THE TENNESSEE VALLEY AUTHORITY'S ATMOSPHERIC FLUIDIZED BED COMBUSTION PROGRAM

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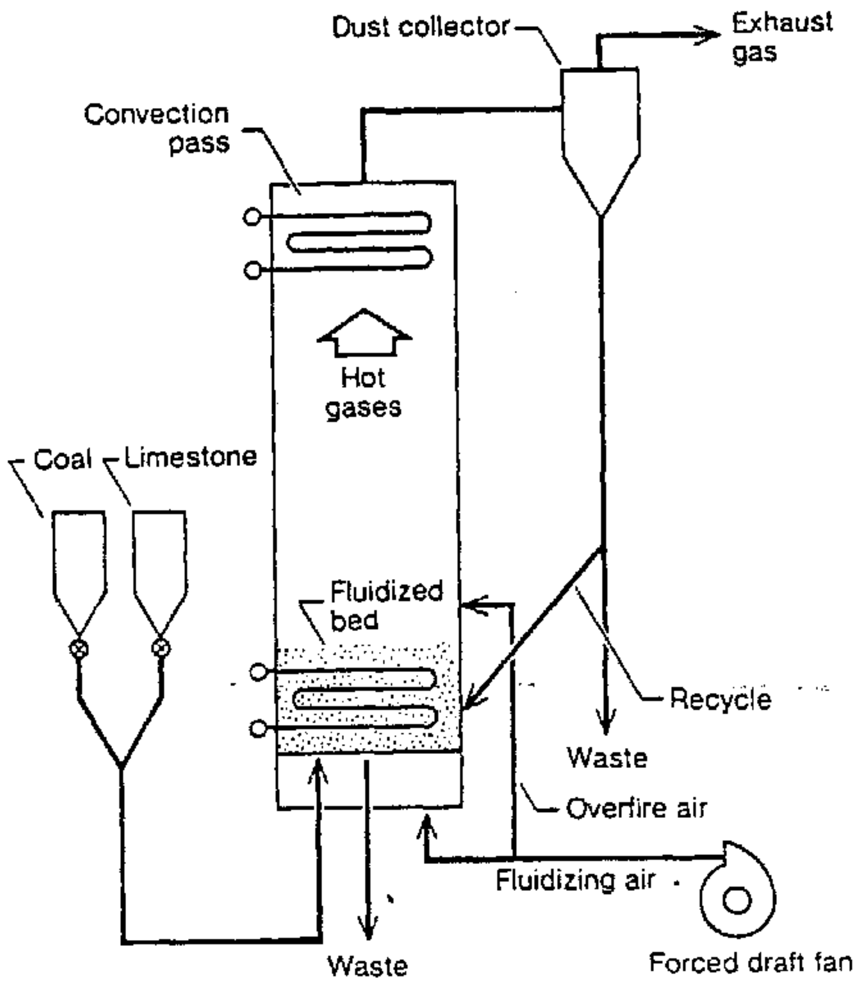
Manville J. Mayfield
Tennessee Valley Authority
Chattanooga, Tennessee 37401
United States of America

Introduction

Fluidized bed combustion (FBC) is an advanced coal burning process which provides a method of burning coal economically and in an environmentally acceptable manner. This technology stands to be a near-term alternative to the conventional pulverized coal steam plants which require complex environmental control technology in order to meet emission control standards. The atmospheric fluidized bed combustion (AFBC) process in principal is very simple (Figure 1). The process involves burning coal in a bed of limestone particles. Air passing through the bed from underneath suspends the coal/limestone mixture turning it into a turbulent mass of hot, dry solids that closely resembles a boiling liquid. Sulfur dioxide, an undesirable byproduct of burning coal, is captured by calcium oxide formed from the limestone to produce calcium sulfate as a byproduct. Studies indicate that this dry, solid byproduct may have useful applications or may at least provide a material which can be economically disposed of in an environmentally acceptable manner. In addition, since the operating temperature of the fluidized bed is around 1,550°F (roughly one half the temperature of a conventional coal-fired boiler) the formation of nitrogen oxides, a pollutant which is receiving increasing attention, is also greatly reduced.

In addition to environmental control capabilities, there are other advantages that the atmospheric fluidized bed combustion (AFBC) process has to offer. The efficient heat transfer characteristics of boiler tubes within the fluidized bed reduce the physical size of the boiler. Since the need of flue gas scrubbing is eliminated, the overall plant efficiency is improved. Another major advantage of an AFBC boiler is that it can burn a variety of fuel types without significant performance deterioration. This means that the large quantities of low rank coals available in the United States can be successfully burned without reliability problems associated with slagging or fouling in the boiler. The result is a utility power plant that is potentially lower in capital and operating cost, and is capable of meeting projected environmental standards. In addition, the burning of low quality fuel resources that were formally considered waste products, such as coal cleaning plant residues and coal mine waste, are feasible with this process.



Simple AFBC Process Schematic

Figure 1

History of TVA's Program

With 63 boilers located at 12 generating stations and a rated capacity of almost 18,000 MW, coal-fired steam plants are currently the backbone of TVA's electrical generation system. As one of the country's largest users of coal (30 to 40 million tons per year) TVA is committed to developing new coal technologies that will enable us to augment or replace our existing coal-fired steam plants. In September 1976, TVA's Board of Directors approved Phase I of a program leading to the design and construction of a utility atmospheric fluidized bed combustion power plant. Contracts were awarded to three major boiler manufacturers to obtain preliminary designs and cost estimates for a 200-MW demonstration plant and an 800-MW commercial-size AFBC boiler. In parallel with these contracts, TVA's Division of Engineering Design (EN DES) carried out designs and cost estimates for the plant site, coal and limestone handling facilities, power plant building, turbine/generator, and other balance of plant facilities.

Using these studies as a basis, an economic analysis was performed. The results indicated that, in comparison to a conventional pulverized coal plant with a wet limestone scrubber, an AFBC power plant can produce electricity at a cost which is 10 to 15 percent lower than the conventional plant. Siting studies were conducted for the selection of a suitable site somewhere in the Tennessee Valley region to locate a 200-MW demonstration facility. This information was utilized in the preparation of a draft environmental impact statement (EIS) for the demonstration plant. In the early stages of the project, it was recognized that a pilot plant which could be operated under utility conditions was needed in order to confidently design a demonstration plant.

