Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System

**Volume I
Executive Summary**

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**Prepared for
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TECHNICAL AND ECONOMIC ASSESSMENT
OF FLUIDIZED BED AUGMENTED COMPRESSED
AIR ENERGY STORAGE SYSTEM
VOL I - EXECUTIVE SUMMARY

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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 During subsequent daytime peak load periods, the compressed air would be withdrawn from storage, heated, and expanded through turbines to generate peak power.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 technical and economic assessment 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 and Acres American Incorporated. 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. The work described herein was initiated in November 1978 and completed in April 1980.

The results of this assessment effort are presented in three volumes. Volume I - Executive Summary provides a concise overview of all major elements of the assessment including the conclusions. Volume II - Introduction and Technology Assessment presents a discussion of program background and an in-depth coverage of both fluid bed combustion and turbomachinery technology pertinent to their application in a CAES power plant system. Volume III - Preconceptual Design contains the system analysis which led to the identification of a preferred component configuration for a fluidized bed combustion augmented compressed air energy storage system, the results of the effort which transformed the preferred configuration into preconceptual power plant design, and an introductory evaluation of the performance of the power plant system during part-load operation and while load following.

The United Technologies Research Center provided overall program management and major contributions in the areas of turbomachinery technology assessment, systems analysis, turbomachinery preconceptual design, power plant economics, part-load operation, and load following. This effort was performed under the general guidance of F. L. Robson, Chief, Utility Power Systems and involved the following people:

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Coal Processing Consultants Limited provided contributions in the areas of fluid bed combustor technology and fluid bed combustor preconceptual plant design. These efforts involved the following people:

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Acres American Incorporated provided contributions in the areas of balance-of-plant preconceptual design and institutional factor identification. These efforts involved the following people:

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

The study program was conducted under the general direction of W. V. Loscutoff 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

VOLUME I - EXECUTIVE SUMMARY

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Executive Summary

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 very high pressure air. The compressed air energy storage (CAES) concept (Fig. 1) involves using off-peak electricity generated from indigenous coal or nuclear sources to compress air, storing the air in large underground facilities, and withdrawing the air during peak-load periods when it would be heated by combustion and expanded through gas turbines to generate power. The attractiveness of the CAES concept is based upon its potential to supply competitively priced peaking energy, to reduce peak-load power plant dependence on petroleum-based fuels, and to provide a means for leveling the utility system load demand. Over the last decade, the CAES concept has evolved through the preliminary study phase to a commercial operation of a 290-MW gas-fired power plant in the Federal Republic of Germany (Ref. 1). However, with the recent rampant escalation in fuel oil costs, it became timely to investigate advanced CAES concepts which totally eliminate dependence on petroleum-based fuels.

In response to this need, the United Technologies Research Center (UTRC) was awarded a subcontract from Pacific Northwest Laboratory (PNL) which is operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute to perform a technical and economic assessment of coal-fired fluidized bed combustor/compressed air energy storage (FBC/CAES) systems. In the performance of this contract, UTRC was assisted by Coal Processing Consultants Limited (CPC) of the United Kingdom and Acres American Incorporated (AAI). This assessment was carried out in a four-phase program having the principal tasks outlined in Table 1.

The conclusions drawn from the FBC/CAES study program are encouraging. They indicate that pressurized FBC/CAES power plants should be technologically feasible, provide good performance, and be economically competitive. Specifically, it is concluded that:

- Coal-fired FBC/CAES systems should be technically feasible in the near future and potentially attractive for peak-load power generation.
- An open-bed PFBC/CAES configuration would provide the best candidate for early commercialization. It has relatively low risk combined with moderate cost and reasonable round-trip heat rate. It also has the potential for future growth options which tend to reduce costs and lower fuel consumption.

