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Solid oxide fuel cell developments at Westinghouse

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Abstract

Since 1958 Westinghouse has carried out research activities to develop solid oxide technology. Past activities have been well published and presented. This paper will present recent activities carried out at Westinghouse concentrating on the last several years. During this period, individual cell performance has exceeded 20 000 h of operation, while bundle and small generator performance has exceeded 5000 h of operation. Cells, bundles and generators up to 20 kW have been operated using pipeline natural gas. Cells of 50 cm length are now routinely made in small production campaigns while 77 cm long cells have been made in the laboratory. Production of 100 cm cells will be initiated this year. Two 25 kW generators are currently in production for delivery late this year and early next year. These units will be shipped to Japan for testing by Japanese electric and gas utilities. This paper will provide data and descriptions of the testing and details of the evolution of tubular solid oxide fuel cell generator design.

Introduction

The tubular SOFC is an electric power generation technology which can cleanly and efficiently utilize our fossil fuel supplies. SOFC technology is in the preliminary design stage of development with plans for field testing of multi-hundred kilowatt and multi-megawatt rated generators during the early to mid 1990s. SOFC technology operates efficiently at atmospheric pressure at 1000 °C and thus has the potential for integral reforming of natural gas and direct utilization of coal derived fuel gas. The economic market potential for the SOFC technology extends from small commercial and small industrial applications to large multi-megawatt plants for large industrial co-generation and all-electric applications. In addition, the SOFC technology offers significant user benefits which include: (i) electrical efficiency greater than 50%; (ii) virtually unlimited plant site selection as a result of low emissions and make-up water requirements; (iii) factory manufactured modular packages which reduce plant lead time, minimize site erection costs, permit high levels of quality control, and enhance user planning flexibility to better match load growth and minimize capital exposure; and (iv) enhanced versatility through fuel adaptability and waste heat recoverability, permitting either baseload or intermediate load all-electric power plant operation or co-generation plant operation.

This paper briefly describes the Westinghouse solid oxide fuel cell design and reviews the technical progress that has occurred during the past several years.

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Basic Westinghouse design

Solid oxide fuel cells are highly efficient electrochemical devices that can operate at atmospheric or elevated pressures and at temperatures in excess of 1000 °C to produce electricity from fossil fuels such as coal derived fuel gas, natural gas or distillate fuel. The temperature of the exhaust gases from the modules is between 500 and 900 °C — a temperature which is attractive for co-generation applications or for use in bottoming cycles for all-electric central station power plants.

SOFC cells readily conduct oxygen ions from an air electrode (cathode), where they are formed, through a solid electrolyte to a fuel electrode (anode), where they react with carbon monoxide (CO) and hydrogen (H_2) contained in the fuel gas to deliver electrons and produce electricity. The state-of-the-art tubular SOFC (Fig. 1) developed by Westinghouse features a porous air electrode made of strontium-doped lanthanum manganite that is overlaid onto a porous, calcia-stabilized zirconia support tube. A gas-tight electrolyte of yttria-stabilized zirconia (approximately 50 μm thick) covers the air electrode, except in an area about 9 mm wide along the entire active cell length. This strip of exposed air electrode is covered by a thin, dense, gas-tight layer of magnesium-doped lanthanum chromite. This layer, termed the cell interconnection, serves as the electric contacting area to an adjacent cell or to a power contact. The fuel electrode is a nickel zirconia cermet and covers the electrolyte surface except in the vicinity of the interconnection.

For operation, air is introduced to the fuel cell through an air injector tube. The air, discharged from the injector tube near the closed end of the cell, flows through the annular space formed by the cell and the coaxial injector tube. Fuel flows on the outside of the cell. Typically, 85% of the fuel is electrochemically utilized (reacted) in the active fuel cell section. At the open end of the cell, the remaining fuel is combusted using the oxygen depleted air stream exiting the cell.

To construct an electric generator, individual cells are 'bundled' into an array of series-parallel electrically connected cells forming a semi-rigid structure that is a basic generator building block. The individual bundles are arrayed in series to build generator

