

**Tubular Solid Oxide Fuel Cell Development Program**

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# Tubular Solid Oxide Fuel Cell Development Program

## CONTRACT INFORMATION

<b>Cooperative Agreement</b>	DE-FC21-91MC28055
<b>Contractor</b>	Westinghouse Electric Corporation 1310 Beulah Road Pittsburgh, Pennsylvania 15235-5098 (412) 256-2125
<b>Contractor Program Manager Program Engineer</b>	Mr. Emerson R. Ray Mr. Christopher Cracraft
<b>METC Project Manager</b>	Mr. Bruce C. Harrington
<b>Period of Performance</b>	April 1, 1991 to November 30, 1996
<b>Schedule and Milestones</b>	

## FY1995 Program Schedule

	O	N	D	J	F	M	A	M	J	J	A	S
Market/User Assessment Studies												
Reference Design												
Base Cell Technology												
100 Cm Porous Support Tube (PST) Cell Dev.												
100 Cm Air Electrode Supported (AES) Cell Dev.												
Alternate Process Development												
100 to 200 Centimeter Cell Development												
Process Scale-up/Optimization/ Cost Reduction												
Facility Construction/Field Test Gen. Support												
Long Cell Test Station Design and Construction												
Cell and Bundle Testing												
Generator Development												
Joint Field Unit Module Fabrication												
Joint Field Unit Gen./System Fab./Test												

## OBJECTIVES

This paper presents an overview of the Westinghouse Solid Oxide Fuel Cell (SOFC) development activities and current program status. The Westinghouse goal is to develop a cost effective cell that can operate for 50,000 to 100,000 hours. Progress toward this goal will be

discussed and test results presented for multiple single cell tests which have now successfully exceeded 56,000 hours of continuous power operation at temperature. Results of development efforts to reduce cost and increase power output of tubular SOFCs are described.

## BACKGROUND INFORMATION

High temperature solid oxide fuel cells (SOFCs) utilizing zirconia-based electrolyte offer a clean, pollution-free technology to electrochemically generate electricity at high efficiencies. SOFCs provide many advantages over traditional energy conversion systems; these include high efficiency, reliability, modularity, fuel adaptability, and very low levels of NO<sub>x</sub> and SO<sub>x</sub> emissions. Furthermore, because of their high temperature of operation (~1000°C), these cells can be operated directly on natural gas eliminating the need for an expensive, external reformer system. SOFCs also produce high quality exhaust heat (600 to 900°C) which can be used in a gas turbine and/or combined cycle application.

A solid oxide fuel cell essentially consists of two porous electrodes separated by a dense, oxygen ion conducting electrolyte. Oxygen supplied at the cathode (air electrode) reacts with incoming electrons from the external circuit to form oxygen ions, which migrate to the anode (fuel electrode) through the oxygen ion conducting electrolyte. At the anode, oxygen ions combine with H<sub>2</sub> (and/or CO) in the fuel to form H<sub>2</sub>O (and/or CO<sub>2</sub>) and generate electricity.

While most fuel cell developers have gravitated to a planar configuration, Westinghouse developed a tubular design with a closed end. Any practical fuel cell generator requires the interconnection of many cells. This interconnection coupled with the necessity to keep fuel separated from oxidant creates design problems associated with seals. The Westinghouse tubular configuration facilitates a generator design which is "seal-less" that is, the generator requires no high integrity seals, necessary in other designs. The Westinghouse tubular design is therefore conducive to free thermal expansion and limited temperature gradients thereby low mechanical stress.

The Westinghouse state-of-the-art tubular SOFC features a doped porous lanthanum manganite air electrode. In order to provide a current path from the air electrode to the exterior of the cell, a gas tight, axial interconnection zone about 9 mm wide is fabricated on the air electrode. The interconnection is a doped lanthanum chromite. The electrolyte, yttria

stabilized cubic zirconia, is deposited over the exposed air electrode, overlapping slightly the interconnection to form a lap joint. The electrolyte is fully dense and gas tight, and about 40 microns thick. The fuel electrode is a porous nickel-zirconia cerment fabricated over the electrolyte surface, except in the vicinity of the interconnection.

