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State of the Art of Pressurized Fluidized Bed Combustion Systems

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MASTER

Fossil
Energy
Program

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STATE OF THE ART OF PRESSURIZED FLUIDIZED BED COMBUSTION SYSTEMS

R. L. Graves

ABSTRACT

This report was prepared at the request of the Tennessee Valley Authority (TVA) to clarify the development status of the pressurized fluidized bed combustor (PFBC) and to place in perspective the problems which are yet to be solved before commercialization of the concept is practical. This report, in essence, supercedes the interim report published in 1979, "Assessment of the State of the Art of Pressurized Fluidized Bed Combustion Systems."

A brief overview of the PFBC concept is included citing potential advantages and disadvantages relative to atmospheric fluidized bed combustion (AFBC) and conventional pulverized coal plants. A survey of existing and developing PFBC experimental facilities is presented in some detail which includes the major accomplishments at the respective facilities. Recent data on plant emissions, turbine/gas cleanup systems, and overall efficiency are provided. Findings of several design studies are also discussed.

The results of recent gas turbine and cascade tests have been encouraging although the full assessment of the accomplishments have not been made. The delay in construction of the Grimethorpe plant causes further delay in proof-testing full-size, rotating turbomachinery.

Several parameters are recommended for further assessment in design studies including:

1. effect of turbine life on cost of power and
2. effect of reduced gas turbine inlet temperature and pressure on cost of power.

INTRODUCTION

Both atmospheric and pressurized fluidized beds are under development and conflicting claims by proponents are prevalent. To help clarify the situation and give perspective to the concept, Tennessee Valley Authority (TVA) has requested that Oak Ridge National Laboratory (ORNL) survey the status of the design and development of pressurized systems including the merits and developmental problems of these systems. As a first step in the program, it was requested that a preliminary scoping

report be prepared surveying the work that has been done on pressurized fluidized bed combustor (PFBC) systems and identifying the key developmental problems. A draft of the scoping report was prepared over about a one month period and was sent to TVA in October of 1978 with final publication in June 1979.¹

This report includes findings of the continuation of the survey of available data from PFBC development activities. An effort was made to collect the most recent information available through the literature and personal communication. The information included in this report reflects data generated up through November 1979 for the most part. A few findings reported as recently as January 1980 are also included.

Major emphasis was placed on development facilities and recent tests conducted at these sites. Recent design study findings and other analytical works are also reported, but work reported before 1976 is generally omitted since the documentation for the earlier studies is readily available.

Overview of PFBC Concept

It has been recognized for about 15 years that there is a major advantage to pressurizing a fluidized bed coal combustion system because the furnace size and hence the number of coal feed points is essentially inversely proportional to the furnace pressure. Thus, it would appear that the size and cost of the furnace can be reduced markedly by pressurizing the unit. However, the power required for compressing the air is so large that this can be accomplished economically only if the high temperature, high pressure combustor effluent gases are used to drive a gas turbine which, in turn, drives the compressor that supplies the pressurized air to the furnace. The incorporation of the gas turbine provides an opportunity to increase the cycle efficiency by using a furnace pressure of ~ 1.0 MPa (~ 10 atm) with a combined gas turbine-steam cycle similar to that of over 200 such units in operation in the United States employing oil or gas as fuel. However, the problems presented by turbine corrosion, erosion, and deposition if coal is used as fuel have made such a system appear more difficult to develop than an atmospheric fluidized bed. This

section presents a brief survey of the situation from the design and development standpoint to indicate the major boundary conditions and the various advantages and disadvantages of the pressurized fluidized bed system as compared to the atmospheric fluidized bed.

Principal Advantages of the PFBC

A principal advantage of the pressurized fluidized bed combustor is a reduced size for a specific thermal output. The heat release in an atmospheric fluidized bed combustor is limited by the maximum achievable mass flow rate and, hence, superficial velocity of the combustion air which causes excessive elutriation of the bed materials. Unless the sorbent particles are made so large that their conversion is too incomplete, the maximum superficial velocity for current AFBC design parameters is about 4 m/s (13 ft/s). As the pressure of the combustion air is increased to several atmospheres, the concentration of oxygen per unit volume is proportionally increased; an equivalent heat release can be achieved at much lower superficial velocities, resulting in increased gas residence time and improved combustion efficiency and sorbent utilization. A higher heat release per unit volume can be obtained at higher velocities as limited by elutriation or the inability to remove all of the heat released. In fact, the heat release can be increased to the point where its limiting factor is determined by the amount of heat transfer surface which can be physically packed into the bed. Deepening the bed allows more volume for heat transfer surface and can be done in a pressurized bed without incurring excessive pumping power losses due to the use of the power recovery turbine. Hence the PFBC can indeed generate the same power as the AFBC in a smaller plan area which also implies that the number of coal feed points will be reduced. A deep bed also has the advantage that it gives a greater transit time for the fine coal particles and gases passing through the bed if a bottom coal feed location is employed, and this in turn increases both the combustion efficiency and the sulfur retention. Note that in the Rivesville atmospheric fluidized bed, the bed depth is limited to about 1.2 m (4 ft). To increase the output per unit area of the bed, a high superficial gas velocity [3.7 m/s (12 ft/s)] has been

employed, and, as a consequence, about 25% of the carbon in the coal fed to the bed has blown out with the fines even with doubly screened coal. To avoid a serious loss in the energy available from the coal, it is necessary to return the fines from the first-stage cyclone to a carbon burnup cell, and this must be operated at a temperature around 1093°C (2000°F) in order to burn the carbon in the high ash material. The high temperature leads to the formation of NO_x and higher SO₂ emissions to a much more serious degree than is the case for the main portion of the fluidized bed.

However, other options to carbon burnup cells are under investigation and also show promise of improving efficiencies. The Electric Power Research Institute (EPRI) and Babcock and Wilcox (B&W) are among those evaluating recycle of collected particulate from the first stage separation equipment back to the main fluidized bed using their 6 ft x 6 ft AFBC at Alliance, Ohio; General Atomic is proposing similar studies using their graphite combustor. TVA's 20-MW AFBC pilot plant is using recycle instead of carbon burnup cells. Second generation (recirculating bed) AFBCs are in various stages of design by Battelle Columbus, Lurgi-Chemie, Stone and Webster Engineering and others.

An important advantage of the deep beds in pressurized furnaces is that the boiler tubes in the bed can be mounted vertically instead of horizontally. This not only makes it possible to eliminate most of the uncooled structure for supporting the boiler tubes in the bed, which is advantageous from the corrosion standpoint, but it also makes it possible to employ a cylindrical furnace with a minimum of awkwardness in tube bundle configuration. Both of these factors tend to reduce the cost of the furnace shell and the tube matrix in the bed. Note, too, that the use of vertical tubes makes it possible to effect good water recirculation in the boiler tubes by natural thermal convection so that a boiler recirculation pump is not required.

The greater bed depth permissible if the furnace is pressurized has a number of subtle but important advantages from the standpoint of control. The greater bed depth, for example, makes possible a larger space between the air tuyeres and the bottom of the boiler tube matrix, this gap being only a small fraction of the total bed depth at full power. The pumping

power associated with such an increment in bed depth is small, while the gap improves mixing of the fuel and air before it reaches the heat transfer matrix so that it reduces the possibility for boiler tube corrosion arising from local regions in which a reducing atmosphere might prevail. Further, the use of a fairly generous plenum between the air tuyeres and coal feed points on the one hand and the bottom of the tube matrix on the other, makes it possible to start-up the fluidized bed with its level a little below the boiler tube matrix so that there would be no boiler tubes immersed in the bed under start-up conditions, and hence, no large heat losses to these tubes. Further, with a fluidized bed depth of the order of 3.7 m (12 ft) at full power, the problems of sensing and controlling bed depth are eased because a change in bed depth represents a much smaller fraction of the total depth than for a typical atmospheric bed. Also, by using bed depth as the prime mechanism for controlling the boiler furnace output, one has a reasonably linear relationship between bed depth and furnace output because the amount of heat transfer surface area immersed in the bed is directly proportional to the bed depth above the bottom of the heat transfer matrix. The exposed tube matrix above the bed will remove some heat from the flue gas which in turn will reduce the flue gas turbine output. The combination of reduced bed heat transfer surface and reduced turbine output can be utilized as a plant load control mechanism.

PFBC Disadvantages

In addition to the principal problems of turbine erosion, corrosion, and deposits (discussed in detail in body of report), pressurizing a fluidized bed poses some very serious problems in feeding the coal and sorbent into the bed against a relatively high furnace pressure. If an atmospheric bed is employed, the feed systems need to operate against a pressure of perhaps 0.014 MPa (2 psig), but if the furnace is pressurized, the feed systems must deliver the materials against a pressure of 0.3 to 1.0 MPa (3 to 10 atm). This can be accomplished with lockhoppers, but these have proved to be a major source of mechanical troubles in every type of chemical process system in which they have been employed. Other

methods of introducing granular solids through some sort of a pressure lock have all given substantial difficulties so that a major set of development problems must be overcome in the development of the coal and sorbent feed systems for pressurized fluidized beds.

Another important disadvantage of pressurized fluidized beds stems from the fact that there is considerably less operating experience with units of this type than with atmospheric fluidized bed coal combustion systems. It is not clear just how serious this disadvantage will prove to be, but it certainly is a factor in the thinking of many people.

Furnace Design

There are many subtle considerations in the design of the boiler furnace that are difficult to quantify. These include the problems of making a furnace shell sufficiently leak-tight so that combustion gas and fine ash do not percolate out into the surrounding area, the problems of retrofitting a new type of furnace to an existing plant, and floor space requirements.

Although not obvious, the pressure drop across an atmospheric fluidized bed is of the order of 0.015 MPa (60 in. of water). Thus, a potential problem exists in leakage of combustion gas and fly ash into the furnace room with conventional rectangular furnaces in which the joints between elements of the structure might be difficult to gasket. As a consequence, there is a major advantage to the use of a cylindrical shell that could be welded to give a simple leak-tight structure. It would be particularly desirable to make this shell so that the bulk of the gasketed flanged joints for access are located on the fresh combustion air side so that any leaks into the furnace room will be of clean air rather than combustion gas plus fine ash. Unfortunately, if an atmospheric fluidized bed is used, it is difficult to arrange the horizontal serpentine tubes required in a good cylindrical array; hence, one is almost required to employ a rectangular furnace shell. If a pressurized fluidized bed is employed, the tubes can be mounted vertically which facilitates making the

heat transfer matrix cylindrical with the boiler tubes suspended from support structure up in the freeboard over the bed. It is difficult to quantify this advantage, but a comparison of various designs for both pressurized and atmospheric fluidized beds indicates that the cylindrical shell weighs substantially less and is substantially less complex to fabricate than a rectangular shell which requires extensive external bracing to carry the bending loads from the internal pressure on the large flat surfaces.

