Introduction: Fuel cells are electrochemical devices that oxidize fuel without combustion to convert directly the fuel’s chemical energy into electricity. The solid oxide fuel cell (SOFC) is distinguished from other fuel cell types by its all solid state structure and its high operating temperature (1000°C). The Westinghouse tubular SOFC stack is process air cooled and has integrated thermally and hydraulically within its structure a natural gas reformer that requires no fuel combustion and no externally supplied water. In addition, since the SOFC stack delivers high temperature exhaust gas and can be operated at elevated pressure, it can supplant the combustor in a gas turbine-generator set yielding a dry (no steam) combined cycle power system of unprecedented electrical generation efficiency (> 70% ac/LHV). Most remarkably, analysis indicates that efficiencies of 60% can be achieved at power plant capacities as low as 250 kWe, and that the 70% efficiency level should be achievable at the two MW capacity level.

Tubular SOFC Description: The Westinghouse SOFC is an air electrode (cathode) supported tubular design configured as a single cell per tube with an axial interconnection. A cross section is shown in Figure 1. As now manufactured with commercially prototypic dimensions at a pilot manufacturing facility in Pittsburgh, the tube is nominally 22 mm (0.867 inches) in diameter by 1500 mm (59 inches) in active length. The cell active area is 834 sq cm, equivalent to a flat plate 11.4 inches square. To generate electricity, the cell must be maintained at operating temperature, about 1000°C; air must be supplied to the tube interior and fuel to the tube exterior. At open circuit, a potential of about one volt will be generated between anode and (cathode) interconnection. When an external circuit is connected between anode and (cathode) interconnection, a current will flow in the external circuit that is in direct proportion to the flow on oxygen ions through the electrolyte. When an oxygen ion reaches the anode/electrolyte interface, it yields two electrons to the external circuit and oxidizes two atoms of hydrogen or carbon monoxide which have diffused into the anode. The electrons pass through the external circuit to the cathode where they create the oxygen ions from the oxygen which has diffused into the cathode from the air. Note that the fuel is oxidized electrochemically in complete isolation from atmospheric nitrogen with no potential for NOx production.

Tubular SOFC Stack Description: At atmospheric pressure, a uniform temperature of 1000°C, 85% fuel utilization, and 25% air utilization, a single tubular SOFC will generate a maximum power of about 220 Watts dc. Operation at an elevated pressure of ten atmospheres will increase maximum output by ten percent. In order to generate commercially meaningful quantities of electricity, many cells must be aggregated into a generator module or stack. In the Westinghouse stack design, the tubular cells are oriented with the axis vertical and closed end down. The cells are arranged into 3 by 8 cell bundles, and the bundles into bundle rows. Between each bundle row is placed an in-stack reformer. This construction is shown in Figure 2. The reformer is radiantly heated by the adjacent rows of cells. The outer container shown applies to an atmospheric pressure unit. When configured for pressurized operation, this container is replaced by a cylindrical pressure vessel. The orientation of this vessel can be vertical for single stack of 1152 cells or a twin stack (see Figure 3) containing 2304 cells. If multiple
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single or twin stacks are to be contained in a single pressure vessel, then the vessel would most likely be horizontally oriented. Because of this modularity, SOFC generators using the basic 1152 cell stack layout can be configured easily to fit applications through tens of MW.

**Tubular SOFC Power Generation Systems:** A process schematic for an atmospheric pressure tubular SOFC power generation system is shown in Figure 4. Ambient air is drawn through an air filter and compressed to the appropriate process pressure by a compressor or blower. The process air is then routed through an exhaust gas heated recuperator to increase the air temperature to approximately 600°C before introduction to the SOFC generator module. Pipeline natural gas at a pressure between one and three atmospheres above process pressure is desulfurized before being introduced to the SOFC generator module. Within the SOFC generator module, the fuel is electrochemically oxidized producing dc electricity. Nominally 85% of the fuel is electrochemically oxidized with the balance burned in the stack's combustion zone. The SOFC exhaust exits the generator module at a temperature of between 700 and 850°C and in atmospheric pressure systems is passed through the exhaust gas heat recovery train. In elevated pressure systems, turbine work is extracted from the gas stream by an expander before the exhaust passes through the recuperator. In Figure 6 is shown a process schematic for a pressurized SOFC (PSOFC)/gas turbine (GT) combined cycle. In this case, the expander drives directly the compressor.

