THE DETAIL DESIGN OF A 100-KILOWATT COAL-BURNING FUEL-CELL POWER PLANT

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ABSTRACT

A 100-kilowatt coal-burning fuel-cell process development plant has been conceived to provide technical and economic information for the design of a utility coal-burning fuel-cell power plant, to test fuel-cell battery performance and life under actual operating conditions, and to provide operating experience. The 100-kilowatt plant detail design incorporates an efficient combination of fuel-cell batteries and fluidized coal bed into a unique, flexible, modular, fuel-cell reactor unit. The reactor design achieves efficient transfer of heat generated during fuel-cell operation to the endothermic gasification of coal by inserting fuel-cell battery bundles into five inch diameter pipes located horizontally in a rectangular fluidized bed of coal. The fuel-cell battery bundles contain up to 40 fuel-cell batteries, 1/2 inch in diameter and approximately 30 inches long. Experimental and theoretical studies verify unique elements of the design.

The work recorded in this paper has been carried out under the sponsorship of the Office of Coal Research, U. S. Department of the Interior. N. P. Cochran and P. Towson have served as contract monitors. The Institute of Gas Technology, Dr. B. S. Lee and Harlan Feldkirchner, and Cameron Engineers, D. Lockwood, were subcontracted to prepare the detail design for the plant.

INTRODUCTION

Westinghouse, under contract to the Office of Coal Research, is developing solid-electrolyte fuel-cells which have the capability of producing electrical energy from coal at high efficiency in large scale power plants. The type of large scale, fuel-cell, power system envisioned comprises fuel-cell battery tubes, each containing many individual cells connected in series; a process for producing carbon monoxide and hydrogen fuel gases from coal; a means for cleaning and circulating the fuel gases; and a means for transferring the heat produced by the fuel cells to the endothermic coal gasification reactions between carbon and CO_2 and H_2O. The heat produced in fuel-cell operation is from resistive and polarization losses and the heat released in oxidation of the fuel gases. The design and operation of solid-electrolyte fuel-cells for application in power plants are reported elsewhere[1,2].

A coal-burning solid-electrolyte fuel-cell power system incorporating these components is shown in Figure 1. Coal is fed to a fluidized bed coal reactor along with a portion of the hot CO_2 and H_2O combustion products from the fuel-cell batteries. The coal reacts with those combustion products to form CO and H_2 fuel gases, which are recycled to the fuel-cell batteries after removal of particulate material and sulfur compounds. The fuel gas from the gas cleaning process is split into two streams - one going to a bank of fuel-cells where partial oxidation occurs and the other going to a bank where essentially complete combustion occurs. Gases from the second cell bank are discharged from the system while the partially oxidized fuel gases are recycled back to the coal reactor. The fuel-cell banks and the coal reactor are combined into a single unit to obtain maximum efficiency from the power plant. The potential advantages which this fuel-cell power system offer are:

- High efficiency (overall operating efficiencies near 60% are anticipated in full scale power plants),
- Minimum air and water pollution,
- Reduced plant size,
- Minimum cooling water requirements.

Westinghouse conceived the 100-kilowatt power plant as a means to test fuel-cell battery performance and life under actual operating conditions, to provide technical and economic information for the design of an economical and reliable coal-burning fuel-cell power plant, and to provide operating experience. The Institute of Gas Technology reviewed the concept and Cameron Engineers prepared the detail design of the 100-kilowatt plant.

BASIS

The design of the 100-kilowatt plant is based on the performance of a 100-watt generator[5] and recent data obtained using more economical electrode materials[1]. The fuel-cell banks are designed for fuel-cell battery tubes 1/2 inch in diameter and approximately 30 inches long. Approximately 40 fuel-cells would be connected in series on each battery tube. Projected fuel-cell operating characteristics for the 100-kW plant are:

1) average polarization voltage ≈ 0.15 volts

2) average fuel-cell resistance ≈ 0.15 ohms/cell

3) current density - varies from 300 ma/cm^2 in cell bank I to 50 ma/cm^2 at the end of cell bank II.

The fuel-cell operating characteristics were combined with the calculated thermodynamic open-circuit voltages to obtain the fuel-cell performance and efficiency. The average power produced per cell is approximately 0.22 watts /cell.

With these specifications, cell bank I requires approximately 6400 batteries and is designed to operate near 80% efficiency. Approximately 7000 batteries are required for cell bank II operating near 70% efficiency. Each bank is designed to produce approximately 60-kW of electrical power.