Furnace floor space requirements are an important factor in determining building size in a new plant and in the feasibility of retrofitting a fluidized bed boiler to an existing plant. Such retrofit projects may be quite important during the coming decades. The difficulties presented by the large cross-sectional area of atmospheric fluidized beds can be mitigated by stacking the beds one above the other. However, at least 2.3 m (8 ft) of freeboard is required above each bed so that the overall height of the stacked beds for a given output is much greater than for a pressurized bed. Further, the cross-sectional area of the fluidized bed in such a stacked array is increased by the cross-sectional area required for the flow passages for flue gas and combustion air required by beds at higher or lower levels.

A major problem in the design of the fluidized bed furnaces is that the weight of material in the bed makes the structural design of the bed support grid progressively more difficult for bed diameters greater than about 4.6 m (15 ft) and for deeper beds. The structural weight tends to go up quite rapidly with bed diameter and depth because differential thermal expansion problems in the bed support grid structure make it necessary to employ a relatively small number of support points. The bending loads in the unsupported span between these support points build up so that the weight of structure required tends to become excessive for bed diameters of more than about 10.7 m (35 ft).

EXECUTIVE SUMMARY

Data generated during 1978-79 have resulted in greater optimism toward the feasibility of PFBC systems and have clarified the problems which require further attention. Significant accomplishments were two coal-fired turbine tests and two stationary cascade tests which generally demonstrated that cyclone particle separators could be made adequate for protecting the gas turbines (single stage) from erosion. The cumulative test durations ranged from 500 to 1000 h with uninterrupted duration being significantly shorter. Results of these tests also verified the swiftness in which turbines can be destroyed upon malfunction of the gas cleanup devices.

Deposition on turbine blades has been evident in practically every test, but the deposits have been found to be soft and removable to a large extent. The erosive effect of spalled deposits on later turbine stages needs to be determined as does turbine performance degradation between cleanings.

Most tests have been of insufficient duration to give a clear picture of the corrosion problem. Under certain conditions, however, sulfidation has appeared within several hundred hours. The quantities of alkalis in the PFBC effluent are significantly higher than the typical levels present in fuel oils such that the corrosion is rate limited as opposed to flux limited. Lower turbine inlet temperature and improved blade materials and blade claddings are seen as likely solutions to the corrosion problem. Longer duration testing is needed for complete proof of materials durability. The addition of clays or similar materials to the combustor to act as alkali getters is also being considered as a corrosion inhibiting technique.

Coal feed systems for the PFBC test units use lockhopper systems for the most part. Metering is accomplished by screw feeders, Petrocarb systems, or rotary valves. Optimization of these systems and development of simpler devices should be pursued.

The large PFBC test rig at Grimethorpe should be a suitable vehicle for advancing the state of the art. This unit will be satisfactory for

testing turbine components more near the size of common industrial gas turbines.

PFBC gaseous emissions (NO_x , SO_2) appear to be acceptable with the present state of technology. It is likely that a final (bag) filter will be necessary for particulate emissions in spite of the extensive gas cleanup required for the gas turbine. Combustion efficiency in the PFBC is high enough (over 99%) to eliminate the need for a carbon burnup cell.

Design studies generally indicate that PFBC systems would generate power at a cost of 10 to 15% less than that for conventional plants with scrubbers. Lower turbine inlet temperatures result in only a small increase in cost of power when holding other variables constant. The effect of the combustor pressure on costs has not been identified in a thorough study. A study indicating the effect of turbine life on the overall cost of power would be very useful.

The concepts of PFBC combined cycles proposed by GE and AEP have a relatively low sensitivity to turbine inlet temperature with regard to cycle efficiency. Adiabatic or air-cooled PFBC cycles would be penalized more if the turbine temperature had to be lowered.

DESCRIPTIONS OF PFBC TEST FACILITIES

The PFBC test units which have been in operation recently or are still operating are described in this section. The areas of research most emphasized at each facility are identified also.

NASA PFBC Facility

The conical PFBC test unit at the NASA Lewis Research Center in Cleveland, Ohio, has been in operation since about 1977.²⁻⁴ The bed has a cylindrical combustion section for the lower end which is 91 cm (3 ft) high and has a 23 cm (9 in.) inside diameter. This section contains horizontal water-cooled tubes which can be replaced with solid test specimens.

The upper part of the furnace is conical varying from a 23 cm (9 in.) inside diameter at the bottom to a 53 cm (21 in.) inside diameter at the top. This section has a vertical length of 203 cm (6.5 ft). The purpose of this design was to make the upper section of the fluidized bed tend to be only slightly fluidized, thereby becoming a granular bed filter of sorts. Bed height is maintained at 61 to 244 cm (2 to 8 ft) by a water cooled auger type solids removal device which can be placed at numerous levels. There is also a television type camera in the top of the combustor as well as a gas sampling probe. A schematic drawing for the system is shown in Fig. 1.

The NASA rig is designed to burn up to 36 kg/h (80 lb/h) of coal in the presence of about 9 kg/h (20 lb/h) of sorbent. The pressure of the combustor can be varied from 0.14 to 0.69 MPa (1.4 to 6.9 atm) and the bed may be operated at temperatures up to 1100°C (~2000°F) producing combustion gases at about 870°C (1600°F).

Coal and sorbent are fed after blending to a lockhopper. A high pressure screw feeder meters the solids from the lockhopper into a pneumatic transport line which carries the solids into the combustor.

The combustor is equipped for either stationary or rotating turbine materials testing. The stationary specimens can be subjected to a high velocity gas stream on the so-called carousel wedge test unit. This unit

Fig. 1. Schematic drawing of combustor and auxiliary components, Ref. 2.

is located directly on top of the furnace and is not preceded by a gas cleanup device.

The turbine used to date is a modified single stage Chrysler automotive turbine. The rotor is 14 cm (5.5 in.) in diameter and has 53 blades. Since the turbine is designed to accommodate much more flow than the combustor generates, it is operated with partial admission and produces 3.7 to 6.0 kW (5 to 8 hp). Rotational speed at test conditions is

38,000 rpm. Speed is regulated by a dual purpose air starter and brake operated with pressurized air.

The gas cleanup system consists of a single Aerodyne cyclone mounted above the combustor. Some modification has been made to this unit to enhance performance.

The major efforts at the NASA Lewis facility have been related to characterizing the effluents from the PFBC under a wide range of operating conditions. Turbine materials testing with stationary specimens were conducted next followed by the small gas turbine operation.

Combustion Power Company (CPC)

CPC has an adiabatic PFBC test unit in Menlo Park, California. The most concerted efforts have been in the areas of attempting to operate a coal-fired turbine and the development of granular bed filters.⁵⁻⁸ The system is known as the CPU-400 process demonstration unit (PDU) and was originally a solid waste burning system built by the EPA. Coal firing began in 1974 with funding eventually supplied by ERDA and DOE.

The combustor is a ceramic-lined cylindrical shell with a plan area of 3.7 m^2 (40 ft^2). No cooling tubes are used in the bed so the excess air used in combustion is necessarily high, about 300%. The unit is designed to operate at about 0.4 MPa (4 atm).

Premixed coal and dolomite are metered by rotary air lock feeder valves into pneumatic transport lines. This system, typical of practically all feed systems, required considerable reworking before acceptable operation was attained. A 3.8 cm (1.5 in.) solids injection pipe penetrates the side of the shell and extends almost to the center of the bed. The gas cleanup system for most of the turbine testing consisted of three stages of inertial separators. The third stage cyclone was eventually replaced by a granular bed filter which suffered a structural failure during a shakedown run in late 1975 and never actually underwent full testing. The schematic of the system is illustrated in Fig. 2. The gas turbine at CPC is a British made Ruston-Hornsby TA-1500. The compressor on the unit supplies the combustion air to the PFBC unit. The turbine is

Fig. 2. Combustion Power Company PFBC installation, Ref. 5.

a two shaft unit with the compressor turbine and power turbine each having two stages. Inlet temperature for the turbine during testing was about 1400°F. A stationary cascade was also used to some extent which received gas from the third stage particle separator followed by another small, high efficiency cyclone.

A smaller atmospheric pressure combustor is also located at CPC which was used largely for hot corrosion studies. The CPC program was quite broad up through 1976, involving operation of both combustors and subcontracts for analytical work to Solar and Westinghouse.

The current efforts at CPC, funded by DOE, deal with development of granular bed filters. Several configurations have been tested during 1978-79 at atmospheric pressure. The PDU has not been operated since 1975. Parametric performance tests have been completed on favored designs. As of October 1979, 600 h out of a goal of 1000 h have been run on a prototype filter.⁹ These test units typically handle 0.84 m³/s (1800 ACFM). Construction of a unit to operate at 0.80 MPa (8 atm) for delivery to DOE for testing is yet to be completed.

Argonne National Laboratory (ANL)

The Argonne National Laboratory (ANL) has been conducting a basic research and development program since early 1969 to demonstrate the feasibility of the combustion of coal in a pressurized fluidized bed combustor. A 15-cm (6.0-in.) diam, pressurized, fluidized bed combustor capable of operating to 0.10 MPa (10 atm) pressure and temperatures in the range of 775 to 975°C (1427 to 1787°F) was used to investigate sulfur retention, combustion efficiency, additive utilization, and heat transfer coefficients.^{10,11}

A series of eleven experiments were performed in 1974 to demonstrate the effects of the bed temperature, fluidizing velocity, and the Ca/S mole ratio upon the sulfur retention, nitrogen oxide levels in the flue gas and the combustion efficiency.

The bed is water-cooled and incorporates a bubble-cap distributor plate. The combustor is about 3.4 m (11 ft) tall and is enclosed in an

outer shell of 30 cm (12 in.) diameter. A flow diagram is shown in Fig. 3.

Since 1974, the 15-cm (6-in.) diam combustor has been operated in conjunction with a lime regeneration system. Recent experiments have involved characterizing the particle size distribution from the combustor. The performance of granular bed filters and some types of cyclones have been evaluated also.

Exxon Miniplant

The Exxon PFBC facility is located at the Exxon Research and Engineering Company facilities in Linden, New Jersey, and has been in operation since 1974. The PFBC miniplant was constructed with EPA funds with initial emphasis placed on obtaining data on sulfur emissions and sorbent utilization. Recently a series of tests on turbine and heat exchanger materials were sponsored by DOE.¹²⁻¹⁴

The combustor is a 10 m (32 ft) tall vessel which is 61 cm (24 in.) in diameter. Refractory lining brings the inside diameter down to 33 cm (13 in.). The combustor is cooled by vertically oriented serpentine coils through which water is circulated. The coils are fabricated from type 316 stainless steel, 1.2 cm (0.5 in.) in diameter (Schedule 40 pipe). Each coil covers a vertical distance of 46 cm (18 in.).

The system operates at pressures to 1.0 MPa (10 atm), bed velocities to 3.05 m/s (10 ft/sec), and temperatures up to 982°C (1800°F). Solids feeding rate is as high as 180 kg/h (400 lb/h). Coal and dolomite are premixed and are injected through the side of the shell at a distance of 30 cm (11 in.) above the air tuyere plate. The feeding system is a modified Petrocarb unit. Two stages of cyclone collectors plus one tertiary cleanup device constitute the particulate removal equipment for the miniplant. Granular bed filters, ceramic bag filters and cyclones were tested as the tertiary device with the cyclone providing the most satisfactory operation. Solids collected in the first stage cyclone are recycled back to the combustor. The test unit is diagrammed in Fig. 4. The bed depth in the combustor can be varied from 2.3 to 6.1 m (7.5 to 20 ft).