For atmospheric pressure SOFC systems configured as in Figure 4, the horizon for electrical generation efficiency is at the low 50 percent (ac/LHV) level. Exhaust gas heat recovery in the form of steam and hot water will yield fuel effectiveness values approaching 80%. Westinghouse is presently completing the fabrication of a 100 kWe SOFC power system for EDB/ELSAM, a consortium of Dutch and Danish utilities. This system will achieve its maximum electrical generating efficiency of 47% (net ac/LHV) at 100 kWe output. In addition, it can generate ac at over 40% efficiency across the power range from 70 kWe to 160 kWe. The EDB/ELSAM 100 kWe SOFC unit is fabricated in five modular assemblies or skids. Shown in Figure 5 is a computer generated isometric of three of these skids, the thermal management system, the SOFC skid, and the fuel supply system skid. Not shown are the power conditioning system skid and the heat export system skid. The assembly shown in Figure 5 is 8.59 meters (28.2 ft) long by 2.75 meters (9 ft) wide, by 3.58 meters (11.7 ft) high. The Dutch utility NUON will operate the 100 kWe SOFC unit in Westervoort (near Arnhem) in the Netherlands, exporting electricity to the local grid and hot water to the district heating system. Site operation is scheduled to begin at year's end 1997.

For PSOFC/simple GT systems as shown schematically in Figure 6, the horizon for electrical generation efficiency is about 65%. Note that because the SOFC requires a process air inlet temperature of between 600 and 700°C, a recuperator is required. Analysis has shown that for recuperated gas turbines with a turbine inlet temperature limited to the SOFC exhaust temperature (850°C), there is no benefit to exceeding a maximum process pressure of 6 to 10 atmospheres. Further, analysis readily shows that there is no efficiency advantage to burning fuel in a gas turbine combustor in order to increase the turbine inlet temperature. Westinghouse has configured for analysis purposes PSOFC/GT concepts ranging in capacity from 250 kWe to several hundred MW. In general, the best configuration will have a ratio of SOFC output to GT output of between 3 and 5.

A 250 kW PSOFC/GT system using the 1152 cell stack of Figure 2 operating at 3.5 atmospheres pressure and coupled with a 50 kW micro-turbine generator is expected to achieve an electrical generation efficiency of 60% (net ac/LHV). A 250 kW PSOFC/GT system package is expected to be about the same size as the atmospheric pressure 100 kW SOFC system shown in Figure 5. Westinghouse signed a contract this past July with the Southern California Edison (SCE) Company for the supply for proof of
concept testing of a 250 kWe PSOFC/GT system. Operation of the system is expected to begin in the first quarter of 1999.

A one MW PSOFC/GT system can be configured using two twin stacks (see Figure 3) (2 x 2 x 200 kWe) operating at 3.5 atmospheres pressure plus a simple single shaft 200 kW gas turbine to yield a system with 63% efficiency. In the conceptual design shown in Figure 7, the two twin stacks are housed in a horizontal pressure vessel. The plan dimensions for the one MW PSOFC/GT power system are 25 ft by 50 ft.

A still higher PSOFC/GT system efficiency can be achieved when a two shaft gas turbine utilizing two stages of air compression with inter-cooling, recuperation, and SOFC reheat for the power turbine is used. Analysis of such systems indicates that an electrical generation efficiency of over 70% can be achieved. For a two MW system, a second pressure vessel would be added to the concept shown in Figure 7 to house two additional twin stacks operating at about nine atmospheres pressure and an inter-cooled twin shaft turbine would replace the simple turbine. The original set of twin stacks would operate at three atmospheres pressure using the vitiated exhaust from the high pressure SOFC as oxidant. The exhaust from the higher pressure (9 atm) SOFC is expanded to intermediate pressure (3 atm) through a turbine driving the compressor. The exhaust from the intermediate pressure SOFC is expanded through a power turbine. The increase in plot plan size is about 30%.