TVA's present AFBC program is composed of three major activities:

- The design, construction, and operation of a 20-MW utility-type pilot plant,
- The design, construction, and operation of a 200-MW demonstration plant, and
- The supporting research and development program and related activities necessary to successfully carrying out these projects.

20-MW AFBC Pilot Plant

A number of small-scale AFBC development units which have been built and operated continue to confirm the attractiveness of this technology. None of these, however, answers the many engineering design and operating questions which must be resolved before this technology can be used in a commercial-size utility plant or permits assessment of the full environmental impact of this technology. In September 1979, TVA committed to purchase a 20-MW AFBC pilot plant in order to provide design confidence and the flexibility to test process improvements along with emission controls.

Project teams needed to carry forward the design, erection, and operation of the 20-MW AFBC pilot plant have been assembled. A concerted effort was made to utilize available expertise and to learn from past and ongoing fluidized bed combustion activities.

The pilot plant project is composed of a facility phase and a test program phase. The facility is being built by Babcock & Wilcox and Stone & Webster under a turnkey contract with TVA. The technical staff at Electric Power Research Institute (EPRI) is providing review and consultation on the facility design. The test program under a cosponsored contract between TVA and EPRI will be conducted by TVA personnel. TVA will operate the facility, assist in the development of the test plan, analyze and interpret the data, and perform other activities related to the operational testing of the pilot plant.

The 20-MW AFBC pilot plant has been designed with a great deal of flexibility in order to reach the following major goals:

- To prove that efficient and cost-effective performance of an AFBC boiler and auxiliary systems can be obtained under utility operating conditions and to facilitate the rapid development of this technology.

- To develop and prove-out operating control schemes required for reliable utility performance relative to variations in power demand (i.e., load following operations).

- To test, compare, develop, evaluate, and select large-scale auxiliary components and AFBC facility configurations.

- To demonstrate adequate emission controls and combustion efficiency over a range of alternate process and equipment configurations.

- To evaluate and/or develop the necessary predictive modeling tools to enable correlation of test results for use in designing larger AFBC utility units with confidence.

- To provide a cadre of trained AFBC engineers and utility operators.

- To establish a data base for a range of coals and limestones to enable scale-up of AFBC to commercial size.

Work on the pilot plant has been actively proceeding for the past one and one-half years. The facility now under construction is located at TVA's Shawnee Steam Plant near Paducah, Kentucky. Site preparation and initial construction began in April 1980. Testing and operation is slated for mid-1982. Schedules for the facility and test program phases are shown in Figures 2 and 3.

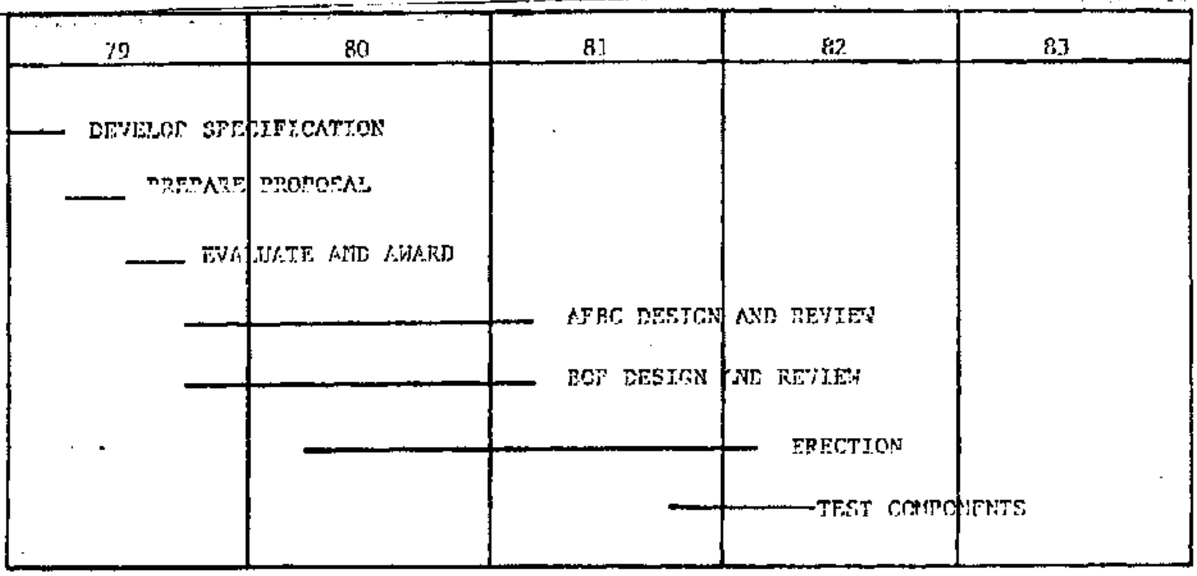
The pilot plant has been designed to test various mechanical subsystems and to optimize parameters for good performance and reliability under utility operating conditions. A cut-away view of the facility is shown in Figure 4. The pilot plant will allow testing of various feed systems (overbed and underbed), fluidizing velocities (4, 8, and 12 feet per second), control and load following techniques, and various environmental control techniques. The main fluidized bed area will contain 216 square feet of active area (12 feet by 18 feet) plus 72 square feet (6 feet by 12 feet) of an oil-fired startup section. The steam conditions are 2,400 psi and 1,000°F.

