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Fuel Cell Power Plant Initiative

Final Report - Volume II
Preliminary Design of a Fixed-Base LFP/SOFC Power System

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1. INTRODUCTION

This report documents the preliminary design for a military fixed-base power system of 3 MWe nominal capacity using Westinghouse's tubular Solid Oxide Fuel Cell [SOFC] and Haldor Topsoe's logistic fuels processor [LFP]. The LFP provides to the fuel cell a methane rich sulfur free fuel stream derived from either DF-2 diesel fuel, or JP-8 turbine fuel.

Fuel cells are electrochemical devices that directly convert the chemical energy contained in fuels such as hydrogen, natural gas, or coal gas into electricity at high efficiency with no intermediate heat engine or dynamo. The SOFC is distinguished from other fuel cell types by its solid state ceramic structure and its high operating temperature, nominally 1000°C. The SOFC pioneered by Westinghouse has a tubular geometry closed at one end. A power generation stack is formed by aggregating many cells in an ordered array. The Westinghouse stack design is distinguished from other fuel cell stacks by the complete absence of high integrity seals between cell elements, cells, and between stack and manifolds. Further, the reformer for natural gas [predominantly methane] and the stack are thermally and hydraulically integrated with no requirement for process water.

The technical viability of combining the tubular SOFC and a logistic fuels processor was demonstrated at 27 kWe scale in a test program sponsored by the Advanced Research Projects Agency [ARPA] and carried out at the Southern California Edison's [SCE] Highgrove generating station near San Bernardino, California in 1994/95. The LFP was a breadboard design supplied by Haldor Topsoe, Inc. under subcontract to Westinghouse. The test program was completely successful. The LFP fueled the SOFC for 766 hours on JP-8 and 1555 hours of DF-2. In addition, the fuel cell operated for 3261 hours on pipeline natural gas. Over the 5582 hours of operation, the SOFC generated 118 MWH of electricity with no perceptible degradation in performance. The LFP processed military specification JP-8 and DF-2 removing the sulfur and reforming these liquid fuels to a methane rich gaseous fuel. Results of this program are documented in a companion report titled "Final Report-Solid Oxide Fuel Cell/ Logistic Fuels Processor 27 kWe Power System".

The 27 kWe SOFC system tested at SCE used 576 tubular air electrode supported [AES] cells of 185 cm sq active area [16 mm diameter by 500 mm active length]. In February 1996 Westinghouse commenced the manufacture in a pilot manufacturing facility of commercial size cells, (22 mm diameter by 1500 mm in active length yielding a cell active area of 834 cm sq.) A natural gas fueled 100 kWe SOFC generation system, using 1152 of these commercial size tubular SOFCs, is being sponsored by EDB/ELSAM [a consortium of Dutch and Danish utilities] and will be delivered in the fall of 1997 to NUON, the host utility in the Netherlands. The EDB/ELSAM 100 kWe SOFC system operates at atmospheric pressure on natural gas fuel and generates electricity at 47.5% efficiency. The maximum capacity of the system is however approximately 160 kWe ac net. The SOFC stack is capable of producing 200 kWe dc.

Westinghouse has corroborated theoretical estimates of SOFC performance at pressures up to 15 atm. in cell tests conducted at Ontario Hydro Technologies [OHT]. SOFC operation at elevated pressure permits the synergistic integration of gas turbines [GT] with the pressurized solid oxide fuel cell [PSOFC] in a combined cycle power plant where the PSOFC supplants the GT combustor. Conceptual design studies sponsored by Westinghouse and a group of North American utilities found that integer MWe natural gas fueled PSOFC/GT combined cycle power plants could be configured to economically yield 63% electrical generation efficiency [net ac/LHV]. Design studies considering packaging and transportation limitations have revealed that an SOFC generator submodule containing approximately 2304 cells has weight and dimensional parameters consistent with easy transport via truck. A pressure vessel to house multiple SOFC submodules for pressurized operation is envisioned as a horizontally oriented cylinder with a diameter consistent with truck transport. A one MWe class natural gas fueled system, for example, would use two SOFC generator submodules of 500 kWe nominal capacity at elevated pressure contained within a single pressure vessel operating in tandem with a GT engine generator set of nominally 300 kWe capacity. Each 500 kWe SOFC submodule uses two 1152 cell stacks siamesed in a single canister. Each 1152 cell stack is virtually identical with the stack in the 100 kWe atmospheric pressure SOFC generator module now in fabrication.

In order to achieve a nominal power plant capacity of 3 MWe, six PSOFC submodules will be required. These six could be arranged as one six-pack of PSOFCs and one GT, two three-packs of SOFC and one or two GTs, or as three twin-packs of SOFC and three GTs. The basis for the design for a 3 MWe fixed-base military power plant is based upon this latter

configuration, three PSOFC twin-packs, each coupled with a GT. This arrangement has several advantages. The first is enhanced transportability, since the twin pack PSOFC module elements are truck transportable. Second, the arrangement yields enhanced reliability since a failure of any one PSOFC submodule, or any one GT, would only place one third of the power plant out of service. Third, this arrangement provides greater flexibility for variable load dispatch since the overall power ranges from the minimum power for a single twin-pack to the maximum power for the sum of all twin-packs. Fourth, since the GT can be fueled with liquid diesel or turbine fuel during start-up, a cold start in isolation from a conventional electric grid is feasible. Lastly, given new Department of Defense directives to maximize the use of technology from within the civilian sector, perhaps the greatest advantage to the three twin-pack configuration is that the single twin-pack plus single GT configuration yielding nominally one MWe is that which Westinghouse, its major subcontractors, and its major utility supporters believe will be a unit with great plurality in the civilian marketplace.

The logistics fuel processor for the 3 MWe SOFC/LFP fixed-base military power system is based directly on the Haldor Topsoe, Inc. supplied brassboard tested with the 27 kWe SOFC at SCE. However, the 3 MWe LFP will use water recovered from the SOFC spent anode gas for logistic fuels processing, making the system water neutral during normal operation, rather than stored process water as was done for the 27 kWe unit. Further, the hydrogen required for the hydrodesulfurization of the logistic fuels will be recovered from the LFP process stream and recycled, rather than using stored hydrogen as was done for the 27 kWe demonstration.

The PSOFC/LFP enables a new class of highly efficient, multi-fueled power systems to be configured for both civilian and military fixed-base use, thereby contributing directly to a reduction in the consumption of fossil fuels and a concomitant reduction in the evolution of CO_2, the greenhouse gas, with virtually no emission of NOx or SOx.

2. POWER SYSTEM DESIGN

2.1 SYSTEM DESCRIPTION

The power system design is based on the integration of a pressurized solid oxide PSOFC generator module with a GT. The PSOFC module operates on fuel gas provided by the LFP and the electrochemically-unused part of that fuel is then reacted in the GT combustor. Supplemental fuel is needed at the turbine combustor to provide the design point gas temperature to the turbine inlet, and that fuel is liquid DF-2 or JP-8. The power generating portion of the system is composed of the PSOFC module, the GT engine/generator, and a heat recovery system (HRS). The function of the HRS is to supply steam to the LFP and to preheat air for the PSOFC module. The PSOFC/GT system is designed to deliver 1 MW net ac power. Three of these units would be teamed with the LFP to produce the required 3 MW PSOFC/GT/LFP power system.

Figure 2.1, a process flow diagram for the LFP, illustrates the basic integration of the LFP with the PSOFC/GT power system. The LFP is discussed in detail in Section 5.0. As the figure shows, there are three points at which the LFP interfaces with the PSOFC/GT system. At two points, LFP fuel gas and condensate are supplied to the PSOFC/GT system, and at the third interface point, the PSOFC/GT system delivers steam at the flow rate, pressure, and temperature required by the LFP. It should be noted that the steam generation rate exceeds the condensate flow rate. This implies that other sources of water must be found within the system for it to achieve water self-sufficiency. The principal additional water source is the depleted-fuel stream that emanates from the SOFC module. Another is the gaseous fuel stream from the LFP. The latter stream contains over 20% water vapor, which can be cooled to condense a portion of that vapor.

Figure 2.2, the process flow diagram for the PSOFC/GT system, shows the three LFP interface points that were identified above. The fuel-gas stream arriving from the LFP system can be found in the upper left-hand corner of the diagram, and the LFP condensate stream merges with water from other sources at the power system condensate tank; steam to be returned to the LFP system is provided by the HRS.

STREAM NO.		1		2		3		4		5		GAS SEP
DESCRIPTION		RAW DIESEL		DIESEL & RECYCLE H2		PSA H2		GAS TO REFORMER		GAS FROM REFORMER		GAS SEP
COMPONENT	MOL WT	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR
OXYGEN	31.999											
HYDROGEN	2.016				83.06		100		41.57		30.76	
NITROGEN	28.013											
CARBON MONOXIDE	28.011											
CARBON DIOXIDE	44.010								0.86		1.09	
ARGON	39.948								15.03		18.94	
METHANE	16.043								39.04			
											49.21	
DIESEL												
TOTAL (DRY)			100		16.94				3.50			
WATER KMOL/HR.		2.28	100.00	13.43	100.00	11.15	100.00	64.98	100.00	103.11	100.00	42.6
TOTAL KMOL/HR (WET)		0.0		0.0		0.0		157.49		137.39		0.4
TOTAL KG./ HR.		2.28		13.43		11.15		222.47		240.50		43.07
AVG. MOL. WT.												
PRESSURE. BAR ABS		220		38.91		2.02		19.08		17.65		
TEMPERATURE. DEG. C		ATM		45.1		18.0		21.1		20.6		
		25		57.9		43.0		480.0		530.0		

R-101	R-102	R-103	P-101A/B	K-103	E-101	E-102	E-103	K-1
HYDROGENATOR	DESULFURIZER	REFORMER	FEED PUMPS	EJECTOR	RECYCLE COOLER	FEED/EFFLUENT EXCHANGER	PROCESS GAS HEATER	HYDRO RECYC COMPRE

CALCULATION # 175984

LEGEND	REV
△ STREAM NUMBER	△
○ PRESSURE, BAR ABS	△
▢ TEMPERATURE C	△
⟩ DUTY, KV	△
⬭ FLOW, KG/H	△
⬭ FLOW, m³/h	△
⟩ POWER, KV	△

Figure 2

	7 GAS TO ANODE		8 PSA OFF-GAS																
MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	
30.76		11.65		6.25															A
1.09		1.39		1.47															
18.94		24.17		25.64															
49.21		62.79		66.64															
100.00	40.40	100.00	31.50	100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00	B
	12.25		0.42																
	52.65		31.92																
17.16		20.56		22.46															
19.6		2.0		1.5															
60.0		459.0		35.0															

E-105 PROCESS GAS PREHEATER

E-104 PSA OFF GAS HEATER

K-101 PSA OFF GAS BLOWER

E-107 BFW PREHEATER/STEAM PRODUCTION

E-106 AIR COOLER

X-100 PSA

B-101 REFORMED GAS SEPARATOR

STEAM

SOFC AND WASTE HEAT RECOVERY SECTION

PSA

X-100

K-101

E-105

E-107

E-104

E-106

B-101

BFW

CONDENSATE

l - LFP process flow diagram.

Figure 2.2 - PSOFC/GT system process flow diagram.

2-3

The fuel gas delivered by the LFP is at a moderately high temperature, 459°C, and its pressure, 2 bar (abs), is below the power system operating pressure of 3.8 atm. To facilitate fuel compression, the gas is cooled at the fuel cooler, and its water content is reduced in the process. The heat removed is presently assumed to be rejected to the ambient air, although it is conceivable that a system use could be found for that heat, and the condensate is pumped to the condensate tank for power system water-balance purposes. The fuel-gas temperature at the cooler exit is approximately 50°C. The dried/cooled fuel-gas, after compression, is delivered to the PSOFC module.

The module is also supplied with preheated air. The required air temperature at the module inlet will typically be in the vicinity of 500°C. The air is heated in part by work of compression at the GT compressor, and by the recuperation of turbine exhaust heat at the HRS.

The PSOFC module produces dc electric power. As Figure 2.2 indicates, this power can be converted to ac form by the power conditioning system.

Two gas streams emerge from the PSOFC module. One is composed of depleted SOFC fuel (SOFC anode exhaust), and other is depleted air (SOFC cathode exhaust). The power system design incorporates this two-stream feature to ease the problem of recovering water from the SOFC exhaust in order for the system to be water neutral. Implementing this feature requires that the SOFC module be designed mechanically to keep the streams separated within the module, and to let them pass separated from the module. The depleted-fuel stream flow rate is small, but it has the high water vapor content due to the electrochemical fuel oxidation process. The water needed to complete the power system water balance is removed at the depleted-fuel condenser, and the cooled, dried, depleted-fuel stream is supplied to the gas turbine combustor. The heat withdrawn from the depleted-fuel stream at the condenser is significant, and if it were integrated with the heat recovery system to assist in the process of generating steam for the LFP, then system efficiency could be improved relative to the present analysis where an ambient air cooled condenser is considered for the sake of system simplicity. The depleted-air stream serves as the oxidant for the GT combustor. The oxygen contained in the stream is sufficient to combust the hydrogen and carbon monoxide in the depleted fuel, and the liquid diesel. The combustor exhaust is at the temperature required at the gas turbine inlet. The shaft work delivered by the turbine drives the compressor section; surplus work goes to the generation of additional ac power at the turbine generator.

The hot turbine exhaust will typically be at temperatures in the range of 600°C. Sensible heat in this stream is recovered at the HRS to heat air and to generate LFP steam. Note that the steam generator superheater section is placed ahead of the recuperator to provide the steam temperature, 480°C, required by the LFP. In general, the recuperator effectiveness should be as large as possible to maximize the system operating efficiency, but it can be set no higher than the value that will still provide for an acceptable pinch temperature differential at the HRS evaporator section. In this design study, the evaporator pinch was required to be no smaller than 8.3°C. Supplying heat for steam generation from another source, such as the depleted-fuel condenser, or reducing the steam design pressure and/or temperature, would allow the recuperator to be designed with a higher effectiveness, and this would provide for increased power system efficiency.

A plan view of the 3 MWe fixed-base PSOFC/GT/LFP power generation system is provided in Figure 2.3.

2.2 SYSTEM PERFORMANCE

2.2.1 Cell Basis

The design study and the power generation system performance estimates were based upon the air-electrode-supported Westinghouse tubular SOFC design depicted in Figure 2.4. The cell has four parts - the air electrode (cathode), fuel electrode (anode), the electrolyte, and the interconnection. The cell diameter is 22 mm and its active length is 1500 mm. Fuel gas contacts the fuel electrode, and air is supplied to the air electrode through the air injection tube that is shown in Figure 2.5. The pressurized SOFC module contains 4608 such cells divided evenly between two SOFC submodules. Additional pressurized module design detail is provided in Section 3.

2.2.2 Cell Voltage-Current Density (V-J) Characteristics

Cell V-J estimates for this study were developed analytically as a function of SOFC fuel utilization. These estimates, applying to atmospheric-pressure operation, are provided in Figure 2.6. Cell voltage estimates for the regions between curves were obtained by linear interpolation, and the incremental effect of elevated pressure on cell voltage is obtained using the Nernst Equation. The effect of pressure on cell voltage is presented in Figure 2.7.

3 MWe FIXED BASE LFP PSOFC/GT SYSTEM
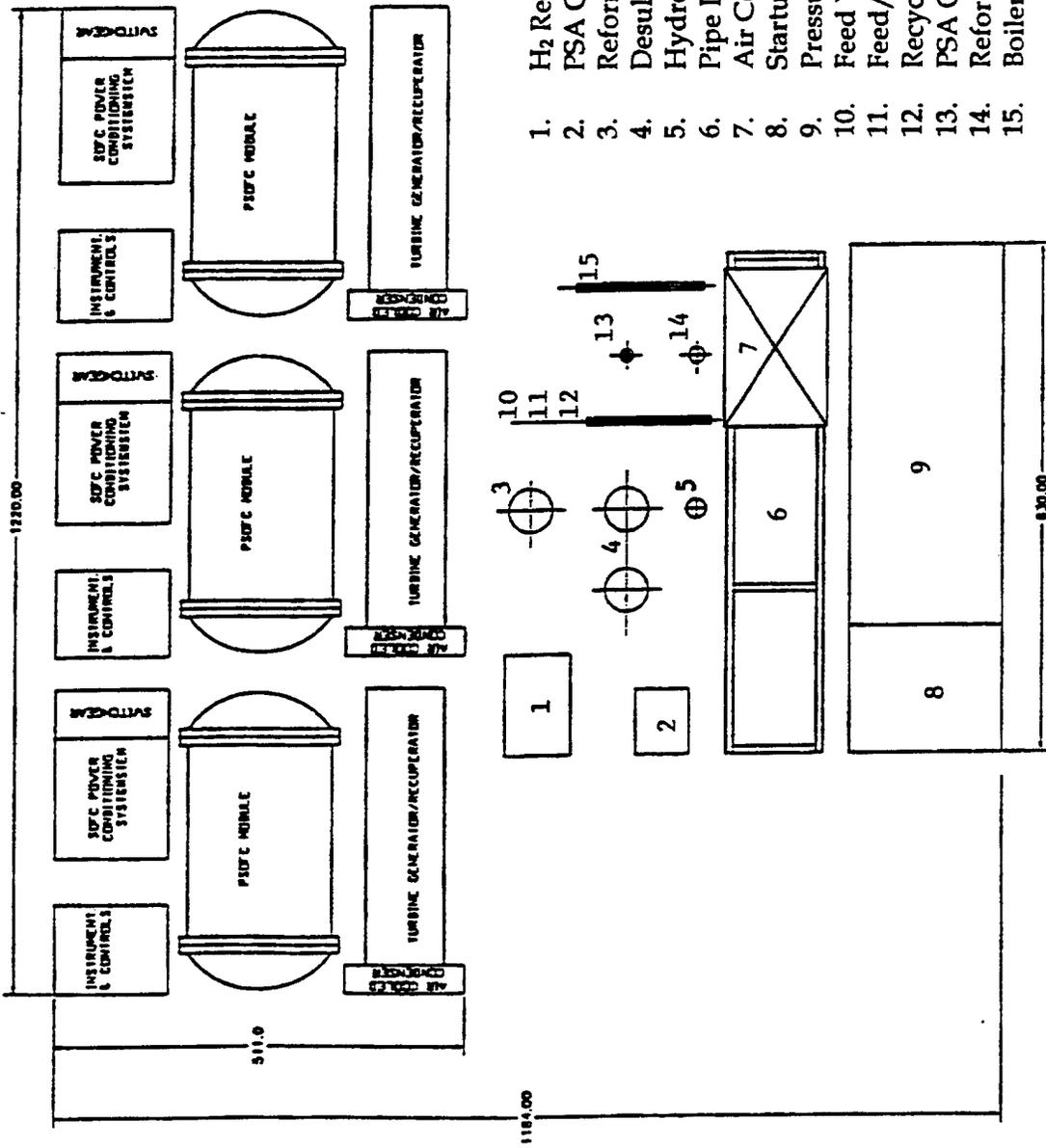
1. H_2 Recycle Compressor
2. PSA Offgas Blower
3. Reformer
4. Desulfurizers
5. Hydrogenator
6. Pipe Rack
7. Air Cooler
8. Startup Heater
9. Pressure Swing Absorption Unit (PSA)
10. Feed Vaporizer
11. Feed/Effluent HEX
12. Recycle Cooler
13. PSA Offgas Heater
14. Reformed Gas Separator
15. Boiler Feedwater Preheater

PLAN VIEW

Figure 2.3 - 3 MWe fixed base PSOFC/GT/LFP power generation system.

