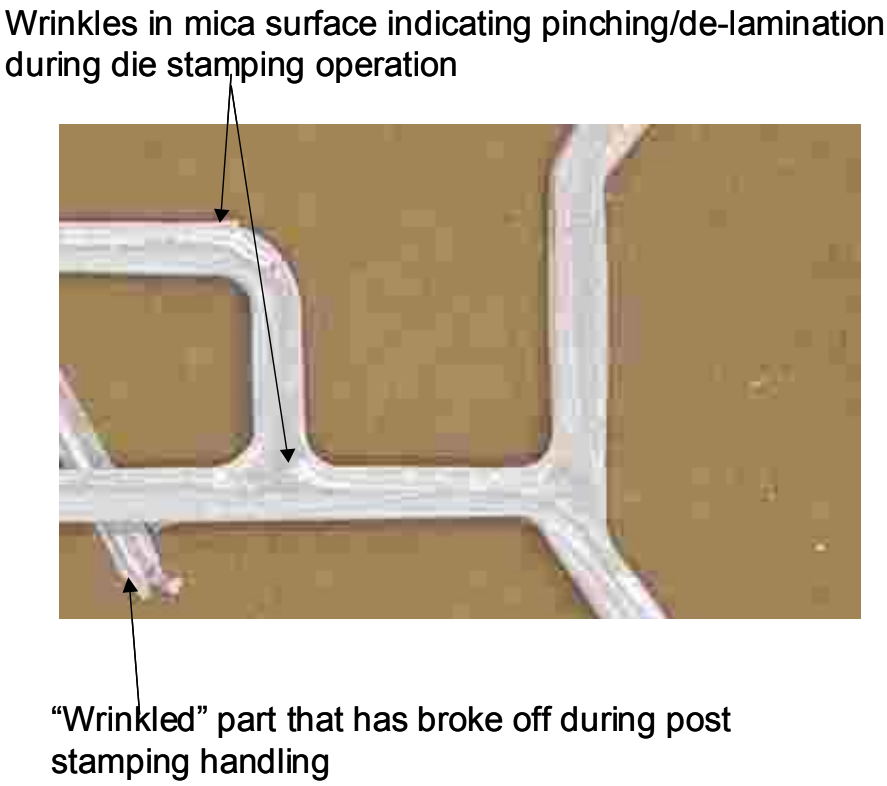


Figure 4.4.3.1-3 Die–Cut Gasket, Close-up

4.4.3.2 Integrated Component Manifold

The Integrated Component Manifold is a critical Hot Zone Component in that it structurally provides a mounting surface for the stacks, reformer and heat exchangers. It is also a complex manifold, which transports the necessary gases, (high-temperature inlet and exhaust air, fuel and waste gases), within and to and from the hot zone.

The requirements for the Integrated Component Manifold include a steady-state operating temperature range of 700 ^{o}C to 1000 ^{o}C, internal pressure range from 15 to 45 KPa gage, and overall temperature ranges from –40 ^{o}C external on cold start, up to 1650 ^{o}C internal temperatures.

The construction of the Integrated Component Manifold is accomplished by brazing together 5 layers of high temperature Nickel Alloy materials. These layers form the component mounting surface on the top plate, internal gas passages on the upper and lower flow plates, and external inlet and exhaust connections.

At this time, several unique Integrated Component Manifold designs have been developed. Integrated Component Manifolds numbers 1 through 6 were previously built to prove out design conceptualization and demonstrate manufacturing feasibility. Integrated Component Manifolds number 7 & 8, built during this reporting period, were the first to incorporate an internal ceramic thermal barrier coating for improved thermal management.

A reduction in the overall mass of the Integrated Component Manifold was accomplished by incorporating mass reduction voids and by reducing most rib wall thicknesses. Additionally, several other new features have been built into these assemblies, including a heat treated, 6.3 mm thick, top plate, reversed stack bolting to increase gasket compression loading, removable Nickel foam inserts used as oxygen getters, and recessed top plate surfaces to reduce ground surfaces.

Internal to the Integrated Component Manifold is a combustion chamber for burning waste gases exiting from the stack. The by-product of this process is a clean exhaust gas used to pre-heat incoming cathode air. The combustor walls are also coated with the ceramic coating, 0.5 mm minimum thick Zirconia, allowing an additional 150 ^{o}C thermal gradient to form across combustor walls. This captures more internal heat, thus reducing the heat lost to the system or the environment.

All surfaces of the Integrated Component Manifold to be coated are left exposed while surfaces to be protected are masked either by a metal cover or through the use of high-temperature tape. After completion of the thermal barrier coating, the Integrated Component Manifold components are placed through a final braze which completes the assembly. The final braze process includes positional fixturing for layer alignment, external piping manifolds, thermocouple mounts and other system related components. The braze alloy used is “Nicrobraz 150”.

Integrated Component Manifolds 9 &10 incorporate a co-flow stack design (for Gen 3 stacks) with an insertable GPC feature. This combustor design allows for mixing of external by-pass air, stack air and stack exhaust, and flow into the combustor where ceramic igniters ignite the mixture. The spent gases are then exhausted to the Cathode Heat Exchangers. The removable concept of the combustor allows for short turn-around design optimization of the combustor. Design, fabrication and initial system testing with these Integrated Component Manifolds were completed during this period. Integrated Component Manifold numbers, 11 – 13, are presently being fabricated and will incorporate design variations to the Gas Phase Combustor.

Figure 4.4.3.2-1 depicts part of the ceramic coating application to the Integrated Component Manifold.

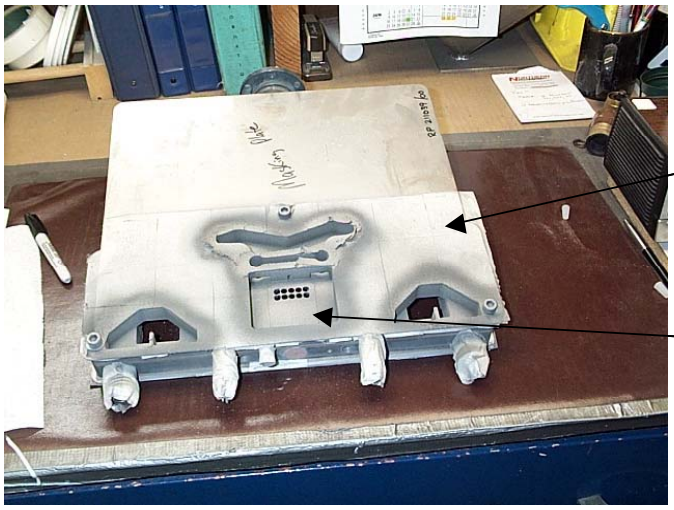


Figure 4.4.3.2-1 Applied Thermal Coating – Integrated Component Manifold 6

Figure 4.4.3.2-2, Figure 4.4.3.2-3 and Figure 4.4.3.2-4 illustrate the ceramic coating application at other levels. **Figure 4.4.3.2-2** depicts the final ceramic coating on the upper flow plate.

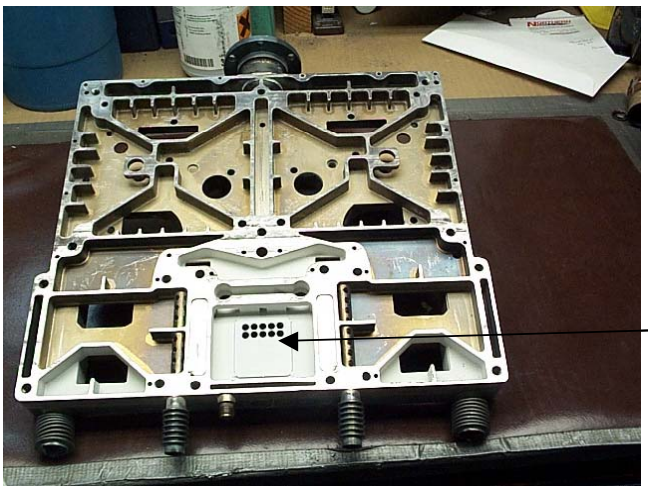


Figure 4.4.3.2-2 Ceramic Coating with Mask removed – Integrated Component Manifold 6

Figure 4.4.3.2-3 illustrates the final ceramic coating on the lower flow plate and **Figure 4.4.3.2-4** illustrates the final ceramic coating on the underside of the top plate, and also show the cut-outs for access to the oxygen getters.