AFBC PILOT PLANT SCHEDULE

FACILITY PHASE

Figure 2

CALENDAR YEARS

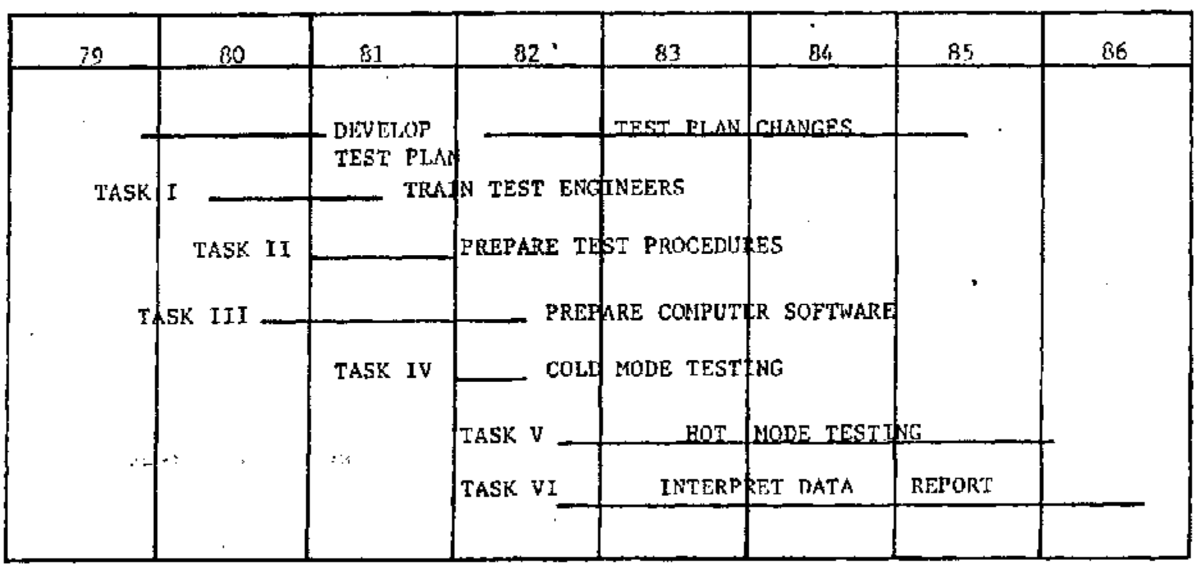


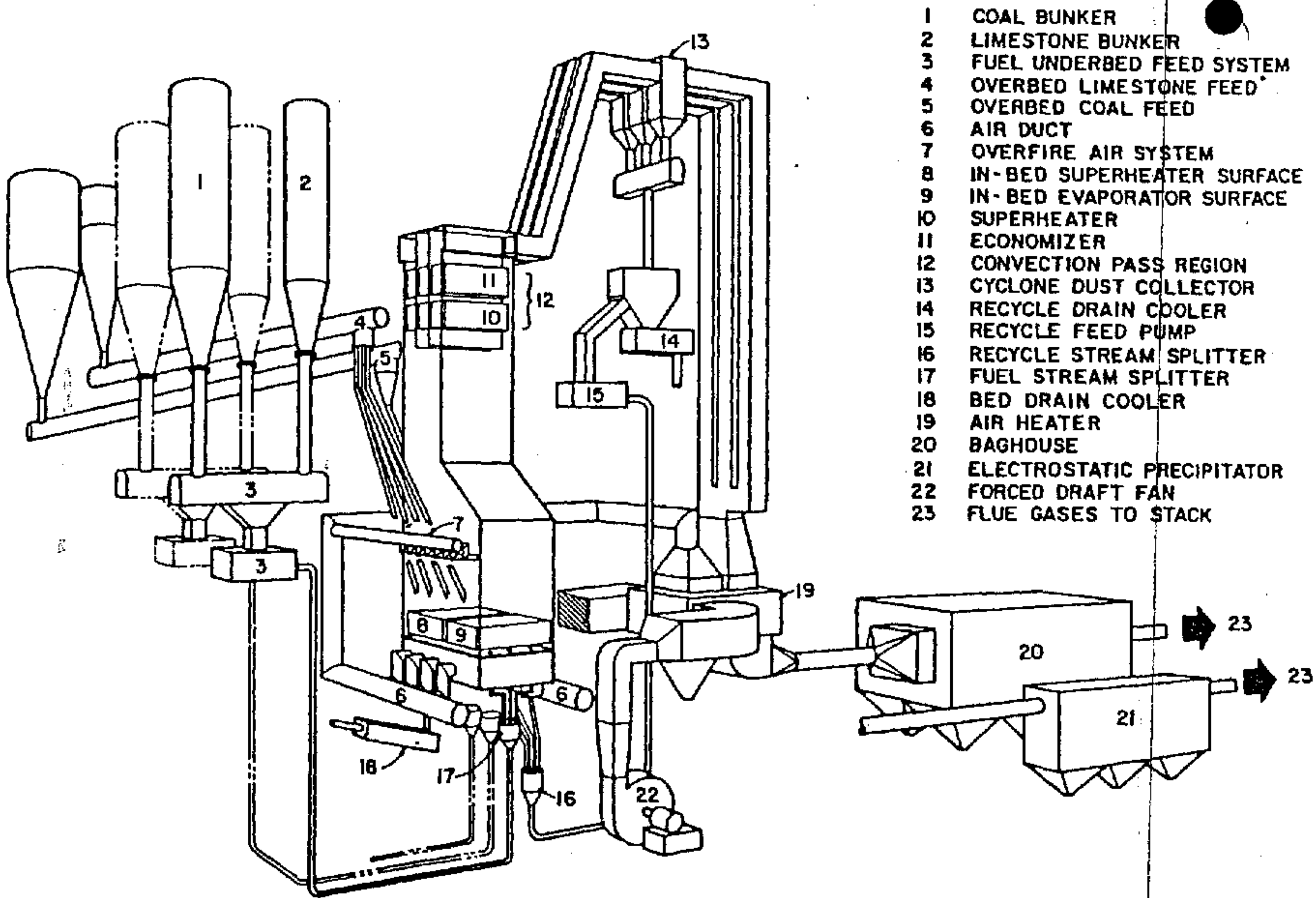
AFBC PILOT PLANT SCHEDULE

TEST PROGRAM PHASE

Figure 3

CALENDAR YEARS





TENNESSEE VALLEY AUTHORITY
20 MW AFBC PILOT PLANT

Figure 4

The nominal design conditions are 8 feet per second fluidizing velocity, 4-foot bed depth (with provision for 4 to 6 feet) and 1,550°F in-bed temperature (with provision for 1,400°F to 1,700°F). The design (Figure 5) incorporates:

- Recycle of char to the main bed (the carbon burnup bed was deleted from the design).
- A feed point spacing of 1 per 18 square feet (with provisions 1 per 9 square feet).
- A water-cooled bubble cap distributor plate.
- A combustor designed for a 2-second gas pass residence time.
- A direct digital computer control data acquisition system.

