10 kW SOFC Power System Commercialization
SECA Semi-Annual Report 41244R02

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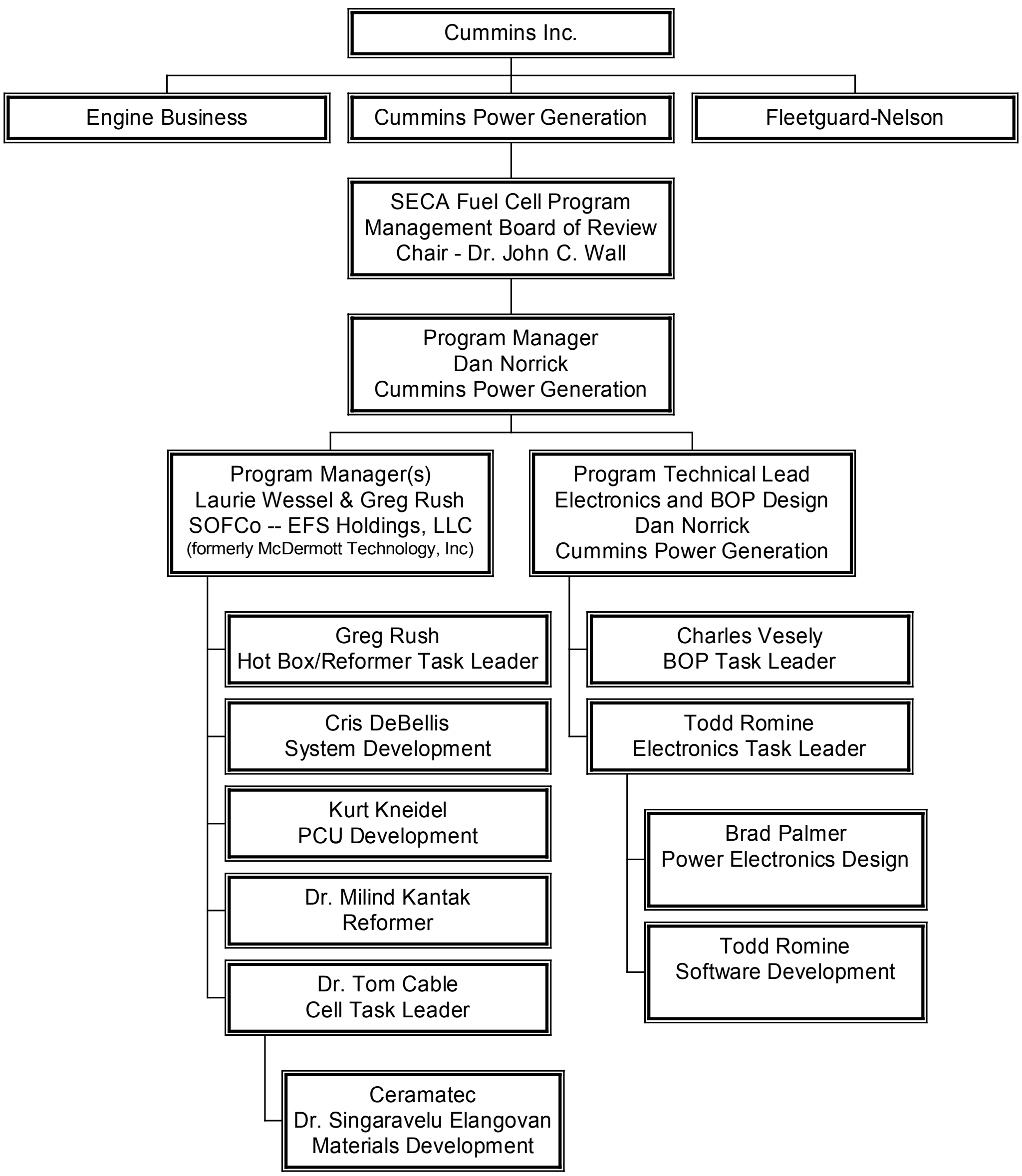
Abstract / Summary

Background.

Participants in the SECA 10 kW SOFC Power System Commercialization project include Cummins Power Generation (CPG), the power generation arm of Cummins, Inc., SOFCo – EFS Holdings, LLC (formerly McDermott Technology, Inc.), the fuel cell and fuel processing research and development arm of McDermott International Inc., M/A-COM, the Multi-Layer Ceramics (MLC) processing and manufacturing arm of Tyco Electronics, and Ceramatec, a materials technology development company. CPG functions in the role of prime contractor and system integrator. SOFCo – EFS is responsible for the design and development of the hot box assembly, including the SOFC stack(s), heat exchanger(s), manifolding, and fuel reformer. M/A-COM and SOFCo -- EFS are jointly responsible for development of the MLC manufacturing processes, and Ceramatec provides technical support in materials development.

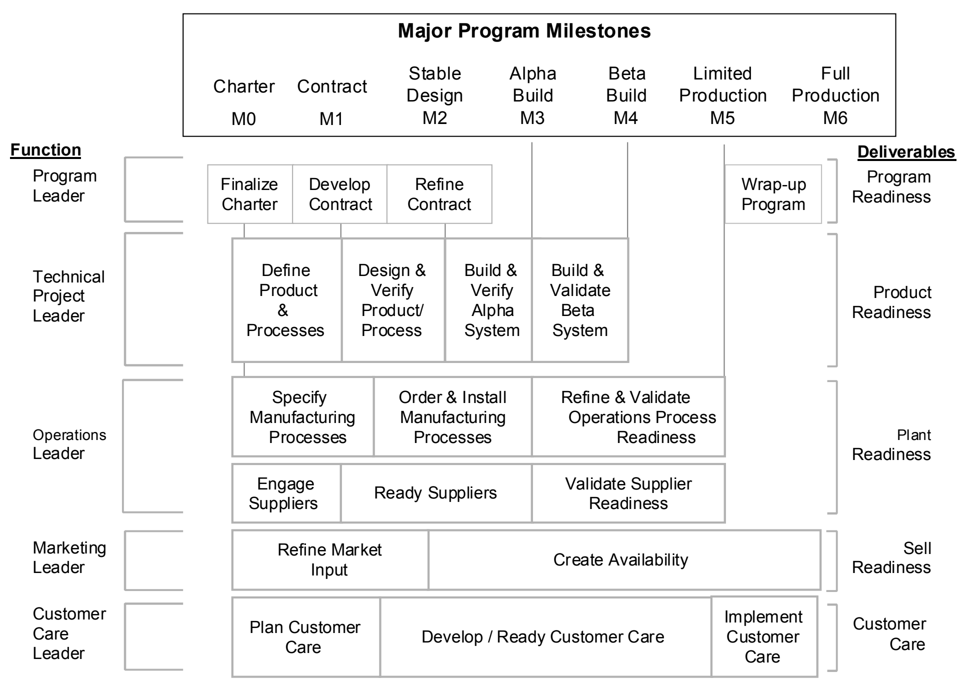
Project Organization Chart



Program scope / plans.