Fig. 3. Schematic flow sheet of ANL PFBC system, Ref. 10.

Fig. 4. Schematic of Exxon miniplant.

The turbine blade test section was supplied by G.E. and contains four rows of turbine blades which direct the flow through four 90° turns. The first three cascades consist of impulse blades while the last is a reaction stage. The rectangular duct containing the cascades is 1.6 cm (0.625 in.) deep and 6.66 cm (2.625 in.) wide. Chord length of the airfoil specimens is 2.54 cm (1.0 in.). The combustion gas must be supplementally heated with methane to maintain temperature at the turbine test section.

The experiments at the miniplant have been directed toward a number of areas:

1. SO₂ emissions,
2. NO_x emissions,
3. sorbent regeneration,
4. turbine and heat exchanger materials evaluation.

The combustor had operated for over 3,300 h in runs of up to 260 h before EPA funding ran out in August 1979 and the facility was shut down.

Grimethorpe — International Energy Agency (IEA)

The PFBC test unit at Grimethorpe, England, is a venture involving principally the National Coal Board (NCB) and the IEA. Under their management in 1975 an agreement to build the facility was reached among the United Kingdom, United States, and Germany. Construction costs have been borne in part by each country. Shakedown testing of the facility was scheduled to start in early 1980.¹⁵ This date has slipped to early 1981 due to a host of procurement and contractual delays.

The system diagram is presented in Fig. 5. The combustor has a capacity of about 80 MW operating at pressures of 0.6 to 1.2 MPa (6 to 12 atm) with off-gas temperature of 800 to 950°C (1472 to 1742°F). Maximum design temperature is 1100°C (2012°F). The pressure shell, built in Germany, is about 4 m (13.1 ft) in diameter and 14 m (46 ft) in height. The shell is constructed of shaped steel plates butt welded together. Power for air compression is supplied by a steam turbine which utilizes the steam generated in the combustor. Excess steam is to be exported to an adjacent power plant.

A 2 m (6.6 ft) square cross section furnace is situated within the shell. Water walls are used for heat absorption and containment for the fluidized bed. The distributor plate is a bubble cap design. The water-cooled tube bundles lie in a horizontal orientation.

The solids injection system was built by Petrocarb and feeds nine nozzles which penetrate the distributor plate. Coal is dried and mixed with dolomite prior to injection.

The flue gas leaving the top of the combustor is divided among four primary cyclones arranged circumferentially around the combustor. The gases then pass through a second bank of cyclones and then through a cooler before entering the cascade test section. The facility will provide important information since its gas flow of 39 kg/s (85 lb/s) is large enough to permit testing of full-size turbine blade cascades or rotors.

Fig. 5. Grimethorpe Experimental Facility plant layout-elevation,
Ref. 15.

Curtiss-Wright

The Curtiss-Wright Small Gas Turbine (SGT) test rig is located at the Curtiss-Wright plant in Wood-Ridge, New Jersey. This PFBC test unit is among the largest in existence and has been operating since early 1978. The SGT unit was to provide a technology base for a larger pilot plant demonstration which to date is not yet under construction.¹⁶⁻¹⁸

The combustor is 0.91 m (3 ft) in diameter and has an expanded bed height of 9.7 m (16 ft) and a 4.6 m (15 ft) freeboard. The bed is air-cooled by vertical tubes which are 10.2 cm (4 in) in diameter and 9.7 m (16 ft) long. The tubes are of the bayonet or reentry type and have external vertical fins. The entire rig is about 23 m (75 ft) tall. A schematic flow diagram is shown in Fig. 6.

Fig. 6. Curtiss-Wright SGT technology rig.

The combustor operates with a pressure of about 0.65 MPa (6.5 atm) and produces hot air at a maximum temperature of 899°C (1650°F); bed temperature during testing ranges up to 911°C (1672°F). Combustion is maintained with 30% excess air. The maximum coal flow rate is about 266 kg/h (585 lb/h) accompanied by about 114 kg/h (250 lb/h) of dolomite. Coal and dolomite are injected into the combustor separately. Both systems employ lockhoppers followed by pneumatic transport. The solids are fed through the side of the combustor shell.

The Curtiss-Wright concept for a combined cycle power plant incorporates an air-cooled combustor where the heated clean air is mixed with the combustion gas after the gas is subjected to extensive cleanup. The SGT rig utilizes this same approach. The ratio of clean air to flue gas is about 2/1 on a mass basis. The latest version of the gas cleanup system consists of 3 stages of conventional cyclones followed by an Aerodyne cyclone which uses a small portion of the clean air to generate a high rotational velocity of the gas in the cyclone. The matter collected in the first stage cyclone is recycled to the combustor.

A Rover gas turbine is driven by a small fraction of the air and gas mixture. The turbine is a single stage wheel with impulse blading and is about 17.8 cm (7 in.) in diameter. Normal operational speed is about 40,000 rpm. The design of the turbine is not conducive to long life when operating on dirty gas, and the test results would therefore be rather conservative with respect to erosion resistance.

As of December 1979 about 3000 h of operation had been accumulated on the test unit with the gas turbine in operation for 1000 h.

Curtiss-Wright has developed plans for a pilot plant to be located at the same site. The coal feed rate for this unit would be about 4545 kg/h (10,000 lb/h) and the maximum gas turbine output would be about 7000 kWe. The engineering for the pilot plant is essentially complete. Some pre-construction activity has been started such as procuring a limited amount of equipment.

Leatherhead — National Research Development
Corporation (NRDC)

The PFBC at Leatherhead, England, is operated by the Coal Utilization Research Laboratory (CURL) which was formerly British Coal Utilization Research Association (BCURA). Tests at this facility have been carried out since 1972 which, at that time, were funded by the Office of Coal Research (OCR). ERDA continued support as is DOE. The so-called Mark II combustor was operable in 1972 but was modified slightly around 1975 to a Mark III configuration and was modified again in 1978.¹⁹⁻²¹ The Mark III version is shown in Fig. 7. The combustor consists of a refractory-lined rectangular casing situated inside a cylindrical pressure shell. The fluidized bed in the casing is 0.6 m × 0.91 m (2 ft × 3 ft) in cross section. Water-cooled horizontal tubes traverse the bed over a 2.1 m (6.9 ft) vertical distance. The air distributor plate has multiple tubes attached to plate which extend about 3.8 cm (1.5 in.) into the bed. The layer of unfluidized material below the air ports serves as insulation for the distributor plate. Material removal is accomplished via a tube which drains through the distributor plate.

Four water-cooled coal feed nozzles penetrate the sides of the combustor. The solids transport system is a Petrocarb lockhopper system. Control of the coal feed rate is accomplished by adjusting the pressure differential between the coal feeder and the combustor. Dolomite is fed from a small, separate lockhopper system.

Tests during 1976-77 saw the combustor operating at 866 to 899°C (1590 to 1650°F) and 0.44 to 0.50 MPa (4.4 to 5.0 atm) with a bed height of about 2.4 m (8 ft). Test durations were typically 70 to 100 h. Excess air was varied from 25 to 120%.

Corrosion test specimens are located in the fluidized bed. The Mark III system was also equipped with a turbine blade cascade test section. Two stages of cyclone separators precede the cascade. Behind the cascade are located some pin specimens.

In 1978 modifications were started to incorporate cascades and clean-up systems provided by G.E. and Stal-Laval. American Electric Power's

(AEP's) PFBC plant concept utilizes the Stal-Laval turbine and three stages of cyclones similar to those being tested at Leatherhead. The G.E. supplied cleanup system incorporates an electrostatically enhanced cyclone plus two stages of conventional cyclones.

These latest tests involved simultaneous turbine materials and gas cleanup experiments with AEP, Stal-Laval, G.E. and Combustion Systems Ltd. as the principal participants. DOE and EPRI also supplied funding or materials. For these tests the internal parts of the combustor were completely reworked. The bed is now tapered similar to the NASA rig.

The gas stream is split into two flows which feed into turbine material test sections monitored by G.E. and Stal-Laval, respectively. The Stal-Laval section has a single shortened turbine blade from a large gas turbine (GT-120) while the G.E. test section has cascades each composed of six very small blades of about 2.5 cm (1.0 in.) chord length. Propane is burned in the GE stream to maintain high temperature.

A 50-h shakedown run was performed on the new facility in mid-July 1979, and the 1000 h test was started soon thereafter. The 1000 h had been accumulated by December 1979. A rotary valve coal metering system was in use on the new combustor and proved superior to the previously used Petrocarb feeders.²²

RECENT DATA FROM PFBC TEST FACILITIES

Data on emissions, performance, material compatibility, etc. are presented in the following subsections. The data are merely representative of a much larger body of information available in the referenced documents.

Emissions from a PFBC

Data from a variety of sources are included in this section on PFBC effluents. Included are discussions on sulfur oxides, nitrogen oxides, trace elements and particulate matter.

Sulfur capture in the PFBC

The sulfur dioxide formed during the combustion of coal is captured by a sorbent in the fluidized bed. This sorbent is usually limestone or dolomite. Limestone is principally composed of calcium carbonate, CaCO_3 , while dolomite is an aggregate consisting of practically equal parts of magnesium carbonate, MgCO_3 , and CaCO_3 .

The overall sulfur capture reaction is

With dolomite the MgCO_3 calcines to MgO at moderate temperatures but does not account for capturing sulfur as MgSO_4 except perhaps at pressure greater than about 0.20 MPa (20 atm). The calcining of MgCO_3 does, however, increase the porosity of the dolomite solid and enhances its effectiveness as a sorbent. As a result, dolomite is more effective on a molar basis than limestone under pressurized combustion where the calcination of CaCO_3 to CaO (prerequisite to CaSO_4 formation) is suppressed. Usually in a PFBC, dolomite exhibits a slightly greater effectiveness on a weight basis. The bulk of the data on sulfur retention in a PFBC has been generated at the Leatherhead, Exxon, and ANL facilities.

Data from early tests at Leatherhead, which were compiled from data presented in reference 19, are shown in Fig. 8. The higher retention per mole of Ca for the dolomite is clearly evident. More recent tests at

Fig. 8. Retention of sulfur in the NRDC 0.6 x 0.9-m precalcined fluidized bed combustor, Ref. 19.

