CONCEPTUAL DESIGN AND PERFORMANCE ANALYSIS OF A 300 MWe LNG-FUELED PRESSURIZED SOFC/GAS TURBINE POWER PLANT

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ABSTRACT

Power plants based on the simplest integration of a pressurized solid oxide fuel cell (PSOFC) generator and a gas turbine (GT) are capable of converting LNG fuel energy to electric power with efficiencies of approximately 55% (net AC/HHV), and more complex PSOFC/GT power plants can be configured to achieve even higher efficiencies. The results of a program are discussed that was focused on the development of a conceptual design for a 300 MWe LNG-fueled PSOFC/GT power plant. A key design objective was 65% efficiency, and this was accomplished by integrating in the power plant cycle an intercooled, recuperated, reheated gas turbine with two PSOFC generators – one operating at high pressure, and providing heat to drive one turbine section, while the second generator, operating at lower pressure, provides heat for the reheat turbine. Another important design requirement was a small plant footprint; a footprint of less than 30,000 m² was required, while the footprint achieved has an area of only 8,400 m². The power plant cycle is described, the physical arrangement of plant components is discussed, and the technique to be used in installing PSOFC generator modules, and then accessing them for maintenance, is reviewed. Power plant performance and emissions estimates are presented.

INTRODUCTION

This paper summarizes the results of a recently completed research project funded by the Institute of Applied Energy of Japan, acting in behalf of electric power companies of Japan. The purpose of the project was to develop the conceptual design for a 300 MWe pressurized solid oxide fuel cell (PSOFC)/gas turbine (GT) power plant. The power plant fuel was LNG. There were two key design objectives. One, and most importantly, was high electric generating efficiency. Referenced to the fuel HHV, the power plant net AC efficiency was to be at least 65%. The second objective was a small power plant footprint; design requirements established early in the project specified that the footprint, accounting for all equipment between the vaporized LNG supply and utility AC grid interface points, should be less than 30,000 m².
POWER PLANT CYCLE DESCRIPTION

The direct integration of a PSOFC generator and a gas turbine in the basic PSOFC/GT hybrid cycle, Figure 1, enables the generation of electric power at high efficiencies – typically in the 50% to 55% (net AC/HHV) range. The high efficiencies are the result of the extended processing by the gas turbine of fuel energy that is not converted electrochemically to power by the fuel cell, and also to the operation of the SOFC generator at pressures near the compressor pressure level. Figure 2 shows the effect of pressure on cell voltage. The relationship was developed from the results of pressurized cell performance tests performed for Siemens Westinghouse Power Corporation by Ontario Hydro Technologies (OHT) at OHT facilities in Toronto, Ontario, Canada. The PSOFC/GT power system cycle operates with a peak cycle temperature of 870°C, which occurs at the PSOFC generator exhaust. The optimum compressor pressure ratio, at which maximum cycle efficiency occurs, increases with the peak cycle temperature, and at 870°C, it is approximately 3:1. The optimum pressure ratio is found by trading the positive effect of increasing pressure on SOFC efficiency against the negative effect of having to operate the SOFC generator at higher, less efficient, cell currents. As the design pressure ratio is increased, while the turbine inlet temperature is fixed at 870°C, more expansion occurs across the turbine, the temperature at the turbine exhaust drops, cooling the recuperator inlet, while the SOFC generator is required to operate at higher cell currents to maintain the SOFC operating temperature.

![Figure 1. Basic PSOFC/GT cycle.](image1)

![Figure 2. Effect of pressure on cell voltage.](image2)
The 300 MWe LNG PSOFC/GT power plant is based on the advanced power system cycle depicted in Figure 3. It builds upon the basic PSOFC/GT hybrid cycle (Figure 1), but it provides for increased system efficiency by three mechanisms - (1) higher SOFC operating pressure (>3 bar (abs)), (2) compressor intercooling, and (3) turbine reheat. Since the peak cycle temperature, occurring now at two turbine inlets, is still 870°C, the optimum expansion across each turbine will again be in the 2.5:1 to 3.0:1 range, but due to the series arrangement of the turbines, the pressure at the high pressure (HP) turbine inlet, and hence at the HP PSOFC generator, will now be in the 6 bar (abs) to 9.0 bar (abs) range, while the LP PSOFC generator will operate, as does the generator in the basic PSOFC/GT cycle, at pressures of 2.5 bar (abs) to 3.0 bar (abs). Consequently, there will be a larger positive effect of pressure on cell voltage in the HP PSOFC than there is in the basic hybrid cycle, and a larger impact on power plant efficiency. Intercooling reduces compressor work, at the expense of an intercooler heat rejection power requirement, causing a net increase in the gas turbine net AC power output; intercooling also contributes to an increased cycle efficiency, provided the cycle is recuperated, which will preclude the need to add heat to replace that rejected at the intercooler. Reheating, again in combination with recuperation, increases the average Brayton cycle heat reception temperature relative to the heat rejection temperature, and this also translates directly to a higher Brayton cycle efficiency. The system components identified in the cycle diagram (Figure 3) are flow matched, and fuel cell operating points are selected such that SOFC generator exhaust temperatures are approximately 870°C, with no firing of fuel at the gas turbine combustor and air heaters. The combustors and heaters will typically function only during system startup operations.