A number of technical areas of concern need to be resolved from operation of the AFBC pilot plant. These include the following.

Coal/Limestone Distribution

In the area of coal/limestone distribution, several alternate feed systems will be tested. Included are an overbed stoker feed system, separate overbed limestone feed, and underbed pneumatic feed of coal and limestone. The distribution of coal and limestone to the fluid bed has been a primary area of concern limiting large-scale AFBC development. Reliable delivery of fuel and sorbent to a small test unit does not present a problem. Distribution of coal and limestone to a utility-size boiler unit with several hundred feed points presents a major problem. To date, no feed system has been proven reliable and durable enough for utility-type operation. Conveying line design, allowable velocities with respect to moisture, erosion, splitting effectiveness, and feed nozzle design are among the items which must be better understood and optimized. These will be addressed in the pilot plant and in the coal feed test facility which TVA is currently operating. This facility will be discussed in more detail later in this paper.

Boiler Construction Materials

Previous research and testing has indicated that standard materials used in fossil power plants will perform satisfactorily in an AFBC boiler. However, coal/limestone and distribution, system control and operation, and bed performance could produce localized reducing conditions which might impact the long-term performance of boiler materials. Testing during pilot plant operation will address these potential problems.

Another materials problem involves the fabrication of welds between 2-1/4 chrome 1 molybdenum ferritic boiler tubes and stainless steel superheater tubes. Conventional practice is to use high nickel filler materials, but experience in AFBC indicates that high nickel materials should not be used due to sulfidation attack. In the pilot plant design, this issue was avoided by using a dual-pass superheater with both banks fabricated from stainless steel. Dissimilar weld samples will be tested in a flue gas slipstream to provide data for full-scale commercial units.

20-MW AFBC PILOT PLANT
OPERATING PARAMETERS

	DESIGN	FLEXIBILITY
BED DEPTH	4 ft	4-6 ft
FLUIDIZING VELOCITY	8 ft/sec	4-12 ft/sec
COAL FEED RATE	5.9 t/hr	up to 11.4 t/hr
LIMESTONE FEED RATE	2.4 t/hr	up to 13.5 t/hr
RECYCLE RATE/COAL RATE	1.8	5 max
CALCIUM/SULFUR (MOLAR)	2.8*	1.9-6.0

(*2.0 PREDICTED FOR RECYCLE RATIO=5)

MAIN STEAM		
FLOW RATE	111,248 lbs/hr	up to 167,733 lbs/hr
TEMPERATURE	1000 F	1000 F
PRESSURE	2400 psig	2400 psig

Figure 5

Erosion

To achieve acceptable bed performance, recycle of elutriated fine particles back to the main bed will be needed in an AFBC boiler. This recycle will cause higher dust loadings which could result in potentially more erosive conditions than in the convective heat transfer region of a conventional boiler. Conversely, because of lower combustion temperatures, the AFBC dust is much less erosive. In the pilot plant, erosion test racks will be placed in the convection pass to determine actual erosion rates.

Recycle

The original design for the AFBC pilot plant incorporated a carbon burnup bed in order to achieve acceptable combustion efficiencies and limestone utilization. Based on the results of recent research, the 20-MW AFBC pilot plant will be designed to return elutriated fines containing unburned coal and limestone back to the main combustor without the use of a carbon burnup bed. Through the use of recycle, combustion efficiencies of about 99 percent are expected and sulfur capture greater than 90 percent can be economically achieved.

The pilot plant will initially be constructed with a 750°F multiclone and be designed for recycle rates of up to five times the coal feed rate. Provisions have also been made for a 1,550°F recycle to be added later. It is predicted that with the designed recycle rate, New Source Performance Standards can be met with a calcium-to-sulfur ratio of 2:1 or less.

Pilot Plant Test Program

The major objective of the pilot plant project is to make the best use of the facility as a link between the sub-scale technology development units and the larger demonstration and utility-scale commercial plants. A test program which will evaluate the advantages and uncertainties of AFBC technology has been formulated. A detailed test plan has been written which will will serve as a control document for this work. Six major tasks describe the activities required to accomplish the test program objectyives. These are:

Task I, Test Engineer Training

Activities are being conducted at various facilities to indoctrinate and train the test engineers in AFBC theory and practice. Computer systems, boiler controls, sampling, and data reduction techniques have been emphasized.

Task II, Procedure Development

A set of standard test and operating procedures is being developed by the personnel who will be operating the unit and conducting the test program.

Task III, Computer Software Development

Various data reduction routines are being developed to efficiently and effectively handle the large amounts of data produced during the test program.

Task IV, Cold Mode Testing and Calibration

A preoperational, shake-down phase will condition the pilot plant for light-off and steam production. This will include the contractor operability tests and generate initial baseline performance data.

Task V, Hot Mode Testing Campaigns

This is the major thrust of the test program. Basic design and design modifications will be tested and evaluated to develop AFBC technology and enhance larger-scale demonstration and commercialization.

Task VI, Data Reduction, Analysis, and Results Presentation

Data packages for each test and initial data analysis will be prepared at the test site. The major data analysis and reporting will be accomplished by the project staff located in Chattanooga. Work on the test program began in 1979 with the development of a test plan which is now nearing completion. The test plan is conceived to be an adaptive, controlled document which allows for design modifications as test results are obtained and analyzed. Testing is scheduled into mid-1985.

Activities under the test plan are divided into five major campaigns:

Campaign I, Basic Operational Testing (approximately 8 months)

Achieve stead state, acceptable combustion efficiency, and compliance with environmental standards.

Campaign II, Turndown Testing (approximately 6-1/2 months)

Assess individual techniques of segmental fluidization, bed temperature, and bed depth; recycle rate variation; and establish limits for various techniques.

