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# Planar solid oxide fuel cell integrated system technology development

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## Abstract

Planar solid oxide fuel cell technology is being developed at SOFCo in order to demonstrate compact, high-efficiency power-generation systems with multi-fuel capability that can meet commercial performance goals. Current research focuses on stock development and system integration for pipeline natural gas operation, logistic fuel operation and cell and stock technology for low-temperature operation. Published by Elsevier Science S.A.

*Keywords:* Solid oxide fuel cells; Logistic fuel; Low-temperature electrolytes; Stack technology

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## 1. Introduction and objective

Planar solid oxide fuel cell (SOFC) technology development at SOFCo, a McDermott Technology, Inc./Ceramatec partnership, has the primary objective of demonstrating compact, high efficiency power generation systems with multi-fuel capability meeting commercial performance goals. Current programs synergistically address this goal through an internally funded program focusing on stack development and system integration for pipeline natural gas (PNG) operation, a DARPA sponsored program to demonstrate logistic fuel operation, and a program to develop cell and stack technology for low temperature operation supported by EPRI.

Recent advances made in planar SOFC stack performance and endurance enabled SOFCo to successfully demonstrate several small scale integrated systems using pipeline natural gas fuel. These advances have enabled verification of system concepts at tall stack scale (more than 60 cells, 10.2 × 10.2 cm) with commercial level endurance. The system concept using the patented CPn® design, thermally integrates the stack, air preheater, and the reformer by co-locating these components. This platform provides the flexibility to accommodate stacks based on advanced thin film cells currently under development. Multiple system tests enabled development and demonstration of continual improvements at the system level. The design and fabrication of a logistic fuel reformer has been completed in a parallel activity. Process integration of a 1-kW CPn® system with the logistic fuel reformer has been planned for the third quarter of 1997.

## 2. Approach

With the recognition of the system costs and endurance benefits from lower operating temperatures, developmental efforts have been focused in three key areas.

- Stack technology development (SOFCo). Advancement of low temperature electrode technology through materials and process improvement; construction and testing of short stacks; system verification of tall stacks in the environment of an integrated natural gas reformer and air recuperator.
- New materials development (EPRI). Development and optimization of new electrolyte materials.
- Fuel processor development (DARPA). Development and integration of logistic fuel reformation technology.

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Optimum fuel cell technology development is based on the requirements of integrated power systems, rather than considering only isolated individual cell and stack components and plant equipment. SOFCo developments including the CPn® design and logistics fueled generator are being developed with this system based approach.

The SOFCo CPn® concept evolved through recognition of the impact of balance of plant (BOP) on the economy and efficiency of the total system. The design optimizes the total system and maximizes the efficiency of the system while simultaneously reducing the number of high temperature components peripheral to the stack. The CPn® module consists of a multistack arrangement that allows multistage oxidation of the fuel. Efficiency is enhanced by effective thermal coupling of the stacks with fuel and air processes. The CPn® power system comprises planar SOFC stacks, fuel processor components and the BOP equipment.

The most salient CPn® design feature is the thermally integrated SOFC module, which houses the fuel cell stacks, an air heat exchanger, reforming catalyst, and a spent fuel burner. Air, used as the fuel cell oxidant and coolant, is preheated by heat exchange with the stack air exhaust and delivered to the SOFC stacks. This heat exchanger is incorporated into the wall of the module housing. The fuel processing system is coupled to the stacks within the thermal enclosure accomplishing internal reformation of hydrocarbon fuels. Thermal integration of key process streams within the module provides optimum system performance in a compact, reliable power system.

The key to achieving a low-cost, reliable system is the iterative design and manufacturing development of primary components from a systems perspective, rather than independently developing components separately then combining them into a system. The SOFCo CPn® power system has been successfully demonstrated in a 1.4-kW and several multi-100-W modules.