The program is organized into three developmental periods. In Phase 1 the team will develop and demonstrate a proof-of-concept prototype design and develop a manufacturing plan to substantiate potential producibility at a target cost level of $800 / kW factory manufacturing cost. Phase 2 will further develop the design and reduce the manufacturing cost to a level of $600 kW. Depending on an assessment of the maturity of the technology at the end of Phase 1, Phase 2 may be structured and supplemented to provide a limited production capability. Finally, in Phase 3, a full Value Package Introduction (VPI) Program will be integrated into the SECA program to develop a mass-producible design at a factory cost of $400 / kW with full cross-functional support for unrestricted commercial sales.

The path to market for new technology products in the Cummins system involves two processes. The first is called Product Preceding Technology, or PPT. The PPT process provides a methodology for exploring potentially attractive technologies and developing them to the point that they can be reliably scheduled into a new product development program with a manageable risk to the product introduction schedule or product quality. Once a technology has passed the PPT gate, it is available to be incorporated into a Value Package Introduction (VPI) Program. VPI is the process that coordinates the cross-functional development of a fully supported product. The VPI Program is designed to synchronize efforts in engineering, supply, manufacturing, marketing, finance, and product support areas in such a way that the product, when introduced to the market, represents the maximum value to the customer.



VPI Process Overview

Organization.

The project is organized by Work Breakdown Structure (WBS) into six major sections as follows:

1) Integration, Tests and Administrative
2) Cell and Stack Development
3) Hot Box / Reformer Systems Development
4) SOFCo -- EFS Program Management
5) Balance of Plant
6) Electronics

The body of this report follows that general outline.

Significant achievements in the second six months of the project include:

System steady state model. The system steady state model continues to be refined and used to exercise alternative operating strategies to optimize efficiency.

System Transient model. The system transient model continues to be refined and used to evaluate operating envelope limitations around start-up and load changes.

P&ID (Process & Instrumentation Drawing). P&ID's for both the C1 and C2 continue to serve as vehicles for documentation of system configuration and system operating parameters as determined by the steady state and transient models.

System physical layout. The system physical layout has been updated as revised design geometries for Hot Box, BOP, and Controls & Power Electronics components are defined.

Control System and Power Electronics. Initial control loops have been defined and a process for startup of the fuel cell has been developed. The fuel cell boost circuit board has been designed and built and is awaiting test. Subsystem test activity of the blower and the fuel air mixer has begun.

Shared secure project database. The shared secure database has expanded as additional design documentation and reports are stored.

Webpage on the Cummins, Inc. Corporate website.

Future Plans.

Plans for the first half of calendar 2003 are focused on

- confirming and documenting the resolution of the cell and interconnect cracking problem,
- cell and stack development for improved performance
- definition and implementation of the Power Cell Unit (PCU) design for C1
- completion of the C1 Hot Box Design
- completion of the C1 Fuel Processor design with material procurement
- procurement of sample BOP components and BOP subsystem development testing,

- continuing definition and evaluation of the controls and power electronics architecture
- component procurement and sub-system development testing on the DC boost and inverter subsections
- completion of a preliminary design FMEA
- refinement of the costed BOM as the design definition develops.

Table of Contents

List of Graphical Materials

Executive Summary

Background. Participants in the SECA 10 kW SOFC Power System Commercialization project include Cummins Power Generation (CPG), the power generation arm of Cummins, Inc., SOFCo – EFS Holdings, LLC (formerly McDermott Technology, Inc.), the fuel cell and fuel processing research and development arm of McDermott International Inc., M/A-COM, the Multi-Layer Ceramics (MLC) processing and manufacturing arm of Tyco Electronics, and Ceramatec, a materials technology development company. CPG functions in the role of prime contractor and system integrator. SOFCo – EFS is responsible for the design and development of the hot box assembly, including the SOFC stack(s), heat exchanger(s), manifolding, and fuel reformer. M/A-COM and SOFCo -- EFS are jointly responsible for development of the MLC manufacturing processes, and Ceramatec provides technical support in materials development.

In October 2002, McDermott announced its intention to cease operations at McDermott Technology, Inc. (MTI) as of December 31, 2002. This decision was precipitated by several factors, including the announced tentative settlement of the B&W Bankruptcy which would result in all of the equity of B&W being conveyed to a trust, thereby eliminating McDermott's interest in the company, and the desire to create a separate fuel cell entity to facilitate its commercial development. The new fuel cell entity is named SOFCo – EFS Holdings, LLC. All of McDermott's solid oxide fuel cell and fuel processing work will be conducted by SOFCo – EFS, using personnel previously engaged in that work. SOFCo – EFS will continue to be located in the Alliance, OH facility and use the existing infrastructure and test facilities for its activities. While the effort needed to accomplish this reorganization has detracted somewhat from SOFCo's efficiency during the fourth quarter, we believe the improved focus on the core fuel cell and fuel reformation resulting from the reorganization will have a positive impact on the SECA project in the long run.

Program scope / plans. The program is organized into three developmental periods. In Phase 1 the team will develop and demonstrate a proof-of-concept prototype design and develop the manufacturing plan to substantiate potential producibility at a target cost level of $800 / kW factory manufacturing cost.