Campaign III, Load Following and Control Analysis (approximately 5 months)

Determine dynamic response to changes in control inputs and establish data base for control system design.

Campaign IV, Parametric Characterization and Optimization (approximately 12 months)

Characterize and optimize feed size, recycle rate, excess air, calcium-to-sulfur ratio, and overfire air.

Campaign V, Alternate Fuels (approximately 6 months)

Test Western coals and lignites.

Technology Transfer and Commercialization

Before utilities will accept AFBC technology as a coal-fired alternative for electricity generation, their management must be convinced that the investment risks are more favorable than, or at least competitive with, existing coal-fired alternatives that are commercially available.

Specific AFBC operating experience and valid experimental data for engineering evaluation are essential prerequisites to the development of a comparative analysis of options for utility management decisions. Such an analysis must adequately address the more significant utility issues that influence the total cost of producing electricity, namely:

- o Fuel flexibility and plant thermal efficiency.
- o Operating reliability and maintenance.
- o Environmental impact and waste product control.
- o Operating flexibility versus system needs.
- o Time required for total plant construction.
- o Capital investment and warranties.
- o Personnel and training levels required.

The AFBC pilot plant will be operated at utility steam conditions. It will simulate the various transient maneuvers that a coal-fired plant is typically subjected to in the utility operating environment where load demands fluctuate extensively and frequently. While carefully operating the pilot plant using a preplanned test program, an extensive amount of experimental data will be obtained from an array of instruments, sensors, probes, etc. These data will provide the real knowledge essential to adequately address the issues set forth above. This information will be made available to utilities, boiler manufacturers, and architectural engineers as the 4-1/2-year test program is carried out.

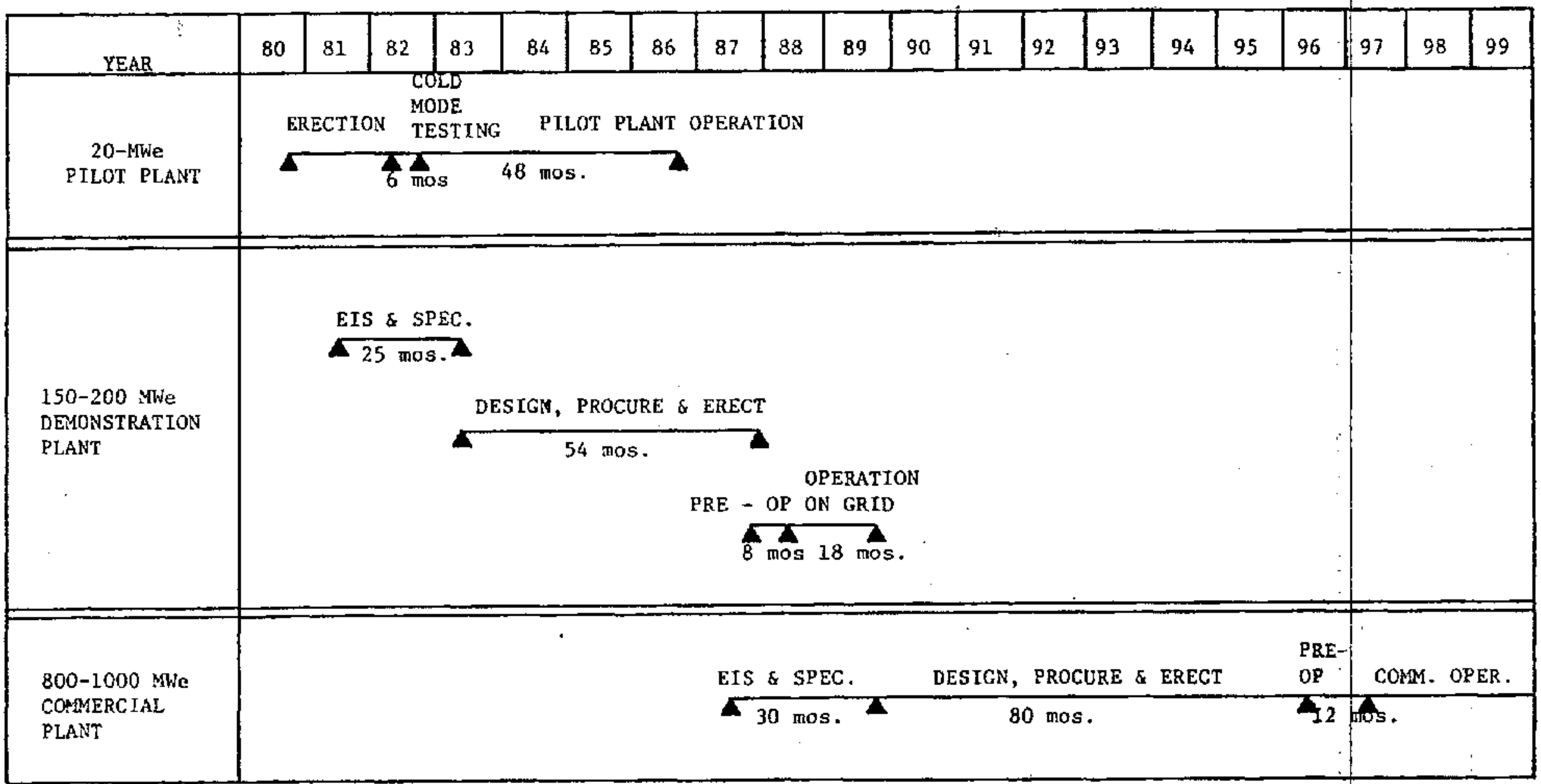
200-MW AFBC Demonstration Plant Study

TVA began design activities for a 200-MW AFBC demonstration plant in September 1976. The ultimate objective is the final design, construction, and operation of a central station AFBC plant to establish this option for future electric utility generation plants. Three alternate options are being investigated. These are:

- o A new stand-alone power plant additional capacity.
- o Replacement of an existing boiler with an AFBC add-on unit.
- o Retrofit of an existing pulverized coal boiler.

