**Technical and Economic
Assessment of Fluidized Bed
Augmented Compressed Air
Energy Storage System
System Load Following Capability**

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September 1981

**Prepared for
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TECHNICAL AND ECONOMIC ASSESSMENT
OF FLUIDIZED BED AUGMENTED COMPRESSED
AIR ENERGY STORAGE SYSTEM
SYSTEM LOAD FOLLOWING CAPABILITY

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Foreword

Compressed air energy storage (CAES) is a technique for supplying electric power to meet peak load requirements of electric utility systems. A CAES plant uses low-cost power from base load plants during off-peak periods to compress air in an underground reservoir -- an aquifer, solution mined salt cavity or mined hard rock cavern. During subsequent daytime peak load periods, the compressed air would be withdrawn from storage, heated, and expanded through turbines to generate peak power.

Studies have shown that the CAES concept is technically feasible and, with a proper utility power generation mix is economically viable. Replacement of current oil-fired gas turbine peaking units by CAES systems could result in an annual savings of more than 100,000,000 barrels of oil. Already, a CAES plant is being operated by Nordwestdeutsche Kraftwerke AG. in Germany and other plants are being planned or considered by U.S. utilities.

In view of the potential benefits the CAES concept offers, the Department of Energy (DOE) has undertaken a comprehensive program in order to accelerate commercialization of this technology. The Pacific Northwest Laboratory (PNL) was selected by DOE as lead laboratory for the CAES Technology Program. As such, PNL is responsible for assisting the DOE in planning, budgeting, contracting, managing, reporting, and disseminating information. Under subcontract to PNL are a number of companies, universities and consultants that are responsible for various research tasks within the Program.

This report describes the results of a study subcontracted by PNL to the United Technologies Research Center on the engineering feasibility and economics of a CAES concept which uses a coal fired, fluidized bed combustor (FBC) to heat the air being returned from storage during the power production cycle. By burning coal instead of fuel oil, the CAES/FBC concept can completely eliminate the dependence of compressed air energy storage on petroleum fuels.

This study is a part of the "Second Generation CAES Systems" task of the CAES Technology Program. The general objective of the Second Generation task is to develop advanced CAES technologies that would reduce or eliminate the dependence of CAES systems on petroleum fuels. Other concepts receiving preliminary attention in this task are:

- Adiabatic CAES utilizing mined hard rock caverns for compressed air storage.

- Adiabatic CAES utilizing aquifers for storage of compressed air and part of the heat of compression
- CAES cycle integrated in a coal gasification plant
- Solar assisted CAES
- Combined CAES and coal-fired steam plant.

At the present time PNL is directing the limited research and development funding resources to advancement of CAES concepts utilizing thermal energy storage. The CAES/FBC concept appears technically feasible and economically competitive with conventional CAES. However, significant advancement is required in FBC technology before serious commercial commitment to CAES/FBC can be realized. At present, other elements of DOE, industrial groups, and other countries are performing the required R&D for advancement of FBC technology. The CAES/FBC will be reevaluated at a later date when FBC technology has matured and many of the concerns now plaguing FBC are resolved.

Foreword

This evaluation of the load following capability of fluidized bed combustion augmented compressed air energy storage systems was performed by United Technologies Research Center with subcontract assistance from Coal Processing Consultants Limited of the United Kingdom. The study program has been prepared under Subcontract No. B-51299-A-L for Pacific Northwest Laboratory which is operated for the U.S. Department of Energy by Battelle Memorial Institute under Prime Contract DE-AC06-76RLO-1830. The technical work described herein was initiated in April 1980 and completed in September 1980.

The results of this evaluation study are presented in two parts. The first part is an Executive Summary which provides a concise overview of all major elements of the study including the conclusions. The second part is a detailed Technical Report describing the part-load and load following capability of both the pressurized fluid bed combustor and the entire pressurized fluid bed combustor/ compressed air energy storage system.

This evaluation study is based upon an earlier study performed under Subcontract No. B-51299-A-L for Pacific Northwest Laboratory. The documentation of this earlier study appears in United Technologies Research Center Report No. UTRC R80-954490-20 and is entitled Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System (Volume I - Executive Summary; Volume II - Introduction and Technology Assessment; and Volume III - Preconceptual Design).

The United Technologies Research Center provided overall program management and major contributions in the areas of system part-load and load following. This effort was performed under the general guidance of F. L. Robson, Chief, Utility Power Systems and A. J. Giramonti, Senior Project Engineer. It involved the following people:

R. D. Lessard, Program Manager
W. A. Blecher
S. J. Lehman

Coal Processing Consultants Limited provided contributions in the areas of fluid bed combustor part-load and start-up operation. These efforts involved the following people:

D. Merrick, Project Manager
M. J. Cairns
W. B. N. Rowlands
J. E. Stantan

Additional assistance was provided by the Department of Energy, Electric Power Research Institute, and Potomac Electric Company in making available data from their ongoing CAES assessment study.

The study program was conducted under the general direction of W. V. Loscutoff and F. R. Zaloudek of Pacific Northwest Laboratory.

The support and assistance of all of the aforementioned individuals and organizations in contributing to the successful completion of this study program is acknowledged with sincere appreciation.

TECHNICAL AND ECONOMIC ASSESSMENT OF FLUIDIZED BED
COMBUSTION AUGMENTED COMPRESSED AIR ENERGY STORAGE SYSTEMS

SYSTEM LOAD FOLLOWING CAPABILITY

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Executive Summary

INTRODUCTION

An energy storage system which could be attractive for future electric utility peak-load applications is a modified gas turbine power system utilizing underground storage of a very high pressure air. The compressed air energy storage (CAES) concept (Fig. 1) involves: 1) using off-peak electricity generated from indigenous coal or nuclear resources to compress air; 2) storing the air in underground facilities; and 3) withdrawing the air during peak-load periods when it would be heated by combustion and expanded through a gas turbine to generate power. In general, the attractiveness of the CAES concept is based upon its potential for supplying competitively priced peaking energy, for providing a means of leveling the utility system load demand, and for reducing peak-load power plant dependence on petroleum-based fuels.

A CAES concept which would accentuate the last attribute by totally eliminating the dependence on petroleum-based fuels was the subject of the Ref. 1 assessment study. In this concept, the CAES combustor is a coal-fired fluid bed combustor (FBC). The conclusions drawn from the assessment of the FBC/CAES concept are encouraging. They indicated that a power plant based upon the most promising FBC/CAES system configuration, an open-bed pressurized fluid bed combustor (PFBC)/CAES power plant (Fig. 2), should be technologically feasible, provide good performance, and be economically competitive.

As part of the Ref. 1 study, a preliminary evaluation was made of the load following capability of the PFBC/CAES power plant. This evaluation was deemed necessary because any generating unit, especially a peak-load unit, must be capable of responding to changes in load. This preliminary evaluation produced the conclusion that the PFBC/CAES plant should have acceptable load following capability. However, the importance of load following capability to a utility system warranted the continuation of this investigation. Consequently, an effort was initiated to provide a more detailed evaluation of the load following capability of the PFBC/CAES power plant. A commentary on the highlights associated with this effort provides the basis for the report contained herein.

The study effort has been carried out along two paths which have been designed to converge and in so doing achieve a definitive indication of the steady-state, part-load, and the load following capability of both the open-bed PFBC and the entire PFBC/CAES system. The specific tasks in this investigation are outlined in Table 1.

SIMPLIFIED COMPRESSED AIR ENERGY STORAGE SYSTEM

FIG. 1

COAL-FIRED PFBC/CAES SYSTEM

FIG. 2

Table 1

PFBC/CAES LOAD FOLLOWING CAPABILITY PROGRAM

- Define the steady-state, part-load operation of the CAES open-bed PFBC.
- Estimate the steady-state, part-load performance of the PFBC/CAES system and evaluate any possible operational constraints.
- Simulate the performance of the PFBC/CAES system during transient operation and assess the load following capability of the system.
- Establish a start-up procedure for the open-bed PFBC and evaluate the impact of this procedure.

CONCLUSIONS

The conclusions drawn from this evaluation of the load following capability of the open-bed PFBC are encouraging. They indicate that the open-bed PFBC/CAES power plant should be responsive to the utility load following requirements for a peak power plant, should provide good part-load and transient performance, and should have no major equipment-related constraints. Specifically, it is concluded that:

- No major problems associated with the performance or design of either the open-bed PFBC or the PFBC/CAES power plant in steady-state, part-load operation are envisioned.
- The steady-state, part-load heat rate increase of 14 percent for the PFBC/CAES system at 25-percent design output as compared to the heat rate at 100-percent of design output is approximately half that expected from a conventional gas turbine.
- The open-bed PFBC/CAES power plant would have a load following capability which would be responsive to electric utility requirements for a peak-load power plant.
- The open-bed PFBC could be brought to full operating conditions within 15 minutes after weekday or weekend shutdown by employing a hot-start mode of operation.
- The PFBC/CAES system would be capable of rapid changes in output power (12 percent of design load per minute) over a wide output power range (25 percent to 100 percent of design output).

PFBC PART-LOAD OPERATION

The application of an open-bed PFBC to a peak-load power plant such as the CAES system is a unique concept. Consequently, special attention was directed to the investigation of the behavior of the PFBC component. One element of this investigation dealt with defining the performance of the PFBC under steady-state operation at reduced load.

The open-bed PFBC/CAES power plant system would achieve part-load operation by concurrently and proportionately varying the mass flow of both the air and coal to the PFBC to produce a varying thermal output. Operation in this manner will also: 1) produce a constant bed temperature and, therefore, a constant low-pressure turbine inlet temperature because the air and fuel flows remain proportional; 2) provide a bed pressure that is directly proportional to the flow through the bed because the low-pressure turbine nozzle area is fixed resulting in choked flow; and 3) yield essentially a constant fluidizing velocity in the bed over the entire load range because the flow rates are proportional to pressure and the bed temperature remains constant.

To provide the input necessary for the PFBC part-load analysis, reasonable estimates of the PFBC operating conditions were obtained by simulating the PFBC/CAES system in steady-state, part-load operation. Based upon these operating conditions, the behavior of key operating parameters were examined. This led to refinements in the operating data which were then used as input to subsequent PFBC/CAES system simulations.

The key operating parameters which were investigated are: combustion efficiency, freeboard and cyclone combustion, sulfur retention, fluidization, elutriation, and solids handling. These parameters were studied at 100-percent, 50-percent, and 25-percent design load.

The combustion efficiency is expected to be at least 98.5 percent over the operational range of 25-percent to 100-percent load at the design bed temperature of 1562 F (850 C)* and fluidizing velocity of 3 ft/sec (0.9 m/s). A higher efficiency of 99 percent could be achieved by increasing the number of solids feed points from the Ref. 1 design value of one nozzle per 35.0 ft² (3.25 m²) to one nozzle per 10.0 ft² (1 m²). Because of the high combustion efficiency, little combustion is expected in the freeboard or cyclones. Such combustion as will occur probably will amount to only a few tenths of one percent of the coal thermal input, and will cause an insignificant rise in gas temperature. Combustion conditions therefore, do not represent a limitation to steady-state, part-load operation.

* See Appendix A for factors to convert English to SI units.

No experimental data on sulfur retention directly related to the expected operating conditions in the combustor are available, and differences among existing sulfur retention models produce predictions which disagree significantly (Table 2). However, no difficulties are envisioned in designing a solids injection system capable of supplying the range of dolomite feed rate that would be required to meet the specified goal of 85-percent sulfur retention.

An analysis of the fluidization conditions expected throughout the 25-percent to 100-percent load range indicates that for coal and dolomite maximum particle size of 1/8 inch (3000 μm) satisfactory fluidization could be maintained during steady-state operation within the load range. An estimate of the solids loading in the combustion gas at the cyclone entry revealed an increase in loading with increasing output load (Table 3). This increase results partly from the increased solids feed rate and partly from the higher proportion of feed material elutriated due to the denser fluidizing gas. However, because the gas velocities in the cyclones remain nearly constant over the load range, resulting in nearly constant efficiency, and because the dust elutriated at high output loads is coarser than at low loads, the increase in dust loading in the cleansed gas will be less than at the cyclone inlet. Consequently, elutriation should not pose a problem as long as the detailed design of the solids handling equipment takes into account the momentary high particulate loadings in the combustion gas on turnup after prolonged part-load, steady-state operation. The magnitude of this loading could be approximately seven times the steady-state value for 100-percent output power with a load change from 25-percent to 100-percent of design in 15 minutes.

Table 2

PREDICTIONS OF Ca/S MOL RATIO FOR 85-PERCENT SULFUR RETENTION

<u>Model</u>	<u>Load</u>		
	<u>100%</u>	<u>50%</u>	<u>25%</u>
Combustion Systems Ltd.	1.5	1.5	1.7
Exxon			
(unmodified)	1.2	1.6	2.3
(modified)	1.3	1.5	1.8
Westinghouse			
(fully precalcined sorbent)	1.8	1.4	1.3
(half precalcined sorbent)	2.5	2.0	1.7

Table 3

SUMMARY OF ELUTRIATION DATA

	Load, percent		
	<u>100</u>	<u>50</u>	<u>25</u>
Elutriation lb/sec (kg/s) ⁽¹⁾	3.68 (1.67)	1.94 (0.88)	1.06 (0.48)
lb/sec (kg/s) ⁽²⁾	4.85 (2.20)	2.23 (1.01)	
Gas flow lb/sec (kg/s)	731.5 (331.8)	443.1 (201.0)	259.7 (117.8)
Solids concentration at cyclone entry	5033 ⁽¹⁾	4378 ⁽¹⁾	4075
(ppm mass fraction)	6631 ⁽²⁾	5025 ⁽²⁾	

Notes:

- (1) Standard Ca/S ratio (based on Combustion Systems Ltd. model).
 (2) Pessimistic Ca/S ratio (based on Westinghouse model).

PFBC/CAES SYSTEM PART-LOAD OPERATION

As a result of the investigation of the PFBC at steady-state, part-load operation, revised combustor performance data were prepared. These data were used as the basis for the revised simulation of the entire PFBC/CAES system at steady-state, part-load operation.

Part-load PFBC/CAES system simulations were prepared incorporating different estimates for Ca/S ratio to evaluate the effect Ca/S ratio has on system performance. Based upon these system simulations, it was determined that the selection of a Ca/S ratio value within the predicted range had little effect on system performance e.g., a 67 percent increase in Ca/S ratio produced approximately a one percent increase in coal rate.

The analysis of the PFBC/CAES part-load performance indicated that it would possess good part-load efficiency relative to a conventional gas turbine. For example, the generation heat rate would rise only 14 percent at 25-percent load as compared to design heat rate (Fig. 3). In addition, the analysis revealed that the increase in generation heat rate with decreasing load resulted partly from: 1) the shift in output power contribution from the more efficient low-pressure turbine to the less efficient expansion turbine (20.9-percent expansion turbine contribution at 100-percent load to 34.6-percent at 25-percent load), and 2) an increase in stack temperature resulting in greater heat rejection from the system.

Part-load operation of the PFBC/CAES system is achieved by throttling the airflow and decreasing the coal rate. These are varied such that a constant bed temperature is maintained and the bed pressure is decreased in order to maintain good fluidization in the bed. The reduction in inlet pressure into the low-pressure turbine results in a reduced expansion ratio across the turbine. This, combined with the constant bed temperature of 1562F (850 C), produces an increased low-pressure turbine exhaust (hot-side recuperator inlet) temperature (Fig. 4). This could create a cause for concern. Upon closer examination, however, no equipment limitations were uncovered that could not be readily corrected by state-of-the-art design modifications. Specifically, the stainless steel design of the recuperator was found to be compatible with the higher part-load temperatures it would experience; the low-pressure turbine would be compatible if in the last turbine stages either higher temperature resistant blades were used or if blade cooling were employed. Both approaches to achieving turbine compatibility would involve minor additional costs.

PART-LOAD GENERATION HEAT RATE
STEADY STATE

PART-LOAD RECUPERATOR HOT-SIDE INLET TEMPERATURE
STEADY STATE

PFBC/CAES SYSTEM TRANSIENT OPERATION

The ability of a generating unit to respond to load changes is an important factor affecting its desirability to a utility system. This is especially true of a peaking unit such as the CAES system. While interconnecting tie-lines will lessen the effect of load disturbances on a utility system, it is generally required that these disturbances be corrected by either increasing or decreasing utility output in less than 10 minutes. While there is no universal requirement for the response time of the generating units within a utility, a typical guideline would require a utility system to impose a load change capability of between 3 and 5 percent of design load per minute on their load following units. These rates will vary from utility to utility depending on the size and characteristics of other units in the utility. For example, if a utility uses a large percentage of base-load power from units with limited response capability, the load following units must make up for this by having a proportionately greater capability.

To determine the ability of the system to respond to load changes, a transient simulation model of the PFBC component was prepared. A block diagram of the PFBC representation is shown in Fig. 5. In this figure, bed temperature is shown as a function of coal rate and air flow. A change in coal rate effects the heat release in the bed and, thus the bed temperature via two mechanisms. In the first mechanism, a change in coal rate changes the volatile matter availability. The volatile matter releases heat almost instantaneously after injection into the bed. In the second mechanism, a change in coal rate changes the mass of carbon in the bed. The heat release from carbon burn-up is a function of the mass of carbon in the bed. As a result, when the coal feed rate is increased, heat release is initially increased only by the volatile matter. The remaining increase occurs as carbon inventory builds up over a time constant of approximately four minutes. A change in air flow directly affects the rate of heat removed from the bed. Because of the good heat transfer between the gases in the bed and bed material, the entire bed temperature must change with combustor outlet temperature. This results in a time constant between the change in air flow and bed temperature of approximately 6 minutes. Because of the difference in time constants when both fuel rate and air flow are changed together to produce the same steady-state bed temperature, bed temperature does not remain constant, but is temporarily disturbed before returning to its initial value. This is shown in Fig. 6 for a simultaneous increase of 10 percent in both fuel and air flow rate. If it were desired that bed temperature remain constant, fuel flow would have to be changed initially by more than the corresponding fractional air flow change.

COMBUSTOR DYNAMICS

FIG. 5

BED TEMPERATURE RESPONSE

10-PERCENT INCREASE IN COAL & AIR FEED RATE

FIG. 6

To determine the effect of other parts of the CAES system on PFBC response, the dynamic PFBC model described above was incorporated into the UTRC PFBC/CAES system simulation model. Other than the PFBC, the major factors affecting PFBC/CAES system response are the recuperator thermal mass and the volumetric lag associated with changing pressure in the PFBC containment vessel. The effect of these factors on the bed temperature response to the same 10-percent increase in both air flow and fuel rate is shown in Fig. 7. When compared with the results when simulating only the PFBC (Fig. 6), it can be seen that the magnitude of the temperature disturbance for the PFBC/CAES system is decreased and the time to reach the peak disturbance is lengthened from 5 to 8 minutes.

Because it will be necessary to hold bed temperature relatively constant to avoid damage to the refractory material in the bed, it appears that coordination of fuel rate and air flow will be an important factor in fuel system design. To identify the required response of the fuel feed mechanism, a number of different rates of change of air flow (which approximates power level change) were examined. At a 15-percent-per-minute change in throttle valve restriction (this produces an output power change approximately three times greater than the typical load following guideline), the required rate of change in fuel flow is nearly 20 percent per minute. This is shown in Fig. 8 which presents the fuel rate required to maintain constant bed temperature as the throttle valve restriction is changed from 25-percent to 100-percent load in 5 minutes. As shown in Fig. 8, a feed rate of 20 percent in excess of design will be needed to maintain constant bed temperature for the specified transient. While commercial equipment could probably respond at 20 percent per minute, it is generally not sized for much more than 10 percent over the design feed rate. Assuming that fuel rate can respond as shown in Fig. 8, Fig 9 shows the resultant change in output power. Because of volumetric and thermal lags, it takes slightly more than 5 minutes to reach 100-percent output power.

The change in air temperature out of the cold side of the recuperator shown in Fig. 10 is worthy of note. Because of the high cold-side film coefficient, recuperator metal temperature will closely follow this profile. Thus, the heat exchanger will have to be designed to withstand a 250F (140 C) temperature change in approximately 7 minutes.

It is apparent that output changes on the order of 15 percent per minute over a large range are feasible with current state-of-the-art equipment. For smaller excursions (on the order of 25 percent) rates of change of 25 percent per minute may be feasible. Because of these rapid response rates, the desirability of the system should be greatly enhanced.

PFBC EXIT TEMPERATURE RESPONSE
TO 10% CHANGE IN AIR AND FUEL FEED RATE

REQUIRED FUEL FEED RATE FOR CONSTANT PFBC
TEMPERATURE DURING 15%/MIN RAMP

OUTPUT FOR 15%/MIN RAMP

RECUPERATOR COLD-SIDE EXIT TEMPERATURE
DURING 15%/MIN RAMP

PFBC START-UP OPERATION

Another important element of transient performance, especially for a peak-load power plant, is the start-up response. Consequently, the design and performance of the start-up system have been considered. Two main modes for start-up from no load to full load were investigated: a cold start from ambient temperature, and a hot start from temperatures above 1292 F (700 C).

Because short start-up time is an important requirement for a peak power plant such as the PFBC/CAES system, a combustor design was selected which would allow the hot-start mode to be the normal mode of operation after overnight or weekend shutdown. In this mode the bed cools down to only 1292 F (700 C) upon shutdown rather than ambient temperature as would occur in a cold-start design. This is accomplished by incorporating sufficient insulation around the bed to maintain the temperature above 1292 F (700 C) during overnight and weekend shutdown periods (Fig. 11). A hot-start design permits coal to be fed directly on initiation of the start-up sequence with only a small amount of distillate fuel being used after weekend shutdown.

Even though the hot-start mode of operation is the normal mode of operation for a hot-start design, the PFBC is still capable of a cold-start after periods of extended shutdown, such as for annual maintenance. In a cold-start, distillate fuel will be burned to bring the bed temperature to 1292 F (700 C) at which point coal feed can commence as in the hot-start mode.

For a cold-start, the factors limiting the start-up time are the rate of firing of distillate fuel and the temperature at which hot combustion gases can be fed to the bed through the distributor plate. The limiting factors for a hot-start are thermal stress considerations for metallic and insulating ceramic components in the combustor and the response of the coal injection system.

It is estimated that the time required for a hot-start is 15 minutes (Fig. 12). The estimate for a cold-start is 50 minutes. This consists of 35 minutes to reach the hot-start initiation temperature of 1292 F (700 C) using distillate fuel (see Fig. 13), plus the 15-minute hot-start period. By ensuring that the air flow to the combustor required at the beginning of the hot start is the same as that used at the end of a cold start, the former can follow the latter without interruption. The air flow rate is also chosen so that the fluidizing velocity is approximately constant during a hot start and the solids feed rate lies within the turndown capability of the fuel injection system.

TEMPERATURE DECAY DURING SHUT DOWN

VARIATION OF BED TEMPERATURE DURING HOT START

INCREASE IN BED TEMPERATURE DURING COLD START

REFERENCE

1. Giramonti, A. J., R. D. Lessard, D. Merrick, and M. J. Hobson: Technical and Economic Assessment of Fluid Bed Combustion Augmented Compressed Air Energy Storage System. UTRC Report R80-954490-20 supported by Battelle Pacific Northwest Laboratory Subcontract B-51299-A-L, June 1980.

Technical Report

INTRODUCTION

The ability of a generating unit to respond to changes in load is an important factor affecting its desirability to a utility system. Because of this, all power plants must have some degree of load-following capability. This is especially true of a peaking unit such as the CAES system.