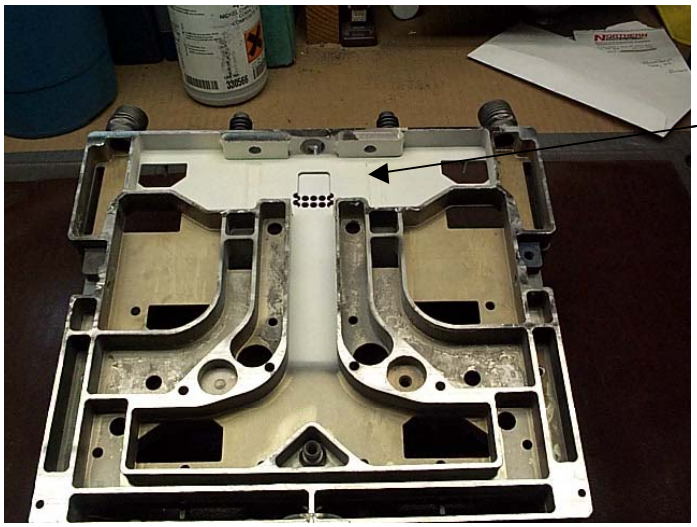


Figure 4.4.3.2-3 Applied Thermal Ceramic Coating

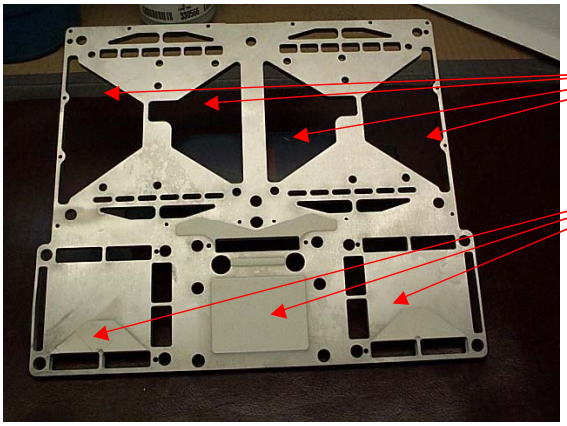


Figure 4.4.3.2-4 Coating Application to Top Plate

Figures 4.4.3.2-5, 4.4.3.2-6, & 4.4.3.2-7 show additional design improvements implemented in the Integrated Component Modules 9 through 13. **Figure 4.4.3.2-5** shows the internal Air diffusers, the thinner wall ribs, the mass reduction voids, and the insertable GPC area. **Figure 4.4.3.2-6** shows the top plate with ground gasket surfaces, and new cutouts for the replaceable oxygen getters. **Figure 4.4.3.2-7** shows the bottom view and further illustrates mass reduction voids. It also shows the GPC in place, thermocouple sensors and spiral bellow manifolds brazed into the assembly.