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- confirming and documenting the resolution of the cell and interconnect cracking problem,
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Program Issues and Challenges. The external funding planned to support the development program at SOFCo – EFS Holdings, LLC (SOFCo) has not yet been secured. This has caused SOFCo to look for ways of accomplishing the program objectives with reduced expenditures. Significant progress has been made toward this end. A single cell test capability has been developed and correlated to stack test results. This will allow much of the testing planned for stacks to be done on single cells, resulting in significant savings in production and testing costs. Because production volume will now be lower, SOFCo can investigate ways of producing parts without the need for significant capital expenditure. In addition, some work has been re-sequenced to allow for more series, and less parallel, development. This simplifies the development, as multiple tasks are not being undertaken at a single time. While further study is required, we believe this re-sequencing can be accomplished with little impact to the overall program schedule.

Subtask 1 Integration, Tests and Administrative.

This section of the WBS provides a location for a number of activities relating to the project as a whole. While not for the most part technical in nature, they do impact the project technical operations.

Program Management -- CPG is responsible for overall program management, including submission of reports, Design for Cost, Documentation Management, and scheduling of review meetings, both internal and external. CPG manages the sub-contract with SOFCo , and submits financial reports.

Support was provided for the SECA Annual Workshop in March 2002, and the Core Technology meeting in Pittsburgh in June, 2002. Presentations on behalf of the program were made at the Ohio Fuel Cell Symposium in Canton, Ohio, on October 4, 2002, and at FuelCell 2002 in Palm Springs, California on November 21, 2002.

Team meetings were held at SOFCo, Alliance, OH, August 13-14, October 21-22, and December 16-17 of 2002.

The first bi-annual report was submitted September 13, 2002, and a presentation of the technical content of the bi-annual report was given at NETL, Morgantown, on September 26, 2002.

Subtask 2.1 Materials Development

APROACH:

This subtask is focused on two primary areas:

1) development of low cost materials for component fabrication and stack assembly; and

2) development of improved cells having higher power densities and reduced degradation rates.

During 2002, the materials cost reduction effort was primarily focused on lower cost starting powders for the interconnect body and alternate materials for the conductors that are incorporated in the interconnect. For the interconnect body, ceramic powders from a number of commercial vendors are being evaluated in the laboratory (Gate B studies). Powders from selected vendors that meet the Gate B criteria will undergo more extensive evaluation through tape casting trials and subsequent prototype production runs (Gate C). One or two powders from selected vendors will then be qualified for interconnect fabrication in the prototype production line. For the conductor materials, candidate materials for the air-side and fuel-side of the interconnect were initially developed in the AMPS Program (partially funded by DOE-NETL). The intent is to further develop these materials and implement them into interconnect production in the SECA Program. Efforts during the reporting period have been primarily aimed at further refinements to the composition and processing conditions. Candidate powder compositions are being prepared in the SOFCo laboratories, or purchased from commercial vendors, followed by characterization of key chemical and physical properties. These powders are then formed into the appropriate conductor configurations and subsequently co-sintered with the interconnect body. Electrical property measurements and SEM examinations are used to characterize the resulting fired conductors (Gate B evaluations). The most promising conductor compositions are subsequently moving to Gate C evaluations which involve the fabrication and testing of prototype interconnects incorporating the new materials.

EXPERIMENTS:

In developing improved cells, the work conducted during the reporting period was primarily aimed at optimization of the electrode composition and microstructure. The SOFCo team is devoting substantial effort to characterize the present co-fired anodes and cathodes, followed by studies to develop improvements in the composition or processing of the electrodes. Fabrication of 2.5cm diameter "button" cells using modified electrode inks and subsequent electrochemical testing and SEM examinations has been the primary approach being used to develop the improved electrodes. As part of this effort, the SOFCo team plans to develop commercial suppliers for the anode and cathode powders.

During the reporting period, resistance stack tests were performed using prototype interconnects to assess interconnect resistance and the stability of the conductor materials under actual fuel cell operating conditions. The first resistance stack test, performed in July, used prototype interconnects having the standard conductor design. Because of an error in stack assembly, no useful data were obtained from this test. A second resistance stack test was performed in September using prototype interconnects having larger air-side conductors and the modified fuel-side composition. Stack resistance was much higher than expected, based on the independent resistance measurements for the conductor materials. Post-test analysis of the stack reviewed possible "leakage" of air into the fuel-side of the interconnect, thereby preventing the NiO-based conductor material from reducing to Ni. A third stack test was performed with similar prototype interconnects and showed similar results. The source(s) for the "leaks" are under investigation; one potential sources for significant "leakage" has been identified. Approaches to eliminating this source are being explored.

RESULTS AND DISCUSSION:

a) Interconnect powders from two suppliers completed Gate B laboratory evaluation during Q2 2002 and are awaiting Gate C tape casting trials. Powder from an additional supplier subsequently completed Gate B testing and is ready to move into Gate C trials. Furthermore, two additional suppliers that may be able to provide the required powders at very low cost have been identified.

b) Progress continued to be made in the development of low-cost conductor materials for the interconnect. Prototype interconnects were made using the initial fuel-side and air-side conductor compositions. Measurements for the fuel-side material showed resistance values that are on par with the present baseline conductor. During the reporting period, slight modifications were made to the composition and starting powder properties to improve the processing characteristics while maintaining the conductivity. For the air-side material, measured resistance values were substantially higher (by 3-4X) than the baseline conductor. Modification of the interconnect design to increase conductor cross-section improved the resistance; however, the values were still too high. It appears that further design changes may be required to achieve the desired interconnect resistance. In parallel with the prototype interconnect fabrication trials and subsequent characterization, SOFCo initiated efforts to develop commercial suppliers for these low-cost conductor materials. As a back-up to the initial air-side conductor material, SOFCo has been developing a second material. During the reporting period, SOFCo made significant progress with this material. In particular, a composition was defined that is compatible with the interconnect body and the multi-layer fabrication processing approach (sintering temperature and shrinkage rate). The new material also has about twice the conductivity of the initial alternate air-side conductor and appears to be more stable to reducing atmospheres. This material appears to be ready to transition to Gate C prototype interconnect fabrication trials.