2-6

Interconnection

Electrolyte

Air
Electrode

Fuel
Flow

Air
Flow

Fuel Electrode
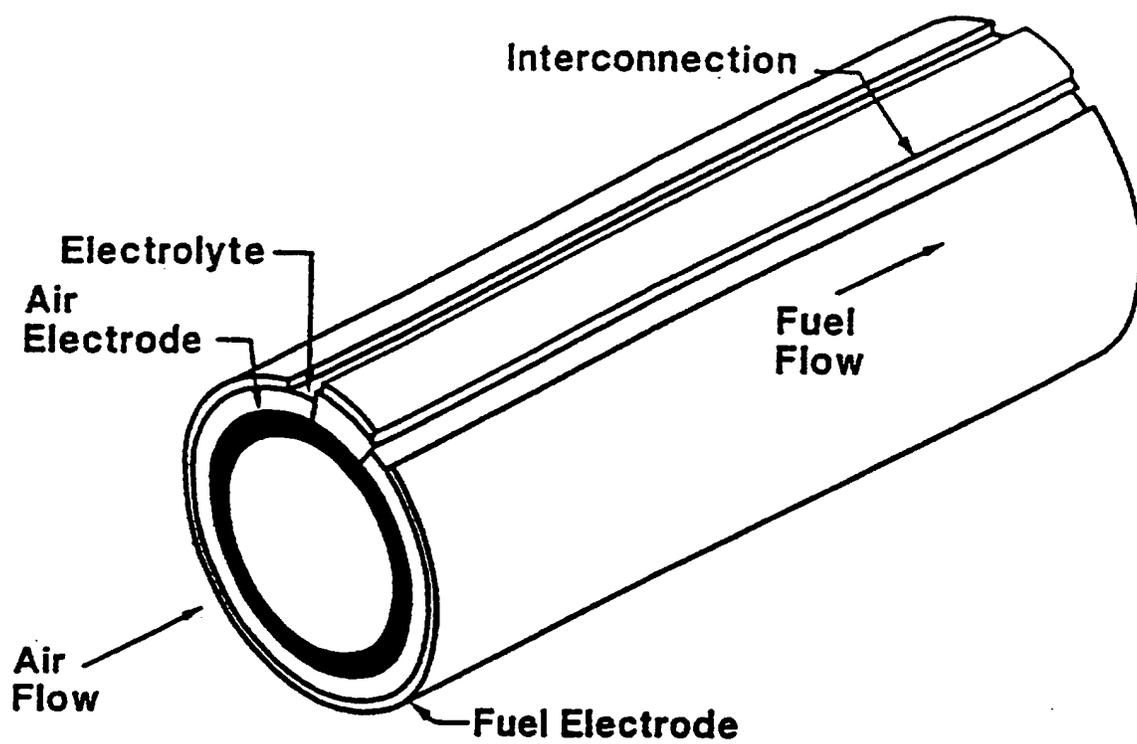
Figure 2.4 - Westinghouse tubular AES cell.

Air

Gaseous
Fuel
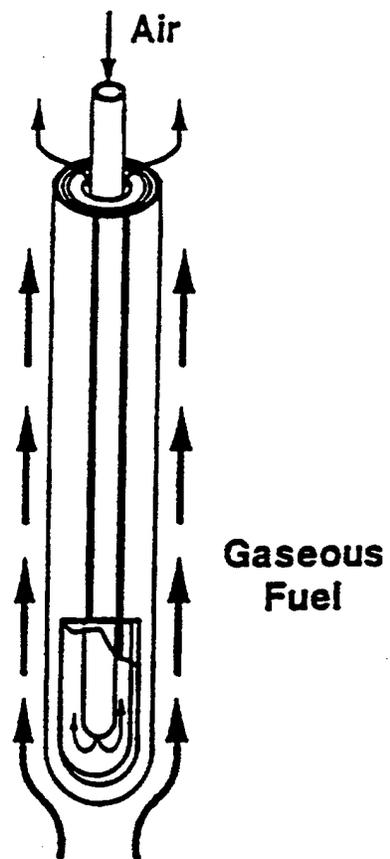
Figure 2.5 - Tubular AES cell with air injection tube.

Pressure: 1 atm

Cell Voltage - volts (y-axis)
Cell Current Density - mA/cm^2 (x-axis)

80
85
90

Fuel Utilization, %

ARPA22
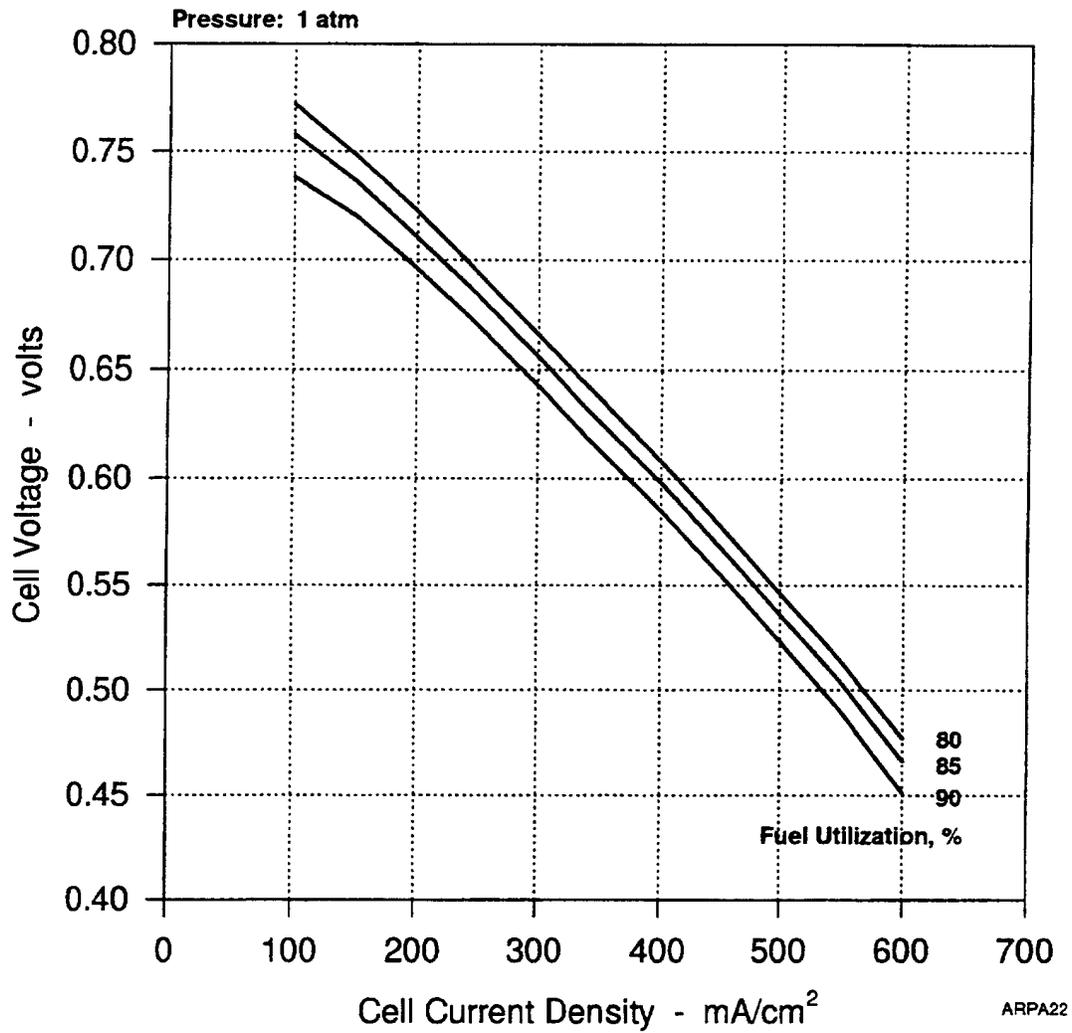
Figure 2.6 - Cell voltage-current characteristics.
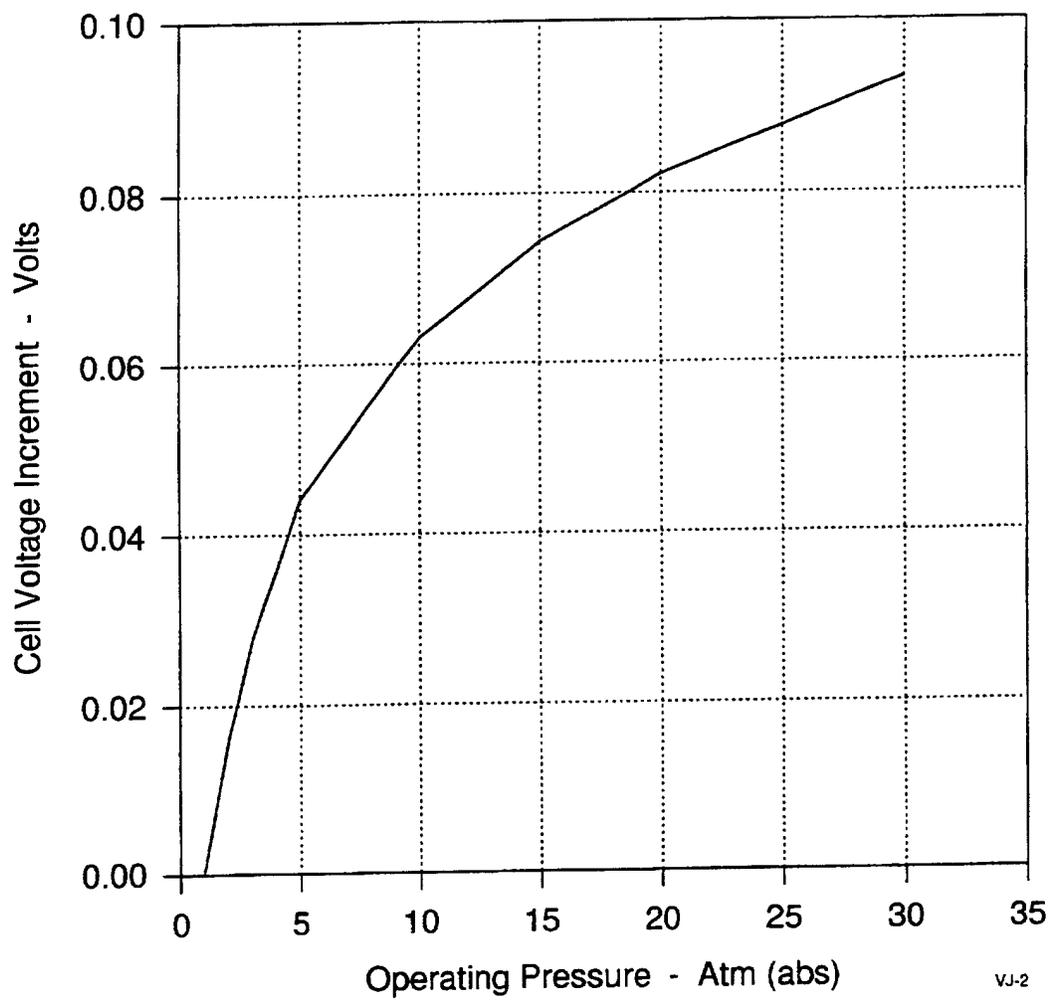
Figure 2.7 - Incremental effect of SOFC module pressure on cell voltage.

Tests being performed jointly by Westinghouse and Ontario Hydro Technologies confirm the validity of this relationship.

2.2.3 Power System Design Basis

Values of key design parameters are identified in Table 2.1.

Table 2.1 - Power Generation System Design/Analysis Parameter Values

Parameter		
SOFC Module		
Fuel utilization	Selected to maximize system efficiency.	
Air Stoichs	3.5	
Power conditioning efficiency	96%	
Gas Turbine		
Pressure ratio	3.8:1	
Turbine inlet temperature	970C	
Air flow rate	Selected to match the air flow req'd by the SOFC module.	
Inlet pressure drop	13.8 mbar	
Exhaust section pressure drop	40.0 mbar	
Turbine generator efficiency	98%	
Heat Recovery System		
Steam temperature	480C	
Steam pressure	35 bar (abs)	
Steam generation rate	1.48 kg/kg fuel from LFP	
Evaporator pinch	8.3C	
Economizer approach	5.6C	
Gas-side pressure drop	34.9 mbar	
Ambient Air		
Pressure	1.014 bar	
Temperature	15C	
Relative humidity	60%	
LFP Fuel Gas Composition, mol fractions	**At Fuel Cooler Inlet**	**At Fuel Cooler Exit**
Hydrogen	.0894	.1097
Carbon monoxide	.0107	.0131
Carbon dioxide	.1855	.2277
Methane	.4817	.5911
Water vapor	.2327	.0584
LFP Fuel Gas Temperature, C	459	49

2.2.4 PSOFC/GT System Design-Point Performance Estimates

PSOFC/GT system design-point performance estimates are presented in Figure 2.8. The power parameter is a net value for each PSOFC/GT system defined as the sum of the gross ac power outputs from the SOFC power conditioning system and the turbine generator, less the electric power required to drive the fuel compressor and the feed/condensate pumps. It does not account for LFP system parasitics[1]. With the SOFC module configuration fixed and including two submodules, each submodule consisting of 2304 cells, each point on the curve applies to a different SOFC operating point - the low-power points to low cell current densities, and the high-power points to high current densities. The GT design, however, is not constant along the curve. For the present analysis, the turbine inlet temperature and pressure ratio are fixed, but the compressor air flow rate varies from point to point as determined by the SOFC air flow requirement, and there is no system design feature to facilitate the bypassing of excess air around the SOFC module. Given a power output requirement of 3 MW total, or 1 MW net ac per PSOFC/GT system, Figure 2.8 enables the specification of GT equipment for integration with the fixed PSOFC module.

2.2.5 Effect of LFP System Steam Requirements on Power System Performance

Due to their influence on recuperator sizing, the pressure and temperature of the steam to be generated by the power system and delivered to the LFP system affect power system efficiency. The sensitivity of the design-point efficiency estimates to variations in steam conditions is indicated in Figure 2.9. The reference curve is from Figure 2.8. These estimates indicate that the effect of steam conditions on power system performance is not insignificant, and they are provided here for reference use during subsequent power system and LFP design projects.

2.2.6 Reference PSOFC/GT System Design-Point Specifications

Based upon the analysis discussed in the preceding section, a reference PSOFC/GT system design has been selected. Values of key design parameters for this design are

---

[1] LFP parasitic power is estimated at 33 kW (Section 5.4.2), one percent of plant output.

PSOFC Module - One, Housing Two Submodules
Gas Turbine - One 200 kW-Class
Gas Turbine Inlet Temperature - 970C
Compressor Pressure Ratio - 3.8:1
SOFC Fuel - LFP
GT Fuel - SOFC Depleted Fuel + Diesel Fuel
SOFC Fuel Utilization - 90%
SOFC Stoichs - 3.5
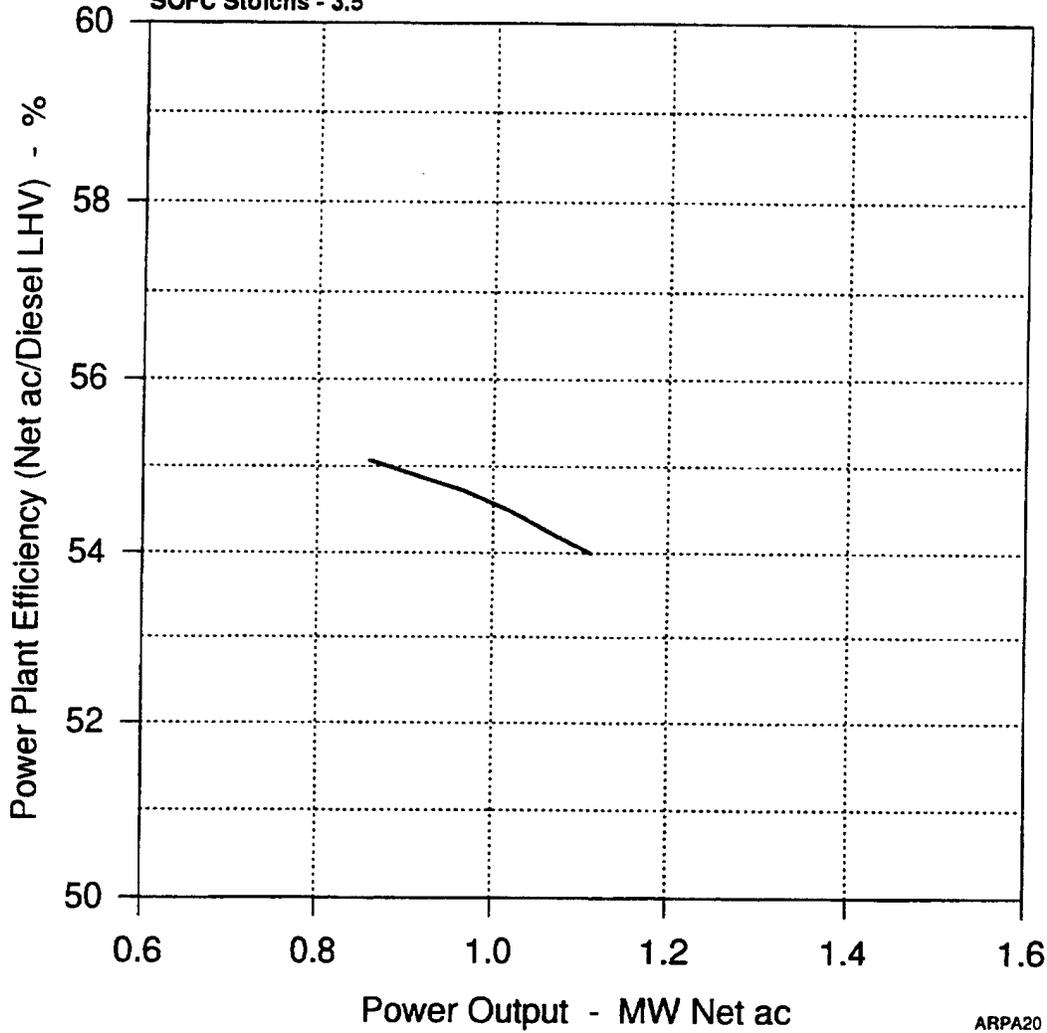
ARPA20

Figure 2.8 - PSOFC/GT system performance estimates.

PSOFC Module - One, Housing Two Submodules
Gas Turbine - One 200 kW-Class
Gas Turbine Inlet Temperature - 970C
Compressor Pressure Ratio - 3.8:1
SOFC Fuel - LFP
GT Fuel - SOFC Depleted Fuel + Diesel Fuel
SOFC Fuel Utilization - 90%
SOFC Stoichs - 3.5

LFP Steam P & T
A - 35 bar (abs), 480C - (Reference Case)
B - 25 bar (abs), 480C
C - 35 bar (abs), 350C
D - 25 bar (abs), 350C
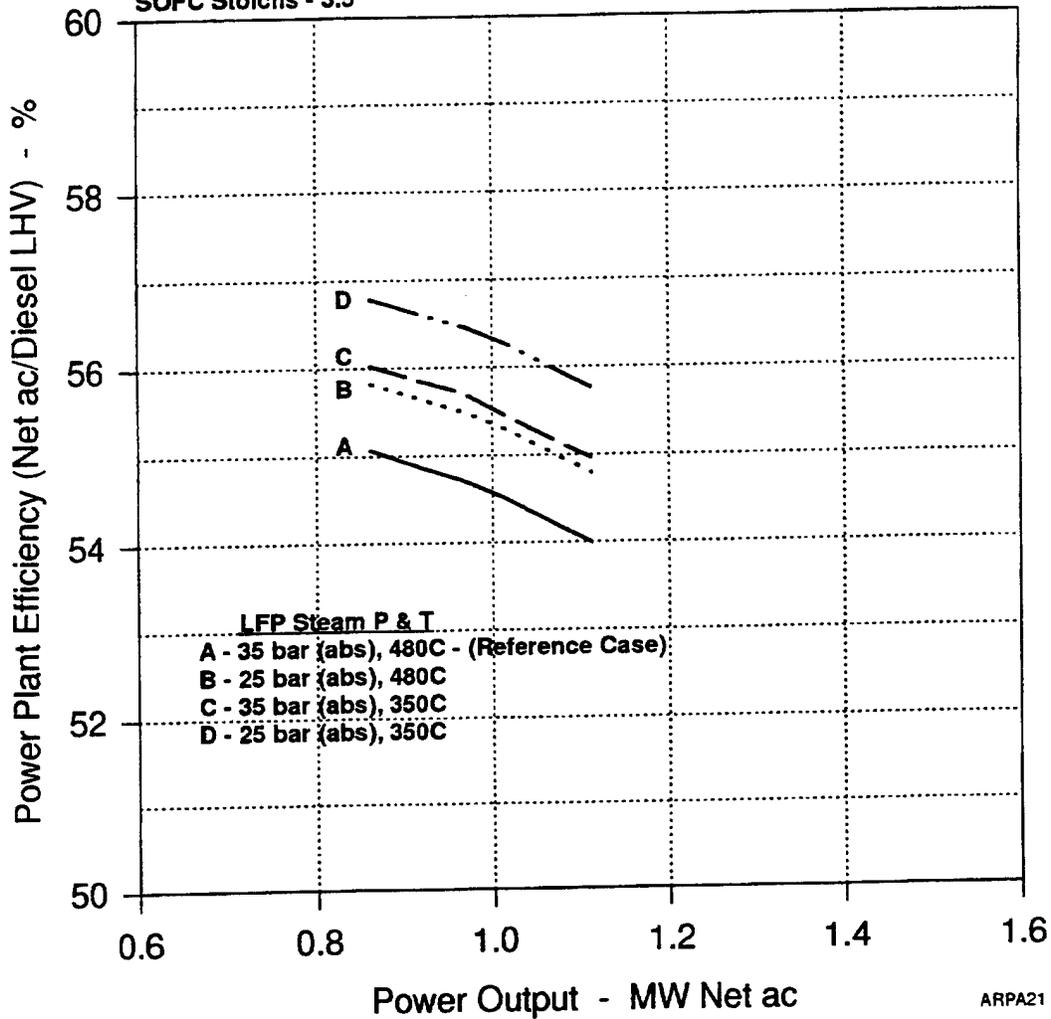
Figure 2.9 - Effect of LFP steam conditions on PSOFC/GT system performance

summarized in Table 2.2, and estimates of design-point performance parameters are also presented.