DETAIL DESIGN

Flow Diagram

A detail design for constructing a 100-kilowatt coal-burning fuel-cell process development plant has been completed except for the detail design of the fuel-cell battery bundle assemblies. The process flow sheet is presented in Figure 2. The material balance and the design are based on the Pittsburgh No. 8 char presented in Table I. Projected operating temperatures, pressures, and flow rates are given in Table II. Provision is made to record all char weights, stream temperatures, pressures, compositions, and flow rates necessary for material balances, energy balances, control, and general information on the performance of the plant.

The main reactor, which combines the fuel-cell batteries and fluidized coal bed, is the critical unit in the plant. The reactor is constructed of 10'1-1/2" x 5'2" x 15" rectangular modules which can be fabricated separately and bolted together. Overall dimensions of the reactor are shown in Figure 3. The fluidized coal bed is approximately 16 feet deep with a 6 foot disengaging section. Each of the 12 fuel-cell containing modules comprising the bed contains 40 pipes which are cantilevered into the reactor as shown in Figure 4. The horizontal pipes house the fuel-cell battery bundle assemblies. The fluidized coal bed for producing fuel gas for the cells surrounds the horizontal pipes. The arrangement facilitates efficient heat transfer from the fuel-cell batteries which operate around 1870°F to the fluidized coal bed which operates around 1750°F. The cantilevered pipes and long crossover pipes minimize stresses and provide for thermal expansion.

A representation of a fuel-cell bundle assembly in one of the horizontal pipes is illustrated in Figures 5 and 6. Fuel gas, rich in hydrogen and carbon monoxide produced in the fluidized coal bed surrounding the pipes, is fed to the inside of each fuel-cell battery. Air is supplied to the outside electrodes of the fuel-cell batteries. This is accomplished by feeding air to the end pipes in a module and allowing the air to pass to other pipes in the module through 1-1/2 inch crossover pipes which connect the 5 inch pipes. This is illustrated in Figure 4. The spent air is exhausted from the other end of the module and passed through a heat exchanger to preheat the inlet air as shown in the flow diagram.

TABLE I

CHAR FEED AND RESIDUE

Stream	Flow Rate, lb/hr	Composition, wt %	
Char Feed	69.16	C	70.50
		H	3.55
		O	10.54
		N	1.29
		S	3.46
		Ash	10.66
			100.00
Spent Char	12.04	C	34.88
		O	7.57
		N	0.57
		S	1.88
		Ash	55.10
			100.00

TABLE II
PROJECTED PLANT OPERATING CONDITIONS

Stream Number*	Description	T, °F	P, psig	Flow Rate lb/hr	Flow Rate lb moles/hr.	Composition Mole %
1-1	Gasifier Effluent Recycle	1750	4.0	352.41	14.85	CO 68.20 CO_2 7.50 H_2 19.85 H_2S 0.45 H_2O 3.40 N_2 0.60 100.00
1-2	Gasifier Effluent Recycle	1750	3.0	352.41	14.85	
1-3	Gasifier Effluent Recycle	923	3.0	352.41	14.85	
1-4	Gasifier Effluent Recycle	800	3.0	352.41	14.85	
1-5	Gasifier Effluent Recycle	800	3.0	352.41	14.85	
1-6	Gasifier Effluent Recycle	800	3.0	352.41	14.85	
1-7	Gasifier Effluent Recycle	800	1.8	351.33	14.85	CO 68.20 CO_2 7.50 H_2 19.85 H_2O 3.85 N_2 0.60 100.00
1-8	Fuel Gas	800	1.8	351.33	14.85	
1-9	Fuel Gas	250	0.5	351.33	14.85	
1-9A	Fuel Gas	250	25	--	--	
1-10	Fuel Gas	400	20	351.33	14.85	
1-11	Fuel Gas	250	20	351.33	14.85	
1-12	Fuel Gas	250	20	236.54	10.00	
1-13	Fuel Gas	250	20	114.79	4.85	
2-1	Fuel Cell Bank I Effluent Recycle	600	8.5	296.62	10.00	CO 41.30 CO_2 34.40 H_2 9.20 H_2O 14.50 N_2 0.60 100.00
2-2	Fuel Cell Bank I Effluent Recycle	1650	8.5	296.62	10.00	

