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Carbonate Fuel Cell System with Integrated Carbon Dioxide/Thermal Management

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DISCLAIMER

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Carbonate Fuel Cell System With Integrated Carbon Dioxide/Thermal Management

CONTRACT INFORMATION

Contract Number DE-FG05-93-ER81511

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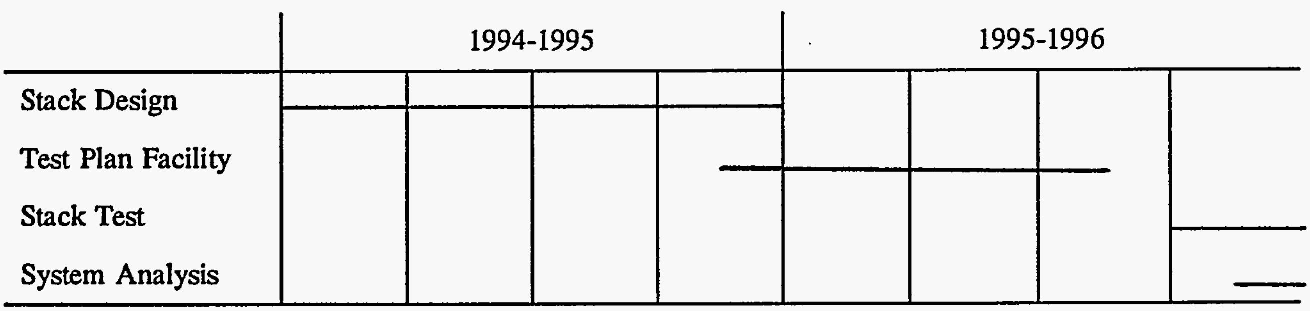
Schedule and Milestones

Program Schedule



OBJECTIVES

The objective of the present work is to define the stack design and system requirements for a commercial-scale carbonate fuel cell with an integrated carbon dioxide management system. Significant simplification and cost reduction of the system is achieved by direct transfer of the fuel exhaust to the oxidant inlet of the fuel cell, thereby eliminating the anode exhaust converter and high temperature piping utilized in conventional system designs.

BACKGROUND

A carbonate fuel cell flow diagram is shown in Figure 1. Carbonaceous fuel at the fuel cell anode provides the source of hydrogen for the anode reaction, while steam and carbon dioxide appear as by-products in the anode exhaust. At the cathode, oxygen and carbon dioxide are consumed. Oxygen is obtained from air, but the carbon dioxide needs to be transferred from the anode exhaust to the cathode inlet. The conventional carbonate fuel cell power plant design collects the anode exhaust from multiple stacks and directs it to a converter where the hydrogen is combusted with excess air. The combustion products, including carbon dioxide, are then directed to the cathode inlet manifolds of the fuel cell. This fuel cell system arrangement is the basis for the direct fuel cell power plant shown schematically in Figure 2.

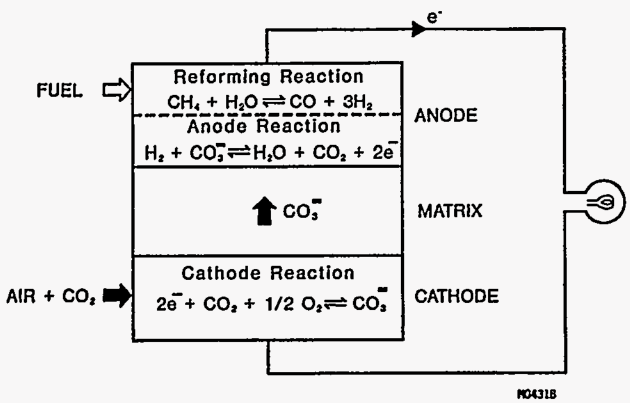


Figure 1. Direct Fuel Cell Diagram:
Carbon Dioxide Needs to be Recycled from Anode to Cathode

While this method of recirculating the carbon dioxide is convenient and results in an efficient fuel cell plant, there is a significant cost associated with the anode exhaust converter and high temperature stainless steel piping required for the hot gases. The converter and associated piping can be eliminated and their functions integrated directly into the fuel cell stack itself. This is accomplished by rearranging the stack flow path so that the spent fuel is combusted and the carbon dioxide is transferred *directly* along the face of the stack at the cathode inlet. This concept design is described in U.S. patent 5,422,1950 issued to ERC on June 6, 1995 (1).