Table 2.2 - PSOFC/GT System Design-Point Parameter Values and Performance Estimates

Parameter	
No. pressurized SOFC modules	1
No. submodules/module	2
No. cells/submodule	2304
Compressor air flow	5734 kg/h
Compressor pressure ratio	3.8:1
Turbine inlet temperature	970C
Recuperator effectiveness	81.6%
Cell current density	320 mA/cm^2
Cell current	275 amps
Cell voltage	668 mV
SOFC submodule terminal voltage	512 V
SOFC module terminal current	824 amps
SOFC fuel utilization	90%
SOFC stoichs	3.5
SOFC gross ac power	0.810 MW
Gas turbine gross ac power	0.225 MW
Power system net ac power	1.02 MW
Diesel supply to LFP	122.9 kg/h
Diesel supply to gas turbine combustor	29.9 kg/h
Efficiency (net ac/diesel LHV)	54.5
Exhaust flow	5886 kg/h
Exhaust temperature	206C

Note: Three PSOFC/GT systems required.

*The performance estimates presented in this table are based on the assumption that heat from the depleted-fuel condenser is integrated with the HRS to reduce the amount of heat that must be recovered from the turbine exhaust for the generation of LFP steam. This enables the use at the HRS of a large-effectiveness recuperator, and it results in maximum system efficiency. However, the equipment design and arrangement concept discussed in this report does not reflect this heat integration, but it should be included in future development work on the power system concept. If the high-grade heat from the depleted-fuel condenser is not integrated with the HRS, the required recuperator effectiveness is 68.7% (vs. 81.6% with heat integration), and the power system efficiency slips to 51.2% (vs. 54.5%).

3. PRESSURIZED SOFC MODULE

3.1 SOFC TECHNOLOGY BASIS

Much of the PSOFC Power Generation system design philosophy and implementation are influenced by technology derived from two sources: the current 100 kW SOFC generator operating at atmospheric pressure and the Pressurized Bundle Test Article designed to operate up to 10 atm.

The proposed configuration of the PSOFC/GT system is depicted in Figure 3.1. It illustrates one pressurized SOFC Module coupled to a conventional gas turbine engine/generator. Electric power is generated by both the fuel cell and the rotary induction generator connected to the gas turbine.

These components can be mounted on individually transportable skids to form a modular system.

A key advantage of this concept is a remarkably simple power plant architecture utilizing advanced SOFC fuel cell modules coupled to a commercial gas turbine and induction generator.

3.2 PSOFC SUBMODULE DESCRIPTION

The generator submodule design philosophy is an extrapolation of the existing 100 kW SOFC generator configuration with the exception that two stacks are fueled from a common ejector/pre-reformer section. The entire assembly is subsequently installed into a common canister lined with high performance thermal insulation. This configuration greatly simplifies assembly of internal components by utilizing common parts and a modular, reusable insulation system.

Each stack contains 1152, 1500 mm active length tubular fuel cells, each generating over 200 watts, arranged in 12 bundle rows. The cells are arranged in three parallel paths yielding a stack terminal voltage of approximately 250 volts.

EXHAUST STACK

AIR INLET

AIR COOLED CONDENSER

RECUPERATOR

TURBINE GENERATOR

SOFC MODULE

INSTRUMENTATION AND CONTROLS

SOFC POWER CONDITIONING SYSTEM

SWITCHGEAR

517.0

402.0
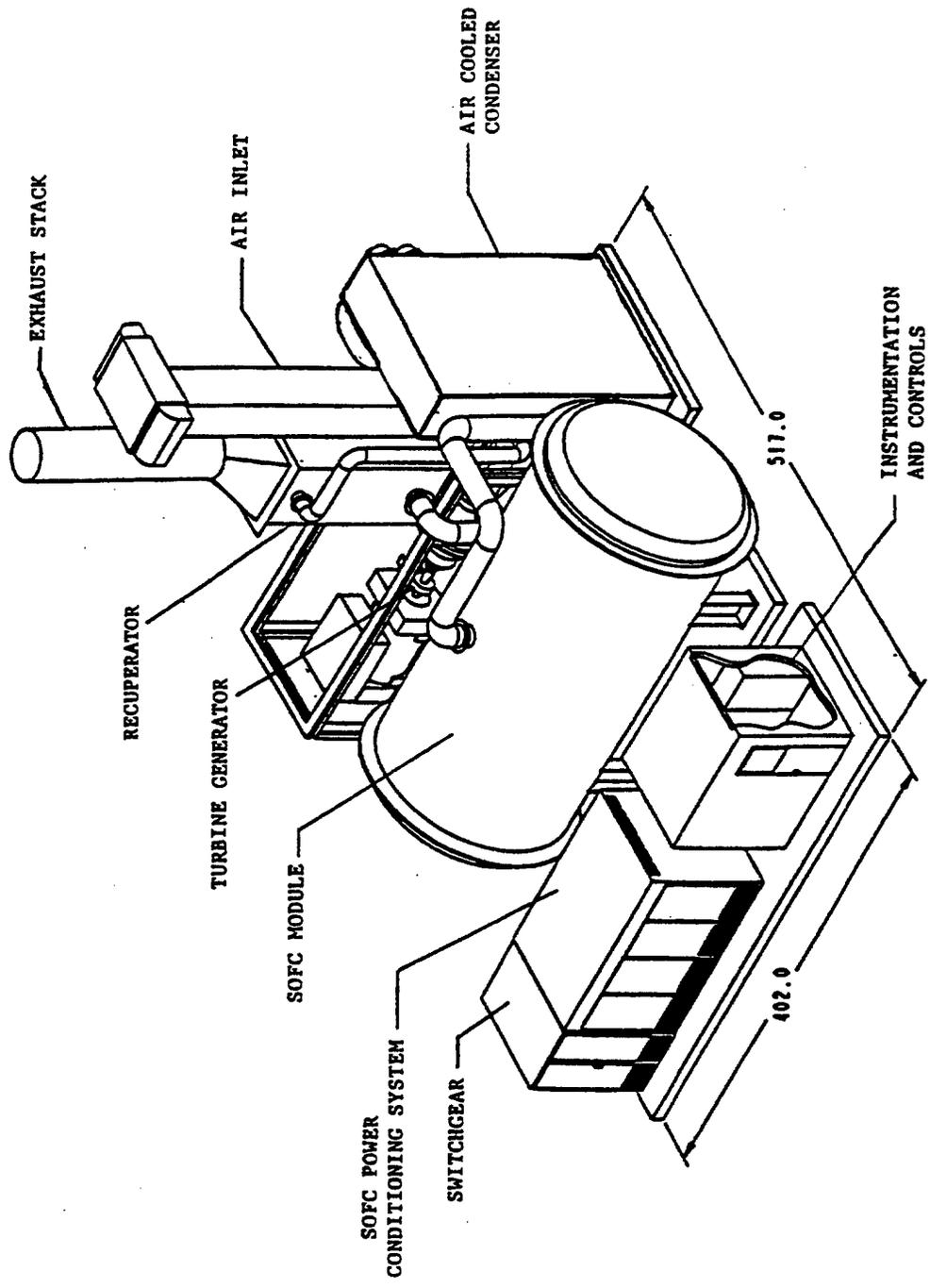
Figure 3.1 — One MW LFP/SOFC power system.

The submodule's configuration is depicted in Figure 3.2. As shown, each includes two internal fuel cell stacks, a common fuel pre-reformer with integral fuel distribution manifold and recirculation plenum, dc power leads and internal insulation.

Both stacks are fed from a common fuel supply system including a recirculation loop, an ejector, a pre-reformer and a fuel manifold. Because of the size of the stacks, there are two recirculation plenums and two ejectors feeding a common pre-reformer. The recirculation plenum is used to mix the depleted fuel extracted from the stack with the fresh incoming fuel injected through a nozzle. The mixture is then directed through an ejector into a pre-reformer chamber where higher hydrocarbons are reformed to prevent carbon deposition in the stack reformers where full reformation of methane occurs. From the pre-reformer exit, the fuel mixture is distributed to both stacks through a series of bottom manifolds. Figure 3.3 shows the centrally located pre-reformer and the fuel manifolds feeding both stacks.

Process air is introduced into the submodule through two lower inlet nozzles located on opposite sides of a bottom plenum, as shown in Figure 3.2. The same air is used to actively cool the canister through a series of parallel vertical ducts surrounding the outer shell and terminating in a large upper plenum. From this area, process air is distributed to an array of smaller air plenums through intermediate bellows type expansion ducts. Each air plenum supplies air to 144 adjacent cells through ceramic air feed tubes. Air flows from the air plenum into the air feed tubes, which convey the oxidant to the lower, closed-end of each fuel cell.

3.2.1 Fuel Cell Stack

The tubular SOFC (see Figure 2.4) features a porous air electrode made of doped lanthanum manganite, a ceramic. An axial strip of air electrode is covered by a thin, dense layer of doped lanthanum chromite. This strip, termed the cell interconnection, serves as the electric contact between the cell cathode (air electrode) and the anode (fuel electrode) of an adjacent cell or a power contact. A gas-tight electrolyte layer of yttria-stabilized zirconia covers the exposed air electrode, overlapping slightly the interconnection. A top layer, the fuel electrode, is a nickel-zirconia cermet and covers the electrolyte surface except in the vicinity of the interconnection.
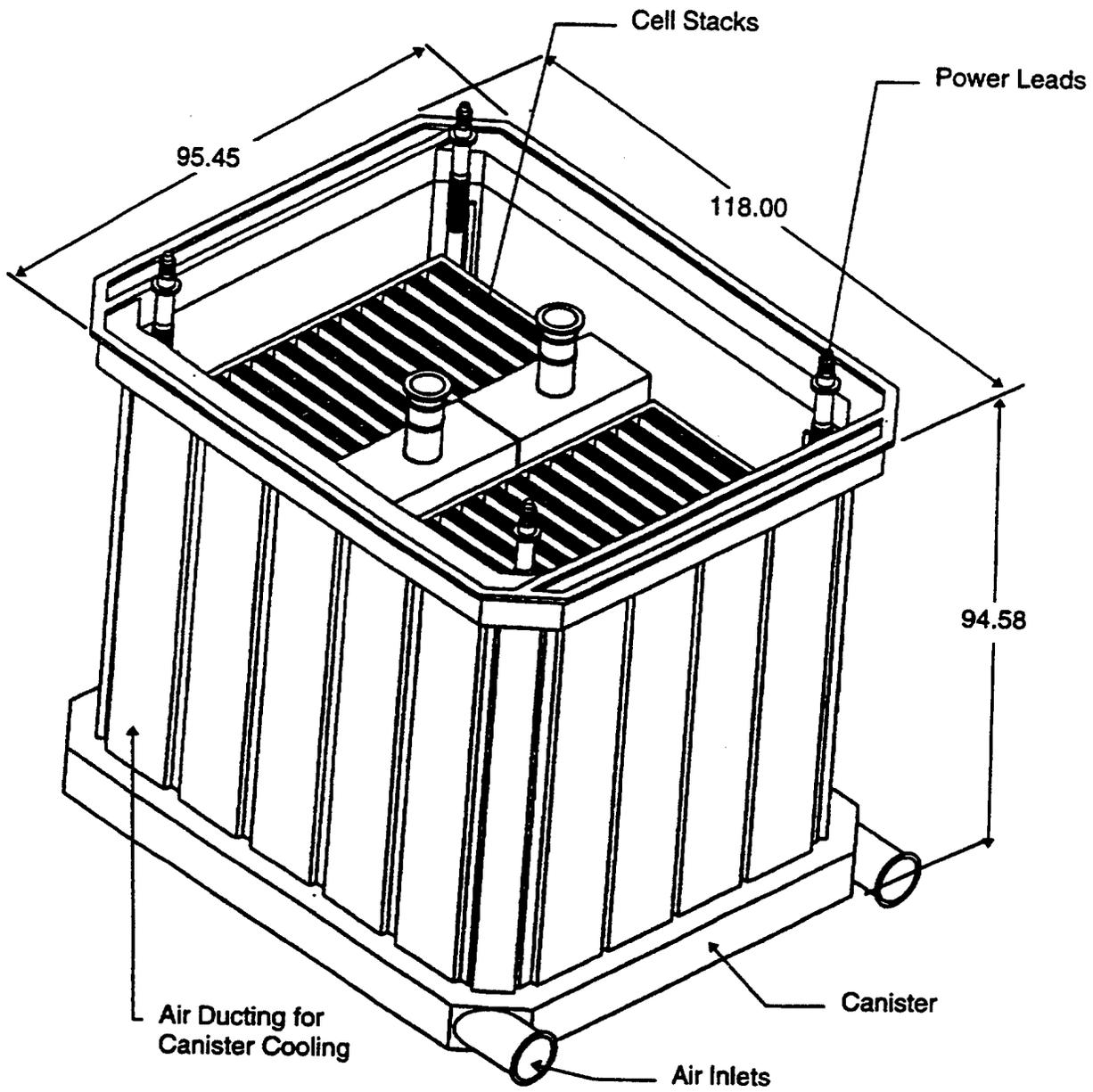
Figure 3.2 — SOFC submodule.
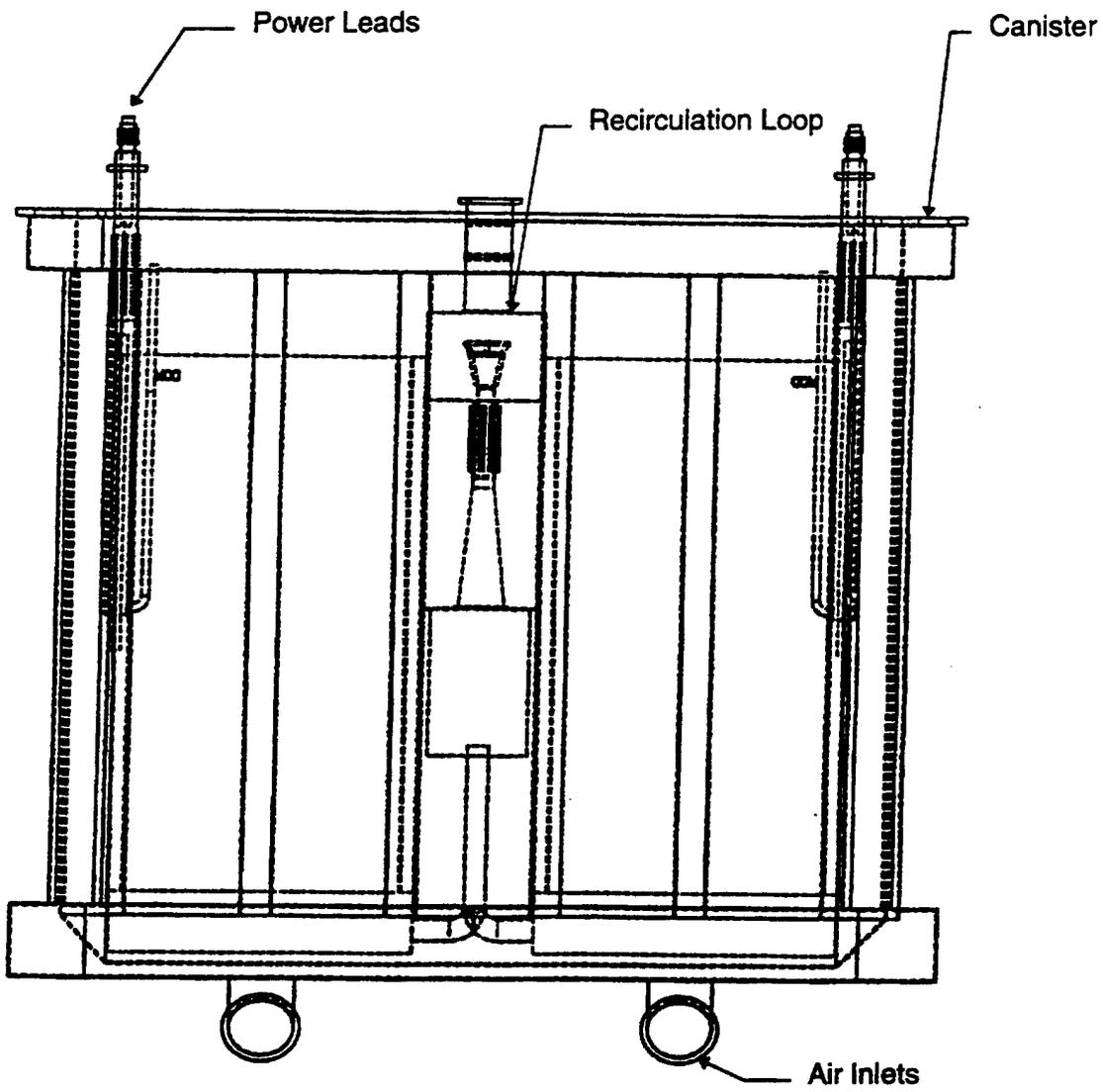
Figure 3.3 — SOFC submodule cross-section.

To construct an SOFC generator, individual cells are bundled into an array of electrically connected fuel cells, forming a monolithic structure that constitutes the basic generator stack, as shown in Figure 3.4. The fuel cell stack consists of 48 bundles, each a 3x8 cell array. Each cell has an active (interconnection) length of 1500 mm. The cells are electrically interconnected in three parallel paths, each with 384 cells connected in series.

The stack cross section, as shown in Figure 3.5, has 12 bundle rows, separated by electrically insulating stack reformers. Each bundle row consists of 96 cells (three parallel paths of 32 series-connected cells)

These bundle rows are series-connected in a serpentine configuration and terminate at power take-offs which transfer current to the two power leads. The power leads are air cooled to withstand the high temperature environment surrounding the cell stack. Each fuel cell stack is supported by a lifting tray which is also utilized during stack assembly.

3.2.2 Fuel Distribution System

The Fuel Distribution System, Figure 3.6, includes a dual fuel nozzle housing, a recirculation plenum system, ejectors, pre-reformer and an array of tubular manifolds connected to the stack reformers.