Load following implies the ability to operate in off-design conditions, i.e., both steady-state and transient part-load conditions. The uniqueness of the open-bed PFBC/CAES system gave rise to reservations about its part-load and load following capabilities. Consequently, a preliminary investigation of these capabilities was initiated and reported in Ref. 1-1. In general, the results of the investigation, which are briefly reviewed in the following paragraphs, indicated that the open-bed PFBC/CAES system should have good part-load performance and should be able to respond to modest changes in load demand within reasonably short periods. However, prior to the review, it is appropriate to describe briefly the PFBC/CAES power plant design which evolved from the Ref. 1-1 preconceptual design and which served as the basis of the load following analyses.

Description of PFBC/CAES Power Plant

The power plant design has been developed from the PFBC/CAES system configuration displayed in Fig. 1-1. This system configuration was selected over twenty other possible system configurations because it has moderate cost and reasonable performance combined with a relatively low technical risk assessment. It features both low-pressure turbomachinery (compressor and turbine) which operate over the range from ambient pressure to an intermediate pressure of approximately 15 atm (bar) and high-pressure turbomachinery (booster compressor and expansion turbine) which operate from the intermediate pressure to a storage pressure of approximately 72 atm (bar). It also features an open-bed PFBC operating at 1562F (850C) and 15 atm (bar). Low-pressure turbine exhaust recuperation is used to provide an elevated expansion turbine inlet temperature while three stages of intercooling are used to lower the air temperature within the compressors. The key design point operating characteristics of a four unit plant based on this system configuration are displayed in Table 1-1.

The site arrangement of the complete four-unit FBC/CAES plant is shown in Fig. 1-2. The underground cavern is located near the upper border of the site. No plant components are positioned above the cavern structure. The compensating reservoir is located adjacent to the underground cavern, in the upper-right corner of the site. The power block (one quadrant of which is shown in Fig. 1-3) is located toward the center of the site and contains the turbomachinery buildings, fluidized bed combustors, coal and dolomite processors, and the central control and administration building. Within the power block, the four

OPEN-BED PFBC/CAES CONFIGURATION

Table 1-1

KEY PFBC/CAES POWER PLANT OPERATING CHARACTERISTICS

Turbine output, MW - 4 units	876.4
Compressor input, MW - 4 units	799.6
Generation heat rate, Btu/kWh (kJ/kWh)	4538 (4788)
Compression heat rate, Btu/kWh (kJ/hWh)	9095 (9595)
Round trip heat rate, Btu/kWh (kJ/kWh)	13633 (14383)
Storage pressure, atm (bar)	71.2 (72.1)
PFBC bed temperature, F (C)	1562 (850)
PFBC bed pressure, atm (bar)	15.0 (15.2)
ET inlet temperature, F (C)	507.5 (264.2)
LT inlet temperature, F (C)	1562 (850)
Annual utilization, hr/yr	2190
Capacity factor	0.25

SITE ARRANGEMENT PLAN

1-4

FIG. 1-2

POWER BLOCK ARRANGEMENT

1-5

FIG. 1-3

turbomachinery systems are arranged to minimize piping and electrical system complexity and achieve optimum coal combustion system control through close grouping of the processing and combustion systems. The electrical switchyard and forced draft wet cooling towers are located adjacent to the power block.

PFBC Plant Design

The fluid bed combustor system encompasses the following equipment: coal and dolomite handling, coal and dolomite preparation, coal and dolomite feeding, fluid bed combustion and particulate cleanup, ash and spent dolomite removal, and controls and instrumentation. The coal and dolomite are unloaded into underrail recovery hoppers and conveyed to stockpiles. Separate mills for the coal and dolomite dry and crush the material to the required top size of 1/8 in. (3mm) for feeding to the combustor. The coal and dolomite, in correct proportion, are fed in batches to a storage/primary injector system. Fuel from the primary injector is continuously fed to the combustor via twenty-four feed lines.

The fluid bed combustor pressure vessel (Fig. 1-4) contains the bed and the three-stage cyclone gas cleanup system. It has a length of 126 ft (38.4 m) and a diameter of 38 ft (11.6 m). It operates at 1562 F (850 C) and 15.2 bar (15 atm) with a fluidizing velocity of 3 ft/sec (0.9 m/s). The coal-dolomite mixture is injected pneumatically through feed points immediately above the distributor plate while the combustion air passes upward through the distributor plate. After combustion in the bed, the combustion gases and entrained particles enter the freeboard where most of the particles are deposited out of the gas stream. The remainder of the harmful particles are removed in three high-efficiency cyclones used for gas cleanup. Ash and spent dolomite are released through a bed level control system into a pneumatic conveying system. After cooling, the solids are discharged through pressure locks, then conveyed to storage.

Turbomachinery Plant Design

The power generation system includes: low-pressure and booster compressors, low-pressure and expansion turbines, clutches, a motor/generator, and heat exchangers. The turbomachinery has been placed on a common centerline (Fig. 1-5) and rotates at 3600 rpm. The compressors and turbines are on opposite ends of the motor/generator and are connected by clutches so that they can alternately drive, or be driven by, the motor/generator during compression or generation periods. The total length of the turbomachinery train is 126 ft (38.4 m), excluding the recuperator duct.

During the off-peak compression mode, an axial-flow, seventeen-stage, low-pressure compressor pressurizes ambient air to 16.8 atm (bar) with one intercooling stage. The air is again intercooled prior to compression to storage pressure in the booster compressor. The booster compressor is a seven-stage, heavy-duty, centrifugal compressor with intercooling after the fourth stage. The air is aftercooled to 120 F (49 C) and put into storage.

FLUID BED COMBUSTOR END VIEW

FIG. 1-4

TURBOMACHINERY TRAIN

FIG. 1-5

During the power generation mode, air from storage is heated in the recuperator and expanded through a two-stage turbine to about 15 atm (bar). After leaving the expansion turbine, the air travels to and from the PFBC via a co-axial inlet/outlet duct (Fig. 1-4) with the cooler, expansion turbine exit air on the outside and the hotter products of combustion on the inside. The hot gas is expanded through a four-stage, low-pressure turbine which produces most of the output power. Heat in the turbine exhaust is recovered in the recuperator.

Balance-of-Plant Design

The balance of plant includes those components and systems required to support the operation of the turbomachinery and PFBC systems. Most of these components and systems are common in both function and size to commercially available facilities. The balance of plant can be separated into three distinct sections: 1) the energy storage system including those items in the PFBC/CAES plant required to deliver, store, and regulate the pressure of the air; 2) the plant mechanical system including the mechanical equipment and systems required to support the CAES turbomachinery and PFBC plant; and 3) the plant electrical system including the electrical equipment and systems required to effect a workable PFBC/CAES power plant.

Preliminary Part-Load and Load Following Evaluation

An overview of PFBC/CAES system part-load and transient operation is included in Ref. 1-1. To provide the overview, it was necessary to investigate utility load following requirements, establish a preliminary part-load operating procedure, and examine the capability of the major equipment to operate in the part-load and transient operating modes.

Utility System Load Following Requirements

The guidelines for load following capability that would be required by an electric utility in an interconnected system were identified. Tie-line interconnections serve to diminish the severity of disturbances which would necessitate load-following operation by individual generating units within a utility system. Nevertheless, a requirement still exists to correct the disturbance by either increasing or decreasing output from the disturbed utility system in less than 10 minutes.

Although there are no fixed requirements for generating unit response time, a typical utility guideline would require a load change capability of between 3 and 5 percent of design load per minute for a generating unit dedicated

to load following. These rates will vary depending on the size and characteristics of other units in the utility. For example, if a utility uses a large percentage of base-load power units with limited response capability, the remaining units must make up for this by having a proportionately greater capability. This is especially true of a peaking unit such as the CAES system.

Part-Load Operation

A simple throttling procedure for achieving part-load operation of the open-bed PFBC/CAES power plant was identified. This procedure entails concurrently and proportionally varying the mass flow of the air and the coal to the PFBC to produce a variation in thermal output and, thus, a variation in output power. Operation in this manner will also: 1) produce a constant bed temperature and, therefore, a constant low-pressure turbine inlet temperature because the air and fuel flows remain proportional; 2) provide a bed pressure that is directly proportional to the flow through the bed because the low-pressure turbine nozzle area is fixed resulting in choked flow; and 3) yield a constant superficial velocity in the bed over the entire load range because the flow rates are proportional to pressure and the bed temperature remains constant.

Transient Response Limitations

Several physical limitations are possible. They are primarily related to thermal cycling during load following and the resulting stresses which could possibly affect the transient response of a PFBC/CAES power plant under changing loads. In the CAES power plant, these limitations would be applied to the expansion and low-pressure turbines plus the recuperator. An evaluation of the turbines' thermal response capability revealed that neither turbine would impose undue limitations on the CAES power plant response.

In the PFBC, both the combustion and sulfur removal efficiencies would be limited, making it highly desirable to operate at constant bed temperatures. A preliminary analysis of PFBC transient response provided an indication that the PFBC should be capable of relatively rapid response.

Scope of Current Investigation

Although the results of the Ref. 1-1 effort were viewed as being encouraging, they were also viewed as being preliminary. Consequently, the objective of the effort documented herein has been to extend the evaluation of the system load following capability. This effort has been divided into two main groups which provide an indication of the part-load and load following capability of the open-bed PFBC and then the part-load and load following capability of the entire PFBC/CAES system. Specifically the tasks in this investigation were concerned with:

1. the part-load operation of the CAES open-bed PFBC,
2. the steady-state, part-load operation of PFBC/CAES system,
3. the PFBC/CAES system load following capabilities, and
4. the operating characteristics of the CAES open-bed PFBC during start-up.

This evaluation was conducted by United Technologies Research Center (UTRC), with subcontract assistance from Coal Processing Consultants Limited (CPC) of the United Kingdom. The study program has been prepared under Subcontract No. B-51299-A-L for Pacific Northwest Laboratory which is operated for the U.S. Department of Energy by Battelle Memorial Institute under Prime Contract DE-AC06-76RLO-1830.

Reference

- 1-1. Giramonti, A. J., R. D. Lessard, D. Merrick, and M. J. Hobson: Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System. UTRC Report R80-954490-20 supported by Pacific Northwest Laboratory Subcontract No. B-51299-A-L, June 1980.

PFBC PART-LOAD OPERATION

The performance characteristics of the open-bed PFBC/CAES power plant used in the Ref. 2-1 report are based on steady-state operation at the full-load design point. In order to simulate both steady-state, part-load operation and transient operation of the PFBC/CAES system, it was necessary to first identify the steady-state, part-load characteristics of the major components. The most important of these components is the PFBC. Consequently, the objective of the effort related to PFBC part-load operation has been to define the performance of the PFBC under steady-state operation at reduced load.

Achieving this objective involved an iterative procedure. Based upon reasonable estimates of the characteristics associated with the PFBC and other major components, computer simulations of the selected open-bed PFBC were generated (see PFBC/CAES System Part-Load Operation) for two steady-state, part-load operating points (25-percent load and 50-percent load) plus the steady-state, full-load operating point (100-percent load). The resulting conditions surrounding the PFBC were then used as input to an analysis which had as its objective the more precise definition of the expected operating conditions of the PFBC in steady-state, part-load operation. The revised PFBC combustor performance data which were generated in the analysis then served as a basis for the final PFBC/CAES part-load simulations.

This chapter summarizes the results of the effort described above. The initial PFBC combustor characteristics are presented, the ensuing analysis detailed, and the revised performance data presented. Lastly, a summary of the findings of the PFBC part-load operation analysis is provided.

PFBC Part-Load Guidelines

The level of performance that a PFBC achieves depends greatly on the operating conditions selected. To initiate the PFBC part-load evaluation, the operating conditions selected correspond to a PFBC having the design point (100-percent load) combustor characteristics displayed in Table 2-1. This table evolved from Table 4-3 of Reference 2-1. The schematic of the power plant system configuration (Fig. 2-1) remains unchanged from that of Fig. 4-2 of Ref. 2-1.

The part-load performance of the PFBC/CAES power plant is based upon a power plant designed for the Table 2-1 full-load operation characteristics. The simulation of this power plant in the 50-percent load and 25-percent load condition is summarized in Tables 2-2 and 2-3, respectively. At these part-load operating conditions, the temperature of the bed was held constant at 1562 F (850 C) and the gas flow and fuel rate allowed to vary to meet the constant bed temperature and output power constraints. A detailed discussion of the PFBC/CAES part-load operation will be deferred to the next chapter dealing exclusively with the subject.

Table 2-1

COMBUSTOR CONDITIONS AT 100-PERCENT LOAD

	<u>Combustor Inlet (1)</u>	<u>Combustor Exit (2)</u>	<u>Turbine Inlet (3)</u>
Mass flow, lb/sec (kg/s)	709.5(321.9)	731.2(331.8)	731.2(331.8)
Temperature, F (C)	251.4(121.9)	1562(850)	1562(850)
Pressure, atm (bar)	15.0(15.19)	13.69(13.87)	13.55(13.73)
Enthalpy, Btu/lb (kJ/kg)	170.3(396.0)	510.8(1187.8)	510.8(1187.8)

Coal feed rate 23.74 lb/sec (10.77 kg/s) as fired

- (1) Station 17 Fig. 2-1
- (2) Station 18 Fig. 2-1
- (3) Station 19 Fig. 2-1

COAL-FIRED PFBC/CAES SYSTEM

FIG. 2-1

Table 2-2

COMBUSTOR CONDITIONS AT 50-PERCENT LOAD

	<u>Combustor Inlet⁽¹⁾</u>	<u>Combustor Exit⁽²⁾</u>	<u>Turbine Inlet⁽³⁾</u>
Mass flow, lb/sec (kg/s)	430.7(195.4)	443.1(201.0)	443.1(201.0)
Temperature, F (C)	389.8(198.8)	1562.0(850)	1562.0(850)
Pressure, atm (bar)	9.25(9.37)	8.32(8.43)	8.24(8.35)
Enthalpy, Btu/lb (kJ/kg)	204.0(474.4)	510.8(1187.8)	510.8(1187.8)

Coal feed rate 13.41 lb/sec (6.08 kg/s) as fired

- (1) Station 17 Fig. 2-1
- (2) Station 18 Fig. 2-1
- (3) Station 19 Fig. 2-1

Table 2-3

COMBUSTOR CONDITIONS AT 25-PERCENT LOAD

	<u>Combustor Inlet</u> ⁽¹⁾	<u>Combustor Exit</u> ⁽²⁾	<u>Turbine Inlet</u> ⁽³⁾
Mass flow, lb/sec (kg/s)	252.6(114.6)	259.6(117.8)	259.6(117.8)
Temperature, F (C)	486.8(252.7)	1562(850)	1562(850)
Pressure, atm (bar)	5.52(5.59)	4.93(4.99)	4.88(4.94)
Enthalpy, Btu/lb (kJ/kg)	227.8(529.7)	510.8(1187.8)	510.8(1187.8)

Coal feed rate 7.47 lb/sec (3.39 kg/s) as fired

(1) Station 17 Fig. 2-1

(2) Station 18 Fig. 2-1

(3) Station 19 Fig. 2-1

Other guidelines included:

- 1) Illinois No. 6 coal with the specification indicated in Table 2-4,
- 2) BCR No. 1337 dolomite with the specifications indicated in Table 2-5,
- 3) sufficient dolomite to result in retention of 85 percent of the sulfur inventory as calcium sulfate, and
- 4) a power plant operating regime as indicated in Table 2-6. Additional operating and design conditions based on the Ref. 2-1 preconceptual design are summarized in Table 2-7.

Discussion of Performance

Based upon the guidelines defined in Tables 2-1 through 2-7, the anticipated effect of part-load operation on certain key performance parameters was examined. These parameters included:

- 1) combustion efficiency,
- 2) freeboard and cyclone combustion,
- 3) sulfur retention,
- 4) fluidization,
- 5) elutriation, and
- 6) solids handling.

The commentary related to the analysis of these parameters provides the basis for the following text.

Combustion Efficiency

The main factors affecting the combustion efficiency in pressurized fluidized bed combustion are: bed temperature (T), excess air (X), superficial gas residence time (t), coal particle size (d), and the bed plan area (arbitrarily taken at the top) per coal feed nozzle (A). Data obtained at the National Coal Board (NCB) Leatherhead facility in rigs operated under conditions relevant to the Ref. 2-1 PFBC design are given in Fig. 2-2 with the operating conditions being summarized in Table 2-8. This figure indicates that the combustion efficiency at high excess air values is sensitive both to bed plan area per coal feed nozzle (A) and to superficial gas residence time (t) where,

$$t, \text{sec} = \frac{\text{bed volume, ft}^3 \text{ (m}^3\text{)}}{\text{gas volume flow, ft}^3/\text{sec (m}^3/\text{s)}} \quad (2-1)$$

Based on experimental work at Leatherhead, the combustion efficiency at atmospheric pressure is found to be lower than at 6 atm (bar) for given values

Table 2-4

COAL ANALYSIS

Moisture Content:	13% w/w, as received
	5% w/w, as fired

Proximate Analysis:

Volatile matter	37.30%, w/w, dry basis
Ash	10.40%, w/w, dry basis
Carbon dioxide	0.18%, w/w, dry basis
Fixed carbon	<u>52.12%</u> , w/w, dry basis
Total	100.00%

Ultimate Analysis:

Ash	10.40%, w/w, dry basis
Carbon	71.35%, w/w, dry basis
Hydrogen	4.60%, w/w, dry basis
Oxygen	8.90%, w/w, dry basis
Nitrogen	1.40%, w/w, dry basis
Sulfur	3.30%, w/w, dry basis
Chlorine	<u>0.05%</u> , w/w, dry basis
Total	100.00%

Notes: 1) The higher heating value (dry basis) of the coal is 12,600 Btu/lb (29,310 kJ/kg).

2) The coal is crushed to a minimum particle size of 1/8 in (3mm) for feeding to the bed.

Table 2-5

DOLOMITE ANALYSIS

Moisture Content:	5.0% w/w, as received
	0.2% w/w, as fired

Analysis:

CaO	29.8%, w/w, dry basis
MgO	21.4%, w/w, dry basis
CO ₂	46.9%, w/w, dry basis
Other	<u>1.9%</u> , w/w, dry basis
Total	100.0%

Table 2-6

OPERATING REGIME

<u>Parameter</u>	<u>Design</u>
Generation Time	8.76 h/weekday 43.8 h/week 2190 h/year
Shutdown Time (maximum)	15.24 h/weeknight 63.24 h/weekend
Annual load factor	25%

Table 2-7

COMBUSTOR OPERATING AND DESIGN CONDITIONS

Fluidizing velocity (at freeboard section)	2.95 ft/sec (0.9 m/s)
Bed temperature	1562 F (850 C)
Pressure at inlet to plenum chamber	
at 100% load	15.0 atm (bar)
at 50% load	9.3 atm (bar)
at 25% load	5.54 atm (bar)
Bed height	10.0 ft (3.05 m)
Freeboard height	10.0 ft (3.05 m)
Bed width (at bed surface)	9.5 ft (2.91 m)
Bed width (at distributor)	4.8 ft (1.45 m)
Bed area (at bed surface)	840.7 ft ² (78.1 m ²)
Bed volume	6304 ft ³ (178.5 m ³)
Number of coal feed nozzles	24
Coal input (at design)	1.020 x 10 ⁹ Btu/hr (299.7 MW(th))
Bed area per feed nozzle	35.0 ft ² (3.25 m ²)
Bed material	
particle density	162.3 lb/ft ³ (2600 kg/m ³)
particle sphericity	0.8
Dynamic gas viscosity	29.96 x 10 ⁻⁶ lb/ft-sec (44.58 x 10 ⁻⁶ kg/m-s)
Fluidized bed density	41.9 lb/ft ³ (671 kg/m ³)
Bed mass	132.1 tons (119.8 t)
Bed heat capacity	47.45 x 10 ³ Btu/lb (110.37 MJ/kg)

VARIATION OF COMBUSTION EFFICIENCY IN PFBC RIGS

Table 2-8

OPERATING CONDITIONS FOR CURL PFBC

Curve	Max. Feed Size, in. (mm)	Feed < 63 μ m, percent	A, ft ² (m ²)	H, ft (m)	X, percent	Bed Temperature, F (C)	Pressure, atm (bar)
A	1/8 (3.2)	2	0.75 (0.07)	2.95 (0.9)	100	1562 - 1652 (850 - 900)	6
B	1/8 (3.2)	1	2.91 (0.27)	7.87 (2.4)	100	1598 - 1652 (870 - 900)	6
C	1/8 (3.2)	18	5.92 (0.55)	4.92 (1.5)	250	1508 (820)	6
D	1/8 (3.2)	18	8.93 (0.83)	8.86 (2.7)	100	1580 (860)	6

A = Bed area/coal feed nozzle

H = Expanded bed depth

X = Excess air

of excess air, gas residence time, and area per coal feed nozzle. Data are not available for higher pressures, but it is thought unlikely that further increases in pressure above 6 atm (bar) will have a major effect.

In the proposed combustor design, turndown is achieved by reducing the operating pressure of the combustor while maintaining the bed temperature and fluidizing velocity. Because the combustion air preheat temperature increases from 252 F (122 C) at 100-percent load to 487 F (253 C) at 25-percent load, the excess air level increases from 230 percent to 270 percent over the same range of duties. The mean gas residence time, however, is constant during turndown. This is because the fluidizing velocity remains approximately constant at 2.95 ft/sec (0.9 m/s) measured at the bed surface. Taking into account the flaring of the bed cross-section from 4.75 ft (1.45 m) at the distributor plate to 9.55 ft (2.91 m) at the design bed height of 10.0 ft (3.05 m), the mean gas residence time is estimated to be 2.5 seconds.

From Fig. 2-2, it can be seen that a combustion efficiency of at least 99 percent may be expected for a coal feed nozzle spacing of one nozzle per 10 ft² (one nozzle per m²) at all loads down to 25 percent for the operating conditions of the present design (see Table 2-7). There are no experimental data available to indicate the maximum permissible nozzle spacing for lower combustion efficiencies, but extrapolation of the data suggests the relationship given in Table 2-9. The higher values of area per coal feed nozzle given in the table represent a major extrapolation of existing experimental data and should accordingly be treated with caution. In the present design, 24 coal feed nozzles are used for a bed area of 840.7 ft² (78.1 m²), giving an area per nozzle of 35.0 ft² (3.25 m²). It is therefore expected that, in the range 25-percent to 100-percent load, the combustion efficiency should be about 98.5 percent (an efficiency of 99 percent was taken for operation at design in the Ref. 2-1 design).

Higher combustion efficiencies could be obtained by increasing the number of coal feed points. Other approaches have been suggested but require further development work:

- 1) the installation of baffles, however, this is probably practical only with a long, narrow bed plan;
- 2) the use of bed circulation techniques (other than the tapered bed), such as gulf-streaming induced by introducing lateral gradients in fluidizing velocity;
- 3) the use of overhead feeding of coarse coal has proved successful in atmospheric pressure developments, but might make sulfur retention more difficult; unless washed coal is used, the design will have to provide for the removal of stone from the bed, however, this appears to be the most promising option.

Table 2-9

ESTIMATED PFBC COMBUSTION EFFICIENCIES

Minimum Efficiency Required	Maximum Area per Coal Feed Nozzle, ft^2 (m^2)
99.0%	10.8 - 21.5 (1 to 2)
98.5%	21.5 - 43.1 (2 to 4)
98.0%	43.1 - 86.1 (4 to 8)

Freeboard and Cyclone Combustion

The effect of combustion in the freeboard or in the cyclone is to increase the temperature of the gas. For an adiabatic combustor with an excess air level of about 250 percent, the combustion of 1 percent of thermal input of coal in the freeboard or cyclones would result in a temperature rise of 13 F (7 C).