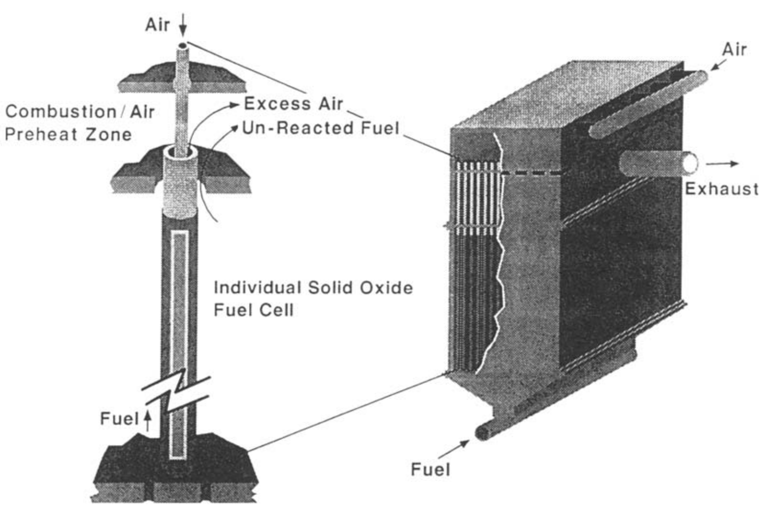

Fig. 1. SOFC module.

voltage and to form submodules. The parallel electrical connection of the cells within a bundle enhances generator reliability. Submodules are further combined in either parallel or series connections to form the generator module.

Figure 1 also illustrates the SOFC module. The adequacy of the basic module design has been demonstrated by the operation of twelve generators, including those operated under field test conditions by the Tokyo Gas Company and the Osaka Gas Company.

Recent developments

Cell performance has significantly improved during the past five years. A cell produced in the 1986/87 time period would typically lose 5–7% of its voltage every 1000 h of operation, whether in single cell tests or in generators. Process improvements made since then have significantly reduced this decay. Figure 2 shows the performance comparisons of cells fabricated in 1986/87 period with cells produced in 1988 and 1989. The 1988 cell was taken off test this year for destructive examination after over 20 000 h of operation at power. The final decay rate was approximately 1.4% per 1000 h.

The 1989 cell shown represents a series of cells put on test at various temperatures from 875–1100 °C and from 250–450 mA/cm^2. As of July 1991, six cells had accumulated over 20 000 h, of which two had been removed for examination. The cells shown on Fig. 2 have all been operated at 1000 °C and 250 mA/cm^2 during their life. We are within striking distance of our 5–10 year operating goal.

In 1986, Westinghouse entered into a contract with the US Gas Research Institute to study a natural gas fueled SOFC. This program culminated in a 3 kW generator operated for approximately 5500 h on natural gas from the local Pittsburgh pipeline with the odorant removed. The generator recycled a portion of its exhaust, thus eliminating the need for an external supply of steam for the reforming reaction. Since the fuel electrode is comprised primarily of nickel and thus is very catalytically active, it was not practical to do all of the reforming on the cells. Therefore, a small reformer was integrated into the bottom of the generator, using exhaust heat to support the endothermic reforming reaction. Seventy-five percent of the reforming was done in

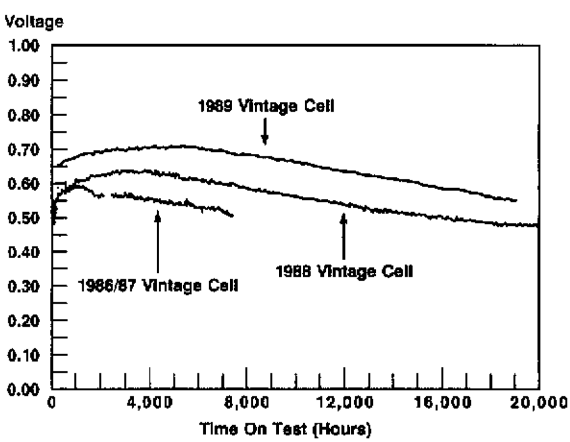

Fig. 2. SOFC development progress: increased cell stability.

the reformer and the remaining 25% on the cells. Performance of the cells is shown in Fig. 3. Notice that the main body of cells was fabricated by using our 1986 technology. The modified process as represented by the 18 cells of bundle A performed as predicted from single cell tests.

While the technology development was continuing in the laboratory, Westinghouse determined that a significant scale-up of manufacturing capability was needed to accomplish the generator test objectives and to put in place the manufacturing processes and quality control to eventually commercialize this technology. A facility that had been designed for pilot plant operations in the steel industry was obtained, Fig. 4, and modified to produce SOFC cells and generators. This increased our capability

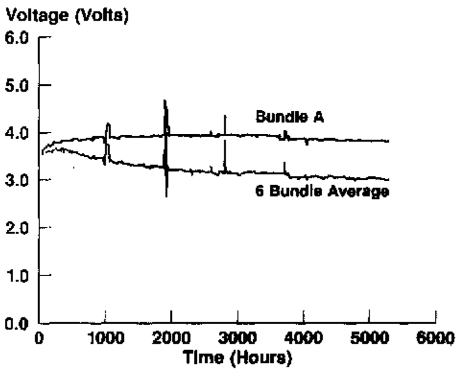

Fig. 3. 3 kW SOFC generator — bundle A.