Final conceptual designs for an AFBC demonstration plant and auxiliary equipment were completed by three boiler manufacturers in January 1981. TVA designed the architectural layout and the balance of plant equipment for each contractor's design. The development of a detailed boiler specification is presently being prepared along with a schedule and cost estimate for a stand-alone 200-MW AFBC demonstration plant. A draft EIS has also been completed.

Our present schedule allows a reasonable amount of time to evaluate the pilot plant test results prior to freezing designs and committing to a demonstration plant. On this timetable, completeion of the demonstration plant is projected for 1988/1989. A decision on the first commercial units (Figure 6) based on this technology would then be possible in the 1990-1995 time frame.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20-MWe PILOT PLANT
ERECTION
COLD MODE TESTING
PILOT PLANT OPERATION
6 mos
48 mos.
150-200 MWe DEMONSTRATION PLANT
EIS & SPEC.
25 mos.
DESIGN, PROCURE & ERECT
54 mos.
PRE - OP
OPERATION ON GRID
8 mos
18 mos.
800-1000 MWe COMMERCIAL PLANT
EIS & SPEC.
30 mos.
DESIGN, PROCURE & ERECT
80 mos.
PRE-OP
12 mos.
COMM. OPER.

Figure 6

Other Fluidized Bed Combustion Activities

Circulating Fluidized Bed (Figure 7)

Under a contract with TVA, Combustion Engineering and Lurgi Chemie prepared a preliminary design and cost estimate for a 200-MW circulating fluidized bed (CFB) combustor. This is an alternate approach to current AFBC designs. This work was completed in December 1980. CFB has some specific advantages over the current bubbling bed designs. A CFB boiler has only a few coal and limestone feedpoints. Test results in subscale units show a potential for higher carbon utilization and lower calcium/sulfur ratios while still meeting SO_2 capture requirements. Potential disadvantages include the higher auxiliary fan power required and the unknowns associated with the large refractory-lined cyclones which are required for this process.

Retrofit

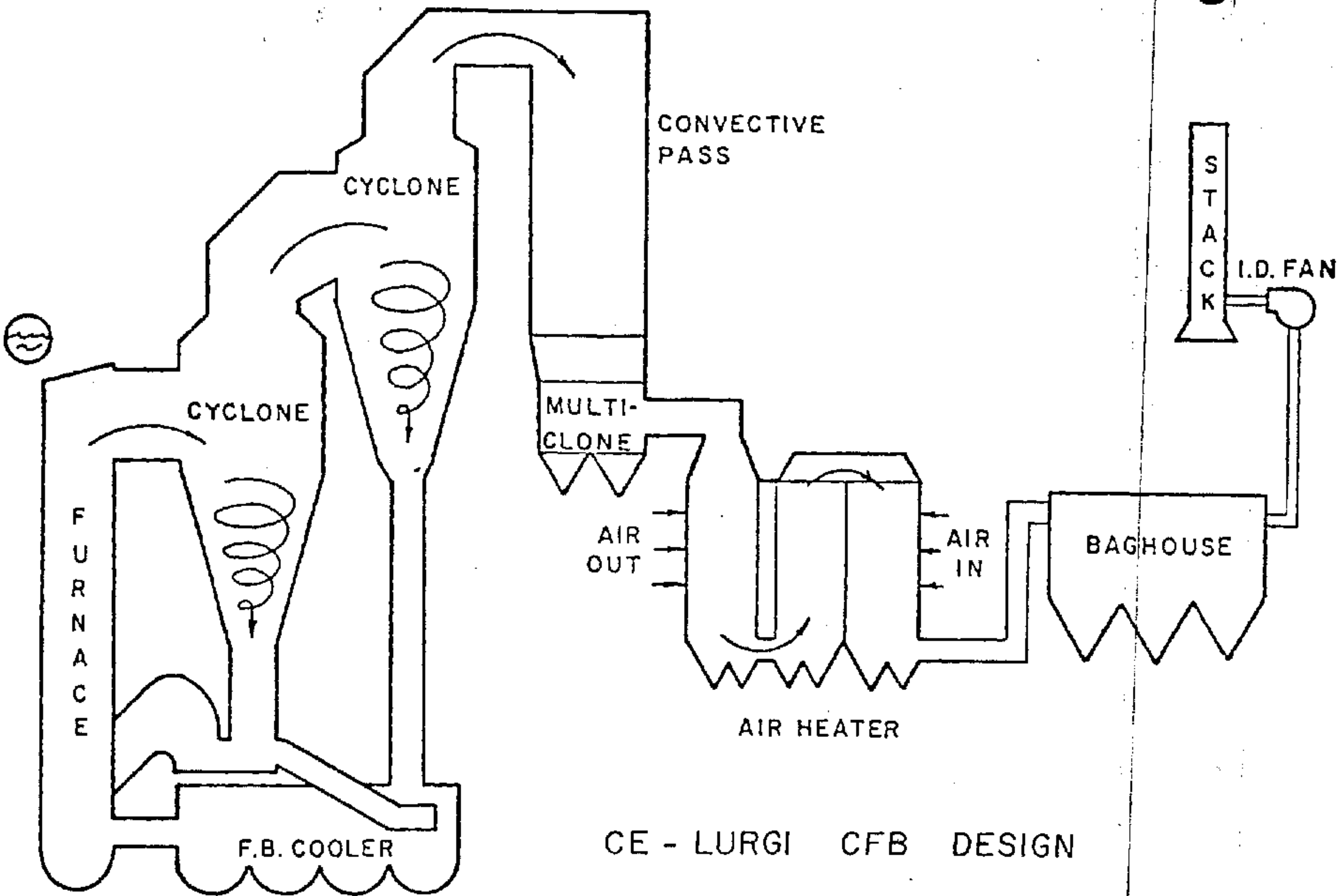
TVA's fossil plants like many throughout the country are getting old and will be needed to provide intermediate "peaking power." Many of these units are not designed to efficiently perform in this manner. Faced with these conditions, a promising option might be to replace an old, inefficient boiler with an AFBC boiler by retrofit or adding a unit adjacent to an existing boiler. A study was initiated to determine the feasibility of such a retrofit and it was concluded that there were no major problems which would prevent removing an existing pulverized coal boiler and replacing it with an AFBC boiler. TVA plans to proceed with further feasibility studies for an AFBC retrofit on the TVA system. Site studies are also being conducted to determine the best candidate site for a retrofit demonstration.

