

THE DESIGN OF A 100-KILOWATT COAL-BURNING
FUEL-CELL POWER SYSTEM*

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INTRODUCTION

The development of an economic solid-electrolyte fuel cell system to produce electrical energy from coal and air at an overall efficiency of 60% or greater is the goal of a project at Westinghouse Research. Work reported previously^(1,2) has shown that solid-electrolyte batteries can utilize flowing H₂-CO mixtures and air to generate d.c. power with only low losses from resistive and polarization voltage drops at current densities up to 700 amperes/ft.².

The high operating temperature of solid-electrolyte batteries -- in excess of 1750°F -- allows the heat produced when power is drawn to be effectively utilized in the gasification of coal. Furthermore, the gasification to form H₂-CO fuel can be carried out using hot H₂O-CO₂ combustion products emerging from the batteries. Since both the heat and the medium required for coal gasification are by-products of fuel-cell operation, a high efficiency for an overall system including both the gasifier and the fuel-cell batteries can be achieved.

A conceptual process scheme for incorporating coal-gasification into fuel cell power systems has been introduced and discussed in a previous paper⁽³⁾. Essentially, this scheme separates the oxidation of the fuel gases derived from coal into two distinct steps, which take place in two different cell banks as illustrated in Figure 1. The fuel gas stream from the gasification unit is split into two streams -- the first going to a bank of cells in which only a partial oxidation occurs. The second gas stream

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goes to a second bank of cells where it undergoes essentially complete combustion. The gases emerging from this second cell bank are discharged from the system, while the partially oxidized fuel gases from the first cell bank are recycled back to the reactor, where they gasify the coal.

A thermodynamic analysis⁽³⁾ of a system similar to that shown in Figure 1 indicates that a maximum system efficiency approaching 100% can theoretically be realized for the coal-burning system. Under normal operation, however, this efficiency is reduced due to irreversibilities which occur within the cell banks and within the coal reactor. Previous analysis has indicated that these irreversibilities are limited so that overall operating efficiencies of 60% or greater are anticipated in full-scale power plants.

A process design for a 100-kw coal-burning solid electrolyte fuel cell power plant has been completed, based on the conceptual scheme of Figure 1. This design incorporates all of the features which now appear necessary to the plant. Details of this design and the predicted operating characteristics of the plant are discussed in this paper.

BASIS FOR SYSTEM DESIGN

The design for the cell banks of the 100-kw fuel cell power system is based on the construction and measured performance of the 100-watt generator shown in Figure 2. This device is the largest solid-electrolyte fuel-cell power system reported to date. The techniques used in fabricating its batteries have been described⁽¹⁾ and the voltage-current curves for the generator have been presented⁽²⁾. The device consists of 400 solid-electrolyte cells of the bell-and-spigot design, fabricated into 20 segmented tube batteries, each consisting of 20 individual cell segments. In this generator, platinum was used as electrode material for both the fuel and air electrodes. The battery tubes were held at the 1880°F operating temperature by means of a large, heavily insulated, 3-zone commercial furnace. The tubes were of typical closed-end construction and were mounted in a cold (< 350°F) metal base plate by means of thick-walled base tubes.

Platinum electrodes are too costly for the fabrication of an economic coal-burning power system, but cheap and plentiful materials are now being developed for both air and fuel electrodes. It is believed that the performance of these materials will meet or exceed that of platinum. For this reason, the performance of the 100-watt unit has been employed as a reasonable basis for the following plant design.

SYSTEM FLOW CHARTS

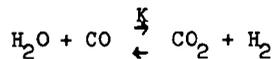
An overall flow chart for the system is presented in Figure 3. Operating conditions are specified in a simplified version of the chart, Figure 4. Material and energy flow quantities throughout a nominal 100-kw plant are shown in Figure 5; equipment sizes, in Figure 6.

Coal is charged to the reactor unit at the rate of 57 lb/hr. This unit, as indicated in Figure 3, is a complex assembly designed to house in adjoining compartments a fluidized bed of coal and tanks of tubular fuel-cell batteries. The compartments are arranged to facilitate heat transfer from the cell banks operating around 1870°F to the coal-derived solids in the reactor operating around 1750°F. Partially oxidized fuel gases from Cell Bank I pass through the fluidized bed at a superficial velocity of 1.3 ft/sec.; this velocity allows for a gas residence time of about 12 sec -- a time sufficient to gasify the 45 lb. of char per hour produced from the coal feed, to convert the mol ratio $(CO + H_2) / (CO + H_2 + CO_2 + H_2O)$ in the flowing gases from 0.58 at the reactor inlet to 0.81 at the outlet, and to increase the gas flow from 5580 standard ft.³/hr. at the inlet to 7240 ft.³/hr. at the outlet.

