Westinghouse SOFC Field Unit Status

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Introduction

Fuel cells are without question the most non-polluting of all fuel consuming power generation technologies. Intrinsically, the potential for NOx generation is virtually non-existent because fuel oxidation occurs electrochemically rather than by combustion, and in the case of the solid oxide fuel cell (SOFC), isolated from contact with atmospheric nitrogen. In general, sulfur must be removed from the fuel prior to its oxidation in a fuel cell, thus there is no potential for the emission of SO_2, the precursor for acid rain. In addition, across the range of power generation capacity levels, a fuel cell power system can generate electricity more efficiently than any other fossil fuel consuming electric power generator. Since power generation at the highest practical efficiency serves to minimize the emission of carbon dioxide while conserving fuel, fuel cells represent the best way to ameliorate concern over the “green house effect” and dwindling or politically insecure sources of fuel. Among fuel cell types, only the SOFC has the recognized potential to achieve power generation efficiencies in excess of 70% using a hybrid cycle that is both simple and dry, the SOFC/Gas Turbine. Further SOFC development is needed, however, in order to achieve commercially competitive cell and stack cost and to demonstrate SOFC power systems at commercially viable capacity levels. In the following will be summarized the status of the Westinghouse SOFC field unit program and its contribution to an improved prospect for SOFC commercialization.

Objective

The objectives of the Westinghouse experimental SOFC field unit program are: the development of a viable SOFC electrical power generation system that meets customer needs; the first-hand demonstration to customers of the beneficial attributes of the SOFC; the exposure of deficiencies through experience in order to guide continued development; and the garnering of real world feedback and data concerning not only cell and stack parameters, but also transportation, installation, permitting and licensing, start-up and shut-down, system alarming, fault detection, fault response, and operator interaction.

Approach

Westinghouse has practiced the deployment with customers of fully integrated, automatically controlled, packaged solid oxide fuel cell power generation systems for over ten years. These experimental field units are an integral part of the Cooperative Agreement between Westinghouse and the United States Department of Energy (DOE) for the development of tubular

SOFC technology. The design and construction of the host systems for SOFC field units has been funded with customer and Westinghouse moneys. DOE has participated in these programs by providing the cells and in part, the stacks or generator modules. Field units have been operated at customer expense and in most cases solely by the customer, with data shared with Westinghouse and DOE. Cells and generator modules are returned to Westinghouse at the completion of the customer test program.

Project Description

A simplified process flow diagram for an atmospheric pressure SOFC cogeneration system is shown in Figure 1. A motor driven blower draws ambient air through a filter and compresses it to a pressure of the order of 1000 mm water column. The process air then flows through an exhaust gas heated recuperator where its temperature is increased to approximately 500°C. From the recuperator, the air flows through an air heater and then into the SOFC generator module. The air heater in field units to date is electrically powered and is used only during start-up and during periods of low power operation when needed to maintain the SOFC at set point temperature, nominally 1000°C. Natural gas at a pressure of nominally three atmospheres gauge is desulfurized and routed to the SOFC generator module through a flow control device. Within the SOFC generator module, the natural gas is reformed to hydrogen and carbon monoxide and subsequently electrochemically oxidized generating dc power. Typically, the SOFC operates at 85% electrochemical fuel utilization. In the SOFC, the electrochemical oxidation of the fuel occurs with complete isolation from nitrogen, therefore with no potential for NOx formation. Depleted fuel is burned completely in a combustion zone within the generator module where it preheats incoming air. Exhaust gas exits from the SOFC generator module with in-stack radiantly heated reformers at a temperature of approximately 850°C. In earlier 25 kW class field units with a convectively heated reformer, the exhaust gas exited at a temperature of approximately 700°C. The exhaust gas is routed through a recuperator, which may consist of a high temperature section, a heat recovery steam generator, and a low temperature section, followed by an exhaust gas heated water heater.