Leatherhead have demonstrated the improvement in sulfur capture with increased residence time of the combustion gas (Fig. 9).²¹ A similar effect can be accomplished by increasing bed depth but is not evident from these data. An explanation was offered that the tube bundles hindered

Fig. 9. Effect of operating parameters on sulphur retention — NRDC data, Ref. 21.

the mixing process in the combustion at the lower velocity.²¹ The effect of combustor temperature on sulfur capture can also be derived from data produced at Leatherhead as shown in Fig. 10. In the PFBC the drop in sulfur capture at high temperature is not dramatic as in the AFBC probably since the exothermic formation of CaSO_4 is favored by increased pressure and that the calcination of CaCO_3 under pressure results in a more porous structure which promotes SO_2 capture. Other hypotheses can be found in the literature.¹⁹

Data from the ANL facility generally agree with the U.K. results.²³ Sulfur capture was found to improve between temperatures of 899 to 954°C (1650 to 1750°F) with Ca/S ratios of 1.0 to 2.0. ANL has also documented the comparison of dolomite and limestone on a weight basis as presented in Fig. 11. Data such as these would be expected to vary with the type of coal and sorbent in addition to the combustor operating conditions. Information for two types of coal were published by Exxon and are shown in Fig. 12.²⁴

Fig. 10. Effect of combustor temperature on sulfur retention with Ca/S mole ratio = 2. Fluidizing velocity 0.6 to 0.75 m/s, bed depth 1.14 to 2.44 m and freeboard pressure 0.35 to 0.60 MPa — NRDC Data, Ref. 19.

The potentially lower solids feed rate in the PFBC relative to AFBC should result in an efficiency and cost advantage. The net energy of the sulfur capture reaction has not been clearly defined but would appear to be more favorable with the PFBC and dolomite over the AFBC and limestone.

Trace element emissions

Release of trace elements or their vapors from coal combustion produces undesirable atmospheric pollution and creates serious corrosion

Fig. 11. Sulfur retention capabilities of additives compared, mass basis — ANL data, Ref. 23.

Fig. 12. SO₂ retention using dolomite sorbent, Exxon, Ref. 24.

and deposition problems in a gas turbine driven by the coal combustion gases. Some effort has been made to characterize these emissions, and examples of the available data are presented here. Discussion relevant to turbine erosion and corrosion is found in a later section. Data on the trace element content of coal combustion gas have been documented by NRDC, CPC, and ANL.

The alkali metals are very active in the corrosion mechanism for the gas turbine materials, and their concentrations are emphasized over other trace elements. These metals form sulfates and chlorides with the SO_2 and chlorine in the combustion products. The sulfates and chlorides have been identified as promoting corrosion and deposition in gas turbines. According to studies performed by G.E., the combustion temperature and chlorine content of the coal are the most important factors in determining the amount of alkali metal vapor in the flue gas.²⁵

The G.E. analytical model predicts a weight concentration of about 10 ppm for sodium and potassium in the combustion products of a PFBC operating at 954°C (1750°F) on a typical U.S. coal (0.1% Cl content). The concentration is about 300 times greater than current limits suggested for petroleum (residual)-fired turbines. The data from the NRDC combustor in Table 1 provide an order of magnitude confirmation of the calculations of G.E. Numerous other factors such as the dolomite feed rate and sulfur retention have influence on the alkali vapor emissions. Tests conducted in 1979 at Leatherhead with more sophisticated equipment have shown similar results of (2 to 8 ppm) alkali in the flue gas.²²

Data from ANL have shown alkali vapor emission to be proportional to combustor temperature with a notable increase occurring at about 816°C (1500°F).²⁶

Some attempts to measure alkali vapor concentrations have been made in conjunction with the CPC programs also. The concentrations of sodium were on the order of 3 ppm.⁵ It should be noted that the data presented in this section emphasize the alkali in vapor phase which is generally not readily removed from the gas stream.

Table 1. Measured alkali vapor concentrations
in NRDC PFBC at Leatherhead

Test No.	1 ^a	2 ^b	3.2 ^c	4.2 ^d	6.1 ^e	7A ^f
Na (weight ppm)	5.2	1.7	3.0	1.5	1.4	0.8
K (weight ppm)	2.7	1.2	2.5	1.3	0.6	0.3

^a0.09% Cl in coal, bed temperature — 888°C (1630°F).

^b0.09% Cl in coal, bed temperature — 952°C (1745°F).

^c0.04% Cl in coal, bed temperature — 902°C (1655°F).

^d0.04% Cl in coal, bed temperature — 949°C (1740°F).

^e0.04% Cl in coal, bed temperature — 871°C (1600°F).

^f0.04% Cl in coal, bed temperature — 877°C (1650°F).

Sources: (1) National Research Development Corporation, *Pressurized Fluidized Bed Combustors*, R&D Report 85, Interim No. 1, prepared for Office of Coal Research, Department of the Interior (1974). (2) A. G. Roberts et al., *Pressurized Fluidized Bed Combustion Annual Report July 1976–June 1977*, FE-1511-43 (September 1977).

NO_x emissions

Emissions of nitrogen oxides from a PFBC appear to be very low according to the available data. Exxon reported that combustion temperature has a slight effect on NO_x emissions but that the excess air has a much greater effect. Some results generated on the Exxon miniplant are shown in Fig. 13.²⁷ Note that the emissions levels are well below the new source performance standard of 0.27 kg/GJ (0.6 lb NO₂/10⁶ Btu).

The adiabatic combustor of Combustion Power Company produced levels of NO_x which were much higher, ranging from 0.32 kg/GJ (0.7 lb/10⁶ Btu) to over 0.68 kg/GJ (1.5 lb/10⁶ Btu).⁵ The adiabatic combustor was operated with about 300% excess air which probably accounts for the high levels of NO_x. The results imply that power plants using adiabatic PFBC's might require an NO_x control scheme.

Fig. 13. NO_x emissions from miniplant fluidized bed coal combustor, Ref. 27.

Particulate matter leaving furnace

The loading and size distribution of particulates leaving the furnace are of great importance in determining the performance requirements of gas cleanup equipment.

G.E. has arrived at a figure of about (11.0 grains/scf) of total particulate matter leaving the furnace with a size distribution as shown in Fig. 14.^{25,28}

Data from the ANL PFBC test unit show total particle loadings of 2.3 to 31 g/m³ (1.0 to 14 grains/scf) but usually on the order of 30 g/m³ (13 grains/scf). They have published the fractional particle size distribution shown in Fig. 15.²⁹

NASA has characterized the particulate effluent from their conical PFBC test unit with the results shown in Fig. 16.⁴ Note that the total solids loading leaving the combustor is quite low relative to the data presented above. Gas velocity at the surface of the bed was only about

Fig. 14. Particle size distribution of PFBC effluent derived by G.E. from available data, Ref. 26.

Fig. 15. Fractional mass distribution of all elutriated particles during a combustion experiment (SGL-1) from the ANL PFBC, Ref. 29.

Fig. 16. Particles in gases from bed, Ref. 4.

0.61 m/s (2 ft/sec) for these tests. The average particle size was about 60μ .

Recent Heat Transfer Data in a PFBC

Heat transfer data is not as abundant for the PFBC as in the AFBC although differences should not be great. Most correlations for heat transfer coefficient show a weak dependence on gas density at the most. Some typical data from the NRDC PFBC facility are shown in Fig. 17.²¹

Curtiss-Wright's vertical finned tubes have been tested in the NRDC facility also and with results in the 228 to $285 \text{ W/m}^2 \cdot ^\circ\text{C}$ (40 to $50 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$) range. The bed material was rather coarse but the fluidizing velocity was 0.7 to 1.1 m/s (2.3 to 3.7 ft/s). A seven tube bundle was used in these tests with three tubes cooled by air, two by water and two

Fig. 17. Heat transfer data from NRDC, Ref. 21.

by steam. These tubes were about 10 cm (40 in.) in diameter and 2.4 m (8 ft) long. The tube spacing was not very tight.

Combustion Efficiency

Most data support the conclusion that combustion efficiency in a PFBC will surpass that with the AFBC. The most often cited reason is the deeper bed in the PFBC allowing longer residence time for small carbon particles. At least one study³⁰ reported in ref. 31 found coal combustion rate to be independent of pressure alone. Data generated at the NASA facility show efficiency increasing with pressure, however.

The greater part of combustion efficiency data come from ANL, Exxon, and NRDC. The effect of fluidizing velocity and temperature on combustion efficiency is seen in Fig. 18 which presents ANL data. Similar data from NRDC are shown in Fig. 19.

Effects of excess air and combustor temperature were studied by Exxon³² with the results shown in Fig. 20. Comparable data from the NRDC are shown in Fig. 21.

There is surprisingly little data on the effect of bed depth in pressurized systems. Bed depth effects are included when residence time (depth/superficial velocity) is used as the basis for data correlation.

Turbine Materials Testing and Hot Gas Cleanup

This section presents recent developments and findings related to hot gas cleanup and turbine materials for PFBC systems. A summary of most of the previous attempts to operate coal-fired turbines has been published recently³³ so the earlier programs are not reexamined here. Likewise, broad surveys of hot gas cleanup devices are available and such information is not reproduced in this report.³⁴

Mechanisms of gas turbine performance degradation in PFBC systems

Brief descriptions of mechanisms for erosion, corrosion, and deposition are presented here. The parameters which significantly influence the rates of the mechanisms are discussed with supporting data.

Fig. 18. Combustion efficiency as a function of bed temperature (ANL), Ref. 23.

Erosion. A loss of blade material in gas turbines can result from the impingement of small particles in the gas stream on the turbine blades. Excessive erosion of the blade causes the airfoil to lose its effectiveness which lowers the turbine efficiency. Data are available to demonstrate the important factors which determine rates of erosion.

The loading of particles in the gas stream is known to directly affect erosion rates. Although dust loading is often quoted as a weight per standard cubic foot, the loading per actual cubic foot is a better reference. Lower pressure air streams, therefore, have a lighter dust

Fig. 19. Effects of combustor temperature on combustion efficiency with 17% excess combustion air (NRDC), Ref. 19.

load per cross-sectional area of the duct for a given particle mass per standard unit volume.

Catastrophic loss of blade material has been experienced recently in cascades with particle concentrations of 2260 mg/m^3 (1.0 grains/scf) when operating at over 760°C (1400°F) and when using typical turbine gas velocities.²² Turbine life under such conditions would probably be on the order of 50 h. The NASA turbine test series also revealed unacceptable rates of erosion with loadings of 3390 mg/m^3 (1.5 grains/scf) after about 12 h [ref. 2]. With average particle concentrations as low as 678 mg/m^3

Fig. 20. Combustion efficiency, Exxon, Ref. 32.

Fig. 21. Effect of operating parameters on combustion efficiency NRDC, Ref. 21.

(0.3 grains/scf) the NASA investigators still found severe pitting and erosion after 164 h of running.³

In recent Curtiss-Wright tests with their SGT unit, minor erosion was evident after 150 h of operation with a particle loading of 339 mg/m³ (0.15 grains/scf). Not until the loading was reduced to 136 mg/m³ (0.06 grains/scf) did visible erosion decline to an insignificant level for runs of 500 to 700 h. Note, however, that a desirable turbine life is about 25,000 h between replacing airfoils. The NASA experience has been similar. Runs of about 400 h produced no significant erosion with a dust loading of about 45 mg/m³ (0.02 grains/scf).³⁵ Cascade tests at Exxon also showed very minor erosion on certain blade materials for particles in the gas stream at about 70 mg/m³ (0.03 grains/scf) after a test duration of about 800 h.