Fresh fuel is injected through a nozzle into each ejector which entrains depleted gas extracted from the upper zone of the fuel cell stack. This fuel mixture is directed to a pre-reforming section where higher hydrocarbon reformation occurs within a catalytic bed.

The fuel stream then exits the pre-reformer and is manifolded through a piping network connected to horizontal manifolds installed at the base of the fuel cell stack. These manifolds are coupled at the periphery of the stack by a quick connect flange assembly.

Each manifold directs the fuel into the stack reformers where nearly total reformation occurs. Reformed fuel is fed to the base of the stack to the exterior of the tubular fuel cells.

3.2.3 Stack Reformers

The stack reformers contain catalytically active material and accomplish approximately 85 to 90% of the fuel reformation, depending on the generator's operating point. Heat is radiated from the adjacent cell bundle region to supply the energy required for the endothermic reformation reaction.
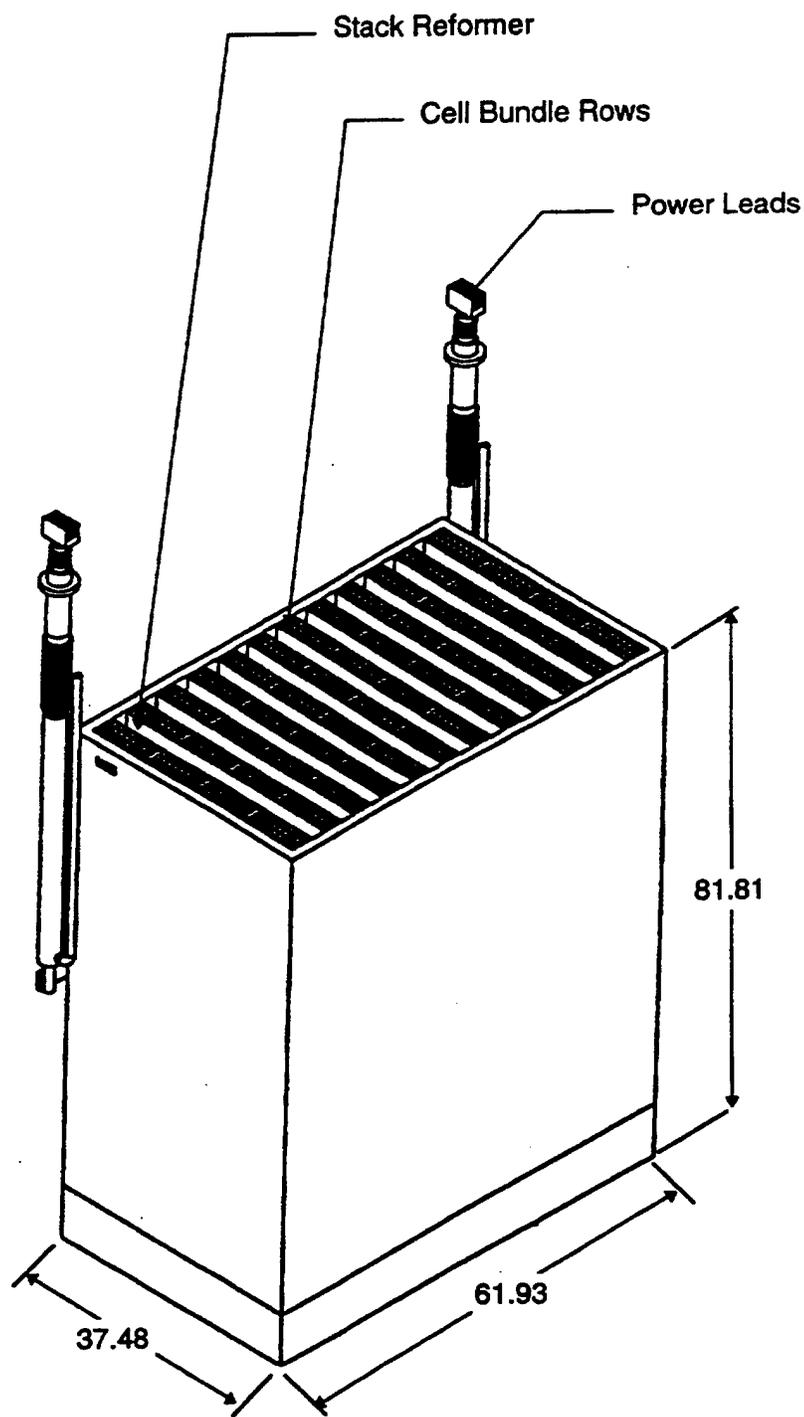
Figure 3.4 — SOFC generator stack.
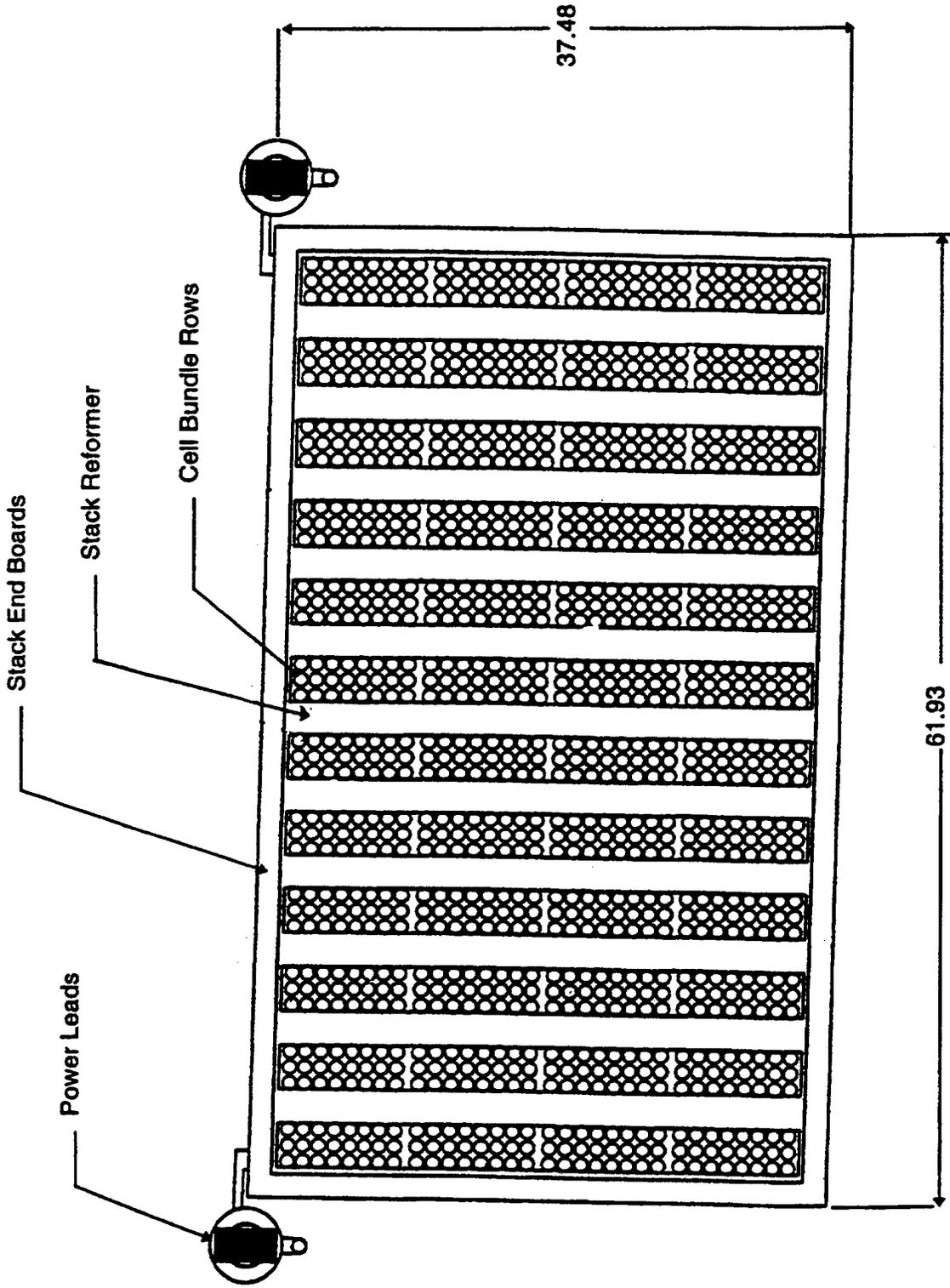
Figure 3.5 — SOFC generator stack cross-section.

37.48

61.93

Power Leads

Stack End Boards

Stack Reformer

Cell Bundle Rows

3-8

Ejector Inlet
Plenum

Ejectors

Prereformer

Distribution Tubes

Fuel Nozzle
Assemblies
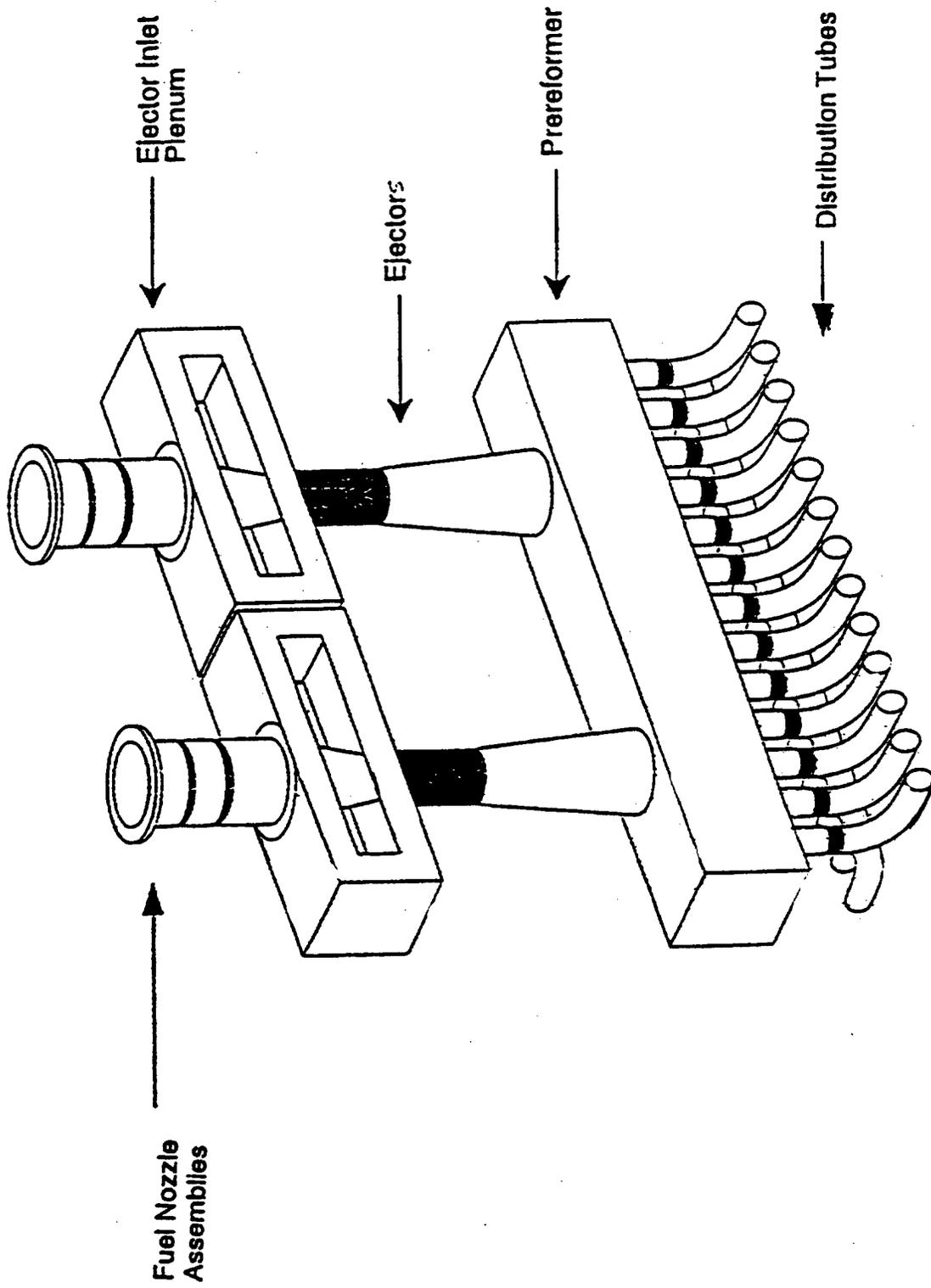
Figure 3.6 — Fuel Recirculation Loop.

3.2.4 Air Supply System

Process air is introduced at the top of the generator submodule into an array of air plenums. Air flows from the air plenums into the air feed tubes, which are coaxial with the fuel cells and convey the air to the bottom of the cell. The air subsequently flows upward through an annulus between the feed tube and the cell inner surface. Spent air exits from the open end of the cells and enters the combustion zone.

A portion of the spent fuel exiting the electrochemically active portion of the SOFC stack is recirculated and mixed with fresh fuel via ejectors as previously described. The portion not recirculated is extracted and directed to an external condenser for water removal. Very little spent fuel is passed to the combustion zone for an SOFC stack intended for operation on logistic fuels. In the Westinghouse seal-less stack design, a more complete separation between combustion zone and spent fuel plenum is accomplished using a thicker [longer leakage path] upper-most baffle board, and appropriate pressure balance. In the combustion zone, any spent fuel entering is consumed.

Because the air feed tubes cross the combustion zone in a manner similar to a gas-to-air heat exchanger, incoming air is heated by the exhaust gas exiting the cell stack. The exhaust gas is directed to an upper dome prior to being manifolded to an external common exhaust duct.

High pressure exhaust gas is collected from both submodules and is conveyed to the gas turbine through insulated piping. The turbine drives the compressor for compressing air that is delivered to the fuel cells.

3.2.5 Canister

Preheated, compressed air is introduced at the base of each submodule canister through two nozzles leading to a lower plenum. From this area, air is diverted to a number of peripheral cooling ducts integral with the vertical wall of the inner canister.

Air exiting the ducts is further collected into an upper peripheral manifold which distributes an equal amount of flow to each air plenum.

The inner canister is a stainless steel 304 L container, air cooled with process air, and internally insulated with a layer of high performance ceramic insulation installed in the cavity surrounding the fuel cell stacks.

Geometric configuration and overall dimensions of the submodule canister are shown in Figure 3.7.

3.2.6 Internal Insulation Package

The internal insulation package consists of a number of highly efficient thermal insulation modules interlocked to form an effective thermal barrier system between the cell stack operating at 1000°C [1800°F] and the inner canister cooled with 650°C [1200°F] temperature air.

The insulation modules are constructed from high purity alumina ceramic material which has a microporous structure. A layer of low density fiber material is bonded to one face to form a compliant composite capable of accommodating cyclic thermal differential expansion between the ceramic cell stack and the steel canister while offering effective bypass gas sealing and outstanding thermal insulation.

3.3 PSOFC MODULE DESCRIPTION

The pressurized SOFC module includes two submodules connected electrically in series to the module terminals.

The submodules are installed within a horizontal pressure vessel containing a supporting structure designed to provide easy access to the internals and easy assembling and replacement of the submodules without interference with the installed internal components.

3.3.1 Pressure Vessel

The pressure vessel, as shown in Figure 3.8, is a horizontal cylindrical shell with two flanged side covers and it is supported by two saddles anchored to the shipping container structural frame.

Pressure bearing components are required to meet construction codes such as the American Society of Mechanical Engineers (ASME) B31.1 piping code or the ASME Boiler and Pressure Vessel (BPV) Code. The allowable stresses for materials currently approved for construction under the rules of Sect. VIII, Div. 1 of the ASME BPV Code are provided in various Code Cases or in Sect. II, Part D.

SUBMODULE CANISTER
OVERALL DIMENSIONS

SCALE 0.015

82.95

92.45

82.79

73.12

92.45

94.58

95.45

79.44

118.00

102.00

105.50

9.10

115.00

115.00

6.00

Ø8.00
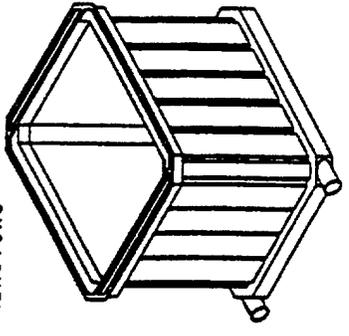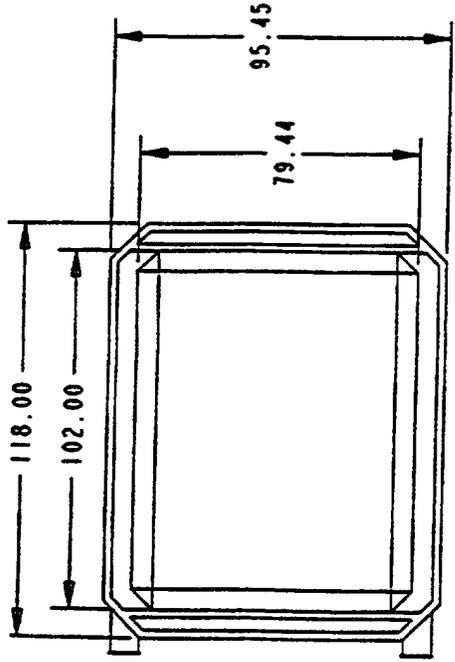
4.55
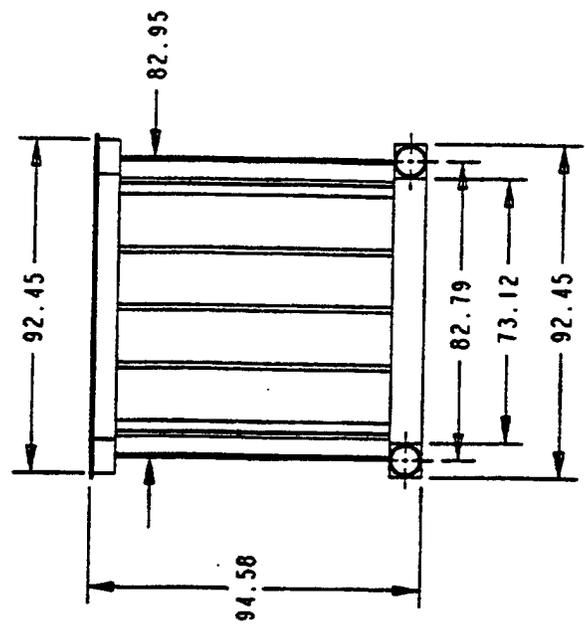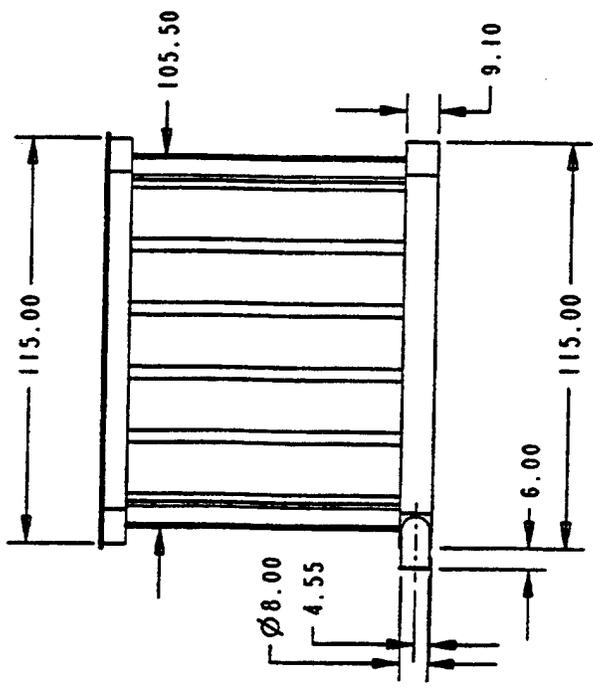
Figure 3.7 — SOFC submodule canister. [Dimensions in inches]

3-12

166.00

175.00

PRESSURE VESSEL ASS'Y
PRZ100596
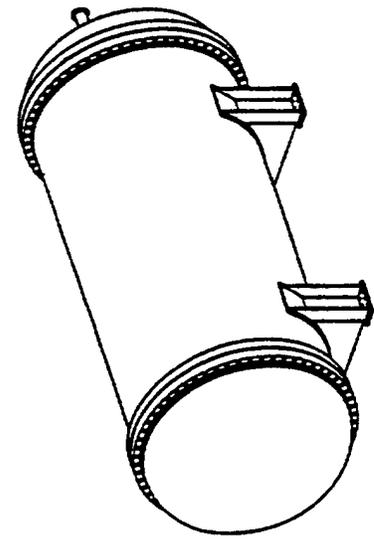
SCALE 0.01

TOTAL DRY WEIGHT: 100078 lb

427.00

Figure 3.8 — PSOFC pressure vessel. [Dimensions in inches]

The design of the components is in compliance with the ASME BPV Code, Section VIII, Div. 1, 1995 Edition. The cylindrical shell material is SA-516, Grade 70 carbon steel which provides a tensile strength range from 70,000 to 90,000 psi. The cylindrical shell thickness is determined by the tangential stress due to the design pressure. Since the maximum longitudinal stress (PR/2t) is only half of the maximum tangential stress, one-half the shell thickness is available for the longitudinal bending stress due to weight at the midspan or in the plane of the saddles, assuming the vessel to behave as its own carrying beam

As shown in Figure 3.9, the pressure vessel is supported by two saddles including four legs and stiffener plates. The saddles are welded to the outer shell of the vessel with a 120 degree contact angle, and they could be anchored to a concrete slab in the field. The saddle reactions are highly concentrated and induce high localized stresses in the shell which are within the allowable stress conditions specified by the ASME Code.