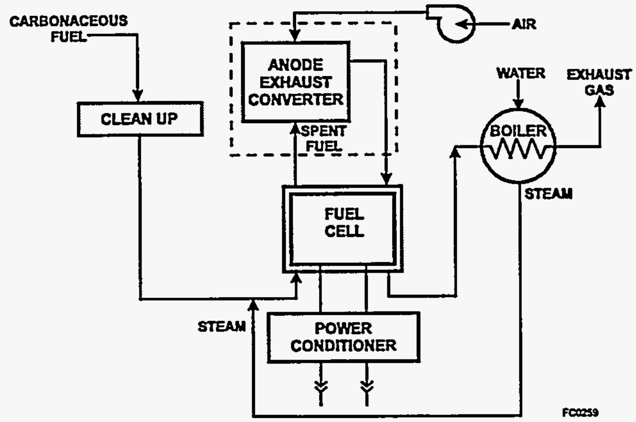


Figure 2. Direct Fuel Cell 2MW Power Plant Schematic:
Advanced System Eliminates Equipment Inside Dotted Box

In Phase I of this program, proof-of-concept testing was conducted with laboratory-scale single cells (250 cm^2 cell size). The anode exhaust of the cell was recycled to the cathode which together with the fresh air made up the oxidant stream for fuel cell reaction. Endurance testing was also performed. Stable performance was achieved in a 6,000 hour test (Figure 3). This was the first time anywhere in the world that a direct carbon dioxide transfer without an external anode exhaust converter was demonstrated in a laboratory-scale test. The temperature dependence on fuel conversion was also evaluated, (Figure 4) and the results showed that near complete conversion of the fuel exhaust stream can be expected in the cathode compartment of the fuel cell in commecial size power plants. A short-term test was conducted on a 2kW stack. The stack was able to continue operation with a low cathode inlet temperature, however, it was not tall enough to be thermally representative of a full-height stack. Phase I results are described in detail elsewhere (2).

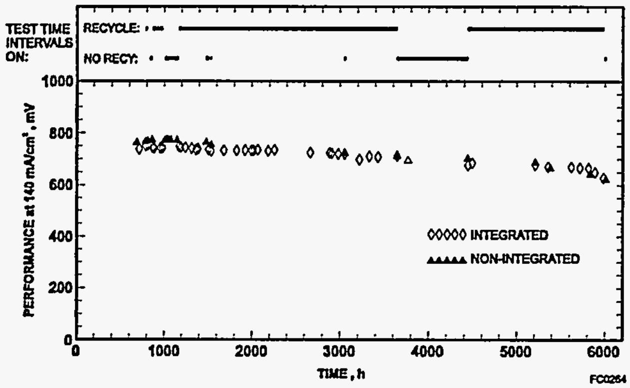


Figure 3. Single Cell Test Results In The Integrated Mode (Fuel Exhaust Recycled To The Cathode):
Stable Performance was Achieved

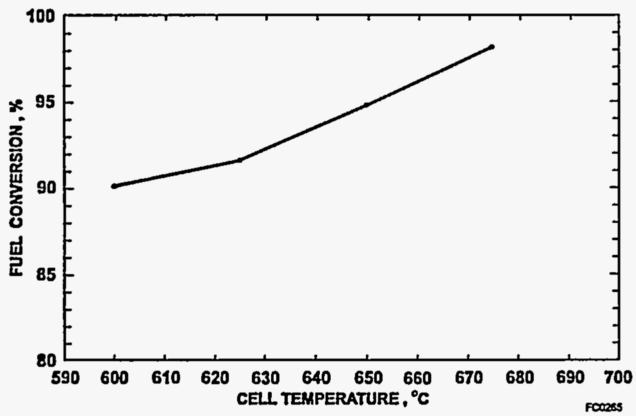


Figure 4. Conversion Of Fuel In The Cathode Gas At Representative Stack Operating Temperatures:
Near-Complete Fuel Conversion is Predicted for Normal Operation

Upon successful completion of Phase I, the Phase II activities were initiated in July 1994 to define the stack design and system requirements for a commercial-scale burnerless carbonate fuel cell stack with an integrated carbon dioxide management system.

PROJECT DESCRIPTION

The major goals of this program are to define the stack design and the system requirements of the integrated design. The approach taken was to maximize the similarities of this stack with ERC's proven baseline stack design and power plant system. Recent accomplishments include a detailed stack design which retains all the essential elements of the baseline stack as well as the power plant system designs. All the auxiliary hardware and external flow patterns remain unchanged, only the internal flow configurations are modified.

