TVA 200 MW (e) AFBC DEMONSTRATION BOILER

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SUMMARY

This paper summarises the design basis, the approach taken and the plant configuration detailed in the final report on a 200 MW (e) demonstration AFBC plant submitted to TVA by the BCI/RSC/FCCL Partnership.

Results of basic coal and limestone test work carried out at the onset of the project are included.

The rationale for selecting the proposed "stacked bed" boiler arrangement as compared to a possible "ranch-style" alternative are discussed. Reference is made to an evaluation of "fines re-cycling" compared to a "carbon burn-up cell".

Boiler design details are included relating to combustor optimisation, disposition and arrangement of heat transfer surface, water and steam flow paths, structural analysis including in-bed tube vibration, materials selection and distributor plate configuration.

Descriptions are provided of the coal and limestone feeding arrangement, ash handling and start-up systems.

The proposed control system is discussed and reference is made to the dynamic simulation work carried out to verify its effect on boiler performance.

INTRODUCTION

For several years the Tennessee Valley Authority (TVA) has been actively involved in the development of atmospheric fluidised bed combustion (AFBC) technology for utility use. AFBC has the potential to provide an economical and environmentally acceptable alternative to conventional coal-fired power plants with flue gas desulphurisation.

As part of their AFBC Program, in August 1979 TVA initiated 16-month design study contracts with Babcock and Wilcox, Combustion Engineering and with a partnership of Babcock Contractors Inc. (BCI), Riley Stoker Corporation (RSC) and Fluidised Combustion Contractors Ltd. (FCCL).

The objective of these contracts was to develop a final design of a 200 MW (e) AFBC demonstration plant in sufficient and accurate detail to ensure that TVA would have adequate information to carry out the necessary technical appraisal and project evaluation. Furthermore, it was the intention that the design submitted would form the basis of plant specifications to be prepared by TVA at the hardware bid stage. The contract also included a conceptual design for a steam generator in the 600 - 800 MW (e) size range.

DESIGN CRITERIA

The following is a summary of the TVA design basis which defined the criteria upon which contractors should base the design of an AFBC boiler and its auxilliaries for a 200 MW (e) capacity demonstration plant.

Design coal (Kentucky No. 9) ultimate analysis on an as-received basis:

Carbon	60.7%	by weight
Ash	14.1%	" "
Moisture	9.0%	" "
Oxygen	6.6%	" "
Hydrogen	4.1%	" "
Nitrogen	1.4%	" "
Sulphur	4.1%	" "
GCV	10940 Btu/lb	
Fuel Size grading	3" x 0	

Design limestone (Lowellville) analysis on an as-received basis:

$CaCO_3$	90.25%	by weight
$MgCO_3$	2.00%	" "
SiO_2	2.75%	" "
Moisture	5.00%	" "
Limestone	3" x 0	

The steam generator should be designed to meet the proposed New Source Performance Standards (NSPS) for air emmissions, which are:

SO_2	1.2lb SO_2/Million Btu
NO_x	0.6lb NO_x/Million Btu
Particulates	0.3lb/Million Btu

The sub-critical pressure, drum type boiler should incorporate an assisted circulation system and be capable of achieving the following specified MCR steam conditions:-

Load	100% MCR
Gross turbogenerator rating MW (e)	200
Superheater steam flow, pounds of steam per hr.	1,325,000
Superheater outlet pressure, psia	2,465
Superheater outlet temperature, ^{o}F	1,005
Reheater steam flow, pounds of steam per hr.	1,122,000
Reheater inlet pressure, psia	550
Reheater inlet temperature, ^{o}F	630
Reheater outlet temperature, ^{o}F	1,005
Reheater outlet pressure, psia	522
Feedwater inlet temperature, ^{o}F	530

Boiler operation should be at full pressure from 100% MCR conditions down to 70% and at sliding pressure from 70% down to 32% (850 psia at 32%).