The side covers are ellipsoidal heads, cold formed from the same material as the pressure vessel, and welded to the mating flanges as shown in Figure 3.10.

To decrease the cost of the heads, a special design from the Hackney & Brighton Company has been selected. This highly efficient design, known as the 80-10® style, meets all ASME BPV Code requirements and it permits significantly higher pressures than other standard configurations selected for the same service because of its geometrically stronger configuration. The 80-10® head typical dimensions include a dish radius that equals 80% of the head diameter and an inside corner radius which is equal to 10% of the head diameter. These dimensions compare to 100% and 6% respectively for standard ASME Flanged and Dished (F&D) heads. For the same internal pressure the 80-10® head is only 66% of the thickness of the ASME F&D head, therefore material cost is minimized. Typical cost of a 80-10® head with an outer diameter of 150 inches and a thickness of 1 inch, is approximately $4600 (10/96 cost).

The four side flanges shown in Figure 3.11, have an outer diameter of 166 inches and a length through the hub of 11.5 inches and are forged from SA-105 carbon steel material. Sixty 2.75 inch diameter radial holes are drilled through the face of the flange for the bolts. The overall weight of each flange is approximately 8000 lb. The cost of this component is significant being a large diameter forged material, and is approximately $33,000 (11/96 cost).

Ø151.50 ID

Ø166.00 OD

92.00

147.00

MATERIAL: SHELL SA-516, GR.70
FLANGES SA-105
TOTAL WEIGHT: 66432 lb

HORIZ PRESSURE VESSEL
PRZ100496

175.00

153.50
OD

1.00 WALL THK

200.00

300.00 OL SHELL

323.00

15.00

30.00

230.00

46.50
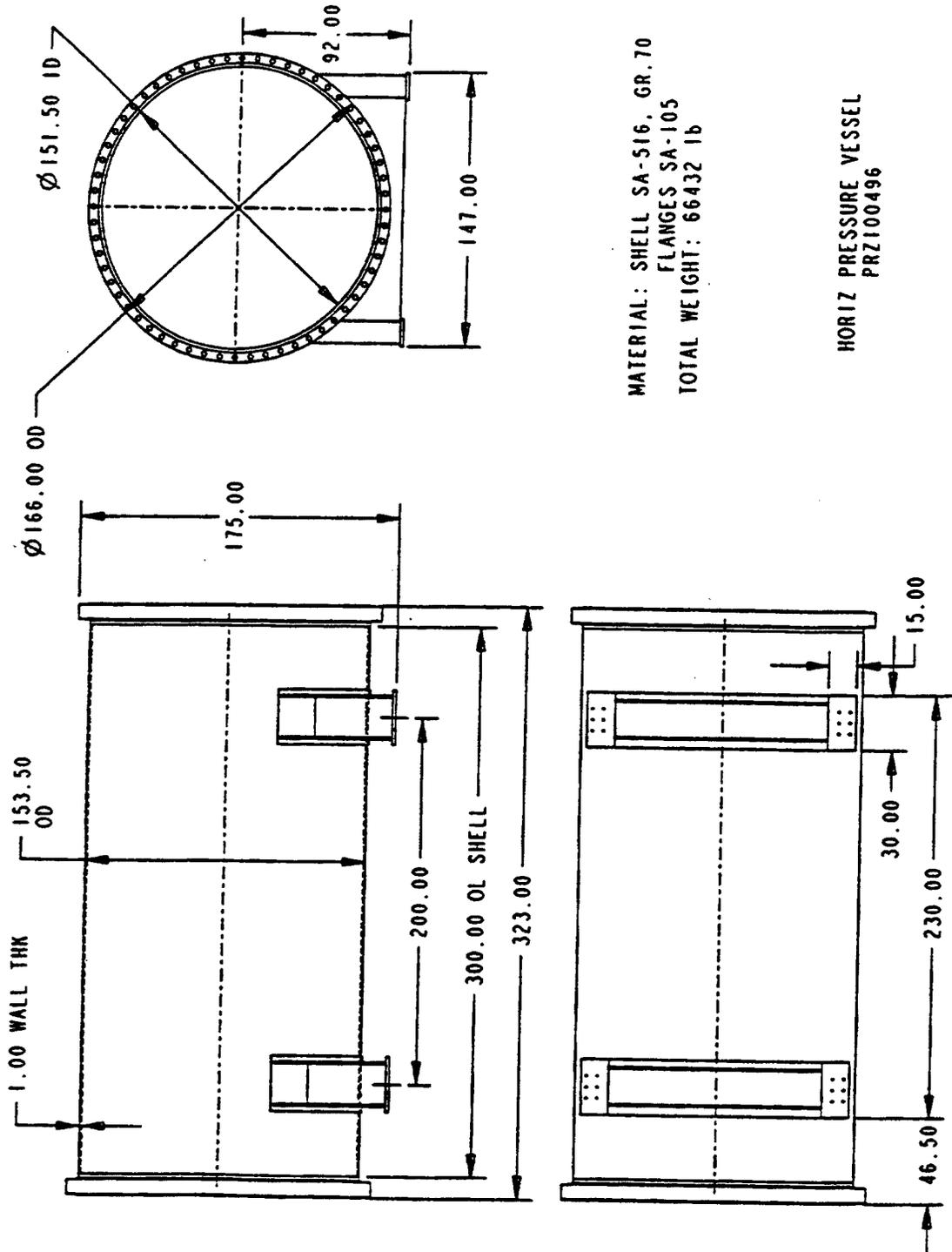
Figure 3.9 — PSOFC pressure vessel - cross-section. [Dimensions in inches]

MATERIAL: ELLIPSOIDAL HEAD SA-516, GR.70
FLANGE SA-105
TOTAL WEIGHT: 16779 lb

Ø151.50 ID

Ø166.00 OD
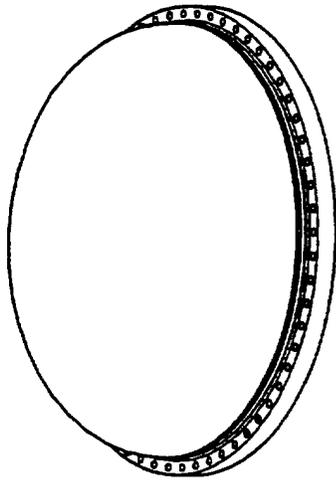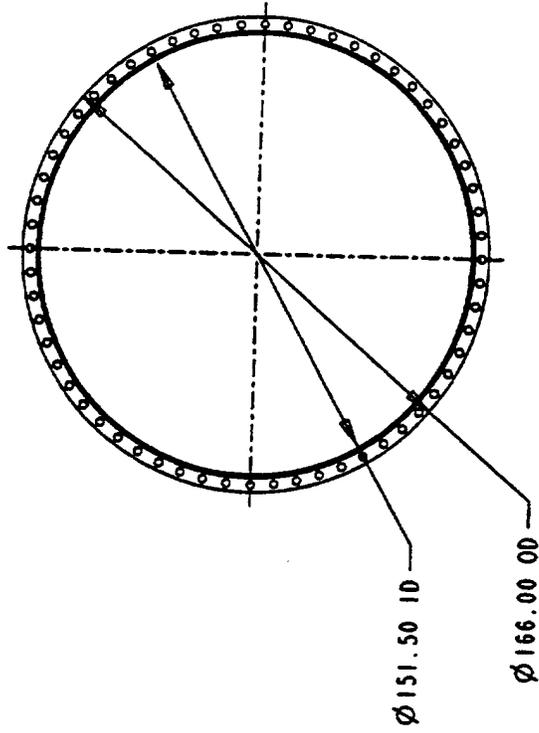
ISOMETRIC VIEW
SCALE 0.020
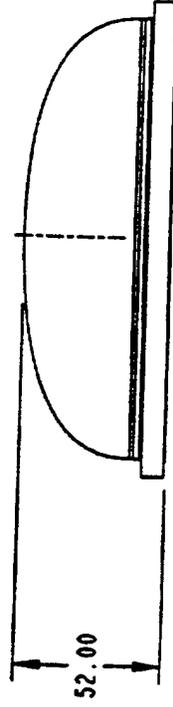
ELLIPSOIDAL FLANGED HEAD
PRZ100296

52.00

Figure 3.10 — PSOFC pressure vessel - heads. [Dimensions in inches]

Material: SA-105
Total weight: 7992 lb

SCALE 0.02

Ø151.50

Ø2.76 TYP
60 HOLES
Ø160.75 BC
Ø166.00

Ø166.00
Ø151.50

SECTION A-A

SEE DETAIL B

PRESSURE VESSEL FLANGE
PRZ090396

11.50

3.00

2.00

8.00

.50

R1.00

.25

1.00

DETAIL B
SCALE 0.15
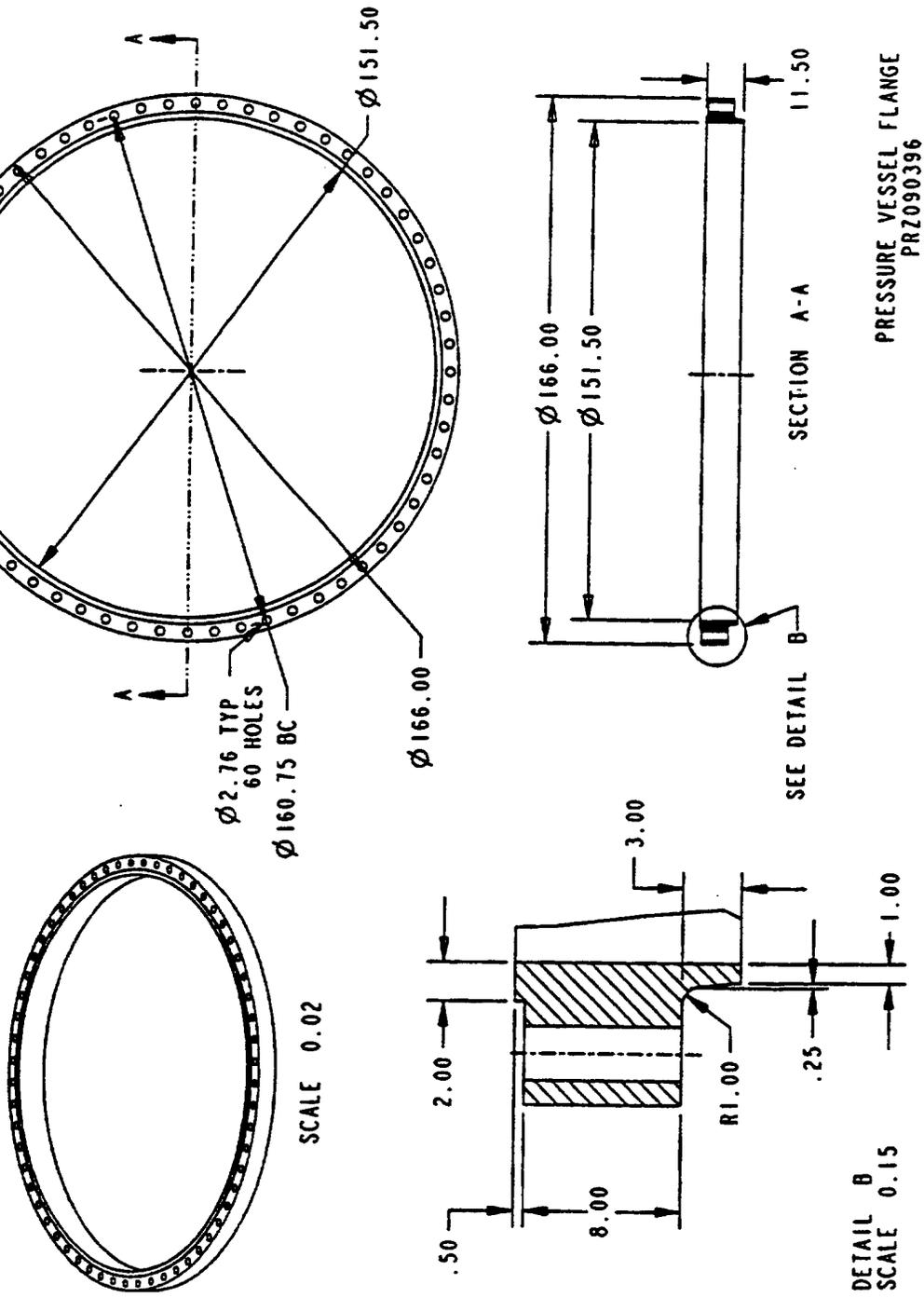
Figure 3.11 — PSOFC pressure vessel - flanges. [Dimensions in inches]

3-17

The left side flanged cover includes three penetrations, one upper exhaust outlet nozzle, one lower air inlet nozzle and one fuel inlet nozzle (not shown). The opposite side flanged cover, on the right, includes two penetrations for the electrical dc power leads plus additional smaller penetrations for each submodule internal instrumentation cables.

Bolting material for pressure connections must conform to the specifications listed in the ASME Code. Specifically, for this design, SA-193 Grade B7 (1 Cr-1/5 Mo) ferritic steel bolts have been selected. To minimize galling when the bolts are tightened, fasteners are made up with a thread lubricant such as Molykote paste. The proposed bolting configuration includes sixty bolts with a 2-3/4 inch bolt diameter in a bolt circle of 160.75 inches.

Appendix A includes a detailed engineering analysis of the pressure vessel components including side covers and flanges.

3.3.2 Internal Submodule Supporting Structure

As shown in Figure 3.12, the pressure vessel incorporates internally a two submodule supporting structure which is embedded in high temperature insulation material. This supporting structure is assembled by utilizing a series of equally spaced ceramic frames over which a steel beam deck is finally installed. This structure provides a convenient assembly passageway for piping, ducting, dc bus and electrical instrumentation without interfering with the assembly/disassembly of the submodules.

A complete assembly of the module internals, including two SOFC submodules and ducting is shown in Figure 3.13.

3.3.3 Air/Exhaust Piping

When both submodules are inserted and positioned within the pressure vessel, they are connected to a common central air feed manifold by utilizing individual spool pieces connected to each submodule inlet nozzle. The central manifold uniformly distributes the incoming pressurized process air to the individual submodules. The air manifold is positioned longitudinally within the pressure vessel, is supported by the ceramic frames and is embedded in the same insulation material surrounding the supporting structure. The final connection of the air manifold is made in correspondence to the side flanged cover nozzle through an expansion joint/adapter.
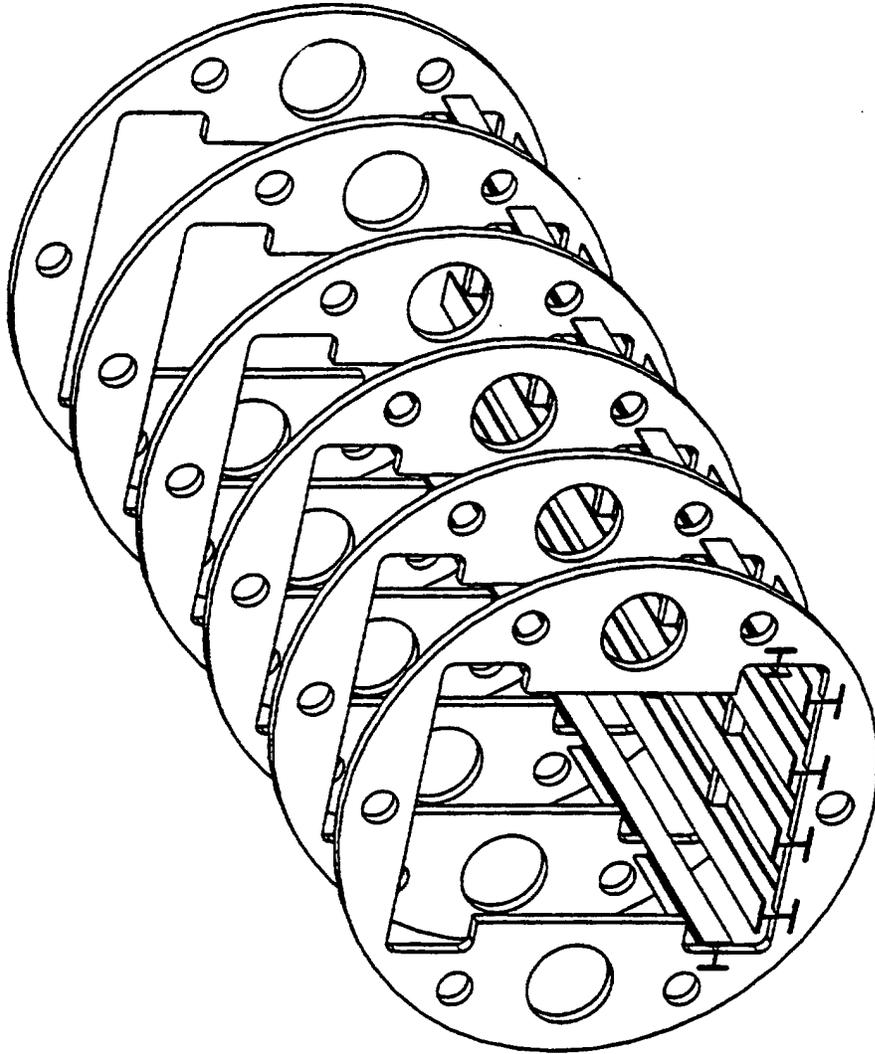
Figure 3.12 — PSOFC pressure vessel internal support structure.
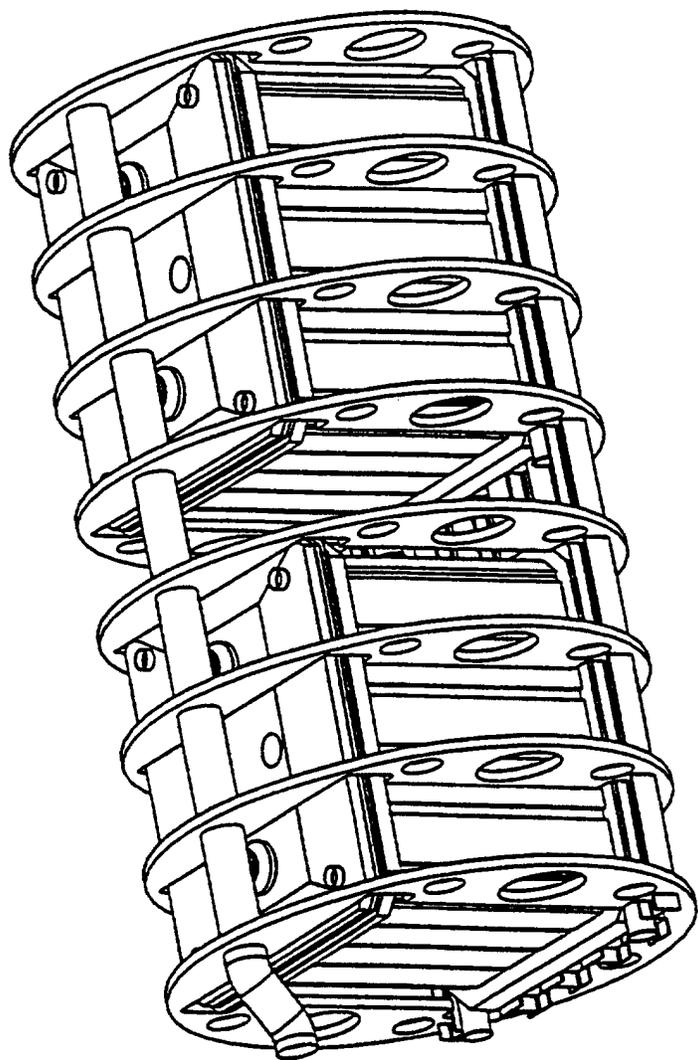
Figure 3.13 — PSOFC pressure vessel with submodules installed.