RESULTS

Stack Definition

The functions of the anode exhaust converter and piping, which are eliminated, were to:

1. Oxidize the depleted fuel,
2. Recycle the carbon dioxide produced in the anode side of the stack and distribute it to the cathode side for reaction, and
3. Preheat the reactant air during start-up and operation.

The first two functional requirements are integrated *within* the stack design, and the third requirement is satisfied by optimizing the system configuration.

Cross-flow, co-flow and counter-flow arrangements of the fuel and oxidant reactants have long been considered and have been well analyzed for carbonate fuel cell stacks. ERC's baseline design utilizes a cross-flow arrangement, primarily due to its simplicity with respect to gas manifolding arrangement. The functional requirements of 1 and 2 above are most easily satisfied with a counter-flow arrangement since the fuel exhaust must be mixed with air at the cathode inlet. A counter-flow configuration is attractive for this design because it tends to provide for more uniform current density and minimum temperature gradients. The hottest part of the stack, the cathode exhaust, is now on the same face of the stack as the coolest part of the stack, the fuel inlet.

The optimized flow path through the stack elements is shown in Figure 5. Carbonaeous fuel and steam enters the fuel inlet manifold where the fuel is reformed to hydrogen and carbon dioxide. Most of the hydrogen is consumed in the fuel cell reaction and the anode exhaust flows into the stack enclosure. Here, the anode exhaust mixes with air and enters the cathode inlet. The cathode exhaust vents through a manifold to the external piping.

An overall manifold isometric view of the stack is shown in Figure 6. This flow arrangement reduces the number of manifolds by half. Only two manifolds are now required, one for the fuel inlet and one for the cathode exhaust. A cell arrangement showing where the fuel exhaust exits from the anode gas chamber and is mixed with the incoming air before being vented through the oxidant gas chamber is shown in Figure 7. Highlights of this design are:

- Simple, distributed, carbon dioxide transfer.
- Elimination of the fuel exhaust manifold.
- Compact, low risk, stack design.

The design for the 8kW advanced fuel cell stack has been completed. Baseline component designs were selected which are the same as those used in ERC's baseline stack. The stack consists of eighteen 2 ft x 3 ft cells. Experience has shown that the central cells from a stack of this size are thermally representative of taller stacks.

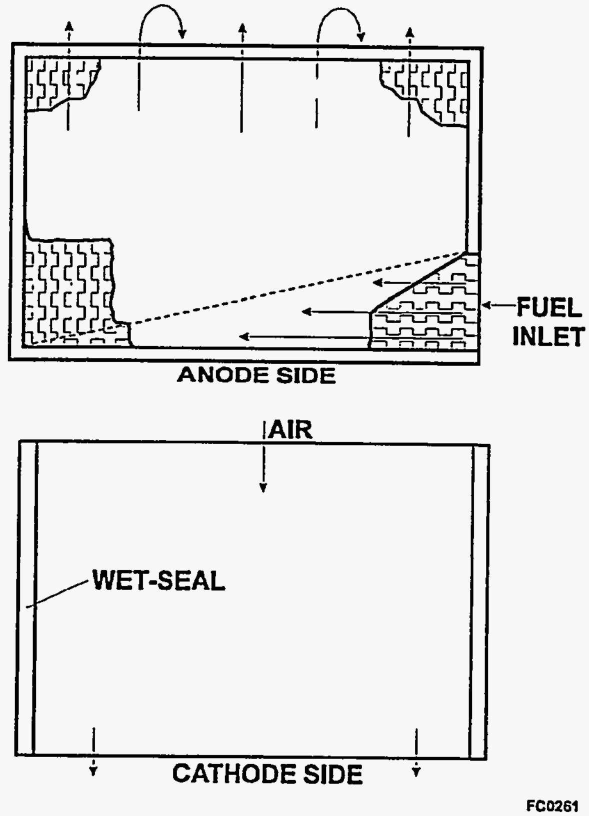


Figure 5. Gas Flow Pattern Through The Various Elements Of The Advanced Carbonate Fuel Cell Stack:
The Path Arrangement Selected for Stack Flow Elements Lends to a Simpler Stack Design