SIMPLIFIED COMPRESSED AIR ENERGY STORAGE SYSTEM

Fig. 1

TABLE 1

FBC/CAES PROGRAM

- - Assess fluid bed combustor and turbomachinery technology relative to integration potential in CAES applications
 - Identify a preferred FBC/CAES power plant system configuration
 - Transform the selected FBC/CAES system configuration into a preconceptual power plant design
 - Evaluate the part-load and load-following capabilities of the selected FBC/CAES power plant.
- Commercial implementation of PFBC/CAES power plants requires continued R&D for both the fluid bed combustor and the turbomachinery. The PFBC R&D would concentrate on extending and improving current designs for cycling operation while turbomachinery R&D would be directed toward establishing materials and blade designs resistant to corrosion and erosion.
- A PFBC/CAES power plant could be designed and built utilizing many standard equipment items and modifications of existing equipment designs. Commercial application during the latter half of the 1980 decade is possible.
- The economic competitiveness of the PFBC/CAES power plant is strong. It could produce lower cost electricity than conventional oil-fired gas turbine and combined cycle competitors for annual utilization above about 1225 hr/yr. Above about 1925 hr/yr it could produce lower cost power than oil-fired CAES plants.
- Preliminary indications are that an open-bed PFBC/CAES power plant should have good part-load performance. Furthermore, it appears that the PFBC and turbomachinery could respond to modest changes in load demand (on the order of 10-percent) within reasonably short periods (on the order of five minutes).

CAES FLUID BED COMBUSTOR AND TURBOMACHINERY TECHNOLOGY ASSESSMENT

In principle, application of a coal-fired FBC in a CAES system would entail substitution for the premium fuel-fired combustor. However, this application creates the potential for a large number of different FBC/CAES power plant system configurations incorporating either a pressurized fluid bed combustor (PFBC) or an atmospheric fluid bed combustor (AFBC).

If a PFBC were used, high-pressure air would be fed into the combustor to serve as combustion air. The combustion gases from the PFBC would then be cleansed before expansion in the turbine. Another possible approach would have the high-pressure airflow split into two streams prior to the PFBC. One stream of the high-pressure air would pass through heat transfer tubes immersed in the bed while the second stream would go directly into the combustor. The combustion gases would then be cleansed and mixed with the clean heated air prior to expansion.

If an AFBC were used, high-pressure air would be heated in tubes immersed in the bed and then expanded through the turbine. The turbine exhaust air could then be fed into the combustor to provide combustion air. The combustion gases from an AFBC would be at atmospheric pressure and could not be mixed with the heated air flowing to the turbine, as in the PFBC, but would be directed to the stack after transferring its thermal energy to the high-pressure air.

Integrating the fluid bed combustor, gas turbine, air storage, and heat transfer equipment into an efficient and economical power plant requires an appreciation of the operational and design limitations imposed by the state of technology associated with each of these major subsystems to ensure compatability among them. In previous conceptual design studies (Refs. 2, 3, and 4) of petroleum-fired CAES power plant systems, considerable effort was expended to ensure that compatability existed among the gas turbine, air storage, and heat transfer equipment. By effectively using the results from these studies, attention can be focused upon the novel feature of the FBC/CAES power plant system, i.e., the substitution of a coal-fired FBC for the premium fuel-fired combustor.

Fluid Bed Combustor Technology

The design of a coal-fired FBC is significantly influenced by the operating conditions. The most important of these are bed temperature, fluidizing velocity, operating pressure, and particle size. The bed temperature of the FBC must be controlled within fairly narrow limits, i.e., 1425 to 1650 F (775

to 900 C). This control is necessary to achieve high combustion efficiency, obtain high heat transfer rates to in-bed tubes, maximize sulfur retention, avoid ash sintering, limit the metal temperature of heat transfer surfaces in the bed, and reduce emissions of nitrogen oxides and alkali metal salts. The fluidizing velocity must also be controlled within fairly narrow limits, i.e., 2.5 to 4.5 ft/sec (0.75 to 1.4 m/s) for a PFBC and 2.5 to 8 ft/sec (0.75 to 2.5 m/s) for an AFBC. Operation within this range will establish bed fluidization, provide oxygen for combustion, and limit elutriation of bed particles. The selection of operating pressure will influence combustion efficiency, sulfur retention, nitrogen oxides emission levels, and capital costs. Operation at elevated pressure (PFBC) will produce beneficial results for all of these parameters as opposed to operation at atmospheric pressure (AFBC). The choice of particle size is related to the choice of fluidizing velocity. The lower limit of particle size is determined by the requirement to avoid excessive carryover of combustible material, unreacted sorbent, and bed material. The upper limit is determined by the desire to achieve high heat transfer rates to in-bed tubes and effective solids mixing without localized segregation. The design of a FBC for CAES applications is also influenced by factors unique to peaking and load-leveling applications. These include good part-load performance, rapid load following, and the ability to start up and shut down everyday.