The Joint Gas Utilities (JGU), a consortium of the Tokyo Gas Company and the Osaka Gas Company, sponsored in 1992 a 25 kW SOFC cogeneration system that utilized two SOFC generator modules in a single packaged enclosure. Each generator module used 576 cells, 16 mm diameter by 500 mm active length, of the now obsolete porous zirconia support tube (PST) design. A description of this unit and its performance can be found in the literature. As this unit did not perform satisfactorily, it was modified and repaired. The JGU cogeneration system was modified to accept a single generator module utilizing 576 air electrode supported (AES) cells of 16 mm diameter by 500 mm active length in place of the previously used pair of PST type modules. This unit was originally scheduled to be shipped to Osaka, Japan for application testing, but the great Hanshin earthquake which struck the Kobe area in January 1995 disrupted the operations of Osaka Gas to such an extent that this proved infeasible. An unequivocally successful extended factory test was initiated on March 22, 1995 and concluded on February 10, 1997.

The world's first 100 kWe class Solid Oxide Fuel Cell (SOFC) power generation system is being supplied by Westinghouse and is sponsored by EDB/ELSAM, a consortium of Dutch and Danish utilities. This natural gas fueled unit will be installed near Arnhem, The Netherlands, at an auxiliary district heating plant [Hulp Warmte Centrale] at the Rivierweg in Westervoort, a site provided by NUON, one of the Dutch participants and will supply ac power to the utility grid and hot water to the district heating system serving the Duiven/Westervoort area.

The 100 kW SOFC generator module utilizes tubular Air Electrode Supported (AES) SOFCs of nominally 22 mm diameter by 1500 mm active length. The generator module or stack is of seal-less design and employs 1152 tubular SOFCs oriented vertically and arranged in twelve bundle rows. Each bundle row consists of four bundles, with each bundle a rectangular cell array having three cells in parallel and eight cells in series. The bundle rows are connected in electrical series yielding a serpentine current path. A cross section of the 100 kW SOFC stack is shown in Figure 2. The thermal-hydraulic design for the 100 kW stack differs from previous Westinghouse practice in that the natural gas reformers are integral with the insulation barriers between bundle rows, with heat supplied by thermal radiation directly from the SOFCs. (In the 25 kW SOFC units, the reformers are hydraulically integrated with the cell stack, but heated by exhaust gas.) As in prior Westinghouse practice, spent anode gas is recirculated and mixed with fresh fuel (desulfurized natural gas) using an ejector with pressurized natural gas as the primary fluid. See Figure 3. The outer canister of the 100 kW generator module is cooled with process air to limit dissipation to the ambient and to limit canister temperature.

The 100 kW SOFC power generation system is composed of five discrete skid mounted assemblies or "skids". The generator skid supports the SOFC stack and the electrically powered process air heater used for startup. The Thermal Management Skid (TMS) supports the recuperators, the air movers (blowers), air and exhaust piping and air control valves, and the Electrical Distribution System (EDS), a shallow set of enclosures which houses all electrical distribution and electronic hardware including the control computer. The Fuel Supply System (FSS) skid supports the fuel and purge gas control valves, the desulfurizers, and the small steam generator used during startup along with a small water supply tank. These three skids are arranged in a rectilinear package as shown in Figure 4 measuring 8.42 m long by 2.75 m wide with a maximum height of 3.58 m. The power conditioner and the hot water heater are also skid mounted, but supplied by EDB/ELSAM.

Westinghouse tubular AES-SOFCs are being tested not only at Westinghouse, but also at the Kansai Electric Power Company in Japan and Ontario Hydro in Canada. Kansai Electric purchased from Westinghouse a fully automated atmospheric pressure tubular cell test stand designed and built by Westinghouse and capable of exercising at steady or cyclic conditions either a single cell or a "short stack" consisting of two or four tubular cells with cell active lengths up to 1500 mm. To date, they have tested two test articles with four 500 mm active length cells and are presently testing a single 1500 mm length cell.

The cell test facility at Ontario Hydro consists of two test stands that can each exercise test articles similar to those at Kansai Electric, but at elevated pressure up to fifteen atmospheres.

The cell test facility built by Ontario Hydro was designed in collaboration with Westinghouse. To date, OH has tested seven test articles.

Ontario Hydro is presently completing the construction of a pressurized bundle test facility designed in collaboration with Westinghouse. The 10 kW test article will contain two bundles of twenty four cells each and is expected to begin operation in the second half of 1997.