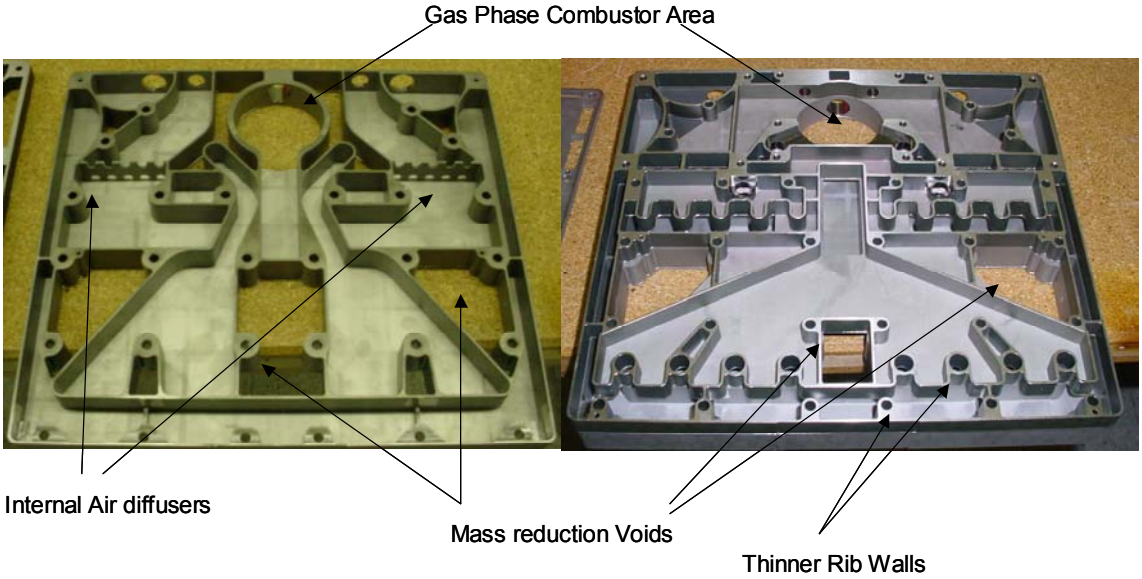


Figure 4.4.3.2-5 Reduced Mass Integrated Component Manifold 9

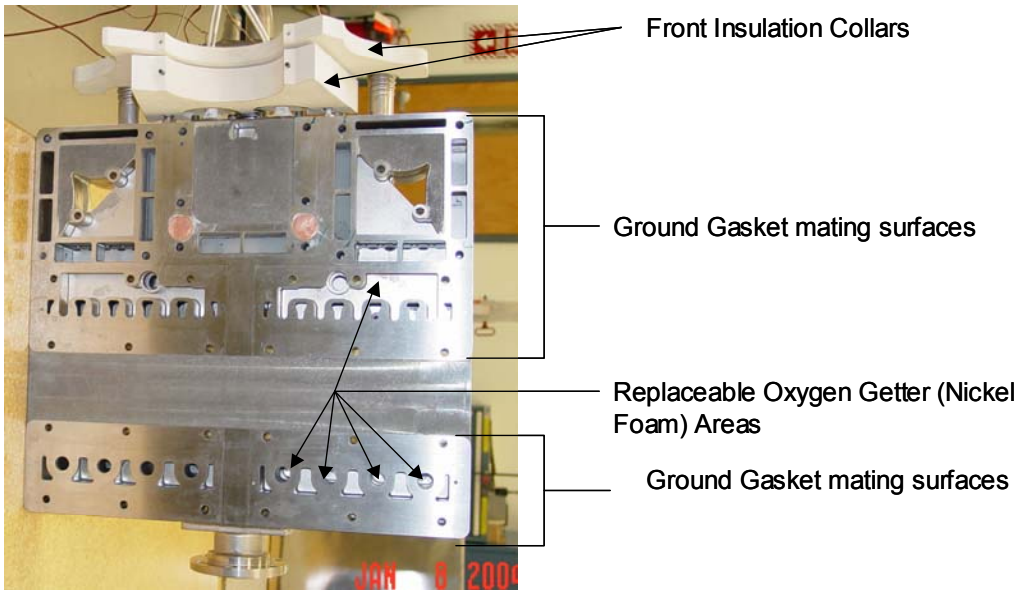


Figure 4.4.3.2-6 Top View, Integrated Component Manifold 9

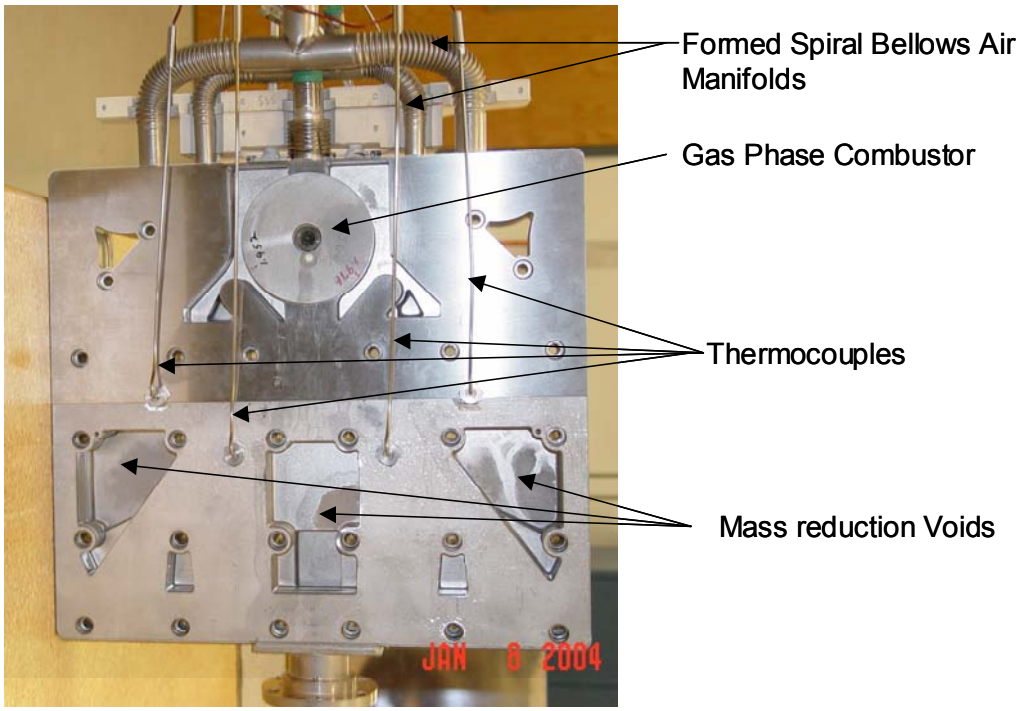


Figure 4.4.3.2-7 Bottom View, Integrated Component Manifold 9

Figures 4.4.3.2-8 & 4.4.3.2-9 illustrate the basic insertable GPC design in Integrated Component Manifolds 9 through 13.

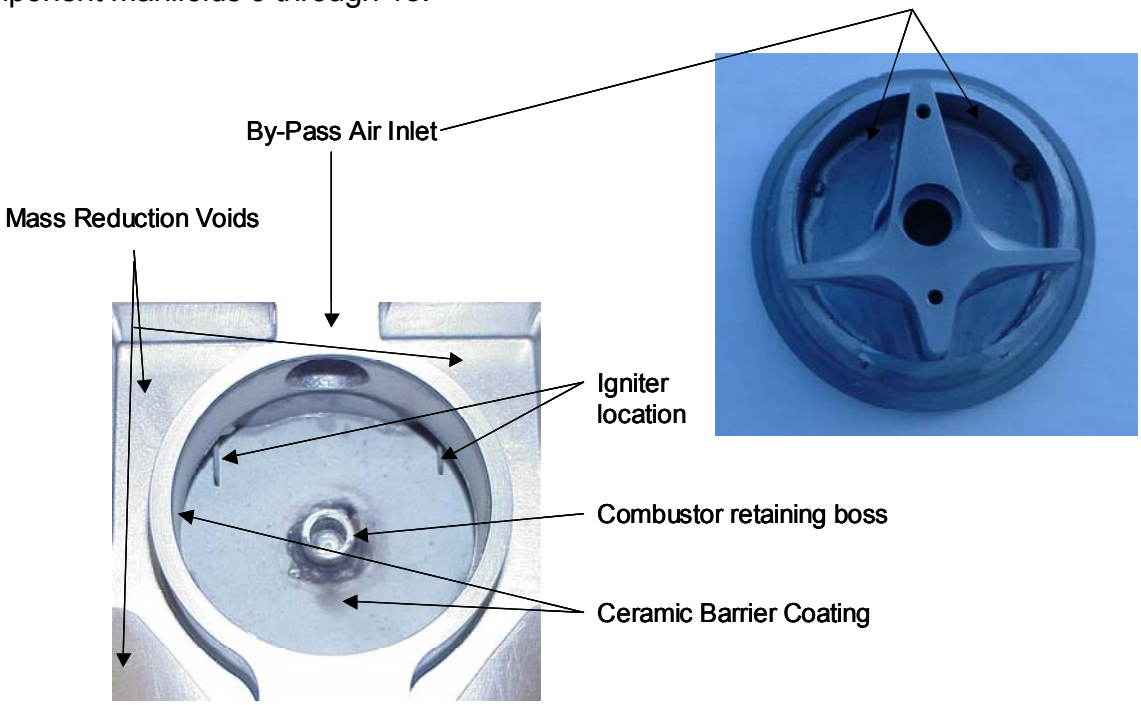


Figure 4.4.3.2-8 Insertable GPC and Combustor Chamber

Figure 4.4.3.2-9 Insertable Gas Phase Combustor

4.4.3.3 Cathode Heat Exchangers

During this period, Delphi has continued to refine the Cathode Heat Exchanger design efforts focused on increasing efficiency while maintaining a low backpressure allocation. Various configurations were characterized relative to the number of parts, number of air passes, Cooling effectiveness, internal pressure drops, mass, and number of braze cycles needed to fabricate. The overall goal is a design with minimal parts, high effectiveness, low-pressure drop, and low mass, that can be fabricated with a single braze cycle. **Table 4.4.3.3-1** lists the various styles fabricated and tested. All values are referenced to the original bar and plate design used in the first prototype designated as “short” style. Configurations listed, as pending test results will be tested on the new Cathode Heat Exchanger Test Stand.

	Parts				Effectiveness		Pressure drop				Weight (kg)		
Description	**# pieces**	Ratio to base CHX	air passes	Height (mm)	**Effetiveness**	Ratio to base CHX	**Pressure drop -Exhaust (KPa)**	Ratio to base CHX	**Pressure drop -air (KPa)**	Ratio to base CHX	**Weight (kg)**	**Weight Ratio (kg)**	Braze cycles
Typical Flat Plate CHE	104	100%	2/1	85	0.68	1.00	4.2	1	3	1	2.2	1	1
Typical Dimpled Plate CHE	104	100%	2/1	85	0.68	1.00	4.2	1	3	1	2.2	1	1
Plate - Tall	168	162%	2/1	106	0.73	1.07	4.4	1.05	3.5	1.17	2.4	1.09	1
Tube/Shell	27	26%	4/1	80	0.72	1.06	4.4	1.05	4	1.33	1.5	0.68	2
Tube/Shell Thick Mainfold	47	45%	2/1	110	0.57	0.84	8.6	2.05	3.7	1.23	1.5	0.68	2
Tube/Shell w/ turbulators	67	64%	2/1	110	0.55	0.81	4.8	1.14	4	1.33	1.5	0.68	2
Fin Plate -Tall	110	106%	2/1	106	under test								1
Fin Plate - Short	86	83%	2/1	90	0.70	1.03	4.61	1.1	3.42	1.14	2	0.91	1
Fin Plate - Short - Angled 90°	86	83%	2/1	90	under test								1
6-bolt Fin	88	85%	2/1	90	under test								1

Table 4.4.3.3-1 Heat Exchanger Comparisons

Advancement of the Heat exchanger design has included the conversion to metric fasteners (6mm) from the previous English (5/16”). This required a minor redesign to the base of the heat exchangers. Additional fasteners, which were added in order to increase gasket loading, required the addition of tapped holes in the base plate of the heat exchanger. Symmetric placement of the tapped holes allowed interchangeability of the right and left heat exchanger.