Turbomachinery Technology

The turbomachinery design is also significantly influenced by the operating conditions which, in a FBC/CAES power plant, depend on whether an AFBC or a PFBC is used. In either case, however, the operating temperature will be characteristic of conditions which were attainable in gas turbines twenty years ago.

The application of an AFBC would require relatively minor modification of clean fuel-fired turbomachinery designs. The AFBC would be used as an air heater, and this heated air would be expanded through the turbine. Although the turbine would be relatively simple to design, an AFBC/CAES system would still be faced with a materials problem. The extensive heat transfer surfaces immersed in the bed and, to a lesser extent, in the hot convective zone following the bed must contain the high-pressure compressed air while being subjected to high temperature in a relatively corrosive environment.

The use of a PFBC would present more of a design challenge to ensure high reliability and low maintenance for the turbine. The size and amount of particulates entering the turbine would have to be controlled within narrow limits by effective hot gas cleanup to minimize turbine erosion and particle deposition. A limited amount of particles between 2 and 10 microns could be tolerated; however, particles greater than 10 microns would have to be removed from the

PFBC effluent gas stream before the turbine. Small particles (1 micron and less in size) have an affinity to adhere on impact; therefore, concentrations sufficient to cause fouling of the airfoils must be avoided. The level of volatilized alkali metal salts in the PFBC effluent gas must be kept to a minimum, and corrosion resistant materials or coatings must be used to reduce the potential for excessive corrosion.

Availability and R&D Requirements

Off-the-shelf FBC and turbomachinery equipment presently do not exist for FBC/CAES applications; thus, there are R&D efforts required for each component.

Small scale, commercial fluid bed boiler systems can be engineered now. However, the larger, higher temperature FBC equipment associated with CAES systems require continued development.

The major R&D requirements for fluid bed combustors for CAES applications include feeders for the coal and sorbent, devices for ensuring efficient lateral distribution of fuel in the bed, containment for the combustor (PFBC), distributors for the fluidizing and combustion air, heat transfer surfaces for both in-bed and above-bed tubes if used, depressurization systems for spent sorbent and fuel ash, and control systems for load following.

If an AFBC were used in a CAES power plant system application, the modification of existing premium fuel-fired turbomachinery should not produce any significant problems. Although recent PFBC/turbomachinery test results (Refs. 5, 6, and 7) are promising, the turbines for expansion of gases from a PFBC still represent a significant design uncertainty at this time.

The major areas of turbomachinery R&D would be directed toward compatibility between a PFBC and the turbine. The effect of erosion on gas turbines must be better documented, and effective hot gas cleanup systems must be developed to control particulates. Methods must be developed which will limit deposition. The corrosion mechanism must be better understood, and coating materials must be developed that will not only withstand corrosion but the combined effects of corrosion and erosion.

SYSTEMS ANALYSIS

The FBC/CAES system integration incorporated a system design philosophy used by UTRC in previous studies (Refs. 2, 4 and 9) wherein the turbomachinery contains both low- and high-pressure components. In such a system, the low-pressure compressor train is used to raise the air to an intermediate-pressure level (typically 10 to 20 atm (bar)), after which the booster compressor is used to increase the pressure to a level compatible with the air storage pressure (typically 40 to 80 atm (bar)). The high-pressure expansion turbine and low-pressure turbine perform the reverse role. Using this system design philosophy as a basis, it is then possible to tailor the high-pressure turbomachinery components to a specific air storage pressure.