The experimental evidence from the operation of the PFBC rig at Leatherhead is that no combustion occurs in the freeboard when the combustion efficiency is greater than about 95 percent. However, the fall in gas temperature in the freeboard of the experimental rig resulting from heat losses would tend to mask minor amounts (on the order of 1 percent) of freeboard combustion.

In general, in the design of a PFBC, combustion in the cyclones has also to be considered. Because high mass transfer rates are favored by high gas velocities, combustion in the cyclones will usually occur to a greater extent than in the freeboard. Experience at Leatherhead has shown that this combustion can occur, but that the amount is generally less than 1 percent of the thermal input of coal.

In view of the high combustion efficiency likely to be obtained in the present combustor design, it is considered that combustion in the freeboard or cyclones is unlikely to be a problem. Such combustion as will occur will probably amount to only a few tenths of 1 percent of the coal thermal input, and will cause an almost imperceptible rise in gas temperature.

Sulfur Retention Models

In Ref. 2-1, the basis for predicting the dolomite requirements was a model developed by Combustion Systems Ltd. (CSL). Because of the absence of directly relevant experimental data, and because of known discrepancies in the available sulfur retention models, it was decided to consider a range of predictions in the present study. The CSL model is still regarded as the most appropriate for the operating conditions envisaged with other models representing an upper bound to dolomite requirements.

The acceptor requirements necessary for the proposed PFBC design to meet the specified 85-percent sulfur retention efficiency have been estimated for steady-state operation at 25-percent, 50-percent and 100-percent load using three calculation methods:

- 1) the Combustion Systems Ltd. (CSL) calculation procedure using empirical relationships based mainly on NCB data;
- 2) the Exxon second-order reaction model and a modified version of it;

- 3) the Westinghouse model which makes use of thermogravimetric analysis (TGA) data; it was necessary to employ other models and calculation procedures to estimate some of the parameters that were used in applying the Westinghouse model.

The calculations all relate to the coal (Illinois No. 6) and dolomite (BCR 1337) specified in Tables 2-4 and 2-5. Dolomite 1337 has been tested extensively at the Leatherhead facility and by Exxon, so that the appropriate data are available for use in the CSL and Exxon correlations. There are few TGA data for the dolomite at relevant operating conditions, but such data do exist for an alternative dolomite which has also been studied by the NCB, and extrapolations have therefore been made.

The operating data given in Tables 2-1, 2-2 and 2-3 have been used to estimate other factors relevant to the calculation of the acceptor requirements (in many cases using proprietary procedures). The results are given in Table 2-10. The mean bed particle sizes in Table 2-10 are the higher of the two sets of values calculated in the next section on Fluidization, and are taken as giving slightly more pessimistic results.

A brief description of the CSL, Exxon, and Westinghouse models is given in the following paragraphs.

The CSL Model

The details of the CSL model are proprietary. It is an empirical model derived mainly from NCB data, which relates the Ca/S mol ratio needed for sulfur retention to bed temperature, pressure, superficial gas residence time, excess air, sorbent maximum particle size, and an index of sorbent reactivity. For the present calculations, the index of sorbent reactivity used was that derived from data acquired in the NCB test programs at Leatherhead with Dolomite 1337.

The Exxon Model

The Exxon model (Ref. 2-2) is derived from a postulated second-order reaction rate equation. Applied to a tapered bed combustor, it has the following form (see nomenclature in Table 2-11):

$$t = \frac{1}{k_2} \frac{Q}{S (C-1)} \ln \frac{(C - E)}{C(1-E)} \quad (2-2)$$

For the present calculations, the second-order constant, k_2 , was taken to have the value of $335.5 \times 10^3 \text{ ft}^3/\text{mole-sec}$ ($9500 \text{ m}^3/\text{mol-s}$) established by Exxon for Dolomite 1337. As explained later, a modified form of equation (2-2) was also used.

Table 2-10

OPERATING VARIABLES
per unit

		Load, percent		
		<u>100%</u>	<u>50%</u>	<u>25%</u>
LP turbine inlet pressure	atm (bar)	13.89	8.55	5.0
Freeboard pressure	atm (bar)	14.92	9.18	5.38
Bed inlet pressure	atm (bar)	15.19	9.42	5.61
Gas volume flow (actual)	ft ³ /sec (m ³ /s)	2543 (72)	2507 (71)	2507 (71)
Superficial gas residence time	sec	2.5	2.5	2.5
Excess air	%	229	254	273
Mean bed particle size	μm	1170	880	730
Bubble volume fraction in bed	-	0.40	0.47	0.54
Fraction of inerts in bed	-	0.50	0.10	0.15

Table 2-11

NOMENCLATURE FOR SULFUR RETENTION MODELS

<u>Symbols</u>	<u>Description</u>	<u>Units</u>
c	SO ₂ concentration in TGA run	10 ³ mole/ft ³ -atm (k mol/m ³ -bar)
C	Ca/S mol ratio	-
E	Fractional sulfur retention efficiency	-
f _I	Fraction of inerts (ash) in the bed	-
f _H	Fraction of bed volume occupied by heat-exchange tubing; for the present purpose f _H = 0	-
k ₂	Exxon second-order reaction rate constant	ft ³ /10 ³ mole-sec (m ³ /kmol-s)
k ₃	Modified second-order reaction rate constant, value 29173 (8892)	ft ³ /10 ³ mole-sec ² (m ³ /kmol-s ²)
K	First-order reaction rate constant measured in TGA	s ⁻¹
K ¹	Modified rate constant in FBC bed	s ⁻¹
P	Ca concentration in sorbent	10 ³ mole/ft ³ (k mol/m ³)
Q	Actual gas volume	ft ³ /sec (m ³ /sec)
R	Coal fuel rate	lb/hr (kg/hr)
S	Sulfur input	10 ³ mole/sec (kmol/s)
t	Superficial gas residence time in bed	s
α	Fraction of calcium sulfated	-
δ	Fraction bubble volume in fluidized bed	-
ε	Fraction voidage in emulsion phase	-
θ	Time elapsed in TGA experiment	s
dα/dθ	Time change in fraction of calcium sulfate	s ⁻¹

The Westinghouse Model

The Westinghouse model is a semi-empirical model which is based on assumptions regarding the distribution through the bed of rates of liberation and absorption of sulfur dioxide. It makes use of reaction rate data obtained by thermogravimetric analysis at appropriate conditions of temperature, pressure and mean particle size. The model is described in Ref. 2-3.

The following sequence of equations is used in applying the model (see nomenclature in Table 2-11):

$$K^1 = -(1/t) \ln (1 - E) \quad s^{-1} \quad (2-3)$$

$$K = K^1 / \{ (1-\delta) \epsilon (1 - f_1) (1 - f_H) \} \quad s^{-1} \quad (2-4)$$

$$d\alpha/d\theta = K(c/p) \quad s^{-1} \quad (2-5)$$

$$C = E/\alpha \quad (2-6)$$

Where c is taken to be 1.535×10^{-3} mole/ft³-atm (5.42×10^{-5} k mol/m³-bar)
and p is taken to be 441.7 mole/ft³ (15.6×10^{-2} k mol/m³)

The only TGA data for Dolomite 1337 obtained under relevant conditions (Ref. 2-4) was from a single test, the curve for which is shown in Fig. 2-3 (details in Table 2-12).

However, data for another, slightly more reactive dolomite, (Plum Run and Ohio dolomite) for which there are also extensive rig data from programs at Leatherhead, are presented in Ref. 2-3 and are shown as curves of reaction rate ($d\alpha/d\theta$) in Figs. 2-4 (1) to 2-4 (10). The key to the conditions in the TGA runs for these curves is given in Table 2-12. Values of Ca/S ratios for the relevant values of $d\alpha/d\theta$ were calculated for interpolations of the curves in the figures. From the curves for half-calcines, fine, medium and coarse Plum Run Dolomite at 16 atm (bar), it was deduced that the excess dolomite requirement was proportional to practical size; a similar relationship was found by the Westinghouse workers. Using this, it was possible to correct for the effect of practical size, and the results indicated that the Ca/S ratio needed at 10 atm (bar) with half-calcined Dolomite 1337 is about 13 percent higher than with the half-calcined Plum Run Dolomite. It has been assumed that this applies to all operating conditions in calculating the Ca/S ratio for BCR 1337 Dolomite from Plum Run Dolomite TGA data.

Sulfur Retention Model Predictions

The models described in the above paragraphs have been used to predict the Ca/S mol ratio for the proposed PFBC system at 100-percent, 50-percent and 25-

TGA CURVE FOR DOLOMITE 1337

420 - 500 μm ;
843 C,
10 BAR
HALF - CALCINED

Table 2-12

KEY CONDITIONS FOR TGA CURVES

<u>Figure Number</u>	<u>Press., atm (bar)</u>	<u>O₂ in gas % v/v</u>	<u>Equivalent Excess air, %</u>	<u>Particle grade</u>	<u>Dolomite</u>	<u>Calcina- tion</u>
2-3	10	16	300	Fine	1337	Half
2-4(1)	1	4	20	Medium	Plum Run	Half*
2-4(2)	1	4	20	Medium	"	Full
2-4(3)	10	4	20	Medium	"	Half
2-4(4)	10	10.5	100	Medium	"	Full
2-4(5)	16	4	20	Medium	"	Half
2-4(6)	16	16	300	Medium	"	Full
2-4(7)	16	10.5	100	Fine	"	Half
2-4(8)	16	10.5	100	Medium	"	Half
2-4(9)	16	10.5	100	Coarse	"	Half
2-4(10)	20	4	20	Medium	"	Half

Temperature 1544 F (840 C)

SO₂ content of gas 0.5%

Fine particle grade, 420-500 μ m (mean 458 μ m)

Medium particle grade, 1000-1190 μ m (mean 1091 μ m)

Coarse particle grade, 2000-2380 μ m (mean 2182 μ m)

* Gas contained 47% CO₂ to ensure half-calcination maintained

TGA CURVES FOR PLUM RUN DOLOMITE

TGA CURVES FOR PLUM RUN DOLOMITE

percent load. The results are summarized in Table 2-13. The CSL model and the Exxon model both predict an increase in Ca/S ratio with a decrease in load, but the Westinghouse model forecasts a reduction in dolomite requirements at low load. The main features of the predictions are described in the following:

The CSL Model

The CSL model is thought to be the most reliable of the three models for the 25-percent load (5 atm (bar)) condition. The relevant combination of temperature, pressure, and excess air have been studied only at Leatherhead, and the data acquired used for validating only the CSL model. The CSL model shows only a small variation with pressure, but since it was derived from data obtained at 1-6 atm (bar), its application to 50-percent (9 atm (bar)) and 100-percent (15 atm (bar)) load represents an extrapolation.

The Exxon Model

The Exxon model predicts a doubling in Ca/S mol ratio with reduction to 25-percent load. This results from the model predicting a variation in sulfur retention with sulfur input per unit of combustion gas volume, although the available experimental evidence indicates little or no such variation. Data obtained at Leatherhead indicate that the value of k_2 in Eq. (2-2) varies with Q , and S according to,

$$k_2 = (k_3 Q/S)^{0.5} \quad (2-7)$$

with appropriate units, thus, the Exxon model (eq. 2-2) can be modified by incorporating eq. 2-7 to yield:

$$t = \left(\frac{Q}{k_3 S} \right)^{0.5} \frac{1}{C-1} \ln \frac{C-E}{C(1-E)} \quad (2-8)$$

The estimates obtained using eq. 2-8 are identified in Table 2-13 as "Exxon model modified". They show a variation with load only a little greater than the CSL estimates obtained. It should be cautioned, however, the values estimated for all loads in either Exxon model represent an extrapolation because the Exxon data used to validate both the unmodified and modified models were obtained at excess air levels only up to about 60 percent.

The Westinghouse Model

There were sufficient TGA data to apply the Westinghouse model to both fully-calcined and half-calcined Plum Run dolomite and hence to extrapolate to Dolomite 1337. For dolomites which have not been precalcined, experience at Leatherhead indicates that:

Table 2-13

PREDICTIONS OF Ca/S MOL RATIO FOR 85-PERCENT SULFUR RETENTION

<u>Model</u>	<u>Load</u>		
	<u>100%</u>	<u>50%</u>	<u>25%</u>
CSL	1.5	1.5	1.7
Exxon			
(unmodified)	1.2	1.6	2.3
(modified)	1.3	1.5	1.8
Westinghouse			
(fully precalcined sorbent)	1.8	1.4	1.3
(half precalcined sorbent)	2.5	2.0	1.7

- 1) the performance is little affected by whether or not operating conditions permit full calcination, and
- 2) the performance approaches that of half-calcined dolomite.

The predictions of the model for half-calcined dolomite are likely to be more realistic for a PFBC than those for the more reactive fully-calcined dolomite. The TGA data cover the entire range of pressure and excess air levels relevant to the load range considered, but need to be confirmed by repeating the TGA experiments with Dolomite 1337. Furthermore, the predictions for 50-percent and 100-percent load have yet to be supported by PFBC operation at the corresponding conditions.

Sulfur Retention Under Varying Loads

There are few data available that enable reliable predictions to be made of the effect of increasing load on sulfur emissions. When operating at low load under steady-state conditions, the sulfur retaining capability of the bed, which is dependent on the dolomite inventory and the degree of sulfation, will achieve an equilibrium value resulting in a constant (say 85 percent) retention of the prevailing sulfur input. If the load is increased from 25 percent to 100 percent at the rate of 5 percent per minute, the rate of sulfur input will be increased over threefold in a period of 15 minutes, but the activity of the bed will be little affected.

For rapid load changes from 25-percent to 100-percent load, it is estimated that a period of a few hours is necessary before the bed returns to the level of activity corresponding to steady-operation at full load. During this period, the sulfur retention will fall rapidly to about 60 percent and will then increase slowly.

The effects of load-changing can be ameliorated by operating at low loads with a Ca/S ratio sufficiently high to give a bed the desired activity for operation at high loads. It is suggested that this could be achieved with a Ca/S ratio of about 2.8 at 25-percent load, when the consequent sulfur retention would be about 95 percent. This estimate is based on the extrapolation of present experimental data; direct experimental work under conditions relevant to the present design is required and may enable economies in Ca/S ratio to be made.

Sulfur Retention Prediction Summary

Based on the above analysis, it is recommended that the acceptor required to give an 85-percent sulfur retention in the present design are as follows:

(1) 100-percent load

A "standard" value of the Ca/S ratio of 1.5 (based on the CSL model and assumed in the Ref. 2-1 preconceptual design), with a "pessimistic" value of 2.5 based on the Westinghouse model predictions.

(2) 50-percent load

A "standard" Ca/S ratio of 1.5 (CSL model) and a "pessimistic" value of 2.0 (Westinghouse model).

(3) 25-percent load

A Ca/S ratio of 1.7 (CSL, modified Exxon and Westinghouse models).

If, however, rapid load changing is required, it is recommended that higher Ca/S ratios be planned for at low load, eg., 2.8 at 25-percent load. It should be noted that, because of the reduced rate of sulfur input, a Ca/S ratio of 2.8 at 25-percent load represents a dolomite feed rate of 47 percent of that at 100-percent load for a Ca/S ratio of 1.5, and 28 percent of that at 100-percent load for a Ca/S ratio of 2.5.

Fluidization

Fluidizing conditions can be assessed in terms of the relationships between two dimensionless numbers (Ref. 2-5) as defined below:

$$\text{Velocity number, } V_n = \mu \{ \rho^2 / [g \mu (\sigma - \rho)] \}^{1/3} \quad (2-9)$$

$$\text{Fluidization number, } F_n = \phi d \{ g \rho (\sigma - \rho) / \mu^2 \}^{1/3} \quad (2-10)$$

where μ = superficial velocity

ρ = gas density

μ = gas dynamic viscosity

σ = particle density

ϕ = particle sphericity*, ie

$$\frac{(\text{surface area of equal volume sphere})}{(\text{surface area of particle})}$$

* In the Ref. 2-1 work, spherical particles were assumed, i.e., a value of 1 was assumed for the particle sphericity.

d = surface mean particle diameter (or, for free-fall, the particle diameter)

g = gravitational acceleration.

Self-consistent units must be used.

Relationships between V_n and F_n are shown graphically in Fig. 2-5 by curves for free-fall, minimum fluidization, and good fluidization. The curves can be employed to estimate the steady-state value of bed mean particle size, the size range of particles that will be elutriated from the bed, and the limiting operating conditions that avoid segregation and defluidization of coarse particles.

Bed Particle Size Distribution Estimating Procedure

Experimental data have been obtained at Leatherhead for operating conditions similar to those envisaged in the proposed PFBC at 25-percent load. These data have been used as the basis for estimating the bed size distribution at this condition, as shown in Fig. 2-6 (differential grading on log-linear paper).

The procedure adopted to estimate the change in bed particle size distribution when changing from 25-percent load to 50-percent and 100-percent load conditions is summarized below:

- (1) Calculate the critical particle size, d_t , for entrainment by calculating the value of the velocity number at 25-percent, 50-percent and 100-percent load from the fluidizing velocity, the pressure, and the properties of the gas. Use Fig. 2-5 to estimate the fluidization number for free-fall, and hence the particle diameter having a free-fall velocity equal to the gas velocity in the freeboard.
- (2) Calculate $r = (d_t \text{ at present load}) / (d_t \text{ at 25-percent load})$, where d_t is the particle size having a free-fall velocity equal to the gas velocity in the freeboard.
- (3) In view of the absence of direct experimental data on bed particle size distributions for the conditions of interest, the size distributions for the 50-percent and 100-percent load cases have been estimated by transposing the differential curve for 25-percent load (Fig. 2-6) towards the right by multiplying particle size by r . This transposition, which is made only for the left-hand (fine) side of the curve, is illustrated in Fig. 2-7. This assumption is somewhat arbitrary, applying strictly to the critical size for elutriation,

RELATIONSHIP BETWEEN VELOCITY NUMBER AND FLUIDIZATION NUMBER

FIG. 2-5

PFBC BED MATERIAL DIFFERENTIAL SIZE GRADING AT 25% LOAD

FIG. 2-6

PFBC BED MATERIAL DIFFERENTIAL SIZE GRADINGS

FINES TRANSPOSITION

FIG. 2-7

and will lead to an overestimate of elutriation rates. Experimental work is required to determine accurately the elutriation rates for the present combustor under a range of operating pressures.

- (4) The transposition represents the reduction in the removal of bed material by the offtake to maintain the same bed level and therefore the additional loss of material by elutriation. By calculating the change in the area beneath the transposed curves, the change in losses of material by offtake and elutriation can be estimated. The areas under the curves in the 50-percent and 100-percent load cases are respectively 95 percent and 88.5 percent of the 25-percent load case. Noting that the size distribution of the material removed by the offtake is the same as that of the bed, at 50-percent load, the proportion of the feed removed by the offtake is 95 percent of the proportion at 25-percent load, and at 100-percent load the proportional offtake is reduced to 88.5 percent of the value of 25-percent load. The increase in elutriation at 50-percent load is therefore 5 percent of the offtake rate at 25-percent load. At 100-percent load, the increase in elutriation is 11.5 percent of the offtake rate at 25-percent load.
- (5) Calculate a new differential size distribution by normalizing the transposed curves given in Fig. 2-7 (i.e., scaling the contents of each size fraction so that the sum of their contents is unity). The new differential size distributions are illustrated in Fig. 2-8.
- (6) Cumulative size distributions can be calculated from the differential size distributions given in Fig. 2-8. Examples are given in Figs. 2-9 and 2-10 referring respectively to log-probability paper and Rosin-Rammler paper.

Distribution Estimates

The assumptions and the calculations carried out using the above procedure are summarized in Table 2-14.

It may be noted that the bed material size grading assumed for the 25-percent load condition ignores the tail of fine material often found in samples of bed material. This tail, which corresponds to particles finer than about 250 μm in the 25-percent load case, accounts for less than 3 percent of the bed material but has a disproportionate effect on the surface mean diameter calculated from the size distribution. It is possible that these fines do not exist in the bed but are generated by decrepitation when the bed material is extracted from the PFBC. Fluidization behavior and bed-side heat transfer coefficients have been found to correlate better with a size distribution that ignores the tail.

PFBC BED MATERIAL DIFFERENTIAL SIZE GRADINGS

NORMALIZED TRANSPOSED CURVES

FIG. 2-8

PFBC BED MATERIAL GRADINGS
(LOG PROBABILITY)

PFBC BED MATERIAL SIZE GRADINGS
(ROSIN-RAMMLER)

FIG. 2-10

Table 2-14

BED OPERATING AND FLUIDIZATION CONDITIONS

		Load, percent		
		100	50	25
<u>Bed Properties</u>				
Gas mass flow	lb/sec (kg/s)	731.3 (331.7)	443.1 (201.0)	259.7 (117.8)
Freeboard pressure	atm (bar)	14.92	9.18	5.38
Gas density	lb/ft ³ (kg/m ³)	0.287 (4.59)	0.176 (2.82)	0.103 (1.65)
<u>Freeboard (free-fall calculation)</u>				
Calculated value of Vn	-	2.45	1.75	1.22
Interpolated value of Fn for free-fall	0	8.0	5.8	4.5
Particle dia having free-fall velocity equal to freeboard gas velocity	μm	260	220	205
<u>Bed (good fluidization calculation)</u>				
Vn calculated for mean superficial gas velocity	-	3.24	2.30	1.60
Interpolated Fn for good fluidization	-	36	23	16
SMD of particles for good fluidization (1)	μm	1170	880	730
SMD estimated for steady-state (2)	μm	850	790	750
Fn calculated for steady-state		26.2	20.6	16.4
<u>Air distributor (estimation of likelihood of segregation)</u>				
Calculated value of Vn	-	4.80	3.40	2.35
Interpolated value of Fn for minimum fluidization	-	335	178	93
Particle dia for minimum fluidization	μm	10900	6800	4250
Maximum particle diameter in bed (3)	μm	3000	3000	3000
Fn calculated for maximum particle diameter	-	92.4	78.6	65.7

Notes:

- (1) Surface mean diameter estimated from good fluidizing curve.
- (2) Surface mean diameter estimated from particle size distribution.
- (3) Assumed to equal maximum feedstock particle size.

The estimated size distributions have been used to derive the mean bed particle size and hence the fluidizing conditions for the proposed PFBC design at 25-percent, 50-percent and 100-percent load. The results are illustrated by the points plotted on the graph of velocity number versus fluidization number given in Fig. 2-11. Also shown in Fig. 2-11 are:

- 1) The changes in the particle size having a free-fall velocity equal to the fluidizing velocity.
- 2) The changes in fluidizing conditions corresponding to the maximum particle size in the feed (3000 μm). Even at the 25-percent load condition, such particles are significantly above the minimum fluidization line, and it can therefore be concluded that bed particle segregation should not be a problem over the range of duties considered.

It is thought that after running at low load for sufficient time to establish steady-state particle size distribution in the bed, an increase in load will result in rapid elutriation of fines and the establishment of a bed with a larger surface mean diameter. On decreasing load, however, the buildup of fines and the establishment of a bed of stable size grading may be a slower process. Nevertheless, consideration of the fluidization conditions plotted in Fig. 2-11 shows that a rapid decrease in load will not have a serious effect on fluidizing conditions.

It can be concluded that satisfactory fluidizing conditions can be maintained in the proposed design over the load range from 25 percent to 100 percent with coal and dolomite of maximum particle size 3000 μm . The use of the calculation method above 6 atm (bar), however, is an extrapolation from existing experience and has yet to be confirmed by direct experimental evidence.