c) Low-level efforts were initiated in two areas to develop low-cost materials used for stack assembly. First, a conductor paste containing a noble metal is presently used between the interconnect and the anode to create a low-resistance contact between the anode and conductors in the interconnect. Initial tests were performed using a paste containing a derivative of the low-cost fuel-side conductor material and gave resistance values about 3-4x higher than desired. Composition adjustments are being made to improve conductivity; further tests are planned. Second, a coating is often applied to the interconnects to reduce the contact resistance between the interconnect conductor and the conductor paste used for stack assembly. Prototype interconnects were fabricated using a low-cost conductor material to coat the interconnect. The initial fabrication trials yielded promising results, particularly on the fuel-side of the interconnects. Further fabrication trials, followed by full testing/characterization, are planned for the low-cost fuel-side conductor.

d) Cell performance efforts were directed at assessing short-term power degradation and re-engineering the electrodes. Studies involving button cell testing and SEM microstructure examinations revealed that small changes in the cathode structure during the first 100 hours of cell operation were the primary cause for short-term performance loss in cells. Solutions to this issue are being investigated as part of the cathode re-engineering effort.

Electrode re-engineering efforts continued to focus on improving cell electrochemical performance and to develop commercial suppliers for the anode and cathode powders. For the anode, adjustments were made to the composition to improve the microstructure. Two commercial suppliers for our unique anode powder were identified and initial batches of powder were procured. Cell fabrication/testing trials are underway to evaluate these powders. For the cathode, commercial suppliers were evaluated and two sources of high-quality cathode powders were identified. These powders appear to be superior to the current cathode powder (produced internally). Improvements in the cathode microstructure and electrochemical performance were achieved with these powders and by modifying the co-firing process. Additional trials are underway to qualify these powders for cell production and to define any required process changes.

Finally, development of an alternate electrolyte material having much higher oxygen ion conductivity (by 3-4 times) than the current electrolyte was initiated. This material should substantially reduce cell ASR. Initial electrolyte powders received from a commercial supplier gave promising results in terms of sintering temperature and shrinkage rates. This work will accelerate in 2003.

CONCLUSION:

A number of suppliers for low-cost interconnect powders have been identified and promising candidate low-cost conductor materials have been developed. While no "show stoppers" have been identified, the air-side conductor material continues to be a challenge. Significant progress continues to be made in the electrode re-engineering effort. Commercial suppliers for the electrode powders have been identified; these powders and modifications to the cell co-firing process should lead to improved performance. However, because of problems experienced in cell integrity during the second half of 2002 (discussed under Subtask 2.3), completion of the electrode re-engineering effort has been pushed out to the middle of 2003.

Subtask 2.2 Stack Transient Performance

APPROACH:

This task involves a number of parallel modeling and testing activities to characterize the transient performance of the SOFC stacks during system heat-up and shut-down, and as a result of load changes. During the first half of 2002, key activities involved: 1) generating information on stack transients for ASPEN system models; 2) performing preliminary modeling for start-up to assess potential heating rates required for test facilities; and 3) initiating design and construction of test stands for stack transient performance testing.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) No significant activity to report.

CONCLUSION:

Work on this activity was suspended because of the cell cracking problem and the need to demonstrate cell operation in stacks operating at steady-state before operation under transient conditions is performed.

Subtask 2.3 Component Production and Scale-up

APROACH:

This subtask is directed at:

1) fabrication of cells and interconnects to support stack assembly and testing activities, including development of the 50-60 cell tall stacks required for the C1 prototype;
2) investigations of poor cell integrity; and
3) assessment of the feasibility for scaling up the cell and interconnect footprint to approximately 15-20 cm.

EXPERIMENTS: None this period.

RESULTS AND DISCUSSION:

The transfer of cell production from Ceramatec to M/A-COM was completed, and M/A-COM initiated engineering projects to improve cell production (improve quality, while simplifying the processes). However, this work was suspended in order to focus the team on resolving a key issue related to mechanical integrity (strength) of the cells. Potential sources for strength limiting defects in co-fired cells were identified; solutions are under investigation. In order to continue stack development efforts in Subtask 2.4, cell fabrication was switched back to a non-co-firing approach that was used at Ceramatec. While these cells do not have desired performance (ASR is about 1.5 ohm-cm^2), they do not break during stack assembly and testing.

Interconnect fabrication continued at M/A-COM through Q3 2002, but was temporarily suspended due to an excessive inventory. Sufficient interconnects are available to support stack development and testing through the end of 2003. Analysis of interconnect production data was performed; yield issues were identified and tracked to the lamination and excising operations. Engineering efforts will be performed in 2003 to address these issues.

There is no significant activity to report on footprint scale-up. While much work is required to develop the larger components, no insurmountable issues have been identified in the work performed to date.

In Q4 2002, M/A-COM announced that the prototype production facility in Buffalo, NY would be closed and that all operations were being transferred to Lowell, MA. As a result, all remaining activities directed at cell fabrication and interconnect engineering were terminated. SOFCo intends to work closely with M/A-COM to insure that production of interconnects is re-established in early 2003 in order to minimize potential disruptions in our stack development efforts.

CONCLUSION:

Integrity of co-fired cells became a major issue during the reporting period. Significant effort was directed at identifying the source(s) of the strength limiting flaws. A number of potential sources were found and effort is underway to eliminate them. In the meantime, robust cells for stack development are being fabricated using a previously established non co-firing method. Finally, interconnect fabrication was suspended due to the closure of the M/A-COM facility in Buffalo, NY. No schedule impact is expected, provided that M/A-COM re-establishes interconnect production at their Lowell, MA location by the end of Q1 2003.

<u>Subtask 2.4 PCU Development</u>

APROACH:

Development of 50-60 cell tall stacks, or Power Cell Units (PCUs), represents a key challenge for the Phase I effort. The present strategy involves the joining of individual cells and interconnects together to form the tall stacks. Two separate parallel paths for assembly of the stacks are being explored, one based on extending the current methods used to assemble short stacks (for electrochemical testing at SOFCo) and the second based on “bonding” together the cells and interconnects. Development of the tall stack assembly methods will initially be performed using 10 cm components. In addition to developing methods for joining cells and interconnects, work will have to be directed at: 1) improving the attachment of current collectors to the stacks; 2) improving the cell-to-interconnect sealing; and 3) developing an acceptable stack-to-manifold seal. Finally, to support the PCU development effort it is expected that structural modeling will be required.