Negotiations are underway for the renewal of the cooperative agreement between DOE and Westinghouse for tubular SOFC development. In addition to a focus upon cell and stack manufacturing cost reduction, the proposed renewal program will design, develop, build, and test pressurized SOFC Gas Turbine (PSOFC/GT) hybrid cycle power systems at customer sites. A simplified schematic for a PSOFC/GT hybrid cycle power system can be seen in Figure 5. Simplistically, the expansion turbine has replaced the blower drive motor, and the compressor has replaced the blower. No electrical power is therefore consumed to move process air, a major element of parasitic power consumption for atmospheric pressure systems, and additional electric power can be generated from the turbine shaft. The first field unit proposed for the renewal program is a 250 kW system which will utilize a stack of the same design as used for the EDB/ELSAM 100 kW unit, but operating at approximately 3.5 atmospheres pressure in conjunction with a micro turbine generator (MTG) of nominally 50 kW capacity. The expected electrical generating efficiency of the 250 kW PSOFC/MTG power system is 60% (ac/LHV). The second field unit, a one MW system, will utilize four SOFC stacks and a 250 kW turbine generator to yield a system with over 60% electrical generation efficiency. The third proposed field unit will upgrade the second field unit by adding four additional SOFC stacks and upgrading the turbo-machinery in order to achieve 70% efficiency. Startup of the 250 kW PSOFC/GT is planned for early 1999 while startup of the one MW PSOFC/GT system is expected in the year 2000.

Results and Accomplishments

A summary of the characteristics and results for Westinghouse SOFC field units to date is given in Table 1. Factory test of the JGU 25 kW AES-SOFC Cogeneration system was initiated on March 22, 1995 at Westinghouse's Pre-Pilot Manufacturing Facility (PPMF) in Monroeville, PA. The unit was shut down after 1200 hours of operation to repair a fuel leak from a reformer and to replace deactivated reformer catalyst. The unit was subsequently relocated to the Westinghouse Pilot Manufacturing Facility at the Westinghouse Science and Technology Center upon decommissioning of the PPMF. Operation of the JGU 25 kW AES-SOFC Cogeneration System was terminated on February 10, 1997 in order to permit contract mandated inspection of the cells and stack internals prior to the end of the Japanese fiscal year on March 31. The JGU 25 kW AES-SOFC Cogeneration System generated power for 13,194 hours (282 MW-hrs). In a maximum power test, the unit generated 25 kW at 84% fuel utilization at 1855 operating hours and 24.9 kW at 79% fuel utilization just prior to shut down at 13,191 operating hours. A plot of kW, Voltage and Amperes vs time can be found in Figure 6. Nominal conditions during operation were 170 Amperes, (306 mA/cmsq), 79% fuel utilization, 1020°C set point temperature. The degradation in terminal voltage over the test period at these set point conditions was 1.86%. Thermal control of the generator to set point is governed by the centroidal temperature of the hottest quadrant. During operation, the centroidal temperatures of the quadrants drifted apart. After adjusting the observed quadrant voltage to a fixed temperature, the coldest quadrant experienced no voltage degradation. During the course of operation, the unit endured a total of ten thermal cycles between operating temperature (1000°C) and ambient temperature and thirteen instances of sulfur break-through from the desulfurizer. Sulfur poisoning was reversible since complete voltage recovery was observed after replacement of the desulfurizer reagent. The longest period of continuous operation without outage of any kind was 6500 hours. Upon disassembly of the stack, visual inspection using a borescope found no cracked cells. The physical appearance of cells and bundles was virtually indistinguishable from newly-manufactured samples. The primary reason for the observed degradation in voltage was the development of porosity in the interconnection resulting in gas leakage between cathode and anode. Interconnection porosity development after 13,000 hours was an increasing function of increasing temperature. At 1000°C, interconnection porosity development was insignificant.