For cell operation (Figure 1), oxidant (air or oxygen) is introduced through a ceramic injector tube positioned inside the cell. The oxidant, discharged 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 from the closed end and is electrochemically oxidized while flowing to the open end of the cell generating electricity.

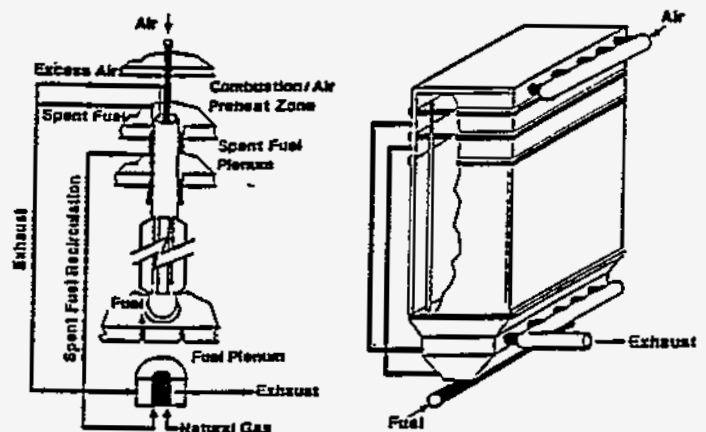


Figure 1. SOFC Generator

At the open end of the cell, the oxygen-depleted air exits the cell and is combusted with the partially depleted fuel. Typically, 85% of the fuel is electrochemically utilized (reacted) in the active fuel cell section. Part of the depleted fuel is recirculated in the fuel stream and the rest combusted to preheat incoming air and/or fuel to the fuel cell.

During the cell operation the gas-impervious electrolyte does not allow nitrogen to pass from the air side to the fuel side, hence the fuel is oxidized in a nitrogen free environment, averting the formation of NO<sub>x</sub>.

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

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

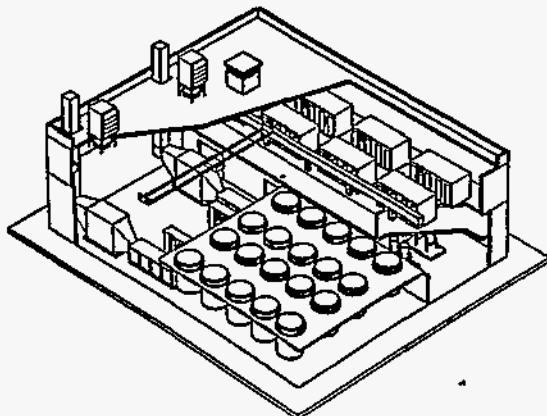
The development of a viable fuel cell electrical power generation system involves not only the development of cell technology, but also the development and demonstration of the generator module. Table 1 shows that the performance of the basic module design has been demonstrated under field test conditions by the operation of 11 generating systems.

**Table 1**  
**Westinghouse SOFC Generating Systems**

System	Generator Rating	Number of Generators	Total Cells	Cell Length	Date
TVA	0.4 kW	1	24	30	1986
Osaka Gas	3 kW	1	144	36	1987
Osaka Gas	3 kW	1	144	36	1987
Tokyo Gas	3 kW	1	144	36	1987
JGU-1	20 kW	2	576	50	1992
UTILITIES A	20 kW	1	576	50	1992
UTILITIES B1	20 kW	1	576	50	1992
UTILITIES B2	20 kW	1	576	50	1993
SCE-1	20 kW	1	576	50	1994
JGU-2	25 kW	1	576	50	1995
SCE-2/ARPA	27 kW	1	576	50	1995
EDB/ELSAM*	100 kW	1	1152	150	1996

\*in production.

Scaleup to the MW-class commercial modules is the next step, and is now underway. These modules would be arranged in a power block concept. Any number of power blocks could then be installed to satisfy the specific requirement for large plants (Figure 2). Conceptual design studies have confirmed the practicality and economic feasibility of the power block concept in applications ranging up to several hundred megawatts.