EXPERIMENTS: None this period.

RESULTS AND DISCUSSION:

Limited work was performed in current collector attachment and stack assembly, as SOFCo’s efforts were directed at addressing the failure of cells in stacks.

For PCU current collector attachment, long-term aging studies revealed that deleterious oxidation was occurring at the current collector-braze interface. Alternate braze materials were investigated, but difficulties were encountered with the brazing process. Corrective actions were identified and documented.

Limited work was performed on the “bonded” stack assembly method. Initial glass compositions were identified; stack assembly trials using these glasses gave promising results.

To address the critical issues associated with cell integrity and short stack performance, substantial work was performed during the reporting period. Short stack tests were conducted to determine whether the stack assembly methods and test conditions contribute to cell failure. After making some minor modifications to the stack assembly method, it was determined that cell failure was caused by problems with the cells and not some adverse conditions within the stacks. After switching to the non co-fired cells (that do not fail), further work was performed to minimize leakage in the stacks. By monitoring temperatures within the stacks, it was concluded that modifications to the cell-interconnect seals and the manifold-stack seal were effective. However, there still appears to be some remaining sources for minor “leakage”. The sources for these minor leaks will continued to be investigated.

CONCLUSION:

The PCU development effort was largely suspended in July 2002, and will not be restarted until the cell integrity and stack performance issues are resolved. Short stack testing was effective in isolating the cell failure problem to the co-fired cells. The source(s) for strength limiting flaws must be eliminated before the co-fired cells are ready for stack development efforts. Using non co-fired cells, substantial progress was made in identifying and eliminating key sources for leakage in the stacks. Remaining source(s) for minor “leakage” are under investigation.

Subtask 2.5 Long-term Performance and Reliability

APROACH:

Achieving low power degradation rates for stacks is a key hurdle that must be overcome to achieve a commercially viable SOFC technology. There are many potential sources for long-term degradation in stacks, including: cell materials and interfaces, interconnect materials and flow passages, cell-to-interconnect electrical contacts and seals, current collector attachments, and manifold seals. The purpose of this subtask is to perform extensive testing of cells, stacks and stack components in order to identify potential sources for degradation and, through iteration with the fabrication efforts, subsequently eliminate such sources for degradation.

EXPERIMENTS: None this period.

RESULTS AND DISCUSSION:

No significant activity to report.

CONCLUSION:

Suspension of this subtask will not affect the project schedule.

Subtask 3.1 Systems Integration

APPROACH:

The ASPEN process modeling computer code, including the SOFCo proprietary fuel cell stack model, is the main analytical tool for determining the steady-state performance of the SOFC stack and power system. In conjunction with ASPEN other analysis tools, for example Excel models, provide additional capabilities to evaluate detailed stack performance, component performance, control methodology and other operating procedures. Throughout the contract these analyses and models will be benchmarked against component and systems operational test data as that information is acquired. Finally, the project team possesses substantial experience in hardware design and testing that will be used to direct system design and integration activities.

EXPERIMENTS: None this period. See Results and Discussion for modeling results.

RESULTS and DISCUSSION:

a) The ASPEN Plus model continues to evolve and show good modeling capabilities without convergence issues. Steady-state analyses were performed at 100, 50 and 20% load conditions. Various system hardware arrangements were examined. Additional air flow paths were examined for control to assure adequate and safe C1 system performance. Model results will be used to size the trim and recuperator heat exchangers. Finally, the ASPEN model was used to assess different control strategies.

b) Work continued on the ASPEN transient model, albeit at a much reduced level as compared to the steady-state analyses. For the first time selected controllers were added in ASPEN Dynamic, and demonstrated ASPEN's ability to model control features in the transient fuel cell system model.

c) Various control methodologies were reviewed. At year-end the team was converging on a control scenario that would vary the stack inlet temperature and air flow to achieve a constant stack "average" temperature over the load range. The combustor outlet temperature would provide feedback to the fuel flow control for system thermal management, thereby minimizing "excess" fuel flow required to keep the system at operating temperature.

d) Control and instrument needs for C1 resulted in further updates to the system P&ID definition.

CONCLUSION:

ASPEN continues to demonstrate significant modeling capability to design and analyze our fuel cell power system. It is ready to support final system design in early 2003 as we move to complete the C1 design and control strategy.

<u>Subtask 3.2 Hot Box Layout Design</u>

APPROACH:

Hot box design with two, 10 x 10.8cm stacks for the C1 apparatus continued to use prior MTI engineering experience to guide hardware design. Computational tools are being developed as needed to supplement existing MTI tools for stack and system performance analysis. Systems analysis is supported under Task 3.1, Systems Integration. Computational fluid dynamics (CFD) modeling of the hot box fuel and air delivery plumbing uses our FLUENT modeling expertise. MTI is using Autodesk Inventor as it's 3-D design platform and will interface with Cummins' ProEngineer, used for their balance of plant design responsibilities.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

b) Work on the hot box was suspended at the end of June and will be resumed in January, 2003. At that time final design will begin.

CONCLUSION:

The conceptual design has progressed well, and having completed internal review of the hot box conceptual layout, is ready for detail design when work resumes in January. There are no critical issues to report.

Subtask 3.3 Stack Manifold Design and Testing

APPROACH:

Conceptual design of the inlet and outlet stack manifolds was completed in conjunction with WBS 3.2 activity. ABAQUS has been used for finite element analysis (FEA) of the inlet manifold to minimize material while maintaining adequate strength for component supports. Detail design is ready to proceed. In addition, high volume and low cost manufacturing techniques have been initially reviewed for the inlet manifold. Of various methods examined to date (welding, casting, stamping, etc.), stamping looks attractive and discussions with a Cleveland, Ohio stamping supplier were initiated to obtain early design input.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) Work on the stack manifold design was suspended at the end of June and will be resumed in January, 2003. At that time final design will begin.

CONCLUSION:

Conceptual design of the inlet and outlet manifolds is complete. There are no critical issues to report.