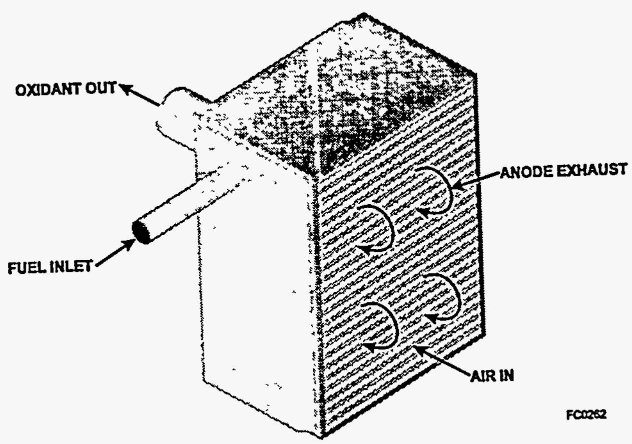


Figure 6. Stack Manifolding With Integrated CO_2 Thermal Management Approach:
Only Two Manifolds are Used

The challenge of this stack design was to obtain a uniform flow profile in a full-size stack while still utilizing baseline cell and stack hardware. The cathode side flow was not altered. Uniform flow distribution was achieved by simple modifications to the baseline anode current collector corrugation.

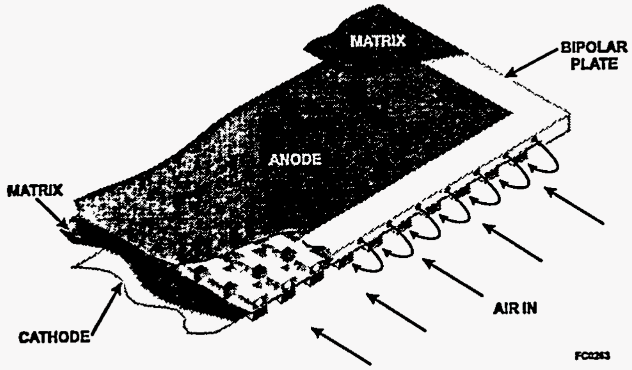


Figure 7. Direct CO_2 Transfer Using Oxidant Inlet Manifold:
A Simple Cell Design was Identified to Provide Direct Transfer of CO_2 to the Cathode Side

A three-dimensional computer model was developed to predict the gas flow distribution in the anode plate. This model is based on the COMMIX-B (3) program and predicts the pressure drop and flow profile based on the type of corrugation used, the flow path and the amount of flow.

The experimental setup shown in Figure 8 was used in conjunction with the computer model. The setup was designed and built to visualize the flow pattern using ammonia sensitive azide paper. Sample ports across the full-size plate allow for local ammonia injections as well as pressure monitoring. Initially, controlled experiments were performed to calibrate the friction factors of flows parallel as well as perpendicular to the corrugation flow channels. Experimental and model-predicted pressure drop data are compared in Figure 9.

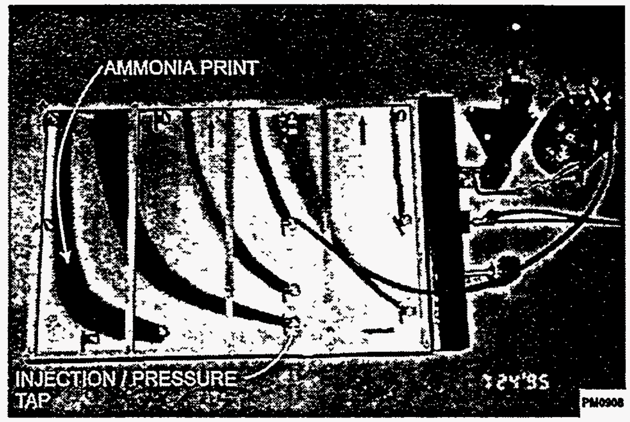


Figure 8. Experimental Setup for Flow Configuration Simulation:
Ammonia and Azide Papers are Used to Visualize Flow Patterns in the Full-Size Corrugated Plate