The gas stream as it leaves the reactor passes through a series of cyclones which remove entrained dust, fly ash, and solid particles and return them to the fluidized bed. The fuel gas, relieved of entrained solids, enters Heat Exchanger I where it is cooled to 970°F. The cooled gas next passes into a series of two fluidized bed absorbers -- each 2 ft. in diameter and 3 ft. high, housed as a single unit. These absorbers contain iron oxide, which acts as a catalyst for the absorption of H₂S and other sulfur containing compounds from the fuel gas stream.

As the absorption of H_2S progresses, the catalyst activity decreases both due to the formation of iron sulfides and to partial reduction of the ore to FeO . In steady state operation, therefore, it is necessary to remove continuously a portion of the catalyst to a second unit into which a stream of air is introduced. Here exothermic roasting of the iron sulfides and reoxidation of the FeO to Fe_2O_3 occur at a temperature around $1470^\circ F$. The gases emerging from this catalyst regenerator are primarily SO_2 and N_2 -- which can either be discharged to a stack or sent to an acid contact plant. The catalyst regenerated in this unit is recycled to the H_2S absorber, where it contributes some of its sensible heat, which along with that of the fuel gas serves to maintain the absorber at a temperature of $750^\circ F$. This sulfur removal process has been developed and successfully used in the treatment of 2-1/2 million ft.³, of coke oven gas per day at the Appleby-Frodingham Steel Company in Great Britain⁽⁴⁾.

The fuel gas leaving the H_2S absorber is at a temperature of about $750^\circ F$. At this low temperature, the water gas equilibrium constant, K ,



is quite high. If the water gas equilibrium is catalytically promoted, most of the H_2O in the fuel gas stream can be converted to H_2 -- a fuel which minimizes the polarization voltage losses in the fuel cells. The fuel gas passes, therefore, through a shift converter measuring about 2 ft. in diameter and 6 ft. high containing a commercial shift catalyst such as chromium-promoted Fe_3O_4 .

Leaving this unit the gases are at about $600-700^\circ F$ and have a typical composition as follows: CO , 45%; H_2 , 33%; CO_2 , 18%; H_2O , 0.5%. At this point in the cycle the gases are introduced to a recirculation pump. A 5-hp drive should be more than adequate to handle any contemplated recycle flow rates.

The gases can, in general, next pass into recycle Heat Exchanger II, in which they receive some heat from the hot exhaust fuel gases. This exchanger is small in size, having an exchange area of less than 10 ft.².

The gases next enter Heat Exchanger I, where they recover sufficient heat from the high temperature fuel gases just beginning the recycle loop to attain a temperature of about 1550°F. In this instance the total heat generated in operating the cell banks is sufficient to preheat the fuel gases and air, and to supply the heat required for coal gasification in the reactor as indicated in Figure 5.

The fuel gas stream then passes through central core of the fuel cell-reactor unit where it is brought to cell operating temperature by heat exchange with the cell banks. It then enters the cell banks at the bottom of the cell bank-coal reactor unit. Here the stream is split into two unequal portions; about a quarter of the gas is sent to Cell Bank II and three-quarters to Cell Bank I. Upon exiting from Cell Bank I the larger stream, now at 1870°F, is recycled to the coal bed. The smaller stream leaves the second cell bank also at about 1870°F with a mol ratio $(\text{CO}+\text{H}_2)/(\text{CO}+\text{H}_2+\text{CO}_2+\text{H}_2\text{O})$ of less than 0.03.

This stream is then sent to recycle Heat Exchanger II where it gives up a portion of its heat to the recycling gases. In a highly efficient plant, it may be necessary to use this stream not only to heat the recirculating gases, but to preheat the air flow as well. This is accomplished as shown in Figure 3 by having the spent fuel stream, upon its discharge from recycle Heat Exchanger II, pass in countercurrent heat exchange with the incoming air.