The exhaust gas flow from each stack is directed to an exhaust collecting plenum overhanging each submodule and is subsequently manifolded into a central duct exiting through the upper exhaust outlet nozzle.

The air ducting operates at a maximum temperature of 760°C [1400°F] and the exhaust ducting temperature does not exceed 871°C [1600°F]. Because the internal differential pressure between process air and exhaust is less than 1 psi as a result of only frictional losses and generator pressure drop, ducting rather than piping is utilized internally. Externally, all piping is fabricated to withstand a 150 psi design pressure.

3.3.4 Fuel Inlet Piping

The fuel inlet piping will operate at a pressure of approximately 50 to 70 psi differential inside the pressure vessel and up to 180 to 200 psi externally. The final pressure will have to be determined on the basis of the selected generator operating range, fuel composition and gas turbine selection.

3.3.5 Purge Air System

Purge air is continuously pumped into the pressure vessel volume for safety reasons. This air flow surrounds the insulated plenum between the inner wall of the pressure vessel and each submodule. It escapes through a gap between the collecting plenum and the submodule and is subsequently entrained by the exhaust gas. This arrangement ensures that the canister will depressurize, if the vessel becomes depressurized. All the purge air is tapped from the main compressed air piping feeding the main vessel.

3.3.6 Electrical Interconnections

Internal electrical interconnections between submodules are accomplished through utilization of a main dc bus bar and flexible cable connectors clamped to each submodule power lead.

High reliability electrical feedthroughs are utilized on the pressure boundary of the module in order to guarantee sound electrical connection between the internal submodules and the external Power Conditioning System.

3.3.7 Generator Instrumentation

The SOFC generator module is equipped with a variety of instrumentation which provides for automatic control with manual capability for plant operation, monitoring and diagnostics.

The generator submodule is instrumented primarily with dc voltage taps and cell stack thermocouples. Within the cell stack, there are a number of voltage taps which monitor the progressive buildup of accumulated cell voltages with the first tap near ground potential and the last at the maximum dc voltage. The submodule external terminal voltage is also monitored as well as the main generator module terminals.

A number of thermocouples are embedded within each cell stack at different elevations to monitor and control the temperature of the generator submodule.

A number of pressure taps may be included into each submodule fuel supply system to monitor differential pressures around the fuel ejector systems and to provide gas sampling as required.

3.3.8 Module Insulation

To minimize heat losses from the internal submodules and at the same time maintain the pressure vessel wall temperature within reasonable limits, it is necessary to embed all the internals in thermal insulation without impairing the capability to easily service and replace internal components including the generator submodules.

This insulation package is composed of modular shapes of high thermal performance insulation material fitted between each frame and around all main manifolds and piping spool pieces.

4. MAJOR SUBSYSTEMS

4.1 GAS TURBINE

The components comprising the GT are factory-mounted on a single skid. They are the turbine, generator, a power conversion cabinet, and a turbine controls cabinet. The skid footprint measures approximately 1.5 m x 2.0 m, and its overall height is approximately 1.5 m. The generator is a high-speed alternator; it is installed on a single shaft with the radial-inflow turbine and the centrifugal compressor. The alternator generates high-frequency alternating current (ac). This ac is converted by the power conversion equipment to direct current, which is then returned to ac form at the required frequency. The overall efficiency of this double conversion process is comparable to that of conventional ac generators.

For the present design study, the 300 kW direct-drive turbine-generator being developed by Solar Turbines, Inc. served as the turbine-generator model. The turbine inlet temperature and compressor pressure ratio for that machine, 970°C and 3.8:1, were retained for use in the study, but the compressor air flow rate was scaled down to achieve a turbine power output of 225 kW. This provided for a good turbine match with the single SOFC module, and it enabled the generation of 1 MW net ac at maximum efficiency by the integrated PSOFC/GT power system. While a turbine-generator having this exact combination of key operating parameters may not be presently available, there is sufficient development activity in the micro-turbine area such that the near-term availability of such a turbine, or one sufficiently similar to it, may be anticipated.

4.2 DEPLETED FUEL CONDENSER

4.2.1 Specifications

Complete specifications for the depleted fuel condenser design, shown in Figure 4.1, are presented in Table 4.1. Air is used as the heat sink, and it is required that the condenser be able to deliver sufficient condensate when the supply air temperature is as high as 43°C [110°F].
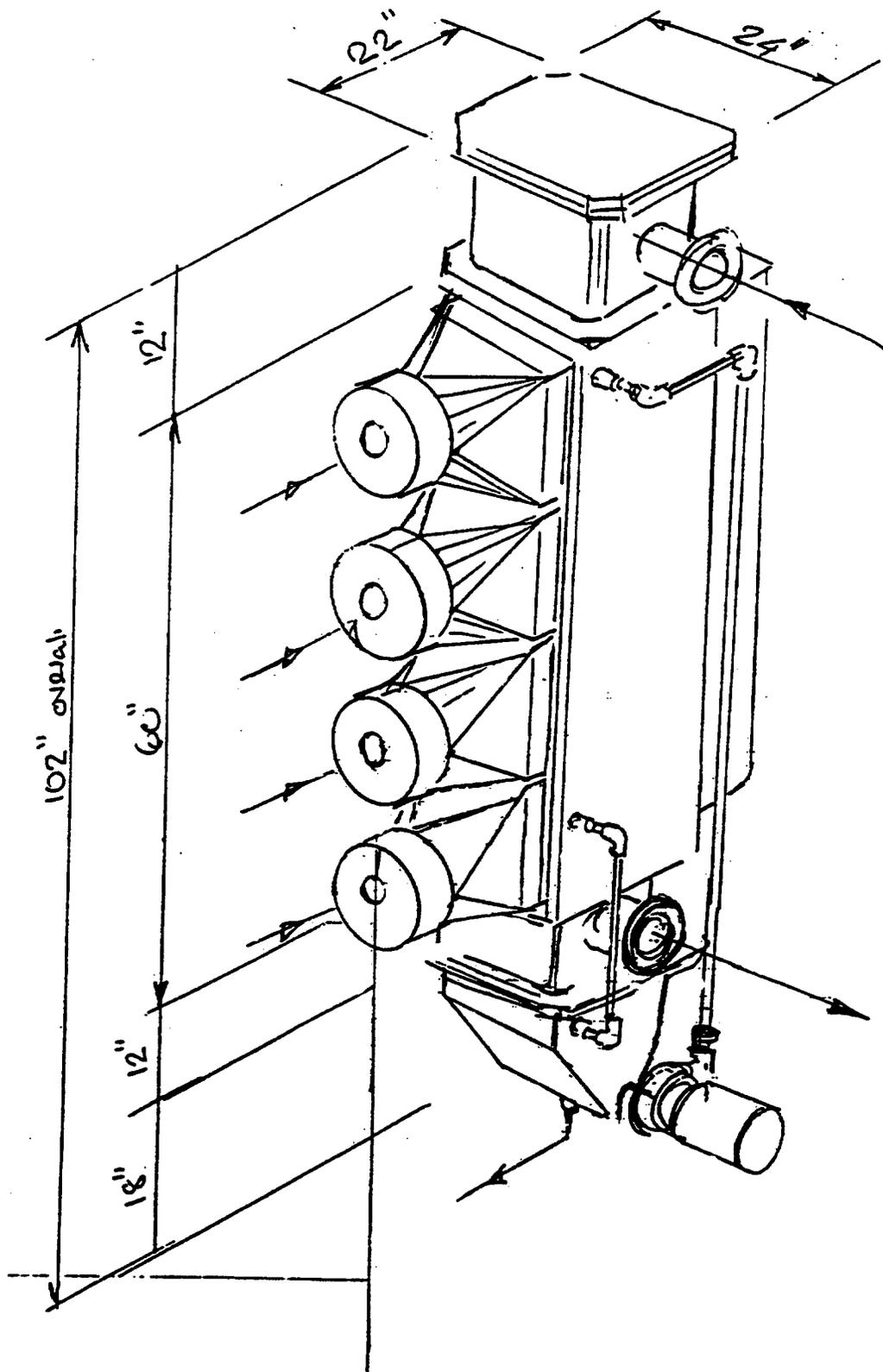
Figure 4.1 — Depleted fuel condenser conceptual design. [Dimensions in inches]

Table 4.1 — Specifications for the Depleted Fuel Condenser[*]

Duty Type	Partial Condenser		
	Extraction of water from H_2O, CO, CO_2, H_2 mixture		
Configuration	Condensing within vertical tubes in down flow		
Coolant	Air		
Coolant Passage	Single pass cross flow over finned tube bank		
Thermal Load	439.5×10^3 Btu/hr.		
Tube Side Inlet Conditions	Pressure	52 psia	
	Mixture Temperature	484°F	
	Flow Rate	1921 lb/hr	
	Mole Fraction	H_2O	.532
		CO	.028
		CO_2	.354
		H_2	.086
Tube Side Exit Conditions	Pressure	50 psia	
	Mixture Temperature	232°F	
	Gas & Vapor Flow Rate	1600 lb/hr	
	Condensate Flow Rate	321 lb/hr	
	Mole Fraction Noncondensed	H_2O	.383
		CO	.037
		CO_2	.466
		H_2	.114
Air Side Inlet Conditions	Max. Inlet Temperature	110°F	
	Pressure Over Atm	1 in H_2O	
	Flow Rate	4470 cfm	
	Face Velocity	11.9 ft/sec	
Air Side Exit Condition	Temperature Elevation Over Inlet	100°F	
	Exit Temperature	210°F	
Number of Condenser Tubes	23		
Tube Type	Circular aluminum fins over stainless steel (304) tube		
Tube Outside Diameter	1 in.		
Tube Wall Thickness	.065 in.		
Fin Root Diameter	1.030 in.		
Fin Outside Diameter	2 in.		
Fins Per Inch	11		
Fin Thickness	.015 in.		
Outside/Inside Area Ratio	21.53		
Tube Length	5 ft.		
Tube Pattern Air Inlet to Air Exit	Row of 5 followed by Row of 4 followed by Row of 5 followed by Row of 4 followed by Row of 5		
Tube Pitch	3.0 in. (equilateral)		
Overall Heat Transfer Coefficient Referred to Tube Inside Wall	102.6 Btu/ft^2 hr °F		
True Mean Temperature Difference	163.5°F		
Tube Inside Wall Surface Area	26.2 ft^2		

Note: Mass flows are 1.5 times those required for two SOFC submodules at design point. One depleted fuel condenser required for each of three PSOFC/GT systems.

4.2.2 Condenser Type and Configuration

The condenser is perhaps best characterized as an in-tube vertical downflow unit. Despite the fact that condensation takes place in the presence of noncondensibles (CO, CO_2 and H_2), the condensing heat transfer coefficient is much higher than the heat transfer coefficient between the tube surface and the air coolant. For this reason, the depleted fuel stream, from which the water is to be condensed, is confined to flow within the tubes while the air flows over the outside of the tubes. The outside tube surface is extended by virtue of fins. The chosen fin pattern provides an outside to inside tube surface area ratio of 21.5 to 1.

A viable design resulted from the use of 23 condenser tubes (7/8 in. I/D) using circular fins of 2 in. O/D at a density of 11 fins per in. Condensate and a mixture of uncondensed steam and noncondensible gases passes from the heat transfer section downwards through plain tube extensions into a hot-well section. The gas and vapor fraction rise through a separate plate to enter an exhaust take-off plenum which is sandwiched between the heat transfer section and the hot well. Condensate forms a liquid level within the hot well. To ensure adequate subcooling of liquid prior to the let-down of pressure, the contents of the hot-well are pumped and thus recirculated through an externally finned subcooler tube which is located in the coolant air path directly upstream of the condenser tubes.

4.3 THERMAL MANAGEMENT SYSTEM

The function of this system is twofold. Using sensible heat recovered from the turbine exhaust stream, it preheats SOFC inlet air, and it generates steam for the LFP at the prescribed pressure, temperature, and flow rate. Figure 2.2 schematically shows the arrangement of components in the thermal management system. The steam generating function is performed by a heat recovery steam generator (HRSG) that consists of an economizer, evaporator, and a steam superheater section. The economizer, located at the exhaust-exit end of the thermal management system, heats feedwater to within 5-10°C of the steam saturation temperature. The feedwater is delivered from the condensate tank to the economizer by the feedwater pump.

From the economizer, the feedwater is delivered to the evaporator where saturated steam is generated, and from the evaporator steam drum, the steam flows to the superheater where the required final steam temperature is achieved. The recuperator, for preheating SOFC inlet air, is positioned between the HRSG evaporator and the superheater. Future power system design projects could evaluate the performance and economics of two-pressure and three-pressure evaporators. Such units could increase the power system efficiency.

It is anticipated that the thermal management system components will be factory-installed on a single skid. The skid will be truck-transportable and will arrive at the installation site ready for interfacing with other power system hardware. The footprint projected by the thermal management system is estimated at 2 m x 6 m, and its overall height will be approximately 2.5 m.

4.4 POWER CONDITIONING SYSTEM (PCS)

The primary function of the power conditioning system is to convert the dc electric power produced by the SOFC module to controlled three phase ac power for delivery to the electric utility grid consistent with utility interface specifications. In addition, the system must isolate and protect the fuel cell from any utility grid disturbances as well as prevent reverse power flow back to the SOFC module. It also must deliver power to the grid based on either a dc demand signal or an SOFC power demand signal, either of which can be continuously variable from 0 to 100% of rating.

The PCS design includes a three-pulse dc boost chopper and two three-phase converter bridges that combine to form a twelve-pulse self-commutated voltage source inverter for interface to the ac grid. A one line diagram of the general power circuit is shown in Figure 4.2. As indicated in the figure, the controlled power switches are gate-turn-off (GTO) thyristors which are well matched in ratings to the power conditioner requirements. It is noted that the present PCS configuration, as the figure indicates, includes a standby power dissipator for temporary use in the event the utility grid becomes unavailable for power export.
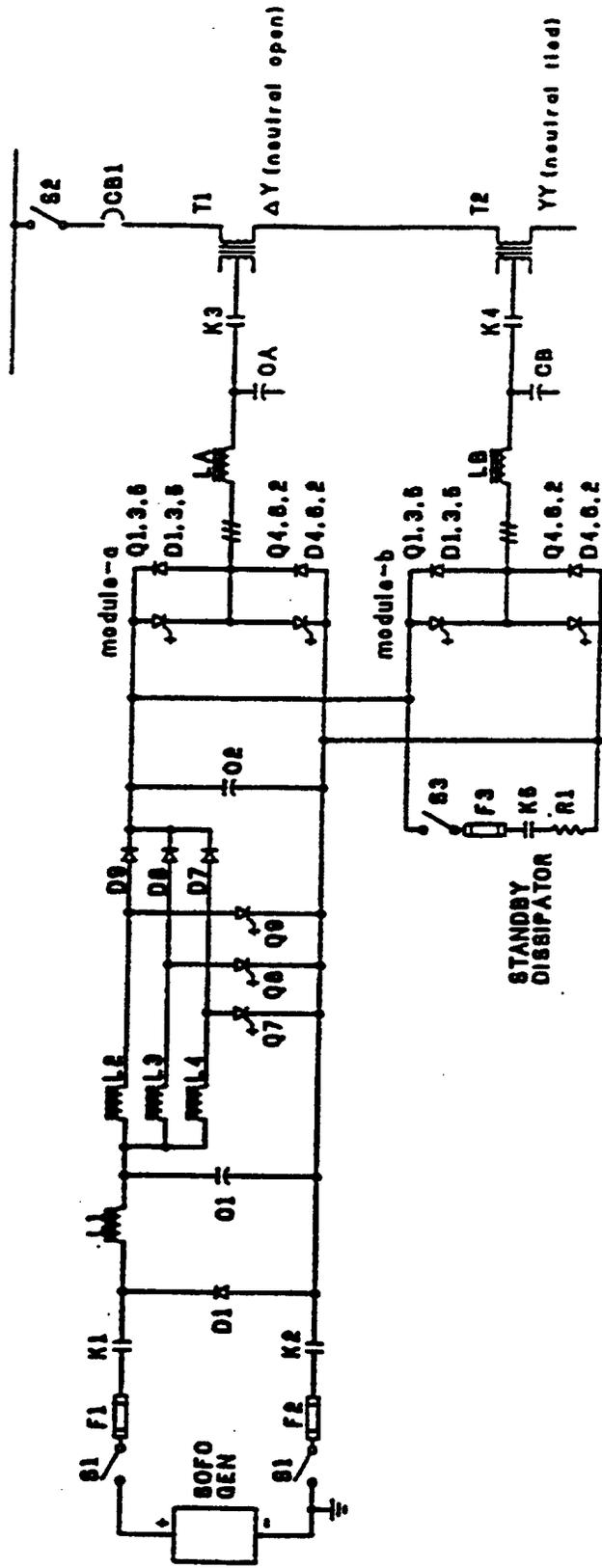
Figure 4.2 — PCS schematic diagram.

At the power system design point, the dc-to-ac efficiency of the PCS is 96%. It is estimated that the PCS and switchgear equipment related to the SOFC module will be housed in cabinetry that projects a footprint measuring approximately 3 m x 4 m; the approximate cabinet height is 2.7 m.

4.5 INSTRUMENTATION AND CONTROL SYSTEM (I&C)

The power system requires continuous modulating control of SOFC/gas turbine fuel flow, SOFC module temperature, SOFC and gas turbine loads, and of discrete devices such as solenoid valves and relays. Critical parameters are to be continuously monitored for alarm conditions. If an alarm condition is detected, the power system dispatching center will be alerted and the I&C system will initiate appropriate automatic actions to protect the power system and personnel. The I&C system includes the following:

- Field instrumentation - thermocouples, pressure transducers, mass flow controllers, voltage taps, etc.
- Operator interface computers, data storage devices, and printers.
- Control modules for performing continuous modulating and discrete control.
- Process interface hardware consisting of input/output modules and termination panels.
- Instrumentation and appropriate control software to enable system configuration and qraphical user interface displays.
- Signal conditioners for converting field device voltage signals to voltages (5 Vdc) that are compatible with the process interface hardware.
- Voltage dividers for converting high-voltage signals from the SOFC module voltage taps to voltages that are compatible with the process interface hardware.
- Single-loop controllers for providing local control for stand-alone systems.
- Data highway permitting multiple drops to be attached to the highway.

The I&C system design will be developed such that such power system control can be exercised either locally or remotely.