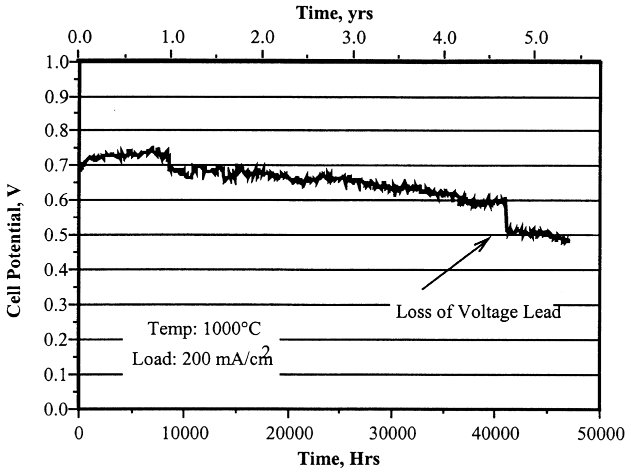

Fig. 1. Single cell endurance test.

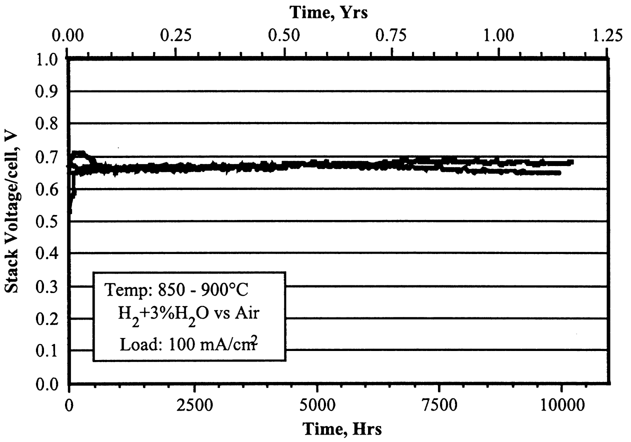

Fig. 2. Stack endurance test.

## 3. Results

### 3.1. Cell/stack development

Early developmental activities focused on establishing stable cell operation at 1000°C. Performance degradation of less than 0.5% per 1000 h has been demonstrated for over 46 000 h of operation (Fig. 1). Electrode improvements have established stable stack performance at 850–900°C. The long-term performance of 5-cell stacks using the improved low temperature electrodes is shown in Fig. 2. Further advances have yielded stacks with demonstrated 800°C operation at an area specific resistance of under 1 Ω $cm^2$ (>250 $mW/cm^2$ peak power density) using a 180-$\mu$m zirconia electrolyte (Fig. 3). Stack performance greater than 95% of single cell performance is now typical.

Single cells have been tested with high sulfur containing fuels ($H_2$ with 500 ppm $H_2S$). Stable cell operation during 150 h of $H_2S$ exposure (Fig. 4) has been shown. Less than a 30 mV loss was registered while operating with the $H_2S$ containing fuel.

Several integrated system level verifications using pipeline natural gas fuel have been completed. The stack module typically consisted of 60 cells of 10.2 × 10.2 cm size. An integrated PNG fuel processor and air preheater were key elements of the system test. The primary objectives of these tests were to establish the stability of stack performance and various sub-systems for multi-100 h, and to provide experimental verification of system thermal models.

Key results from these tests are summarized below.

- Theoretical open circuit voltage using both humidified hydrogen and reformed natural gas for a 62-cell stack over four thermal cycles to room temperature.
- Verification of model predicted system performance (stack performance and thermal distribution).
- Performance stability over 250 h of operation using PNG fuel (Fig. 5).

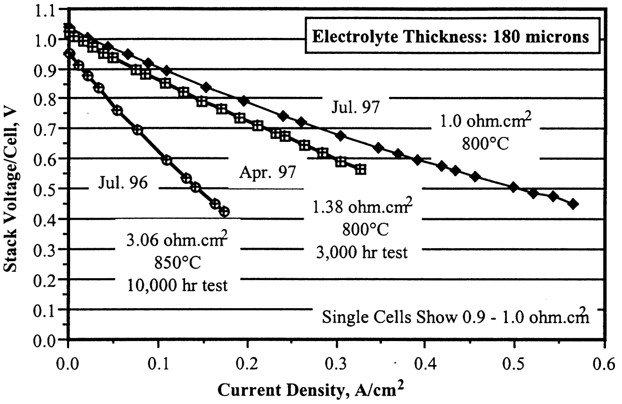

Fig. 3. Stack performance improvement.