The power plant fuel is vaporized liquefied natural gas, with a sulfur-bearing odorant added to facilitate leak detection. To preclude a reaction with nickel materials in the SOFC generator, the sulfur concentration must be reduced to the 0.1 ppmv level prior to generator entry. This is accomplished in this plant design by a heated zinc oxide desulfurizer. The optimum zinc oxide operating temperature is 350°C to 400°C. As Figure 3 indicates, the desulfurizer operating temperature is maintained recuperatively and by electric heat addition.

The HP and LP PSOFC generators produce DC power that is prepared for export to the utility AC grid by power conditioning systems. AC power is also produced for export by the gas turbine. The power plant cycle is equipped with a recuperator for recovering heat from the gas turbine exhaust and applying it to the heating of process air as it flows to the HP PSOFC generator. For

![Figure 3. Advanced power system cycle.](image-url)
high power plant efficiencies, the recuperator should be designed with the highest practical effectiveness – 92% was assumed in the conceptual design study. Designing with a high recuperator effectiveness results in achieving a high temperature at the HP PSOFC generator air inlet, which will enable that generator to run at a low-cell-current/high-efficiency operating point.

POWER BLOCK CONCEPT

The 300 MWe power plant concept involves the combination of eight 40 MWe-class power blocks to achieve the required plant capacity. The eight power blocks are each composed of an intercooled, recuperated, reheated gas turbine, eight HP PSOFC modules, and ten LP modules. As shown in the cycle diagram, Figure 3, the gas turbine supplies air to the modules, first to HP modules, and then to the LP modules. A pictorial view of one power block is presented in Figure 4; the dimensions of the power block footprint are 18 m × 40 m. The vertical positioning of the modules is apparent in the view, an arrangement that was chosen to minimize the land area requirement, and the flow-parallel arrangement of the HP PSOFC modules between the air-supply and exhaust-collection manifolds is also apparent. The PSOFC modules in the LP set are arranged similarly. As the figure indicates, the power block gas turbine is installed at ground level, between the HP and LP modules. In the view presented in Figure 5, the PSOFC modules and certain electrical equipment have been removed, and the power block air and gas handling system that interconnects the gas turbine and modules is more readily visible. The turbine exhaust is conveyed and released to the atmosphere by the tall central stack.

Figure 4 also indicates the positioning in the power block of PSOFC power conditioning system (PCS) equipment. DC power from the modules is bused to PCS cabinets located on four power block levels. Within each cabinet, equipment is installed for the DC/AC conversion, and to step the AC power to AC grid voltage. The grid-ready AC is then consolidated at the switchgear installation on the power block top level.

![Figure 4. 40 MWe LNG PSOFC/GT Power Block.](image-url)
The gas turbine air intake filter is mounted at the turbine on the turbine skid; there is no separate air intake filter house and duct. The space in the power block directly above the gas turbine is utilized by seismic structural cross bracing, piping and utility chases, as well as by the PCS, other electrical equipment, and the turbine exhaust. Each power block is equipped with a service stairway that provides access to all power block levels.

As noted above, eight power blocks are to be assembled to achieve the required power plant capacity. However, the individual power blocks are capable of power operation independent of the status of neighboring blocks. Thus, provided the necessary balance-of-plant equipment is available, one or more blocks can continue operation, generating and exporting power, while other blocks are down for maintenance. This modular power block design approach was selected to provide for increased power plant availability without the need for high-cost, high-temperature valving that would otherwise be needed to isolate down modules.

PSOFC GENERATOR MODULE

Each generator module, both HP and LP, consists of a horizontal, cylindrical pressure vessel that houses 11,520 tubular Siemens Westinghouse SOFCs. The overall vessel length and diameter are 11 m and 3.2 m. An assembled vessel consists of two halves, flanged at the vessel mid-plane. Each tubular fuel cell has an active length of 1500 mm, and a diameter of 22 mm. The cells are arranged in 576-cell substacks (Figure 6), and each vessel half houses ten substacks. A substack includes, in addition to cells, cell air supply manifolding, a combustion zone for the oxidation of fuel that is not reacted.
electrochemically, and DC electric power terminals. It also includes an ejector pump to recirculate depleted fuel and to mix that gas with incoming fresh fuel, and in-stack equipment to reform the fresh fuel and to distribute the reformate to the cells. For reference, it is noted that the EDB/ELSAM atmospheric pressure SOFC combined heat and power system designed by Siemens Westinghouse and EDB/ELSAM, and operated in the Netherlands, used two such substacks.