Design, specification, and vendor selections for the dedicated Cathode Heat Exchanger Test stand has been completed, and components have been ordered. This test stand is expected to be operational the first quarter of 2004.

Figure 4.4.3.3-1 shows the Six Bolt Heat Exchanger.

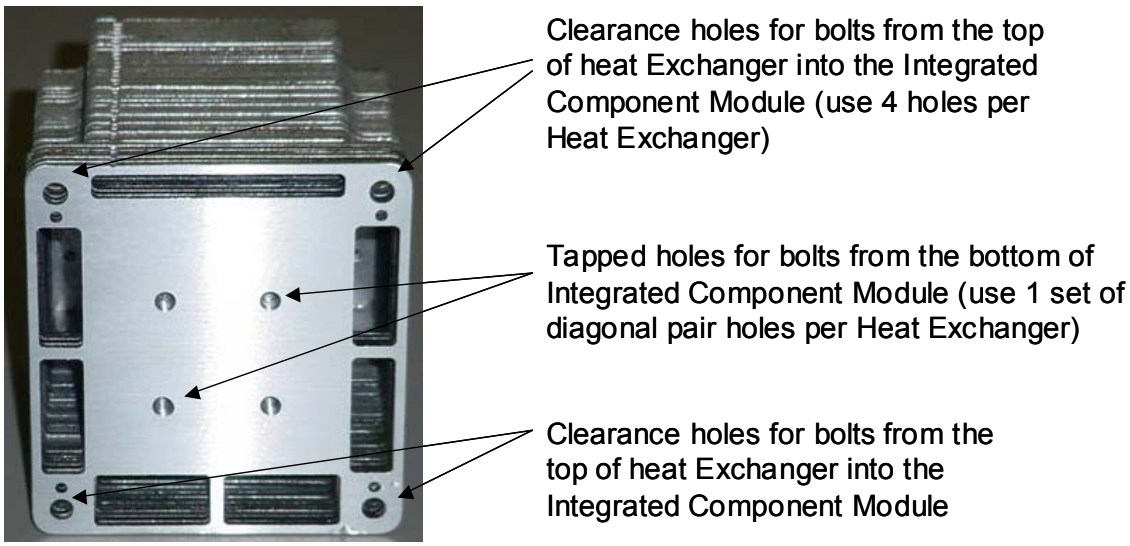


Figure 4.4.3.3-1 Six Bolt Heat Exchanger

Figure 4.4.3.3-2 shows the Heat Exchanger Test Fixture as viewed from the side, and **Figure 4.4.3.3-3** illustrates the test port locations for performance characterization.

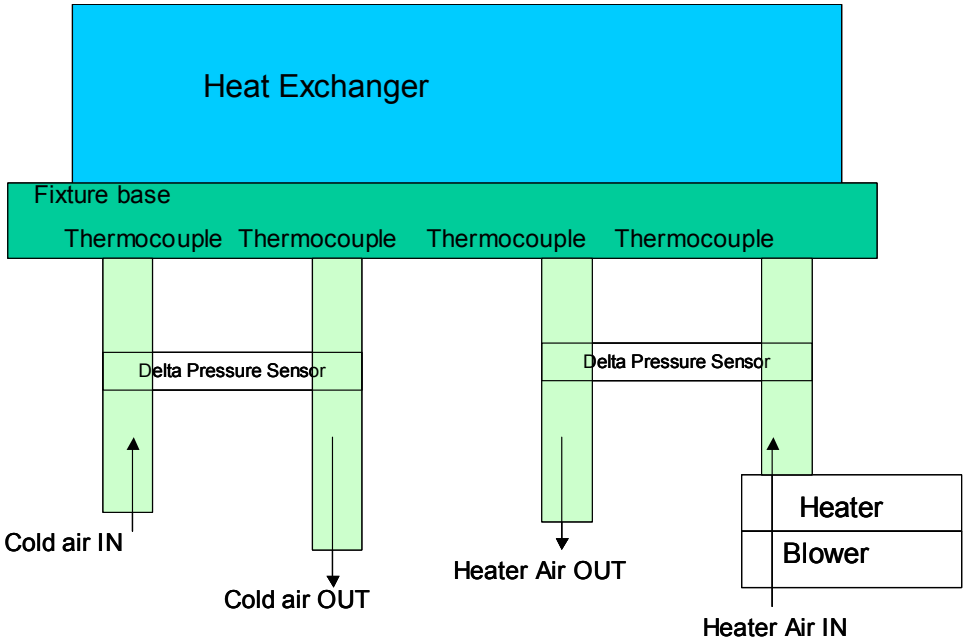


Figure 4.4.3.3-2 Heat Exchanger Fixture

		Possible Additonal TC or Press Sensors						
			CHE Mounting Manifold					
		P5		**P5 (I__)**		P5'		
	T5 (I__)	**T6 (I__)**				**T7(I__)**	**T8 (I__)**	
Heated Air In	----->	----->		**CHE**		----->	----->	Heated Air Out
		H3 (I_)				**H4 (I_)**		
		H1 (I_)				**H2 (I_)**		
Cold Air In	----->	----->				----->	----->	Cold Air Out
	T1 (I__)	**T2 (I__)**		**Test Manifold**		**T3 (I__)**	**T4 (I__)**	
		P3		**P3 (I__)**		P3'		

Figure 4.4.3.3-3 Heat Exchanger Test Port Locations

Figure 4.4.3.3-4 shows a Heat Exchanger with sensor test ports brazed in place. Additional sensor capability, with the new Heat Exchanger test stand, will allow for more detailed data collection and more sensitive analysis of turn-down effects at low flows.

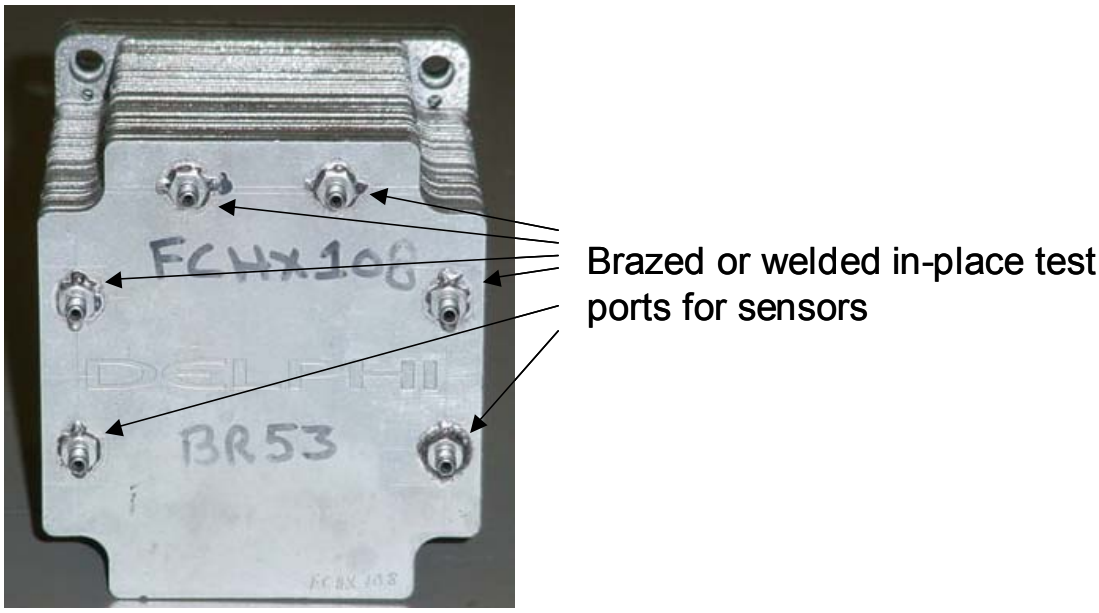


Figure 4.4.3.3-4 Heat Exchanger with Sensor Taps

4.4.3.4 Igniter

Figure 4.4.3.4-1 shows the new High Temperature Igniter with embedded thermocouple and **Figure 4.4.3.4-2** shows it with the embedded thermocouple exposed.