The EDB/ELSAM 100 kW SOFC field unit is presently undergoing a process and control test of the balance of plant (BOP). The SOFC stack is in the final stages of assembly. The power conditioner has satisfactorily completed factory acceptance testing in Europe. The Heat Export System (hot water heater) is in the vendor solicitation phase. Factory acceptance tests are scheduled to begin in September_97 with site acceptance tests expected in December_97. Analytical estimates of performance show that maximum system efficiency will occur at thermal balance, that operating condition where no ancillary energy is required to maintain the SOFC stack at operating temperature. The maximum efficiency of the 100 kW SOFC power generation system is estimated as 47% (net ac/LHV) at 100 kW ac net output. Overall fuel effectiveness at this point will exceed 70%. System maximum power is estimated to be approximately 160 kW-ac with a fuel effectiveness approaching 80%. These estimates of performance are shown in Figure 7. The EDB/ELSAM 100 kW SOFC is expected to operate for two years.

At Kansai Electric Power Company facilities, a short stack of four 16 mm diameter by 500 mm active length AES-SOFCs endured 100 thermal cycles between operating temperature (1000°C) and ambient temperature and generating power for over 10,100 hours at 1000°C, 450 mA/cmsq and 85% fuel utilization. Presently under test is a 22 mm diameter by 1500 mm active length cell which has achieved 1500 hours of operation without evident degradation.

At Ontario Hydro, a 22 mm diameter by 1500 mm active length AES-SOFC is presently under test and has passed 3700 hours of operation at elevated pressure (nominally 5 atmospheres) with no evident degradation after two thermal cycles to ambient conditions.

The SOFC at modest elevated pressure (4 atmospheres) can easily yield a 50% conversion of natural gas fuel energy into electricity. Noting that all of the fuel energy not converted to electricity by the SOFC is contained in the exhaust gas at 850°C, a modest recuperated GT-generator efficiency of 20% will yield a system efficiency of 60%. More elaborate GT cycles that employ an intercooled, recuperated, reheat GT cycle can then be expected to approach and exceed a 70% efficiency level.

Benefits

Westinghouse tubular AES-SOFCs have demonstrated superior voltage stability (approximately 0.1 per cent per thousand hours) in tests exceeding 13,000 hours of power generation at high fuel utilization. Westinghouse tubular AES-SOFCs have demonstrated superior thermal toughness by enduring without deleterious effect 100 thermal cycles from power generation at 1000°C to ambient conditions. Atmospheric pressure tubular SOFC systems can approach a simple cycle power generation efficiency of 50% (net ac/LHV). Pressurized SOFC/ simple cycle Gas Turbine hybrid cycle power systems can exceed 60% efficiency at approximately the 250 kW capacity level while GT cycles with intercooling and reheat can exceed 70% electrical generation efficiency at the integer MW capacity level.

Acknowledgments

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Table 1 — Westinghouse SOFC Field Units

Time Year	Customer	Stack Rating (kW)	Stack Number	Cell Type	Cell Length (mm)	Cell Number	Oper. (Hrs)	Fuel	MWH
1986	TVA	0.4	1	TK-PST	300	24	1760	H_2+CO	0.5
1987	Osaka Gas	3	1	TK-PST	360	144	3012	H_2+CO	6.1
1987	Osaka Gas	3	1	TK-PST	360	144	3683	H_2+CO	7.4
1987	Tokyo Gas	3	1	TK-PST	360	144	4882	H_2+CO	9.7
1992	JGU-1	20	2	TN-PST	500	576	817	PNG	10.8
1992	UTILITIES-A	20	1	TN-PST	500	576	2601	PNG	36.0
1992	UTILITIES-B1	20	1	TN-PST	500	576	1579	PNG	25.5
1993	UTILITIES-B2	20	1	TN-PST	500	576	7064	PNG	108.0
1994	SCE-1	20	1	TN-PST	500	576	6015	PNG	99.1
1995	SCE-2	27	1	AES	500	576	5582	PNG/DF-2/JP-8	118.2
1995	JGU-2	25	1	AES	500	576	13,194	PNG	282.1
				Future Work					
1997	EDB/ELSAM	100	1	AES	1500	1152	TBD	PNG	