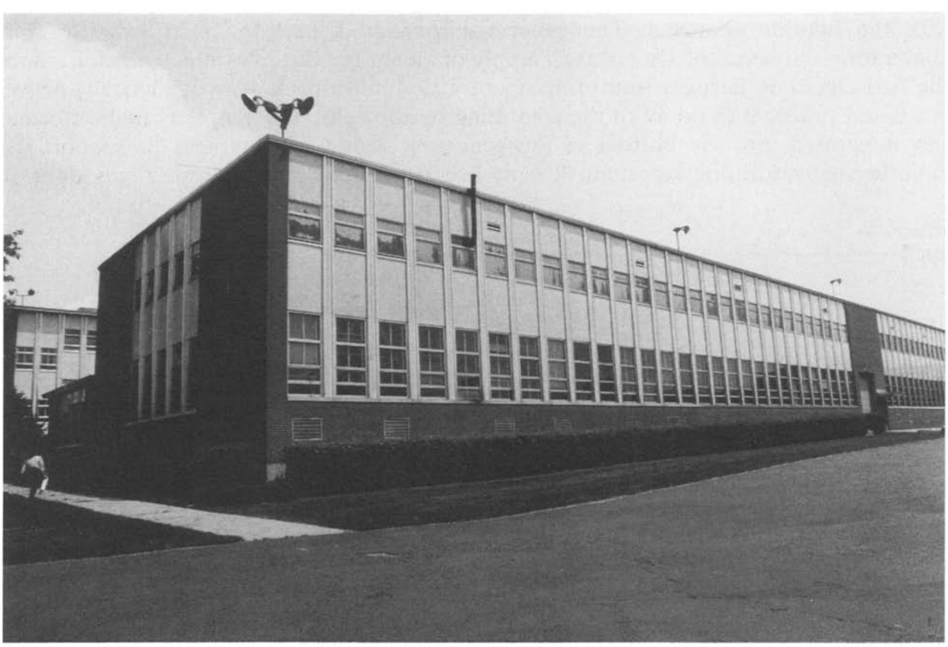

Fig. 4. Westinghouse pre-pilot manufacturing facility.

from approximately 10 kW per year to several hundred kW initially and several MW per year eventually.

The first cells from this pre-pilot plant were put on test in Nov. 1989 in the form of 2–18 cell bundles. After one year (approximately 6500 h of which were at power) the test was shutdown. Performance of the bundle is shown in Fig. 5. At that time, one of the bundles was removed from the generator and replaced with a bundle containing nine sibling cells plus nine cells of an evolutionary design. The evolutionary design utilizes the air electrode as the support tube, eliminating the zirconia support tube. This results in a cell of significantly higher power output and voltage level. As of July 1991, this test had accumulated 1500 h of operation. The original bundle of 18 cells had over 8000 h of operation at that time and is our longest tested bundle.

Our largest generator test has been our so-called multi-kilowatt generator. This generator was the culmination of the most recent US Department of Energy contract. Using the natural gas design concept developed under the GRI contract, with cell and generator technology supported by the US DOE, this unit operated at up to 20 kW for more than 1700 h on Pittsburgh pipeline natural gas. The performance of the generator is shown in Fig. 6. The unit was then shutdown for modifications to the fuel supply system to allow operation with naphtha fuel, scheduled to begin in late 1991.

An important part of the program is the scale-up of cell size. The 3 kW generator utilized cells of 36 cm in length. The recent bundle tests and 20 kW generator utilize 50 cm cells. Cells of 77 cm have been built in the laboratory, while 100 cm cells are scheduled for production late this year at the pre-pilot manufacturing plant. We believe at 100 cm, cell lengths are sufficient for generators in the several hundred kW size range. Longer cells will be developed for MW class generators.

Westinghouse is currently building two packaged, 25 kW test units for customer evaluation.

The first unit, in a joint program with Kansai Electric Company, Osaka Gas Company, Tokyo Gas Company and the US DOE will culminate in the testing of a two module, nominal 25 kW generator delivery d.c. power at the test site on Rokko Island, near Osaka, Japan. Delivery is scheduled for late this year (Fig. 7).