*Refer to Figure 2

TABLE II (Continued)
PROJECTED PLANT OPERATING CONDITIONS

3-1	Air	Ambient	0	1240	42.6	O_2	21.00
3-2	Air	70	20	1240	42.6	N_2	79.00
3-1A	Air	Ambient	20	--	--		100.00
3-3	Air	70	20	533.42	18.35		
3-4	Air	70	20	291.74	10.11		
3-5	Air	70	20	323.57	11.22		
3-6	Air	1455	13	291.74	10.11		
3-7	Air	1455	13	323.57	11.22		
4-1	Spent Air From Bank II	1870	7.5	256.96	9.13	O_2	3.00
4-2	Spent Air From Bank II	200	2.0	256.96	9.13	N_2	97.00
							100.00
5-1	Spent Air From Bank I	1870	7.5	231.68	8.24	O_2	3.00
5-2	Spent Air From Bank I	200	2.0	231.68	8.24	N_2	97.00
							100.00
6-1	Bank II Spent Fuel	600	8.5	181.38	4.85	CO	1.70
6-2	Bank II Spent Fuel	250	2.0	181.38	4.85	CO_2	74.00
						H_2	0.50
						H_2O	23.20
						N_2	0.60
							100.00
7-1	Startup Gas						

Two 21.5 ft^3 char feed hoppers are used to feed the coal to the system. The first hopper is a storage unit for introducing char into the system. The second hopper is the feed hopper.

Char, sized to minus 30 mesh, is screw fed to the center module. This module contains horizontal pipes in order to maintain uniform fluidization throughout the bed and the pipes are also designed to serve as auxiliary gas distributors for start-up. The fuel gas produced in the fluidized bed reactor passes through an electrically traced line to a cyclone. Dust is collected for analysis and is not returned to the bed. The gas then passes through a recycle heat exchanger where heat is supplied to the spent fuel from cell bank I before it returns to the reactor. The fuel gas is cooled to approximately 800°F in a guard cooler before final particulate removal in an electrostatic precipitator. Sulfur is removed to a controlled level by a zinc oxide absorber. Two absorbers are provided to permit zinc oxide replacement during extended runs. The units are 2 ft diameter and 6 ft high and are designed to operate for approximately 3 days with a sulfur concentration of 8-10 grains/100 SCF. The hydrogen sulfide concentration in the gas leaving the absorbers is monitored and the hydrogen sulfide concentration controlled. This capability is provided since trace amounts of hydrogen sulfide may be required to inhibit carbon deposition as the gas is reheated through the critical deposition range. A 2 ft diameter by 6 ft high water gas shift reactor is provided to increase the hydrogen content of the gas. Conversion of H_2O in the fuel gas to H_2 is desirable since H_2 minimizes the polarization voltage losses in the fuel-cells. The fuel gas is compressed through a 20 hp compressor before being split into separate streams and fed to the two fuel-cell banks.

The fuel gas is split into two unequal portions. Approximately one-third of the gas goes to cell bank II and two-thirds to cell bank I. The fuel gas to cell bank II is approximately 97% oxidized and the resulting CO_2-H_2O gas is exhausted from the system. The fuel gas to cell bank I is only partially oxidized (see Table II) and is recycled to the fluidized coal bed. Upon leaving cell bank I, the gas is preheated through the recycle heat exchanger and then introduced into the reactor through the gas distribution module. The gas distribution module, shown in Figure 7, consists of a single row of ten 5 inch diameter pipes which extend across the reactor with 0.0576 inch holes in two parallel rows along the bottom of each pipe. Spent char is removed from the reactor by a residue discharge screw below the gas distributor.

In order to achieve early operation and to facilitate gaining operating experience, the system is designed to operate without fuel-cell batteries by installing electric heaters in the horizontal pipes in place of fuel-cells. When operating with electric heaters the gas normally sent to cell bank II is vented. The composition of the remaining gas can be adjusted by simulating the oxidation process with an oxidizer or by using make-up gas. Thus, the gas can be returned to the fluidized bed coal reactor simulating operation with fuel-cell batteries. This procedure enables the system to be checked out before installing the valuable fuel-cell batteries.

Cost Estimate

The cost estimate for the construction of the 100-kilowatt process development plant, excluding fuel-cell batteries and the bundle assemblies, is \$2.0 million. A summary of the cost breakdown is presented in Table III.

