Conf. 790305--4

DEVELOPMENT PROGRESS ON THE ATMOSPHERIC FLUIDIZED BED COAL COMBUSTOR FOR COGENERATION GAS TURBINE SYSTEM FOR INDUSTRIAL COGENERATION PLANTS

R. S. HOLCOMB
Engineering Technology Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

ABSTRACT

The Atmospheric Fluidized Bed Coal Combustor Program will develop the technology for a fluidized bed coal combustion system to provide a source of high temperature air for process heating and power generation with gas turbines in industrial plants. The gas turbine has the advantages of a higher ratio of electric power output to exhaust heat load and a higher exhaust temperature than do steam turbines in cogeneration applications. The program is directed toward systems in the size range of 5 to 50 MW(e) and is sponsored by the Department of Energy.

A study of industrial energy use has been completed that indicates a large potential market for gas turbine cogeneration systems. Conceptual design studies have been done for typical industrial installations, and some of these results are presented.

The conceptual design of a 300 kW(e) test unit has been completed. A number of furnace design firms have been invited to submit their own designs for a 1500 kW(t) (5×10^6 Btu/hr) combustor, from which a final selection will be made. The design of the balance of the test system will proceed in parallel with the combustor design.

An engineering design study has been completed by AiResearch Division of Garrett Corporation in which the modifications required to adopt an existing AiResearch 831-200 gas turbine to this cycle for both open and closed cycle operation were determined.

Development and testing have been conducted in the areas of fluidization, heat transfer, tube corrosion, and coal feeding. Results from heat transfer, tube corrosion, and coal feeding tests are presented.

Research sponsored by the Department of Energy under contract with Union Carbide Corporation.

INTRODUCTION

The limited supply of domestic oil and natural gas and the trade imbalance created by importing large quantities of oil make it imperative that oil and gas be replaced by coal in fossil-fired stationary plants to the extent that is practical. The industrial energy consumption amounts to about 40% of the total U.S. energy consumption and accounts for about 50% of the natural gas and 15% of the oil consumed. Thus, very significant savings of gas and oil could be realized if coal were used to supply most of the energy for industry.

Concern for the reduction of environmental pollution has led to strict emission limits being imposed on coal-burning plants. Fluidized bed combustion offers a very promising method for burning a wide range of coals within the emission standards. In fluidized bed combustion, coal is burned in a bed of limestone, which reacts with the sulfur dioxide released from the coal to form calcium sulfate. The bed operates at a temperature of about 870 C (1600 F) so that the coal ash is kept below the fusion temperature, and the calcium sulfate and ash is removed as a dry granular solid which is easily handled for disposal. The lower operating temperature reduces the amount of NO_x formed compared to conventional pulverized coal-fired furnaces.

The environmental effect of coal-fired plants can be further reduced if industrial energy is supplied by cogeneration plants to provide both electricity and process heat, and thus reduce the total quantity of coal that is burned. The gas turbine cycle is very well suited for cogeneration systems, particularly for industrial applications where process heat is required at temperatures of 400 F and higher. The exhaust heat from the gas turbine is available at higher

temperatures, and the ratio of electricity to heat is more favorable for gas turbines than for back-pressure steam turbine at these higher temperatures. A fluidized bed coal combustor heating air to drive a gas turbine is an attractive system for industrial cogeneration plants.

A program for the Department of Energy is underway at the Oak Ridge National Laboratory to develop the technology for a gas turbine cogeneration system coupled to a fluidized bed combustor and to assess the potential market for this type of system. The program entitled "The Atmospheric Fluidized Bed Coal Combustor for Cogeneration (AFBCCC) Program" is directed at developing the technology that can lead to commercial systems in the size range from 5 MW(e) to 50 MW(e).

DESCRIPTION OF THE CONCEPT

The AFBCCC concept employs a fluidized bed combustor to heat air inside tubes in the bed to drive either an open or closed cycle gas turbine to produce electricity and recover heat for industrial processes from the air leaving the turbine exhaust. In using air rather than flue gases from the bed to drive the gas turbine, the problems of corrosion, erosion, and deposits on the turbine blades are avoided. In addition, the use of the independent turbine air stream permits the use of a closed as well as an open cycle.

The flowsheet for the concept with a closed cycle is shown in Fig. 1. Air from the compressor is preheated in a recuperator and is then sent through the economizer and fluidized bed combustor. After being heated to 816 C (1500 F), the air is admitted to the gas turbine which drives the compressor and electric generator. From the turbine exhaust, the air passes through the hot side of the recuperator to the waste heat exchanger and the process water heater where it supplies heat to the process heating and hot water systems. The air is then returned to the compressor intake. The turbine power output can be varied by changing the closed system pressure by admitting air from the reservoir or venting air. The combustion air is preheated in the regenerator and then is routed to the combustor where it is used to fluidize the bed and burn the coal. The flue gases pass through the economizer and then go to the hot side of the air preheater. Not shown but to be included in the flue gas system is dust removal equipment, including cyclone separators between the economizer and the regenerator, and a bag filter house between the regenerator and the induced-draft fan. Also, a forced-draft fan is to be used on the inlet air to reduce the power for pumping the combustion air.

The flowsheet for the concept with an open cycle is given in Fig. 2. The flowsheet is identical except that the turbine system is once-through with the compressor, drawing air from the atmosphere and the exhaust air discharged to the stack.

In comparing the closed and open cycle, the closed cycle has two advantages. The first is that the pressure ratio can be selected to yield peak electrical efficiency, and the turbine inlet pressure level can be chosen independently to increase the power density in the system, which may reduce capital cost. The second advantage is that the turbine can follow a changing electrical load by varying the pressure and operate at high efficiency at part load, whereas in the open cycle the turbine inlet temperature must vary, or some air must bypass the turbine which reduces the electrical efficiency at part load. The open cycle has the advantages that existing turbines are more easily adapted for the open cycle concept, and that since the turbine exhaust air is discharged to the atmosphere, it is well suited for direct contact process heating with the hot air.

A conceptual design for a 1.5 MW(t) test combustor is shown in Fig. 3 to illustrate the combustor arrangement for the concept (1). Combustion air enters at the top of the furnace and passes through the outer annulus to the air plenum at the bottom of the furnace. The air flows through orifices in a large number of nozzles in the distributor plate, and into the 0.6 m (2 ft) deep fluidized bed of limestone and ash where combustion of the coal occurs. The combustion gas flows upward through a plenum where the larger particles blown out of the bed fall back into the bed. The flue gas then flows downward outside the tubes in the economizer section and upward through the annulus in the air preheater zone. The turbine air from the recuperator enters the inlet manifold, passes through the tubes in the economizer and plenum and the heater section in the fluidized bed. The air leaves the outlet manifold and then goes to the turbine.