5. DESIGN BASIS OF 3 MWe LOGISTIC FUEL PROCESSOR

5.1 PROCESS DESIGN BASIS

5.1.1 Battery Limits

All equipment and process streams required to convert a liquid fuel to a methane rich gas for the solid oxide fuel cell powerplant, from the liquid fuel storage and supply to the product exit streams. Utilities required for the fuel processor are considered within the battery limits. However, steam will be provided by the fuel cell powerplant heat recovery unit at the temperature and pressure required.

5.1.2 Fuel

Diesel Fuel (DF-2) U.S. Mil spec VV-F-800D (except for sulfur content which is specified below) - and Jet Fuel (JP-8) U.S. Mil spec Mil-T 83133D

    a.   General Characteristics

        1.   Diesel Fuel

Specific Gravity	0.843
Boiling Point Range, °C	
- IBP	190
- 50%	284
- 90%	358
- FBP	366
C/H, wt/wt	6.6 (approx.)
Molecular Weight, g/mole	220 (approx.)
Aromatic Content, wt%	25-30

        2.   Jet Fuel

Specific Gravity	0.815
Boiling Point Range, °C	
- IBP	164
- 50%	206
- 90%	240
- FBP	266

	C/H, wt/wt	6.3 (approx.)
	Molecular Weight, g/mole	161 (approx.)
	Aromatic Content, wt%	22-28

b.	Sulfur content, wt%	0.3 (with option for 0.05)
c.	Temperature, °C	ambient (see climatic conditions)
d.	Delivery pressure, abs bar	1 (see climatic conditions)
e.	Flow rate, kg/hr	500

5.1.3 Fuel Cell Anode Feed - Wet Methane Rich Syn Gas

a.	O/C	2.5
b.	Minimum Methane Content (mole %, dry)	50
c.	Pressure, bar abs	>1.0
d.	Temperature, °C	490-525
e.	Flowrate, kg/hr	1847-2257

5.1.4 Utilities:

a. Nitrogen (start-up and shutdown only):

	Purity	
	N_2 by volume dry	99.9% (min)
	O_2 by volume dry	100 ppm max.
	Quality	oil free
	Pressure, barg	10
	Temperature, °C	ambient

b. Hydrogen (start-up only)

	Composition, mole %	99.9
	Pressure, bar, maximum	61.0
	Pressure, bar, normal	46.0
	Temperature, °C	Ambient
	Flowrate, Kg/hr	8.25 (approx.)

c. Instrument Air:

	Quality	oil free
	Pressure, barg	6.9
	Temperature, °C	ambient
	Dew Point, °C (max)	-20

d.   Electricity

Phase/Frequency	3 /60 Hz
Electric Power Supply	480 VAC
Motors 200 hp and less	480 volts
Lighting	110/208 volts

5.1.5 Climatic Conditions:

Category	Design	Range
Elevation Above Sea Level	0 ft	0-5000 ft
Ambient Temperature	59°F	-25 to 125°F
Relative Humidity	60%	0-100%
Wind Loading @ 33 ft	30 psf (note 1)	-
Snow Load	30 psf (note 2)	-
Precipitation (25 yr, 1 hr)	2.5 inches	-
Seismic	UBC Zone 2	-
Ambient Dust Loading, Ave/Yr	27 $\mu gm/m^3$	-

Notes: 1)   This wind load at 30 psf is based on a wind speed of less than 90 mph
and Exposure C.
2)   This snow load is equivalent to a ground snow load of 40 psf and a snow
exposure factor of 0.7 per UBC-94.

5.1.6 Miscellaneous

a.	Transportation	Truck transportable
b.	Turndown, %	50

5.1.7 Codes and Standards

In general, United States industry standards will be followed.

5.2 PROCESS DESCRIPTION

5.2.1 Introduction

The following is a description of the processes used to convert raw diesel or jet fuel feed into a methane product which can be used as fuel in a solid oxide fuel cell. The process flow diagram for the Logistic Fuel Processor is shown in Figure 5.1.

DESCRIPTION		RAW DIESEL		DIESEL & RECYCLE H2		PSA H2						GAS FROM SEPARATOR		
COMPONENT	MOL WT	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMO
OXYGEN	31.999													
HYDROGEN	2.016				83.06		100						30.76	
NITROGEN	28.013													
CARBON MONOXIDE	28.011												1.09	
CARBON DIOXIDE	44.010												18.94	
ARGON	39.948													
METHANE	16.043												49.21	
DIESEL			100		16.94									
TOTAL (DRY)		2.28	100.00	13.43	100.00	11.15	100.00		100.00		100.00	42.65	100.00	4
WATER KMOL./HR.		0.0			0.0		0.0					0.42		1
TOTAL KMOL/HR (WET)		2.28		13.43		11.15						43.07		5
TOTAL KG./ HR.														
AVG. MOL. WT.			220		38.91		2.02						17.16	
PRESSURE, BAR ABS			ATM		45.1		18.0						19.6	
TEMPERATURE, DEG. C			25		57.9		45.0						60.0	

R-101	H-101	R-102 A/B	R-103	P-101A/B	E-101	E-102	K-102
HYDROGENATOR	START UP HEATER	DESULFURIZER	PREREFORMER UNIT	FEED PUMPS	RECYCLE COOLER	FEED/EFFLUENT EXCHANGER	HYDROGEN RECYCLE COMPRESSOR

LEGEND		REV	DATE	
△	STREAM NUMBER	△		
○	PRESSURE, BAR ABS	△		
□	TEMPERATURE, C	△		
⊃	DUTY, KV	△2	7/23/97	REV
⬭	FLOW, KG/H	△1	11/5/96	GENE
⬭	FLOW, m3/h	△0	10/3/96	ISSU
⊃	POWER, KV			

CALCULATION # 175984

Figure 5.1 — Logistic Fuel Proce

MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %	KMOL/HR	MOL %
11.65		6.25														A
1.39		1.47														
24.17		25.64														
62.79		66.64														
100.00	31.50	100.00		100.00		100.00		100.00		100.00		100.00		100.00		100.00	B
	0.42															
	31.92															
17.16		22.46														
2.0		1.5														
459.0		35.0														

103   E-104   K-101   E-107   E-106   X-100   B-101   FR-1

ED   PSA   PSA   BFW PREHEATER/   AIR   PSA   REFORMED GAS   FLARE

RIZER   OFF GAS   OFF GAS   STEAM PRODUCTION   COOLER   SEPARATOR   (BY OTHERS)

         HEATER   BLOWER

STEAM   FLARE

SOFC AND WASTE
HEAT RECOVERY
SECTION

PSA

X-100

K-101

E-103   E-107   B-101

K-102

E-104   E-106

BFW

CONDENSATE

DESCRIPTION	DRAWN	CHECKED	DRAWN BY	JFC	8-19-96		HALDOR TOPSOE, INC.
			CHECKED				HOUSTON, TEXAS
			PROCESS APPROVED	AGP	9/16/96		VESTINGHOUSE ELECTRIC CORP. PITTSBURGH, PENNSYLVANIA
D CONFIDENTIALITY	BVD		PROCESS MGR APPROVED	JHH	10/31/96		3 MW LOGISTIC FUEL FIXED BASE POWER PLANT
L REVISION	CRS		PROJ MGR APPROVED	HHP	9/16/96		LOGISTIC FUEL PROCESSOR
OR ENGINEERING DESIGN	JFC		CLIENT APPROVED				PROCESS FLOW DIAGRAM

		SCALE	DRAWING NUMBER	REV.
		NONE	65036-FD-010	2

6   7   8   9   10

or Process Flow Diagram.

5.2.2 Desulfurization

The catalysts employed for the steam reforming process are extremely sensitive to sulfur compounds since these will cause deactivation.

Most hydrocarbon feedstocks will normally contain appreciable amount of sulfur-bearing compounds. This should be removed before the steam reforming. This is done in the desulfurization section.

The continuous leakage of sulfur to the reformer from all sources (feedstock, recycle, steam) should preferably be less than 1 ppm by weight relative to the diesel feed. The required adiabatic prereforming catalyst volume is to a large extent proportional to the sulfur concentration in the desulfurized feedstock. The remaining sulfur present in the feedstock, after desulfurization, will be quantitatively absorbed on the prereforming catalyst.

The desulfurization unit contains three reactors, a reactor loaded with nickel-molybdenum-oxide hydrogenation catalyst followed by two reactors containing zinc-oxide sulfur absorption catalyst.

The first reaction in the desulfurization system is catalyzed by a nickel-molybdenum hydrogenation catalyst in a single hydrogenation bed, which is sized to hold enough catalyst for 5 years of operation. The recommended Topsoe catalyst TK-525 has a bulk density of about 0.72 kg/l. The catalyst is delivered as 1.6 mm to 3.2 mm cylinders. It catalyzes the following reactions:

$$RSH + H_2 \rightarrow RH + H_2S$$
$$R_1SSR_2 + 3H2 \rightarrow R_1H + R_2H + 2H_2S$$
$$R_1SR_2 + 2H_2 \rightarrow R_1H + R_2H + H_2S$$
$$COS + H_2 \rightarrow CO + H_2S$$
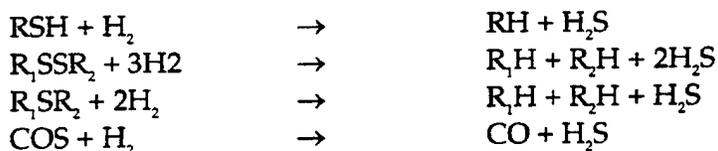
where R is a radical of hydrocarbon.

The feed is diesel/hydrogen mixture beginning with raw diesel flow of 500 kg/h which is pumped to a pressure of 45 bar abs in the feed pump, P-101A/B. Hydrogen from the hydrogen recycle compressor, K-102, is mixed with the high-pressure diesel at a rate of 22.5 kg/hr. The mixture is heated to 385°C in the feed vaporizer, E-103, immediately before entering the hydrogenator, R-101.

Having passed the hydrogenation catalyst in the first reactor, the hydrogen sulfide is absorbed in the second and third reactor in this section - R-102 A/B, which are sized to hold sufficient catalyst for 2500 hours of operation.

The two reactors situated in series are identical. Two reactors were being used in order to meet height restrictions. Each of the two reactors is loaded with Topsoe sulfur absorption catalyst HTZ-3 which is delivered in 3 mm cylindrical extrudates. The bulk density is approximately 1.35 kg/l. The zinc oxide reacts with the H_2S according to the following equation:

$$H_2S + ZnO \qquad\qquad ZnS + H_2O$$

During normal operation, the sulfur content of the feedstock in contact with the zinc oxide catalyst is reduced according to the equilibrium constant:

$$H_2S/H_2O = 1.3 \times 10^{-6}$$

Gas exiting the desulfurizer is heated to 490°C in the feed/effluent exchanger, E-102, before mixing with the steam and passed on to the prereforming unit.

5.2.3 Reforming Section

The mixture of desulfurized feed and steam is sent to the prereforming section where decomposition of hydrocarbons take place over nickel catalyst by reaction with steam.

The steam reforming of hydrocarbons can be described by the following reactions:

(1) $\qquad C_nH_m + nH_2O \qquad\qquad nCO + (n + m/2)H_2$

(2) $\qquad CH_4 + H_2O \qquad\qquad CO + 3H_2$

(3) $\qquad CO + H_2O \qquad\qquad CO_2 + H_2$

Reaction (1) and (2) are endothermic while reaction (3) is exothermic.

In the operation of the prereformer system, carbon formation outside and/or inside the catalyst particles is possible. Carbon deposits outside the particles will increase the pressure drop over the catalyst bed, and deposits inside the particles may reduce their mechanical strength and activity.

In the prereformer, carbon formation is thermodynamically not possible at the conditions foreseen if equilibrium is obtained for each step. However, if the catalyst is deactivated, for instance by sulfur, it will lose its activity and carbon formation may occur. The lower the sulfur content, the better the catalyst will retain its activity.

At very low steam to carbon ratios, there will be a thermodynamic possibility of carbon formation which would result in carbon lay-down, especially inside the catalyst particles. The ratio used in the present unit is sufficiently above the ratio where carbon formation under equilibrium conditions on the catalyst is possible.

The steam reforming takes place in the prereformer, R-103, which is sized to hold enough Topsoe type RKNGR catalyst for 2500 hours of operation. The RKNGR catalyst, decomposes the higher hydrocarbons into hydrogen, carbon monoxide, carbon dioxide, and methane corresponding to reaction schemes (1), (2), and (3).

The RKNGR catalyst is specially treated for low temperature operation (i.e., less than 500°C). The catalyst size is 4.5 x 4.5 mm with a bulk density of 1.35 kg/l. The RKNGR catalyst as supplied is prereduced. It is not pyrophoric at temperatures below 60°C. It may be handled without any difficulties in atmospheric air during loading of catalyst.

RKNGR needs no special activation at start-up of the unit, but great care should be taken to always maintain a reducing atmosphere in order to avoid oxidation of the catalyst which would necessitate a reactivation or replacement of the catalyst.

The reduced RKNGR catalyst is active above a temperature of 400°C, and it is stable at temperatures well in excess of the maximum obtained during normal operation. The decrease in activity will, under normal operation and reducing conditions, be a slow process. The catalyst may, however, be deactivated by a variety of compounds that may be introduced with the process feed or the steam.

As the feed to R-103 will always contain minor amounts of sulfur, a progressive deactivation of the catalyst during its' lifetime will be experienced.

If the steam to carbon ratio drops to very low levels, and especially if the steam flow should stop completely, even for some seconds, a heavy carbon lay-down must be expected.

If the catalyst is exposed to steam alone, it will be oxidized and must be reactivated at the next start-up. Reactivation of the RKNGR catalyst may be carried out in a hydrogen rich stream at the same temperature at which it was oxidized.

The methane – rich gas leaving the prereformer is the main feed sent to the SOFC unit. A small slipstream is – after cooling – passed to a pressure swing absorption unit for recovery of pure hydrogen for the hydrogenation reactor. The PSA off-gas is mixed with the main feed to the SOFC unit.

5.3 DESCRIPTIVE START-UP PROCEDURE

5.3.1 Utilities Required

Electric power 480 V 3ϕ; 120 V, 1ϕ

Instrument air

5.3.2 Feedstocks/Start up Materials

Material	Specification	Quantity
$H_2(g)$	Per Design Basis @45 barg	1,500 Nm³
$N_2(g)$	Per Design Basis @10 barg	36,000 Nm³
Deionized or Boiler Feed Water	37 barg min. pressure	19,200 kg (max.) or 9,300 kg (min.*)
Diesel feed	Per Design Basis	

*assumes fuel cell can reprocess process condensate and return to reformer area

5.3.3 Procedure

After installation of catalyst and calibration of instrumentation, the flow of N_2 is initiated at reduced pressure. Flow will be routed through the start up heater (H-101), R-101, and R-102 on a once-through basis to heat the vessels to operating temperature. The pressure is slowly increased to operating pressure. The N_2 flow can then be stopped to R-101 and R-102.

The flow of diesel and H_2 is started at 1.5 times the normal hydrogen to diesel ratio via the start up heater. Vaporized diesel and hydrogen continues to flow through R-101 and R-102 with the desulfurized product vented to the flare. This will continue until analysis exit R-102 determines that the feedstock sulfur content has been reduced to design levels.

While R-101 and R-102 are being operated on diesel/H_2 feed, N_2 on a once-through basis is introduced to R-103. Heated nitrogen from the start up heater is routed to R-103 to heat the reformer to operating temperature. When R-103 is at operating temperature, steam generation is begun by introduction of water to the start up heater and venting the steam to atmosphere.

When the sulfur content of the desulfurized diesel vapor meets design levels, steam is introduced into R-103 and K-103. Steam to feed ratio for start up would be 1.5 times the normal ratio.

Immediately after the introduction of steam to R-103, the product of R-102 shall be introduced into R-103 and the N_2 flow cut off.

The product gas from B-101 can be flared or sent to the fuel cell area for use as start-up fuel.

When stable operation through the unit is established, the H_2/feed and steam/feed ratios can be reduced to normal levels. The H_2/diesel feed can also be diverted from the start up heater to E-103.

At this time, the PSA unit, together with K-101 and K-102, can be put into operation. When stable operation is achieved, the recovered H_2 from K-102 can be introduced into the H_2/diesel feed stream and he H_2 flow to the start up heater shut off.

When the steam source from the fuel cell area is established, water flow to the start up heater can be terminated and the start up heater shut down.

The estimated time for the fuel processor start up is 20-24 hours from cold.

Normal operations would then continue.

5.4 PRODUCTION & CONSUMPTION FIGURES

5.4.1 Production:

a. Methane Rich Syn Gas:

Pressure:	2	bar abs
Temperature:	459	°C
Flow Rate:	1180	Nm³/h
Mol Weight:	20.56	
Composition: Hydrogen	11.65	Mole % (dry)
Carbon Monoxide	1.39	"
Carbon Dioxide	24.17	"
Methane	62.79	"
Steam/Methane Ratio:	0.48	"

b. Condensate:

Flow:	1017	kg/h

c. Hot BFW:

Flow:	7206	kg/h
Inlet Temp.:	25	°C
Temp. Increase:	80	°C

5.4.2 Consumption:

a. Diesel:

Flow, kg/h	500	kg/h

b. Steam:

Flow:	1600	kg/h
Pressure:	35	bar abs
Temperature:	480	°C

c. Electricity:

P-101A/B	1	kW
K-101	14	kW
K-102	14	kW
E-106	3	kW
Total Duty:	33	kW

5.4.3 Vessels

Item No.	Description	ID, mm	t-t, mm	Type	Design TP °C/bar	Material
B-101	Reformed Gas Separator	500	3500	Vertical with Demistics	90C/22.5	SS316

5.4.4 Misc.

Item No.	Description	Type
X-100	PSA Unit	Package Unit

5.4.5 Heat Exchangers

Item No.	Description	TEMA Type	Area m²	Design T/P °C/bar		Material	
				Shell	Tube	Shell	Tube
E-101	Recycle Cooler	BEM	2.6	560/24	460/24	SS	SS
E-102	Feed/Effluent Exchanger	BEM	2.7	520/30	550/30	SS	SS
E-103	Feed Vaporizer	BEM	4.7	415/50	500/50	SS	SS
E-104	PSA off-gas Heater	BEM	11.8			CS	SS
E-106	Air Cooler						
E-107	BFW Preheater	BEM	9.9	150/23	270/93	CS	SS

5.4.6 Pumps

Item No.	Description	Type	Driver	Horsepower, kw
P-101AIB	Feed Pumps	Positive Displacement Metering	Electric Motor	1

5.4.7 Compressors

Item No.	Description	Type	Driver	Horsepower, kw
K-101	PSA off-gas Blower	Rotary	Electric Motor	14.3
K-102	Hydrogen Recycle Compressors	Reciprocating	Electric Motor	13.5

5.4.8 Reactors

Item No.	Description	ID, MM	t-t, mm	Design T/P, °C/bar	Material
R-101	Hydrogenator	600	4320	450/52	SA-204 Grade A
R-102A/B	Desulfurizer	1400	4740	450/52	SS-204 Gr. A
R-103	Prereformer	1430	4000	580/23.2	SA-204 Gr. 304 N

Contents

6. DISCUSSION

The design requirements set for the LFP required that all hydrogen needed for the hydro-desulfurization process be supplied by systems internal to the LFP. The design solution to accomplish this resulted in the use of a pressure swing adsorption unit and consequently a low fuel delivery pressure to the fuel cell system. Thus, even though the LFP has a very high nominal working pressure [circa 35 bar], the fuel delivery pressure to the fuel cell is 2 bar requiring a fuel compressor to increase the pressure to approximately 4 bar.

During start-up it is assumed that raw diesel fuel, stored process water, stored nitrogen, and stored hydrogen are available. During normal operation no stored consumable other than raw liquid diesel are necessary. For start-up it is assumed that the gas turbine systems will be fired with liquid diesel or jet fuel to provide electrical power, with the thermal management system recovering this heat for heating process air to the SOFC and raising steam for the LFP. Not shown in the process flow diagram are two duct burners that will be necessary to achieve start-up, the first in the process air stream to the fuel cell to assist in its temperature maintenance, and the second at the inlet to the heat recovery train to assist in the raising of steam during start-up. Some hydrogen is necessary to initiate operation of the desulfurizer and some hydrogen or equivalent is necessary in a reducing cover gas [3% hydrogen in nitrogen equivalent] to protect the SOFC anode at elevated temperature non-power producing states such as during start-up and shutdown. Estimated start-up time for the PSOFC/GT system given a methane rich fuel stream is eight to twelve hours. The start-up time for the LFP is approximately twice this and therefore limiting.