Equal amounts of air are fed to each of the cell banks. Internal (to the cell banks) heat exchange between incoming and exiting air streams is sufficient to heat the fresh air -- so that upon its entrance to the active cell region it is about 1470°F. The spent air containing only 3 mol % O₂ discharges to the atmosphere at about 200°F.

DESIGN OF UNIT COMBINING COAL REACTOR AND CELL BANKS

The coal reactor-fuel cell unit consists of a 4 ft. diameter vessel, equally divided by eight spokelike chambers, each 4.25 in. wide and 19 in. long, extending radially from a 10 in. diameter center hub. It is this hub through which the recycle fuel gases flow before they are introduced into the fuel cell banks. The spokelike chambers divide the vessel into 8 pie-shaped slices which extend the height of the vessel -- 16 ft. -- and which contain the fluidized bed of coal.

The cross-sectional area for gas flow through the pulverized coal -- 7.8 ft.², the volume of the fluidized bed -- 125 ft.³, and the quantity of char contained -- 1200lbs. are ample to provide the fuel gases required to produce 100 kw in the cell banks. Reactor computations have been carried out using data collected on char gasification in this laboratory and information published by other investigators⁽⁵⁾.

The 16 faces enclosing the spokes of this wheel design provide ample heat exchange area to transfer heat for the gasifying the coal from cell banks to fuel bed. Heat transfer computations using calculated transfer coefficients between the wall and fluidized-bed have been carried out assuming: 1) that radiation is the sole mechanism for heat transfer from the solid-electrolyte batteries to the walls of the cell banks; and 2) that published empirical formulas⁽⁶⁾ are accurate in predicting heat transfer coefficients from the cell bank walls to the fluidized bed. A temperature difference between the cells and coal of less than 60°F is predicted by these computations.

Each of the spoke chambers contains 1250 fuel cell tubes with each tube containing about 40 individual fuel cells. The tubes are mounted horizontally inside the spokes on 3/4 in. equilateral centers, five tubes to a tier. The tubes themselves extend radially into the unit and are attached to 6 in. long base tubes, which extend through about 7 in. of insulation which surrounds the 4 ft. diameter vessel, and are secured in a cold base plate located at the outside shell of the reactor cell bank unit as shown in Figures 7 and 8. Intermittently spaced in the chambers

housing the fuel cell batteries will be four 6 in. high catalyst beds containing chrome-oxide water gas catalyst. These catalyst beds are sufficient to bring the rising gas to water-gas equilibrium according to data gathered in this laboratory. In this way sufficient H_2 is generated for consumption in the fuel cell batteries section of the cell bank immediately above the catalyst.

It should be pointed out that the rising gas is in laminar flow with respect to the cell batteries, so that no separation or wake formation is incurred, and fuel gas is in contact with each position of the cell fuel electrodes.

Air enters and leaves the system, as shown in Figure 9, by means of an air-exit tube -- which is a 1/8 in. ceramic tube extending along the axis of the battery. Fresh input air flows into the annular space between the battery and the exit tube from an air plenum chamber located in the shell. The battery itself has a closed end⁽¹⁾ so that after traversing the length of the segments and giving up its oxygen to the fuel cell reactions, the now spent air is forced to reverse its direction and flow into the exit tube, where it then flows countercurrent to the incoming air, eventually being discharged to the atmosphere. In the 7 in. insulated region, the counter flow of cold fresh air and hot spent air is sufficient to bring the fresh air up to cell operating temperature. The spent air is thereby cooled, exiting the system at about 200°F.

The design of flowing air inside the cell batteries means that the heated air is only in contact with the ceramic tubes or air electrodes. Nowhere is the hot air in contact with an oxidizable surface. Similarly the metal plates enclosing the fuel cells, the spoke walls, are only contacted by the fuel gas on the cell side and the fuel bed on the reactor side. Thus, the atmosphere surrounding the walls is always reducing, so that the metal of construction of the walls need not be especially oxidation resistant. The electrical performance of the cells in the banks is that predicted from measurements on batteries used in the 100-watt solid-electrolyte fuel-cell generator⁽²⁾. The selected operating current for all the cells in both cell banks is 0.44 amperes -- equivalent to a current density of 220 amperes/ft.².