### 3.2. Low temperature electrolyte development

In the area of low temperature electrolyte materials, two classes of materials were evaluated: doped ceria and lanthanum gallate. Both single cells and stacks were fabricated and tested. Although the ceria electrolyte is known to exhibit electronic shorting under fuel cell operating conditions, exceptional performance stability was observed. A ceria electrolyte single cell was operated for 15 000 h with negligible performance degradation (Fig. 6). Performance models incorporating experimental data showing stack efficiencies of 45% could be achieved using natural gas fuel. The ability of these cells to operate at temperatures of 600–700°C provides an opportunity for lower BOP costs. A lanthanum gallate electrolyte stack (5 × 5 cm, 5 cells) operating at 750°C has shown very low degradation over the initial 3000 h of operation (Fig. 7).

### 3.3. Logistic fuel processor development

SOFCo, through sponsorship from DARPA and the US Army, is working on a three-phase, four-year program to demonstrate a mobile electric power fuel cell generator operating on logistic fuel. The program aim is to integrate planar solid oxide fuel cells with a JP-8 fuel processor into a compact generator module. This integration of fuel processing equipment for reforming high sulfur (0.3% by weight) logistic fuel, with SOFC stacks into a compact hardware configuration will represent a significant advance in the state-of-the-art in SOFC system technology.

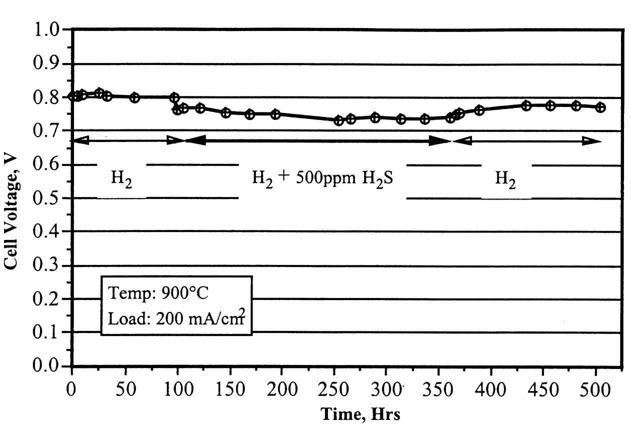

Fig. 4. Sulfur tolerance test.

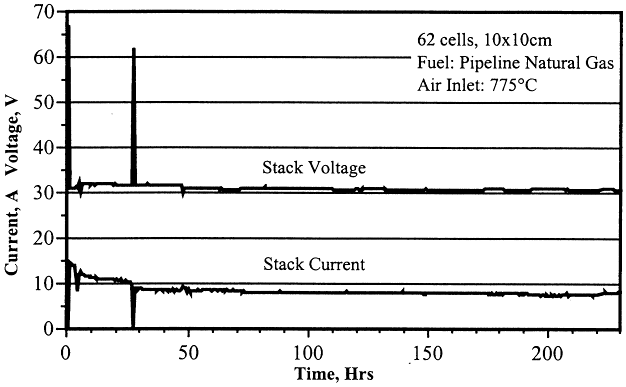

Fig. 5. Tall stack test.

The US Army Lightweight Multipurpose Shelter (LMS) was selected as a target application for this project (Fig. 8). The LMS generator is housed within a small tunnel, measuring approximately 73.7 × 63.5 × 213.4 cm, near the front of the shelter. The LMS selection was based on the Army's interest in an efficient and quiet power supply to

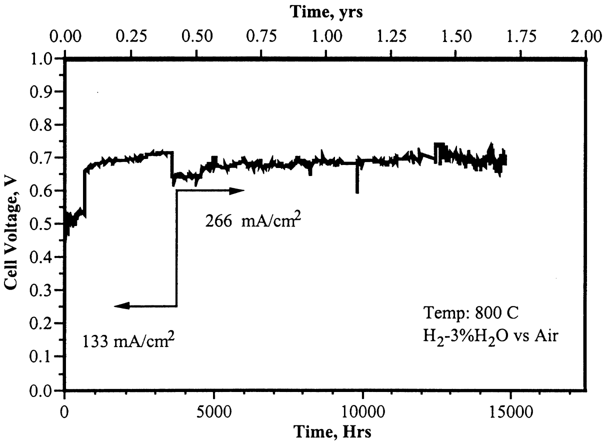

Fig. 6. Low temperature cell endurance test (ceria electrolyte).