The fluidized bed is designed for atmospheric pressure and a temperature of 900 C (1650 F). The superficial velocity of the gas through the bed is 0.6 m/sec (2.1 ft/sec) at design full power of about 1500 kW(t) (5×10^6 Btu/hr). The tube matrix is composed of four bundles with a total of 576 tubes with a 1.3 cm (0.5 in.) OD. The tube matrix is 12 rows deep with a vertical spacing of 3.8 cm (1.5 in.) and a horizontal spacing of 3.8 cm (1.5 in.) in each row.

About a dozen different designs were considered in an effort to evolve a layout that would best meet the boundary conditions. Of these, fairly detailed layout and analytical studies were carried out for four designs. The various designs and the basic problems are discussed in Ref. 2.

DEVELOPMENT PROGRAM

Program Plan

The overall plan for the CCC program is quite comprehensive. The early phases of the program have included conceptual design, application evaluation and component testing, and technology evaluation. The current program includes commercial-sized reference plant design, test system design, and planned construction and operation, a site specific demonstration plant design and market assessment. The present program places emphasis on participation in all these activities by private industrial firms working with ORNL with the goal of commercial acceptance of the system as early as possible.

Component Test Program

The component test program has been directed toward development and testing in four key problem areas: cold flow model studies on fluidization and solids mixing, coal feed system, fluidized bed heat transfer, and fireside corrosion of tubes in a fluidized bed.

Cold Flow Model. A number of tests were conducted with a 1.3 m (4 ft)-square, 4 m (12 ft)-high Lucite model of the fluidized bed furnace, shown in Fig. 4. The areas of testing include fluidizing velocity, pressure drop, air distribution, coal mixing rate, and tube vibration. The fluidizing velocity tests indicate that it should be possible to operate the furnace at about 1/3 of the full power air flow rate. The coal mixing data showed that adequate horizontal mixing of the coal should be obtained from the four coal feed nozzles at 1/3 of the full power air flow rate. Tube vibration was found having a frequency range of 20–50 Hz, but it was of low amplitude. The natural frequency of a full-length furnace tube was measured and found to be 15 Hz with no support under the horizontal U-bend portion. The results of the vibration test led to the decision to provide supports at the ends of the horizontal U-tubes in the ORNL reference design furnace.

The tube bundle arrangement in the cold flow test model with full-scale diameter tubes is shown in Fig. 5.

A photograph of the model of the air distribution plate is shown in Fig. 6. The air tuyeres are pipe stubs with horizontal holes 90° apart to orifice the air. The tuyeres are spaced on a 7.6 cm (3 in.)-square pitch. Coal feed nozzles are located in the four quadrants, and a limestone feed nozzle is located at the center of the plate.

Coal Feed System. Tests have been conducted on components of three different coal feed systems, and endurance testing has been completed on the system that was selected as the reference design. A coal feed system consisting of a gravity flow splitter feeding four air ejectors for transporting the coal (see Fig. 7) has been tested and found to provide four streams that can be maintained within plus or minus 5% of the mean coal flow rate over the entire operating range with repeatable results. A series of batch flow tests was carried out on this system over a total running time of 175 hrs with good success. The system was selected as the reference design coal feed system and was operated continuously for 1000 hrs without incident.

A coal feed system based on a four-way splitting nozzle in the pneumatic transport line also yielded good test results, although not quite as good as the gravity flow splitter feed system. The split among the four streams was about plus or minus 8% of the mean value.

Both of these coal feed systems were tested feeding coal into the fluidized bed cold flow model. Tests were run for coal feed rates and bed superficial velocities corresponding to four power levels from 1/3 to full power. Both systems gave excellent results over the full range of operating conditions, and no interruption of feed from plugging or other problems were encountered.

Heat Transfer Test

A heat transfer test was run on an air-cooled tube in the FluiDyne Engineering Corporation 45 cm (18 in.)-square fluidized bed furnace at a bed temperature of 900 C (1650 F) over a range of fluidizing velocity of 0.25–0.65 m/sec (0.8–2.2 ft/sec) with a bed mean particle size of 460 μm. As may be observed in Fig. 8, the heat transfer coefficient from the bed to the tube was found to vary from about 227 W/m^2- C (40 Btu/hr-ft^2- F) at a fluidizing velocity of 0.25 m/sec (0.8 ft/sec) to a value of about 483 W/m^2- C (85 Btu/hr-ft^2- F) at a velocity of 0.5 m/sec (1.6 ft/sec) and was essentially constant at higher velocities(3).

Fireside Corrosion Test

A corrosion test on air-cooled tubes made up of sections composed of 304, 310, 316 stainless steel, Inconel 600, and Incoloy 800 was run in the FluiDyne fluidized bed combustor. The tubes were maintained at a constant maximum wall temperature of about 870 C (1600 F). The tubes were removed at intervals of 500, 1000, or 1500 hr, and samples were prepared for metallographic examination. The total exposure time was 4500 hr, and examination has been completed for 500, 1000, and 1500 hr exposure.

The results of the examination are encouraging. No evidence of erosion was found, and a thin hard scale composed of about 60% $CaSO_4$ was present on the tubes. No measurable loss of wall thickness was found. A metal oxide layer about 0.025 to 0.038 mm (0.001 to 0.0015 in.) was observed on each of the materials. Intergranular oxidation attack for a depth of about 0.03 m (0.0012 in.) was observed.

No significant increase in the thickness of the metal oxide layer or depth of intergranular attack was found to have occurred between 500 and 1500 hr for the 304, 310, 316 stainless steels and Incoloy 800. Tubes of each of these materials completed the entire 4500 hr test without serious corrosion or tube failures.

Two incidents of high corrosion and wall rupture occurred for Inconel 600 tubes. In both cases, the cause is believed to have been the presence of local reducing conditions at the point of failure. It has been decided that Inconel 600 is too susceptible to corrosion attacks under reducing conditions, and this material was dropped from the test program.

Gas Turbine Evaluation

A survey of gas turbines was made to determine the availability of turbines that could be adapted for use with a coal-fired external heater with a minimum of modification. Only two manufacturers were found that have built gas turbines that have both external combustion chambers and air inlet and outlet ports for a recuperator which would permit adaptation without redesign of the turbine casing. AiResearch Division of Garrett Corporation had built the 500 kW(e) Model 831-200 for the Air Force, and Sulzer-Brown Boveri in Europe has built a number of units in both the 4 MW(e) and 20 MW(e) size.

The AiResearch Model 831-200 turbine was chosen as the reference design for the system test unit. AiResearch was asked to perform an engineering study to evaluate the feasibility of modifying the 831-200 turbine for both open and closed cycle operation with a coal-fired combustor and to determine the modifications that would be required. The study was completed, and they concluded that this turbine could be adapted readily for open cycle operation, and that with somewhat more extensive modification it could also be adapted for closed cycle operation.

Commercial-Sized Plant Conceptual Design

The conceptual design studies of the system included the conceptual design of a 20 MW(e) unit to examine the potential design problems of scaling up to a commercial-sized plant. The primary consideration is the design of the fluidized bed combustor for a heat output of about 90 MW(t) (300 × 10^6 Btu/hr). This sized unit will require a fairly large area for the fluidized bed. The bed area can be minimized by increasing the bed depth, but the economical limit for the bed depth of an atmospheric fluidized bed is probably about 1.8 m (6 ft) deep because of the fan power requirements.