Subtask 3.4 Recuperator Heat Exchanger

APPROACH:

The operating conditions for the heat exchanger are based on the temperature and flow conditions provided by the ASPEN model calculations. These conditions are then used to develop the initial specifications sent to vendors for fabrication assessment and pricing.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) Work on this heat exchanger task was suspended at the end of June and will be resumed in January, 2003. A likely supplier for the C1 heat exchangers has been selected. Final performance specifications will be developed in early 2003, reviewed with the supplier and order placed.

CONCLUSION:

The C1 heat exchanger is commercially available and will be finalized in early 2003. There are no critical issues to report for the C1 unit. Discussions for C2 configuration and supplier will resume in early 2003.

Subtask 3.5 Trim Heat Exchanger

APPROACH:

The operating conditions for the heat exchanger are based on the temperature and flow conditions provided by the ASPEN model calculations. These conditions are then used to develop the initial specifications sent to vendors for fabrication assessment and pricing.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

b) Work on this heat exchanger task was suspended at the end of June and will be resumed in January, 2003. A likely supplier for the C1 heat exchangers has been selected. Final performance specifications will be developed in early 2003, reviewed with the supplier and order placed.

CONCLUSION:

The C1 heat exchanger is commercially available and will be finalized in early 2003. There are no critical issues to report for the C1 unit. Discussions for C2 configuration and supplier will resume in early 2003.

Subtask 5.1 Fuel System Design

APPROACH:

The main goal of Subtask 5.1 is to identify and develop the fuel system portion of the BOP. All component, P&ID, System, and Test setup designs are performed In Pro-Engineer. For communication purposes the Pro-Engineer material is translated into AutoCAD (.dwg) drawings and Adobe (.pdf) file types.

WBS 5.1.4-6 is intended to develop and define the appropriate control devices, for the anode, based on the performance requirements and cost targets detailed in the agreement. The plan is to construct and evaluate reasonable electromechanical control devices and demonstrate the performance, reliability, and cost. Selection of each device will be a function of its individual properties and the overall system characteristics. Evaluations will include the following:

WBS 5.1.4 “Airflow regulation” for the Anode is in the concept stage. Three separate methods are being evaluated:

1) Poppet valve actuated via stepper/solenoid motor.
2) Spool valve actuated via stepper/solenoid motor.
3) Positive displacement meter/pump with stepper/dc-brushless motor drive.

WBS 5.1.5 “Airflow measurement” for the Anode is in the concept stage. Three separate methods of control are being evaluated:

1) Mass flow sensing with hot wire sensor (direct mass flow measurement).
2) Position control with pressure sensing (mass flow calculated as a function of known resistance and pressure differential).
3) Displacement (mass flow calculated as a function of displacement and pressure).

WBS 5.1.6 “Fuel flow regulation” for the Anode is in the concept stage. Three separate methods are being evaluated:

1) Poppet valve actuated via stepper/solenoid motor.

2) Spool valve actuated via stepper/solenoid motor.
3) Positive displacement meter/pump with stepper/dc-brushless motor drive.

WBS 5.1.7 is intended to develop and define the appropriate control algorithms and devices, for the anode fuel, based on the performance requirements of the system. The plan is to develop and evaluate software control algorithms and control devices to demonstrate their performance, reliability, and cost. Selection of each individual components/controls will be a function of its individual properties and the overall system characteristics. Evaluations will include the following:

WBS 5.1.7 "Air/Fuel ratio control" for the Anode is in the concept stage. A/F control will be based on:

a) Fuel requirements for system load.
b) A/F base table for load.
c) A/F trim for POX and system thermal requirements.
d) Feed-forward/anticipatory controls will be evaluated.

Four separate methods of fuel control are being evaluated:

1) Mass flow sensing with hot wire sensor (direct mass flow measurement).
2) Position control with pressure sensing (mass flow calculated as a function of known resistance and pressure differential).
3) Displacement (mass flow calculated as a function of displacement and pressure).
4) Discrete pulse width (injector) fuel metering.

WBS 5.1.8 is intended to develop and define the appropriate control algorithms and devices, for the CPOX fuel and air supply based on the performance requirements of the CPOX. The plan is to develop and evaluate software control algorithms and control devices to demonstrate their performance, reliability, and cost. Selection of each individual components/controls will be a function of its individual properties and the overall system characteristics. Evaluations will include the following:

WBS 5.1.8 "MonoCat POX/MixerHeater" for the Anode is in the development stage. The "Mixer/Heater" was added due to the POX requiring inlet temperature control. The method of control will be by PWM input of 42 VDC from the battery with forward/feedback control based on heater outlet temperature and system load. Mixing will be provided by physical internal geometry of the heater.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

The following paragraphs summarize the results for the period of July through December 2002.

Fabricated sonic air control valve, which utilizes a Saia-Burgess linear stepper motor drive originally designed as a fuel control device for a heating application. Testing is planned to verify the concept followed by designing a scaled version for fuel control.

Preliminary transfer functions for each subsystem defined. A full system control flow chart has been developed. This flow chart defines the basic, steady state, control strategy for the entire system.

An Omega AHPF-121 process gas heater has been procured. It meets the low Watt density requirement to maintain minimum internal surface temperatures to avoid ignition of the POX fuel/air mixture. The mixer/heater control is discussed in WBS 6.2.1 reporting.

CONCLUSION:

Progress has been made in defining the development plans for the fuel system design. Physical construction has begun on the various fuel system components. Full evaluations are planned to begin in the first half of 2003.

Subtask 5.2 Air Supply System Design

APPROACH:

The main goal of Subtask 5.2 is to identify and develop the air supply system portion of the BOP. All component, P&ID, System, and Test setup designs are performed In Pro-Engineer. For communication purposes the Pro-Engineer material is translated into AutoCAD (.dwg) drawings and Adobe (.pdf) file types.

WBS 5.2.1-2 is concerned with the fresh air intake system. The intent is to identify the sound attenuation and air quality requirements of the system. These requirements will be defined by the agreement and the system performance goals set by the "System Profile" developed with the sales and marketing team.