FEEDSTOCK TESTING

To assist in this design study for a large AFBC boiler for power generation, FCCL requested the National Coal Board's Coal Research Establishment, Stoke Orchard, to undertake preliminary testwork on a range of North American feedstocks, as follows:-

Kentucky No. 9 Coal

- Chemical and size analysis
- Preliminary fluidised combustion pot tests
- Ashing and degradability (attrition) tests

Lowellville, Three Rivers, Fredonia & Vulcan Limestones and Road Dolomite.

- Chemical and size analysis
- Ashing and degradability (attrition) tests
- Limestone characterisation (sulphur dioxide absorption tests)

Results from the above indicated that:

- Kentucky No. 9 coal would be a suitable medium reactive fuel for a fluidised combustion system.
- Areas affected by the coal properties are
  i) the limitation of maximum operating temperature due to low ash deformation temperature and
  ii) the limitation of coal injection temperatures due to the high swelling nature of the coal.
- The quality and quantity of the coal ash should be sufficient to maintain a stable bed. With the need for the addition of limestone, for sulphur retention, stable bed maintenance will not be a problem.
- The sulphur retention capabilities of these stones varied from good to poor on a calcium to sulphur mole ratio basis. Purely on calcium utilisation, Road dolomite is superior but when weight of stone is taken into account there is much less to choose between them with Fredonia limestone appearing to be marginally the best. On a weight basis, none of the stones including the design Lowellville limestone, is very reactive.
- As with their sulphur retention characteristics these stones show a wide variation in their attrition characteristics. Although in the raw state they are reasonably hard when calcined they range from very soft to hard. Their resistance to breakage within the fluidised bed should assist in the maintenance of a stable bed in the case of both Fredonia and Lowellville stones. In the cases of the remaining stones especially the very friable calcined Road dolomite little assistance to bed maintenance would be afforded.

A summary of the limestone requirements, predicted by FCCL's model for the TVA plant conditions and based upon the characterisation tests is given in Table 1.

DESIGN APPROACH

The project goal was to achieve a plant design which displays the highest possible operational reliability in the light of present knowledge.

Initial assumptions were based on several years experience obtained from the Babcock Renfrew FBC boiler (1) and a variety of National Coal Board rigs and pilot plants. Thus the fluidising velocity, bed temperature and general design of the fluid bed components were all based firmly on proven work.

Areas of potential risk were identified and wherever possible, existing technology has been applied. This involved the development of a boiler and supporting plant design that incorporates dimensions, construction features and materials that have already been demonstrated either in FBC service or in conventional boiler configurations. Where proven technology or long term operating experience was not available, appropriately conservative design approaches have been utilised.

To meet these goals the following were selected:-

- Superficial fluidising velocity at MCR operating conditions would be approximately 8ft/sec.
- Bed temperature at MCR was to be 1560^{o}F which is close to the optimum operating temperature for SO_2 removal by the addition of limestone

and would provide a degree of latitude both for bed temperature turn-down/load reduction, and for overfiring as may be required.

- In order to achieve the required flexibility in the firing system to meet the boiler operating load range, 8 beds were considered necessary.

- A direct fired underbed feed system incorporating air swept mills for coal and limestone would be used.

- Evaporative, superheat and reheat surface would be placed in the beds.

- Specific bed design details would be based on the successful Renfrew unit.

The major alternative designs requiring comparison/evaluation were considered to be:-

- "Stacked bed" versus "Ranch style" combustor configuration

- Method of achieving the targeted 99% carbon utilisation figure, "Carbon burn-up cell" versus "Fines re-cycling"

- Arrangement and disposition of heat transfer surface.

These alternative options are discussed more fully in the following sections.

"STACKED BED versus "RANCH STYLE"

The total projected bed plan area for a 200 MW (e) combustor operating at a fluidising velocity of 8ft/sec and a bed temperature of 1560°F is approximately 3096ft^2. Whereas a unit generating 800 MW (e) and operating at similar conditions would be four times larger i.e. 12,384ft^2.

A decision was therefore required as to whether a "stacked bed" or "multiple beds on a single level", commonly referred to as a "ranch style", would be the most suitable arrangement.

Individual bed plan areas were nominally fixed on the premise that each of the eight individual beds required to readily cover the boiler operating range would be equi-sized.