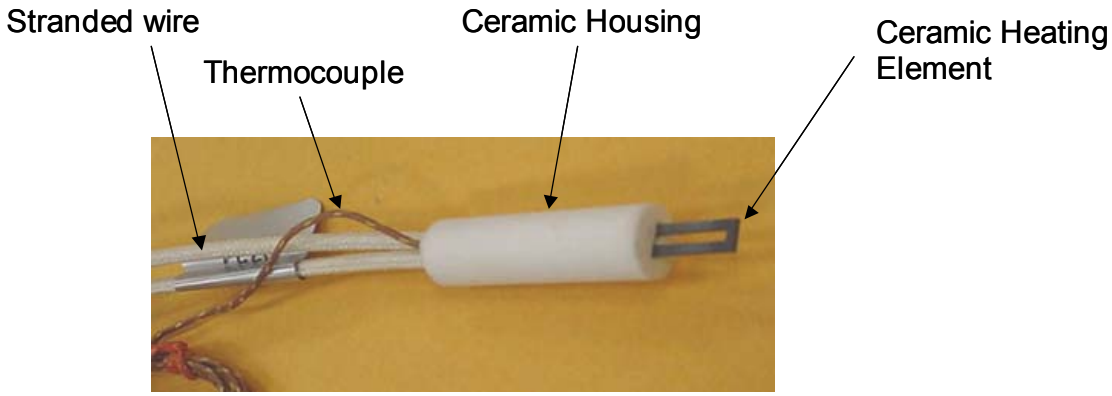


Figure 4.4.3.4-1 High Temperature Igniter with Embedded Thermocouple

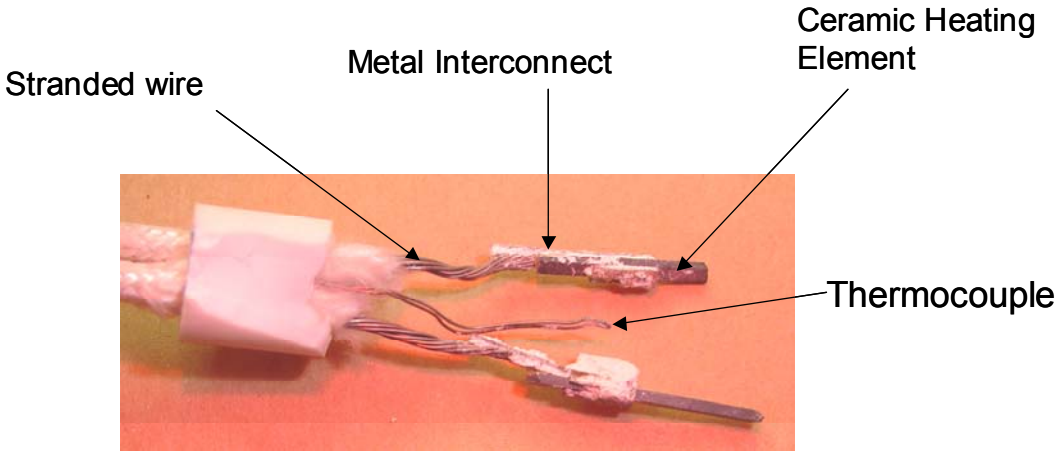
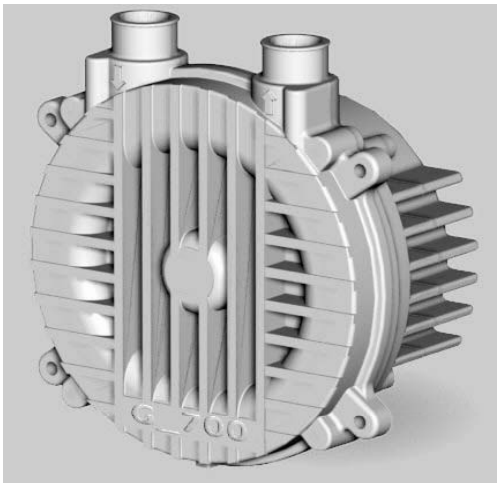


Figure 4.4.3.4-2 High Temperature Igniter Connections

4.4.4 Re-Cycle Pump

In order to increase overall net system efficiency of the APU, a strategy that involved taking a portion of the anode tail gas from the stacks and re-cycling it back into the reformer was developed. A system mechanization for the approach has been developed. Analysis and optimization of re-cycle parameters is currently in process by the system team. Balance of Plant efforts on Re-cycle during this reporting period included writing component specifications, conducting a technology down-select and selecting the supplier. Prototype pumps were ordered and received. Initial testing confirmed significant pump capacity. Future issues to be addressed with the Re-cycle pump involve packaging studies and possible pump re-design for improved thermal robustness. **Figure 4.4.4-1** shows the prototype Re-cycle pump.

G_100 - 280 W



max. 180 mbar
max. 34 m³/h
48 VDC, 58 dB (A)

Figure 4.4.4-1 Re-cycle Pump

The pump evaluated during this period was a Nash-Elmo 280W regenerative side-channel compressor. The balance of plant process air lab is currently limited to testing components with air as the test gas only. A standard test with air allows for pump-to-pump comparisons and provides an indication of generalized performance characteristics. It is within the capability of the lab to supply the pump with heated and variable downstream resistance to flow. This permits fairly detailed mapping of the performance of the pump over a range of speeds, inlet temperature, differential pressures from inlet to inlet, and power consumption levels.

A full-range characterization of the pump is shown in **Figure 4.4.4-2**, for an inlet of 23 °C air.

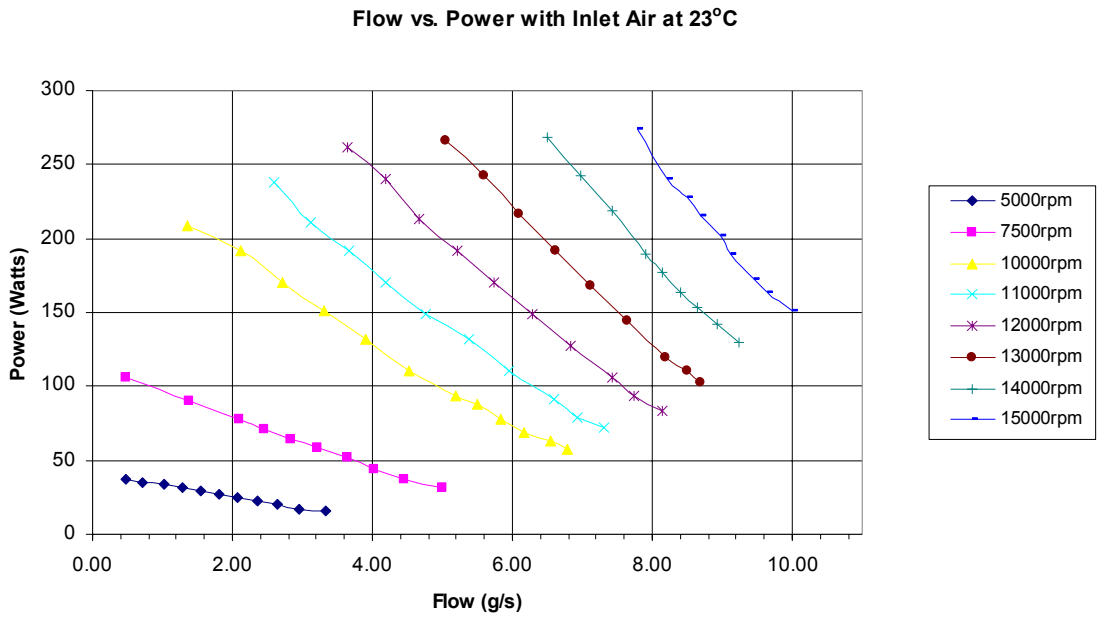


Figure 4.4.4-2 Re-Cycle Pump Performance

Higher temperature testing of the pump is currently in process. Thus far, the pump has demonstrated its ability to withstand temperature excursions in excess of 120 °C. Flow versus power decreases as is expected at higher temperatures; however, the pump remains more than capable of maintaining required flow. Alternative pumps are also being acquired for evaluation.