Elutriation

The solids feed rates to the proposed PFBC have been calculated for 100-percent, 50-percent and 25-percent load, using both the standard dolomite feed rate (based on the CSL model) and the pessimistic dolomite feed rate (based on the Westinghouse model) previously estimated. The results are given in Table 2-15. For simplicity, the calcium carbonate component of the dolomite is assumed to calcine completely in all cases, although this will not occur in the 50-percent and 100-percent load cases.

Experimental work has been carried out on the PFBC at Leatherhead under conditions similar to those corresponding to the operation of the proposed PFBC at 25-percent load. Based on the data obtained, it is estimated that, for the specified coal and dolomite (Table 2-4 and 2-5), 85 percent of the ash and 25 percent of the calcined sulfated dolomite will be elutriated. These estimates have been used, together with the data in Table 2-15, to obtain the bed offtake and elutriation rates at 25-percent load, as shown in Table 2-16.

PFBC FLUIDIZING CONDITIONS

FIG. 2-11

Table 2-15

SOLIDS FEED RATES

<u>Material</u>	<u>Load</u>		
	<u>100%</u>	<u>50%</u>	<u>25%</u>
Coal (as fired), lb/sec (kg/s)	23.74 (10.77)	13.40 (6.08)	7.47 (3.39)
Coal (dry basis), lb/sec (kg/s)	22.55 (10.23)	12.74 (5.78)	7.10 (3.22)
Coal ash, lb/sec (kg/s)	2.34 (1.06)	1.32 (0.60)	0.73 (0.33)
Dolomite Ca/S ⁽¹⁾	1.5	1.5	1.7
Ca/S ⁽²⁾	2.5	2.0	
Dolomite, lb/sec (kg/s) ⁽¹⁾	6.55 (2.97)	3.70 (1.68)	2.34 (1.06)
lb/sec (kg/s) ⁽²⁾	10.94 (4.96)	4.94 (2.24)	
Calcined ⁽³⁾			
sulfated, lb/sec (kg/s) ⁽¹⁾	5.05 (2.29)	2.87 (1.30)	1.74 (0.79)
dolomite, lb/sec (kg/s) ⁽²⁾	7.39 (3.35)	3.51 (1.59)	

Notes:

- (1) Standard Ca/S ratio (based on CSL model).
- (2) Pessimistic Ca/S ratio (based on Westinghouse model).
- (3) Assuming complete calcination of the calcium carbonate.

Table 2-16

RATE OF ELUTRIATION AT 25-PERCENT LOAD

<u>Material</u>	<u>Output Rate, lb/sec (kg/s)</u>	<u>Bed Offtake % output⁽³⁾</u>	<u>Elutriation % output⁽³⁾</u>	<u>Bed Offtake, lb/sec (kg/s)</u>	<u>Elutriation, lb/sec (kg/s)</u>
Coal ash	0.73 (0.33) ⁽¹⁾	15 ⁽²⁾	85 ⁽²⁾	0.11 (0.05)	0.62 (0.28)
Calcined sulfated dolomite	1.74 (0.79) ⁽¹⁾	75 ⁽²⁾	25 ⁽²⁾	1.30 (0.59)	0.44 (0.20)
Total solids	2.47 (1.12)	57.1	42.9	1.41 (0.64)	1.06 (0.48)

Notes: (1) From Table 2-15
 (2) Based on experience at Leatherhead facility.
 (3) Offtake plus elutriation.

At 50-percent and 100-percent load, the percentage of solids feed removed by the bed offtake has been estimated by reducing the percentage offtake for the 25-percent load case taking into account the change in the bed particle size distribution. The estimated percentage offtake has then been used to derive the elutriation rate. The results are given in Tables 2-17 and 2-18.

The total elutriation rates calculated by the above procedure are summarized in Table 2-19, together with the estimated solids loading of the combustion gas at the cyclone entry. The latter parameter increases from 4075 ppm at 25-percent load to 5033 ppm (standard case) and 6631 ppm (pessimistic case). The increase arises partly from the increased solids feed rate and partly because of the higher proportion of feed material elutriated.

However, because the gas velocities in the cyclones remain nearly constant over the load range, it is expected that cyclone grade efficiencies will remain nearly constant. Since the dust elutriated at high loads is coarser than at low loads, the increase in dust loading in the cleaned gas will be less than that at the cyclone inlet.

When the load is increased after a period of steady-state operation at low load, there will be an increase in the rate of elutriation resulting from removal of some of the fines inventory in the bed. The magnitude of this additional elutriation rate during the load change has been estimated as follows:

- 1) Assuming a bed volume of 6304 ft^3 (178.5 m^3) and a bed density at 25-percent load of 4.18 lb/ft^3 (67 kg/m^3), the mass of bed is 132.1 tons (119.8 t).
- 2) It was previously estimated that at 100-percent load there is an additional elutriation loss of 11.5 percent of the bed material present at 25-percent load, i.e., of 15.2 tons (13.8 t).
- 3) Assuming a load change rate of 5 percent per minute, a load change from 25 percent to 100 percent will occupy 15 minutes, and the rate of elutriation will average $30424 \text{ lb/800 sec} = 33.8 \text{ lb/sec}$ ($13800 \text{ kg/900 s} = 15.3 \text{ kg/s}$).

This elutriation rate is about 7.2 times the steady-state value for 100-percent load (Table 2-18) to which the instantaneous rate will fall shortly after the new load has been established.

The additional elutriation during load-changing will be of coarser material (i.e., particles having a larger diameter than that corresponding to free fall condition at 25-percent load). These particles should be collected almost completely by the cyclones. Unless additional fines are produced by attrition in the cyclone, there should not therefore be a great increase in dust emission from the plant during this period. However, provision must be made in the

Table 2-17

RATE OF ELUTRIATION AT 50-PERCENT LOAD

<u>Material</u>	<u>Output rate, lb/sec (kg/s)</u>	<u>Bed Offtake, % output⁽⁴⁾</u>	<u>Elutriation, % Output⁽⁴⁾</u>	<u>Bed offtake, lb/sec (kg/s)</u>	<u>Elutriation, lb/sec (kg/s)</u>
Coal ash	1.32 (0.60)				
Calcined sulfated dolomite	2.87 (1.30) ⁽²⁾ 3.51 (1.59) ⁽³⁾				
Total	4.19 (1.90) ⁽²⁾	53.7 ⁽¹⁾	46.3	2.25 (1.02) ⁽²⁾	1.94 (0.88) ⁽²⁾
solids	4.83 (2.19) ⁽³⁾			2.60 (1.18) ⁽³⁾	2.23 (1.01) ⁽³⁾

Notes: (1) Estimated by reducing the value for 25% load by 5% to allow for the additional loss of bed material.

(2) Standard Ca/S ratio (based on CSL model).

(3) Pessimistic Ca/S ratio (based on Westinghouse model).

(4) Offtake plus elutriation.

Table 2-18

RATE OF ELUTRIATION AT 100-PERCENT LOAD

<u>Material</u>	<u>Output rate,</u> <u>lb/sec (kg/s)</u>	<u>Bed offtake,</u> <u>% output⁽⁴⁾</u>	<u>Elutriation,</u> <u>% output⁽⁴⁾</u>	<u>Bed offtake,</u> <u>lb/sec (kg/s)</u>	<u>Elutriation,</u> <u>lb/sec (kg/s)</u>
Coal ash	2.34 (1.06)				
Calcined sulfated dolomite	5.05 (2.29) ⁽²⁾ 7.39 (3.35) ⁽³⁾				
Total solids	7.39 (3.35) ⁽²⁾ 9.72 (4.41) ⁽³⁾	50.0 ⁽¹⁾	50.0	3.70 (1.68) ⁽²⁾ 4.87 (2.21) ⁽³⁾	3.68 (1.67) ⁽²⁾ 4.85 (2.20) ⁽³⁾

Notes: (1) Estimated by reducing the value for 25% load by 11.5% to allow for the additional loss of bed material

(2) Standard Ca/S ratio (based on CSL model)

(3) Pessimistic Ca/S ratio (based on Westinghouse model)

(4) Offtake plus elutriation

Table 2-19

SUMMARY OF ELUTRIATION DATA

	Load Percent		
	<u>100</u>	<u>50</u>	<u>25</u>
Elutriation lb/sec (kg/s) ⁽¹⁾	3.68 (1.67)	1.94 (0.88)	1.06 (0.48)
lb/sec (kg/s) ⁽²⁾	4.85 (2.20)	2.23 (1.01)	
Gas flow lb/sec (kg/s)	731.5 (331.8)	443.1 (201.0)	259.7 (117.8)
Solids concentration at cycone entry	5033 ⁽¹⁾	4378 ⁽¹⁾	4075
(ppm mass fraction)	6631 ⁽²⁾	5025 ⁽²⁾	

Notes:

(1) Standard Ca/S ratio (based on CSL model).

(2) Pessimistic Ca/S ratio (based on Westinghouse model).

design of the cyclone dust handling, depressurizing and disposal systems for the high rates of dust collection which will occur as the load increases.

Solids Handling

Three aspects of the operation of the solids handling system under part-load operation require consideration.

Coal and Dolomite Preparation

Because the Petrocarb system specified for coal and dolomite injection to the combustor includes a surge hopper, the milling and drying system need not follow the combustor fuel and dolomite demand closely. If, however, prolonged operation at 25-percent load were required, the preparation system would have to turndown to meet the combustor requirements. The turndown required is estimated to be approximately 30 percent of the design coal rate, depending on the Ca/S ratio used. This level of turndown can readily be achieved by conventional milling and drying systems.

Coal and Dolomite Injection System

The Petrocarb lock hopper and solids feeder acts as a splitter for solids flow and produces a number of equal flow streams. The feeds are conveyed pneumatically with constant air velocity in the conveying lines throughout the range of operating conditions. The system has a turndown capability of 100 percent of the design coal rate to 30 percent of the design coal rate while maintaining flow on all feed lines. Further turndown would be provided by isolating a small number of individual feed lines and operating the remaining lines at low load.

As discussed above, steady operation at 25-percent load requires turndown of the solids feed rate to about 30 percent of the design coal rate. At the full load operating conditions, however, an additional margin is required on the fuel delivery capability. If, at 100-percent load, the coal/dolomite system operates at 90 percent of its design coal rate capability, then at 25-percent load the fuel system would be required to turndown to somewhat less than 30 percent of its design coal rate capability. It is possible that the Petrocarb system could be modified to achieve this level of turndown without the need to isolate feed lines. However, isolation of a small number of feed lines, if necessary, should not cause operational problems.

It is envisaged that, during normal start-up, the Petrocarb system will only operate in the range 30 percent of its design coal rate to 100 percent of its design coal rate so that isolation of feed lines is unnecessary. This will help to ensure good coal distribution during the period when the bed temperature is below the design value.

Ash Handling System

Ash is collected from the fluidized bed and cyclone system by a pressurized pneumatic conveying system, carried into a lock hopper system and subsequently discharged to an atmospheric pressure storage hopper for disposal. The ash is conveyed in water jacketed lines which also act as ash coolers. The conveying velocity remains constant throughout the operating range. No operational problems are envisaged for part-load operation of the ash handling system.

In summary, no constraints on the steady-state part-load operation of the combustor are identified as coming from the solids handling systems. The fuel preparation, fuel injection and ash disposal systems are all capable of achieving the turndown required to allow operation at 50-percent load and 25-percent load. On turn-up, however, the ash handling system must be capable of handling the additional elutriation which may occur until steady-state operation at 100-percent load is achieved.

Revised PFBC Performance Data

The data in Tables 2-1, 2-2, and 2-3 were calculated from the performance estimates in Ref. 2-1, and were used as the basis for the preceding analysis part-load performance of the PFBC. As a result of this analysis revised values for Ca/S ratio, combustor pressure drop, and carbon loss percentage have been estimated. Using these revised values, PFBC simulations have been performed, the results of which are summarized in Table 2-20. The revised data of Table 2-20 represent a refinement of the earlier data of Tables 2-1, 2-2, and 2-3, and were used in the PFBC/CAES system part-load and transient performance evaluation phases of the program.

Summary of PFBC Part-Load Operation

The main aspects of combustor performance have been reviewed from the view-point of steady-state operation at 100-percent, 50-percent and 25-percent load.

The combustion efficiency is expected to be 98.5 percent over the operational range of 25-percent to 100-percent load at the design bed temperature and fluidizing velocity. Higher efficiencies could be achieved by increasing the number of solids feed points. Little combustion is expected in the freeboard or cyclones. Combustion conditions do not therefore represent a limitation to steady-state, part-load operation.

No experimental data on sulfur retention directly related to the conditions of the present combustor exist, and model predictions differ significantly. However, no difficulties are envisaged in designing a solids injection system capable of supplying the dolomite required to meet the specified 85-percent sulfur retention efficiency.

Table 2-20

COMBUSTOR DATA

<u>Parameter</u>		<u>Initial</u>			<u>Revised</u>				
Load		100	50	25	100	100	50	50	25
Coal rate									
(as received to driers, 13% H ₂ O)	lb/sec (kg/s)	25.93 (11.76)	14.64 (6.64)	8.16 (3.70)	25.26 (11.46)	25.55 (11.59)	13.98 (6.34)	14.04 (6.37)	7.76 (3.52)
(as fired, 5% H ₂ O)	lb/sec (kg/s)	23.74 (10.77)	13.40 (6.08)	7.47 (3.39)	23.13 (10.49)	23.41 (10.62)	12.79 (5.80)	12.87 (5.84)	7.10 (3.22)
Dolomite rate (as fired)	lb/sec (kg/s)				6.39 (2.90)	10.78 (4.89)	3.53 (1.60)	4.74 (2.15)	2.23 (1.01)
Ca/S ratio		1.5	1.5	1.5	1.5	2.5	1.5	2.0	1.7
Pressure Drops, psia									
Distributor		0.07			0.07	0.07	0.04	0.04	0.03
Bed		0.20			0.20	0.20	0.20	0.20	0.20
Cyclones		1.03			1.03	1.03	0.63	0.63	0.38
Total		1.30	0.94	0.60	1.30	1.30	0.87	0.87	0.61
Turbine exit gas flow									
(for coal and dolomite dryers)	lb/sec (kg/s)	33.3 (15.1)	18.8 (8.5)	10.5 (4.8)	32.41 (14.7)	34.61 (15.7)	11.24 (5.1)	11.68 (5.3)	4.85 (2.2)
Heat loss, % of calorific value of coal input									
Carbon loss		1.0	1.0	1.0	1.5	1.5	1.5	1.5	1.5
Spent ash & unreacted dolomite		*	*	*	1.02	1.52	1.02	1.27	1.13
Thermal loss		1.0	1.77	3.18	1.0	1.0	2.0	2.0	4.0

* Note: Spent ash and unreacted dolomite were not calculated separately in the initial data.

No problems are expected to arise as a result of the changes in fluidization, elutriation, or solids handling requirements for steady-state operation over the range of 25-percent to 100-percent load. However, the detailed design of the ash handling equipment will have to take into account the transient high particulate loadings in the combustion gas expected on turn-up after prolonged operation at part load.

References

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PFBC/CAES SYSTEM PART-LOAD OPERATION

The preceding chapter focused on the definition of PFBC performance during steady-state operation at reduced load. Although the PFBC is deserving of such individualized attention because of the uniqueness of its application to the CAES concept, other major components in the CAES system deserve scrutiny to assess their performance at part load. Likewise, the performance of the entire PFBC/CAES system at part-load is of sufficient import to warrant investigation. Consequently, the objective of the effort related to PFBC/CAES part-load operation has been to define the performance of the PFBC/CAES system and its major components under steady-state operation at reduced load.

As with the evaluation of the PFBC part-load operation, the evaluation of the PFBC/CAES system involved an iterative process. Initially, reasonable estimates of the steady-state, part-load characteristics associated with the PFBC/CAES system were developed for two operating points (25-percent load and 50-percent load). These characteristics were based upon the preconceptual design of Ref. 3-1 for 100-percent load operation. The conditions surrounding the PFBC were then extracted and utilized in the detailed analysis of the PFBC (as reported in the preceding chapter) resulting in refinements to the PFBC performance estimates. These refined PFBC data were then used as the basis for a final part-load simulation of the PFBC/CAES system.

This chapter describes the efforts associated with defining the steady-state part-load operation of the PFBC/CAES system and its major components. The initial PFBC/CAES system characteristics are presented. The results of the simulations of the PFBC/CAES system incorporating the revised PFBC data are also presented. An analysis of the revised simulations is provided. A commentary on possible equipment part-load operation concerns is also provided. Lastly, a summary of the findings of the PFBC/CAES part-load operation is furnished.

Preliminary PFBC/CAES Part-Load Operation Estimates

To initiate the investigation of the PFBC/CAES part-load operation the characteristics associated with the PFBC/CAES preconceptual design were referenced. These characteristics (Table 4-3 of Ref. 3-1) are reproduced for convenience in Table 3-1. The schematic of the preconceptual design (Fig. 4-2 of Ref. 3-1) is also reproduced and is displayed as Fig. 3-1. As noted in Table 3-1, the conditions defined for each of the station numbers indicated in Fig. 3-1 correspond to estimates at the design point (100-percent load).

Although Table 3-1 has been included in this study report, it is presented solely to provide continuity between Ref. 3-1 and the current effort because

Table 3-1

HEAT AND MASS BALANCE FOR COAL-FIRED PFBC/CAES CONFIGURATION

Preconceptual Design

100-Percent Load (Per Unit)

Note - Stations 1 through Cavern for Compression Mode

Stations 12 through 23 for Generation Mode

PFB Pressure = 15.0 atm (bar)

LT Turbine Inlet Temperature = 1562 F (850 C)

Station No. ⁽¹⁾	1	2	3	4	5	6	7	8	9	10	11	Cavern
W, lb/sec	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8
T, F	58.7	58.7	345.	160.9	500.0	200.	377.6	200.	409.3	120.	120.	120.
P, psia	14.7	14.6	60.2	59.0	243.8	240.9	469.8	464.8	999.8	989.8	978.1	1045.7
H, Btu/lb	124.0	124.0	193.0	148.5	231.1	157.9	201.0	157.9	208.8	138.7	138.7	138.7
Station No. ⁽¹⁾	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	731.3 ⁽²⁾	731.3	731.3	731.3	709.5	709.5	730.4	730.4	746.8	713.5	23.10	33.3
T, F	120.	120.	507.5	507.5	250.7	250.7	1562.0	1562.0	684.1	300.	--	684.1
P, psia	948.1	938.1	918.1	888.1	225.4	220.4	201.3	199.3	15.2	14.9	--	15.2
H, Btu/lb	138.7	138.7	232.8	232.8	170.1	170.1	510.8	510.8	278.4	181.8	--	278.4

<u>Compressor Power, MW</u>		<u>Turbine Power, MW</u>		<u>Net Heat Rate, Btu/kWh</u>		<u>Heat Exchanger Heat Transfer, Btu/sec</u>	
					HHV		
LC	56.2	ET	47.1	Generation	4538	IC1	33929
HC	67.2	LT	174.8	Compression	9095	IC2	55730
BC	76.5	Total, gross	221.9	Round trip	13633	IC3	32819
Total	199.9	Aux.	- 2.0			Aftercooler	53387
		Total Net	219.9			Recuperator	68815

(1) Station numbers refer to locations identified in Fig. 3-1 (all at surface except for cavern).

(2) This is 4 percent less than compressor flow rate to adjust for cavern leakage.

COAL-FIRED PFBC/CAES SYSTEM

FIG. 3-1

the table was not used directly as the basis for the PFBC/CAES part-load evaluation. Between the generation of the performance numbers displayed in Table 3-1 and the initiation of the load following evaluation effort a substantial period of time had elapsed. During that period the Corporate-sponsored program to continually update and refine the SOAPP* computer model (the computer model used to simulate the PFBC/CAES system) had been progressing. As a result of this progress, there was a change in the treatment of the moisture associated with as-fired coal. This refinement, when incorporated in the PFBC/CAES simulation and exercised to generate performance characteristics for the part-load evaluation, produced a slight increase in coal rate as reported in Table 3-2. It should be noted, however, there were no performance changes of sufficient consequence to warrant redesign of any of the major equipment components. Consequently, the revised estimates of Table 3-2 rather than the estimates of Table 3-1 were used as the basis for the part-load simulation.

Simulations of the Table 3-2 power plant in the 50-percent and 25-percent load conditions are summarized in Tables 3-3 and 3-4, respectively. The conditions surrounding the PFBC in Tables 3-2, 3-3, and 3-4 correspond to the conditions noted in Tables 2-1, 2-2, and 2-3, respectively. Only the stations associated with the generation mode of operation are displayed in Tables 3-3 and 3-4 because the operating characteristics during the compression mode are independent of the load during the generation mode. The preliminary estimates displayed in Tables 3-2, 3-3, and 3-4 were used primarily to initiate the PFBC analysis discussed in the preceeding chapter. Therefore, although the variations in station conditions resulting from part-load operation are of interest, commentary on the variations will be deferred until introduction of the performance characteristics which were developed by utilizing the revised PFBC data (see Table 2-20).

Revised PFBC Data Effect on PFBC/CAES System

The performance estimates of Tables 3-2, 3-3, and 3-4 provided a basis for the detailed analysis of the PFBC part-load operation presented in the preceeding chapter. This analysis in turn furnished refined PFBC data (Table 2-20) which were then used to revise the PFBC/CAES system performance estimates.

It should be mentioned that the procedure used for generating part-load PFBC/CAES data involves first analytically developing a 100-percent load design by means of the SOAPP computer program (i.e., the computer model has the

* SOAPP - State-of-the-Art Performance Program. The chief simulation tool used within United Technologies Corporation for power plant system modeling.

Table 3-2

PRELIMINARY HEAT AND MASS BALANCE FOR COAL-FIRED PFBC/CAES CONFIGURATION
100-Percent Load (per unit)

Note - Stations 1 through Cavern for Compression Mode
Stations 12 through 23 for Generation Mode

PFBC Pressure = 15.0 atm (bar)
LT Inlet Temperature = 1562 F (850 C)

Station No. ⁽¹⁾	1	2	3	4	5	6	7	8	9	10	11	Cavern
W, lb/sec	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8
T, F	58.7	58.7	345.0	160.9	500.0	200.0	377.6	200.0	409.3	120.0	120.0	120.0
P, psia	14.7	14.6	60.2	59.0	243.8	240.9	469.8	464.8	999.8	989.8	978.1	1045.7
H, Btu/lb	124.0	124.0	193.0	148.5	231.1	157.9	201.0	157.9	208.8	138.7	138.7	138.7
Station No. ⁽¹⁾	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	731.3 ⁽²⁾	731.3	731.3	731.3	709.5	709.5	731.2	731.2	747.4	714.1	23.74	33.3
T, F	120.0	120.0	508.0	508.0	251.4	251.4	1562.0	1562.0	684.7	300.0	—	684.7
P, psia	948.1	938.1	918.1	888.1	225.4	220.4	201.3	199.3	15.2	14.9	—	15.2
H, Btu/lb	138.7	138.7	233.1	233.1	170.3	170.3	510.8	510.8	278.6	181.9	—	278.6
<u>Compressor Power, MW</u>		<u>Turbine Power, MW</u>		<u>Net Heat Rate, Btu/kWh</u>		<u>Heat Exchanger Heat Transfer, Btu/sec</u>						
LC	56.2	ET	47.2	Generation	4663	IC1	33900					
HC	67.2	LT	174.8	Compression	9093	IC2	55764					
BC	76.5	Total, gross	222.0	Round Trip	13756	IC3	32833					
Total	199.9	Aux.	−2.0			Aftercooler	53402					
		Total, net	220.0			Recuperator	69035					

Table 3-3

PRELIMINARY GENERATION MODE HEAT AND MASS BALANCE
50-Percent Load (per unit)

PFBC Pressure = 9.3 atm (bar)
LT Inlet Temperature = 1562 F (850 C)

Station No. ⁽¹⁾	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	443.9	443.9	443.9	443.9	430.7	430.7	443.1	443.1	452.9	434.1	13.41	18.8
T, F	120.0	120.0	733.6	733.6	389.8	389.8	1562.0	1562.0	962.2	360.5	-	962.2
P, psia	1009.7	1006.3	999.4	594.0	139.5	136.0	122.3	121.1	14.9	14.8	-	14.9
H, Btu/lb	138.7	138.7	289.7	289.7	204.0	204.0	510.8	510.8	351.2	196.8	-	351.2

<u>Turbine Power, MW</u>		<u>Net Heat Rate, Btu/kWh</u>	
ET	39.1		<u>HHV</u>
LT	<u>71.9</u>	Generation	5268
Total, gross	111.0		
Aux.	<u>1.0</u>		
	110.0		

(1) Stations numbers refer to locations identified in Fig. 3-1.