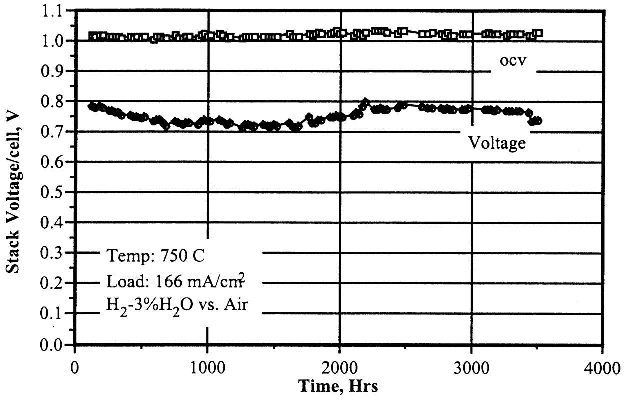

Fig. 7. Low temperature stack endurance test (lanthanum gallate electrolyte).

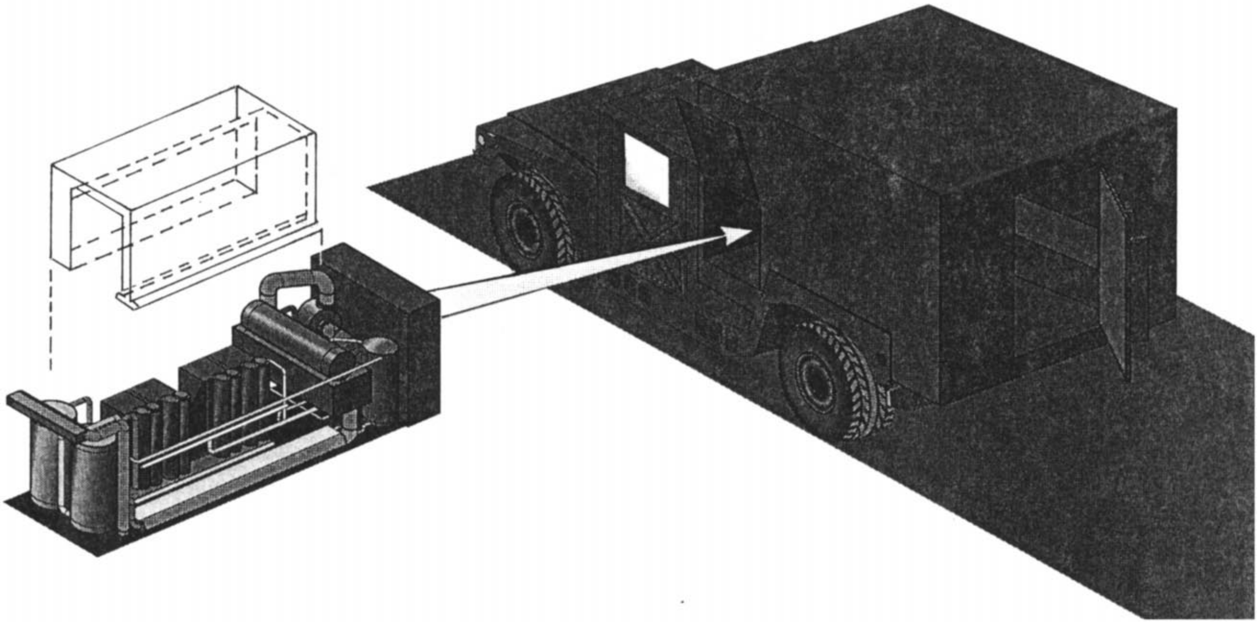

Fig. 8. SOFCo MEP generator conceptual design for Army LMS application.

replace the current diesel generator, and the suitable match between the LMS power requirement and the 10 kW demonstration size for the current program.