TABLE III

COST ESTIMATE SUMMARY

Description	Equipment, Materials, and Labor	Total
Purchased Equipment	$131,000	
Fabricated Equipment	179,000	
Instruments and Control Panel	297,100	
Electrical	152,800	
Structural and Concrete	207,800	
Valves	93,900	
Pipe and Tubing	156,300	
Insulation and Refractory	26,300	
Sub-Total		$1,244,200
Indirect Costs (37.6% of equipment, materials and labor)		467,800
Sub-Total		1,712,000
Contingency (15%)		257,800
Total Estimated Plant Cost		$1,969,800

DISCUSSION

Design Features

The 100-kilowatt process development plant is designed to test and prove out fuel-cell batteries and to provide technical and economic information for scale-up. The process development plant design cannot be directly scaled to an economic commercial design. Much longer fuel-cell batteries are required for a power generator serving as a central station plant -- the 30 inch battery length currently limits the reactor size and shape severely. Batteries on support tubes which can be directly immersed in the fluidized coal bed are also required -- the costs of separate fuel-cell protection tubes and manifolding appear prohibitive for a central station plant. However, answers required for the development of an economical and reliable coal-burning fuel-cell power system can be provided by the process development plant. The plant can be used to study:

1) fuel-cell battery performance and life at actual operating conditions;

2) procedures for operating large numbers of fuel-cell batteries; e.g., methods to vary power loads, methods of current collection, requirements for abnormal operating conditions such as cell failure or short circuits, etc.;

3) tolerance levels for dust and hydrogen sulfide for the fuel-cell batteries;

4) reaction rates of different chars and coals at various operating conditions;

5) heat transfer between the fuel-cell batteries and the fluid bed;

6) conditions of fluidization;

7) materials of construction;

8) start-up, shut-down, and emergency procedures;

9) maintenance and replacement problems; and

10) safety requirements.

In order to carry out these studies, three phases of plant operation are proposed:

1) operation of the coal reactor system using electric heaters in place of fuel-cells.

2) study of test fuel-cell bundles to evaluate mechanical and electrical operability under operating conditions and the testing of the fuel and air piping systems,

3) operation of the system as a whole to produce 100-kW.

The first two steps are recommended in order to check out and characterize the system before inserting the valuable fuel-cell batteries. A summary of the projected experimental program is presented in the Appendix.

The 100-kilowatt process development plant design incorporates an efficient combination of fuel-cell batteries and fluidized coal bed into a unique, flexible fuel-cell reactor unit. The reactor is designed to accept 20 inches of active battery length; however, the modular design permits modules to be constructed which would accept horizontal fuel-cell batteries up to 3-1/2 feet long. The reactor could also be modified to accept batteries in the vertical position greater than 10 feet long. The reactor volume is based on conservative estimates of the gasification rate[3,4,6]. This will permit a wide range of coals, cokes, or chars to be studied. The reactor can also be used to study simultaneous fluidized bed coal gasification and desulfurization with limestone sorbents, which may be attractive for commercial application. When fuel-cell performance reaches 0.5 watts/cell, it will be possible to produce more than 300 kilowatts in the present system. The flexibility of this reactor design far outweighs any considerations for going to a compact design at this stage of the development. The system does not give high overall system efficiency, since it is not practical to eliminate all the heat losses on the 100-kilowatt development unit. However, the design does provide the information for projecting the efficiency of large-scale plants.

The auxiliary equipment has been designed using present day technology. This will minimize start-up and operating difficulties and will allow the evaluation of problems associated with the development of a commercial power system.

Evaluation of Critical Design Features

The reactor, which combines the fuel-cell batteries and fluidized coal bed, is the critical unit in the plant. In order to verify the operability of the design, Westinghouse conducted experimental and theoretical studies and had IGT and Cameron Engineers make a thorough evaluation of the structural design. Results of these evaluations indicate the reactor design is structurally sound and operable.

Fluidization and heat transfer experiments were made on a Plexiglas model of the reactor[7,8]. Temperature profiles were also recorded around a 1 inch diameter tube with internal heat generation in a 3-9/16 inch diameter fluidized bed of char maintained at 1600°F[9]. The results of these studies were combined with the projected fuel-cell performance to evaluate the fuel-cell reactor system[10]. The analysis indicates the maximum temperature gradient between the fluidized bed and the fuel-cell bundles will be less than 150°F and the maximum temperature gradient within the bundles will be less than 100°F. The models predict the temperature gradient will be approximately 100°F and 50°F, respectively with uniform heat transfer from the fuel-cell bundle assemblies to the fluidized bed. These results indicate the fluidized bed will operate at 1700°F or higher where the reaction kinetics are favorable without exceeding the upper temperature limit of the fuel-cell batteries.