Table 3-4

PRELIMINARY GENERATION MODE HEAT AND MASS BALANCE
25-Percent Load (per unit)

PFBC Pressure = 5.5 atm (bar)
LT Inlet Temperature = 1562 F (850 C)

Station No. ⁽¹⁾	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	260.4	260.4	260.4	260.4	252.6	252.6	259.6	259.6	265.3	254.8	7.47	10.5
T, F	120.0	120.0	893.6	893.6	486.8	486.8	1562.0	1562.0	1150.1	398.1	-	1150.1
P, psia	1033.3	1032.1	1029.8	370.1	83.4	81.1	72.4	71.7	14.8	14.7	-	14.8
H, Btu/lb	138.7	138.7	330.2	330.2	227.8	227.8	510.8	510.8	401.8	206.1	-	401.8

Turbine Power, MWNet Heat Rate, Btu/kWh

ET 27.3
LT 28.2
Total, gross 55.5
Aux. 0.5
55.0

HHV
Generation 5868

(1) Station numbers refer to locations identified in Fig. 3-1.

capability of supplying the physical characteristics of all the major components at design load). This design is fixed and then, by means of off-design relationships such as compressor and turbine maps, the part-load conditions are estimated.

Part-Load Simulations

The revised data of Table 2-20 provide for the simulation of five separate operating conditions:

- 1) 100-percent load with a Ca/S ratio of 1.5,
- 2) 100-percent load with a Ca/S ratio of 2.5,
- 3) 50-percent load with a Ca/S ratio of 1.5,
- 4) 50-percent load with a Ca/S ratio of 2.0, and
- 5) 25-percent load with a Ca/S ratio of 1.7.

The PFBC/CAES operating characteristics produced by simulating these operating conditions are summarized in Tables 3-5 through 3-9. Tables 3-5 and 3-6 supply a comparison between the two Ca/S ratios at 100-percent load; Tables 3-7 and 3-8 supply a similar comparison at 50-percent load; and Table 3-9 is simply a simulation at the recommended Ca/S ratio.

PFBC Performance Comparison

The first comparisons made were between the PFBC data generated by the UTRC PFBC/CAES simulation model and the CPC PFBC model. This was an essential comparison to determine whether the two models were agreeing in their simulations of the PFBC part-load performance. The parameter chosen to illustrate this comparison is the estimated fuel consumption rate (Table 3-10).

The first observation that can be made in reviewing Table 3-10 is that the UTRC coal rate estimates are consistently lower than the estimates generated by CPC. After a review of both models, it was determined that the variation was caused by the different gas property sources used. In the UTRC model both the Keenan and Kayes Gas Tables and the JANAF gas properties are used, while in the CPC model API empirical equations are used. Taking into account the differences in gas enthalpy as calculated by these sources it was possible to establish that the source calculation methodology accounted for the differences in coal rate estimates.

The second observation that can be made is that both models predicted a change in coal rate with changing Ca/S ratio. The percent change in coal rate was predicted identically by both models.

Table 3-5

GENERATION MODE HEAT AND MASS BALANCE
 100-Percent Load (per unit)
 Ca/S = 1.5
 PFBC Pressure = 15.0 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

Station No. ⁽¹⁾	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	731.3	731.3	731.3	731.3	709.5	709.5	730.3	730.3	746.5	713.1	22.82	33.3
T, F	120.0	120.0	507.4	507.4	250.0	250.0	1562.0	1562.0	685.0	300.0	---	685.0
P, psia	448.1	938.1	924.8	894.6	225.4	220.4	201.3	199.3	15.2	14.9	---	15.2
H, Btu/lb	138.7	138.7	233.0	233.0	170.0	170.0	517.2	517.2	278.6	181.9	---	228.6

Turbine Power, MW

ET	47.3
LT	<u>179.4</u>
Total, gross	226.7
Aux.	<u>2.0</u>
	224.7

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4387

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-6

GENERATION MODE HEAT AND MASS BALANCE
 100-Percent Load (per unit)
 $Ca/S = 2.5$
 PFBC Pressure = 15.0 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	731.3	731.3	731.3	731.3	709.5	709.5	731.4	731.4	747.6	714.3	23.07	33.3
T, F	120.0	120.0	508.9	508.9	251.0	251.0	1562.0	1562.0	685.6	300.0	---	685.6
P, psia	948.1	938.1	924.8	894.6	225.4	220.4	201.3	199.3	15.2	14.9	---	15.2
H, Btu/lb	138.7	138.7	233.3	233.3	170.2	170.2	517.2	517.2	278.7	181.9	---	278.7

Turbine Power, MW

ET	47.4
LT	<u>179.6</u>
Total, gross	227.0
Aux.	<u>-2.0</u>
	225.0

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4429

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-7

GENERATION MODE HEAT AND MASS BALANCE
50-Percent Load (per unit)

Ca/S = 1.5

PFBC Pressure = 8.5 atm (bar)

LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	407.3	407.3	407.3	407.3	395.2	395.2	406.1	406.1	415.1	398.2	12.04	16.9
T, F	120.0	120.0	631.1	631.1	338.3	338.3	1562.0	1562.0	832.6	328.7	---	832.6
P, psia	1015.4	1012.5	1008.6	526.7	127.3	124.2	112.3	111.3	14.9	14.8	---	14.9
H, Btu/lb	138.7	138.7	263.8	263.8	191.4	191.4	516.9	516.9	316.9	189.0	---	316.9

Turbine Power, MW

ET	30.2
LT	<u>83.2</u>
Total, gross	113.4
Aux.	<u>-1.0</u>
	112.4

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4631

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-8

GENERATION MODE HEAT AND MASS BALANCE
 50-Percent Load (per unit)
 Ca/S = 2.0
 PFBC Pressure = 9.3 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	407.1	407.1	407.1	407.1	395.0	395.0	406.2	406.2	416.2	398.2	12.10	17.0
T, F	120.0	120.0	631.3	631.3	338.6	338.6	1562.0	1562.0	832.8	328.9	---	832.8
P, psia	1015.4	1012.5	1008.6	526.4	127.3	124.2	112.3	111.2	14.9	14.8	---	14.9
H, Btu/lb	138.7	138.7	263.9	263.9	191.5	191.5	516.9	516.9	316.9	189.0	---	316.9

Turbine Power, MW

ET	30.2
LT	<u>83.2</u>
Total, gross	113.4
Aux.	<u>-1.0</u>
	112.4

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4652

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-9

GENERATION MODE HEAT AND MASS BALANCE

25-Percent Load (per unit)

Ca/S = 1.7

PFBC Pressure = 4.9 atm (bar)

LT Inlet Temperature = 1562 F (850 C)

Station No. (1)	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	233.4	233.4	233.4	233.4	226.4	226.4	232.4	232.4	237.5	228.4	6.50	9.1
T, F	120.0	120.0	769.9	769.9	440.7	440.7	1562.0	1562.0	993.0	355.5	---	993.0
P, psia	1035.7	1034.8	1033.5	319.4	74.6	72.6	65.1	64.5	14.8	14.7	---	14.8
H, Btu/lb	138.7	138.7	298.9	298.9	216.5	216.5	516.9	516.9	359.3	195.6	---	359.3

Turbine Power, MW

ET	19.7
LT	<u>37.1</u>
Total, gross	56.8
Aux.	<u>-0.5</u>
	56.3

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4999

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-10

PFBC COAL RATE COMPARISON

<u>Condition</u>	Table 2-20 (1) <u>estimate, lb/sec</u>	PFBC/CAES (2) <u>Simulation, lb/sec</u>
100% Load; Ca/S = 1.5	23.13	22.82
100% Load; Ca/S = 2.5	23.41	23.07
50% Load; Ca/S = 1.5	12.79	12.04
50% Load; Ca/S = 2.0	12.87	12.10
25% Load; Ca/S = 1.7	7.10	6.50

(1) Generated by CPC on their proprietary PFBC performance simulation model.

(2) Generated by UTRC on their proprietary PFBC/CAES performance simulation model.

Additional comparisons were made between the estimates provided by the two models such as exhaust gas composition, heats of reaction, etc., to verify that the models were producing compatible estimates. The conclusion drawn from this verification effort was that both models were indeed handling the performance estimates in a mutually consistent manner.

Effect of Ca/S Ratio Variation

There exists a significant disagreement in the recommended Ca/S ratio, i.e., dolomite/coal feed ratio, which should be used to achieve 85-percent sulfur retention. As mentioned in the preceding chapter, this disagreement arises from the differing estimates provided by the three sulfur retention models which could be used. Consequently, the reason for running simulations at all the Ca/S ratio values cited in Table 2-20 was to ascertain whether the variation in Ca/S ratio had any significant effect upon the PFBC/CAES system.

To provide a comparison between the Ca/S ratios at different loading conditions, the coal rate and generation heat rate can be isolated from Tables 3-5 through 3-8 and reviewed (Table 3-11). The increase in coal rate is slight being about one percent when the Ca/S ratio is increased 67 percent. This increase results primarily from the requirement to heat up a greater mass of dolomite. There is also a similar increase in heat rate. Obviously, these variations resulting from a variation in Ca/S ratio do not represent a significant effect on performance.

A review of the conditions in Tables 3-5 through 3-8 associated with each of the major components produces a like conclusion relative to the design of the major components in the CAES plant. It should be noted however, that a larger dolomite requirement will effect the design of the dolomite storage, handling, and preparation systems as well as the coal/dolomite injection system. These design variations could affect the transient response of the fuel system and, thus, the response of the PFBC/CAES system. This concern will be addressed in the treatment of the PFBC/CAES transient analysis in the next chapter.

Analysis of Revised PFBC/CAES Part-Load Performance

One conclusion resulting from the analyses of the effect of the revised PFBC data on the performance of the PFBC/CAES system was that the Ca/S ratio variation between 1.5 and 2.5 had little effect on part-load performance but could possibly effect transient response. Consequently, to minimize the dependence of the transient response analysis on Ca/S ratio selection, it was decided to fix the Ca/S ratio at a mid-range value of 2.0 for all design, steady-state part-load, and transient simulations. Because this decision will

Table 3-11

Ca/S RATIO VARIATION EFFECT ON PFBC/CAES PERFORMANCE

<u>Percent Load</u>	<u>Ca/S</u>	<u>Coal Rate, lb/sec</u>	<u>Generation Heat Rate, Btu/kWhr</u>
100	1.5	22.82	4387
100	2.5	23.07	4429
50	1.5	12.04	4631
50	2.0	12.10	4652

affect slightly the steady-state, part-load characteristics of the PFBC/CAES system, an additional set of part-load data were generated. These data are summarized in Tables 3-12 through 3-15, for 100-percent load, 75-percent load, 50-percent load, and 25-percent load, respectively. The variations in operating conditions produced by the variation in load will be the subject of the following commentary.

It should be mentioned that in the illustrations which accompany the commentary in this section dependent parameters such as generation heat rate, coal rate, airflow, and inlet and exit pressure and temperature are plotted against percent of design output power. Four steady-state data points for that parameter are plotted and a curve has been drawn through these four data points. This curve is an interpolation of the data and represents an estimate of the value of the dependent parameter at some intermediate steady-state, part-load output power conditions. It does not represent the value of the dependent parameter at that same intermediate output power condition as the PFBC/CAES system is undergoing transient operation.

Generation Heat Rate

A plot of generation heat rate is provided in Fig. 3-2. There is a clear tendency for the heat rate to increase with decreasing output power; e.g., it is approximately 14 percent greater at 25-percent load than at 100-percent load. This trend toward increasing heat rate at reduced load is characteristic of gas turbines but the 14-percent increase experienced in the PFBC/CAES system is approximately one-half of the increase expected from a conventional gas turbine. Thus, a PFBC/CAES power plant would have very good part-load performance relative to a conventional gas turbine.

The increase in heat rate occurs because the coal rate does not decrease in direct proportion to output power; rather, the coal rate decreases less than does the output power (Fig. 3-3). Although the interrelationships which define the performance of the PFBC/CAES system are numerous, the heat rate trend can be at least partially explained by the part-load operating characteristics of the major components.

At part-load conditions, the inlet pressure to the PFBC decreases (Fig. 3-4) as well as the air flow (Fig. 3-5) to maintain a fluidizing velocity in the PFBC within the range which will provide good bed fluidization. This means that the low-pressure turbine expands the 1562 F (850 C) PFBC exhaust gases over a lesser pressure ratio resulting in a higher exhaust temperature from the low-pressure turbine. This higher exhaust temperature, when passed through the recuperator, results in a higher inlet temperature to the expansion turbine. Because the expansion turbine, unlike the low-pressure turbine, can maintain a relatively constant expansion ratio and does so to maximize output power, there

Table 3-12

FINAL HEAT AND MASS BALANCE FOR COAL-FIRED PFBC/CAES CONFIGURATION

100-Percent Load (per unit)

Note - Stations 1 through Cavern for Compression Mode

Stations 12 through 23 for Generation Mode

PFBC Pressure = 15.0 atm (bar)

LT Turbine Inlet Temperature = 1562 F (850 C)

(1)												
Station No.	1	2	3	4	5	6	7	8	9	10	11	Cavern
W, lb/sec	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8	761.8
T, F	58.7	58.7	345.0	160.9	500.0	200.0	377.6	200.0	409.3	120.0	120.0	120.0
P, psia	14.7	14.6	60.2	59.0	243.8	240.9	469.8	464.8	999.8	989.8	978.1	1045.7
H, Btu/lb	124.0	124.0	193.0	148.5	231.1	157.9	201.0	157.9	208.8	138.7	138.7	138.7
(1)												
Station No.	12	13	14	15	16	17	18	19	20	21	22	23
(2)												
W, lb/sec	731.3	731.3	731.3	731.3	709.5	709.5	730.9	730.9	747.0	713.7	22.94	33.3
T, F	120.0	120.0	508.3	508.3	250.5	250.5	1562.0	1562.0	685.3	300.0	--	685.3
P, psia	948.1	938.1	924.8	894.6	225.4	220.4	201.3	194.3	15.2	14.8	--	15.2
H, Btu/lb	138.7	138.7	233.1	233.1	170.1	170.1	517.2	517.2	278.7	181.9	--	278.7
Compressor Power, MW		Turbine Power, MW		Net Heat Rate, Btu/kWh		Heat Exchanger Heat Transfer, Btu/sec						
								HHV				
LC	56.2	ET	47.1	Generation	4408	IC1		33929				
HC	67.2	LT	179.5	Compression	8890	IC2		55730				
BC	76.5	Total, gross	226.9	Round trip	13298	IC3		32819				
Total	199.9	Aux.	-2.0			Aftercooler		53387				
		Total, net	224.9			Recuperator		69080				

(1) Station numbers refer to locations identified in Fig. 3-1 (all at surface except for cavern).

(2) This is 4 percent less than compressor flow rate to adjust for cavern leakage.

Table 3-13

FINAL GENERATION MODE HEAT AND MASS BALANCE
 75-Percent Load (per unit)
 PFBC Pressure = 11.8 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	571.4	571.4	571.4	571.4	554.4	554.4	570.7	570.7	583.3	558.7	17.55	24.6
T, F	120.0	120.0	557.4	557.4	285.3	285.3	1562.0	1562.0	744.5	312.1	--	744.5
P, psia	986.1	980.2	972.4	715.0	177.0	172.9	157.3	155.7	15.0	14.8	--	15.0
H, Btu/lb	138.7	138.7	245.3	245.3	178.5	178.5	517.1	517.1	294.0	184.9	--	294.0

Turbine Power, MW

ET	39.2
LT	<u>130.9</u>
Total, gross	170.1
Aux.	<u>-1.5</u>
	168.6

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	4499

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-14

FINAL GENERATION MODE HEAT AND MASS BALANCE
 50-Percent Load (per unit)
 PFBC Pressure = 8.4 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	407.1	407.1	407.1	407.1	395.0	395.0	406.2	406.2	415.2	398.2	12.10	17.0
T, F	120.0	120.0	631.8	631.8	338.9	338.9	1562.0	1562.0	832.9	328.7	--	832.9
P, psia	1015.4	1012.5	1008.6	526.4	127.2	124.1	112.3	111.1	14.9	14.8	--	14.9
H, Btu/lb	138.7	138.7	264.0	264.0	191.5	191.5	516.9	516.9	317.0	188.9	--	317.0

Turbine Power, MWNet Heat Rate, Btu/kWh

ET	30.2
LT	<u>83.2</u>
Total, gross	113.4
Aux.	<u>-1.0</u>
	112.4

	<u>HHV</u>
Generation	4653

(1) Station numbers refer to locations identified in Fig. 3-1.

Table 3-15

FINAL GENERATION MODE HEAT AND MASS BALANCE
 25-Percent Load (per unit)
 PFBC Pressure = 4.9 atm (bar)
 LT Inlet Temperature = 1562 F (850 C)

(1) Station No.	12	13	14	15	16	17	18	19	20	21	22	23
W, lb/sec	233.3	233.3	233.3	233.3	226.4	226.4	232.4	232.4	237.6	228.4	6.52	9.2
T, F	120.0	120.0	770.6	770.6	441.3	441.3	1562.0	1562.0	993.3	355.3	--	993.3
P, psia	1035.8	1034.8	1033.5	319.3	74.5	72.6	65.1	64.5	14.8	14.7	--	14.8
H, Btu/lb	138.7	138.7	299.1	299.1	216.6	216.6	516.5	516.5	359.3	195.5	--	359.3

Turbine Power, MW

ET	19.6
LT	<u>37.1</u>
Total, gross	56.7
Aux.	<u>-0.5</u>
	56.2

Net Heat Rate, Btu/kWh

	<u>HHV</u>
Generation	5012

(1) Station numbers refer to locations identified in Fig. 3-1.

PART-LOAD GENERATION HEAT RATE
STEADY STATE

PART-LOAD COAL RATE
STEADY STATE

PART-LOAD PFBC INLET PRESSURE
STEADY STATE

PART-LOAD AIR FLOW
STEADY STATE

is the potential for the expansion turbine to generate more output power per mass flow at the part-load conditions than at full load. The total output power is simply the summation of expansion turbine output power and low-pressure turbine output power. Consequently, if the expansion turbine generates more of the total output power at part-load (20.9 percent at 100-percent load (see Table 3-12) and 34.6 percent at 25-percent load (see Table 3-15)) the low-pressure turbine generates less. However, in the PFBC/CAES design, the expansion turbine is a modified steam turbine with a lower efficiency than the low-pressure turbine. As a result, the shifting of output power to the expansion turbine from the low-pressure turbine produces a higher heat rate. Summarizing the above argument, it can be stated that at least part of the observed increase in heat rate can be attributed to the shift in output power generation to the less efficient expansion turbine from the more efficient low-pressure turbine.

A more obvious reason for the increase in heat rate is the increasing stack temperature with decreasing output power (Fig. 3-6). This is an indication that a lesser proportion of the available thermal energy is being converted to output power. This occurs because bed temperature is maintained constant while bed pressure is reduced for part-load operation. The resulting greater thermal energy per mass flow associated with the higher low-pressure turbine exhaust temperatures is too great to be effectively rejected to the expansion turbine inlet air in the recuperator. Thus, a higher stack temperature results.

Coal Rate

As mentioned previously, the coal rate does not decrease in direct proportion to output power (Fig. 3-3). Unfortunately, Fig. 3-3 does not conveniently convey this impression. Consequently, Table 3-16 has been prepared to more clearly present this observation.

The factors affecting the variation in coal rate with output power were covered in the preceeding section on heat rate in as much as heat rate is merely the ratio of the output power to the coal rate expressed in its equivalent thermal content. However, a coal rate variation will create variations in other parameters. To maintain combustion air within acceptable excess air limits, air flow to the combustor has to vary (Fig. 3-5) with coal rate. With the air flow decreasing with output power, the combustor pressure must also decrease to maintain constant fluidizing velocity (Fig. 3-4). This pressure reduction in turn lowers the inlet pressure to the expansion turbine (Fig. 3-7) so as to maintain the expansion ratio across this turbine to values around 4.0.

Recuperator Conditions

The recuperator in the PFBC/CAES system serves to recover the thermal energy remaining in the gas stream after its expansion in the low-pressure turbine. This thermal energy then increases the temperature of the air headed

PART-LOAD STACK TEMPERATURE
STEADY STATE

Table 3-16

COAL RATE VARIATION

<u>Gross Output Power, MW</u>	<u>Coal Rate, lb/sec</u>	<u>Mass-Energy Ratio, lb/sec/MW</u>
226.9	22.94	0.101
170.1	17.55	0.103
113.4	12.10	0.107
56.7	6.52	0.115

PART-LOAD EXPANSION TURBINE INLET PRESSURE
STEADY STATE

to the expansion turbine inlet. The parameters describing the recuperator performance are displayed in Figs. 3-6, 3-8, and 3-9. These illustrations display stack temperature (recuperator hot-side exhaust), expansion turbine inlet temperature (recuperator cold-side exhaust), and recuperator hot-side inlet, respectively. The recuperator cold-side inlet temperature remains fixed at 120 F (49 C).

In part-load operation the recuperator hot-side inlet temperature increases (Fig. 3-9). As a result, the recuperator is no longer able to lower the stack temperature to the design condition of 300 F (149 F) and there is an increase in stack temperature (Fig. 3-6). The hotter inlet and exhaust conditions on the hot-side of the recuperator produce a higher cold-side exhaust temperature (expansion turbine inlet temperature, Fig. 3-8). This in turn will produce a higher PFBC inlet temperature (expansion turbine exhaust temperature) as seen in Fig. 3-10. The expansion turbine inlet temperature along with the air flow to the expansion turbine (Fig. 3-5) will also contribute to the determination of the expansion turbine inlet pressure (Fig. 3-7) as the pressure must be varied to maintain a constant flow parameter (product of mass flow times the square root of the absolute temperature divided by the absolute pressure) to the expansion turbine.

Equipment Part-Load Considerations

Generally speaking, there do not appear to be any major problems in applying the equipment cited in the Ref. 3-1 preconceptual design to part-load operation. Possible concerns with operating the PFBC in the part-load mode were covered in the preceeding chapter. The turbomachinery and recuperator will be commented upon in the following sections.

Turbomachinery

The primary concern with the turbomachinery rests with the high exhaust temperature (Fig. 3-9) experienced at low part-load operation. This high temperature would create a need to redesign the last stages of the Ref. 3-1 preconceptual turbomachinery design.