During June 1996 (Phase 2 in the program) SOFCo demonstrated a 10-kW$_e$ partial oxidation (POX) fuel processor in combination with a 100-W solid oxide fuel cell stack (Fig. 9). This was the first successful demonstration of a planar SOFC stack operating on JP-8 fuel [1].

The Phase 2 fuel atmospheric pressure processor used partial oxidation (POX) to reform the JP-8 into a hydrogen-rich synthesis gas (syngas) for use in the fuel cells. While a 100-h demonstration of the fuel cell/fuel processor system was achieved, further development in the areas of maintenance, portability, and efficiency was planned for Phase 3 before overall system physical integration could begin.

The Phase 3 fuel processor objectives focus on reducing maintenance, improving fuel conversion efficiency, and demonstrating a soot management system compatible with MEP mobility requirements. A new, proprietary POX reactor design is the key to achieving these goals. The new design, which is based on proven gasification experience, will accommodate the temperatures and gas residence times required for efficient, long-term operation. In addition, efforts to prevent or minimize coke and soot formation rely on detailed analysis of the reactant mixing and synthesis gas handling. A key challenge is to demonstrate suitable performance in the system which is 1/200th the scale of industrial units.

Proprietary numerical models for the primary partial oxidation reactions were used, together with existing industrial gasifier design and performance correlations to evaluate various POX reactor designs. The POX reaction numerical models include zero-, one-, and two-dimensional flow representations with quasi-global kinetic modeling. In particular, two-dimensional models, which include full reaction kinetics were used to predict reactor flow patterns, mixing performance, gas residence times, temperature fields and gas composition. The models were benchmarked with data from the Phase 2 fuel processor and then validated using industrial reactor data.

To validate and confirm multi-dimensional numerical models, physical flow visualization tests were conducted. Plexiglas models based on candidate reactor and flow nozzle designs were tested. Air flow rates were adjusted to match stream momentum.

Smoke particles, illuminated in a two-dimensional laser sheet, were used to evaluate mixing patterns. Fig. 10 shows smoke being injected into a model reactor to investigate potential short circuiting of the reactor which could result in unreacted fuel in the product syngas. This approach of combining physical and numerical modeling allowed several different design configurations to be evaluated and optimized.

The Phase 3 fuel processing train has been physically separated to allow optimization of the fuel conversion performance through independent control of operating parameters. The fuel processing train is shown in Fig. 11. Included are separate components which accomplish fuel and water vaporization, air preheating, JP-8 partial oxidation, synthesis gas cooling, soot filtering, desulfurization, and reheating. The system is designed to operate over a wide range of temperatures (up to 1648.9°C) and residence times. It is predicted to achieve a 75% cold gas efficiency[1]. This is significantly higher than the 50–55% conversion level achieved in Phase 2.

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[1] Cold gas efficiency = higher heating value of ($H_2$ + CO) products/ higher heating value of feedstock.