For the systems analysis, the performance, cost and risk of over twenty different FBC/CAES system configurations were assessed to identify the system configuration that has the greatest potential for near-term commercialization. They were placed into four generic groups and then ranked relative to each other (Table 2). The AFBC/CAES systems with low-temperature air tubes were judged to be questionable for commercial applications. These systems would have low risk resulting from the lack of turbine corrosion/erosion problems, but they also have relatively high cost and poor performance. The open-bed PFBC/CAES systems were identified as an attractive near-term candidate systems (Fig. 2). This is based on the relatively low risk for the PFBC design (no tubes in bed), the moderate costs, and the respectable round trip heat rates which these systems exhibited. The PFBC/CAES systems with low-temperature air tubes were also an attractive candidate (Fig. 3). Their cost and heat rate were lower than for the open-bed PFBC/CAES systems; however, because of the tubes in the bed, the risk is increased slightly. The open-bed very high pressure (VHP) PFBC/CAES systems exhibit superior performance but have high risk, unknown costs, and a more long-term commercialization potential. This concept may become a future candidate once better design and costing data become available.

Because it was evident that the open-bed PFBC/CAES and immersed-tube PFBC/CAES system configurations were the most attractive, only these system configurations were considered further for the preconceptual design effort. Of the two, the latter has the lower cost and heat rate, but it could not become commercial until about 1990 (Fig. 4). The former has lower risk and could be commercialized after 1985 (Fig. 4). Based upon this potential for earlier commercialization, the open-bed PFBC/CAES system configuration (Fig. 2) was selected for the preconceptual design effort.

TABLE 2
ASSESSMENT OF FBC/CAES SYSTEMS

<u>System</u>	<u>Performance</u>	<u>Cost</u>	<u>Risk</u>	<u>Prognosis</u>
AFBC/CAES- tubes	P	P	G	Questionable
PFBC/CAES- open bed	P-M	M	G	Attractive Candidate
PFBC/CAES- tubes	M-G	M-G	M	Attractive Candidate
PFBC/CAES- open bed, VHP PFBC	G	?	P	Future Candidate

G = Good
M = Moderate
P = Poor

OPEN-BED PFBC/CAES CONFIGURATION

Fig. 2

IMMERSED-TUBE PFBC/CAES CONFIGURATION

Fig. 3

FBC/CAES TECHNOLOGY TIME SCALE

Fig. 4

PFBC/CAES POWER PLANT PRECONCEPTUAL DESIGN

After the open-bed PFBC/CAES system was selected, it became the subject of a critical review to define the system in detail sufficient to serve as the basis for the preconceptual design effort. This review included the implementation of a design approach philosophy which mandated the maximum utilization of existing CAES component and plant designs (Refs. 2, 4, 8 and 9). It also included modification, where necessary, to the operating requirements and/or existing designs to assure compatibility between them.

For the purposes of this preconceptual design, a four-unit plant was selected. The key full-load design point operating characteristics of the plant are summarized in Table 3. The generation, compression, and round trip heat rates represent the energy consumption during the corresponding operating periods per unit of electrical energy generated during the peak-load period. These energy requirements are approximately the same order of magnitude as the corresponding requirements for oil-fired CAES systems, but with coal being the primary energy source.

The site arrangement of the complete four-unit FBC/CAES plant is shown in Fig. 5. The underground cavern is positioned on 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. For the purposes of this study, rail access has been established at the lower-left corner of the plant site.

The power block (one quadrant of which is shown in Fig. 6) contains the turbomachinery buildings, fluidized bed combustors, coal and dolomite processors, and the central control and administration building. To reduce the impact of noise on surrounding properties, the power block is located toward the center of the site, away from boundaries. Within the power block, the four 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 is located adjacent to the power block, since it is tied directly to it through several sets of power conductors. The forced draft wet cooling towers are located on the lower side of the site, adjacent to the power block. Their location is in close proximity to the power block to reduce the cost of the large piping systems required to direct cooling water between the power block and cooling towers.