Particle size distribution and particle concentration cannot be decoupled when discussing erosion. Generally, larger particles are responsible for most of the erosion, and particles below 5 μ in size are often said to be of no consequence. Particles as small as 2 μ , however, are reported to have produced erosion.

The dependence of erosion on the particle velocity has been documented by NASA and others. The NASA carousel wedge tests were performed recently on their PFBC test unit and showed erosion to increase by a factor of 4 with a factor of 2 increase in particle velocity. Erosion seen as a power function of velocity is common and suggests that erosion may be drastically reduced by a decrease in turbine blade speed. The angle of impingement is a related variable which also influences erosion rate.

The effect of temperature on erosion has been investigated by NASA, Combustion Power Company, and the University of Cincinnati among others. The NASA results were inconclusive showing both increase and decrease in erosion with temperature, depending on the blade material.² The dust loading in these tests was very high, however, and may have masked the effects of other parameters. A decrease in erosion can apparently be accomplished by using harder blade materials which would support the idea of a temperature dependence. The Combustion Power data indicate a temperature at which erosion is overtaken by deposition.⁶ At about 450°C (840°F)

they found that deposition rates were about equal to erosion resulting in a fairly constant test specimen weight. At higher temperature, deposition became dominant.

The University of Cincinnati has performed erosion tests using a simulated PFBC exhaust gas stream. The tests at this facility revealed a clearly defined rapid increase in erosion as the metal specimen temperature was increased beyond 649°C (1200°F). The particle loading for the tests was high at about 7 g/m³ (3 grains/ft³) and velocities ranged from 100 to 300 m/s (328 to 985 ft/s).

Deposition. The build-up of deposits on gas turbine blades reduces the flow area resulting in loss of power and efficiency. It is also possible that cooling air passages could become blocked which would reduce the life of the turbine.³⁶ Deposition and erosion are intimately related as mentioned previously and depend somewhat on the same parameters. A significant difference is that deposition can be caused by particles of very small size on the order of 1μ.

The gas stream and blade temperatures seem to be of extreme importance in deposit formation. Results of tests in Australia using coal ash and other salt mixtures showed a well-defined maximum deposition rate at 700 to 900°C (1300 to 1650°F).³³ As noted already, Combustion Power found deposition to increase continually between 400 to 750°C (750 to 1380°F). A compilation of data reported in ref. 34 showed that the higher temperatures resulted in the formation of deposits by progressively smaller particles as seen in Fig. 22. Documentation is also available indicating fouling to be proportional to particle loading in the gas stream.³³

The influence of pressure on deposition has generally been neglected, but data brought forward by NASA² indicate a strong dependence on pressure for certain levels of alkali in the gas stream (Fig. 23). Combined levels of Na and K were generally less than 1 ppm by weight. The alkali vapor content in PFBC effluent is generally several times this value and may result in a less notable effect of pressure. The basis for the pressure effect is associated with its influence on the condensing temperature of alkali vapors in the gas stream. The amount of alkali present in the gas is strongly dependent on the PFB combustion temperature and contributes to the deposition phenomenon.

Fig. 22. Dependence of deposition phenomena in turbines on variations in particle size and inlet gas temperature, Ref. 34.

Fig. 23. Calculated effect of pressure on deposition rates, Ref. 2.

Corrosion. Erosion is a relatively peculiar problem to coal-fired turbines but corrosion is evident in gas turbines operating on practically any fuel, natural gas being perhaps the least offensive. Significant effort has been expended with corporate funds in developing corrosion resistance airfoil materials to allow turbines to operate on crude oil, for example. Oxidation and sulfidation are the two most prominent corrosion modes.

The character of oxidation is seen in Fig. 24 as an actual weight gain by the blade material as an oxide layer grows. Depending on the material, this oxide layer may spall and give rise to a continual loss of blade material.³⁷ Growth of the oxide layer is obviously temperature dependent. A similar trend with temperature has been reported by G.E.³⁸ with the rate of oxidation increasing by a factor of 3 resulting from increasing firing temperature from 871 to 982°C (1600 to 1800°F).

Sulfidation is a corrosion mode generally involving levels of sodium and sulfur. For over 25 years G.E. has conducted programs to improve

Fig. 24. Oxidation of In 792, Ref. 37.

turbine life in the presence of compounds of sodium, potassium, vanadium and lead which enter the machine via fuel and air.

Hot corrosion involves two competing mechanisms:³⁸

1. Condensation of corrosive deposits is increased by lower temperature and higher pressure.
2. Chemical reaction rates increase with temperature.

The typical sequence of hot corrosion as reported by G.E.³⁸ is as follows:

1. Hot corrosion begins with the presence of Na and S which form Na_2SO_4 in a hot atmosphere which condenses on the turbine material surface.
2. Na_2SO_4 reacts in such a way that the protective oxide layer formed by superalloys is destroyed. Sulfur then penetrates the metal forming chromium sulfides.
3. Diminishing level of chromium retards the formation of the protective oxide film.
4. Decreased capacity for forming oxide accelerates the attack on the metal.

The effect of corrosion on turbine life has been represented as dependent on alkali content in the gas stream and temperature as shown in

Fig. 25.³⁸ Some quantitative data from G.E.³⁹ are presented in Fig. 26 to show the importance of Na concentration.

The effect of temperature on corrosion rates has been recently documented by United Technologies in a study sponsored by EPRI.³⁷ The data were generated by heating metal specimens in a furnace which had been sprayed with a solution of Na_2SO_4 in distilled water. Some of the results are shown in Fig. 27. The presence of small quantities of NaCl was found to decrease the time to visible corrosion by about 90% for most of the alloys which were tested. The trend of increased life at lower temperature was still evident. Addition of vanadium produced the same type of effect as the chlorine. Vanadium, however, is present in only very small amounts in coal.⁴⁰ It should be noted that for oil-fired gas turbines presently in service with fuel sodium at over 2 ppm and vanadium at

Fig. 25. Life vs alkali concentration for gas turbine (schematic), Ref. 38.

Fig. 26. Quantitative data on turbine life in presence of alkalis.

between 0.5 and 10 ppm the turbine inlet temperature is limited to 705°C (1300°F) even with the use of fuel additives to inhibit corrosion.³⁸

Synergistic modes of turbine degradation. The destructive modes of erosion, deposition, and corrosion often can combine to produce an accelerated degradation of the turbine materials. One hypothesis which has been proposed concerns a synergistic erosion/corrosion phenomenon. Erosion is instrumental in removing the protective oxide layer which forms on superalloys thus making the metal susceptible to corrosion (sulfidation) attack. The corrosion weakens the metal thus promoting erosion at an accelerated rate.

Fig. 27. Sulfidation corrosion, Ref. 37.

Implications for Turbine Design

Design features of the turbine can promote increased life by compensating for the degradation modes described above. Some of these design parameters are presented here.

From the discussion on erosion it is evident that the following design features should improve turbine life.

1. Lower blade velocities or nozzle velocities (would result in more turbine stages).

2. Use of hard materials.
3. Removal of practically all particles larger than about 5μ .
4. Use of straight inlet passages to avoid concentration of particles via a centrifuge action.
5. Use of lower turbine inlet pressure which reduces particle concentration over flow area. Lowering the turbine inlet temperature is also likely to help due to the greater hardness of the metal and the reduced chances of a synergistic erosion/corrosion mechanism.

Deposition can probably be reduced through:

1. lower turbine inlet temperature,
2. removal of practically all particulate matter from the gas, and
3. use of lower turbine inlet pressure.

Corrosion is likely to be reduced by:

1. use of corrosion resistant materials,
2. lower turbine inlet temperature,
3. any design feature that limits erosion, and
4. blade cooling.

Improvements in blade life which might be accomplished through use of clad superalloys are shown in Fig. 28.⁴¹ GE 2541 is an iron base cladding. Although coatings for blades are currently in use, claddings are still under development.

Estimated Limits for Gas Turbine Particulate Loading

The life of gas turbine hot gas path parts is adversely affected by dust and corrosive compounds in the hot gas stream. A considerable amount of work has been done in this area — the problem is not unique to PFBC system. Specifications are usually supplied by turbine manufacturers for fuel content and levels of air cleanliness. Specifications may vary among manufacturers and among different machines. Some estimated specifications for coal-fired turbines are presented Fig. 29.

In discussing removal of particulate matter it is helpful to establish a baseline loading of particulates from a PFBC. The reader should

Fig. 28. Gas turbine life in PFB environment, GE estimate of blade life improvement through use of cladding, Ref. 41.

refer to the section of this report on PFBC emissions for such information.

Estimates of the particulate loading which can be tolerated by gas turbines are available from both G.E. and Westinghouse work. The Westinghouse estimates⁴² reflect the philosophy that particles over 5μ in size are very dangerous while the G.E. estimate, although the trend is similar, is significantly more relaxed.²⁵

Summary of recent turbine materials and gas cleanup tests

A number of significant developments in PFBC turbine technology have emerged in the last few years. Most of these test results are discussed here.

Exxon cascade tests. Exxon has tested granular bed filters, ceramic bag filters, and cyclones at their miniplant. The most promising turbine cascade tests were run with three cyclone stages.

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Fig. 29. Estimated turbine erosion tolerance limit for 25,000-50,000 h life.

A brief summary of the experience with a Ducon granular bed filter can be found in ref. 14. Pressure drop across the filter was found to be excessive until the inlet screens were modified to prevent plugging. Blowback was used to remove collected matter. A significant part of the collected matter was retained in the bed, however, and would eventually make its way through the filter. Outlet particle loadings were seen to increase with time in all runs. The blow back procedure was also found to cause a loss of filter media and disturbances in the coal feed control system.

Tests on an Accurex ceramic bag filter were conducted late in 1978. The longest continuous test duration was 19 h. A series of back-pressure pulses were used to clean the filter about every 5 min. Pressure drop across the filter increased steadily between pulses with a maximum of about 14 kPa (0.14 atm). Filtration efficiencies were usually between 96 and 99.5% with outlet particle loadings on the order of 0.003 to 0.20 g/m³ (0.0013 to 0.09 grain/scf). The ceramic filter bag eventually failed during a blow back cleaning cycle. High temperature corrosion of the 304 stainless steel filter support screen was reported to be a contributing factor.

The four-stage cascade test was run with turbine materials supplied by G.E. and funding support from DOE.^{12,14} Three stages of cyclones were used for the cascade tests because of previous operational difficulties with granular bed filters. The first significant tests were in December 1977 consisting of a series of runs accumulating about 100 h of operation with the longest single run of about 37 h duration. The cyclones were relatively effective giving a final particle loading of 0.07 to 0.16 g/m³ (0.030 to 0.081 grain/scf) into the cascade section. A temperature of about 843°C (1550°F) was maintained at the inlet to the test section. Deposition was very evident after the 100 h of operation. By November 1978, 735 h of operation had been accumulated. Particle loadings of 0.047 to 0.12 g/m³ (0.02 to 0.05 grain/scf) were typical during the runs. Average particle size was about 1.2 μ at the test section inlet. About 95% of the particles were smaller than 6 μ . At this time corrosion and erosion were not pronounced. Deposits were still significant

in thickness but were soft and easily removed. The cumulative test time eventually reached 1000 h.