As part of the natural design evolution, alternative potential configurations were reviewed in order to highlight likely problem areas.

The method of construction for a ranch style design, particularly with reference to the anticipated combustor dimensions for an 800 MW (e) unit would require intensive and protracted investigations.

A 800 MW (e) ranch style design would probably require a bottom supported combustor/bed structure, approximate dimensions 144'-0" x 86' - 0", in conjunction with a conventional top supported convection surface region. The interface of these two sections would require the design and development of a suitable gas tight expansion joint which would be subject to large differential movement.

There was concern that the ranch style design could not readily incorporate water cooled supports deemed necessary for in bed surface restraint.

The combustion process with particular reference to the prediction of freeboard combustion in a ranch style generator of 800 MW (e) was considered to be a risk area due to the scale-up effect, particularly at part load operation.

A stacked bed arrangement appeared to offer a more favourable design with reference to combustor dimensions and the incorporation of the bed modules so as to provide a top supported integral water cooled membrane wall structure.

Structural analysis indicated that a water cooled distributor plate constructed from membrane panels could reasonably span 9' - 0", Thus each individual bed would have dimensions of 43' - 0" x 9' - 0", which, in essence, would be akin to four Renfrew plants placed side by side. Additionally by using similar freeboard dimensions on outer beds this gave a high level of confidence in the prediction of combustor performance.

"CARBON BURN-UP CELL (CBC) versus "FINES RE-CYCLE" CYCLE"

As part of both overall design evolution and comparative evaluation of alternative re-firing techniques a "base stacked bed boiler" concept was developed.

In order to facilitate a valid comparison, flowsheets, material balances and specifications were developed for both CBC and fines re-cycle schemes. The re-firing of cyclone and baghouse fines was included in each scheme.

For the CBC, 96% of the coal fed to the plant was fired to the main beds, 4% being fed to the CBC as a support fuel for the re-fired fines. The CBC was arranged as an auxiliary cell to the main combustor and designed to operate with a fluidising velocity of 4ft/sec and a bed temperature of 1750 °F.

A capital cost comparison, based on a differential boiler material take-off, and erection allowance, budget quotations received for re-injection equipment, and in-house designs and estimates for materials handling and miscellaneous items were carried out.

The operating cost analysis considered variations in carbon utilisation, limestone consumptions and changes to auxiliary power consumptions.

This economic analysis gave a conclusive verdict in favour of grit re-cycling to the main beds. Furthermore, limited direct operating experience of CBC did not agree with with philosophy of a "design which could be built with minimum risk today".

BOILER DESIGN

Figure 1 shows the proposed stacked bed boiler arrangement.

The design employs eight main beds, the two bottom, central beds are divided in two at distributor plate level to effectively provide four half size beds. These bottom central beds contain evaporative surface only. The six outer beds contain a mix of superheat, reheat and a nominal amount of evaporative surface. In accordance with the TVA specification pump assisted circulation is provided. A parallel superheat and reheat convection pass is employed to complete the balance of superheat and reheat duties, whilst providing a method for trimming the final steam temperature, by spray attemperation.

Saturated steam leaves the drum and flows down the convection pass rear wall. From its header steam is collected and routed to the superheat circuits in the main beds. Steam flow leaves these beds, passes through the attemperator and then passes counter current to the gas flow in the superheat convection pass, where final steam temperature is achieved.

Similarly, reheat flow enters the reheat circuits in the beds and is then collected and routed to the convection pass inlet header. Steam flows up through the convection section where final reheat outlet temperature is attained.

Whilst this approach does not utilise the high heat flux potential within the beds to its fullest extent, it does give a design where the maximum metal temperatures are comparable to those experienced in conventional PF fired boilers.

Economiser surface is located within the parallel convection pass.

The air and gas flow paths are similar to conventional boilers. Combustion air enters the individual air plenums to support combustion in the bed. The gases leaving the bed flow through the furnace and enter the rear pass convection section. Gases leave the boiler and pass through mechanical collectors, regenerative air heaters and a baghouse before entering the ID fan and then the stack.