Feed System

In addition to the design projects described above, considerable effort has been devoted to addressing research and development on technical problems related to AFBC. As discussed earlier, one problem which is nearly always identified with AFBC is the development of reliable coal and limestone feed system. In order to address this problem prior to starting the 20-MW pilot plant, a project involving the testing of a full-size Fuller-Kinyon feed-pump and splitter system was initiated. A test facility (Figure 8) constructed at our Watts Bar Steam Plant will simulate operating conditions by utilizing coal off the plant coal pile. A 12-month testing program is currently underway. The Fuller-Kinyon pump (Figure 9) from the cement industry appears to be uniquely well suited for feeding an AFBC boiler. This facility will help to ensure against pilot plant operational delays and increase the probability of successful performance.

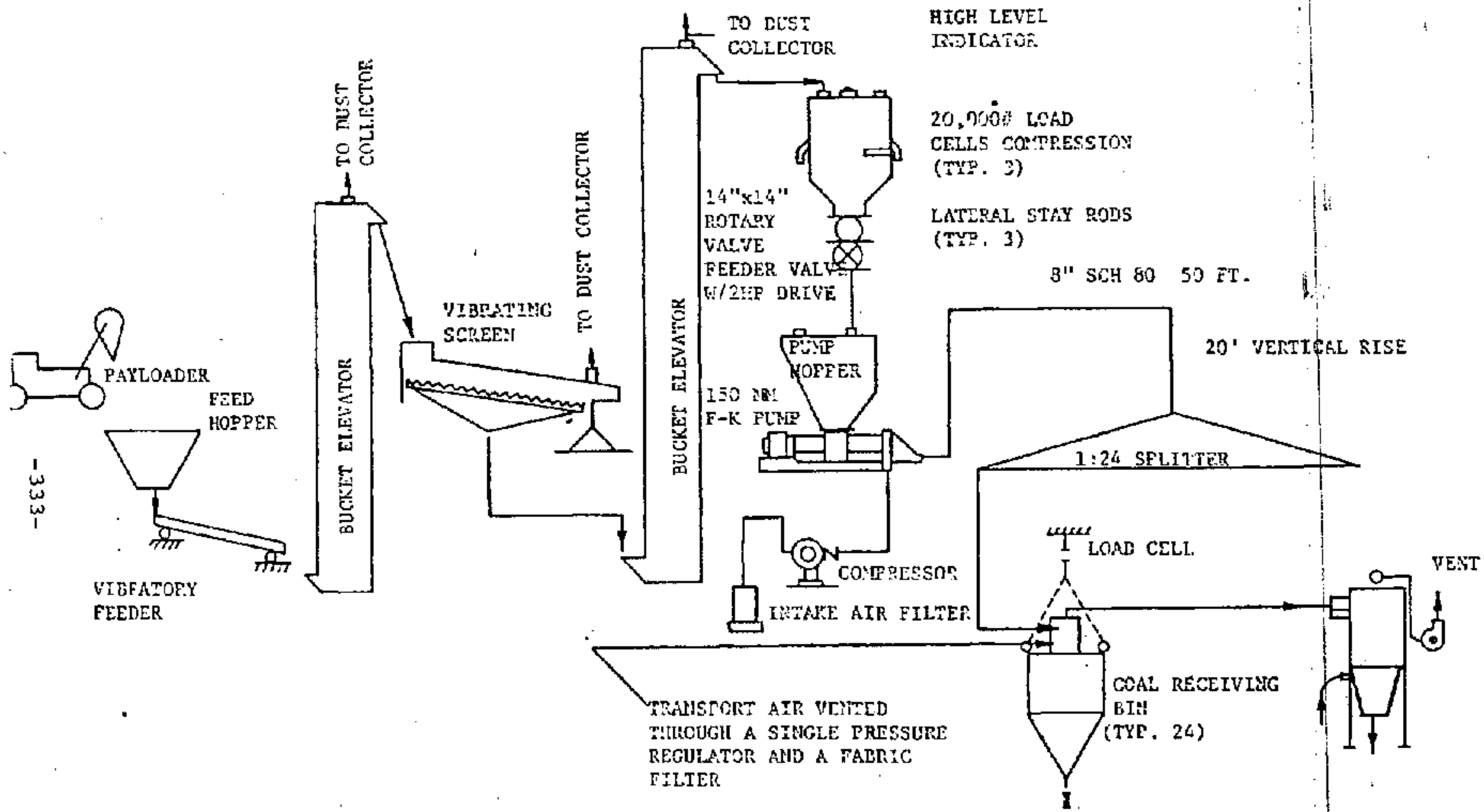
Recycle

The ERPI/B&W 6' x 6' AFBC test unit at Alliance, Ohio, has provided evidence that adequate carbon utilization and a significant decrease in limestone utilization could be obtainable simply by recirculating a portion of the fly ash to the combustor rather than using a second combustor or a carbon burnup cell. Tests of this approach with high recycle rates have been undertaken as Oak Ridge National Laboratory (ORNL) and at General Atomic (GA). ORNL has found that a calcium to sulfur ratio of 2 to 1 is obtainable as reasonable recycle rates. Follow-on work at GA is designed to obtain more exact carbon and calcium utilizations as well as heat transfer and corrosion effects with different dust loadings through the convection paths.