NRDC cascade tests. In May through August of 1973 the NRDC ran a series of tests using Illinois and Pittsburgh coals and a two-cyclone stage cleanup system.¹⁹ Cascades were tested at a temperature of about 871°C (1600°F) with the combustor pressure at about 0.45 MPa (4.5 atm). Test duration was typically 50 h with about 200 h accumulated over the period mentioned above.

Very hard deposits formed on the primary cyclone wall but were possibly the result of start-up procedure. No deposition was found in the second cyclone. Deposition on the cascade increased notably when the cascade inlet temperature was increased from about 857 to 899°C (1575 to 1650°F). Most of the deposits could be cleaned with a conventional on-line abrasive cleaning material. Erosion was not pronounced in these short tests even though the particle loading was about 0.25 to 0.32 g/m³ (0.11 to 0.14 grain/scf). The particles were small, however, with about 95% less than 10 μ in size. The deposits consisted mainly of CaO, MgO, and SiO₂. Sulfur presence in the gas was usually low since the sulfur retention ranged from 75 to 99%.

A test of 100 h uninterrupted duration was performed early in 1977 again using two stages of cyclones for gas cleanup. The bed temperature was about 871°C (1600°F) meaning that the cascade inlet would run somewhat cooler. Soft deposits were formed on the cascade during this test although a more tenacious formation had been found after a previous run of shorter duration.²⁰

During 1979 a 1000 h cumulative time cascade test was conducted with both Stal-Laval and G.E. supplying turbine materials and gas cleanup systems. Tests were run in 100 h segments with scheduled shutdowns over weekends. The test series was started early in July.

The AEP gas stream enters the cascade section at about 790°C (1450°F) at a velocity of 230 m/s (755 ft/s). The G.E. cascade was subjected to temperatures of 843°C (1550°F) at velocities of 275-425 m/s (900-1400 ft/s). Several advanced clad blades were tested by G.E. The temperature of the blade materials was about 805°C (1480°F).

Except for some early problems, the three-stage cyclone system in the G.E. stream, which includes the electrostatically augmented cyclone, has been effective in removing particles down to the 2 to 5 μ range. An early test produced a particle loading of 2.26 g/m³ (1.0 grain/scf) into the cascade destroying the blades in about 60 h. In later tests deposition was notable with the formation consisting of a thin tenacious deposit covered by rather soft layers. The hard deposits were primarily iron oxide and sulfates and were found to form during the first few hours of operation but would not continually accumulate. It is possible that these initial hard deposits are caused by sintering of the small particles as they strike the cascade which causes a sharp rise in the particle temperature.

Pin samples in the AEP stream have been removed and examined every 200 h. No significant erosion has been found with the particle loading measured at about 0.12 g/m³ (0.055 grain/scf) and a mean size of about 1.5 μ . These particular material samples have been located in an area of the test section where the gas velocity is about 630 m/s (2070 ft/s) but where the temperature would be somewhat lower than 790°C (1450°F). No visible evidence of corrosion has been found although material samples which are exposed the full 1000 h provide more definitive data on corrosion.

Deposits on the samples have been minimal and soft. The composition has primarily been spent dolomite and silicon oxides.

After 615 h one stage of cyclone was removed from the AEP stream which increased the particle loading to about 0.016 g/m³ (0.07 grain/scf) but did not increase the mean particle size.

The 1000 h of operation were completed in December 1979.

NASA cascade tests. Erosion tests were conducted in 1977 using wedge-shaped materials in a stream of gas from the NASA conical PFBC test unit.² Particle loading was very high at 2.3 to 4.4 g/m³ (1.0 to 2.0 grains/scf) and test velocities were 150 to 270 m/s (492 to 886 ft/s). The test specimen temperature was 720 to 800°C (1328 to 1472°F). Several materials were tested including U-700 (nickel base), IN-792 (nickel base), and MM-509 (cobalt base). No attempt to remove particles from the gas stream was made. Specimens were exposed for durations of

36-100 h. Erosion was very severe under these conditions. However, evidence of deposition was found on the same specimens which were highly eroded. The erosion was seen to be strongly dependent on the gas velocity and particle loading.

Scanning electron microscopy and energy dispersive spectroscopy were employed in looking for evidence of corrosion. Only the high temperature tests produced sulfidation in these relatively short exposure times. Sulfidation occurred in all alloys tested.

Combustion Power Company turbine tests. The coal-fired turbine at Combustion Power Company was operated in 1974-75.^{5,6} Various cyclone configurations were used, usually with three stages. Total operating time with the turbine was about 500 h. The turbine inlet temperature was typically 688 to 760°C (1270 to 1400°F). Generally the system was plagued by recurring plugging of the cyclone separators, especially the multiclones which consisted of 8.9 cm (3.5-in.) diam inertial tubes in the third stage separator. The multiclones were eventually replaced for this reason. A summary of the numerous tests and configurations are presented in Table 2. The superficial velocity during most of the tests was about 1.8 m/s (6 ft/s) which is somewhat higher than the practice at the NRDC facility. This operation may have produced a higher loading of solids on the cyclones than these devices could handle.

Through most of 1979 tests have been conducted on several granular bed filter designs. The filter concept utilizes a recirculating filtering medium (aluminum oxide pellets) which is cleaned by passing the pellets through a small fluidized bed where trapped particles are elutriated and disposed. Overall particle collection efficiencies of about 98% have been demonstrated during hot flow tests at atmospheric pressure.

NASA turbine test. The installation of a small turbine on the NASA test rig followed the cascade tests described earlier in this section. The turbine rotors tested were composed of IN792 + Hf (nickel base with Cr, Al, and Ti) and Alloy 713LC (similar composition), respectively.³ The relative velocities at the rotor inlet were about 260 m/s (853 ft/s). A single Aerodyne cyclone separator was used in the initial phase of testing. Gas turbine inlet temperatures were about 690 to 780°C (1274 to 1436°F).

Table 2. Summary of Combustion Power coal-fired turbine tests

Test designation	Gas cleanup device	Turbine inlet temperature [°C (°F)]	Typical particle loading [g/m ³ (grain/scf)]	Results
P-201-202	1 stage conventional cyclone — 2 stages multiclones	688 (1270)	0.61 (0.27) ^a	High levels of erosion and deposition in the turbine
P-203	1 stage conventional cyclone — 2 stages multiclones	688-760 (1270-1400)	0.59-0.88 (0.26-39)	Heavy deposits of calcium rich deposits plus some potassium salt deposits ^b
P-401	2 stages conventional cyclones plus one plenum chamber as 3rd stage	760 (1400)	0.54 (0.24)	Baseline test for new particulate removal system.
P-402	2 stages conventional cyclones plus one plenum chamber as 3rd stage	760 (1400)	0.86 (0.38) ^c	Tested calcium-aluminum silicate as corrosion inhibitor — no definitive trends seen.
P-403A	2 stages conventional cyclones plus one plenum chamber as 3rd stage	760 (1400)	1.04 (0.46) ^d	Notable deposition
P-403B	2 stages conventional cyclones plus one plenum chamber as 3rd stage	760 (1400)	0.86 (0.38)	Significant erosion and deposition

^aAs high as 0.01 g/m³ (0.004 grain/scf) > 5 μ size.

^bCyclone malfunction caused very high particle load.

^cAs high as 0.070 g/m³ (0.032 grain/scf) > 5 μ size.

^dSeparator malfunction.

Particle loadings into the turbine were quite high with a minimum of about 0.50 g/m^3 (0.22 grain/scf) during a 164 h run. Even at this lower loading, however, over 40% of the particles were greater than 100μ in size. Average loading was about 0.72 g/m^3 (0.32 grain/scf).

Erosion at 164 h was significant with deposition also appearing. Acceleration of erosion by centrifuging in the turbine could be detected.

Oxide layers on the turbine blade affected material deeper into the blade than would be found with air-oxidation. Conditions which favored the growth of a thin, protective oxide layer were apparently disrupted in the PFBC exhaust environment. Parts of the oxide layers were found to be high in sulfur content. The heaviest deposits were aluminum, silicon, iron, sulfur, calcium, and potassium compounds.

A subsequent test was run with some improvements to the gas clean-up system which reduced the particle content to about 0.05 g/m^3 (0.02 grain/scf). After 400 h of running with the improved system, erosion was very light and deposits were not considered to be very serious.³⁵ Turbine inlet temperature was about 815°C (1500°F).

Curtiss-Wright turbine test. The major segment of the turbine testing on the Curtiss-Wright SGT rig began in the summer of 1979. Initial tests indicated that the first two stages of cyclones (one Dynatherm, one Ducon) were operating poorly resulting in a turbine inlet particle loading of about 0.29 g/m^3 (0.13 grain/scf) with a mean size of 3.7μ . After accumulating 150 h of operating time, erosion was visible on both the rotor and stator and modifications were started on the cyclones. The Ducon unit was successfully modified and the particle load dropped to 0.20 g/m^3 (0.087 grain/scf) at a mean size of 1.5μ . After 600 h (November 1979) the turbine blades showed practically no erosion and minimal deposition. Gas turbine inlet temperature was maintained at about 815 to 870°C (1550 to 1600°F) during the tests by supplemental heating of the gas with jet fuel.⁴³

The stator vanes for the tests are composed of numerous alloys including IN738 and FSX414 (cobalt base with chromium and tungsten) some of which are coated. The rotor blades are U-720 again with coatings on some of the blades. The coated blades have generally shown a superior

resistance to erosion. Microscopic inspection for corrosion is scheduled after accumulation of 1000 h of operation. The effect of the cooling and reheating of the gas prior to entering the turbine is uncertain. It is conceivable that some of the alkalis might be lost by condensation on the duct walls or on particles which are removed from the gas stream.

ANL cyclone tests. Performance characterization tests are being conducted by ANL on a TAN-JET (model name of manufacturer, Donaldson Co.) cyclone.⁴⁴ This cyclone uses a secondary flow of clean air to boost the tangential velocity of the dirty gas in order to improve particle collection.

Gas for the cyclone tests is provided by the ANL PFBC test unit. A single stage of conventional cyclone precedes the TAN-JET unit. The range of particle loadings at the TAN-JET inlet has been about 0.5 to 3.5 g/m³ (0.22 to 1.55 grains/scf). Outlet particle loading has been 0.07 to 0.24 g/m³ (0.03 to 0.11 grains/scf) which indicates an overall particle collection efficiency greater than 90% in most cases. Test pressures were as high as 810 kPa (8.1 atm) with the efficiency being more erratic at the higher pressure. This behavior is believed to be correctable with some modification to the ash discharge line. The cyclone seemed to be very effective in removing particles smaller than 10 to 20 μ in diameter.

Conceptual PFBC Power Plant Performance

There are numerous system configurations which have been proposed using pressurized coal combustors. Basically they can be grouped into the following categories:

1. adiabatic PFBC combined cycles,
2. air-cooled PFBC combined cycles, and
3. steam-cooled PFBC combined cycles.