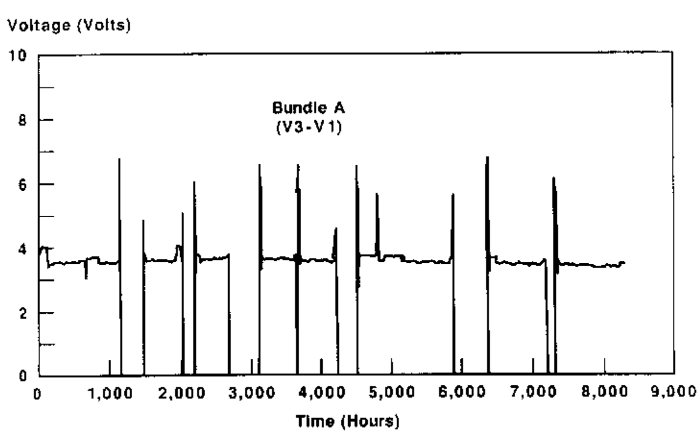

Fig. 5. BT4 — bundle A voltage.

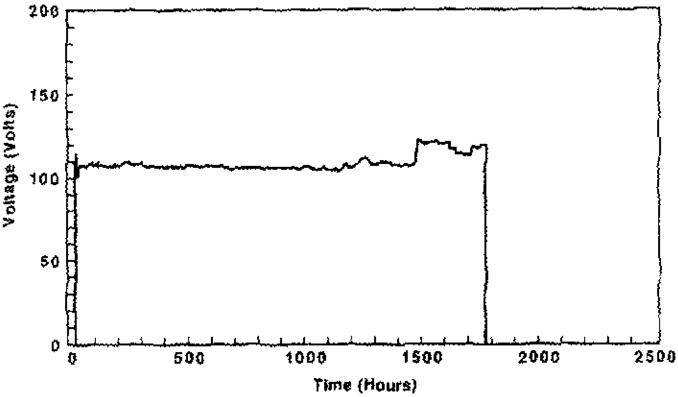

Fig. 6. 20 kW SOFC module: performance summary.

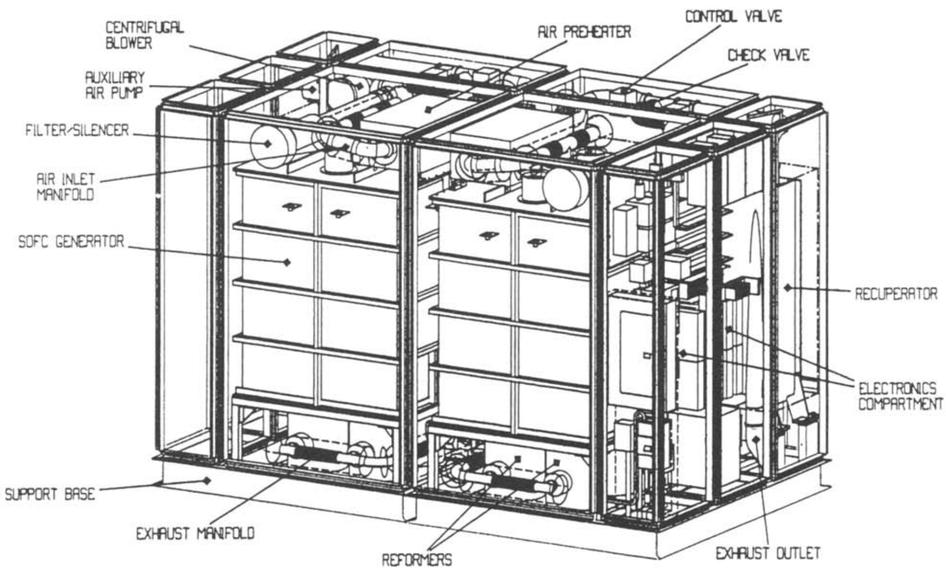

Fig. 7. 25 kW_e SOFC field unit.

The second unit, also nominally rated at 25 kW and supported by Osaka Gas Company and Tokyo Gas Company, will supply a.c. power and steam to another site in Japan. Delivery of this unit is scheduled for early 1992.

Earlier this year a new contract called a Cooperative Agreement was entered into between Westinghouse and US DOE. Over a five year period the US DOE will support Westinghouse with \$64 000 000 towards the further development of the tubular solid oxide fuel cell. Support by Westinghouse and others is expected to more than double that figure.

A major milestone of this program is the operation of a 100 kW SOFC co-generation system in 1993. This is a joint project supported by the Southern California Gas Company, the US Department of Energy and Westinghouse. The system will generate a.c. power and intermediate pressure steam. This system will operate on pipeline natural gas.

A final objective of the program is a 2 MW SOFC plant in 1995.