Water for LFP process purposes is recovered by condensation from the LFP feed to the SOFC system and from the SOFC spent anode gas. This condensation is accomplished against ambient air as the heat sink for several practical reasons. First, the LFP and the SOFC are located at significant separation distance making transport of heat an issue. Second, the gas streams from which water is to be condensed are very hot, limiting the practical choice for a heat sink fluid to a gas, especially when considering start-up, off design, and upset conditions.

The efficiency of the power system could be improved if this condensation energy could be fully applied to process steam generation.

Present Westinghouse SOFC stack technology utilizes an elegant seal-less design which requires no high integrity seals between cell elements, cells, or stack and manifolds. In order to recover sufficient process water to satisfy the LFP, the SOFC stack design must be modified so as to separately remove from the stack the spent anode gas and the spent cathode gas. In the present design, these two streams meet in a combustion zone. The separation between the active stack and the spent fuel plenum, and between the spent fuel plenum and the combustion zone is accomplished with ceramic insulation board baffles which are of a controlled leakage design so that by pressure balance the various zones are sufficiently isolated. In order to permit the extraction of all or at least most of the spent fuel not recirculated for methane reformation, the barrier between the spent fuel plenum and the combustion zone must be redesigned for higher flow impedance, and an additional exit penetration must be installed. The detailed design to accomplish this has not been performed, and the concepts under consideration must be verified by experiment in at least a bundle test.

The heat recovery section for the PSOFC/GT has been sized and analyzed to supply the entire heat burden for generating steam for the LFP from condensate. Inspection of the process flow diagram for the LFP shows a boiler feed water heater that could supply a fraction of this heat. In addition, within the PSOFC/GT system, the inlet fuel cooler/condenser and the spent anode gas condenser represent additional potential places where recovered heat could be used to reduce the heat burden on the SOFC heat recovery train. The design effort to accomplish this higher degree of thermal integration has not been expended. The estimated gain in system efficiency at design that thereby has been foregone is a few points. The tighter integration would most likely reduce operational flexibility. In addition, a coordinated trade-off study to optimize the operating pressure of the LFP considering the impact upon overall system efficiency has not been conducted. As pointed out in the PSOFC/GT design description, the thermal burden upon the SOFC thermal management system would be reduced considerably and system efficiency improved if lower pressure steam could be used by the LFP.

The PSOFC stack design uses in-stack reformers for natural gas [methane]. The catalyst in these in-stack reformers could be reformulated for higher hydrocarbons such as desulfurized diesel if the recirculation ratio of spent fuel to fresh fuel could be increased so as to ensure

sufficient water vapor and CO_2 to suppress carbon deposition and support diesel reformation. Unfortunately, the ejector concept can not yield the required recirculation ratio. A mechanical pump could yield the required recirculation ratio. The stack would require desulfurized diesel fuel however. The analysis of this system has been beyond the resources and constraints of this program.

The system configuration adopted for the preliminary design uses three PSOFC/GT systems of nominally 1 MW capacity interfacing with a single LFP. This configuration is judged to have the greatest operational flexibility and the highest probability of power generation availability. Perturbing the design to use two SOFC three-packs instead of three twin-packs and one or two gas turbines instead of three presents no particular challenge given the modularity of the fuel cell and the availability of small turbines. There is the potential to gain perhaps a point or two in efficiency because of lower heat losses and the higher inherent efficiency of larger turbo machines. The choice of SOFC twin-packs has been influenced in part by the fact that in the relatively near term Westinghouse plans to demonstrate a natural gas fueled system utilizing a pressurized SOFC twin-pack and a single GT.

7. CONCLUSIONS

1) A PSOFC/ GT combined cycle electric power generation system and a LFP can be integrated to produce a power plant for military fixed-base application fueled by either DF-2 diesel or JP-8 turbine fuel with an electric generation efficiency [net ac/ LHV] greater than 50 percent [estimating LFP parasitic electric power at one percent of power plant rating, or 30 kW and limiting thermal integration to the PSOFC/GT exhaust stream] that requires no process water.

2) The imposition of water neutrality on a system configuration utilizing an external LFP requires that the existing Westinghouse seal-less SOFC stack design be modified to permit separate exodus of spent anode gas and spent cathode gas so that process water for the LFP can be recovered from the spent anode gas. This design change may compromise an elegantly simple stack design and therefore represents a technical risk.

3) The thermal burden of hydro-desulfurization, plus adiabatic reformation dependent upon separation of water from fuel gas by condensation and the subsequent generation of steam from the condensate penalizes design basis system efficiency by ten points relative to the performance achievable by the PSOFC/GT using natural gas fuel [63%].

4) At the expense of increasing system complexity and decreasing operating flexibility the design point efficiency of the design basis system could be improved an estimated 3 to 5 points by tighter thermal integration.

5) The gain in power generation efficiency of a factor of two over simple gas turbine engine generator sets comes at the expense of more complexity, a longer start-up cycle, and considerably more real estate.

6) The PSOFC/GT/LFP military fixed-base power system is best suited to relatively stable locations with a continuous but not necessarily steady requirement for electric power, and considerable expense associated with delivery of fuel.

8. RECOMMENDATIONS

1) The preliminary design of a Westinghouse PSOFC/GT integrated with a Haldor Topsoe LFP should be enhanced in detail at 1 MWe scale, including tighter thermal integration, in order to contrast the design and performance with the natural gas fired system expected to be developed and demonstrated in the near future.

2) A preliminary design/ development study at 1 MW scale should be implemented to examine the feasibility of eliminating the separate LFP and utilizing instead a mechanical spent fuel recirculation pump for the SOFC stack and the in-stack SOFC reformers to accommodate jet fuel and perhaps diesel. [It is recommended further that this study be constrained to sulfur free liquid fuel in order to limit scope and cost. Further, it is recommended that fundamental parameters be verified in an SOFC bundle test.]

3) Given a favorable result from the design studies recommended above, a demonstration phase should be supported to complement the DOE funded SOFC development program.

9. NEW TECHNOLOGY

9.1 NON-PATENTABLE DISCOVERIES

The use of a mechanical anode gas recirculator in lieu of an ejector will enable very high spent fuel recirculation ratios which may permit the direct use of desulfurized logistic fuels in the SOFC stack.

9.2 PATENTABLE INVENTIONS

None.

APPENDIX A

Pressure Vessel Components engineering analysis per the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1

ASME Section VIII, Division 1
1992 Edition, 1993 addenda
Advanced Pressure Vessel
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Job/Quote No : 1   Customer:
Shell Desc. : SOFC HORIZ. CYL.
Designed: P.ZAFRED   Design Date: August 30, 1996
Checked :   Approved:
                 External loads do not control design.

             Cylindrical Shell - Internal Pressure
Design Pressure : 150.00 PSI   Static Head: 0.00 PSI
Shell Material : SA-516, Grade 70   Joint Efficiency: 70 Pct.
                                       Design Temperature: 70 °F
Matl stress(hot):   17500 PSI   Material stress (cold):   17500 PSI
Shell Length   : 300.000 In.   Corrosion Allowance : 0.0625 In.
Shell Area   : 1004.7 Sq. Ft.   Outside diameter :153.5000 In.
Shell Weight   : 40675.0 Lbs.
Specific Gravity: 1.0000   Shell Estimated Volume: 23413.9 Gal.
Weight of Fluid : 195601 Lbs.   Total Flooded Shell Weight:236276.3 Lbs.
Actual Stress   :   17457 PSI   Actual Longitudinal Stress: 8621 PSI

Min. temp curve : B   Minimum Design Metal Temperature: -20 °F
Pressure at MDMT: 150.00 PSI   Computed minimum temperature: 11 °F
UCS-66(b) reduction: Yes   UCS-68(c) reduction: No

          Longitudinal Stress Calculations - UG-27(c)(2):
t = PR /(2SE +0.4P) =150 * 75.8125 /(2 * 17500 * 0.70 ÷ 0.4 * 150)
t = 0.4630 +0.0625 (corrosion)   = 0.5255 In. min

          Design Thickness per Appendix 1-1(a)(1)
          Circumferential Stress Calculations:
t = PRo /(SE +0.4P) = 150 * 76.7500 / (17500 * 0.70 + 0.4 * 150)
t = 0.9353 +0.0625 (corrosion)   = 0.9978 In. min

          NOMINAL SHELL THICKNESS SELECTED = 1.0000 Inches

Westinghouse Energy Center
August 30, 1996

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Job/Quote No : 1   Customer:
Head Desc.   : COVER
Designed: P.ZAFRED   Design Date: August 29, 1996
Checked :   Approved:
                  External loads do not control design.

                  Ellipsoidal Head - Internal Pressure
Design Pressure : 150.00 PSI   Static Head: 0.00 PSI
Head Material   : SA-516, Grade 70   Joint efficiency: 70 Pct.
                                         Design Temperature: 70 °F
Matl stress(hot): 17500 PSI   Material stress (cold):   17500 PSI
Actual Stress   : 16254 PSI   Corrosion Allowance: 0.0625 In.
Head Location   : Bottom   Outside diameter :153.5000 In.
Head Quantity   :   2
Total Head Area :   361.5 Sq. Ft.   Total Head Est. Volume: 4155.2 Gal.
Total Head Wt. : 16571.9 Lbs.   Weight of Fluid :   34655 Lbs.
Specific Gravity: 1.0000   Total Flooded Head Weight: 51226.6 Lbs.

Straight Flange : 1.5000 In.   Thin Out : 0.0625 In.

Head Depth (ho) : 38.9375 In.   K = 1/6 [2 + Sq (D/2h)]:   1.00

Min. temp curve : B   Minimum Design Metal Temperature: -20 °F
Pressure at MDMT: 150.00 PSI   Computed minimum temperature: 8 °F
UCS-66(b) reduction: Yes   UCS-68(c) reduction: No

                  Design Thickness per APPENDIX 1-4(c)
t = PDoK / (2 SE + 2 P(K - 0.1))
t = 150 * 153.5000 * 1.00 / (2 *17500 * 0.70 + 2 * 150 (1.00 - 0.1))
t = 0.9296 +0.0625 (corrosion) +0.0625 (thin out) = 1.0546 In. min.

          NOMINAL HEAD THICKNESS SELECTED = 1.1250 Inches

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Flange description: SIDE FLANGES
:sign Pressure : 150.00 PSI   Design Temperature: 70 °F
.lange Material : SA-105
Hot Stress (Sfo): 17500 PSI   Cold Stress (Sfa): 17500 PSI
Flange Weight   : 18873 lb   Flange MAWP (at design):   0.00 PSI

MDMT Calculations

Min. temp curve : B   Minimum Design Metal Temperature: -20 °F
Pressure at MDMT: 150.00 PSI   Computed minimum temperature: 104 °F
UCS-66(b) reduction: Yes   UCS-68(c) reduction: No
Bolting Material: SA-193, Grade B7,>=2.5-4"
Hot Stress (Sb) : 97000 PSI   Cold Stress (Sa) : 97000 PSI
Wall Material   : SA-516, Grade 70
Hot Stress (Sno): 17500 PSI   Cold Stress (Sna): 17500 PSI
Wall thickness, tn: 1.0000 in.   Integral type config.: Fig. 2-4(6)

Gasket and Facing Details

Gasket Material : Spiral wound metal, asbestos filled
Gasket Type   : Carbon   Gasket Factor m: 2.50
Configuration   : Full face   Seating stress y: 10000 PSI

Bolting Details

Number of bolts :   60   Nominal bolt diameter (a): 2.7500 in.
Bolt root area : 5.2590 in^2   Bolt correction factor applied: No

Flange Dimensions

Bolt circle (C) :160.7500 in.   Outside diameter (A):166.0000 in.
¨nside diameter :151.5000 in.   Corrosion Allowance: 0.0625 in.
ɔrroded I.D.(B):151.6250 in.   .   Hub thickness at small end: 1.0000 in.
íub length (h) : 3.0000 in.   Hub thickness at large end: 1.2500 in.

Gasket Calculations

$) = (C - B) / 4 = (160.7500 - 151.6250) / 4 = 2.2813$ in.
$\iota G = (C - B)(2B + C) / (6 (B + C)) = 2.2590$ in.
$\iota G' = (A - C)(2A + C) / (6 (C + A)) = 1.3195$ in.
$\colon = C - 2 hG = 160.7500 - 2 * 2.2590 = 156.2320$ in.

Load and Bolting Calculations

$Gy = (Pi)bGy = Pi * 2.2813 * 156.2320 * 10000 = 11197015$ lb
$Gy' = (hG / hG') HGy = (2.2590 / 1.3195) * 11197015 = 19169425$ lb
$m2 = HGy + HGy' = 11197015 + 19169425 = 30366440$ lb
$= (Pi/4)(G^2)P = (Pi / 4) * Sqr(156.2320) * 150.00 = 2875551$ lb
$\jmath = 2b(Pi)GmP = 2 * 2.2813 * Pi * 156.2320 * 2.50 * 150.00 = 839776$ lb
$\jmath' = (hG / hG') Hp = (2.2590 / 1.3195) * 839776 = 1437707$ lb
$\mathfrak{n}1 = H + Hp + Hp' = 2875551 + 839776 + 1437707 = 5153034$ lb
$\mathfrak{n}1 = Wm1 / Sb = 5153034 / 97000 = 53.1241$ in^2
$\mathfrak{n}2 = Wm2 / Sa = 30366440 / 97000 = 313.0561$ in^2
$\iota = $ greater of Am1 or Am2 = greater of 53.1241 or 313.0561 = 313.0561 in^2
$) = $ No. of bolts * Bolt root area = 60 * 5.2590 = 315.5400 in^2
$= (Am + Ab)Sa/2 = (313.0561 + 315.5400) * 97000 / 2 = 30486911$ lb

Moment Calculations - Operating Conditions

$= (Pi/4)(B^2)P = (Pi / 4) * Sqr(151.6250) * 150.00 = 2708462$ lb
$= H - HD = 2875551 - 2708462 = 167089$ lb
$= ((C - B) / 2) - g1 = ((160.7500 - 151.6250) / 2) - 1.1875 = 3.3750$ in.
$= R + (g1 / 2) = 3.3750 + (1.1875 / 2) = 3.9688$ in.
$= (R + g1 + hG) / 2 = (3.3750 + 1.1875 + 2.2590) / 2 = 3.4108$ in.
$= HD * hD = 2708462 * 3.9688 = 10749344$ in.-lb
$= HT * hT = 167089 * 3.4108 = 569907$ in.-lb
$= MD + MT + = 10749344 + 569907 = 11319251$ in.-lb

A-4

Radial Bending Stress at Bolt Centerline

$HG = W - H = 30486911 - 2875551 = 27611360$ lb

$hG" = hG \cdot hG' / (hG + hG') = 2.2590 \cdot 1.3195 / (2.2590 + 1.3195) = 0.8330$ in.

$MG = HG \cdot hG" = 27611360 \cdot 0.8330 = 23000263$ in.-lb

Shape constants

Calculated from FIG. 2-7.1, where $K = A / B = 166.0000 / 151.6250 = 1.0948$

   $T = 1.8791$ $U = 23.4813$ $Y = 21.3680$ $Z = 11.0712$

$h0 = SqRt(B \cdot g0) = SqRt(151.6250 \cdot 0.9375) = 11.9226$ in.

$h / h0 = 3.0000 / 11.9226 = 0.2516$ $g1 / g0 = 1.1875 / 0.9375 = 1.2667$

Calculated from equations from TABLE 2-7.1 :

   $F = 0.8935$ $V = 0.4429$ $f = 1.0000$

$d = (U / V)h0(g0^2) = (23.4813 / 0.4429) \cdot 11.9226 \cdot Sqr(0.9375) = 555.5587$

$e = F / h0 = 0.8935 / 11.9226 = 0.0749$

$L = ((te + 1) / T) + (t^3 / d) = ((8.9884 \cdot 0.0749 + 1) / 1.8791) +$

                              $(8.9884^3 / 555.5587) = 2.1976$

Minimum thickness calculations

Minimum thickness = 8.9884 in.   **Nominal thickness = 9.0000 in.**

Bolting moment correction factor was not considered ($Cf = 1$).

Stress Calculations - Operating Conditions

$SH = f \, Cf \, Mo / (L \, (g1^2) \, B) =$
   $1.0000 \cdot 1.0000 \cdot 11319251 / (2.1976 \cdot Sqr(1.1875) \cdot 151.6250) = 24090$ PSI

$SR = ((4/3)te + 1) \, Cf \, Mo / (L \, (t^2) \, B) =$
   $((4/3) \cdot 8.9884 \cdot 0.0749 + 1) \cdot 1.0000 \cdot 11319251 /$
   $(2.1976 \cdot Sqr(8.9884) \cdot 151.6250) = 798$ PSI

$ST = (Y \, Cf \, Mo / (B \, t^2)) - (Z \, SR) =$
   $(21.3680 \cdot 1.0000 \cdot 11319251 / (151.6250 \cdot Sqr(8.9884))) -$
   $(11.0712 \cdot 798) = 10910$ PSI

$(SH + SR) / 2 = 12444$ PSI

$(SH + ST) / 2 = 17500$ PSI

$SHmax =$ smaller of $1.5 \, Sfo$ or $2.5 \, Sno = 26250$

Since, $(SH <= SHmax)$, $(SR <= Sfo)$, $(ST <= Sfo)$,
      $((SH + SR) / 2 <= Sfo)$,   and $((SH + ST) / 2 <= Sfo)$ then
      minimum thickness is adequate for operating conditions.

Stress Calculations - Radial Bending at Bolt Centerline

$SR = (6 \, MG) / (t^2 \cdot (Pi \, C - n \, d1)) =$
   $(6 \cdot 23000263) / (Sqr(8.9884) \cdot (Pi \cdot 160.7500 - 60 \cdot 2.8750)) = 5024$ PSI

Since $(SR <= Sfo)$, minimum thickness is adequate for radial bending.

Ab >= Am, bolting is adequate for flange design.

Nominal t >= Minimum t, flange thickness is adequate for flange design.

:em	Design Pressure	Static Head	MAWP New & Cold	MAWP Hot & Corr.
SOFC HORIZ. CYL.	150.00	0.00	160.45	150.37
COVER	150.00	0.00	171.72	161.50

-- SUMMARY --

New and cold component with lowest MAWP: (MAWP = 160.45 PSI)
    SOFC HORIZ. CYL.

Hot and corroded component with lowest MAWP: (MAWP = 150.37 PSI)
    SOFC HORIZ. CYL.

Pressures are exclusive of any external loads.

Item	Material	Curve	Pressure	MDMT
OFC HORIZ. CYL.	SA-516, Grade 70	B	150.00	11 *
COVER	SA-516, Grade 70	B	150.00	8 *

-- SUMMARY --

* - indicates one or more components do not meet the design MDMT of -20.

A-7

WEIGHTS:

	dry	flooded
Shell weight	40675 Lbs.	236276 Lbs.
Head weight	16572 Lbs.	51227 Lbs.
Total Weights	57247 Lbs.	287503 Lbs.

VOLUME:

Shell volume	23414 Gallons
Head volume	4155 Gallons
Total Volume	27569 Gallons

AREA:

Shell area	1005 Sq. Ft.
Head area	361 Sq. Ft.
Total Area	1366 Sq. Ft.

HYDRO TEST INFORMATION
Gauge at Top

Controlling Components

Ratio: SOFC HORIZ. CYL.
Pressure: SOFC HORIZ. CYL.

Design Pressure * 1.5 * (Cold Stress / Hot Stress) = Hydro Test Pressure
     150.00 * 1.5 * (17500   /   17500) =   225.00 PSI