The layout drawing for one concept of the combustor is shown in Fig. 9. In this design the bed tube bundle is composed of two bundles of U-tubes that extend halfway across the width of the bed with the turbine air inlet and outlet manifolds on each side of the bed. The combustion plenum, air distributor plate, and tube bundles are designed to be removed as a unit from one side of the combustor by disconnecting the turbine air inlet and outlet pipes and removing bolts from the air plenum flange. In this layout the economizer tube bundle is located above the freeboard. The plenum width is decreased in the economizer region to increase the flue gas velocity through the economizer for improved heat transfer. The combustor is lined with refractory and does not make use of cooling tubes in the combustor walls. The tube bundle is divided into 12 modules to reduce the airflow per manifold. Each bed module has a separate combustion air plenum and air distributor to allow each module to be started up individually to reduce the heating requirements during startup. The principal design parameters are given in Table 1.

Table 1. System parameters for a conceptual design of a 90 MW(t) fluidized bed combustor for a gas turbine cogeneration plant.

Turbine air flow, lb/sec	522
(Kg/sec)	(237)
Turbine inlet temperature, F	1500
(C)	(816)
Compressor outlet pressure, psia	175
(MPa)	(1.2)
Compressor pressure ratio	4.3
Number of tubes in bed	8640
Tube OD, in.	1
(cm)	(2.54)
Tube length in bed, ft	12
(m)	(3.7)
Horizontal tube pitch, in.	2.4
(cm)	(6.1)
Vertical tube pitch, in.	2
(cm)	(5.1)
Number of tube layers in bundle	24
Tube bundle depth, in.	49
(cm)	(124)
Expanded bed depth, in.	58
(cm)	(147)
Freeboard height, ft	12
(m)	(3.7)
Bed width, ft	12
(m)	(3.7)
Bed module length, ft	12
(m)	(3.7)
Number of bed modules	6
Total bed area, ft^2	864
(m^2)	(80)
Superficial velocity, ft/sec	5.5
(m/sec)	(1.7)
Bed temperature, F	1650
(C)	(900)
Number of coal feed points per bed module	16

System Test Program

It is planned for the test system to be designed as a small-scale version of the commercial-sized reference plant design, both of which are to be designed by a private industrial organization or team. The test system is to be fabricated by a commercial boiler or furnace manufacturing firm.

A test program is to be conducted to obtain operating data that will provide answers to the key technology questions. Performance data will be obtained to establish the combustion efficiency, SO_2 and NO_x emissions of the combustor. Endurance testing will be conducted to determine the corrosion/erosion rates on the tubes in the bed and the reliability of the combustor and the system.

Industrial Energy Assessment

One of the tasks in the program was to survey the use of energy for industrial process heat and electricity. The survey has been completed, and the results have revealed some significant information(4). A number of industrial energy surveys have been performed, and most of the information required for this program can be obtained from the literature. The energy consumption by industry in 1974 was estimated to be about 28 × 10^{15} Btu/yr (30 × 10^{15} J/yr) which amounted to about 39% of the total energy used in the United States. Of the energy used by industry, 36% was supplied by natural gas, 21% by petroleum, 15% by coal, and 28% by electricity(5). These data indicate that a considerable amount of natural gas and oil can be conserved as the use of coal for industrial fuel is increased. The amount of electricity used by industry indicates a very good potential application for cogeneration systems.

The use of energy by industry is concentrated in a few industries that are very large users. The industries that are ranked as the six largest consumers of process heat use about 80% of the total heat(6). In order of their ranking by process heat use, these categories are (a) chemicals; (b) primary metals; (c) petroleum refining; (d) pulp and paper; (e) stone, clay, glass, and cement; and (f) food products. In order to have significant impact on industrial fuel use, applications for gas turbine cogeneration systems would need to be found in one or more of these categories of industry.

One of the most important factors in assessing the suitability of the gas turbine cycle for an industrial application is the temperature at which the process heat is used. From one of the surveys on industrial heat use(7), it is estimated that about 30% of the process heat is used at temperatures below 177 C, (350 F), another 30% at temperatures from 177—593 C (350—1100 F), and the remaining 40% at temperatures above 593 C (1100 F). In the lower temperature range heat can be supplied easily from either steam or gas turbine systems. The gas turbine cycle is better suited to provide heat with a cogeneration system in the middle range of temperatures. The gas turbine cogeneration system is not adapted to supplying heat at temperatures above about 593 C (1100 F). If the CCC system was used to supply the electricity and the process heat used at temperatures of 593 C (1100 F) or less in the six major industry groups, it would represent a savings of 1.5 million barrels/day of oil and almost 5900 m^3/sec (18 billion ft^3/day) of natural gas.

REFERENCES

1 Fraas, A. P., "Conceptual Design of a Coal-Fired Gas Turbine for MIUS Applications: Phase II Summary Report," (to be published), Oak Ridge National Laboratory, Oak Ridge, Tennessee.

2 Fraas, A. P., et al., "Design Study for a Coal-Fueled Closed Cycle Gas Turbine System for MIUS Applications," IEEE Catalog No. 75 CHO 983-7TAB, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

3 Holcomb, R. S., "Heat Trasfer Performance of an Air-Cooled Tube in a Fluidized Bed Furnace," (to be published), Oak Ridge National Laboratory, Oak Ridge, Tennessee.

4 Graves, R. L., Holcomb, R. S., and Tallackson, J. R., "Assessment of an Atmospheric Fluidized Bed Coal Combustion Gas Turbine Cogeneration System for Industrial Application," (to be published), Oak Ridge National Laboratory, Oak Ridge, Tennessee.

5 Federal Energy Administration, National Energy Information Center, "Monthly Energy Review," March, 1976.

6 McDonnel-Douglas Astronautics Co., West, "Industrial Applications of Solar Energy," SAN/1132-1, January, 1977.

7 Intertechnology Corporation, "Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat, Volume 1, Final Report," COO28-1, February 1977.