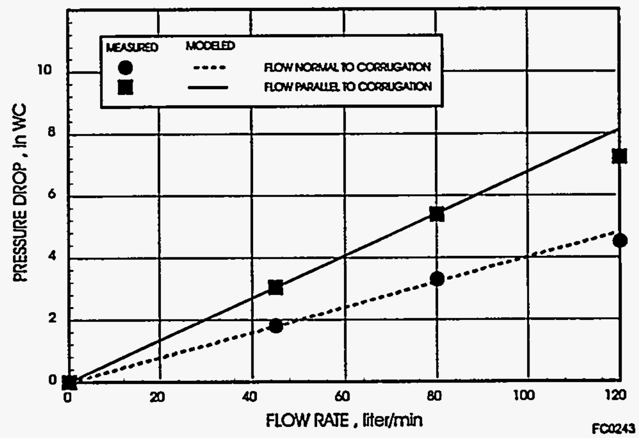


Figure 9. Comparisons of Measured and Computed Pressure Drops in Anode Corrugated Plate:
The Computer Model Closely Predicts the Measured Pressure Drop, Especially at the Full Load Operating Flow Rate of ~45 lpm

Two types of corrugation were modeled and experimentally verified. The first corrugation used was 1994 state-of-the-art anode corrugation.

A second, low-cost corrugation option was also evaluated. This type of corrugation was later chosen as the future standard. Plate design studies, therefore, continued using the low-cost corrugation.

Computer simulations predicted that uniform flow patterns could be obtained with a baffling system. After several baffling studies and extensive computer simulation, an optimized plate design was obtained which incorporates uniform flow and manufacturing simplicity. The experimental and computer modeling results at full load flows are compared in Figures 10a and b. The flow pattern obtained with the ammonia/azide paper in the experimental setup agrees with the model prediction. Both the model and the experimental setup gave a pressure drop of 2.9 inches of water from the fuel inlet. Velocity profiles were computed at these conditions for two distances from the anode exit. The results, shown in Figure 11, predict a ±10% flow velocity variation along the width of the plate. This is well within the design goal.

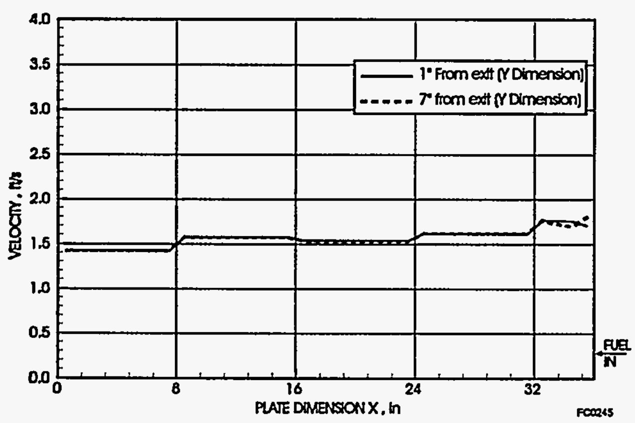


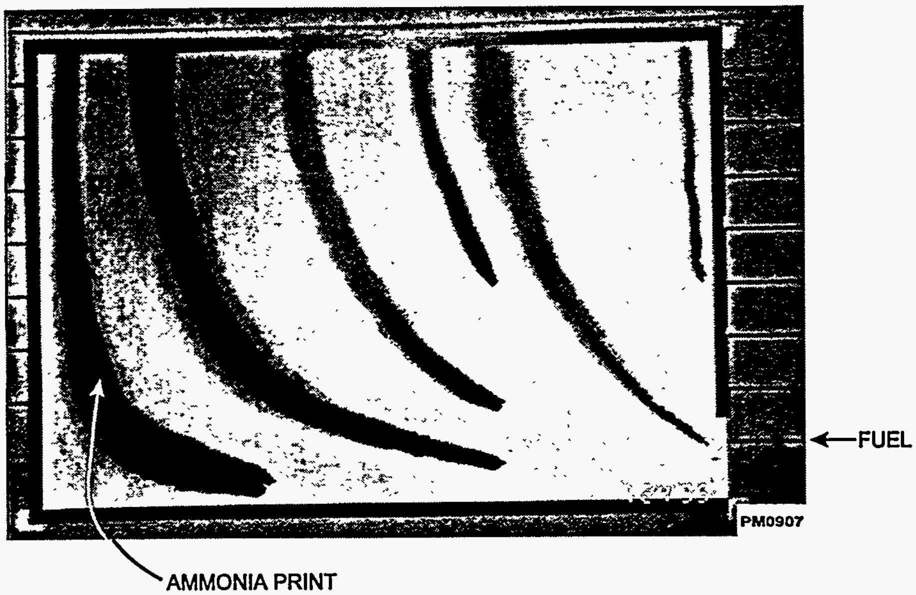
Figure 11. Computed Velocity Profiles with Full Load Flows:
Uniform Velocity Profiles are Projected

Fabrication of this stack will now be initiated. The repeating active components are being provided by ERC's subsidiary Fuel Cell Manufacturing Corporation (FCMC). The auxiliary hardware (compression plates, gas manifolds, etc.) are designed, and the parts are ordered.