The horizontal pipes in the reactor are subjected to a reducing gas containing hydrogen sulfide near 1800°F. In order to assure reactor life and the ability to evaluate different coals and chars, several materials were considered and tested for the horizontal pipes. The results of corrosion tests indicate that Incoloy 800 can be used with de-sulfurized chars (< 0.7% sulfur in coal or char). Corrosion tests with L-605, a cobalt base alloy, indicate sulfur contents in coals or chars near 3% can be used based on a 10,000 hour reactor life. L-605 has greater strength and a smaller thermal expansion than Incoloy 800 and can be substituted in the design without any modifications.

Many aspects of the reactor design cannot be completely evaluated until the unit is built; such as gas distribution, reliability of welds and the air piping design, fluidizing conditions, etc. All of these aspects have been evaluated on bench scale apparatus or analyzed to check the design.

CONCLUSIONS

A 100-kilowatt coal-burning fuel-cell process development plant has been designed. The plant will test fuel-cell battery performance and life under actual operating conditions; will provide technical information on gasification, heat transfer, coal handling, materials, and control; and will provide operating experience. The design provides an efficient combination of the fuel-cell batteries and the fluidized coal bed into a unique, flexible, modular fuel-cell reactor unit. This is achieved by inserting fuel-cell battery bundle assemblies horizontally into a rectangular fluidized bed of coal. Experimental and theoretical evaluations of the fuel-cell reactor unit indicate the design is structurally sound and operable. The estimated cost for constructing the 100-kilowatt process development plant is $2.0 million.

The detail design of the process development is complete. The decision on whether to build the plant has been deferred while additional development is being carried out on the batteries.

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APPENDIX

PROJECTED EXPERIMENTAL PROGRAM FOR 100-KILOWATT PROCESS DEVELOPMENT PLANT

I. OPERATION WITHOUT FUEL-CELL BATTERIES

A. Fluidization

1. Cold Studies
   Fluidize the bed with an inert to evaluate minimum fluidizing velocity, ΔP, uniformity of fluidization, cyclone operation, dust sampling systems, effect of particle size distribution, operation of gas distributor, coal feed system, ash removal system, compressors, level control, and auxiliary equipment.
2. Hot Studies
   Fluidize coal bed with inert gas and supply heat with electrical heaters. Evaluate operation of equipment as suggested during cold study.

B. Start-Up and Shut-Down Procedures

1. Check start-up procedure without fuel-cells present - combustion of char, heating rates, operation techniques.
2. Check emergency and shut-down procedures.

C. Heat Transfer

1. Study with Inert Gas
   Study effect of temperature, flow rates, particle size on heat transfer from the fuel-cell pipes. Determine the effects of fuel-cell pipes not producing heat.
2. Study with Fuel Gas
   In addition to the parameters investigated with the inert gas, determine the effect of various coals.

D. Reaction Rate

1. Study the effect of temperature, gas flow rate, oxygen content of the inlet gas, H/C ratio in the gas and solid feed streams, char residence time, particle size, and char composition on rates of gasification.
2. Study segregation of ash in the bed, and the effects of various ash contents and compositions on bed performance.

E. Sulfur Removal

1. Study removal of sulfur in the fluidized bed.

II. OPERATION WITH TEST FUEL-CELL BATTERY BUNDLES

Note: The following evaluations will be conducted on dummy fuel-cell bundles (i.e., a bundle of ceramic support tubes) before operating with production fuel-cell bundles.

1. Check manifolding, instrumentation, and control of the gas flow to the batteries.
2. Determine the effect of vibrations on the batteries, inlet gas temperatures and flow rates on cell performance, pressure drop across the batteries, various fuel gas compositions from the reactor on cell performance.
3. "Short" life tests of battery bundles.