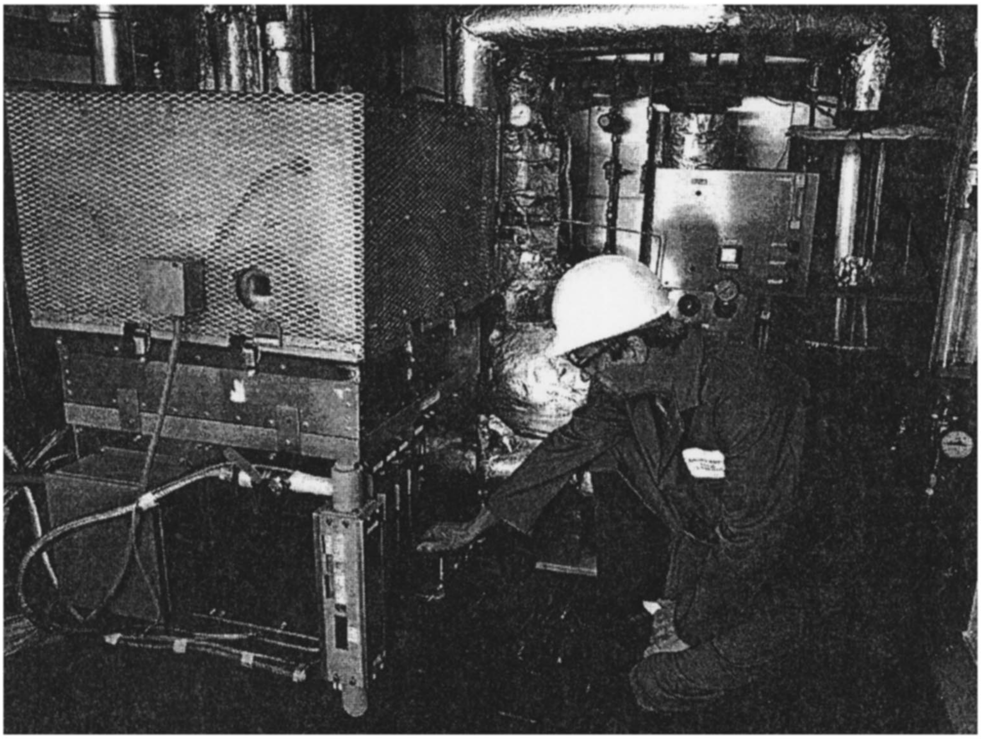

Fig. 9. Phase 2 breadboard system arrangement.

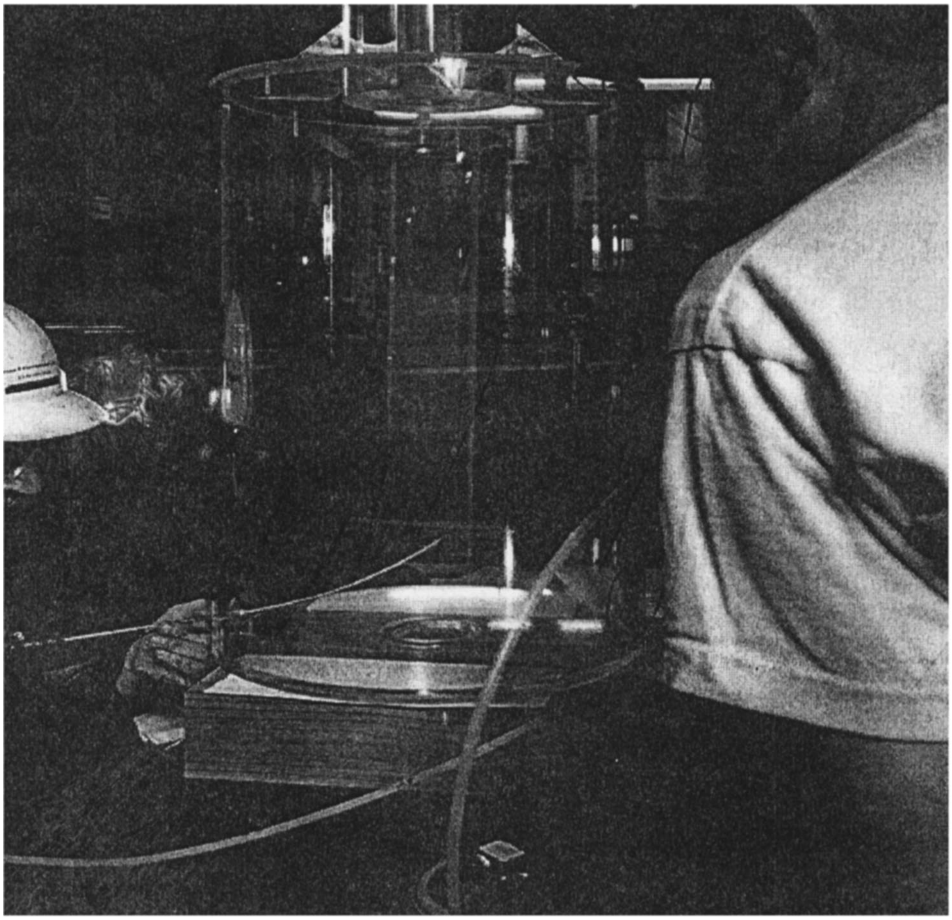

Fig. 10. Cold flow visualization studies used to verify numerical modeling results.