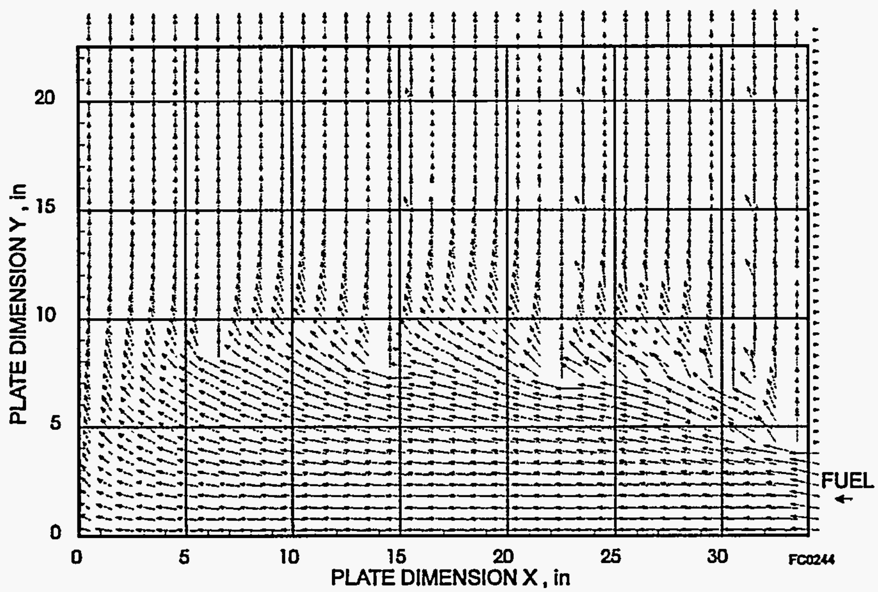
TEST PLAN AND FACILITY

The detailed test plan for the 8kW stack is being finalized. Test conditions will be optimized by varying recycle flow and cathode air inlet temperature as the power output is monitored. Following approximately 500 hours of performance characterization and the establishment of the optimized flow parameter settings, an extended test period is planned. The stack facility available at ERC for baseline short stack tests will be used for this test.

A major effort is focused on defining the operating procedures for a stack with direct and integrated transfer of the fuel exhaust to the cathode inlet. The first step in this process was to review the operating experience obtained from Phase I and ERC's in-house tests. Changes in operating procedures are required because there is no isolation between the fuel and oxidant streams. To accommodate this, the operating strategy was changed for the fuel stream from flow control to differential pressure control. This will protect the anode chambers from air infiltration. After the fuel is exhausted from the anode chambers, it will mix directly with the cathode inlet air along the face of the stack. The flammability of the mixed fuel and oxidant streams was calculated as a function of fuel utilization and temperature, based on the system analysis runs performed in Phase I. These calculations predict where the fuel will combust. At low fuel utilizations, a weak flame is sustainable outside of the stack in the cathode inlet manifold, while at a high fuel utilization combustion will not occur until the mixed gas is preheated within the cathode gas chamber. Therefore, the release of the heat of combustion will be controlled by the operating condition.



a) Experimental Flow Pattern



b) Computer Modeled Flow Pattern: Arrow Length Defines Local Flow Velocity

Figure 10. Experimental and Computer Model Flow Configuration at Full Load Flows: The Flow Pattern Obtained in the Experimental Setup Verified the Computer Model Simulation

First time start-up and conditioning, hot idle, load increase, emergency shutdown, cool down and reheat procedures have all been defined and are currently being incorporated into the test plan.

FUTURE WORK

Near term activities will include:

- Stack Manufacture
- Finalization of Test Plan

ACKNOWLEDGEMENT

The authors wish to acknowledge the support of the DOE/SBIR program.

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3. Argonne National Laboratory, "COMMIX-1B: A Three-Dimensional Transient Single-Phase Computer Program for Thermal Hydraulic Analysis and Multi-component Systems", NUREG/CR-4348, ANL-85-42, September 1985.