The average cell voltage at this loading is 0.75 volts in Cell Bank I and 0.65 volts in Cell Bank II -- equivalent to an overall average of 0.7 volts per cell. The calculated power output for 400,000 cells contained in both banks is, therefore, over 120 kw; and the overall efficiency of the plant -- the electrical output of the cells divided by the heat of combustion of the coal -- is 58%. Improvements in solid-electrolyte cell performance have been achieved since the testing of the 100-watt power generator and it now seems likely that an overall efficiency greater than 60% might be obtained from a coal-burning solid-electrolyte fuel-cell power plant.

DISCUSSION

The 100-kw fuel-cell power plant design presented in this paper illustrates several important points:

1. Solid electrolyte cells can be used as the basis of a system to convert coal to electric energy at an overall efficiency approaching 60%.
2. A 100-kw fuel-cell plant based on current fuel-cell and gasification technology is technically feasible; it would not be unreasonable in size or complexity.
3. Sufficient heat is generated in operating the cell banks to provide heat for the endothermic coal gasification process and to maintain the system at the desired operating temperatures.
4. The requisite heat can be transferred from the cells to the coal with a temperature difference of 100°F or less. Gasification can be carried out, therefore, at a reasonably high temperature without exceeding the upper temperature limit of the solid-electrolyte fuel-cells.

The design utilizes only present day technology as far as battery construction and installation are concerned. The current state of this art demands that closed end tubes, fastened in relatively cool base plates form the basic design pattern. This restriction imposes no insurmountable obstacle

in the 100-kw plant, as the technique of mounting the individual cell batteries horizontally allows the cool reactor shell section to serve as a fuel cell base plate. The enclosure of tiers of such batteries into individual chambers allows sufficient heat transfer surface to be built into the unit. However, this design also allows sections of cell batteries to be inserted into or removed from the unit, independent of the remaining batteries. Thus, the assembly can be made up of sections or modules of batteries, each with specific test functions to perform. The ability to test independently fuel-cell batteries incorporating the latest laboratory developments is thus a significant feature of the design.

It should be further pointed out that the volume assigned to the coal reactor is based upon the gasification of 45 lb/hr of a coke or char material. The balance of the 57 lb/hr coal feed is removed from the reactor as ash and carbon associated with the ash. Since the presence of volatile materials in coal will make it considerably more reactive than either coke or char, the design is thus conservative. However, in a pilot plant unit such as the 100-kw plant is intended to be, the conservative design allows for a maximum range of coals, cokes, or chars to be used. This advantage far outweighs any considerations of compact design at this time, and hence the reactor is somewhat oversized. In eventual installations, when fuel-cell performance reaches 0.5 - 1.0 watts/cell and a specific coal is selected as a fuel, it will be possible to produce upwards of 400-kw in a unit the size of the proposed 100-kw assembly.

Another feature of interest in the fuel cell reactor unit is the chrome oxide catalyst beds, housed in the individual spokelike chambers. These beds of catalyst are relatively small, occupying about 9 ft.³ out of a total volume of 200 ft.³; their function is to insure H₂ performance from the fuel-cells by promoting the water gas reaction. Placed in the fuel-cell chambers much in the manner of retractable drawers, these catalyst beds are easily replaceable so that various types and forms of the basic catalyst can be tested in the unit.

A final feature of interest in the unit is the fluidized bed of coal, which has a common bottom from which individual pie-shaped fingers extend upward. The use of the central hub of the unit as a recycle pre-heater solves effectively the problem of longitudinal temperature gradients in the fuel-cell chambers.

The pieces of process equipment in the system flow chart other than the reactor are all standard items, and little difficulty is anticipated in their operation. It might be mentioned, however, that the temperature of operation of the H_2S absorber could possibly be raised above $750^\circ F$. This temperature was selected at Appleby-Frodingham as an effective minimum. (It was necessary to heat the input gases.) In the 100-kw plant, the recycle gases to the H_2S absorber are first cooled, the degree of cooling depending upon the desired operating temperature of the unit. If it were possible to raise this operating temperature, then either lower heat losses in the recycle operation or smaller heat exchanger sizes would result.

In summary, therefore, a 100-kw coal-burning, solid-electrolyte fuel-cell, power plant has been designed, scaling up essentially test data from a 100-watt bench-scale unit. The 100-kw plant incorporates a novel combination of fuel-cell batteries and fluidized coal beds into a single fuel cell-reactor unit. This unit together with suitable gas and solids inlets and outlets and certain auxiliary equipment constitute the complete coal-burning system.