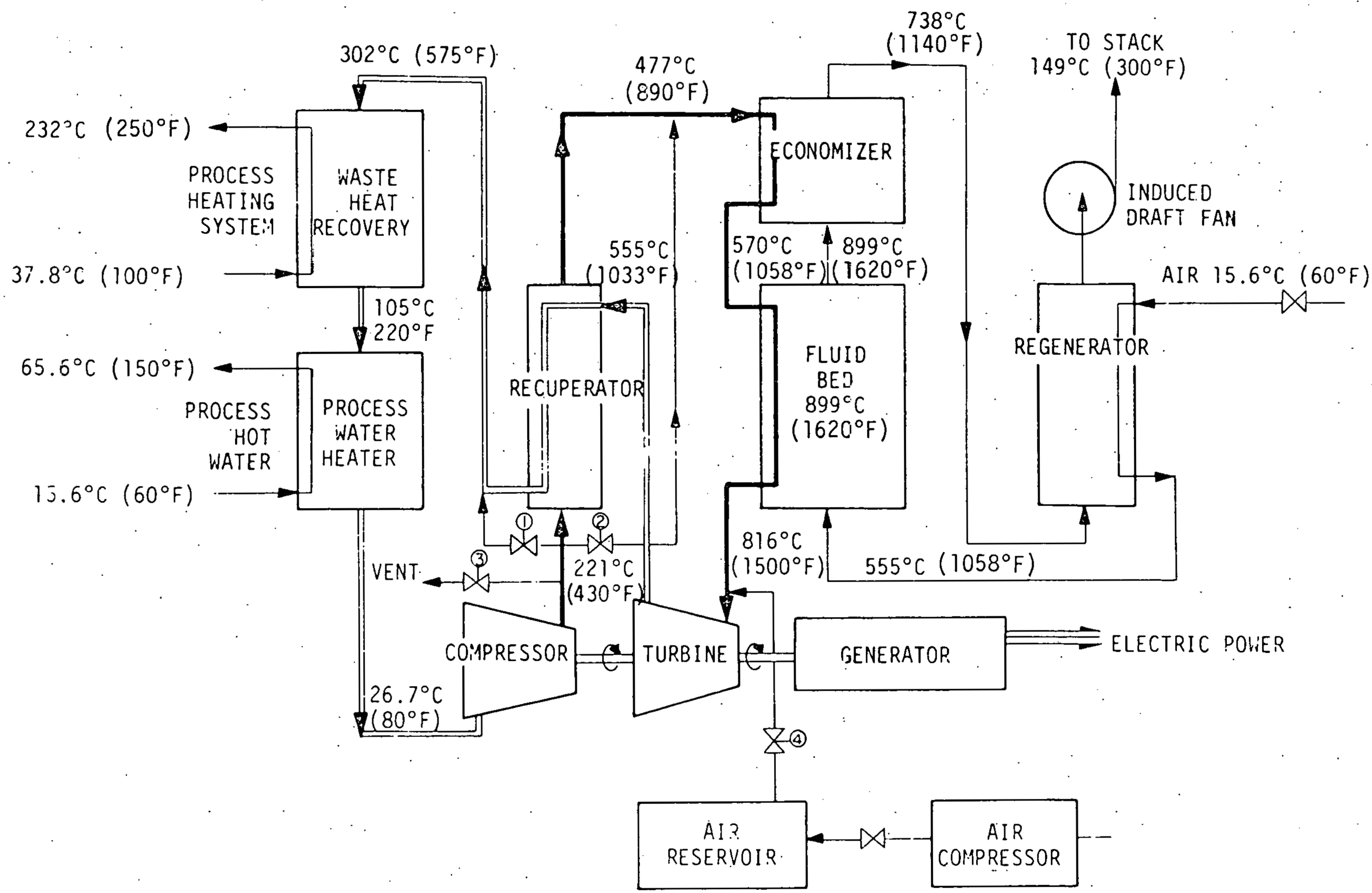

Fig. 1. Flowsheet for a closed gas turbine cycle coupled to a fluidized bed combustor.

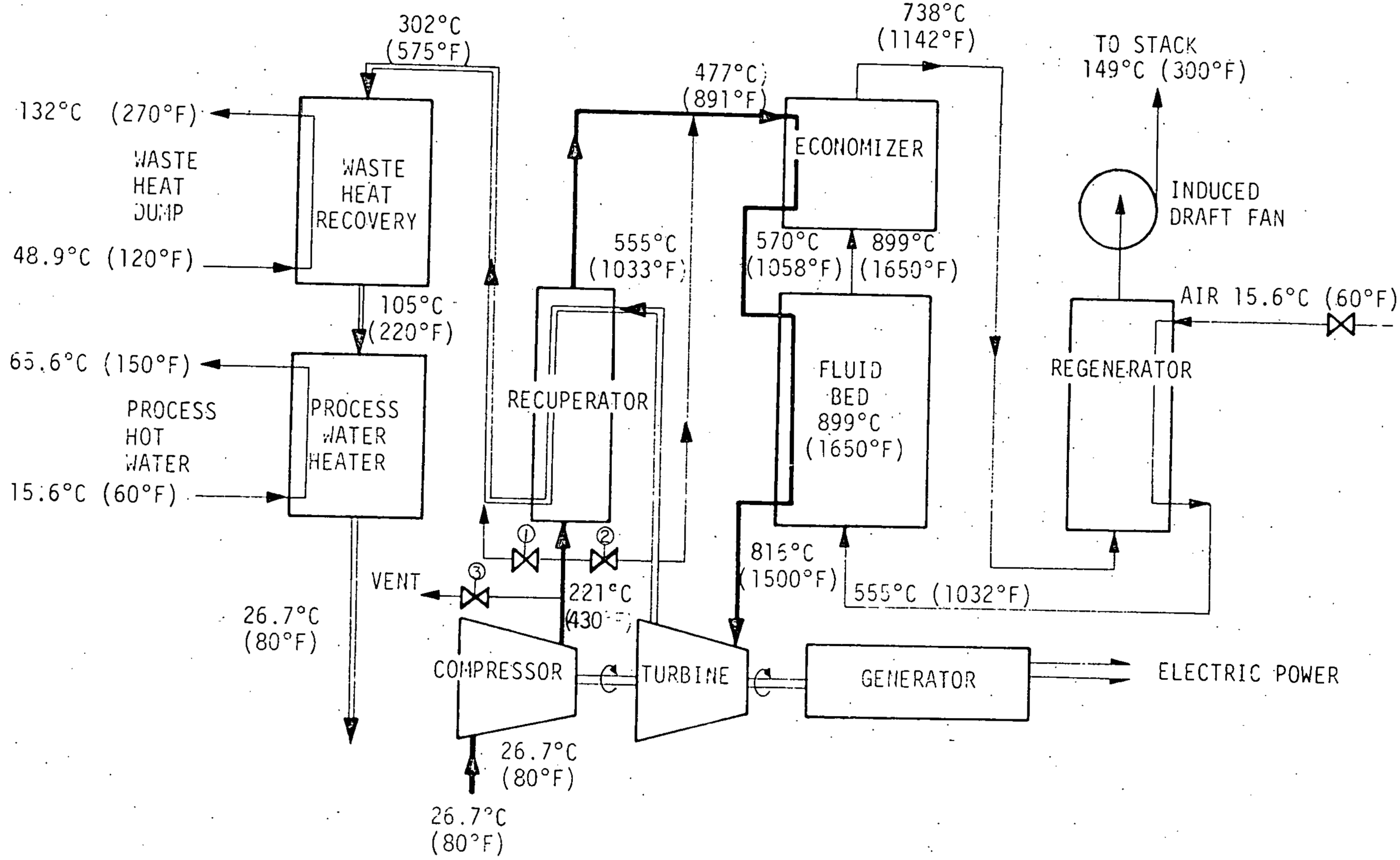

Fig. 2. Flowsheet for an open gas turbine cycle coupled to a fluidized bed combustor.