TABLE 3

KEY PFBC/CAES POWER PLANT OPERATIONAL CHARACTERISTICS

Turbine output, MW - 4 units	876.4	
Compressor input, MW - 4 units	799.6	
Heat Rate, Btu/kWh (kJ/kWh)		
Generation	4538	(4788)
Compression	9095	(9595)
Round trip	13633	(14383)
Storage pressure, atm (bar)	71.2	(72.1)
PFBC bed temperature, F (C)	1562.0	(850)
PFBC bed pressure, atm (bar)	15.0	(15.2)
ET inlet temperature, F (C)	507.5	(264.2)
LT inlet temperature, F (C)	1562.0	(850)
Annual utilization, hr/yr	2190	
Capacity factor	0.25	

SITE ARRANGEMENT PLAN

POWER BLOCK ARRANGEMENT

FIG. 6

Pressurized Fluid Bed Combustor System

The fluid bed combustor system encompasses the following:

- 1) coal and dolomite handling - rail lines, conveyance from rail lines to stockpile, and from stockpile to power block;
- 2) coal and dolomite preparation - drying and milling;
- 3) coal and dolomite feeding - injection to combustor;
- 4) fluid bed combustor and particulate cleanup;
- 5) ash and spent dolomite removal - removal of waste from combustor, conveyance to storage, and removal from storage; and
- 6) controls and instrumentation.

Two 40-car unit trains deliver approximately 7716 tons/week (7000 tonnes/w) of coal and 2480 tons/week (2250 tonnes/w) of dolomite to the site. They utilize two sidings which run parallel to the main rail line (Fig. 5). The coal and dolomite are unloaded into underrail recovery hoppers and conveyed to stockpiles which hold 60-calendar days supply.

Separate mills for the coal and dolomite dry and crush the material to the required top size of 1/8 in (3 mm) 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. 7) 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). The bed itself is horizontal, refractory-lined, and tapered from top to bottom with a 2 to 1 area ratio. The bed measurements are 88 ft (26.8 m) long, 9.5 ft (2.9 m) wide at its maximum point, and 10 ft (3.0 m) high with a 10 ft (3.0 m) freeboard. The maximum bed area is 870 ft² (78.1 m²). It operates at 1560 F (850 C) and 15 atm (15.2 bar) 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.

FLUID BED COMBUSTOR END VIEW

FIG. 7

Ash and spent dolomite are released through a bed level control system into a pneumatic conveying system. After cooling and solids removal in a cyclone, the conveying air is further filtered, cooled, and then returned to the combustor. The solids are discharged through pressure locks, then conveyed to storage. The fines collected from the gas cleanup cyclones are handled in the same way.

Power Generation System

The power generation system encompasses the following:

- 1) compressors - low pressure and booster;
- 2) turbines - low pressure and expansion;
- 3) clutches;
- 4) motor/generator; and
- 5) heat exchangers - intercoolers, aftercooler, and recuperator.

All the turbomachinery has been placed on a common centerline (Fig. 8) 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, the turbines are uncoupled and the motor/generator drives the compressors. An axial-flow, seventeen-stage, low-pressure compressor pressurizes 761.8 lb/sec (345.5 kg/s) of ambient air to 16.6 atm (16.8 bar). There is one stage of intercooling after the seventh compressor stage. The compressed air from the low-pressure compressor is 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.

During the power generation mode, the compressors are uncoupled and the turbines drive the motor/generator. 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 (refer to Fig. 7) with the cooler, expansion turbine

TURBOMACHINERY TRAIN

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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 Equipment

The balance of plant includes those components and systems required to support the operation of the main turbomachinery and PFBC system. Most of these components and systems are common in both function and size to commercially available facilities. Others are unique to the CAES system and reflect a departure from standard power plant design practice.

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) plant electrical system including the electrical equipment and systems required to effect a workable PFBC/CAES power plant.

The energy storage system (Fig. 4) includes those major surface and underground structures which store air compressed during utility off-peak hours. Compressed air could be stored in salt, aquifer, or hard rock formations. The latter option was selected for this study so that maximum use could be made of storage system designs prepared during previous CAES studies (Refs. 2, 4, and 9). The compensating reservoir maintains the compressed air storage pressure at an essentially constant value by supplying a constant head of water to the air storage cavern. It is approximately 900 ft (275 m) in diameter with a dike height of 35 ft (11 m) to accommodate the 25 ft (7.5 m) fluctuations of reservoir height. The water shaft is a 20 ft (6.1 m) diameter, concrete-lined structure extending approximately 2200 ft (670 m) between the surface reservoir and cavern. A separate air shaft connects the surface air piping and underground cavern. It is constructed of stainless steel approximately 4 ft (1.2 m) in diameter and supported by an outer concrete casing approximately 2 ft (0.6 m) thick.