4.5 Manufacturing Development (Privately Funded) – (Task 5.0)

Details for manufacturing development activities are reported on within subcomponents of the solid oxide fuel cell system.

4.6 System Fabrication (Task 6.0)

4.6.1 Transportation APU System Fabrication

During the period covered by this technical report, the following systems were fabricated and tested:

- Gen 2B Close-Coupled System
- Gen 2B APU
- Gen 2C Close-Coupled System

The fabrication of the Gen 2B APU is shown in **Figure 4.6.1-1**. The design differences between the Gen 2B and Gen 2C system consist of the SOFC stack and associated Integrated Component Manifold. This hardware is located within the Hot Zone Module. Therefore, the system images presented in **Figure 4.6.1-1**, **Figure 4.6.1-2**, and **Figure 4.6.1-3** are representative and typical for system hardware fabricated during the period covered by this report.

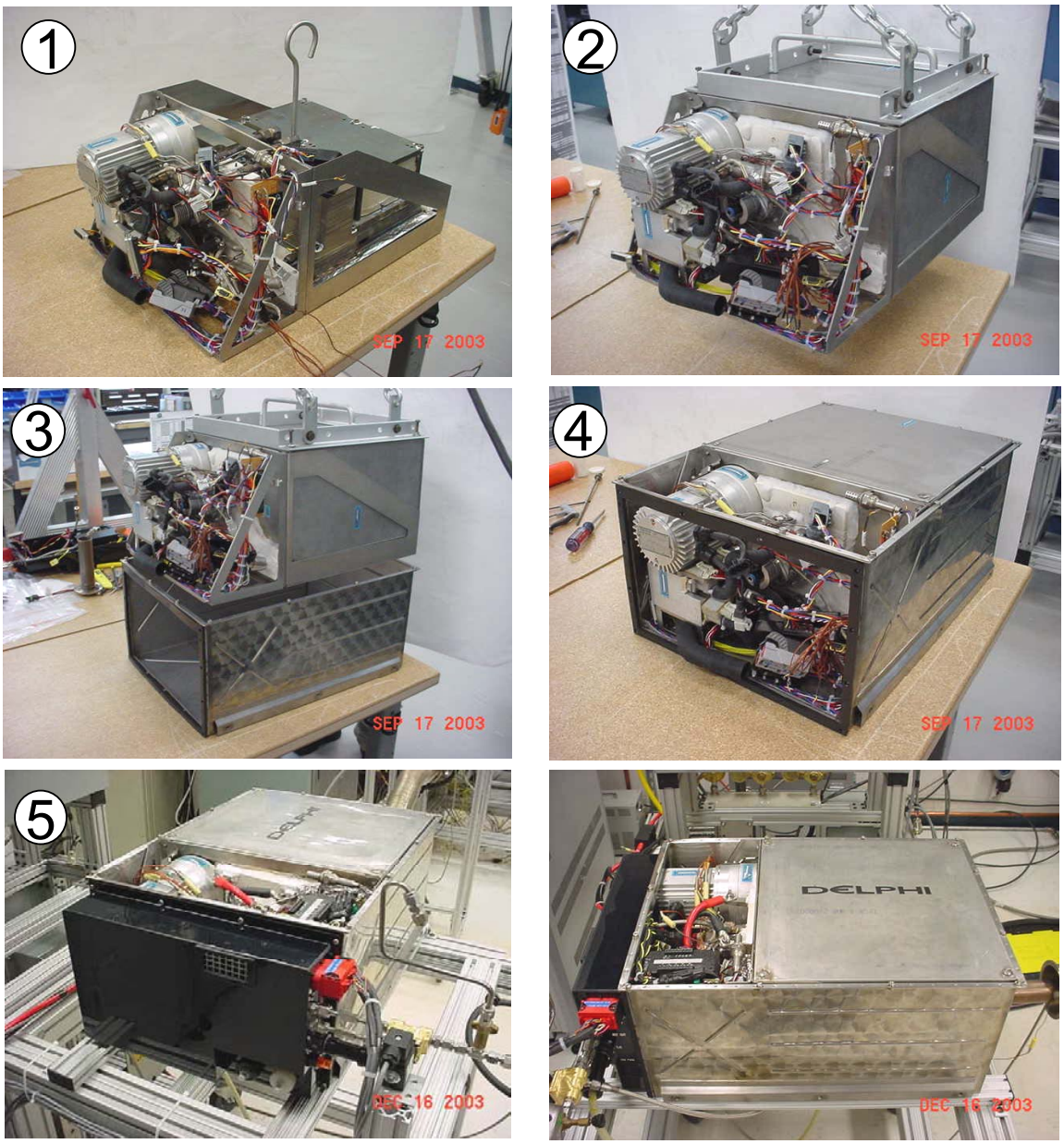
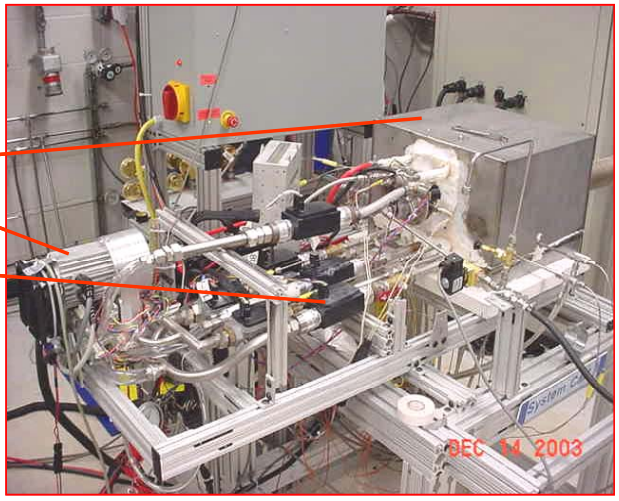