ORNL-DWG 75-9227

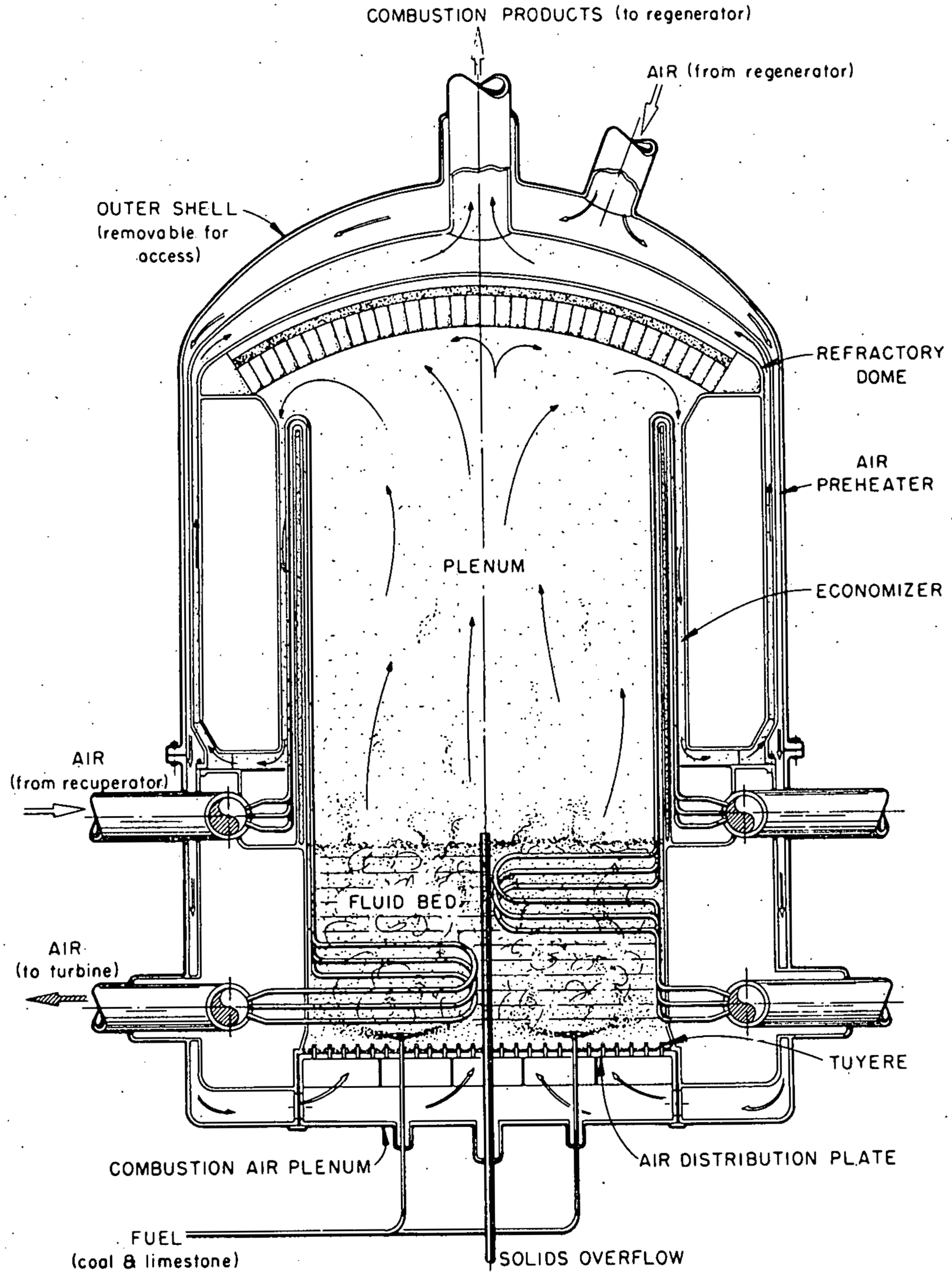

Fig. 3. Conceptual design of a fluidized bed combustor for a gas turbine system.