WBS 5.2.3 is intended to develop and define the appropriate air supply device based on the performance requirements and cost targets detailed in the agreement. The plan is to construct and evaluate commercially available devices and demonstrate the performance, reliability, and cost. Selection of each device will be a function of its individual properties and the overall system characteristics. It is anticipated that the final device will be engineered specifically for the system.

WBS 5.2.4 is intended to develop and define the appropriate control algorithms and devices, for the cathode and anode air supply, based on the performance requirements of the system. The plan is to develop and evaluate software control algorithms and control devices to demonstrate their performance, reliability, and cost. Selection of each individual components/controls will be a function of its individual properties and the overall system characteristics. Evaluations will include the following:

Four separate methods of air control are being evaluated:

1) Blower speed and barometric pressure (pump characteristic curves).
2) Mass flow sensing with hot wire sensor (direct mass flow measurement).
3) Position control with pressure sensing (mass flow calculated as a function of known resistance and pressure differential).
4) Displacement (mass flow calculated as a function of displacement and pressure).

WBS 5.2.5 is intended to develop and define the appropriate plumbing to connect the operational BOP components based on the performance requirements of the system. The plan is to develop and evaluate component connection device sizes, materials, design, and construction relative to their function and environment. Evaluation will include the following:

1) Analytical pressure loss modeling and requirements.
2) Empirical pressure loss measurements.

3) Joint integrity, sealing, strength, reliability, and cost.
4) Material reactions to their environment.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

The following paragraphs summarize the results for the period of July through December 2002.

A Rietschle SGP-16 has been procured for development testing.

Designed and fabricated the blower speed control card for subsystem development. Verified speed control card function on SGP-16 blower. This will allow blower testing prior to having the system control completed.

Reviewed alternative blower styles and suppliers and chose an Ametek model 116409-13 two stage tangential discharge bypass blower as a lower potential cost (retail cost is 1/3 that of the brushless) and higher efficiency (albeit lower performance) relative to the side channel style.

Air filtration requirements have been agreed at 10-micron maximum particle passthrough. An air cleaner element and housing have been procured for blower system development.

Pipe sizing for C1 designed based on 60-ft/sec maximum velocity throughout C1 BOP system. The intent of this compromise, between frictional losses and material costs, is to have the C1 scaled similar to the expected dimensioning of a commercial product. Tubing and fittings have been received for the C1 BOP test apparatus.

Fabricated sonic air control valve, which utilizes a Saia-Burgess linear stepper motor drive originally designed as a fuel control device for a heating application. Future testing is planned to verify the concept followed by designing a scaled version for fuel control.

CONCLUSION:

Progress has been made in defining the development plans for the air supply system design. Physical construction has begun on the various fuel system components. Full evaluations are planned to begin in the first half of 2003.

<u>Subtask 6.1 Control Concept and Architecture</u>

APPROACH:

During this period we developed a baseline Simulink model to describe the partially distributed control system architecture defined in the last semi annual report. This model is being used to allocate functional requirements of the control system and to define and simulate the algorithms and components of the control system. Simple models of other components of the system are also being developed (i.e. the plant). This will allow the verification of control algorithms and overall control approach in a bench environment prior to controlling an actual fuel cell.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) See appendix for top-level block diagram of the Simulink model of the control system.

b) The majority of the inter-module i/o has been defined along with some data rates and some scaling information.

c) Control algorithms and other logic are being added as they are defined.

CONCLUSION:

The control strategy is being developed and analyzed using dynamic modeling and simulation. Requirements for each component of the control system are being derived from this activity. The requirements are being used to drive the control design effort.

Subtask 6.2 Electronic Design

6.2.1 Control System Design

APPROACH:

Initial control loops were identified during this period. The controlled variables were identified along with the required actuator function. In addition the component dynamic models, that will be necessary to model the control system, were identified.

The fuel air mixer heater is part of the subsystem, which mixes the fuel and air fed to the POX reactor. In addition to mixing the fuel and air the component heats the mixture to the proper inlet temperature for the POX reactor. A Matlab Simulink, dynamic thermal, model of the mixer heater heat system was developed. This model will aid in the design of the control system for this subsystem component.

A preliminary process for bringing the fuel cell up to operating temperature (i.e., "starting up" the fuel cell) was defined during this period. The C1 intent is to carefully bring the fuel cell up to operating temperature without damaging the fuel cell or any of the other components in the system. Some key design considerations include the maximum fuel cell stack temperature of 900°C, the maximum stack inlet to outlet temperature gradient of 200°C and the stack minimum temperature to produce electricity of 600°C to 700°C.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) See Limited Rights Data Appendix for the details of the proposed control loops.

b) The dynamic model of the mixer heater is diagrammed below. This model is a simple dynamic model that incorporates the transient heat and mass transfer as simple first order linear systems, with a 2-D look up table for the temperature rise as a function of input electrical power and mass flow rate. The lookup table and transfer function time constants will be determined empirically.

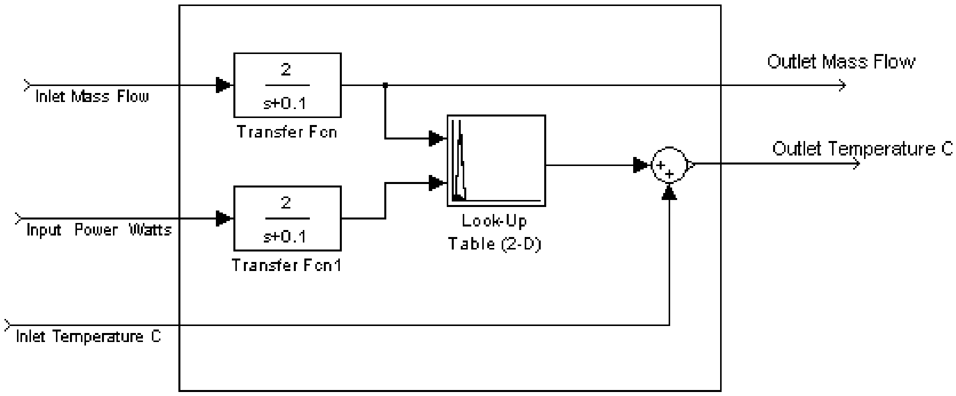

Figure 1 -- Mixer Heater Dynamic Thermal Model

c) The C1 startup process is divided into the following stages: initial heat up, stack temperature gradient control, initial power generation and steady state power generation and load control. See Limited Rights Data Appendix for the details of each stage. A startup thermal model predicts that the time required to bring the fuel cell stack inlet temperature up to 700°C is 2 to 3 hours and the amount of propane fuel used during this process is approximately 1 lb.