Figure 4.6.1-1 Transportation SOFC APU – Gen 2B System Hardware

System Stand 1
(Close-Coupled System)
Transportation-Gasoline
SOFC APU[1] Gen 2C

Hot Zone Module (Insulated)
Process Air Module
Massflow Meter Instrumentation



Process Air Module
Stack to 42V DC Converter
System Controller
Motor Controller

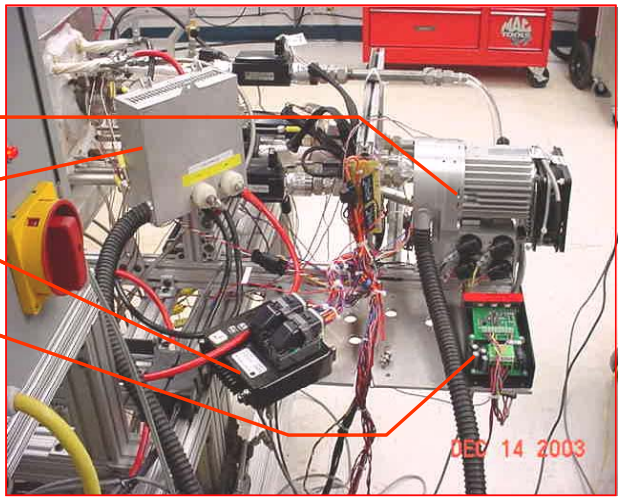


Figure 4.6.1-2 Transportation SOFC APU - System Test Stand 1

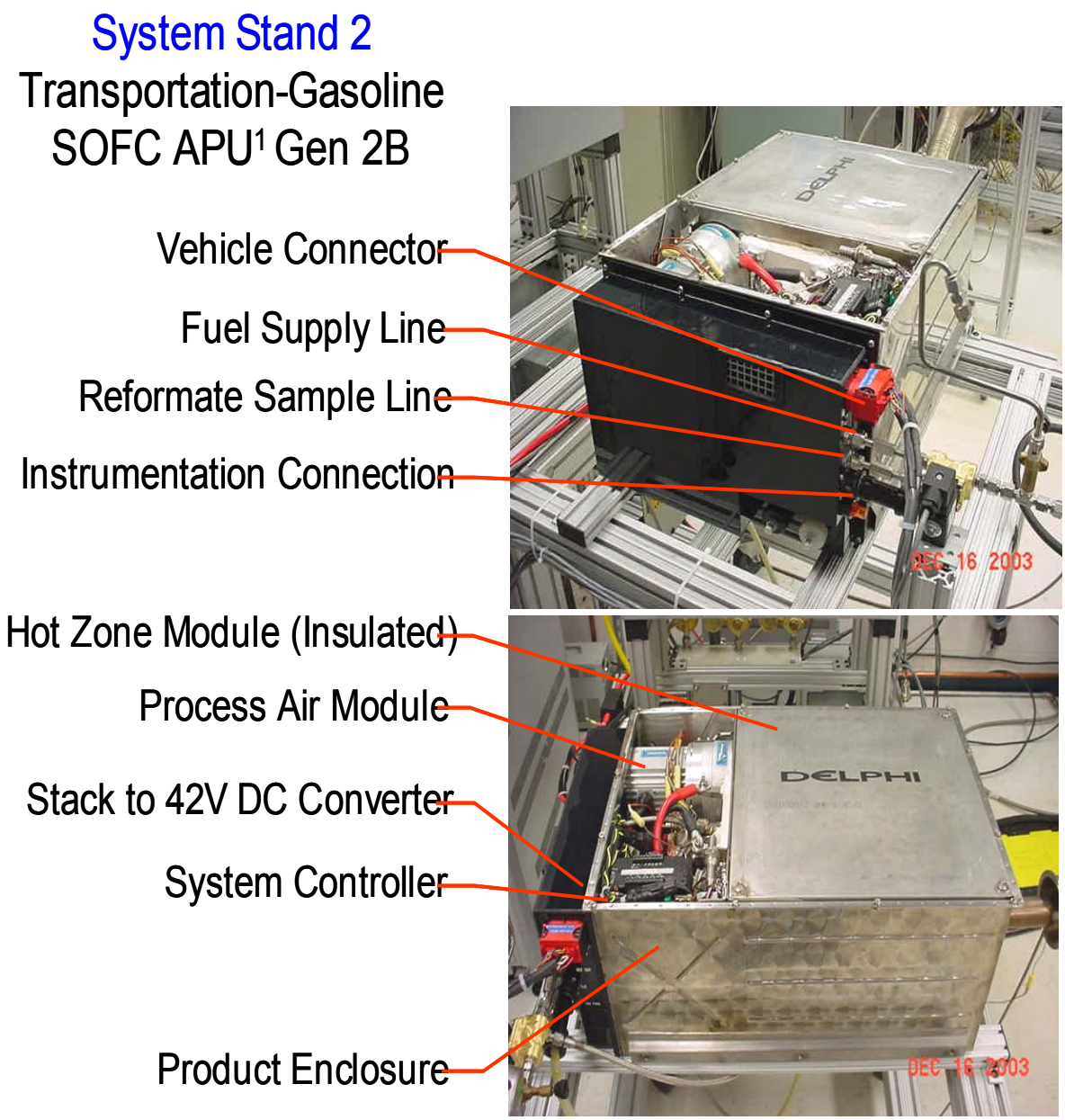


Figure 4.6.1-3 Transportation SOFC APU - System Test Stand 2

4.7 System Testing (Task 7.0)

During the period covered by this technical report, the goals of system testing and development were as follows:

- Build and Test a Gen 2B APU
- Demonstrate 5 thermal cycles on an Gen 2B APU

- Deploy the ECU to the system and demonstrate automatic control of the system with APU 08 Control Software
    - The product intent ECU replaces the large control cabinet and Micro-Autobox® controller used for earlier system testing and development
- Build and test a Gen 2C APU.
    - Demonstrate function of Gen 3, 2x30 cell, SOFC stacks at the system level

A summary of system integration and testing progress during the period is as follows:

- **Build and Test APU: Complete**

  During the July – December 2003 period, to support the system integration and development efforts, 36 tests were conducted on the Gen 2B close-coupled system on System Stand 1, and 17 tests were conducted on System Stand 2 with the Gen 2B APU.

  November 04, 2003, a successful APU integration test was conducted with thermal stack, full product enclosure, ECU, and power conditioner. Stack power was emulated with a power supply to verify function of the APU power management system.

5.0 CONCLUSIONS

5.1 System Design and Integration (Task 1.0)

5.1.1 Transportation Power Unit System Design and Integration

During the period covered by this technical report, focus has been placed on Gen 3B Transportation APU system targets and component requirements to support the Gen 3B APU design effort.

Extensive analysis has been performed to determine the strategy for system operating points for both peak and off-peak electrical loads. The current projected operating points for the system are well suited to high-power density operation of the SOFC stacks (moderate fuel utilization, high reformate quality). Power targets should be able to be met with the expected progression of stack power density capability, or with additional stacks in the system. However, there is a limit to current and projected system efficiencies that is independent of choice of fuel utilization in the stack or anode tail gas recycle fraction, but highly dependent on reformer operating temperature. Based upon current reformer operating temperature projections, projected system efficiencies for the commercial application (5 kW APU) are between 30 and 35 %. Certainly, improvements in reformer technology that allow for reduced operating temperature will improve the waste energy recovery in the system and ultimately allow for higher system efficiencies.

- To support the Gen 2C APU performance targets, improvements in the APU conceptual design have been made between Gen 2B and Gen 2C design levels. The engineering changes on this hardware have been focused on deployment of Gen 3.0 SOFC stacks to the system and improved sealing at high-temperature interfaces. Based upon initial system test evaluations, these engineering changes have resulted in a net improvement of system output power and potentially thermal cycle capability.

- To support the Gen 3B APU performance targets, improvements in the APU conceptual design have been made between Gen 2C and Gen 3B design levels. The Gen 3B APU design will be distinguished by improved thermal management, reduced package size, improved seals at high temperature interfaces, and dramatically improved output power and system efficiency. Additionally, the Gen 3B APU design will have improved assembly access vs. its predecessors.

- Several changes have been made to the Gen 3B physical plant mechanization during the period covered by this technical report. The addition of anode tail gas recycle, addition of fixed burner air bypass, and separate process air and system cooling air (purge air) streams, are designed to address capability gaps in current system hardware.

5.1.2 SPU System Design and Integration

Output from this period for requirements, design, and planning.

SPU conclusions that can be drawn from this period focus on the differences identified between the APU market and the Stationary Power unit market. The differences in the durability and thermal cycling expectations are going to be raised in the combined stack requirements and new or increased tests may be the outcome. Design changes specific to the system needs of these two markets will be rolled into that teams plan for the next two years.