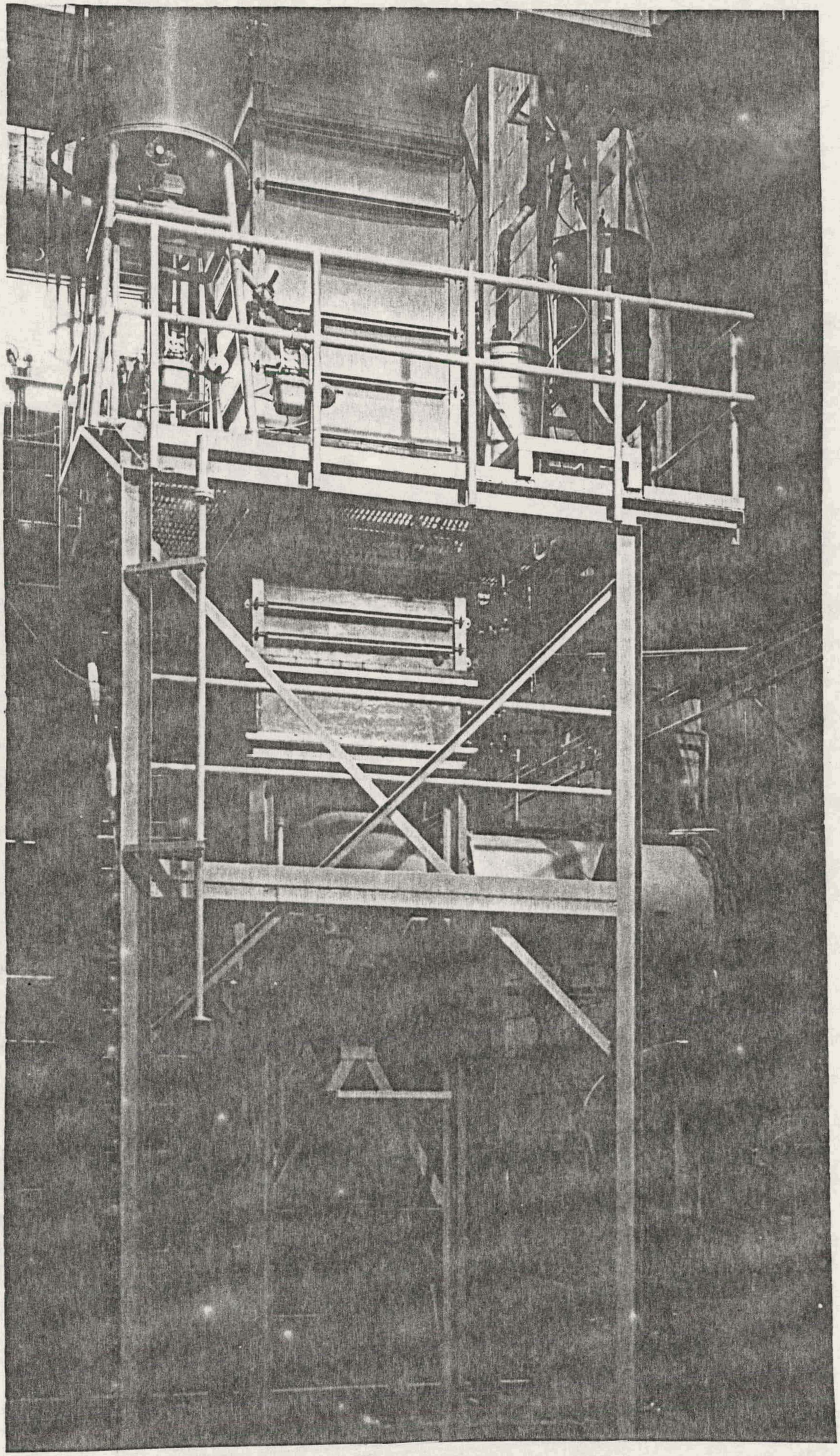

Fig. 4. Fluidized bed cold flow test model.

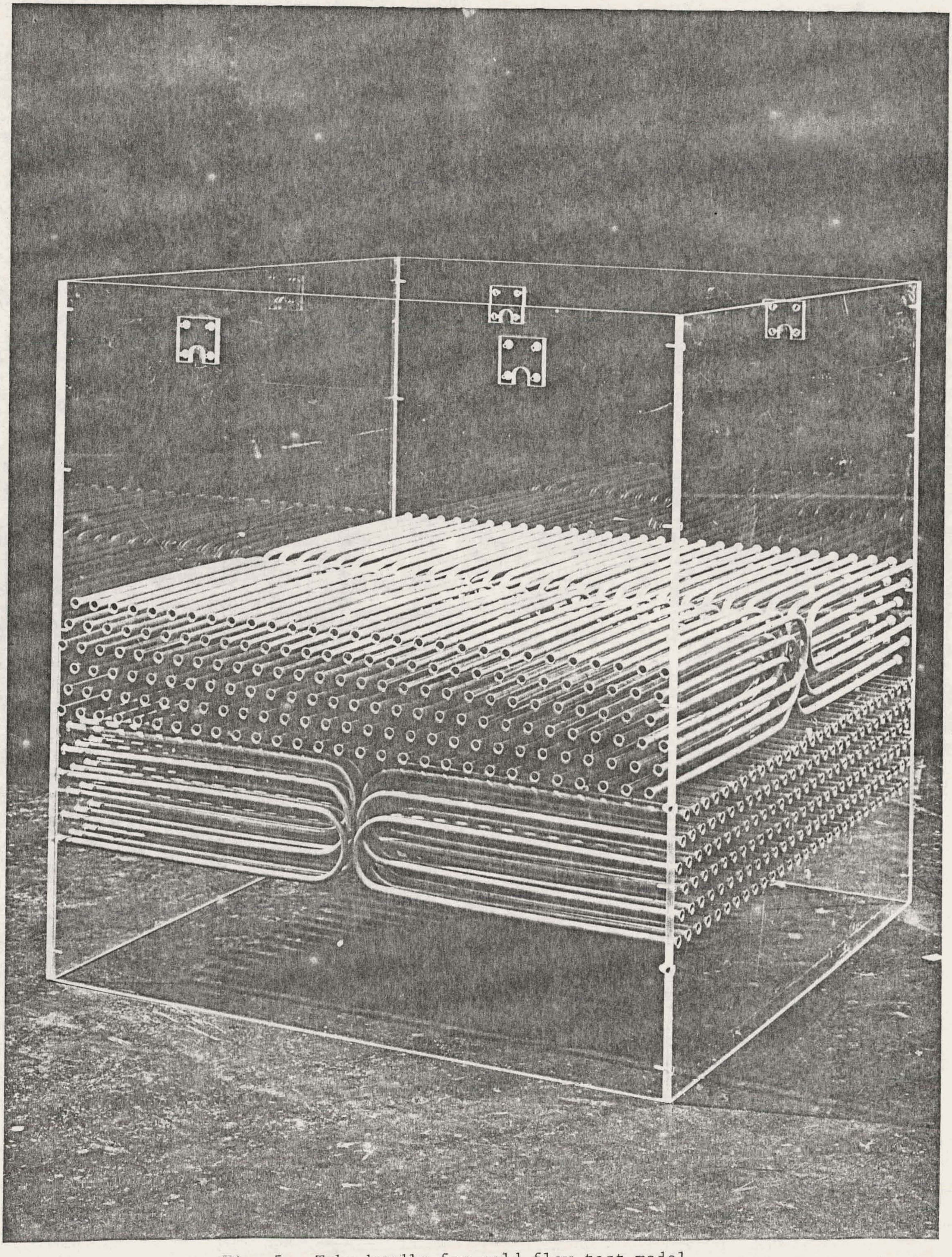

Fig. 5. Tube bundle for cold flow test model.