**Figure 2. SOFC MWe-Class Power Plant**

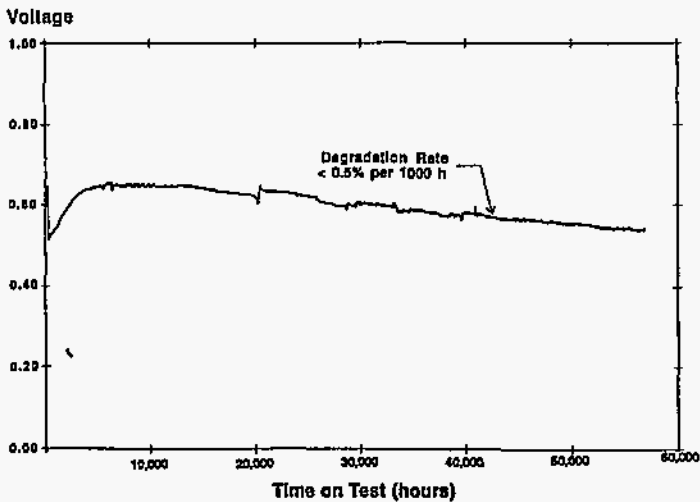
## PROJECT DESCRIPTION

The development of the Westinghouse tubular SOFC technology is being advanced under a six-year cooperative agreement between DOE-Morgantown Energy Technology Center, Mr. Bruce C. Harrington, Program Manager, and Westinghouse. This program, extending from 1991 through 1996, is focused on continuing to develop, improve, and scale up the tubular SOFC technology.

The primary objective of the program is the design, fabrication, and testing of multi-hundred kilowatt and multi-megawatt SOFC generators, both at Westinghouse and at customer sites. As shown in Table 1 Westinghouse has practiced the deployment with customers of fully integrated, automatically controlled, packaged solid oxide fuel cell power generation systems. Testing at customer sites has and will continue to provide operational feedback, field experience, and greater awareness of SOFC technology.

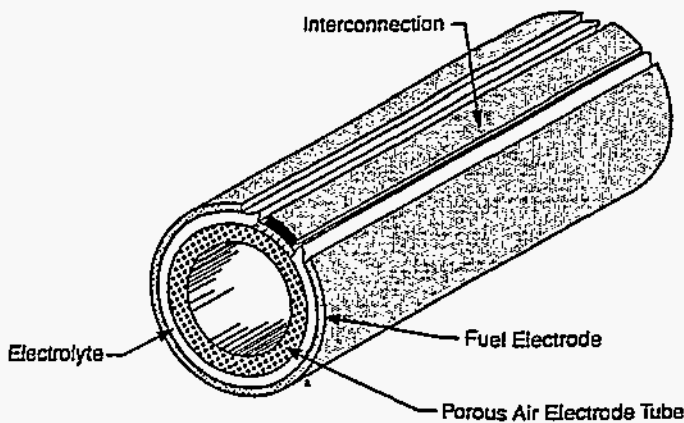
Successful commercialization of tubular SOFC technology will depend on the ability to produce cost competitive systems that can operate for five to ten years before replacement of the SOFC module(s). Westinghouse is focusing its efforts on developing a thorough understanding of the parameters that limit cell and generator lifetime in order that new processes and/or materials, as may be needed, can be developed. Furthermore, a detailed understanding of the cost of manufacturing cells and generators is being pursued so that more cost effective processes and procedures can be implemented, and mass production facilities designed.

Two Westinghouse tubular solid oxide fuel cells have been continuously generating power for over 56,000 hours (6.5 years) with degradation rates less than 0.5% per 1000 hours (Figure 3). These cells are the longest operating SOFCs in the world and show that Westinghouse is advancing the tubular SOFC technology toward commercialization. To date, Westinghouse has produced and operated for extended periods several thousand cells and has systematically improved cell performance, life, and voltage stability. Other long running cells have been shut down intentionally for detailed analysis in order that improvements can be made in future cells. Still other advanced cells have been under test for up to three years with similar degradation rates.