Two redesign approaches are possible. The first would involve substituting blades capable of withstanding the higher temperature. This is a state-of-the-art solution because blade materials are available from aircraft gas turbines where the temperatures in the last stages routinely exceed the temperatures which would be experienced in part-load PFBC/CAES operation. The second approach would utilize cooling of the existing blade material. Because blade cooling is accepted practice, this could also be classed as a state-of-the-art solution. However, unlike the first approach, blade cooling could result in a

PART-LOAD EXPANSION TURBINE INLET TEMPERATURE
STEADY STATE

PART-LOAD RECUPERATOR HOT-SIDE INLET TEMPERATURE
STEADY STATE

PART-LOAD PFBC INLET TEMPERATURE

STEADY STATE

minor performance degradation because a bleed stream of air would be needed and the air used would be introduced at less than PFBC bed temperature and pressure.

Both the aforementioned approaches would add an additional cost to the Ref. 3-1 turbomachinery cost estimate. It is beyond the scope of the current program to estimate this cost increment. However, it would be only a small addition to just one component of the PFBC/CAES system, and would have only a minor impact on power plant cost.

Recuperator

As with the turbomachinery, the primary concern associated with the recuperator deals with a high gas temperature, in fact, the same gas temperature which creates concern in the low-pressure turbine. It would appear, however, that the Ref. 3-1 preconceptual design is compatible with the high hot-side inlet temperature (Fig. 3-9) encountered at low part-load operation because the recuperator was designed and costed using stainless steel which should be capable of withstanding temperatures of 1100 F to 1200 F (593 C to 649 C). If the recuperator had been designed with the use of low-carbon steel, then it would be limited to a maximum operating temperature of 800 F to 850 F (427 C to 454 C) given the pressure differential of up to 70 atm (bar) across the recuperator.

Summary of PFBC/CAES Part-Load Operation

The simulation of the PFBC/CAES power plant at steady-state part-load operation did not uncover any major problems associated with this type of operation.

The revised system characteristics based upon data generated during a detailed review of the PFBC matched closely the initial estimated system characteristics. The PFBC characteristics generated by the separately developed PFBC models which UTRC and CPC possess are compatible, indicating that the PFBC is being modeled in sufficient detail and accuracy in the PFBC/CAES model to effectively simulate the PFBC/CAES system. Based on system simulations, it was determined that selection of values for the Ca/S ratio within the acceptable range of 1.5 to 2.5 has a negligible effect on system performance.

The analysis of the PFBC/CAES part-load performance provided an indication that the PFBC/CAES system with a generation heat rate rise of only 14 percent at 25-percent load as compared to design heat rate would possess good part-load efficiency relative to a conventional gas turbine. In addition, the analysis revealed that the increase in generation heat rate with decreasing load resulted partly from the shift in output power contribution from the more efficient low-pressure turbine to the less efficient expansion turbine with decreasing output power, and partly from the increased stack temperature. The coal rate

is influenced by the same factors effecting generation heat rate. The coal rate, in turn, influences both the combustor air flow and pressure to maintain an essentially constant fluidizing velocity in the bed at part load. The recuperator design was determined to influence the stack temperature as well as the expansion turbine inlet temperature with both increasing at part load.

No equipment limitations were uncovered that could not be readily corrected by state-of-the-art design modifications. Specifically, the recuperator was assessed to be compatible with the part-load operating conditions it would experience while the low-pressure turbine would be capable of handling the higher temperature encountered in part-load operation by either substituting higher temperature resistant blades or utilizing blade cooling. However, both would involve the addition of a minor cost increment to the plant cost.

Reference

- 3-1 Giramonti, A. J., R. D. Lessard, D. Merrick, and M. J. Hobson:
Technical and Economic Assessment of Fluid Bed Combustion Augmented
Compressed Air Energy Storage System. UTRC Report R80-954490-20
supported by Battelle Pacific Northwest Laboratory Subcontract
B-51299-A-L, June 1980.

PFBC/CAES SYSTEM TRANSIENT OPERATION

In this chapter, the evaluation of the ability of the PFBC/CAES system to respond to required load changes is presented. Previous work in this area (reported in Ref. 4-1) had been limited to a relatively simple representation of the PFBC. As part of the current effort this model was re-evaluated and system response time was made to be a function of load. Using the proprietary SOAPP computer model, the important dynamics (thermal and volumetric) of the CAES system integrated with the PFBC were simulated to evaluate the effect of various load change rates on the PFBC/CAES system and its components. In addition, the response requirements of the air flow control and coal feed mechanism were identified.

PFBC/CAES Response Requirements

The previous work (cited above) examined the operation of electric utility generating systems and their interconnections. In general, the interconnections between utility generating systems serve to minimize the effect of load disturbances on any individual system by spreading the effect of the disturbance over the interconnected area. As a result, individual generating unit response requirements within a generating system are mitigated relative to the requirements which would be imposed upon a generating unit in an isolated generating system. Nevertheless, it is desirable for a generating unit to be capable of response rates in excess of the minimum required, since it would ease the response requirements imposed on other units in the system. The specification of response requirements however, must be tempered by other factors. For example, when a unit has low operating costs, as does a nuclear plant, it is desirable to operate it at rated load and shift the responsibility for load regulation or load following to other less economical units.

Because each utility generating system has a different mix of equipment and different operating needs, the transient requirement placed upon new equipment may vary considerably. A generalized graphical representation of desired unit response for a large interconnection (from Refs. 4-2 & 4-3) is shown in Fig. 4-1. It shows the progression from very rapid, by small excursions required for frequency regulation to the relatively slow but large excursions required during unit commitments. Individual utility requirements may differ from this general estimate. A particular set of requirements developed for a compressed air storage system is given in Table 4-1 (Ref. 4-4). The requirements of Table 4-1 are more stringent than shown as "typical" in Fig. 4-1 and quite likely reflect the faster response that is expected of pumped storage units.

Table 4-1

TYPICAL REQUIRED OPERATING CAPABILITIES FOR A GENERATING UNIT

Minimum Generation

- a) Each unit must be capable of maintaining synchronous speed and carrying station service load while not connected to the electric system.
- b) Each unit must be capable of operation as a synchronous condenser.

Load Following

- a) Each unit must be able to transfer from synchronous condenser operation to maximum emergency generation in under ten minutes. This capability will be utilized solely under emergency conditions when reduction of machinery life expectancy is acceptable.
- b) From any point between its minimum and maximum generation points, each unit must be capable of changing load at the rate of 3 1/3 percent of nameplate generator rating per minute under normal conditions.

Regulation

- a) From a variable set point between fifteen and eighty-five percent of generation nameplate rating, each unit must be capable of maintaining a regulation band plus or minus 15 percent of generator nameplate rating, with a rate of change of 5 percent of generator nameplate rating per minute.

Turnaround

- a) Each unit must be capable of instantaneous electrical disconnect when pumping at motor nameplate rating under emergency conditions when reduction of unit life expectancy is acceptable.
- b) Each unit must be capable of transfer from pumping at motor nameplate rating to maximum emergency generation within thirty minutes under emergency conditions when reduction of unit life expectancy is acceptable.

Comment:

These criteria present an ideal from a system operating standpoint. They are not absolute, however, and are subject to trade-offs in costs and plant reliability.

DESIRED GENERATING UNIT RESPONSE

LARGE INTERCONNECTION

PFBC Simulation

The basic steady-state PFBC model used during the Ref. 4-1 effort performs a heat and mass balance around the combustor using enthalpy and heat of formation data based on the JANAF and the Keenan and Kayes tables. The degree of calcination and sulfur capture percentage are input as are other characteristics such as carbon utilization and heat loss. An iterative procedure is used to close on the overall combustor heat balance.

The approach to dynamic modeling of the PFBC was basically that outlined in Ref. 4-1. This previous work established a set of linearized equations to represent the inertial effects of bed temperature and carbon inventory. The equations describing the PFBC dynamics are given in Fig. 4-2 and a linearized block diagram (using Laplace transform notation) is shown in Fig. 4-3. It is assumed that the rate of carbon combustion is proportional to the amount of carbon in the bed. Thus, the rate of heat release cannot be increased by simply increasing the flow of air and coal. Instead, it is necessary to increase the amount of carbon in the bed, which can only be done over a finite time period. The time constant associated with the change in carbon inventory is the mass of carbon in the bed divided by the carbon feed rate. This remains constant as load changes and is approximately 4 minutes. However, there is a fast path from fuel flow to heat release caused by the release of volatiles from the coal and their subsequent combustion. It has been estimated that time between the release of volatiles and combustion is on the order of 2 seconds (Ref. 4-5) which is two orders of magnitude faster than the carbon inventory dynamics. Consequently the release of volatiles has been assumed to be instantaneous.

There is also a time constant associated with heat release and gas outlet temperature, because the bed thermal mass produces a single first order lag given by the ratio of bed thermal mass divided by the air flow rate and its specific heat. The value of that time constant increases with decreasing load. At design conditions it is approximately 6 minutes. Because of the time lag between fuel rate and heat release, when both fuel rate and air flow are changed together to produce a variation in output power but the same steady-state bed temperature, the bed temperature does not remain constant but is temporarily disturbed before returning to its initial steady-state value. This is shown in Fig. 4-4 for a 10-percent change in both fuel and air flow rate. For that calculation the PFBC is treated as a stand-alone module and the bed inlet air temperature is assumed to be constant. If bed exit temperature were to remain constant, the fuel flow change would have to be more than the corresponding fractional air flow change.

In a separate, Corporate-funded effort, the dynamic characteristics were incorporated into the existing coal-fired PFBC steady-state simulation, and the resulting dynamic model was used in the simulation of PFBC/CAES transient operation. The remaining parts of the PFBC/CAES system were simulated as described in the following section.

COMBUSTOR EQUATIONS

HEAT BALANCE

$$M_B C_B \frac{dT_B}{dt} = W_G C_G (T_{IN} - T_B) + Q_C$$

HEAT RELEASE

$$Q_C = K_{CB} M_{CB} (HHV_C) + K_V W_C$$

CARBON INVENTORY

$$\frac{dM_{CB}}{dt} = K_C W_C - K_{CB} M_{CB}$$

- $M_B C_B$ = HEAT CAPACITY OF BED MATERIAL — kJ/C (Btu/F)
- T_B = BED TEMPERATURE — ALSO OUTLET GAS TEMPERATURE — C (F)
- $W_G C_G$ = COMBUSTION GAS FLOW TIMES SPECIFIC HEAT — kJ/s-C (Btu/sec-F)
- T_{IN} = AIR TEMPERATURE INTO BED — C (F)
- Q_C = HEAT RELEASED BY COMBUSTION IN BED — kJ/s (Btu/sec)
- K_{CB} = RATE OF CARBON COMBUSTION/CARBON IN BED — 1/sec.
- M_{CB} = AMOUNT OF CARBON IN BED — kg (lb)
- HHV_C = HIGHER HEATING VALUE OF CARBON — kJ/kg (Btu/lb)
- K_V = HEATING VALUE OF VOLATILES PER POUND OF COAL — kJ/kg (Btu/lb)
- W_C = COAL FEED RATE — kg/s (lb/sec)
- K_C = WEIGHT FRACTION OF FIXED CARBON IN COAL

COMBUSTOR DYNAMICS

FIG. 4-3

BED TEMPERATURE RESPONSE

10-PERCENT INCREASE IN COAL & AIR FEED RATE

FIG. 4-4

PFBC/CAES System Simulation

Both steady-state and transient performance estimates can be made using the UTC computer model. The model permits simulation of thermal storage effects, volume dynamics, and both fluid and rotating inertia. For the PFBC/CAES system, the component response times were sufficiently slow so that rotating inertial effects could be neglected. The effects of both thermal storage, especially in the combustor bed, and volume on the compressible flow have a decided influence on the system response characteristics. The significant dynamics of the major components and the method of simulation are described in this section.

Recuperator

The Ref. 4-1 design of the recuperative heat exchanger is quite similar to that of a conventional gas turbine waste heat boiler. The low-pressure, high-temperature exhaust gases flow on the outside of tubing that carries the cool high-pressure air from the storage cavern. As a result, the cool high-pressure side air density is quite high, and the heat transfer film coefficient on that side is also high compared to the low-pressure, high-temperature side. Consequently, the metal temperature in the heat exchanger follows the cold-side air temperature more closely than the hot side, thereby, minimizing both the metal temperature level and the variation in temperature as load changes.

For the transient simulation, the recuperator has been broken into three sections or nodes. In each, the metal temperature is uniform and heat transfer calculations are based on average air temperatures. This approximation is valid because the mass flow ratio between the two sides of the recuperator is very close to unity and the log mean temperature difference is equal to the average temperature difference. The use of three nodes provides a reasonable simulation of the distributed nature of the recuperator dynamics. Despite the extremely large recuperator volume ($\approx 12000 \text{ ft}^3$ (340 m^3)), gas residence time is less than one second and the recuperator material is the primary factor in the dynamics.

Heat transfer film coefficients are specified at the design conditions and are varied with gas conductivity, flow, and viscosity as shown in equation 4-1.

$$h = h_D \left(\frac{k}{k_D} \right) \left(\frac{W}{W_D} \frac{\mu_D}{\mu} \right)^{0.8} \quad (4-1)$$

where h = film coefficient;

k = gas conductivity;

W = gas flow rate;

μ = gas viscosity, and

D = design value, all in consistent units.

Heat exchanger mass is estimated to be approximately 320,000 lbs (145,150 kg) giving a thermal inertia of 38,000 Btu/F (72,160 kJ/C). By comparison, the thermal capacity of the gas stream is approximately 11,000 Btu/min - F (20,890 kJ/min - C) indicating that the effect of the heat exchanger thermal mass on the system dynamics will be quite significant.

Air Throttle Valve

No dynamics were assumed for operation of the air throttle valve. It is represented by an input value of pressure loss of the form $\Delta P/P$. In the evaluation of system response characteristics the valve pressure loss was varied to produce the desired change in air flow rate.

Ducting

The dynamic characteristics of the interconnecting ducts are simulated by both volume (gas compressibility) and wall thermal inertia effects. In all cases these are significantly lower (≈ 100 times) than those associated with the combustor pressure vessel or the recuperator. As a result they do not appear to have a significant effect on the system dynamics.

Combustor Pressure Vessel

While the principal heat storage dynamics are associated with the thermal mass of the combustor bed, the major volume of the overall assembly is associated with the pressure vessel as shown in Fig. 4-5. Nearly all of the pressure vessel volume is occupied by the inlet air. The volume of the inlet air is approximately 91,000 ft³ (2575 m³) which compares to the volumetric air flow rate of approximately 51,000 ft³/min (1445 m³/min) at design conditions. As a result of this volume, the combustor bed volume and the exit ducting volume (20,000 ft³ (525 m³) and 9,000 ft³ (225 m³), respectively) there is a significant lag between throttle valve position and low-pressure turbine pressure and flow rate.

While the pressure vessel is quite massive, the inner surface of the Ref. 4-1 design is refractory lined and the relatively low conductivity of the refractory material tends to decouple it from changes in the air temperature. As part of this study effort, the design of the PFBC was modified by insulating the bed rather than the pressure vessel (see the next chapter). This change was received late in the program and was not incorporated in the transient simulations discussed herein. However, a preliminary evaluation of its effect indicated that the exposure of the additional thermal mass represented by the pressure vessel without internal insulation would tend to diminish the rate of

COMBUSTOR PRESSURE VESSEL

4-10

FIG. 4-5

air temperature variation which would occur within the pressure vessel during transient operation. This would in turn moderate the response requirement of the coal feed system i.e., percent change in coal feed rate per minute. Consequently, the simulation performed can be considered to be conservative in that it placed more severe requirements on system transient response.

In the combustor exit stream, thermal mass is not normally a factor since combustor exit temperature is maintained at a constant level.

Turbines

For either the steam turbine modified for use as the expansion turbine or the industrial gas turbine which is used for the low-pressure turbine, turbine response time is quite rapid when compared to the other parts of the system. For this study, turbine speed was assumed to be constant since it is connected to a large grid. Consequently, the only dynamics of interest are due to the volume and the thermal mass of the turbine and housing. Both of these are insignificant when compared to the recuperator and combustor characteristics.

Turbine output power is determined in the same manner as for steady-state calculations. Off-design performance is estimated using an empirically derived "map" that relates pressure ratio, flow, speed, and efficiency.

PFBC/CAES System Dynamic Characteristics

In examining the system dynamics, two approaches were taken. First, to establish a link with previous work the air flow and fuel feed rates were changed concurrently and the disturbance in PFBC temperature and other system parameters were noted. Second, as air throttle valve position was changed, fuel feed rate was changed as required to maintain constant PFBC temperature. This second approach provided data necessary for the design of the fuel feed control system and for the definition of the thermal change requirements for other parts of the system.

Concurrent Change in Air and Fuel Feed Rate

As discussed above, the major factors beside the PFBC combustion dynamics that influence CAES system response are the recuperator thermal mass and the PFBC pressure vessel volume. It is interesting to compare the difference in temperature response of the stand-alone PFBC to a change from 90 percent to 100 percent in air and fuel flow (Fig. 4-4) with that of a fully integrated PFBC/CAES system (Fig. 4-6). In the stand-alone case, the combustor air inlet temperature is held constant and the air flow into the combustor is changed instantaneously by 10 percent. In the integrated PFBC/CAES the air flow is changed by changing

PFBC EXIT TEMPERATURE RESPONSE
TO 10% CHANGE IN AIR AND FUEL FEED RATE

throttle valve restriction. The air flow through the valve will increase (or decrease) almost instantaneously. However, because the PFBC pressure vessel volume is so large the pressure in the vessel will require time to build up, resulting in the air flow rate to the bed taking nearly 5 minutes to reach its steady-state value as is shown in Fig. 4-7. This tends to reduce the disturbance in bed temperature and also to lengthen the time to reach the peak temperature deviation from 5 minutes as was shown in Fig. 4-4 to 8 minutes as is shown in Fig. 4-6.

It should be noted that in the integrated system, bed inlet air temperature also varies as fuel and air flow are changed. In fact, as shown in Fig. 4-8, it changes in a direction that would tend to increase the PFBC temperature disturbance. The initial decrease in PFBC inlet temperature is caused by an increased expansion ratio across the expansion turbine as the throttle valve is opened. The long-term part of the response is the result of the temperature decrease downstream of the PFBC which is felt through the recuperator. The hot-side inlet and cold-side outlet temperatures at the recuperator are shown in Fig. 4-9.

From the above, it is clear that the disturbance in PFBC temperature, caused by a rapid change from a throttle valve setting corresponding to 90-percent air flow to a valve setting corresponding to 100-percent air flow with a concurrent change in fuel feed rate, is not increased by the integration of the PFBC. There are, however, certain circumstances when it could be. For example, if the initial decrease in air temperature to the PFBC were to be accompanied by an immediate increase in air flow, the two would combine to increase the PFBC temperature disturbance. While PFBC pressure vessel volume reduces this disturbance, it also decreases the rate at which power output changes in response to throttle valve setting. Thus, it is important in performing the analysis to consider the probable configuration of the power plant system since it can be a significant factor in the ability of the system to provide the desired response.

Constant PFBC Temperature

Because of the desirability of a constant PFBC temperature, the control system design will likely use a coordinated control of throttle valve flow and fuel feed rate. Therefore, cases were studied where fuel feed rate was varied as needed to maintain constant PFBC temperature while changing throttle valve air flow to produce a desired change in power output. In this manner, required specifications for the performance of the fuel feed device can be developed as a function of the rate of change of throttle valve air flow which is closely related to output power.

A series of calculations were made at various rates of change of throttle valve flow. As would be expected, at lower rates of change (5 percent per

PFBC INLET AIR FLOW RESPONSE
TO 10% CHANGE IN AIR AND FUEL FEED RATE

PFBC INLET TEMPERATURE RESPONSE
TO 10% CHANGE IN AIR AND FUEL FEED RATE

RECUPERATOR TEMPERATURE RESPONSE
TO 10% CHANGE IN AIR AND FUEL FEED RATE

minute), the output power changes at almost the same rate as throttle valve flow. However, at the higher rates there is a substantial difference. For example, if throttle valve position is changed at a rate corresponding to a design output change of 15 percent per minute, the corresponding power change is 12 percent of design output power per minute.

Typical utility requirements would be met with a rate of change of the throttle valve corresponding to 5 percent of design power per minute. Valve position is represented as valve pressure drop divided by upstream pressure. The assumed variation is shown in Fig. 4-10. It produces a change in output power of approximately 4.6 percent per minute as shown in Fig. 4-11. To maintain constant temperature in the PFBC, fuel feed rate must change according to the curve of Fig. 4-12. This curve shows a maximum change rate of approximately 6 percent per minute with a peak feed rate 10 percent greater than the design value. Both of these values fall comfortably within the capabilities of currently available coal feed devices. Standard Petrocarb units of the kind selected for the Ref. 4-1 preconceptual design are reported to have the capability of changing from zero to 100 percent output in 15 minutes, and specially designed units are capable of such a change in 5 minutes or less.

As can be seen in Figs. 4-10 through 4-19 if the throttle valve is changed over a period of 15 minutes (corresponding to 5-percent-per-minute change) all of the other parameters reach their final or steady-state value within approximately 18 minutes. In addition, the relation between the various parameters during this transition period is almost the same as at steady-state conditions. Flow rate to the expansion turbine (Fig. 4-13) closely follows valve position. The PFBC pressure vessel volume causes pressure to build up in the bed through a lag of approximately 2 minutes giving the pressure and flow response shown in Figs. 4-14 and 4-15 respectively. Hot-side recuperator inlet (Fig. 4-16) and cold-side recuperator outlet (Fig. 4-17) temperatures change at approximately the same rate. Because of the high cold-side film coefficient, metal temperature will follow the cold-side profile closely and can be expected to have a maximum rate of change of 25 F/min (14 C/min). Expansion turbine output (Fig. 4-18) experiences a slight overshoot due to the change in inlet temperature (Fig. 4-17) which continues after the flow rate (Fig. 4-13) has ceased to increase. The overall inlet temperature change to the expansion turbine (250 F (139 C)) is within the limits normally allowed for cycling steam equipment. Because of the constant bed temperature, the low-pressure turbine sees no change in inlet temperature, and output (Fig. 4-19) varies almost directly with bed pressure and flow.

To define component requirements at faster response times, throttle valve opening rates of 10, 15, and 25 percent per minute were considered. When changing from 25-percent to 100-percent output a rate of 15 percent per minute, the required change in fuel feed rate appears to approach the limit of current coal feed designs. Over smaller ranges (e.g., from 75 to 100 percent) the

THROTTLE VALVE PRESSURE DROP FOR 5%/MIN RAMP
FROM 25 to 100% POWER

OUTPUT POWER FOR 5%/MIN RAMP

REQUIRED FUEL FEED RATE FOR CONSTANT PFBC
TEMPERATURE DURING 5%/MIN RAMP

AIR FLOW TO EXPANSION TURBINE DURING 5%/MIN RAMP

PFBC PRESSURE DURING 5%/MIN RAMP

PFBC INLET AIR FLOW DURING 5%/MIN RAMP

RECUPERATOR HOT-SIDE INLET TEMPERATURE
DURING 5%/MIN RAMP

RECUPERATOR COLD-SIDE EXIT TEMPERATURE
DURING 5%/MIN RAMP

EXPANSION TURBINE OUTPUT DURING 5%/MIN RAMP

LOW-PRESSURE TURBINE OUTPUT DURING 5%/MIN RAMP

higher change rates could be achieved by allowing a small deviation and bed temperature. As discussed earlier, a throttle valve change rate of 15 percent per minute results in an output power change of approximately 12 percent per minute. As the rate of change is increased and the total change decreased, the system dynamics, rather than the throttle valve, become the controlling factor in the output power change.