Overall efficiency in the proposed system is estimated to be 58%. In order to meet these high efficiency figures, it is necessary to limit the energy losses from the system to those indicated in Figure 5. Furthermore, the net unburned carbon loss from the system must be limited to about 10% of the coal fed. In the design it was assumed that carbon was removed from the bed only in the ash-withdrawal system.

The plant is simple in construction, and its operation involves only the pumping about of various gas streams, the cleaning of these streams, and heat exchange between various of them. This simplicity, together with the great flexibility allowed by the reactor design, make the proposed plant appear as both reasonable and technically feasible.

The economic feasibility of the coal-burning, solid-electrolyte fuel-cell power plant depends on the development of cheap electrode materials and battery fabrication methods. Considerable progress has been made toward producing effective fuel electrodes from non-noble metals and air electrodes from electrically conductive oxides as replacements for costly platinum. Intensive work is now being devoted to the perfection of suitable procedures for high-volume, low-cost production of solid-electrolyte batteries. If these materials and fabrication techniques produce a long-lived battery whose performance equals that measured in the 100-watt power generator, a new means of practical power generation will have been achieved.

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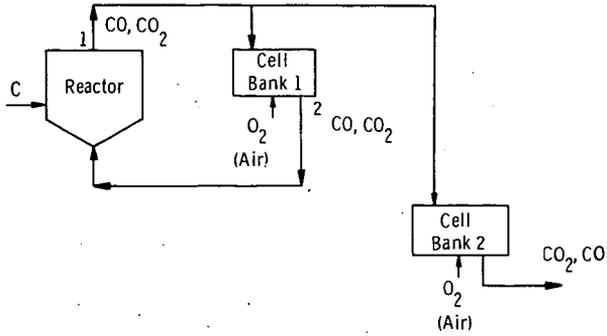


Fig. 1—Simplified coal-burning fuel-cell system

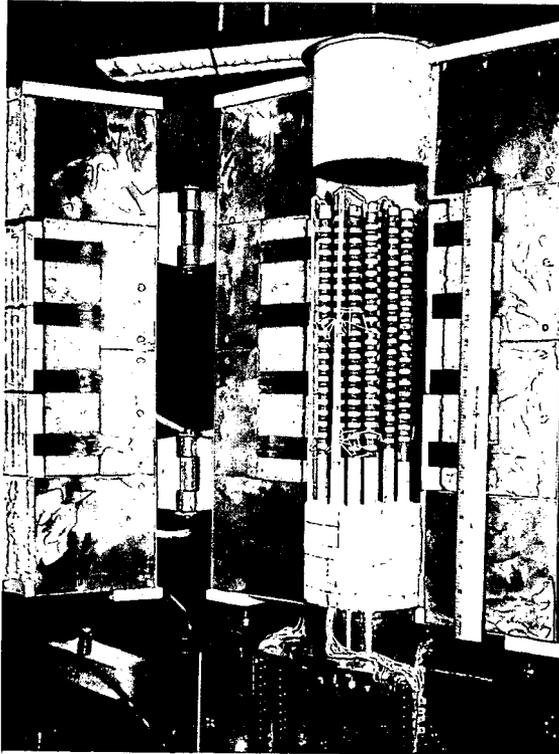


Figure 2 -- 100-watt solid-electrolyte fuel-cell power supply with the furnace door open.