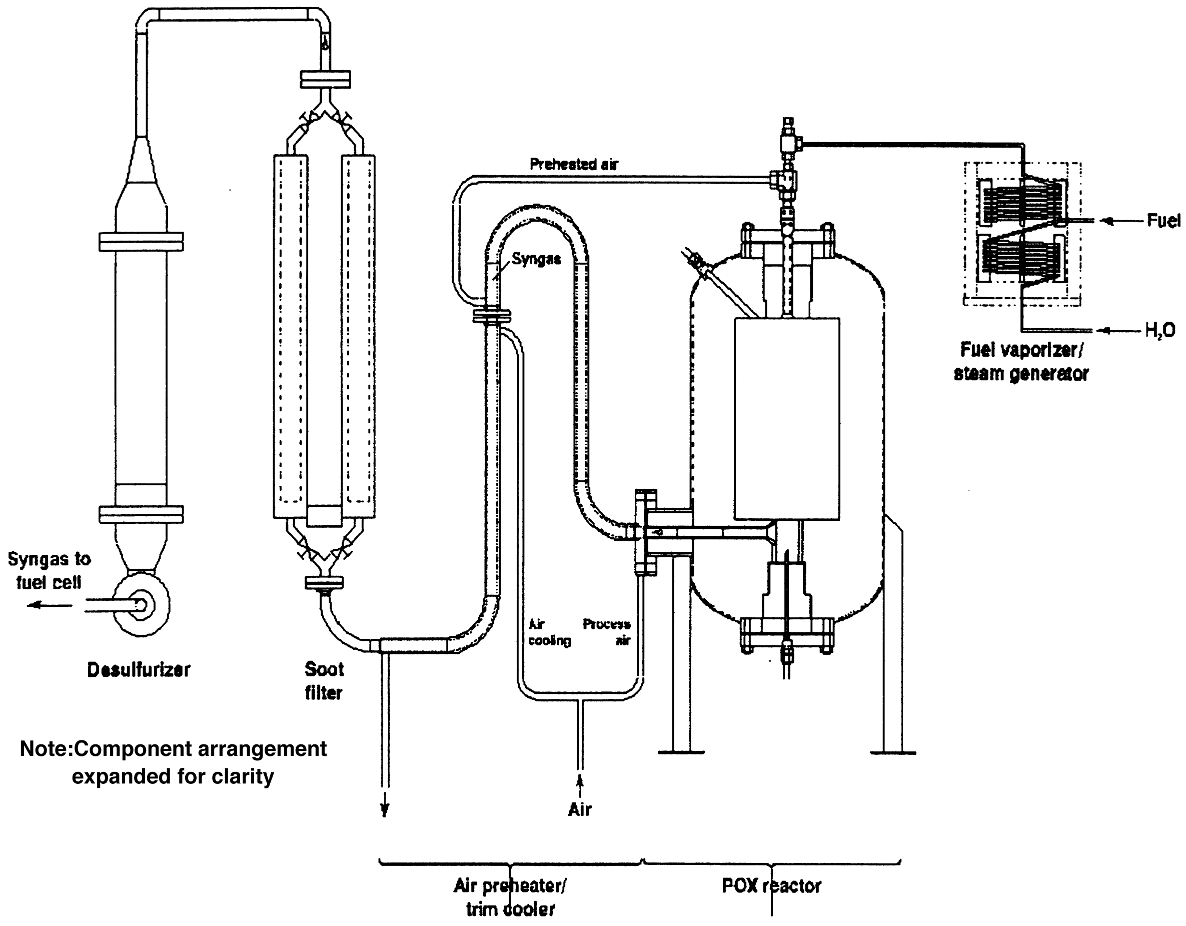

Fig. 11. Schematic of unintegrated JP-8 fuel processor.

Physical and thermal re-integration of the fuel processor will follow subsystem optimization. This integration, including the fuel cell heat and steam byproducts is expected to provide substantial size and weight savings necessary to meet the aggressive constraints of the Army LMS application and will benefit the overall system efficiency.