Requirements for stationary power units have placed a renewed focus on performance, efficiency, durability and productive costs. This is a move from the auxiliary power unit's focus on packaging and high power density. Our primary focus for the SPU completion plan is a 5000-watt net power system. The study of larger output systems (up to 10 kilowatts) will need to be studied by Delphi commercialization activities.

The review and design issues that are being considered will be more available upon completion and approval of Delphi engineering processes. Most system engineering work on the SPU in this report period was incomplete and unfit for publish as of December 2003.

Activities for the next technical report (January to June 2004) will include details on some of the strategic product decisions will be more readily available for the next reporting period. The technical report contribution for the SPU in the next reporting period will be increased significantly as Delphi ramps up the activity focused on this task in 2004. The Phase 1 development plan for 2004 and 2005, final system design configurations and system analysis will be available.

5.2 Solid Oxide Fuel Cell Stack Development (Task 2.0)

Key milestones were achieved in closing out the Gen 2 stack development and transitioning to a more manufacturable and lower cost Gen 3 stack design. Hundreds of Gen 3 cassettes and multiple large 15-cell stacks were successfully fabricated and tested with encouraging results. Power densities of greater than 300 mW/cm^2 were achieved on 15-cell Gen 3 stacks. Ten thermal cycles was achieved on these stacks. Further development is focused on improving power density at high utilization and addressing long-term continuous and thermal cycling durability issues.

5.3 Reformer Developments (Task 3.0)

5.3.1 Reformer Subsystem

Initial testing of recycle based reforming using appropriately endothermic capable reformer designs has been accomplished and has provided much needed preliminary information and given rise to many new areas of inquiry.

The importance of minimizing heat losses within the reformer, and in particular to the adjoining Integrated Component Manifold, has been quantified.

Several combustor geometries have been tried and an initial understanding of their behavior was gained.

New concepts aimed at maximizing heat transfer and thermal isolation are in process. Basic kinetics research to help size these concepts is also underway.

5.3.2 Catalyst

While progress has been made in optimizing washcoat formulations, a significant amount of confirmation work needs to be done, focusing on durability testing. The newly developed rapid aging test should help in this effort. Recently developed advanced analytical methods are now in position to enhance the understanding of reforming catalysts, leading to improved formulations and kinetics understanding. A framework for use of this type of kinetics information now exists and will be used to help sub-system reformer development and design. We are also now in a position to determine the impact of processing variables on catalyst performance, which will also help in the efforts to improve catalyst formulation and process optimization.

5.4 Develop Balance of Plant Components (Task 4.0)

5.4.1 Combustible Gas Sensor

The sensor testing performed during this reporting period confirmed that if the current sensor is to be implemented as a safety sensor in the system, additional calibration work is required as well as the development of signal filtering for noise reduction. In order to address future packaging constraints and cost targets, new sources for this technology will need to be evaluated.

5.4.2 Develop Air Delivery and Process Air Sub-System

The new Process Air Module design will lead to better product performance and manufacturability. Improvements in the impeller and manifold designs will result in lower power utilization and should provide enhanced controllability.

The machine technology analysis allowed the team to identify the optimal technology for this application, as well as, system trade-offs. Extensive system and component level analyses have created a strong foundation for clearly understanding system operation along with additional confidence that the final design is robust. The increased torque and resultant power capabilities of the Delphi designed motor and controller subsystem will allow for enhanced performance of the Process Air Module. **Table 5.4.2-1** provides a performance comparison of the Delphi and current vendor (Thomas-Rietschle) systems.

System	Torque (N-mm) @60,000RPM	Efficiency (%) (Motor / Controller)
Rietschle*	57	50
Delphi	73	81
*Rietschle torque value is calculated based on measured system adiabatic power. This value is an estimate only.		

Table 5.4.2-1 Motor Performance Comparison

5.4.3 Develop Hot Zone Components

5.4.3.1 Gasket Development

Advancements were made in sealing capability during this reporting period; however, more development is still required. Additional test capability will be developed including a thermo-cycle test for seals. Development milestones for 2004 will require sealing solutions capable of 250 thermal cycles. Delphi's sealing approach to accomplish this will be revisited during the first quarter of 2004.

5.4.3.2 Integrated Component Manifold

Prototype Integrated Component Manifolds fabrication has been successfully demonstrated. Production intent manufacturing strategies need to be developed for reducing mass and meeting Delphi's cost targets.

5.4.3.3 Cathode Head Exchangers

Cathode Heat Exchanger fabrication has been demonstrated and the manufacturing process have reliably produced numerous designs. The new dedicated Heat Exchanger test stand is scheduled for completion in first quarter of 2004. This test stand will help facilitate rapid design turns for further performance optimization. Heat exchanger durability testing will be initiated in the next reporting period.

5.4.3.4 Igniters

The higher temperature igniters procured during this period appear to address the previous igniter failure mechanisms and have led to a more reliable design. Future work will involve durability testing.

5.4.4 Re-Cycle Pump

The prototype re-cycle pump currently specified appears to meet short-term needs. Going forward, additional activity on this component will involve more detailed testing on the bench and in a system.

5.5 Manufacturing Development (Privately Funded) (Task 5.0)

Details for manufacturing development activities are reported on within subcomponents of the SOFC system.

5.6 System Fabrication (Task 6.0)

System fabrication conclusions are covered with Sections 5.1 and 5.7.

5.7 System Testing (Task 7.0)

5.7.1 Transportation APU System Testing

During the period covered by this technical report, significant experimental effort at the system level was conducted. System testing and experiments to support current system development was conducted at both close-coupled and full APU integration levels for Gen

2B system hardware, and at the close-coupled level of integration for the Gen 2C system hardware. Development and test emphasis was placed on control software development, left-to-right temperature balance in the system, system turn-down, and thermal management issues.

The build and successful testing of the Gen 2B APU was a significant milestone achieved during the reporting period. This represented the first Delphi SOFC APU system including product enclosure, internal controller, and output power conditioner to achieve net output power.

The Gen 2B APU was the first Delphi system to experience 3 full thermal cycles from 25 ºC to 750 ºC. Power levels were below expectation, and degraded sharply cycle to cycle.

The Gen 2B APU output power levels have been below expectation. Seal leakages in the stack and/or system as well as poor fuel distribution in the stack due to gas manifold mal-distribution are suspected causes.

An important highlight during the period was the successful test of 2x15 cell Gen 3.0 stacks in a Gen 2C close-coupled system. In contrast to the low power levels in the Gen 2B hardware, the Gen 3.0 stacks in the Gen 2C system produced expected output power from the stacks, and also the highest net electrical power from a Delphi system to-date.

During the next reporting period, it is expected that the Gen 2C system will be tested as a full APU with 2x30 Gen 3 SOFC stacks. At current power density levels in the SOFC stack, projected net power output should be in the 1-1.5 kW range.

By the end of the next reporting period, it is projected that Gen 3B system hardware should be performing to the target 2.2 kW net output level with an electrical efficiency of 21%.

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7.0 REFERENCES

None required.

8.0 BIBLIOGRAPHY

None required.

9.0 LIST OF ACRONYMS AND ABBREVIATIONS

A	
APU	Auxiliary Power Unit
C	
CAN	Controller Area Network
CPO	Catalytic Partial Oxidation
D	
DIV	Division
DOE	Department of Energy
E	
ECU	Engine Control Unit
EPACT	Energy Policy Act
G	
GEN	Generation
GPC	Gas Phase Combustor
N	
NETL	National Energy Technology Laboratory
S	
SECA	Solid State Energy Conversion Alliance
SOFC	Solid Oxide Fuel Cell
SPU	Stationary Power Unit

10.0 APPENDICES

Per Cooperative Agreement DE-FC26-02NT41246 EPAct Information considered restricted, proprietary, and confidential to Delphi are presented in Appendix A to this document per FAR 52.227-14, Rights in Data-General.