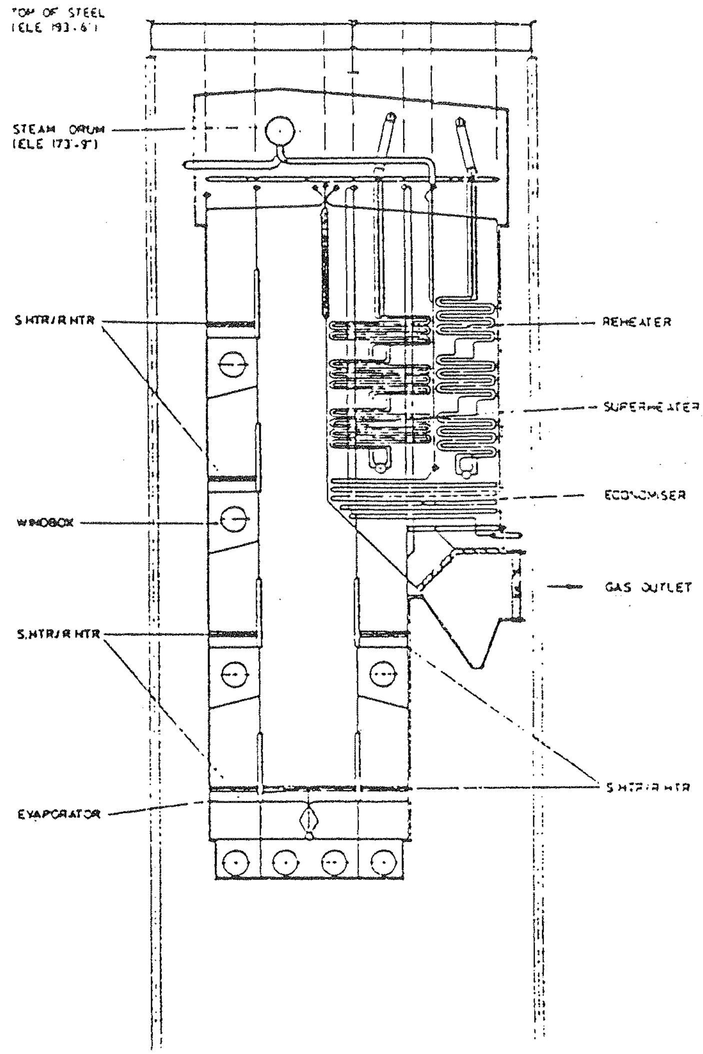


Figure 1

The unit is entirely top supported through seven major lines of support. Boiler enclosure walls are stiffened through a standard buck-stay design integrated with truss assemblies. Particular attention was paid to the integral water cooled distributor plate, whose design was adopted to permit high windbox temperatures during start-up. System pipe routings were studied for flexibility.

Detailed process calculations were carried out on the overall boiler configuration in order to optimise the combustor design.

Figure 2 shows the overall plant arrangement.