In addition to increased efficiency and reduced maintenance, another important functional requirement for the Phase 3 fuel processor is the ability to operate with a soot filtering system compatible with the MEP mobility requirements. In the Phase 3 demonstration, an automated system using two parallel soot filters will be used. This will allow continuous on-line soot filtering by cycling between the filters. Cleaning of the off-line filter will be accomplished by injecting air to oxidize the collected soot. The new system requires less space than the soot filter system used during Phase 2.

The feasibility of oxidizing the soot to clean the filter was evaluated with a one-third scale bench test. A sintered metal filter was installed within a vessel and positioned in a furnace to control temperature. Soot collected during Phase 2 testing was first fluidized in a nitrogen stream and applied to the outside surface of the filter. After soot application, a low flow-rate of air was directed through the filter to oxidize the soot. Analysis of the exhaust gas composition (CO and $CO_2$) was used to monitor the rate of soot oxidation.

Encouraging results were obtained from the soot filter cleaning tests as shown in Fig. 12. These tests demonstrated the ability to clean the sintered metal filter on-line and achieve a clean condition (as determined by pressure drop). The time required to oxidize the soot was determined by monitoring the oxygen concentration in the product gas. Repeated cycles of soot filtering and soot oxidation demonstrated the ability to return to a repeatable filter pressure drop. These results indicate that there will not be a gradual increase in pressure drop across the filter from repeated cleaning cycles over the hundreds of hours of fuel processor operation.

System installation is nearing completion in the test facility at the McDermott Technology, Inc., Alliance Research Center in Alliance, Ohio. Fuel cell system demonstration is planned for late September, 1997. Following successful demonstration of the breadboard logistics fueled solid oxide fuel cell system, efforts are planned to address physical integration and transient operation.

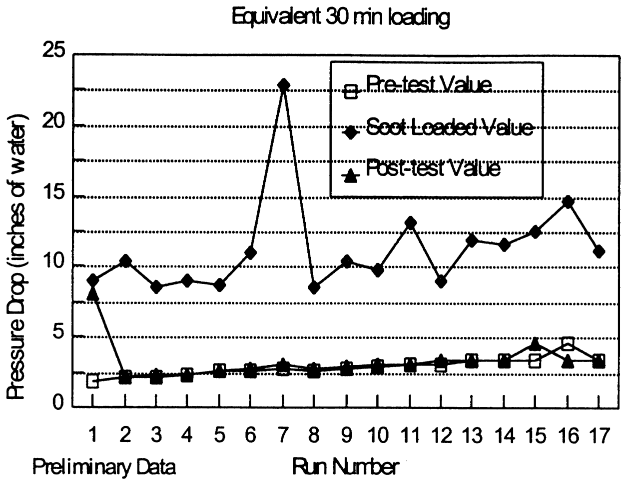

Fig. 12. Results from soot filter regeneration tests.

## 4. Future activities

In addition to the EPRI and DARPA/US Army sponsored work, SOFCo also has several initiatives aimed at the commercial development of planar, solid oxide fuel cell technology. The Distributed Power Initiative (DPI) is currently developing a 2-kW natural gas fueled Technology Demonstration Unit (TDU). This TDU will be the first complete integration of a thermally self-sustaining planar SOFC system including the reformer, storage, inverter, controller and heat recovery components. A subsequent 10-kW TDU is also being designed and will be constructed in 1998.

The DPI's ultimate goal is to make use of both previous and current research to develop a commercial system for an initial market entry sized from 10–50 kW. Field demonstration units will be built for specific high-value applications in an effort to penetrate the commercial market in those areas where higher priced initial units can be introduced at a premium. Although specific to the market segment in which the units will be introduced, much of the work associated with the DPI is aimed at both standardizing component design and manufacturing. In addition, an aggressive manufacturing cost reduction program also accompanies the DPI wherein high rate/high volume manufacturing techniques are being developed in an effort to reach cost targets derived from market based demand and performance parameters.

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## References

[1] R. Privette, M. Perna, K. Kneidel, J. Hartvigsen, S. Elangovan and A. Khandkar, *1996 Fuel Cell Seminar*, Orlando, FL, 17–20 Nov., 1996.