PNG = Pipeline Natural Gas
TK-PST = Thick Wall Porous Support Tube

TN-PST = Thin Wall Porous Support Tube
AES = Air Electrode Supported

24 March 97

Figure 1 — Process flow schematic for an SOFC Cogeneration System

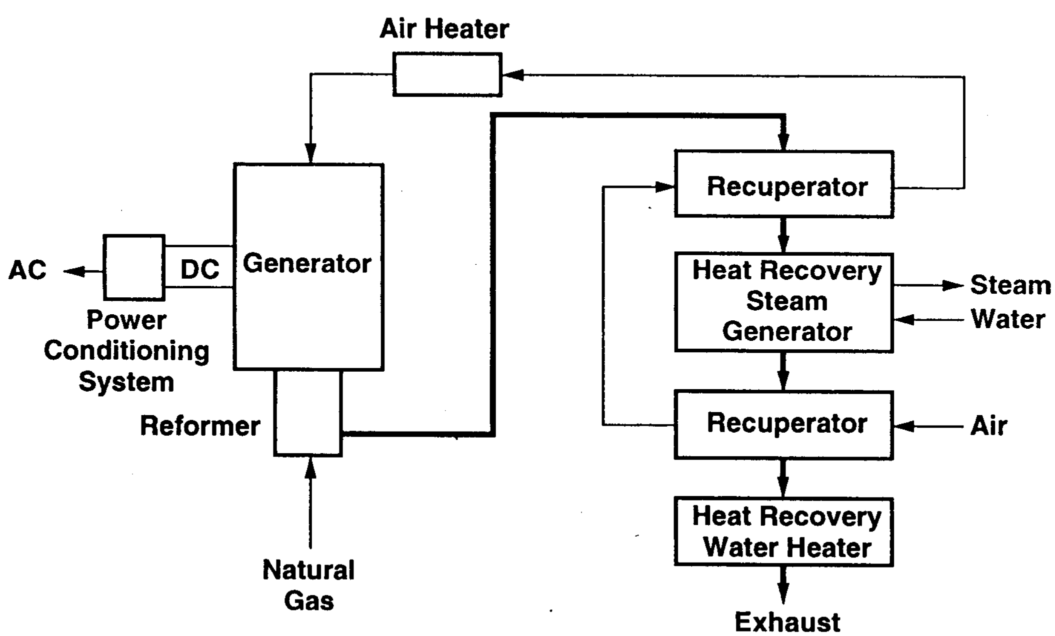