The effects of major parameters such as pressure and turbine inlet temperature on the plant efficiency are somewhat different for each concept. Available data are presented in this section for each concept.

Adiabatic PFBC combined cycles

Westinghouse derived a multitude of adiabatic combustor configurations some time ago.⁴⁵ However, the basic system shown in Fig. 30 is typical and would probably be the choice for utility application. The adiabatic PFBC serves the same purpose in this case as the combustion cans on a conventional oil-or gas-fired combustion turbine since there is no heat transfer surface in the bed or freeboard. The combustion temperature is controlled by the amount of excess air which is necessarily high (≈ 200 to 300%) to maintain the temperature at 816 to 927°C (1500 to 1700°F).

A parametric study of plant efficiency has been published by Morrow.⁴⁶ Emphasis was placed on the compressor pressure ratio and combustor temperature effects. The major ground rules utilized are shown in

Fig. 30. Simple-combined cycle with adiabatic combustor, Ref. 5.

Table 3. An abbreviated set of data are provided in Fig. 31. The sensitivity of efficiency to peak temperature for this system is quite high which is characteristic of topping cycles of this configuration.

Table 3. Parameters for adiabatic PFBC system study

Compressor efficiency (isentropic), %	89
Turbine efficiency (isentropic), %	89
Steam system maximum temperature, °C (°F) ^a	538 (1000)
Steam system maximum pressure, MPa (psi) ^a	18.0 (2600)
Maximum reheat temperature, °C (°F)	538 (1000)

^aSteam conditions were optimized for each gas turbine temperature and pressure ratio.

Fig. 31. Efficiency of adiabatic PFBC combined cycle.

Data generated by Westinghouse were reviewed for comparison and generally predict lower efficiencies. The discrepancy is on the order of 7% or 3 percentage points of efficiency. Westinghouse accounted for pressure losses in the combustor and it is not clear whether Morrow did so. The pressure loss generally has a non-negligible effect on the gas turbine output.

Air-cooled PFBC combined cycles

Curtiss-Wright has investigated the efficiency characteristics of at least two air-cooled systems. The concept which mixes clean air with the combustion gases is the basis for the Curtiss-Wright small gas turbine test unit, pilot plant, and full size power plant designs. A simplified diagram of the system is shown in Fig. 32. The system performance as a function of temperature is presented in Fig. 33.⁴⁷ The effect of pressure ratio was reported to have a relatively small effect. For example, at 927°C (1700°F) turbine inlet changing the pressure ratio from 7 to 10 only improved efficiency by about 0.5 percentage points which is comparable to the data presented for the adiabatic bed. In a system such as this the gas turbine produces over half of the plant power output.

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Fig. 32. Diagram of air-cooled, split flow PFBC power system.

Fig. 33. Efficiency of air-cooled, split flow PFBC combined cycle, Ref. 47.

A parametric study of an air-cooled PFBC which does not mix the clean air and flue gas was recently sponsored by EPRI.⁴⁸ The system is illustrated schematically in Fig. 34. A turbocharger is used to pressurize the combustor, but the unit generates only a small amount of net power since the inlet temperature to the power recovery turbine has been limited to 621°C (1150°F). In the analysis of this system the steam system was assumed to be a dual pressure design with an energy conversion efficiency of 27% which is typical for such a steam system having an upper boiler pressure of 5.86 MPa (850 psia) and temperature of 330°C (625°F). Some error is introduced by not allowing the steam conditions to vary when different pressure ratios and temperatures are used for the gas turbine topping cycle. The efficiencies reported had been based on the fuel lower heating value (LHV) and have been corrected to a higher heating value basis for inclusion in this study in Fig. 35. It should also be noted that supplemental firing was incorporated in the analysis

Fig. 34. Simplified flow diagram of PFB air heater system, Ref. 48.

Fig. 35. Efficiency of air-cooled PFBC combined cycle, Ref. 48.

in the high temperature case since 1066°C (1950°F) is beyond the capabilities of fluidized bed heaters alone.

Steam-cooled PFBC combined cycles

Combined cycles using steam-cooled combustors differ from the systems discussed previously since the steam is generated in the combustor and not via the heat in the turbine exhaust. The gas turbine exhaust is generally used for feedwater heating as shown in Fig. 36. This configuration allows the use of more conventional steam conditions. The analysis of this system must include the effect of the amount of heat which is supplied to the feedwater stream from the gas turbine exhaust stream. This heat input alters the extraction flows and therefore the steam turbine output. The steam cycle calculations must be performed for each gas turbine condition to be investigated and short-cuts to this approach will introduce substantial error.

Data for a wide range of design parameters have been generated by ORNL (funded by TVA) for the steam-cooled PFBC system. The steam system used in the analysis was a typical 16.6 MPa/538°C (2400 psia/1000°F) system with a single reheat to 538°C (1000°F). Pressure losses in the

Fig. 36. Schematic of typical steam-cooled PFBC combined cycle.

gas system were considered and gas turbine efficiencies were varied somewhat according to pressure ratio. A more complete description of the analytical procedure is included in a related report.⁴⁹ Data for the efficiency of the steam-cooled systems are shown in Fig. 37. The contribution of the total system power by the gas turbine varies from about 5% at low inlet temperature to 20% and the highest inlet temperature considered. The reference point for the AFBC is based on the same steam system as used in the PFBC calculations.

The efficiency of this approach to combined cycles is the least sensitive to the gas turbine inlet temperature. The system is attractive if it is determined that the temperature must be reduced to obtain acceptable turbine life. On the other hand if materials are developed to withstand corrosion at higher temperatures $> 925^{\circ}\text{C}$ (1700°F) greater benefit in efficiency would be seen with the adiabatic or air-cooled systems.

Fig. 37. Efficiencies of steam-cooled PFBC combined cycle.

The ORNL study included a look at the importance of gas turbine efficiency with regard to the plant efficiency. The effect of gas turbine efficiency is significant for high temperature systems as indicated in Fig. 38. The results imply that an even greater effect for each gas turbine condition would be seen for the air-cooled systems where the gas turbine power output is a much greater fraction of the plant output.

The performance of a gas turbine reheat cycle (Fig. 39) has also been studied by ORNL. The purpose of the reheat cycle is to obtain attractive efficiency at modest gas turbine inlet temperatures which should result in longer turbine life. The reheat loop indeed provides some benefit in efficiency as shown in Fig. 40. The technical and economic feasibility of this system has not been explored.

Fig. 38. Effect of reduced gas turbine efficiency on steam-cooled PFBC plant performance.

Fig. 39. Steam-cooled PFBC with gas turbine reheat.

Fig. 40. Effect of gas reheat on steam-cooled PFBC plant efficiency

SURVEY OF DESIGN STUDIES FOR PFBC PLANTS

Design studies have recently been completed by or are underway in the following organizations:

1. Curtiss-Wright (DOE funds),
2. Burns & Roe (DOE funds),
3. G.E. (DOE funds),
4. American Electric Power (AEP) (AEP funds),
5. Oak Ridge National Laboratory (ORNL) (DOE funds).

The Curtiss-Wright system and one of several systems examined by Burns & Roe use the PFBC to heat clean air for use as part of the gas turbine working fluid. Other systems studied by G.E., AEP, ORNL, and Burns & Roe use the PFBC as a steam generator and the combustion gases as the gas turbine working fluid. Gas turbine reheat systems have been proposed by ORNL and Burns & Roe. A brief description of the major variations in the power systems follows.

General Electric System

The G.E. coal-fired combined cycle (CFCC) is essentially the same system studied by G.E. in the ECAS program and is similar to the AEP concept. G.E. proposes a higher gas turbine inlet temperature and lower pressure than AEP, however. The system flow sheet is shown in Fig. 41. Foster-Wheeler has recently reported a steam generator design study performed in support of the CFCC program.⁵⁰ Since these results are the most recent, the data reported here are from that study.

The major parameters for the CFCC system are shown in Table 4. Foster-Wheeler examined a number of combustor vessel designs and arrived at the horizontal cylindrical shell which contains two fluidized beds which are formed by waterwalls. Although the vessel weight for the concept is not the lowest of those studied, Foster-Wheeler felt that its cost would be the lowest since it would be cheaper to fabricate and provide piping for the single large vessel. Three gas turbines and one

Fig. 41. Simplified schematic diagram for General Electric PFBC steam power plant.

Table 4. Data for recent G.E. CFCC design

Plant size studied, MWe	626
Gas turbine power, % of total	24
Steam turbine power, % of total	76
Combustor pressure, MPa (atm)	1.0 (10)
Combustor temperature, °C (°F)	954 (1750)
Diameter of combustor module, m (ft)	11 m (36 ft) ^a
Number of modules for rated output	1
Gas turbine inlet temperature, °C (°F)	927 (1700)
Steam turbine inlet temperature, °C (°F)	538 (1000)
Steam turbine inlet pressure, MPa (psia)	24 (3500)
Condenser pressure, kPa (in. Hg)	0.07 (2.0)
Steam reheat temperature, °C (°F)	538 (1000)
Overall plant efficiency, HHV basis, %	40.5

^aVessel is horizontal at length of 31.3 m (103 ft).

steam turbine would be used to generate the rated output for one module at 626 MW(e).

AEP System

AEP has proposed a system similar to the G.E. CFCC but has recommended a combustor pressure of about 1.6 MPa (16 atm).⁵¹ The combustor is intended to be enclosed in a spherical shell. The flow sheet for the cycle is shown in Fig. 42 and the major parameters are listed in Table 5. The steam generator design incorporates horizontal tubes in a toroidal fluidized bed.

Curtiss-Wright System

The concept proposed by Curtiss-Wright (C-W) uses a mixture of clean, hot air and combustion gas as the gas turbine working fluid.¹⁷ The steam for the bottoming cycle is generated in an unfired heat recovery steam generator. The system flow sheet is shown in Fig. 43. The major cycle parameters and other characteristics are presented in Table 6.

The most complete description of the design can be found in ref. 17. A somewhat unique feature is the vertical finned tubes used to heat the clean air. The tubes are a reentry or bayonet design. The ratio of clean air to combustion gas is about 2/1.

Oak Ridge National Laboratory

ORNL is involved in the development of a concept which has been designated as a supercharged fluidized bed combustion system (SCFBC).^{49, 52} The technically correct term would be turbocharged since the exhaust gas from the combustor is used by a turbine to drive the compressor with very little net power generated. The design study is in its very early stages. A broad range of pressure and temperature conditions in the PFBC system are to be studied comparatively. A flow sheet for the SCFBC is shown in Fig. 44, and some data from preliminary studies are included in Table 7.

Fig. 42. Schematic of AEP PFBC concept, Ref. 51.