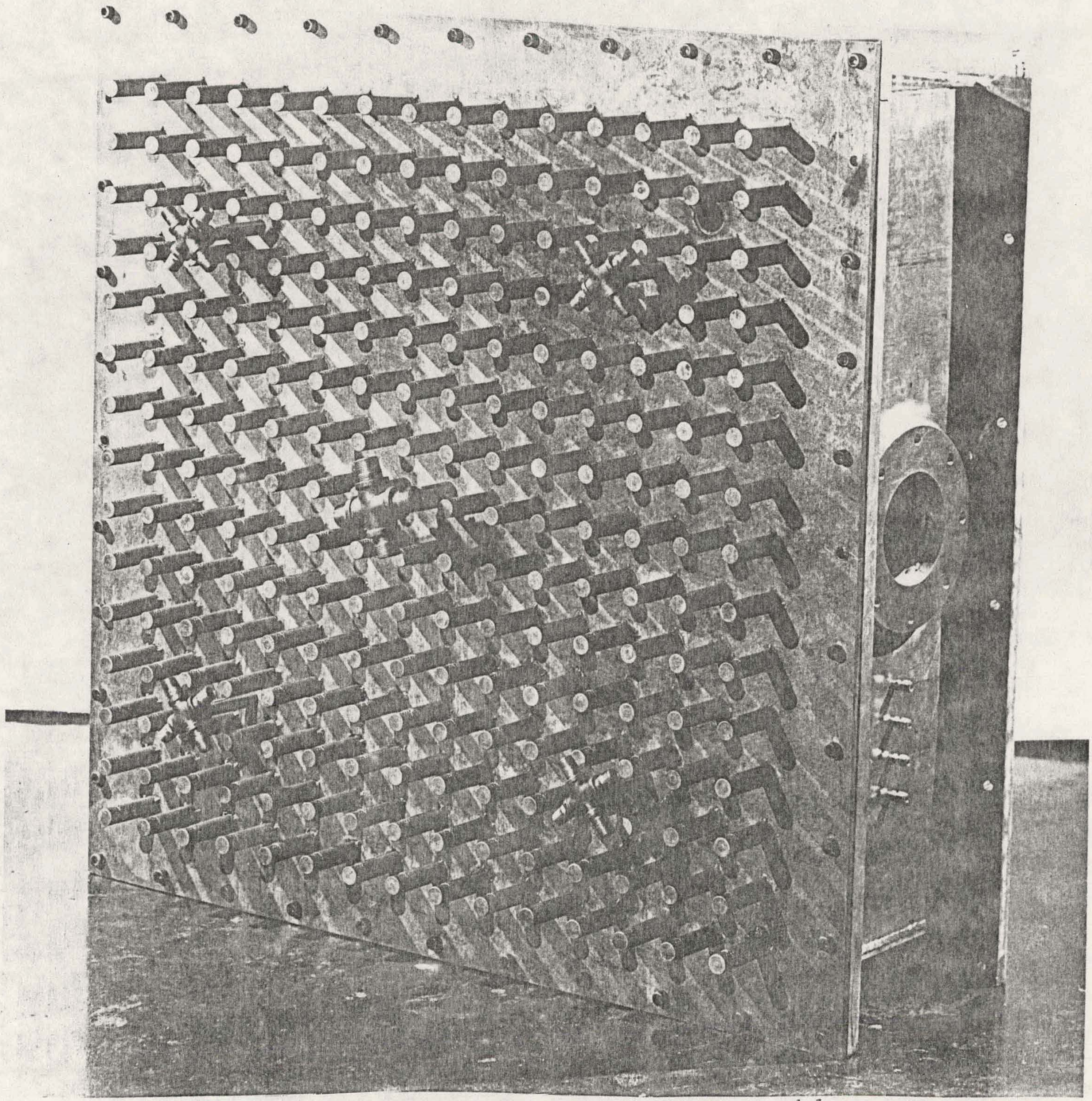

Fig. 6. Air distributor for cold flow test model.

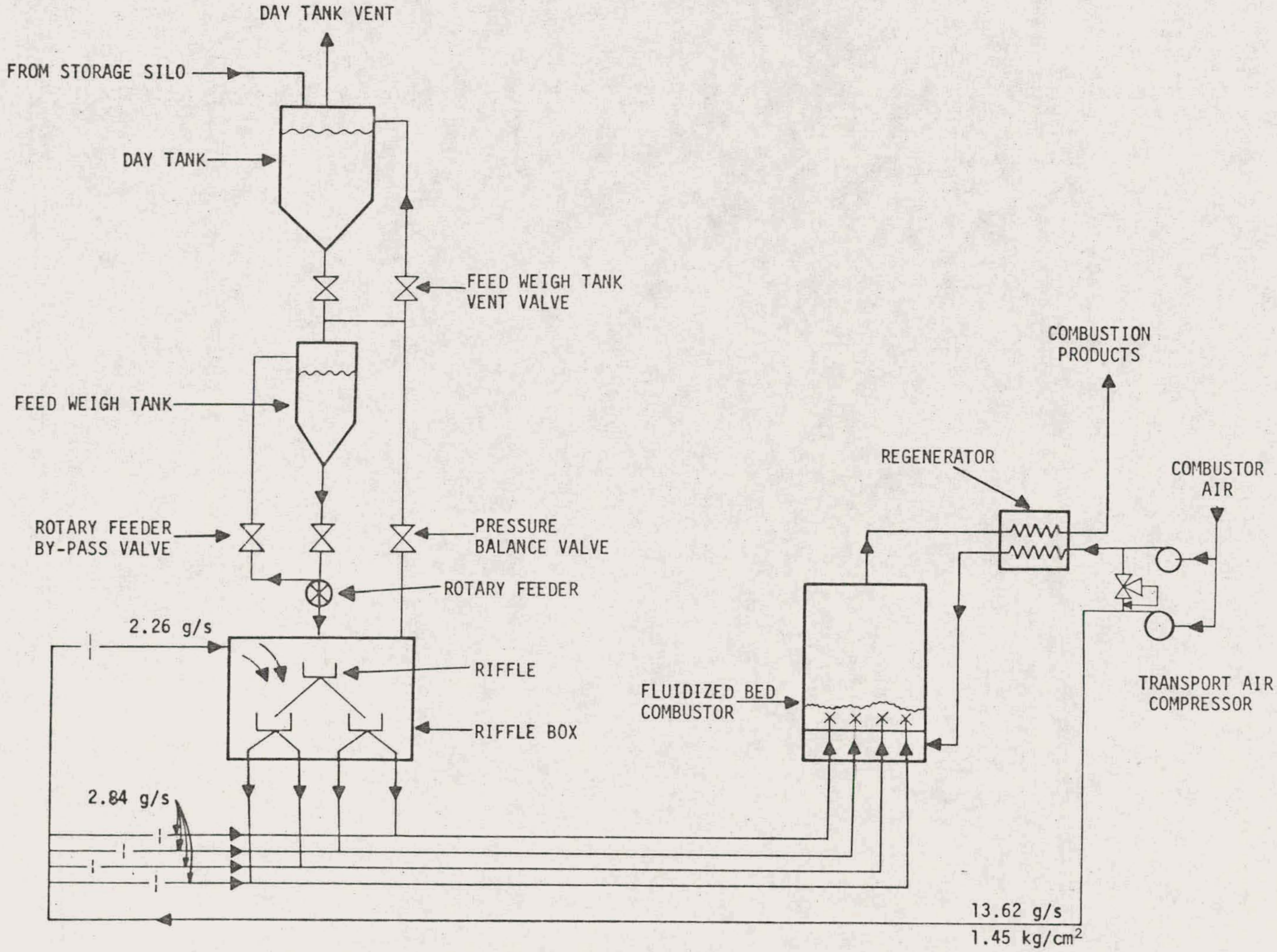

Fig. 7. Flowsheet of a coal feed system for the fluidized bed combustor.