**Figure 3. Longest Operating SOFC Test**

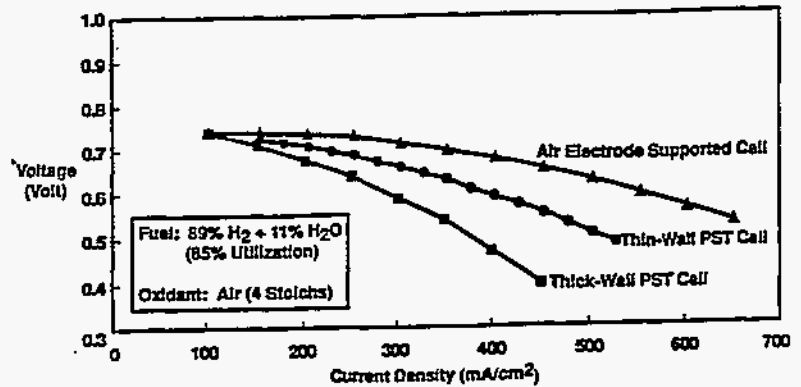
Increased power output per unit cell length is desirable to improve SOFC power plant economics. The earlier technology tubular SOFC was fabricated on a calcia-stabilized zirconia porous support tube (PST). Although sufficiently porous, this tube presented an inherent impedance to air flow toward the air electrode. In order to reduce such impedance to air flow, the wall thickness of the PST was first decreased from the original 2 mm (the thick-wall PST) to 1.2 mm (the thin-wall PST). The calcia-stabilized zirconia support tube has now been completely eliminated and replaced by a 1.9 mm wall thickness doped-lanthanum manganite tube in the state-of-the-art technology tubular SOFCs. These latest technology tubular cells are designated as air electrode supported (AES) cells; schematic design of such a cell is shown in Figure 4.



**Figure 4. AES Type Tubular SOFC**

The voltage-current characteristics of the AES cells (1.6 cm diameter, 50 cm active length)

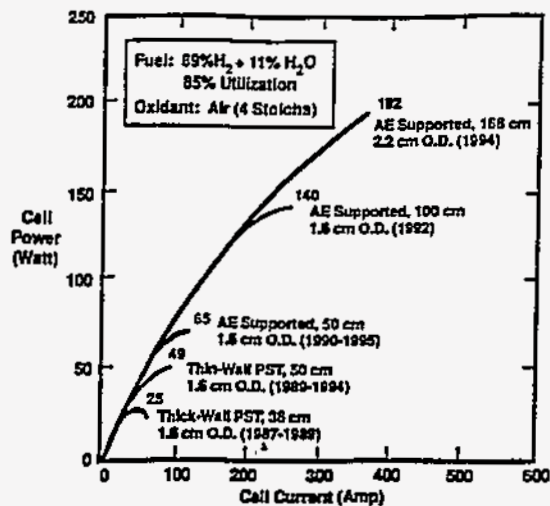
at 1000°C are compared with those of the thick-wall PST and the thin wall PST cells, with 89% H<sub>2</sub> + 11% H<sub>2</sub>O Fuel (89% fuel utilization) and air as oxidant (4 stoichs), in Figure 5. The curves in Figure 5 clearly illustrate the significantly improved performance of the AES cells over the PST-type cells. Elimination of one component (ceramic support tube) combined with the higher performance yields a lower cost SOFC (\$/W) than the earlier technology PST-type cells.



**Figure 5. V-I Comparison of thick-wall PST, thin-wall PST, and AES cells.**

In addition to eliminating the calcia-stabilized zirconia support tube, the active length of the cells has also been continually increased to increase the power output per cell. A greater cell power output decreases the number of cells required in a given power size generator and thus improves SOFC power plant economics. The active length has been increased from 30 cm for pre-1986 thick-wall PST cells to 150 cm for today's commercial prototype AES cells. Additionally, the diameter of the tube in longer length AES cells has been increased from 1.6 cm to 2.2 cm to accommodate larger pressure drops encountered in longer length cells. Figure 6 shows the power output from different cells illustrating the many-fold increase in power output from the latest technology AES cells.