In the module transportation/installation concept, the pressure vessel halves can arrive at the installation site independently of the fuel cell stack. The mass of each vessel half is 11,000 kg, and vessel transport by barge to a seashore plant installation site is envisioned. At the installation site, each vessel half would be combined with an assembly of ten cell substacks, and the two assembled halves would then be interfaced, and their flanges bolted. Each ten-substack assembly weighs 19,000 kg, and is qualified in Japan, without the need for permit, for transport by truck.

**GAS TURBINE**

The function of the gas turbine is to maintain the steady, controlled flow of air to the PSOFC generator modules during all phases of power block operation - startup, normal steady-state power operations, and planned/unplanned shutdowns and cooldowns. In addition, it is to apply net shaft power, derived from the expansion of SOFC exhaust, in the generation of additional electric power. The air supplied to the PSOFC generator modules by the turbine is to be preheated, using heat recovered from the turbine exhaust.

The gas turbine compressor, as presently conceived, has two radial-outflow stages, with intercooling between stages. Operating at the power block design point, the compressor intakes air at 37 kg/s, and compresses it to 7 atm (abs). The pressure ratio across each stage, allowing for intercooler pressure drop, is 2.7:1.

The engine has two turbine stages, an HP turbine, and an LP reheat turbine. Each is an axial unit, and both are mounted on a common shaft with the two compressor stages and the AC generator. If the LP turbine were a free power turbine, the expansion across the HP gasifier turbine would be set by work-balancing the HP turbine with the compressor. Given a compressor pressure ratio, values for the SOFC exhaust temperatures, and a recuperator effectiveness value, this would determine the gas temperatures at the HP and LP PSOFC inlets, and the cell current levels. However, with the single-shaft turbine arrangement, the HP turbine expansion ratio can be an independent variable, and since it does influence the performance of both the HP and LP PSOFC generator modules, an optimum value for the expansion ratio can be found that will yield maximum power.
system efficiency. For a compressor ratio of 7.0:1, the optimum HP turbine expansion ratio is 2:0:1.

Controlled airflow to the PSOFC generator modules is enabled by the single-shaft turbine design and the ability to modulate the load on the turbine generator to maintain a set-point shaft speed. Airflow control is a necessity to provide for PSOFC stack temperature management.

As indicated above, achieving high power system operating efficiencies depends upon designing the recuperator for high-effectiveness operation. For the power block design discussed herein, the recuperator effectiveness at the power block design point is 92%.

POWER BLOCK PERFORMANCE ESTIMATES

Power block design-point and part-load performance estimates are summarized in Table 1, and design-point emissions estimates are presented Table 2. The NOx emission is very low since there is no firing of fuel in the gas turbine combustor. Carbon dioxide emissions are also low, commensurate with the high power plant efficiency, and SOx emissions are virtually zero, a result of the fuel desulfurization process.

Table 1. Power Block Performance Estimates

|                                | Design-Point | Part-Load |
|--------------------------------|--------------|-----------|
| Compressor pressure ratio      | 7.0:1        | 4.5:1     |
| Compressor air intake rate, kg/h| 133,000      | 82,100    |
| HP turbine inlet temperature, C | 874          | 725       |
| HP turbine expansion ratio     | 2.0:1        | 2.0:1     |
| LP turbine inlet temperature, C | 870          | 728       |
| LP turbine expansion ratio     | 3.1:1        | 2.1:1     |
| HP PSOFC AC power, MWe         | 18.0         | 8.0       |
| LP PSOFC AC power, MWe         | 14.5         | 7.8       |
| Gas turbine AC power, MWe      | 10.0         | 3.6       |
| Power block auxiliary power, MWe| 0.6          | 0.6       |
| Power block net AC power, MWe  | 41.9         | 18.8      |
| Power block LNG fuel requirement, MW HHV | 64.8 | 31.7 |
| Efficiency (Net AC/HHV), %     | 64.7         | 59.4      |

Table 2. Power Block Emissions Estimates

|                                |               |
|--------------------------------|---------------|
| Exhaust flow rate              | 136,920 kg/h  |
| Exhaust temperature            | 210 C         |
| Carbon dioxide                 | 290 kg/MWh    |
| NOx (based on assumed 1 ppmv concentration) | 0.006 kg/MWh |
| SOx                            | Virtually zero |
300 MWe POWER PLANT CONCEPT

A pictorial view of the 300 MWe LNG PSOFC/GT power plant is presented in Figure 7. The plant is arranged in two banks of independent power blocks, described above, with four blocks in each bank. The banks are separated by an equipment access space that is serviceable from a traveling, overhead, rail-mounted crane. The power plant projects a footprint that measures 52 m x 161 m and has an area of 8,372 m² (0.84 hectare); the footprint includes a 1 meter-wide walkway around the entire structure. The steel structure height-above-grade is 33 m, and the maximum plant height, to the tops of the eight exhaust stacks, is 37 m.