III. 100-KILOWATT OPERATION

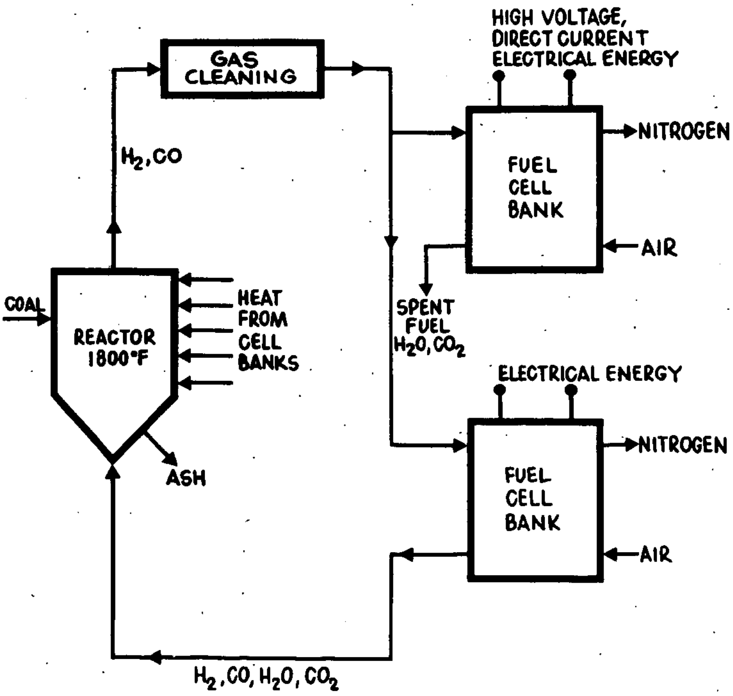

FIGURE 1 - COAL BURNING SOLID-ELECTROLYTE
FUEL CELL POWER SYSTEM

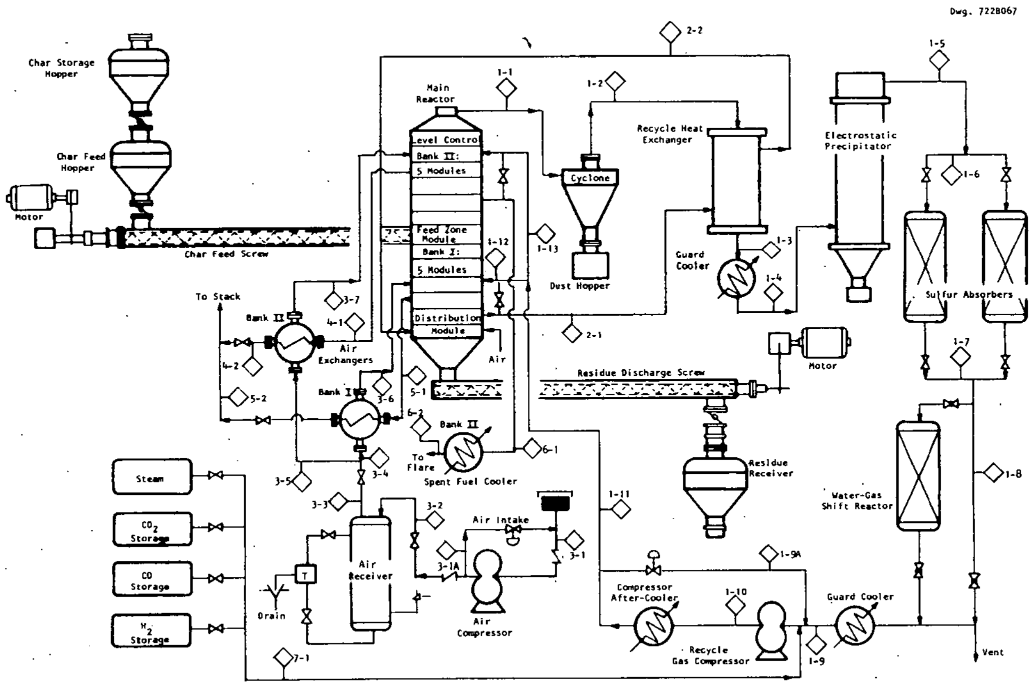

FIGURE 2 - PROCESS FLOW SHEET FOR 100-KW PROCESS PLANT