Figure 2 — 100 kW SOFC Stack Cross Section

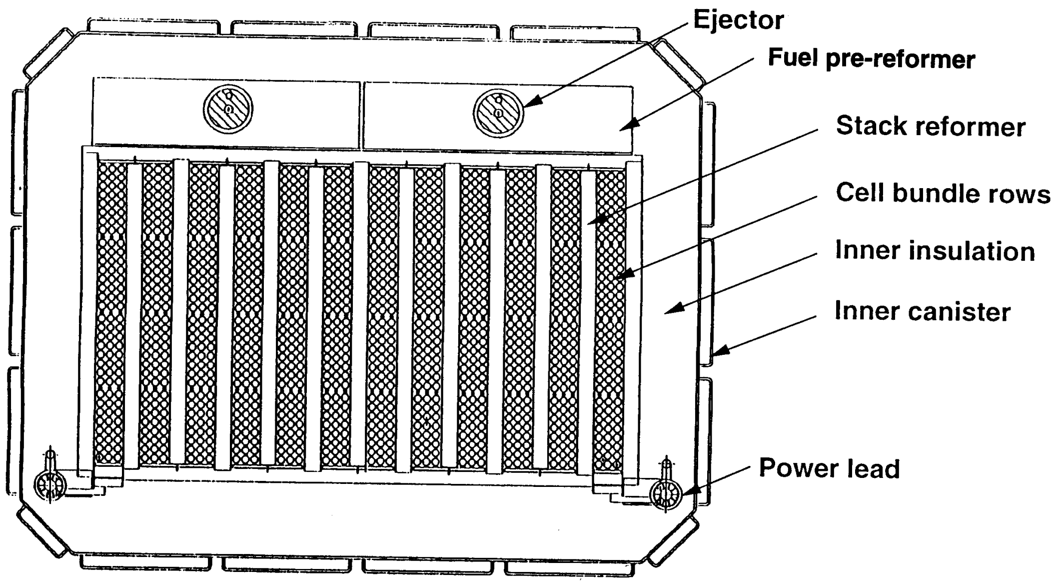

Figure 3 — 100 kW SOFC Stack Gas Flows

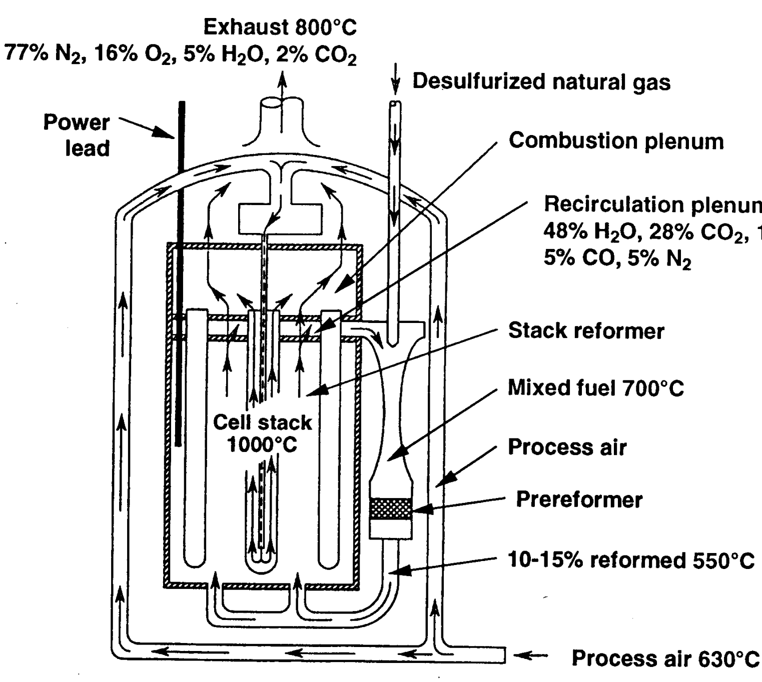

Figure 4 — 100 kW SOFC Field Unit (interior view)