The access space between the two banks of power blocks (see Figure 7) is used for the installation and removal of individual PSOFC generator modules, and other plant equipment as well. The space can be traversed over its entire length by the 70-ton overhead crane, and a maintenance cage suspended from the crane can be indexed to each of seventy-two module locations. At each location, a complete generator module can be extracted, or the reverse operation can be performed. To remove a module, the electric load on all eighteen modules in the effected power block is removed, the flow of fuel to the modules is simultaneously terminated, and the modules are cooled. Next, the maintenance cage is moved into position at the location of the module to be serviced, and secured in place. This is followed by the disconnection of the short piping runs between the air and exhaust manifolds and the module, and by the breaking of module interfaces with the fuel, electric, and I&C systems. Next, once the anchors that fasten the module to the power block structure are removed, the module is moved by a wheeled carriage to the maintenance cage. The cage is then taken to grade level where the module is off-loaded, and on-site or off-site maintenance operations are begun. In the meantime, the maintenance cage could return to the down power block with a replacement module, and power block operation could resume upon completing its installation.

Figure 7. 300 MWe LNG PSOFC/GT Power Plant.
In developing the power plant conceptual design, the potential for seismic activity has been considered, assuming the plant was to be installed in the Tokyo, Japan vicinity. The design employs an efficient horizontal and vertical structural steel bracing system that would transfer transient seismic forces to the vertical-column bases. The structural design concept includes deep foundations to react the steady state and transient loads. It is estimated that 630 steel piles will be required for the main power plant structure, and that miscellaneous structures would be supported by 300 piles. In the present concept, each "H" section pile has a 360 mm web, two 360 mm flanges, a mass of 150 kg/m, and an overall length of approximately 30 m.

POWER PLANT COST ESTIMATE

A summary of estimated power plant costs is presented in Table 3. Mature commercial technologies were assumed. For each equipment item, the cost presented includes purchase/fabrication, freight, and installation components. The plant power output basis for the $/kWe calculation was 335.2 MWe.

Table 3. 300 MWe LNG PSOFC/GT Power Plant Installed Cost Summary

| Equipment                                      | $/kWe |
|------------------------------------------------|-------|
| SOFC Generator Equipment                      | 430   |
| Gas Turbine                                    | 170   |
| SOFC Power Conditioning System                 | 190   |
| Instrumentation & Controls                     | 40    |
| Electrical Distribution/Switchyard             | 70    |
| Piping & Insulation                            | 60    |
| Auxiliary Systems & Support Equipment           | 20    |
| Subtotal                                       | 980   |
| Site Preparation, Foundations, Structural Steel| 60    |
| Project Management                             | 50    |
| Indirect Costs, Overhead, Profit Allowance     | 230   |
| Subtotal                                       | 340   |
| Total                                          | 1,320 |

The costs reported above are viewed as best estimate values to which no contingency or uncertainty factors were applied. Pittsburgh, Pennsylvania labor and material rates were used, and sales taxes, finance charges, construction interest, land acquisition, spare parts, and plant startup were not considered.

CONCLUSIONS

- A concept for a 300 MWe LNG-fueled power plant for central station application in Japan has been developed. It is based on a PSOFC/GT hybrid cycle that employs SOFC reheat, and the project results indicate that power plants based on this cycle can achieve high electric efficiencies, approximately 65% (net AC/HHV).
• The power plant design is based on the combination of eight 40 MWe PSOFC/GT power blocks. The power blocks operate independently, increasing the availability of the plant to generate power.

• The footprint estimate for the 300 MWe power plant is 8,400 m².

• Power plant NOx emissions are low, 6 grams/MWh. Carbon dioxide emission rates are also low (290 kg/MWh), commensurate with the high operating efficiency of the power plant, and the exhaust SOx concentration is virtually zero due to the desulfurization of all fuel that is supplied to the plant.

• The power system installed-cost estimate is $1320/kWe. Sales taxes, finance charges, construction interest, and the costs of land, spare parts, and plant startup were not included in this estimate.

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