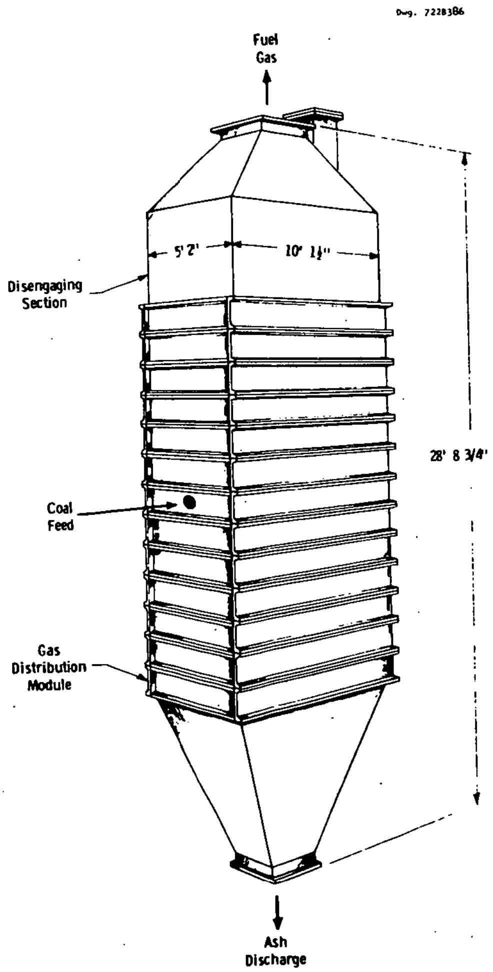

FIGURE 3 - 100-KILOWATT COAL-BURNING FUEL-CELL REACTOR

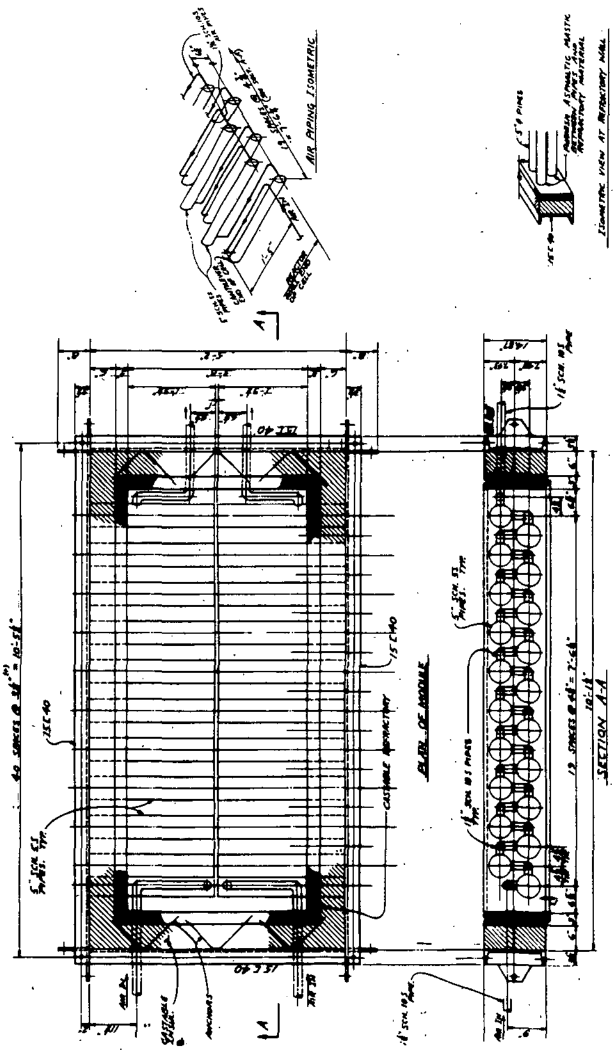

FIGURE 4 - FUEL-CELL REACTOR MODULE

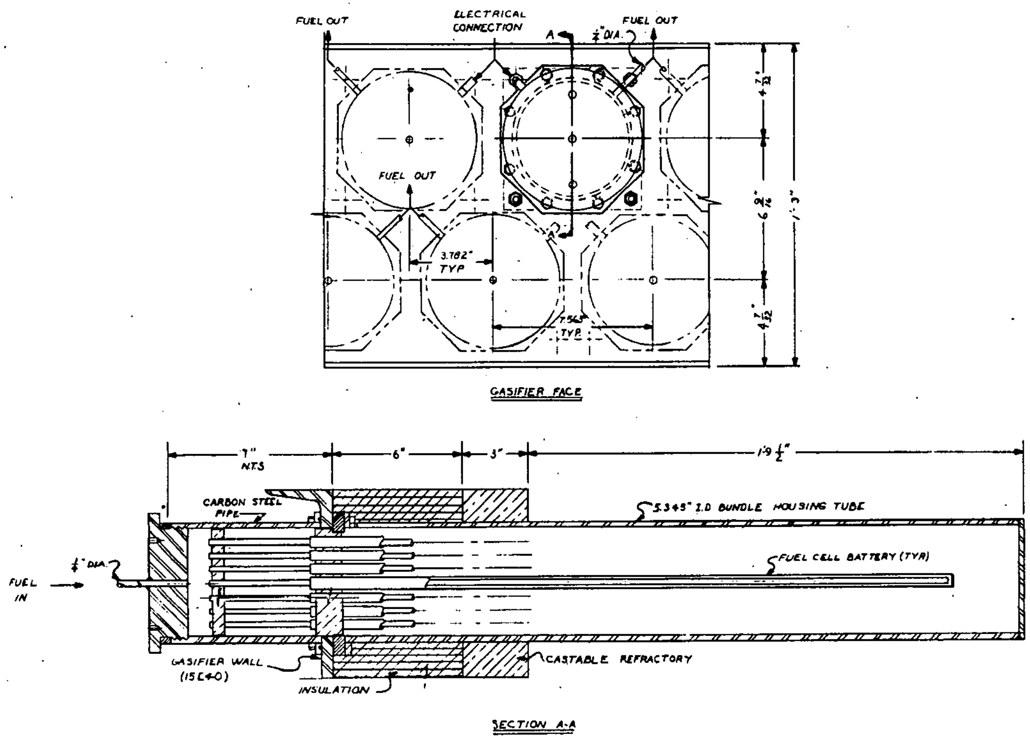