As described above, Westinghouse development programs are successfully producing longer cells and increasing the power output per unit cell length so as to contribute to improve power plant economics. Also, Westinghouse has development programs in place to reduce the cost of the cells and generators by utilizing alternate fabrication techniques. These development programs will enhance the economic viability of tubular SOFCs for commercialization.



**Figure 6. Power Output of Different Type and Length Cells.**

The Pre-Pilot Manufacturing Facility (PPMF), located near Pittsburgh, PA, has been dedicated to the tubular SOFC technology. This unique facility has provided the means to move the technology from the laboratory environment to a manufacturing environment, while enabling the processes and quality control programs to be put in place that will be required to commercialize the technology during the 1990's.

This year a new facility will be completed, also located near Pittsburgh, PA, called the Pilot Manufacturing Facility (PMF). This facility represents a scaleup in production and SOFC size capability, and incorporates the refined processes and quality control programs developed at the PPMF. At the PMF, only the latest tubular SOFC technology, utilizing AES cells, will be produced.

The first 100 kWe Field Demonstration System, incorporating 150 cm AES cells will be fabricated and factory tested at the PMF, and then delivered to the Netherlands to a group of utilities consisting of the Dutch EDB consortium and the Danish ELSAM consortium. The system will be installed at NUON, one of the group of five Dutch gas and electricity distribution utilities which belong to the EDB consortium. The successful operation of this unit will represent a major milestone in the commercialization of advanced technology tubular SOFCs for large-scale power generation.

Most recently demonstrated was a 27 kWe field unit, which utilizes 50 cm AES cells and operates on natural gas and logistic fuels. Funding for this unit is provided by ARPA. The unit is being tested by Southern California

Edison. Additional details of the operation and performance characteristics is the subject of a companion paper, to be presented by Dr. Stephen Veyo.

## SUMMARY

A number of significant developments and accomplishments have been realized during the past year of the tubular SOFC program:

- Single and multi-cell SOFCs have operated continuously for more than 56,000 hours in cell tests at power.
- Improved cell voltage stability (as low as 0.5% per 1000 hours degradation rate) has been achieved in single cell tests.
- A 20 kW SOFC was operated by Southern California Edison (SCE) for 6015 hours.
- The JGU 25 kWe SOFC customer unit began operation in 1995.
- The ARPA 27 kWe SOFC began operation at SCE in 1995.
- A pressurized test article operated for 5000 hours at Ontario Hydro Technologies (OHT).

High temperature SOFCs offer many advantages over traditional energy systems. These include high conversion efficiency, reliability, modularity, fuel adaptability, and virtually unlimited siteability due to very low NOx emissions. Furthermore, these cells produce high quality exhaust heat which can be used in a gas turbine and/or combined cycle to further increase the overall plant efficiency. Westinghouse has developed the materials and fabrication processes for these cells, increased the power output per cell, and has successfully employed and tested these cells for power generation in successively larger generators.

When fully commercialized, the SOFC systems are expected to serve a wide range of power and heat applications, such as multi-megawatt size distributed electric power plants located near load centers, repowering of existing

units, and large central station all-electric power plants.

## **FUTURE WORK**

The existing Cooperative Agreement between Westinghouse and the Department of Energy was initiated in April, 1991 and will continue through November 1996. This six year program includes considerable financial contributions from Westinghouse, from domestic and foreign utilities, and from other agencies, in addition to the U.S. Department of Energy. Under this program Westinghouse will continue development of the tubular solid oxide fuel cell technology and generator systems and plans for field testing of multi-hundred kilowatt and multi-megawatt rated generators during the mid to latter-1990's. The ultimate objective of this program is to develop tubular SOFC technology to the point of acceptable risk for private sector commercialization.

Development of the tubular solid oxide fuel cell technology is being supported by the Westinghouse Electric Corporation, the United States Department of Energy (DOE-METC), and various utility and industry sources. The Cooperative Agreement between Westinghouse and DOE is administered by the Morgantown Energy Technology Center (METC), Mr. Bruce C. Harrington, Project Manager.