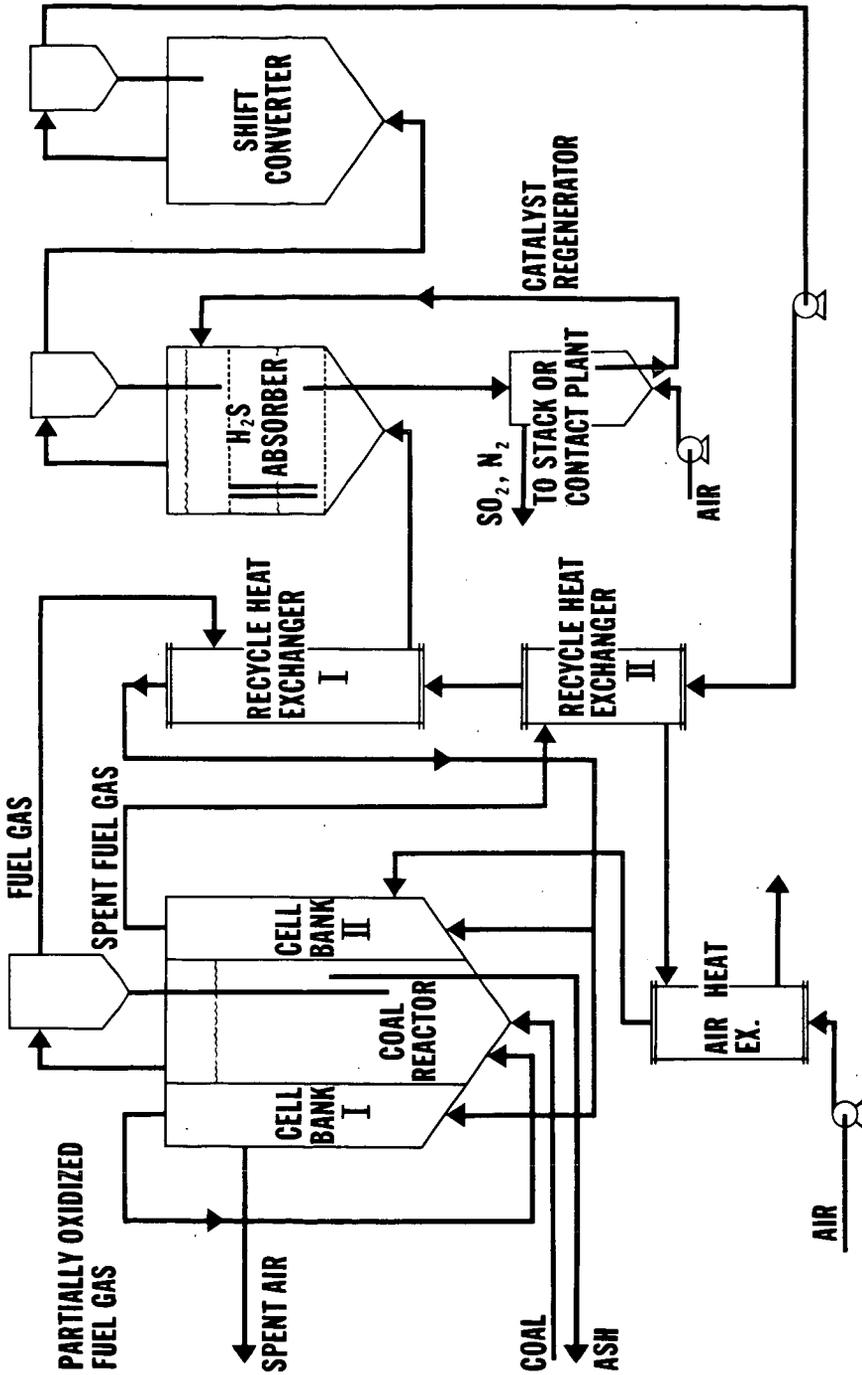


Figure 3 **FLOW CHART FOR 100 kW COAL-BURNING FUEL CELL POWER PLANT**

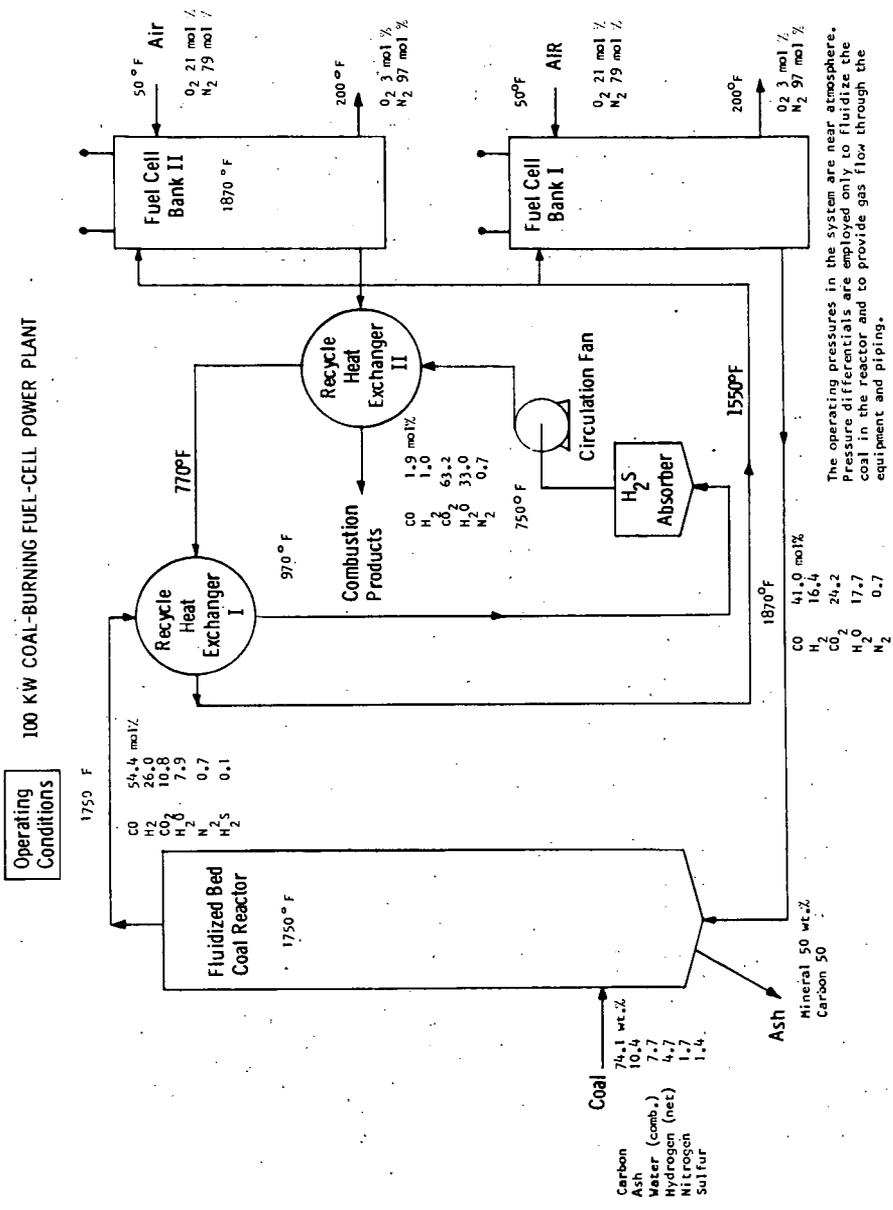