For the 15-percent-per-minute change in valve restriction shown in Fig. 4-20, the resultant variation in input power is given in Fig. 4-21. The corresponding change in fuel feed rate is shown in Fig. 4-22. The maximum rate of change of fuel feed is nearly 20-percent-per-minute and the peak feed rate is approximately 20 percent greater than at the full-load design condition. A modified Petrocarb feed unit at Leatherhead has been shown to be capable of such a change rate.

For comparative purposes, the same parameters shown previously for the 5-percent-per-minute case are presented in Figs. 4-20 through 4-29 for a 15-percent-per-minute change in valve restriction. In this case, while the throttle valve reaches its final position in 5 minutes, many of the other parameters take nearly twice that time to approach a steady-state condition. This is not true of air flow to the expansion turbine (Fig. 4-23) which closely follows valve position. However, the effect of PFBC pressure vessel volume is apparent in Figs. 4-24 and 4-25 which show combustor pressure and inlet flow respectively. It is interesting to note that hot- and cold-side (Figs. 4-26 & 4-27 respectively) temperatures have almost the same profile despite the large thermal mass of metal in the recuperator. This is due to the lag between cold- and hot-side flow rates. As cold-side flow increases, it tends to reduce the cold-side exit temperature and causes the temperature to respond more rapidly. If both hot and cold flows were to increase together, there would be an obvious lag between hot- and cold-side temperatures. As mentioned earlier, the recuperator metal temperature will closely follow the cold-side temperature which is shown in Fig. 4-27. Expansion and low-pressure turbine output variations (Figs. 4-28 & 4-29) show a profile similar to those at 5-percent-per-minute.

Over a smaller range it is generally possible to make more rapid variations. Therefore, a change of 25 percent (from 75-percent to 100-percent power output) in one minute was examined. As before, throttle valve restriction was changed and the resultant response observed. The change in output power is shown in Fig. 4-30. Clearly, the system dynamics are limiting the response at this rate. Fuel feed rate (Fig. 4-31) was changed at just over 20 percent per minute and the peak rate was less than 10 percent over the full load design value. The recuperator thermal transient was less severe than for the larger excursion at 15-percent-per-minute. Hot-side inlet temperature and cold-side exit temperature are shown in Figs. 4-32 and 4-33 respectively. The initial change in output is due primarily to the increased flow through the expansion

THROTTLE VALVE PRESSURE DROP FOR 15%/MIN RAMP
FROM 25 TO 100% POWER

OUTPUT FOR 15%/MIN RAMP

REQUIRED FUEL FEED RATE FOR CONSTANT PFBC
TEMPERATURE DURING 15%/MIN RAMP

AIR FLOW TO EXPANSION TURBINE DURING 15%/MIN RAMP

PFBC PRESSURE DURING 15%/MIN RAMP

PFBC INLET AIR FLOW DURING 15%/MIN RAMP

RECUPERATOR HOT-SIDE INLET TEMPERATURE
DURING 15%/MIN RAMP

RECUPERATOR COLD-SIDE EXIT TEMPERATURE
DURING 15%/MIN RAMP

EXPANSION TURBINE OUTPUT DURING 15%/MIN RAMP

LOW-PRESSURE TURBINE OUTPUT DURING 15%/MIN RAMP

OUTPUT POWER FOR 25%/MIN RAMP IN THROTTLE VALVE
FLOW FROM 75 TO 100% POWER

REQUIRED FUEL FEED RATE FOR CONSTANT PFBC
TEMPERATURE DURING 25%/MIN RAMP

RECUPERATOR HOT-SIDE INLET TEMPERATURE
DURING 25%/MIN RAMP

RECUPERATOR COLD-SIDE EXIT TEMPERATURE
DURING 25%/MIN RAMP

turbine. The outputs from the expansion and low-pressure turbines are presented in Figs. 4-34 & 4-35. For small disturbances, rapid response can be achieved by throttle valve motion which directly affects the output of the expansion turbine.

Evaluation of Transient Capabilities

From the above analysis, it is clear that large transients involving a 15-percent-per-minute change in valve restriction can be accommodated at rates of up to 12-percent-per-minute change in output power because component requirements at this rate still appear to be reasonable. A fuel feed rate change of 20-percent-per-minute would be required, however, a modified Petrocarb feed system at Leatherhead has a demonstrated capability to change at this rate and the manufacturer feels that rates as high as 33-percent-per-minute can be achieved with careful design and with sufficient air supply. The air supply is needed to increase the pressure in the pressurized feed hopper during an increasing power transient. In the PFBC/CAES system, cavern air is available and rapid change rates should pose no problem. However, even at currently demonstrated fuel feed change levels, overall system performance is more than adequate as evidenced by the ability to increase power at a rate of 12-percent-per-minute over a large (75-percent) excursion.

While the present study considered only ramp changes in throttle valve restriction, a control system operating on both the throttle valve and fuel feed mechanism could be developed in a more detailed design study. Such a control system could improve the response to small disturbances by utilizing the rapid response available to the expansion turbine output. Also, the restriction imposed on bed temperature could be relaxed to allow temperature excursions of as much as 100 F (55 C). Both of these effects would improve the response capabilities over those estimated in the current study.

Temperature excursions in the recuperator and expansion turbine inlet both occur at a relatively rapid rate (50 F/min (28 C/min)). However, the overall excursion is less than the normal instantaneous excursion in a cycling steam turbine. Neither component is expected to pose a design problem due to temperature changes.

EXPANSION TURBINE OUTPUT DURING 25%/MIN RAMP

LOW-PRESSURE TURBINE OUTPUT DURING 25%/MIN RAMP

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- 4-5 Tung, S. E., J. Goldman, and J. F. Louis: FBC-Modeling and Data Base. Proceedings of the Fifth International Conference on Fluidized Bed Combustion, Washington, DC, December 1977.

PFBC START-UP OPERATION

Start-up time is an important index of peak-load power system performance, and the analysis of this parameter is an important step in the evaluation of the load following characteristics of the open-bed PFBC/CAES concept. Accordingly, the objective of the effort dealing with the start-up operation is to provide an evaluation of the start-up capability of the open-bed PFBC chosen for the PFBC/CAES system.

For the PFBC design in the Ref. 5-1 report, three possible start-up operating modes can be considered:

1) Cold start

A cold start from ambient temperature will only occur after a prolonged shutdown such as for annual maintenance or during commissioning.

2) Warm start

This was the mode indicated in the Ref. 5-1 report as being the normal start-up mode following weeknight and weekend shutdowns. It involves cooling the bed on shutdown to a temperature (approximately 570 F (300 C)) at which the structural components within the pressure vessel can survive without additional cooling. This is achieved by continuing the flow of fluidizing air for a period after shutdown. During start-up, the bed is reheated using auxiliary fuel to raise the temperature to the level (approximately 1290 F (700 C)) at which combustion of coal can begin.

3) Hot start

This mode involves installing insulation to maintain the bed temperature within the operating regime for coal firing (i.e., above 1292 F (700 C)) during a weeknight or weekend shutdown. Coal can therefore be used from the beginning of the start-up sequence. For this option, the fluidizing air would be supplied to the bed during shutdown.

It should be noted that all start-up systems, even those designed primarily for warm or hot start-up modes, must be capable of bringing a combustor to full load from a cold start condition.

Because coal injected into the bed can be expected to burn without the emission of volatile matter containing tars which would cause fouling of the cyclones and turbine only above 1292 F (700 C), it is necessary to heat the bed to this temperature using auxiliary fuel. Thus, all the start-up systems must incorporate auxiliary fuel combustors.

Design Criteria

The CAES plant and its start-up system will be designed to comply with the operating regime identified in Table 2-6. The performance of a start-up system can be assessed in terms of the requirements for auxiliary fuel, air, coal, dolomite, and time. The relative importance of these factors depends on the application. For a CAES system, the criterion selected is start-up time, consequently, systems with only a cold start capability are unlikely to be suitable.

The following parameters have been identified as influencing the start-up response:

- 1) the bed temperature at start-up (cold, warm, or hot),
- 2) the response of the solids handling system, and
- 3) thermal stress considerations.

The relative importance of each of these parameters will depend on the design selected. In the cold and warm start concepts the factor which limits start-up response is thermal stress. This stress can arise from two sources:

1) Refractories

If conventional refractories are used, such as in the design of Ref. 5-1, the permissible heating rate is limited to a low value, typically 360 F/hr (200 C/h) to avoid spalling. This would lead to a start-up time of more than two hours in the warm start concept and to a considerably longer start-up time in the cold start concept.

2) Metallic support components

It would be possible to increase the heating rate and, thus, diminish the impact of the heating rate constant by using refractory materials having a low mechanical strength, with support being provided by metallic components.

It is anticipated that the heating rate limitation imposed by these stresses in such a design would be considerably in excess of the 360 F/hr (200 K/h) limitation of conventional refractories. The design outlined in Ref. 5-1 was assembled as indicative of the size and cost of the combustion system. Extensive engineering work would be required to reappraise and optimize this design to ensure that the required rate of temperature change during cold or warm start-up could be tolerated. This is beyond the scope of the present study.

Faced with the inability of conventional refractories to respond quickly in the cold and warm start modes because of thermal stress considerations, and the absence of data to accurately predict the thermal response limitations of the metallic support components of low mechanical strength refractories, it was deemed prudent to select a start-up mode which would not impose a large heating rate requirement. Thus, a design permitting hot starts after overnight and weekend shutdown periods has been adopted. It should be noted, however, the system must also be capable of start-up from cold, as mentioned previously. This design is described in the following section.

Design Considerations

A hot-start capability has been adopted so that design conditions can be achieved rapidly after overnight or weekend shutdown periods. This results in a short time to reach full load and low auxiliary fuel requirements during start-up.

In order to achieve a hot start, the design of the combustor must take into account the constraints imposed on the coal and dolomite feeding system, distillate fuel burners, air supply system, bed contaminants, and ash removal system. The system must also be capable of start-up from cold during commissioning or after prolonged shutdowns. It is therefore necessary to consider the implications of a cold start for the start-up system design because the size and specification of some equipment items are determined by this duty. These considerations are discussed below.

Coal and Dolomite Feeding

The coal and dolomite preparation system feeds into surge bunkers which can be filled before plant shutdown. The response of the preparation system should not, therefore, represent a constraint on the start-up response. The coal and dolomite flow from the Petrocarb system can be started quickly. An increase from zero to design conditions may be possible in less than 15 minutes for commercially available units, with a 5-minute response having been demonstrated using a modified unit at Leatherhead.

Distillate Fuel Burners

In order to start up from ambient temperature (cold start), a hot start system would require auxiliary fuel burners, together with the associated fuel storage and pumping equipment. Two possible methods of heating the bed to 1292 F (700 C) can be considered:

1) Overbed heating

This approach uses burners placed over the bed and has been found to be effective in both experimental and commercial scale atmospheric FBC units which have relatively shallow beds. However, the rate of heat transfer from overbed burners to the bed is determined by the bed area. It follows that the heating rates achievable in deep beds are less than those achievable in shallower beds. This factor mitigates against the use of overhead burners in a PFBC which has relatively deep beds.

2) Underbed heating

The alternative which has been adopted for the PFBC in the CAES plant is to preheat the air supply to the bed. With an air supply sufficient for fluidization, heat transfer to the bed is efficient because of the good gas-solids contacting. This, therefore, is an effective method of bringing the bed to the required temperature.

Two methods of preheating the fluidizing air were considered:

1) Remote heating

The remote heating alternative was envisaged as a system utilizing a heating chamber with hot gas ducted to strategic locations in the combustion chamber. This method was considered to be fraught with engineering difficulties arising from the need for numerous hot pipes and hot vessel penetrations.

2) Heating within the combustion chamber

The system utilizes standard gas turbine burners within the combustor vessel. The burners fire into the fluidized bed plenum chamber which is insulated to maintain the bed support structure at an acceptable temperature.

Of these two options, the second was chosen.

In order to meet the requirements of the cold start condition, it is estimated that a total burner output of 273.0×10^6 Btu/hr ($80 \text{ MW}_{\text{th}}$) is required. Standard gas turbine burners fueled by No. 2 distillate would be used. The higher heating value of the fuel is taken to be 19,491 Btu/lb (45336 kJ/kg). The number and distribution of the burners will depend on several parameters, including:

- 1) the standard sizes of burners available from manufacturers at the time of construction,

- 2) the access available for burners (this would be considered during a detailed design phase), and
- 3) the system requirements to ensure even bed heating.

It is not possible at this time to determine exactly how the burner duty will be divided among individual units, although it is likely that approximately ten burners would be required.

Air Supply

During a shutdown period, the temperature of the bed containment structure is maintained at approximately 570 F (300 C) by ventilating the plenum chamber (the space within the pressure vessel exterior to the combustor and cyclones). The temperature of the plenum is therefore slightly higher than at 25-percent load. Accordingly, 572 F (300 C) is the design condition and permits the use of carbon steel for the bed containment structure. The internal refractory lining of the pressure vessel as described in the Ref. 5-1 preconceptual design is no longer necessary (see Fig. 5-1). Ordinary external insulation of the pressure shell (not illustrated in figures) will be sufficient for heat conservation purposes. By keeping the plenum chamber temperature close to the operating temperature, thermal stresses set up during start-up should be moderated. It is therefore expected that combustor components will not cause limitations in the start-up time, although this remains to be confirmed by detailed engineering studies, as mentioned previously.

Before coal feeding can commence, the bed has to be fluidized. However, during the period when only the auxiliary burners are operating, three options exist:

- 1) the air flow can be less than that required to fluidize the bed,
- 2) the air flow can be directed toward a section of the bed thus permitting that section to be fluidized, and
- 3) the air flow can be sufficient to fluidize the entire bed.

In the first option, for the underbed burners selected, the rate of heating has an upper limit because gas flow is less than that required for fluidization. This option is, incidentally, unsuitable for overbed burners because of poor heat transfer within the bed.

In the second option, a section of the bed is brought to full load conditions (i.e., the coal in that section is burning at the full load rate) and then adjacent sections of the bed are fluidized and heated to a temperature at which coal feeding can start by the diffusion of the bed material. This method is economical in the use of auxiliary fuel but it is also slow to achieve 100-percent load conditions. In addition, it may have problems of control.

MODIFIED COMBUSTOR LAYOUT

The most rapid start-up method involves fluidizing the entire bed. To minimize the start-up time for hot and cold starts, it is proposed that this approach be adopted. This method of operation however, does not minimize auxiliary fuel requirements during a cold start. The variation of air supply rate and fluidizing velocity during start-up are discussed in a later section.

During start-up from cold, air would be withdrawn from the storage cavern and passed through the recuperator and the high-pressure turbine before being fed into the fluidized bed through the start-up burners. The air would be heated to a suitable temperature by the underbed start-up burners, and these would provide the sole means of bed heating until a bed temperature of 1292 F (700 C) was achieved. The temperature to which the air would be heated is governed by:

- 1) the requirement to reduce start-up times to a minimum, implying as high an air temperature as possible; and
- 2) the constraints on the design of the distributor through which the hot gas will pass, although these constraints can be eased somewhat by a low preheat temperature.

In the absence of a detailed engineering design for the distributor plate, it was decided to assume a moderate air preheat temperature of 1472 F (800 C), determined primarily by the second of the above two considerations. The plenum chamber would not be compartmented; for maximum response, start-up and load following would be carried out using the whole bed. The design for the distributor plate and plenum chamber incorporate proprietary concepts developed prior to the present contract, and details cannot be revealed at this stage.

During hot restart, a small quantity of No. 2 distillate fuel will be fired, if necessary, to prevent the fluidizing air from cooling the bed below 1292 F (700 C) while the coal flow is being established.

Bed Containment

The proposed start-up system assumes that the combustor design can incorporate the following items (see Fig. 5-2):

- 1) Sufficient insulation is provided to maintain the bed at the required temperature during shutdown periods. Specifically, the design criterion is that the mean bed temperature after a weekend shutdown period (i.e., about 63 hours) is at least 1292 F (700 C).
- 2) A method of construction is used which will not cause failure of the insulation thermal shock during rapid temperature rises. The design of the bed containment insulation is, therefore, an important aspect of the hot start concept proposed for CAES applications.

INSULATION AND BED CONTAINMENT DESIGN

The insulation normally specified for combined cycle PFBC plants is a light-weight castable faced by a dense castable to reduce erosion. Typically, the light castable would have a thermal conductivity of approximately 0.116 Btu/hr-ft-F (0.2 W/mC) at the bed operating temperature and the dense phase facing material would have a somewhat higher value of 0.462 Btu/hr-ft-F (0.8 W/mC). This would not provide sufficient insulation to keep the bed temperature above 1292 F (700 C) during a weekend shutdown unless a thickness of approximately 3.3 ft (1 m) is used. Such a thickness would, of course, cause severe constructional difficulties, and resistance to thermal shock would be minimal. The use of lightweight castable faced with dense castable is therefore considered unsuitable for CAES applications because either heating rates would be limited by the refractory thickness or insufficient insulation would be used for a hot start to be possible. For these reasons, an alternative approach to the combustor insulation was considered desirable.

Several vendors offer a range of calcium silicate insulating slabs and cast shapes to the engineering industry. The most notable features of this material are listed below.

- 1) Its thermal conductivity is low (approximately 0.04 Btu/hr-ft-F (0.07 W/mC) at the bed operating temperature).
- 2) It is a relatively light material which can be provided in easily handled units.
- 3) The material is fibrous in nature and exhibits reasonable shock resistance.
- 4) The low coefficient of thermal expansion combined with the softness of the material permits some absorption of thermal stresses within the structure.
- 5) Unlike refractories which can change shape during operation, calcium silicate insulation is expected to remain stable. The expansions and contractions which affect refractories as they dry out would not affect this material because of its porous structure.

In view of the above, calcium silicate insulation is proposed for the bed and freeboard, as shown in Figs. 5-1 and 5-2. The material would be arranged in layered slabs to achieve a composite thickness of 0.98 ft (300 mm), and each composite block of slabs would be retained within an erosion resistant skin. The blocks would be of a size which suited the convenience of installation, and would be installed with small gaps between the adjacent blocks to permit thermal expansion. The material of the erosion resistant skin would be chosen from those which have been examined metallurgically in FBC environments. Two materials which have been noted to provide good corrosion resistance are ASTM austenitic steels type 310 and 347. Of these, type 347 appears to be less

susceptible to sigma phase embrittlement, and has therefore been chosen for this duty. The skins would be perhaps 1/8-in. (3-mm) thick and would be bolted back to the bed containment shell. A detailed design would take into account the need for easy maintenance and replacement.

During shutdown periods, there will be a small heat loss from the insulated bed/freeboard chamber. This could cause some of the structural components within the pressure vessel to reach an unacceptably high temperature, and a means of cooling this region is proposed. A controlled ventilating procedure would be implemented to prevent the bed containment structure exceeding a temperature of 572 F (300 C). Vent valves on the main pressure vessel shell would be opened during the shutdown periods and a fan would be used to blow cold air through the vessel plenum. It is estimated that about 194×10^3 Btu/hr (57 kW) will have to be dissipated by the cooling air. To achieve an air outlet temperature of 482 F (250 C), a fan capacity of 494 ft³/min (14 m³/min) would be required.

Ash Removal System

The systems for removing ash both from the bed and cyclone legs can be pre-started prior to fluidization of the bed, and they should not, therefore, introduce an additional delay in the start-up procedure.

Summary of Selected System

The start-up system selected, although capable of a cold start from ambient temperature, would normally operate in a hot start mode for start-up after an overnight or weekend shutdown period. This is achieved by installing sufficient insulation around the combustor to maintain the bed temperature above 1292 F (700 C) during an overnight or weekend shutdown period. This permits coal to be fed directly on initiation of the start-up sequence. A small amount of distillate fuel oil may be used for start-up after a weekend shutdown.

For a cold start, distillate fuel will be burned to bring the bed temperature to 1292 F (700 C) at which point coal can be fed as in the hot start mode.

In both the cold and hot start modes, the entire bed is fluidized (i.e., no compartmentation of the bed is employed). It is expected that hot restarts after an overnight or weekend shutdown can occur quickly with the probability of being able to establish 100-percent load output within 5 to 15 minutes of fluidizing the bed. The limiting factors in the proposed design are outlined below.

- 1) The response of the Petrocarb system (5 to 15 minutes, as indicated).
- 2) The possibility of heating rate limitations arising from thermal stress in metallic components. Although this aspect has not been considered in the present study, it is worth noting that, should this

prove to be a problem, the coal feed rate could be allowed to reach a level corresponding to 100-percent load before the bed temperature reached 1562 F (850 C). This would provide a rapid initial increase in output, with a slower final approach to 100-percent load output because of the reduced cycle efficiency at the lower combustion gas temperature.

The proposed system is suitable for automation of the restart sequence, and the equipment does not pose any inherent limitation on operating characteristics.

Start-Up System Performance

Having selected the start-up system design, it is now appropriate to discuss the performance of the system. Comments will be provided on the system performance during the three possible modes of system operation: shutdown, start-up from a cold start, and start-up from a hot start.

Shutdown

The hot start concept relies on the installation of sufficient insulation to maintain the bed temperature above 1292 F (700 C) during a weekend shutdown. The calcium silicate insulation is available in a variety of standard and special shape slabs from a number of vendors. The relationship between the average thermal conductivity of a block varies with the hot face and cold face temperatures as shown in Fig. 5-3. The properties refer to a material called "Calsil" which can withstand hot face temperatures (corresponding to the bed temperature) of up to 1832 F (1000 C).

The heat loss through the insulation is calculated from

$$Q = K (T_b - T_{cf})/d, \text{ Btu/ft}^2 \text{ (W/m}^2\text{)} \quad (5-1)$$

where Q is the heat loss, Btu/hr ft² (W/m²)

K is the insulation thermal conductivity, Btu/hr-ft-F (W/m C)

T_b is the bed temperature, F (C)

T_{cf} is the cold face temperature, F (C)

d is the insulation thickness, ft (m)

(see nomenclature in Table 5-1)

The variation of the heat loss during shutdown is illustrated in Fig. 5-4 for a range of cold face temperatures assuming an insulation thickness of 0.98

THERMAL CONDUCTIVITY OF INSULATION BLOCKS

Table 5-1

PERFORMANCE NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
A	area of insulation	ft ² (m ²)
c	mean specific heat of reactants & products	Btu/lb F (J/kg C)
d _b	mean specific heat of bed material	Btu/lb F (J/kg/C)
D	Ca/S ratio	
d	insulation thickness	ft (m)
K	insulation thermal conductivity	Btu/hr-ft-F (W/m C)
M _b	mass of bed material	lb (kg)
M _t	mass flow rate at LP turbine inlet	lb/sec (kg/s)
Q	heat loss	Btu/hr-ft ² (W/m ²)
Q _c	heat of combustion of coal	Btu/lb (J/kg)
Q _d	heat of combustion of distillate fuel	Btu/lb (J/kg)
P _b	pressure at bed inlet	atm (bar)
P _t	pressure at LP turbine inlet	atm (bar)
R _a	rate of air supply	lb/sec (kg/s)
R _c	rate of coal supply	lb/sec (kg/s)
R _d	rate pf distillate fuel supply	lb/sec (kg/s)
R _s	rate of dolomite addition	lb/sec (kg/s)
T	temperature at LP turbine inlet	R (K)
T _b	bed temperature	F (C)
T _{br}	absolute bed temperature	R (K)
T _{bo}	initial bed temperature	F (C)

Table 5-1 (Cont'd)

<u>Symbol</u>	<u>Description</u>	<u>Units</u>
T_{cf}	cold face temperature	F (C)
T_{input}	temperature of the combustion gases after the burners	F (C)
T_o	initial temperature of the air and distillate fuel	F (C)
t	time	sec (s)
u_f	fluidizing velocity	ft/sec (m/s)

HEAT LOSS DURING SHUTDOWN

ft (300 mm). On shutdown, the insulation cold face temperature is assumed to be that for 100-percent load, steady-state operation, and is estimated to be 392 F (200 C). However, the cold face temperature is expected to rise to approximately 572 F (300 C) during shutdown, when the only external cooling effect is from the small quantity of air passed through the pressure vessel. The heat loss profile assumed in the present calculations is indicated by the broken line on Fig. 5-4.