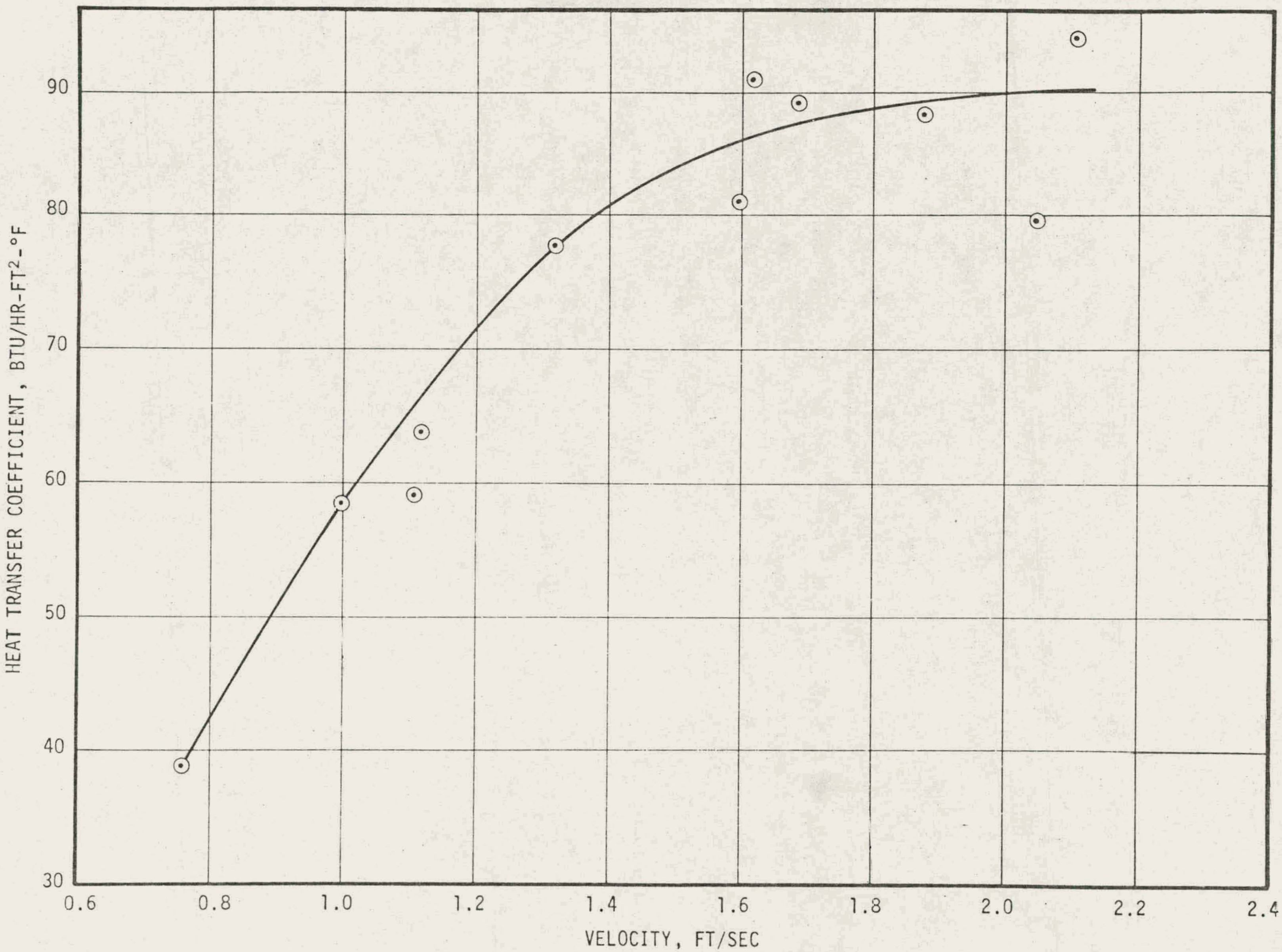

Fig. 8. Heat transfer coefficients to air-cooled tubes in a fluidized bed combustor.

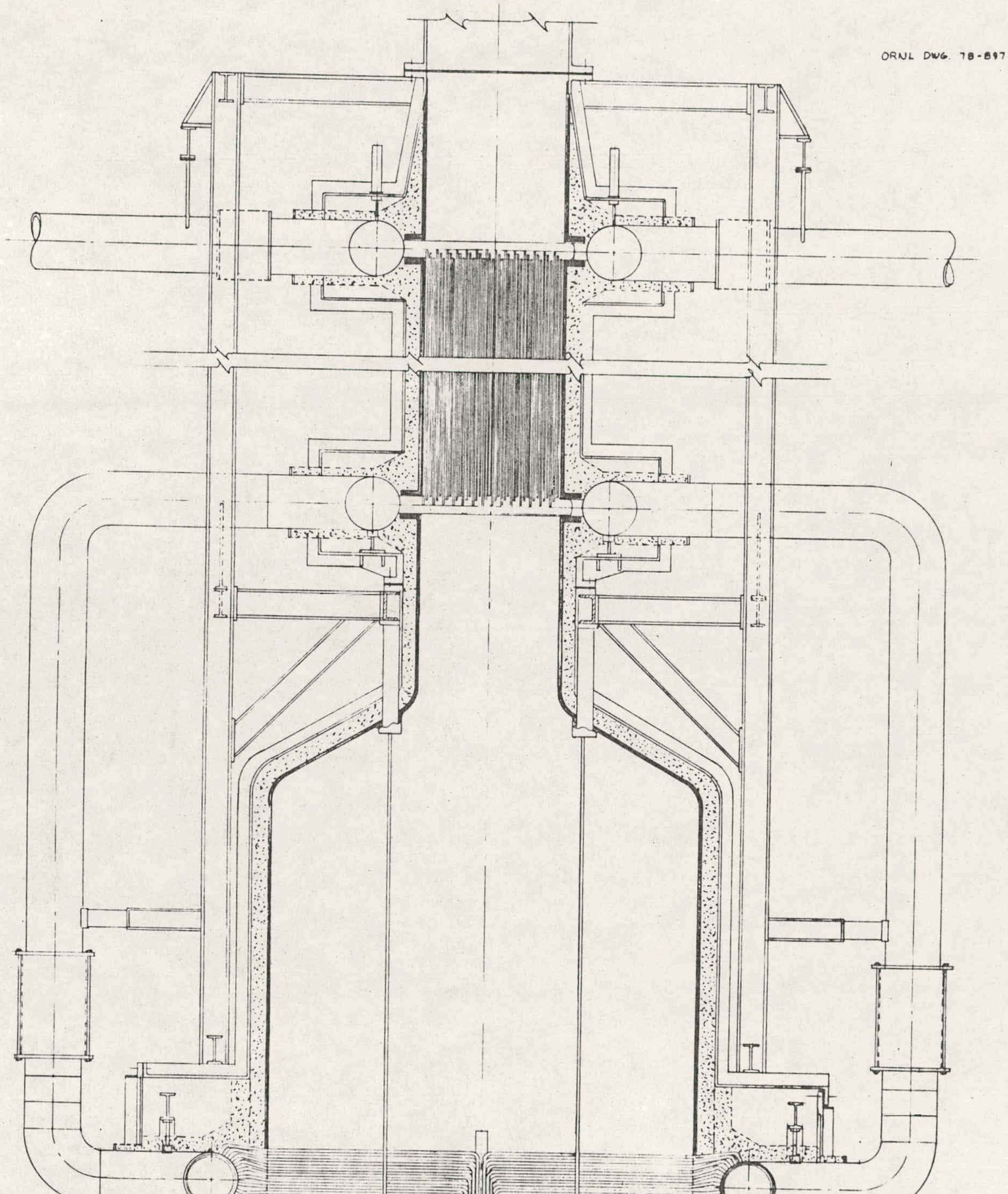

Fig. 9. Conceptual design of a 90 MW(t) fluidized bed combustor for a gas turbine cogeneration system.