Figure 4 - Operating Conditions for 100-kw Coal-burning Fuel-cell Power Plant

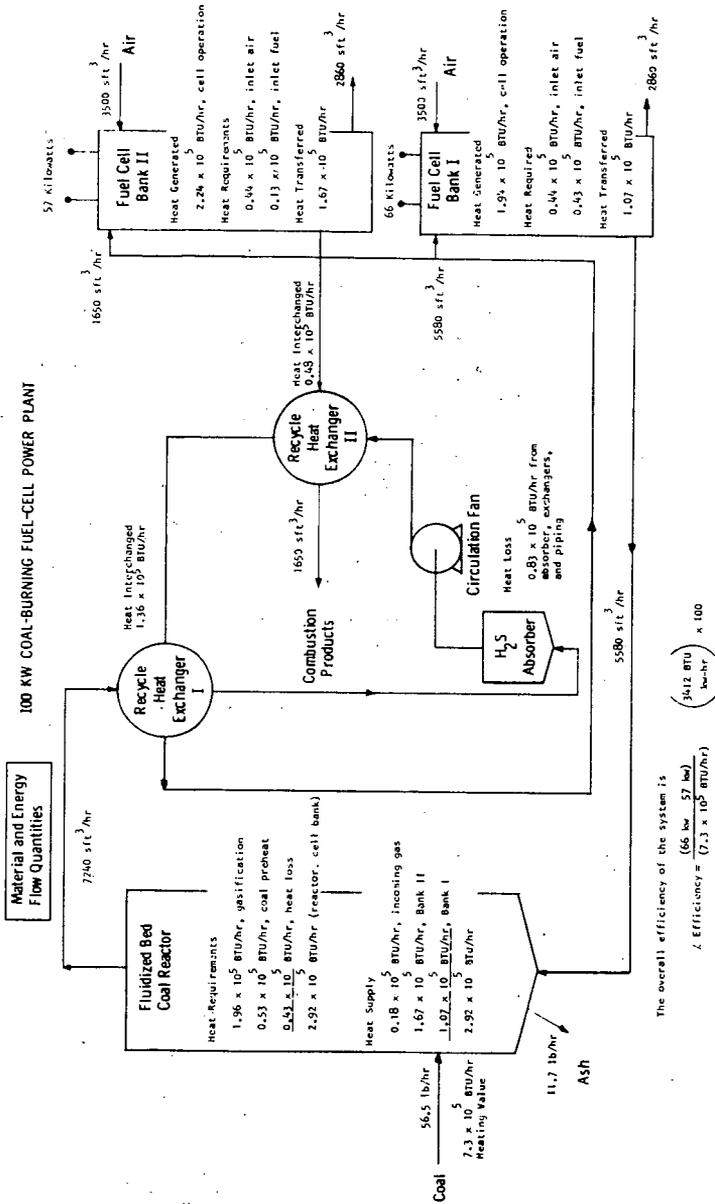


Figure 5 - Material and Energy Flow Quantities for 