CONCLUSION:

During this period the fuel cell startup procedure, control loops and dynamic models were identified and a simple dynamic model of the mixer heater was assembled.

6.2.4 Inverter Boost Design

APPROACH:

The inverter boost will be used to step up voltage from the fuel cell and provide a regulated dc-bus voltage of 200Vdc to the inverter. It is sized for an input voltage range of 70-105Vdc and deliver 13.2kW of power to the inverter at the rated dc-bus voltage. All components required for the design were obtained and the first concept-level prototype has been constructed.

The prototype will be tested for complete functionality and further optimized for size, cost and overall electrical performance. A 15kW DC power source capable of providing the specified voltage range will be used in place of the fuel cell for prototype testing.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

The inverter boost prototype has been developed and testing will proceed as soon as a DC power source is available. A 15kW DC power source has been ordered and is expected to arrive by the end of the first quarter of 2003. Testing of the inverter boost will include obtaining a stable control loop for the specified ratings, power capabilities of delivering 13.2kW at the boost output and optimizing size and cost of major power electronic components.

CONCLUSION:

Development of the inverter boost has been on schedule, however, further testing on the prototype has been postponed until the DC power source is available. Completion of the first working prototype is expected by the end of April 2003.

Subtask 6.3 Sub System Test

APPROACH:

The blower subsystem supplies the pressurized air for the fuel cell and for the partial oxidation reactor. The blower will be powered from the 42Vdc battery bank and will interface to the system controls through a CAN network. A brushless DC motor was chosen to drive the blower for its reliability. The blower subsystem for C1 has been procured and the interface electronics has been designed and partially constructed.

The mixer heater is the part of the subsystem that preheats and mixes the fuel and air fed to the POX reactor. The mixer heater unit has been selected and procured. The interface electronics for the mixer heater has been designed. A test plan has been developed to characterize the performance of the mixer heater/blower subsystem. This test plan also will measure the dynamic performance of this subsystem and the data will be used to develop a dynamic systems model for the mixer heater.

EXPERIMENTS: None this period.

RESULTS and DISCUSSION:

a) A test plan has been developed to characterize the dynamic performance of the mixer heater subsystem. This will be used to develop the dynamic control model for this subsystem.
b) The interface electronics for the blower subsystem has been designed.
c) The interface and control electronics for the mixer heater has been designed.

CONCLUSION:

Progress has been made on the air and fuel handling subsystem. A simple dynamic model of the heater mixer subsystem has been setup and will be verified through subsystem testing of blower and heater electronics.

REFERENCES

Not applicable

BIBLIOGRAPHY

Not applicable

LIST OF ACRONYMS AND ABBREVIATIONS

10cmxN – 10cm by yet to be determined measurement
2-D – Two dimensional
3-D – Three dimensional
3D Solid Model - Commercially available software
A/F – Air/Fuel
ABAQUS – Commercially available software
AC – Alternating Current
AC – Alternating current
AMPS –
Amps – Unit of current
Arms – Amps root mean square
ASPEN – Commercially available software
ASR – Area Specific Resistance
ASTM- American Society for Test and Materials
ATR – AutoThermal Reforming
AutoCAD – Commercially available software
BOP – Balance of Plant
C – Celsius
C1 – Phase 1 Development Prototype
C2 – Final Phase 2 deliverable Prototype
CAN – Controller Area Network (ISO11898)
CFD – Computational Fluid Dynamics
cm – centimeter
Cm^2 – squared centimeters
CO – Carbon Monoxide
CPG – Cummins Power Generation
CPOX – Catalytic Partial Oxidation Catalyst
dB(A) – Decibels A weighted
DC – Direct Current
DOE – U.S. Department of Energy
EZ-Thermal ™ – Commercially available software
FEA – Finite Element Analysis
FLUENT – Commercially available software
FMEA – Failure Mode Effects Analysis
Gate A, B, C – Levels of managerial evaluations
GHSV – Gas Hourly Space Velocity
HD-5 – California Air Resources Board Emission Certification Propane Fuel
hrs – Hours
HX – Heat Exchanger
Hz – Hertz
I/O – Input/Output
ID – Inside Diameter
kg/hr – kilogram per hour
kPa – Kilo Pascal
kW – kilowatt
L – Liter
lbs/hr – pounds per hour

LIST OF ACRONYMS AND ABBREVIATIONS (cont'd)

LPG – Liquid Propane Gas
m – meters
M/A-COM – Division of Tyco Electronics, Subcontractor to MTI
Mathworks - Commercially available software
MLC – Multi-Layer Ceramics
msec – millisecond
MTI – McDermott Technology, Inc.
mxn – to be determined cell footprint dimension
NETL – National Energy Technology Lab
NG – Natural Gas
Ohm – unit of resistance
P&ID – Process and Instrumentation Drawing
PCU – Power Cell Unit
PNNL – Pacific Northwestern National Lab
POC – Proof-of-Concept
POX – Partial oxidation
Ppmv – parts per million volume
PPT – Product Preceding Technology
ProEngineer - Commercially available software 3-dimensional design modeler
Q1..Q4 – quarters of calendar year
QD – Quiet Diesel (Cummins-Onan TM product)
S/C – Steam to Carbon
SECA – Solid State Energy Conversion Alliance
SEM – Scanning Electron Microscope
SI – LeSystemme International d'Unites
SOFC – Solid Oxide Fuel Cell
SOFCo – Solid Oxide Fuel Cell Company
SR – Steam Reforming
US – microseconds
V – Volts
VAC – Volts Alternating Current
VDC – Volts Direct Current
V-I – Voltage - Current
VPI -- Value Package Introduction, a Cummins proprietary process
WBS – Work Breakdown Structure