The efficiency advantage of PSOFC/GT power systems across the capacity range of interest for distributed generation and beyond is shown graphically in Figure 8. The development, design, fabrication, and test of both a one MWe 63% efficient system and a multi MWe 70% efficient system are part of the recently signed five year cooperative agreement with the US-DOE. Dependent upon federal and non-federal funding levels, initial operation of the one MWe PSOFC/GT system is scheduled for the third quarter of the year 2000, with the 70% efficient unit an upgrade scheduled for late 2001.

Suitability for Distributed Generation: SOFC systems will be affordable. At the several MW system capacity level, commercial PSOFC/GT combined cycle systems are expected to be available to customers for about $1300/kWe. These competitive commercial price levels are expected to be achievable after the first commercial factory has produced its full annual capacity of 100 MW of SOFC per year. Given that our DOE sponsored development program remains on schedule, Westinghouse and equity partners will construct the first commercial factory in the United States beginning in the year 1999, with production expected to begin in the year 2001.

SOFC systems should be highly reliable. SOFCs have operated in the laboratory for over 69,000 hours generating power. A “short stack” of four SOFCs endured 100 thermal cycles to ambient temperature and generated power for over 10,000 hours without deleterious effect. In February 1997, an atmospheric pressure 25 kW SOFC system containing 576 cells completed 13,000 hours of power generation with an availability of over 90%, with a 6500 hour period of continuous operation without outage of any kind. The elegant simplicity of the SOFC power generation system will yield high reliability.

SOFC systems operate unattended and can be remotely dispatched. Westinghouse has had eleven systems operated unattended by customers over the past ten years. Note that SOFC systems use no process water, and have no boiler or steam generator for either bottoming cycle purposes or for reforming.

SOFC systems use process air for cooling. No cooling tower or radiator bank or cooling system anti-freeze protection is needed.
SOFC systems are quiet. In atmospheric pressure systems with 3 bar gas pressure available, the process uses only one major moving part—the blower. There are, of course, small fans used to cool electronic cabinets and various valves. In PSOFC/GT systems, the turbine generator set is at most one third the capacity of the system, thus generating far less noise than a simple GT power system of similar capacity.

SOFC systems are environmentally advantageous. Since the emission of CO₂ is inversely proportional to power generation efficiency, PSOFC/GT systems will emit half the CO₂ per unit of capacity than the aggregate average for presently active power generation. In addition, SOFC systems have little potential for NOₓ emissions, with measured values to date less than 2 ppmv. Further, since the fuel must be desulfurized before admission to the fuel cell, there are no SOₓ emissions.

SOFC systems can cogenerate. Since the SOFC exhaust is available at high temperature, recovered heat can take the form of process steam or hot water.

SOFC power systems are modular. Thus, they are quick to install and flexible in rating.

SOFC power systems are capable of rapid repair. At the system level, components and subsystems are accessible for service access and replacement. In addition, the design modularity of constituent skids makes rapid replacement of entire skids feasible. Further, the SOFC generator module can be repaired if any cell or group of cells is damaged or fails. The nature of the stack design isolates rows of cells from one another. The cells contain no acid or other corrosive material permitting easy handling of used cells and stack components. Repair or rebuilding of a stack is therefore feasible. In fact, Westinghouse recently has demonstrated the ability to remove cells from an in situ cell bundle in a small stack, implant replacement cells, and restart successfully the stack.

**Conclusion:** Westinghouse PSOFC/GT and SOFC power systems are the ideal distributed generation systems—affordable, clean, quiet, environmentally friendly and fuel conserving—"a green machine".

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Figure 1 — Westinghouse Solid Oxide Fuel Cell

Figure 2 — 100 kWe Stack Cross-Section
Figure 3 — Isometric of Twin Stack (2304 Cells)

Figure 4 — Process Schematic for Atmospheric Pressure SOFC Cogeneration System
Figure 5 — 100 kWe SOFC Power System

![100 kWe SOFC Power System](image)

Figure 6 — Process Schematic for PSOFC/GT Combined Cycle (simple single shaft) GT

![Process Schematic for PSOFC/GT Combined Cycle](image)
Figure 7 — SureCell™ 1 MWe PSOFC/GT Power Plant

Figure 8 — SURECELL™ PSOFC/GT Systems are Unmatched in Electrical Efficiency