CE - LURGI CFB DESIGN

Figure 7



FLOW DIAGRAM - WATTS BAR AFBC COAL FEEDING TEST FACILITY

Figure 8

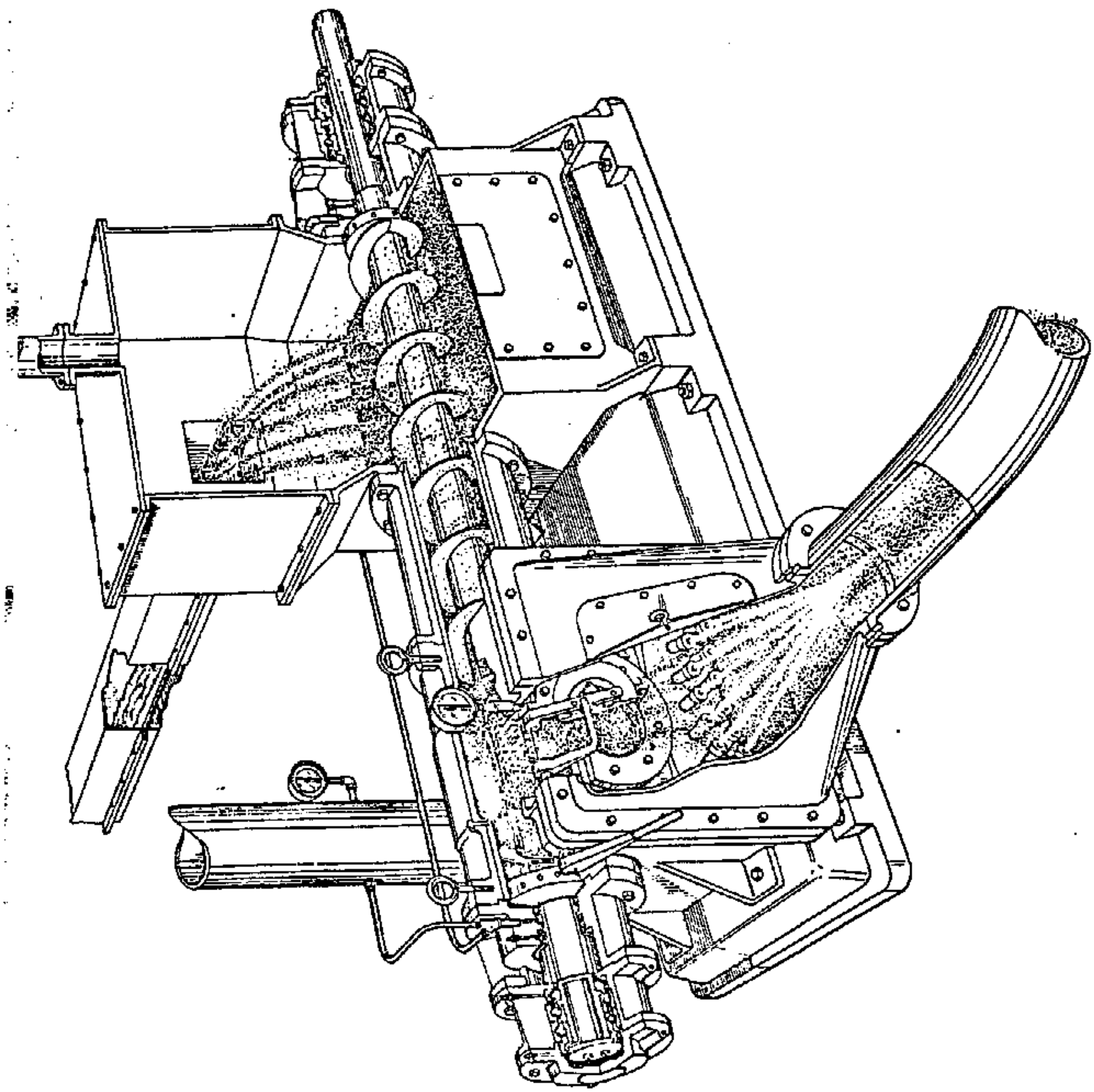


Figure 9

Modeling to Improve Scale-up and Automatic Control

A predictive steady state model for the 20-MW pilot plant is nearing completion at ORNL. To verify the model, a moderate amount of additional experimental work is being undertaken to provide more data on mass transfer between bubbles and the emulsion phase and on devolitization rates with small coal particles. In addition, to improve process automation, a transient model is also being developed. Our objective is to combine theory and testing for process improvement and extrapolation to larger-scale plants on a sound basis.

Load Following

One approach to load following involves reducing the output by reducing the fuel and airflow to allow the fluidized bed level to fall below a portion of the in-bed heat transfer tubes. This could result in a 25-percent reduction in output because of the lower heat transfer for exposed tubes versus in-bed surface. Further load reduction can be accomplished by shutting down some portion of the active beds. Partial bed slumping will be tested on an adequate scale for the first time in the AFBC pilot plant. Results from small-scale cold models at ORNL indicated that full-scale hot testing would be required to evaluate this approach. Another load following scheme involves varying the bed operating temperature. This can be done, but only over a range of about 200°F and still maintain good performance characteristics.

Boiler Materials of Construction

Earlier concerns over sulfidation of nickel in T304 stainless steel superheater tubes with potential in-bed reducing atmospheres do not appear to be a problem. The absence of attack in hot tests at low oxygen levels in studies at Fluidine and ORNL indicates satisfactory performance under these conditions. We now believe that standard boiler materials may be used with due regard to maintaining an oxygen excess through correct design and process control. The 20-MW AFBC pilot plant should provide the required confirmation that standard practices are adequate.

Pressurized Fluidized Bed Combustion

The technological developments of pressuri ed fluidized bed combustion (PFBC) certainly deserve continued consideration. The higher thermal efficiency made possible by expanding hot gases from a pressurized combustor through a gas turbine ahead of the steam generator provides a potential economic incentive. Hot gas cleanup appears to be a major technical problem which must be resolved before high efficiency standard gas turbines can be utilized with this approach.

Summary

Based on the technology improvements made in the last year or so, the economics and attractiveness of AFBC have been significantly enhanced. Some of the more significant improvements include boiler designs which provide adequate residence time for reactions in the bed and freeboard area; the use of increased recycle of elutriated fines, and the introduction of secondary air above the bed for 2-stage combustion. With these changes, the calcium to sulfur stoichometry required for 90-percent sulfur removal has been cut in half. Carbon utilization has been increased to the 98- to 99-percent level required for utility applications and oxides of nitrogen should be in the range of 0.2 pounds per million Btu or less. When completed next year, the 20-MW AFBC pilot plant is expected to confirm the performance capabilities which have been achieved in smaller units and provide the design and information needed to confidently scale-up this technology for use in utility-size AFBC boilers.