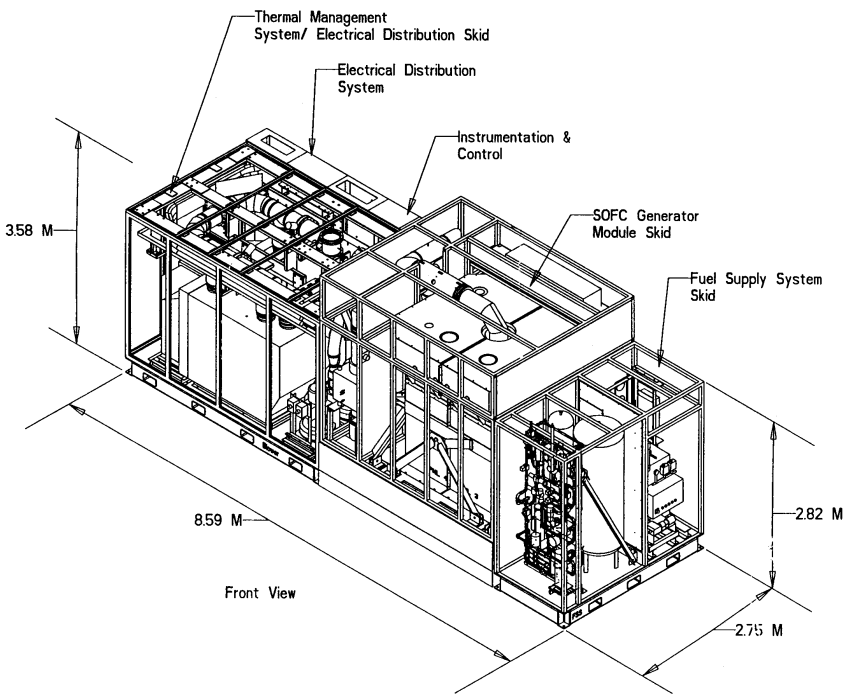

Figure 5 — Single Shaft PSOFC/GT

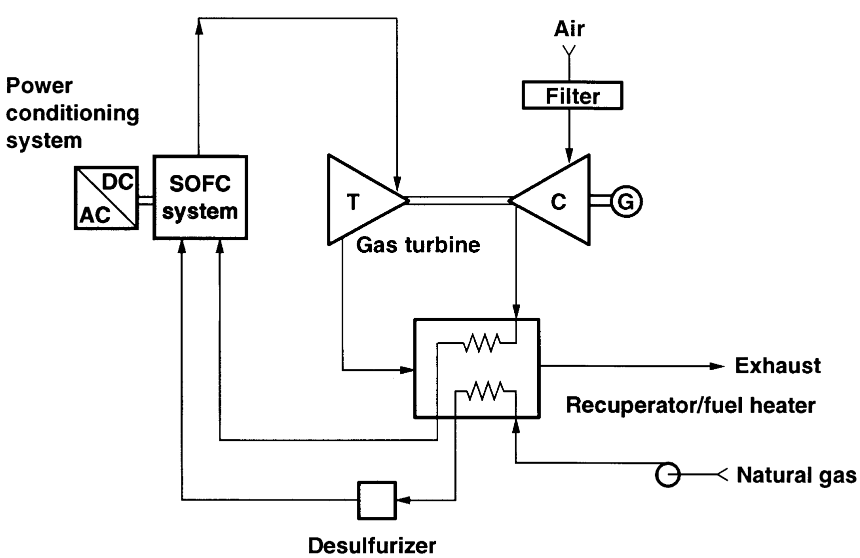

Figure 6 — JGU 25 kW AES-SOFC Power System Performance

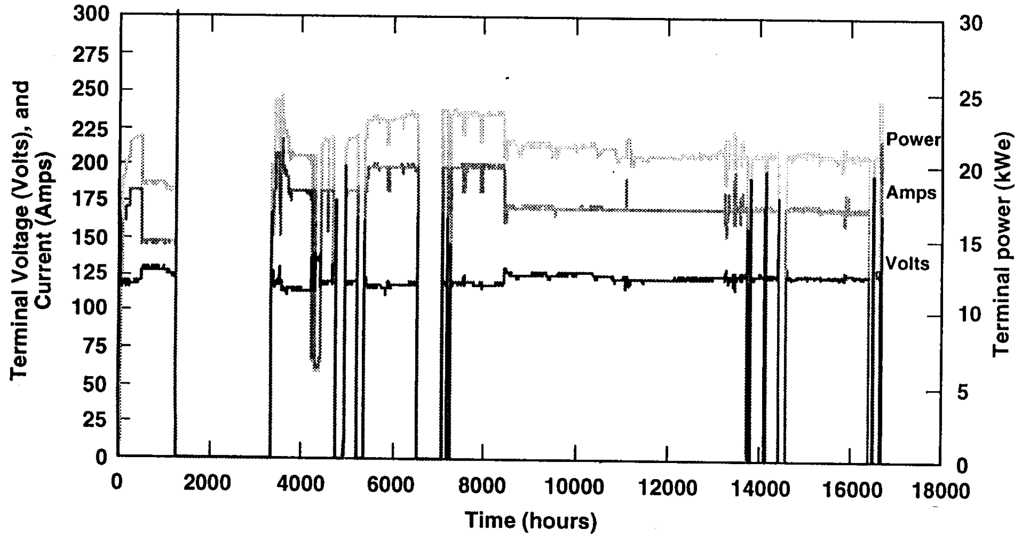

Figure 7 — EDB/ELSAM 100 kW SOFC Performance Estimate

Rated Power (net)	**100 kWe AC**
Efficiency @ Rating (AC/LHV)	**47%**
Maximum Power (net)	**160 kWe AC**
Thermal Recovery @ Rating (Hot Water)	**52 kWth**
Thermal Recovery @ Maximum (Hot Water)	**125 kWth**
Maximum Fuel Effectiveness	**80%**