The underground cavern provides storage space for the compressed air and compensating water volumes. The underground cavern consists of four hard-rock

tunnels interconnected by collection tunnels at the two ends. Each tunnel is approximately 60 ft (18 m) in width, 1400 ft (425 m) in length, and 85 ft (20 m) in height. In addition to the required 780,000 yd³ (744,000 m³) of live storage volume, the underground cavern provides adequate freeboard and dead water storage to provide a margin against complete air depletion and overcharging with compressed air, respectively. Rock which is excavated during construction of the underground cavern is used to construct the dike walls of the compensating reservoir.

The remaining mechanical and electrical equipment incorporate features and capabilities normally found in fossil-fueled electric power generation stations of similar size and are not discussed further.

Economic Analysis

The economic analysis focused initially on developing realistic equipment cost estimates for the major equipment. This was followed by estimates of the capital investment and operating costs. The resulting costs were used to estimate levelized busbar power costs which were then compared against alternative peaking system costs.

The plant direct costs were tabulated according to the system of cost accounting codes identified in Table 4. The PFBC system, including all coal handling and processing, is the most expensive item and accounts for about 43 percent of the total direct cost. The turbomachinery and compressed air storage systems account for about 25 and 13 percent, respectively, of the cost.

The power plant total capital investment (assuming a January 1990 commercial operation date) was obtained by accounting for escalation prior to construction, a contingency allowance, an engineering and management fee, escalation during construction, and interest during construction. The values for these parameters were prescribed by DOE. The January 1990 dollar estimate was then deflated to January 1980 dollars. The resulting capital investment is presented in Table 5.

Power plant operating costs were estimated for fuel, compression energy, and operating labor plus maintenance. These operating costs were calculated on a levelized basis using an EPRI/DOE costing procedure and combined with the annual capital cost to produce a levelized annual cost estimate and a levelized busbar electric cost estimate. The resulting levelized annual costs are depicted in Fig. 9 for a range of capacity factors. The levelized busbar cost corresponding to an annual utilization of 2190 hr/yr is 118 mills/kWh.

Preliminary cost comparisons were made with a select group of competing oil-fired power plants. This comparison was made on a levelized annual cost basis and is also included in Fig. 9. It appears from this illustration that the coal-fired PFBC/CAES system emerges as the lowest cost alternative considered for annual utilization above 1925 hrs/yr.

TABLE 4

PFBC/CAES POWER PLANT TOTAL DIRECT COST SUMMARY

Budgetary Estimate

July 1979\$

4 Units

876.4 MW

<u>Account</u>	<u>Description</u>	<u>Cost, 10⁶\$</u>
10	Construction preparation	11.4
20	Surface facilities	13.5
30	Storage system	58.3
40	Generation/compression system	115.5
50	Mechanical systems	20.6
60	Switchyard	27.8
70	Plant electrical systems	15.3
80	Coal handling and combustion	<u>196.5</u>
	Total direct cost	458.9
	Specific capital cost (\$/kW)	523.6

TABLE 5

PFBC/CAES POWER PLANT CAPITAL INVESTMENT SUMMARY

Start Construction - April 1982

Commerical Operation - January 1990

4 Units

876.4 MW

<u>Description</u>	<u>Cost, 10⁶\$</u>
Total direct cost (July 1979\$)	458.9
Escalation prior to construction (April 1982, at 6%/yr)	79.7
Subtotal I	538.6
Contingency (at 15% of Subtotal I)	80.8
Subtotal II	619.4
Engineering plus management (at 15% of Subtotal II)	92.9
Subtotal III	712.3
Escalation during construction (at 6%/yr applied to Subtotal III)	215.1
Interest during construction (at 10%/yr applied to Subtotal III)	338.3
Total capital investment as of January, 1990	1,265.7
Total capital investment (January 1980 at 6%/yr)	706.7
Specific capital cost (\$/kW)	806.4

COST COMPARISON

FIG. 9

80-4-109-2

Sensitivity studies were also conducted to assess the effect which variations in key parameters would have on electrical energy cost. These parameters included fuel price, contingency allowance, engineering and management fee, operating labor plus maintenance costs, compression energy cost, capital investment, and length of construction time. Variations in the estimated capital investment had the greatest effect on costs, but did not substantially alter the overall economic viability of the coal-fired PFBC/CAES plant.