The rate of temperature decay of the bed is determined by a complex pattern of mutual transient heat transfer within and between the bed, freeboard, and insulation. This should be the subject of a detailed design study on insulation at a subsequent stage. For the present analysis, a simplified approach involving the assumption of a uniform bed temperature was adopted. With this assumption, the rate of temperature decay can be related to rate of heat loss by the equation:

$$A Q = c_b M_b \frac{dT_b}{dt} \text{ Btu/hr (W)} \quad (5-2)$$

where c_b is the mean specific heat of the bed material, Btu/lb F (J/kg C)
 M_b is the mass of bed material, lb (kg)
 and A is the area of the insulation, ft² (m²)

The specific heat of the bed material increases from approximately 0.151 Btu/lb F (633 J/kg C) at 32 F (0 C) to 0.264 Btu/lb F (1106 J/kg C) at 1832 F (1000 C). A constant value of 0.220 Btu/lb F (920 J/kg C), corresponding to a temperature of 1112 F (600 C), has been assumed throughout the present analysis, i.e., c_b equals 0.220 Btu/lb F (920 J/kg C). The mass of the bed is assumed to be constant at 264,104 lbs (119800 kg), i.e., M_b equals 264,104 lbs (119800 kg).

The choice of the effective area, A , for heat transfer has, as the upper bound, the containment area of the bed (excluding distributor plate) and freeboard (5199 ft² (483 m²)), see Fig. 5-1). This is regarded as a conservative basis for the calculations, and has been used to estimate that a refractory thickness of 1.15 ft (350 mm) would be required to maintain the bed temperature above 1292 F (700 C) during the weekend shutdown period.

A more realistic estimate is obtained by assuming that heat transfer takes place across the bed containment area and 60 percent of the freeboard containment area (3552 ft² (330 m²)), see Fig. 5-1). This makes allowance for the reduced rate of heat transfer expected in the freeboard section. Based on this assumption, the temperature decay rate has been calculated for a refractory thickness of 0.98 ft (300 mm). The results are illustrated in Fig. 5-5. As shown in the figure, an overnight shutdown of about 15 hours gives a final bed temperature of 1444 F (812 C), and a weekend shutdown of about 63 hours gives a final bed temperature of 1323 F (717 C). The bed would not reach 1292 F (700 C) until approximately 74 hours have elapsed.

TEMPERATURE DECAY DURING SHUT DOWN

The freeboard, cyclones, and ducting will cool to a greater extent during a shutdown period than the bed. Although this will not affect the capability to use the hot start mode after an overnight or weekend shutdown, the heating rates to which these components are subjected and the consequent thermal stresses require consideration at the detailed design stage.

Cold Start

A cold start procedure using distillate fuel has to be adopted if the initial bed temperature is less than 1292 F (700 C). Air is supplied at a constant rate to gas turbine burners in which No. 2 fuel oil is burned, the hot combustion gases passing via the distributor plate to the fluidized bed.

A diagram illustrating the simple model used to describe this system is shown in Fig. 5-6 (see Table 5-1 for nomenclature).

An energy balance on the start-up burners gives:

$$Q_d R_d = c (R_a + R_d) (T_{input} - T_o), \text{ Btu/hr (W)} \quad (5-3)$$

where Q_d is the heat of combustion of the distillate fuel, Btu/lb (J/kg)

c is the mean specific heat of the reactants and products, Btu/lb-F (J/kg C)

T_{input} is the temperature of the combustion gases after the burners, F (C)

T_o is the initial temperature of the air and distillate fuel, F (C)

R_d is the rate of supply of distillate fuel, lb/sec (kg/s)

R_a is the rate of air supply, lb/sec (kg/s)

An energy balance on the combustor bed gives:

$$c_b M_b \frac{dT_b}{dt} = c (R_a + R_d) (T_{input} - T_b), \text{ Btu/hr (W)} \quad (5-4)$$

The following assumptions were made:

- 1) The air supply rate was constant at 30 percent of the steady state design flow rate, i.e., R_a equals 213.0 lb/sec (96.6 kg/s). This assumption is made to match the minimum coal feed rate of 30 percent of design when coal injection is initiated at 1292 F (700 C).
- 2) The heat of combustion of the distillate fuel (Q_d) is 19,491 Btu/lb (45.336×10^3 kJ/kg).

MODEL OF COLD START SYSTEM

- 3) The mean specific heat of the reactants and products (c) is assumed constant at 0.260 Btu/lb F (1087 J/kg C). This value was derived to be consistent with the stream enthalpies given in Table 2-1, and corresponds approximately to the mean specific heat of air from 32 F to 1562 F (0 C to 850 C).
- 4) The feed temperature is assumed to be constant at 120 F (48.9 C), i.e., T_o equals 120 F (48.9 C). In practice, the air supply temperature will increase during the start-up period as the recuperator begins to operate, preheating the air from the LP turbine exhaust gases. The effect of ignoring this factor in the present calculations is to make the estimates of distillate fuel consumption conservative.
- 5) The temperature to which the burners preheat the air (T_{input}) is 1472 F (800 C). Substituting equations c_b , M_b , and R_a into equations 5-3 and 5-4 yields:

$$\frac{dT_b}{dt} = \frac{1.429 - 971 \times 10^{-6} T_b}{0.776 - 971 \times 10^{-6} T_b} \quad \begin{matrix} \text{F/sec} \\ \text{C/s} \end{matrix} \quad \begin{matrix} (5-5a) \\ (5-5b) \end{matrix}$$

and a value of 3.90 lb/sec (1.772 kg/s) or, alternatively, 274×10^6 Btu/hr (80.34 MW) for the rate at which No. 2 distillate fuel oil is fired during start-up (R_d).

The temperature increase is given by the solution of equations 5-5, assuming an initial bed temperature of 120 F (48.9 C) at $t = 0$:

$$T_b = \begin{matrix} 1472 - 1352 \exp(-971 \times 10^{-6} t), \text{ F} \\ 800 - 750.2 \exp(-971 \times 10^{-6} t), \text{ C} \end{matrix} \quad \begin{matrix} (5-6a) \\ (5-6b) \end{matrix}$$

The increase in bed temperature with time is illustrated in Fig. 5-7. The time taken for the bed to reach the minimum temperature (1492 F (700 C)) for coal firing is 34.6 min, starting from a temperature of 120 F (48.9 C). During this time, 8111 lbs (3679 kg) of distillate fuel and 442,100 lb (200542 kg) of cavern air will be required.

For simplicity, it has been assumed that the turbine response conforms to an idealized system in which:

$$M_t \sqrt{T/P_t} = \text{flow parameter} = \text{constant} \quad (5-7)$$

where M_t is the mass flow rate through the low-pressure turbine, lb/sec (kg/s)

T is the absolute temperature at the turbine inlet, R (K)

P_t is the pressure at the turbine inlet, atm (bar)

INCREASE IN BED TEMPERATURE DURING COLD START

The value of flow parameter is expressed in $\text{lb-R}^{1/2}/\text{sec-atm}$ ($\text{kg-K}^{1/2}/\text{s-bar}$). Equation 5-7 has been estimated to be 2457 (820) from the data in Table 2-1 for the 100-percent load condition, so that:

$$M_t \sqrt{T/P_t} = 2457 \text{ (820)} \quad (5-8)$$

Equation 5-8 is compared with actual turbine performance data in Fig. 5-8. The deviation is not considered large for inlet pressures greater than 2 atm (bar).

The variation in turbine inlet pressure during start-up has been estimated from equations 5-6 and 5-8, using the total mass flow (M_t) given by:

$$M_t = R_a + R_d = 216.9 \text{ lb/sec (98.4 kg/s)} \quad (5-9)$$

The results are illustrated in Fig. 5-9. As shown in the figure, the turbine inlet pressure increase from approximately 2 atm (bar) to 3.75 atm (bar) during the cold start period.

The variation in the bed fluidizing velocity has been estimated assuming that the combustion air behaves as an ideal gas,

$$R_a + R_d = \text{constant} \times P_b u_f / T_{br}, \text{ lb/sec (kg/s)} \quad (5-10)$$

where P_b is the bed inlet pressure, atm (bar)
 u_f is the fluidizing velocity, ft/sec (m/s)
 and T_{br} is the absolute bed temperature, R (K)

Substituting the values of R_a , P_b , U_f and T_{bk} into equation 5-10 for the 100 percent design condition (Table 2-1) gives:

$$R_a + R_d = 59017 P_b u_f / T_{br}, \text{ lb/sec (kg/s)} \quad (5-11)$$

For simplicity, the pressure at the bed inlet is taken to be 10 percent higher than at the turbine inlet, i.e.,

$$P_b = 1.1 P_t \text{ atm (bar)} \quad (5-12)$$

Equations 5-11 and 5-12 have been used to estimate the variation of fluidizing velocity during the cold start period. The results are illustrated in Fig. 5-10. At the beginning of the cold start procedure, the fluidizing velocity is 1.64 ft/sec (0.56 m/s), but rises to 2.85 ft/sec (0.87 m/s) when the bed temperature reaches the target value of 1292 F (700 C). The final fluidizing velocity of 2.85 ft/sec (0.87 m/s) is close to the design value of 2.95 ft/sec (0.9 m/s) for steady state operation at between 25 percent and 100 percent load. It is not envisaged that dolomite would be added to the bed during a cold start period.

VARIATION OF $M_t\sqrt{T}/P_t$ DURING START-UP

VARIATION OF LP TURBINE INLET PRESSURE DURING COLD START

VARIATION OF FLUIDIZING VELOCITY DURING COLD START

Hot Start

If the bed temperature is above 1292 F (700 C) then the hot start procedure can be implemented. This situation arises:

- 1) after an overnight shutdown,
- 2) after a weekend shutdown, and
- 3) during completion of the cold start procedure when the bed temperature has been brought to 1292 F (700 C) using distillate fuel.

In the hot start procedure, coal is fed to the bed as soon as fluidization is established. No distillate fuel is required once the coal flow is established. However, there may be a delay of up to 2 minutes in establishing the coal flow. During this time, fluidization with air at about 248 F (120 C) could cool the bed by approximately 144 F (80 C). Since the bed temperature must be at least 1492 F (700 C) for coal firing, start-up from a bed temperature below about 1472 F (800 C) requires distillate fuel to be fired during this 2-minute period. The start-up burners would be fired at their nominal rating of 3.91 lb/sec (1.772 kg/s) of distillate requiring 470 lb (213 kg) of No. 2 fuel oil per start. Referring to the cooling curve in Fig. 5-4, distillate fuel will only need to be fired after a weekend shutdown, and not after an overnight shutdown period.

A diagram illustrating the simple model used to describe this system is shown in Fig. 5-11 (see Table 5-1 for nomenclature). This model does not take into account the distillate fuel which may be needed during the initial 2-minute period, and assumes that coal feeding begins an initiation of the start-up sequence.

An energy balance on the combustor bed gives,

$$Q_c R_c = c_b M_b \frac{dT_b}{dt} + c (R_a + R_c)(T_b - T_{input}), \text{ Btu/hr (W)} \quad (5-13)$$

where R_c is the rate of coal feed, lb/sec (kg/sec)

and Q_c is the heat of combustion of the coal, Btu/lb (J/kg)

The assumptions used follow those of the previous section, with the addition of the points detailed below:

- 1) The effective heat release in the fluidized bed by combustion of the coal (Q_c) is taken to be 10,514 Btu/lb (24.456×10^3)

MODEL OF HOT START SYSTEM

kJ/kg). This value has been derived from the data in Table 2-1 and therefore includes allowances appropriate to design conditions for unburned carbon, thermal losses, sensible heat loss in the ash and dolomite, heats of calcination and sulfation of the dolomite, and latent heat loss.

- 2) The air rate is assumed to be controlled to maintain a constant excess air level equal to that at design throughout the hot-start period. From the data in Table 2-1, the rate of air supply is therefore specified by:

$$R_a = 29.889 R_c, \text{ lb/sec (kg/s)} \quad (5-14)$$

- 3) The fluidizing air is assumed to be preheated by the recuperator to the same temperature as for steady operation at design, i.e., T_{input} equals 251.4 F (121.9 C). This assumption tends to overestimate coal requirements since the LP turbine exhaust gases will be hotter than at design during the initial stages of a hot start owing to the low expansion ratios.

Substituting c_b , M_b , c_b , and Q_c , R_a , and T_{input} into equation (5-13) gives,

$$\frac{dT_b}{dt} + 138.2 \times 10^{-6} R_c T_b = 0.215 R_c, \text{ F/sec} \quad (5-15a)$$

$$\frac{dT_b}{dt} + 3.046 \times 10^{-4} R_c T_b = 0.259 R_c, \text{ C/s} \quad (5-15b)$$

Solving this equation gives,

$$T_b = \frac{1562 - (1562 - T_{b0}) \exp(-138.2 \times 10^{-6} R_c dt), \text{ F}}{850 - (850 - T_{b0}) \exp(-3.046 \times 10^{-4} R_c dt), \text{ C}} \quad (5-16a)$$

$$(5-16b)$$

where T_{b0} is the initial bed temperature at $t = 0$, F (C)

It is interesting to note from equation 5-16 that the total coal consumed under these conditions (i.e., $R_c dt$) depends only on the initial and final bed temperatures and not on the time profile followed by the coal feed rate, R_c . This arises from the assumptions of constant air-to-coal ratio and constant air inlet temperature. The form of equation 5-16 also indicates that the bed temperature approaches 1562 F (850 C) asymptotically under the present assumption of constant excess air level.

It is envisaged that the Petrocarb injection system would be brought into operation at the minimum feed rate of 30 percent of design (i.e., 7.12 lb/sec (3.23 kg/s) as-fired) and increased linearly to design (i.e., 23.74 lb/sec (10.77 kg/s)) over a period of 15 minutes. This pattern of operation is illustrated in Fig. 5-12. The coal feed profile shown in the figure has been assumed to apply to all hot starts in the present analysis, although some of the constraints may be less stringent when starting up after an overnight shutdown than after a weekend shutdown. More detailed work is required to confirm that the stresses generated during the 15 minute start-up sequence are tolerable. Such work would also indicate the potential for reducing the start-up time when the bed temperature is greater than 1492 F (700 C). As, for example, following an overnight shutdown period. The total coal consumption during the 15-minute hot start period is 13,890 lb (6300 kg).

During the hot start period, the variation of the coal feed rate with time can be described by the equation:

$$R_c = \begin{array}{l} 7.12 + 18.470 \times 10^{-3} t, \text{ lb/sec} \\ 3.23 + 8.378 \times 10^{-3} t, \text{ kg/s} \end{array} \quad \begin{array}{l} (5-17a) \\ (5-17b) \end{array}$$

The variation of bed temperature with time during a hot start has been calculated from equations 5-16 and 5-17 for initial starting temperatures of 1292 F, 1382 F, and 1472 F (700 C, 750 C, and 800 C). The results are illustrated in Fig. 5-13. The bed temperatures at the end of the 15-minute start-up period are 1522 F, 1535 F, and 1544 F (828 C, 835 C, and 843 C) for initial temperatures of 1292 F, 1382 F, and 1472 F (700 C, 750 C, and 800 C), respectively.

Because it is assumed that the bed is operated throughout the hot start procedure at the same excess air level as for 100-percent load (709.65 lb/sec (321.9 kg/s)). The air rate is given by:

$$R_a = \begin{array}{l} 212.46 + 0.552 t, \text{ lb/sec} \\ 96.6 + 0.2503 t, \text{ kg/s} \end{array} \quad \begin{array}{l} (5-18a) \\ (5-18b) \end{array}$$

The total air requirement during a hot start is 415,118 lbs (188311 kg).

In the situation where a hot start procedure has been initiated following a cold start using distillate fuel, the air rate required at the beginning of the hot start phase is the same as that used during the cold start phase (i.e., 30 percent of design or 212.96 lb/sec (96.6 kg/s)).

It is further assumed that 91.4 percent of the coal as fed to the combustor (derived from the data in Table 2-1) contributes to the combustion gas mass flow. The mass flow rate into the low-pressure turbine during a hot start is therefore given by:

$$M_t = R_a + 0.914 R_c, \text{ lb/sec (kg/s)} \quad (5-19)$$

INCREASE IN COAL FEED RATE DURING HOT START

VARIATION OF BED TEMPERATURE DURING HOT START

The variation in the low-pressure (LP) turbine inlet pressure during a hot start has been estimated using equations 5-8, 5-16 and 5-19. The results are illustrated in Fig. 5-14. The main factor determining the low-pressure turbine inlet pressure is the mass flow rate. Temperature is a secondary factor, the computed values for starting temperatures of 1292 F, 1382 F, and 1472 F (700 C, 750 C and 800 C) differing by about 0.1 atm (bar) from the line shown in the figure. Because the mass flow rate increases linearly over the 15-minute period, the pressure also increases linearly (excluding the small effect of temperature).

The fluidizing velocity during a hot start is given by setting R_d equal to zero in equation 5-11. Substituting from equations 5-8, 5-12, 5-14, and 5-19 gives the following relationship for the fluidizing velocity,

$$u_f = \sqrt{T_{br}} / 15.14, \text{ ft/sec} \quad (5-20a)$$

$$u_f = \sqrt{T_{pk}} / 37.02, \text{ m/s} \quad (5-20b)$$

The fluidizing velocity therefore depends only on the bed temperature in the present start-up system, the effect of mass flow rate and pressure being self-cancelling. The range of fluidizing velocities is correspondingly small, increasing from 2.76 ft/sec (0.84 m/s) at 1292 F (700 C) to 2.95 ft/sec (0.9 m/s) at 1562 F (850 C). The value at 1292 F (700 C) differs slightly from that given for the end of a cold start phase because, in the latter case, the mass flow of combustion products of the distillate fuel is included.

For the coal specified in Table 2-4, the dolomite feed rate is related to the coal feed rate by the equation:

$$R_s = 0.1842 D R_c, \text{ lb/sec (kg/s)} \quad (5-21)$$

where R_s is the rate of stone (dolomite) addition, lb/sec (kg/s)
and D is the Ca/S ratio.

For a constant Ca/S ratio, the dolomite feed rate is proportional to the coal feed rate and, therefore, increases linearly with time during a hot start in the present system. Similarly, the total dolomite consumption is proportional to the total coal consumption. The choice of Ca/S ratio on start-up will depend on the composition of the bed immediately prior to shutdown. Prolonged operation at part load may necessitate a higher Ca/S ratio on turn up than would be predicted for steady-state operation. It is, however, expected that the Ca/S ratio required during a hot start will lie in the range 1.5 to 2.8, giving dolomite requirements of 3838 lb to 7163 (1741 kg to 3249 kg).

Summary of PFBC Start-Up System Operation

The design and performance of the proposed start-up system has been considered in the preceding commentary.

VARIATION OF LP TURBINE INLET PRESSURE DURING HOT START

Two main modes for start-up from no load to full load are discussed:

- 1) A cold start from near ambient temperature, using distillate fuel to preheat the bed to 1292 F (700 C).
- 2) A hot start from temperature above 1292 F (700 C), carried out using coal, supplemented by a small amount of distillate fuel when initial bed temperature is less than 1472 F (800 C).

To meet the requirement of a short start-up time for CAES applications, the combustor design now proposed incorporates sufficient insulation around the combustor to maintain the bed temperature above 1292 F (700 C) over a weekend shutdown. The insulation proposed is a calcium silicate material and has good resistance to thermal stress. No insulation on the inside of the pressure vessel would be necessary. The use of insulation permits a hot start to be the normal start-up mode after a weekend or overnight shutdown. Although a small amount of distillate fuel may be required for start-up after a weekend shutdown, it is not expected that distillate fuel will be required for start-up after an overnight shutdown period.

For a cold start, the factors limiting the start-up time are the rate of firing of distillate fuel and the temperature at which hot combustion gases can be fed to the bed through the distributor plate. The limiting factors for a hot start are thermal stress considerations for metallic and ceramic components in the combustor and the response of the Petrocarb coal injection system.

By ensuring that the air rate required at the beginning of the hot start is that used during a cold start, the former can follow the latter without interruption. The rates are also chosen so that the fluidizing velocity is approximately constant during a hot start and the solids feed rate lies within the turndown capability of the Petrocarb system.

It is estimated that the time required for a hot start is 15 minutes and for a cold start 50 minutes (35 minutes to reach 1292 F (700 C) on distillate fuel, and a 15-minute hot start period).

The performance of the combustor during hot and cold starts is summarized in Table 5-2. It should be noted that the proposed start-up procedure is based on simple assumptions, and should be regarded as indicative only. In particular, the assumption of constant excess air level does not optimize heating rates or fuel requirements. Optimization of the procedure is outside the scope of the present study, but may result in significant reductions in the start-up time and materials' requirements (i.e., distillate, air, coal and dolomite).

Table 5-2

SUMMARY OF START-UP PERFORMANCE

	<u>Cold start</u>	<u>Hot start overnight</u>	<u>Hot start weekend</u>
Distillate, lb (kg)	8111 (3679)	-	470 (213)
Air, lb (kg)	442,112 (200,542)	415,148 (188,311)	415,148 (188311)
Coal, lb (kg)	0	13889 (6300)	13889 (6300)
Dolomite, lb (kg)			
Ca/S 1.5	0	3838 (1741)	3838 (1741)
Ca/S 2.8	0	7163 (3249)	7163 (3249)
Time, min	34.6	15	15

Reference

- 5-1 Giramonti, A. J., R. D. Lessard, D. Merrick, and M. J. Hobson.
Technical and Economic Assessment of Fluidized Bed Augmented Compressed
Air Energy Storage System. UTRC Report R80-954490-20, Supported by
Pacific Northwest Laboratory Subcontract No. B-15299-A-L, June 1980.

Appendix A

CONVERSION FACTORS

<u>Unit</u>		<u>Equivalent</u>
atmosphere (atm)	=	101,325 Nm ⁻²
bar	=	100,000 Nm ⁻²
British thermal unit (Btu)	=	1,055 J
British thermal unit/hour (Btu/hr)	=	0.293 071 W
Fahrenheit (F)	=	[5/9 (F-32)] C
foot (ft)	=	0.3048 m
inch (in.)	=	25.4x10 ⁻³ m (mm)
micron	=	10 ⁻⁶ μm
pound mass (lb)	=	0.4536 kg
psi	=	6894.76 Nm ⁻²
Rankine (R)	=	5/9 K
ton	=	1016.05 kg
tonne (t)	=	1000 kg
watt (w)	=	J/s
giga (g)	=	10 ⁹
mega (m)	=	10 ⁶
kilo (k)	=	10 ³
milli (m)	=	10 ⁻³
micro (μ)	=	10 ⁻⁶

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