FIGURE 5 - FUEL CELL BUNDLE ASSEMBLY

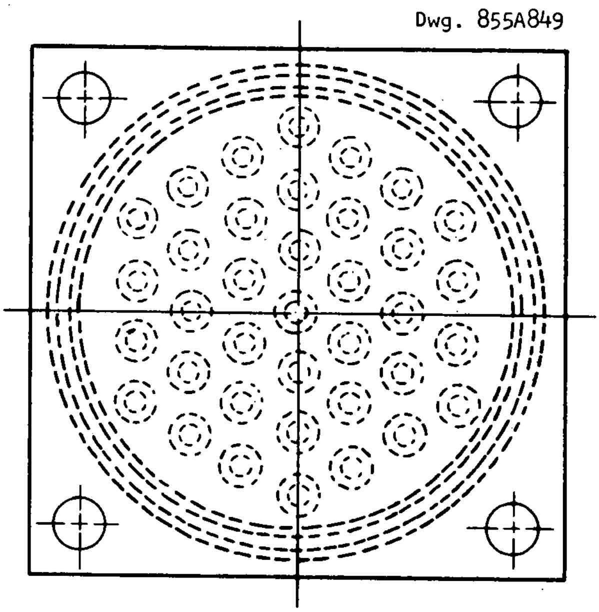

FIGURE 6 - END VIEW OF FUEL CELL TUBE BUNDLE ASSEMBLY

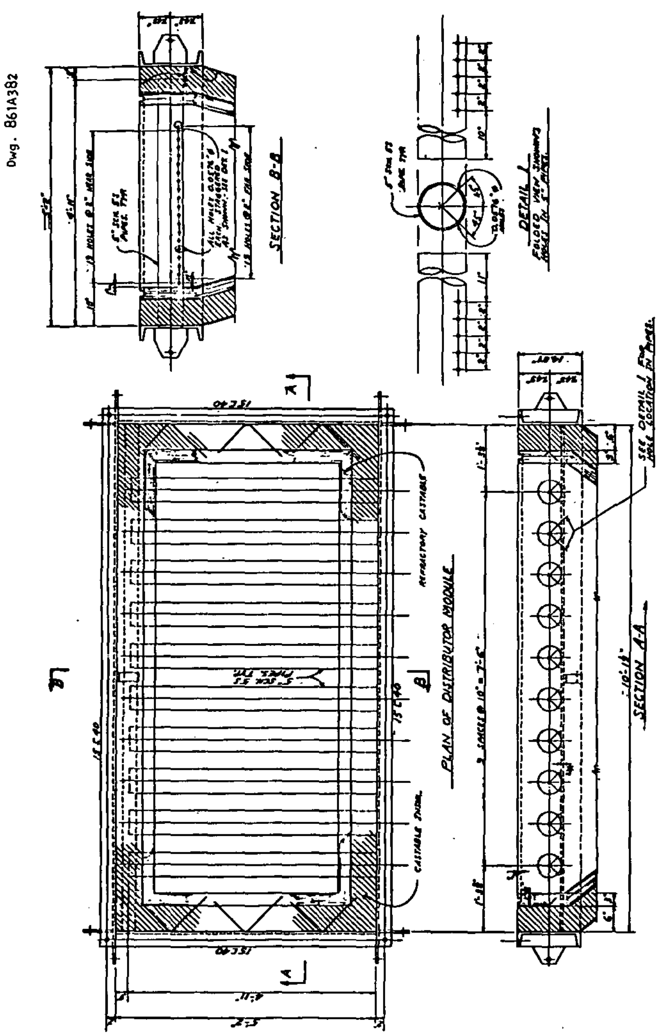

FIGURE 7 - GAS DISTRIBUTION MODULE SCHEMATIC