PART-LOAD AND LOAD-FOLLOWING CAPABILITY

A peak-load power plant must be capable of load following. Although preliminary indications suggest that the open-bed PFBC/CAES power plant developed in the preconceptual design should be capable of providing this capability, no definitive evidence existed because of the novelty of the concept. Consequently, an assessment of the load-following capability of the power plant was initiated. This investigation was conducted in two separate parts. The first part assessed the ability of the power plant to load follow by cycling and estimated its probable response characteristics. The second part involved a modification of the power plant system wherein the PFBC and turbine operate continuously at the full-load design point and variable geometry compressors provide a means of load following by shifting power between the compressors and the turbines.

Cycling PFBC/CAES System

In the open-bed PFBC/CAES system for which the preconceptual design was developed, the assumption was made that the PFBC could be cycled between the full-load warm start conditions and that any load following during the generation mode could be accomplished by varying coal flow and airflow to the PFBC. The part-load, steady-state performance estimates resulting from this variation are shown in Fig. 10 for two methods of controlling air flow. As shown in the figure, reducing the flow either by throttling or utilization of a partial admission turbine would have a relatively minor effect on the overall system performance.

The transient conditions related to part-load operation are less precisely defined. An assessment of the turbomachinery equipment thermal cycling limitations indicated that the turbines should be tolerant of anticipated transient operation. A cursory dynamic analysis of PFBC response to a 10-percent change in both coal feed and airflow rates indicated that the maximum fluid bed

PART-LOAD PERFORMANCE

— Partial admission turbine
-- Throttle valve

Round trip
heat rate,
Btu/kWh

FIG. 10

temperature excursion that would be experienced should be on the order of 25 F (14 C), and that after approximately five minutes, the excursion would disappear (Fig. 11). Thus it would appear that the PFBC should be tolerant of anticipated transient operation.

Continuous Firing PFBC/CAES System

An alternative PFBC/ CAES system was investigated which did not require PFBC cycling. Rather the PFBC and turbine would be operated continuously. During off-peak periods, the total turbine output would be used to drive the compressors with the excess air being stored. Load following would be achieved by modulating the power demand variable geometry compressors which permit constant discharge pressure down to about 70-percent flow and approximately 70-percent power requirement. When peak power is required, the compressors could be declutched so the entire turbine output could go to the grid.

The addition of supplemental compressors to the continuous firing system was also investigated. These supplemental compressors would be operated using off-peak power from the grid. The additional air provided by these compressors would significantly extend the peak load generation time of the power plant.

The round trip heat rate of the continuous firing PFBC/CAES system was estimated to be almost twice as high as that for the cycling PFBC/CAES system, due entirely to the low efficiency during compression and primarily the lower utilization time (1508 hr/yr) associated with the continuous firing system compared to the cycling system (2190 hr/yr). By adding supplementary compressors to the system, the round trip heat rate would be reduced and ultimately approaches that for the cycling system.

A preliminary cost estimate for continuous firing was also prepared. The continuous firing mode operating with an annual utilization of 1508 hr/yr was estimated to have an annual nonlevelized cost of electricity approximately 7-percent greater than the cycling PFBC/CAES operating with an annual utilization of 2190 hr/yr. If a slight amount of supplementary grid-powered compressors are added so that the annual utilization for continuous firing can be increased to 2190 hr/yr, the cost differential increases to about 14-percent. Further compressor additions continue to increase the cost differential.

BED TEMPERATURE RESPONSE

10-percent increase in coal and air feed rate

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