100-kw Coal-burning Fuel-cell Power Plant

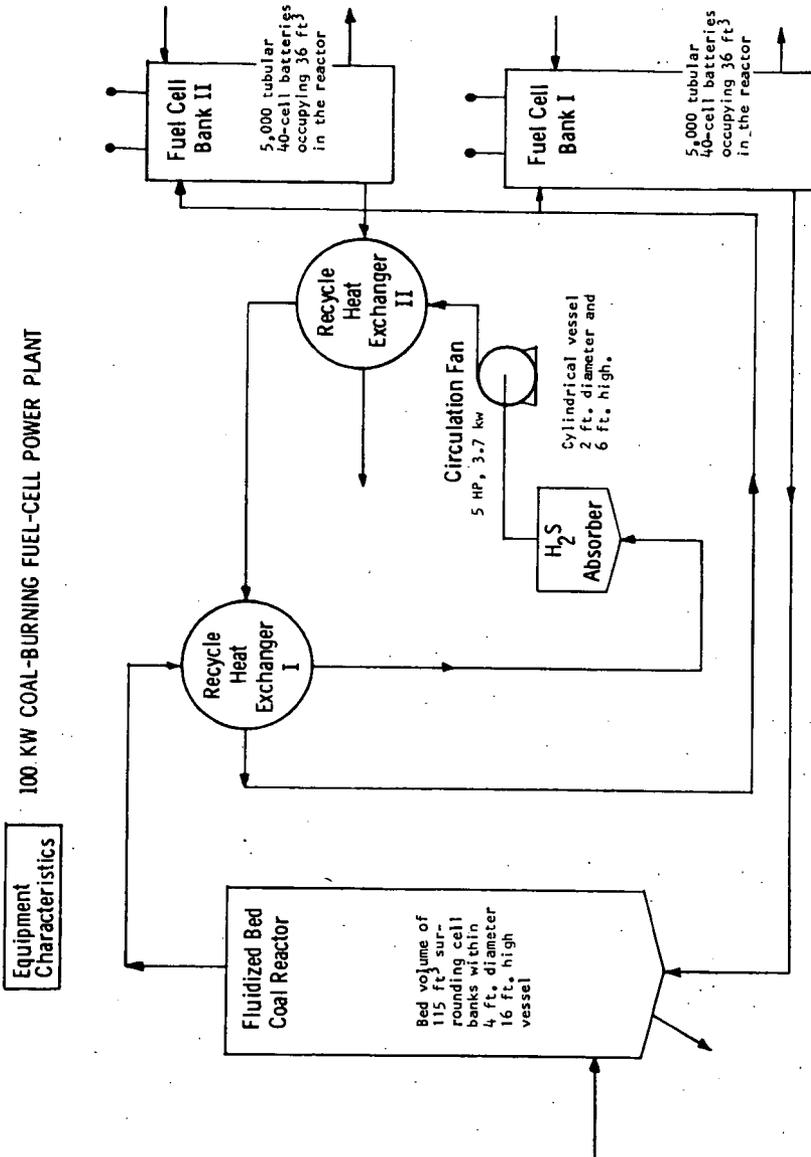


Figure 6 - Equipment Characteristics for 100-kw Coal-burning Fuel-cell Power Plant