Table 5. Data for AEP PFBC plant design

Plant size studied, MWe	500
Gas turbine power, % of total	28
Steam turbine power, % of total	72
Combustor pressure, MPa (atm)	1.5 (15)
Combustor temperature, °C (°F)	843 (1550)
Diameter of combustor module	
Number of modules for rated output	2
Gas turbine inlet temperature, °C (°F)	799 (1470)
Steam turbine inlet temperature, °C (°F)	538 (1000)
Steam turbine inlet pressure, MPa (psia)	17.7 (2600)
Condenser pressure	
Steam reheat temperature, °C (°F)	538 (1000)
Overall plant efficiency, HHV basis, %	39.4

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Fig. 43. Diagram of Curtiss-Wright PFBC power system.

Table 6. Data for C-W PFBC plant design

Plant size studied, MWe	500
Gas turbine power, % of total	60
Steam turbine power, % of total	40
Combustor pressure, MPa (atm)	0.70 (7)
Combustor temperature, °C (°F)	899 (1650)
Diameter of combustor module, m (ft)	8.5 (28)
Number of modules for rated output	6
Gas turbine inlet temperature, °C (°F)	870 (1600)
Steam turbine inlet temperature, °C (°F)	441 (825)
Steam turbine inlet pressure, MPa (psia)	5.5 (800)
Condenser pressure, kPa (in. Hg)	0.07 (2.0)
Steam reheat temperature	None
Overall plant efficiency, HHV basis, %	40.0

The design study is being planned with the help of TVA who has recommended the subcritical forced circulation steam system. Use of a separate vessel for the superheater is believed to ease control of the system. The boiler bundles are envisioned as being sets of vertical tubes.

Burns & Roe System

The commercial plant design treated in the most detail employs a PFBC combustor and gas turbine which exhaust to an AFBC steam generator.⁵³ The flow sheet is shown in Fig. 45. A considerable amount of alternate system evaluation and trade-off studies were performed before arriving at this configuration. The design conditions for the plant are itemized in Table 8. Vertical U-tubes are used to heat clean air in the PFBC. The AFBC incorporates a carbon burnup bed. The overall configuration is similar to a supplementally-fired combined cycle which is reasonably well-known as an oil-or gas-fired system.

Table 7. Preliminary data on SCFBC design

Plant size studied, MWe	800
Gas turbine power, % of total	5
Steam turbine power, % of total	95
Combustor pressure, MPa (atm)	0.35–0.50 (3.5–5)
Combustor temperature, °C (°F)	899 (1650)
Diameter of combustor module, m (ft)	7.5 (25 ^a)
Number modules for rated output	4
Gas turbine inlet temperature, °C (°F)	593 (1100)
Steam turbine inlet temperature, °C (°F)	538 (1000)
Steam turbine inlet pressure, MPa (psia)	16.5 (2400)
Condenser pressure, kPa (in. Hg)	0.08 (2.5)
Steam reheat temperature, °C (°F)	538 (1000)
Overall plant efficiency, HHV basis, %	37

^aPlus superheater vessel slightly smaller.

Other Proposed Designs

There are numerous other design variations on the PFBC concept. These systems are mentioned briefly here and references for more detailed information are provided.

Burns & Roe

Burns & Roe has examined a number of alternate configurations other than their reference design.⁵⁴ These include:

1. steam-cooled PFBC similar to G.E. GFCC,
2. adiabatic PFBC with supplemental firing in AFBC,
3. devolatilizer PFBC system,
4. air-cooled system similar to Curtiss-Wright, and
5. air-cooled PFBC with gas turbine reheat.

Fig. 45. Burns & Roe PFB/AFB combined cycle power plant, Ref. 53.

Table 8. Data for Burns & Roe PFBC/AFBC system

Plant size studied, MWe	574
Gas turbine power, % of total	22
Steam turbine power, % of total	78
Combustor pressure (PFBC), MPa (atm)	1.0 (10)
Combustor temperature, °C (°F)	
PFBC	899 (1650)
AFBC	843 (1550)
Diameter of combustor module (PFBC only), m (ft)	6 (20)
Number of modules for rated output	4
Gas turbine inlet temperature, °C (°F)	870 (1600)
Steam turbine inlet temperature, °C (°F)	538 (1000)
Steam turbine inlet pressure, MPa (psia)	16.5 (2400)
Condenser pressure, kPa (in. Hg)	0.07 (2.0)
Steam reheat temperature, °C (°F)	538 (1000)
Overall plant efficiency, HHV basis	37.9

ORNL

A reheat gas turbine PFBC cycle has been proposed which provides a plant efficiency of about 39% at a gas turbine inlet temperature of only 649°C (1200°F).⁴⁹ The concept is quite dissimilar to the Burns & Roe reheat concept.

Bergbau-Forschung GmbH

The proposed concept has a PFBC operating at about 0.45 MPa (4.5 atm).⁵⁵ A unique feature is the planned attempt to use an electrostatic precipitator to remove particles from the gas stream. A pilot plant to test the concept is being designed. A higher pressure concept is to be evaluated in order to enhance the electrostatic precipitator performance.

Recent Economic Comparisons of Plant Concepts

EPRI

EPRI is sponsoring economic comparisons of air-cooled and steam-cooled PFBC power systems. However, since the results of these studies have not been finalized or released by EPRI, no further information is provided in this document.

Exxon Research and Engineering

PFBC power systems using sorbent regeneration were compared with systems using once-through sorbent utilization.^{5b} Comparisons to AFBC and conventional systems were also discussed. A significant approach used in the designs was to incorporate cyclones for gas cleanup in lieu of granular bed filters and noting the effect on overall cost. A lower efficiency turbine, similar to a cat cracker unit, was used in the study as well. Effects of the turbine inlet temperature were also evaluated. The conclusions from the study are summarized below.

1. Only the less-proven sorbent regeneration schemes appeared to offer an economic advantage over once-through dolomite use in a PFBC.
2. Although the cyclones/expander PFBC system had a lower overall efficiency than a plant with granular filters and a high efficiency turbine, the cost of electricity for the former system was 17% lower.
3. Dropping the turbine inlet temperature from 871 to 760°C (1600 to 1400°F) increased the cost of power about 2%. Lowering the inlet temperature to 649°C (1200°F) resulted in an additional 2% increase in cost of power.

The pressure of the PFBC systems was about 1.0 MPa (10 atm) in all cases.

Curtiss-Wright

An air-cooled system was subjected to a cost estimate under sponsorship of EPRI.⁴⁸ The PFBC was assumed to be totally air-cooled with no split air flow. Pressurization power was supplied by a turbo-expander with an inlet temperature of 620°C (1150°F). Clean air was heated to

760°C (1400°F) in the PFBC and used in a gas turbine superimposed on a steam cycle. This configuration and operating conditions produced a low plant efficiency and the cost of the system was not viewed as competitive.

DOE Independent Cost Estimating Staff.

The Office of the Controller, Office of Independent Cost Estimating performed a cost study of air-cooled vs steam-cooled PFBC. A team from industry and DOE was formed to carry out a rather quick analysis which was completed in the period of November 1, 1979-January 1980. A numbered report has not yet been released on this study and, therefore, the details and the findings have not been included here. Reference to the study has been brought forward for the sake of completeness.

CONCLUSIONS

Some general conclusions can be drawn with respect to each major section of this report.

Facilities

Current PFBC test facilities are satisfactory for emissions studies and materials testing on a small scale. None of the facilities currently operating are large enough to test full-scale turbine machinery. Furthermore the facilities are generally incapable of operating at a variety of pressure and temperature conditions. Facilities for development and testing of coal-feeding equipment for PFBC generally do not exist separately. The Curtiss-Wright facility is the largest operating PFBC in this country. The air-cooled concept, however, appears to offer no appreciable economic advantage over the steam-cooled commercial plant concepts. None of the operating PFBC test facilities use a gas turbine driven compressor which would permit system operation and control experimentation.

Turbine Life

Cyclone particle separators have been proven to be effective in collecting particles to a degree sufficient to keep turbine erosion very light. Malfunction of the devices, however, can lead to very rapid destruction of the turbine blades.

Deposits appear in turbines or on cascade samples practically without exception. Although the deposits are often soft, data indicate that moderately different operating conditions or different coal may produce a tenacious deposit. Possible turbine damage caused by spalling deposits has not been investigated. Degradation of turbine output as deposits build should be factored into economic evaluations of the concept.

Conclusive evidence from PFBC tests concerning corrosion has not been produced. More data have been generated from small scale lab tests using doped fuels. Longer duration tests on PFBC rigs are needed to confirm the durability of turbine materials. The effect of cooling and

reheating the flue gas prior to passage through materials test sections needs to be clarified.

Power Plant Design Concepts

Steam-cooled PFBC combined cycles have been shown to suffer a lesser efficiency penalty than air-cooled systems when the gas turbine inlet temperature is lowered. Economic comparisons of air- and steam-cooled systems are somewhat inconsistent and incomplete as this time.

A study has shown that the gas turbine inlet temperature can be lowered without a dramatic increase in cost of power (steam-cooled PFBC). The effect of pressure on the system has not been thoroughly investigated. The use of cyclones in lieu of granular bed filters greatly reduces the cost of PFBC plants.

A number of areas have been identified as deserving further attention in concept evaluations:

1. Alternate gas turbine or expander cost and reliability.
2. Cost associated with gas turbine degradation between cleanings or repairs.
3. Gas turbine cleaning frequency and cost.
4. Cost of gas ducting and cleanup system as functions of gas turbine inlet temperature.

Commercialization

Commercialization of the PFBC plant concepts which have received the most attention will depend heavily on the development approach and results of efforts. Successful operation of a number of proposed PFBC pilot plants would bring commercialization within reach by 1990.

The Grimethorpe plant should provide some meaningful results by 1983 on full size turbine component life and further proof testing of gas cleanup equipment. However, testing of an actual rotating turbine may not take place until perhaps 1985.

The Curtiss-Wright pilot plant is scheduled for start-up in 1982 meaning that probably by 1984 some conclusions can be drawn with regard to the commercialization potential of that concept. Apparently AEP has elected to build a 1/18 scale pilot unit of the proposed repowering demonstration unit at their Tidd plant. The small unit is to be built in Sweden at Stal-Laval. The planned start-up date for the Tidd unit is 1984.

Of the presently defined power plants, the 170 MW AEP Tidd plant would be the first to incorporate both a gas and steam turbine. It would appear that a demonstration of the entire system is necessary before commercialization would proceed. Hence the 1990-1992 time frame would be logical for operation of a commercial PFB system, barring any technical problems which hinder progress.

Moderate performance PFBC systems, which use relatively low gas turbine inlet temperatures, may be ready for earlier commercialization since there is less risk of delays arising from technical difficulties. Due to the need for gaining experience and data on operating PFBC systems (not just subsystems), it would not be advisable to bypass the pilot plant or demonstration phase even though there is less risk involved. The Grime-thorpe or Curtiss-Wright pilot plants could be used toward the purpose of commercializing the evolutionary PFB as well as the high technology systems. Also, as in the AEP approach, repowering an existing plant could serve as a demonstration project. Hence 1990 is also a reasonable date for a commercial "conservative" PFBC system. However, the date can be projected with greater confidence due to lesser risk associated with development of the turbine and gas cleanup subsystems.

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