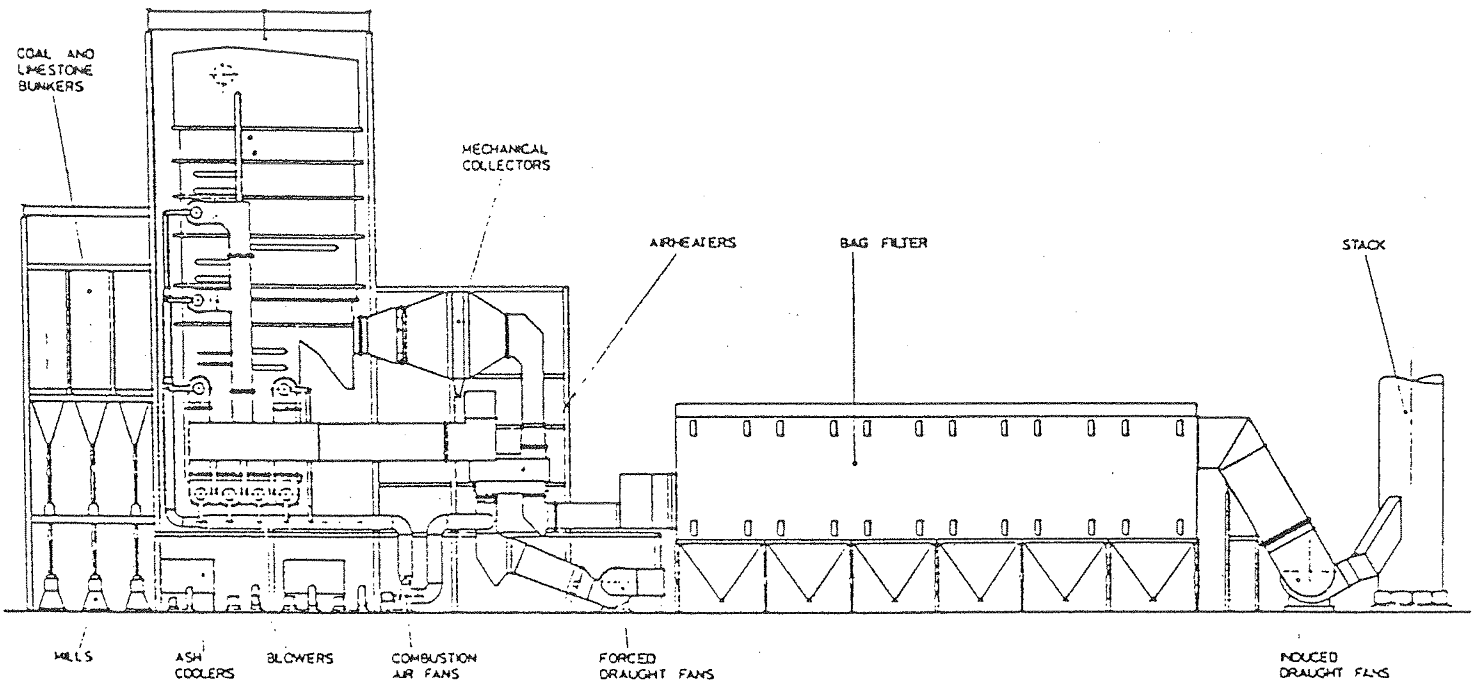


Figure 2

Considerable effort was dedicated to the design and support of in-bed surface. Each row of horizontal surface is supported by furnace wall tubes that have been taken out of the distributor plate. Cradles and wear pads are provided on the evaporative support and heat transfer surface respectively so that tubes are locked into position and are constrained against any motion induced by bed excitations; this tube arrangement uses the concept of keeping superheat and reheat tube bends all in the horizontal plane. This approach allows for relatively easy field erection of the heat transfer surface, and for replacement of tubing through the side walls of the furnace.

Additionally a study was undertaken to analyse the various mechanisms influencing the dynamics of the in-bed tubes with the objective of predicting :-

- Force/time histories on individual tubes
- Force/time histories on the tube banks
- Fretting rates

This study led to experimental work being carried out to investigate in-bed tube vibration in a fluidised bed as reported separately (2).

In making the in-bed tubes material selection, the operating environment and the performance of each candidate material was assessed from testwork in similar environments. Materials selected were as follows:-

- Evaporative surface - carbon steel SA-210 A1
- Superheater surface -) Austenitic Alloy SA 213 TP 347N
- Reheater surface -)

Whilst performing its primary function of air distribution, the distributor plate also serves to house fuel feed points, fines re-injection points and ash drain pipes whilst being designed to maintain mechanical integrity over many cycles of start-up/operation/shut-down.

The distributor plate consists of a series of stand pipe type air nozzles, as used on the Renfrew boiler. The air holes are drilled radially through the nozzle wall near to its upper end. This proven configuration not only prevents the fall back of bed material but has the design feature of creating a static layer of bed material on the surface of the distributor plate which acts as an insulating layer. Consequently, the operating temperature of the distributor plate will, itself, be well below

Figure 3 indicates pictorially a section through a typical outer bed.

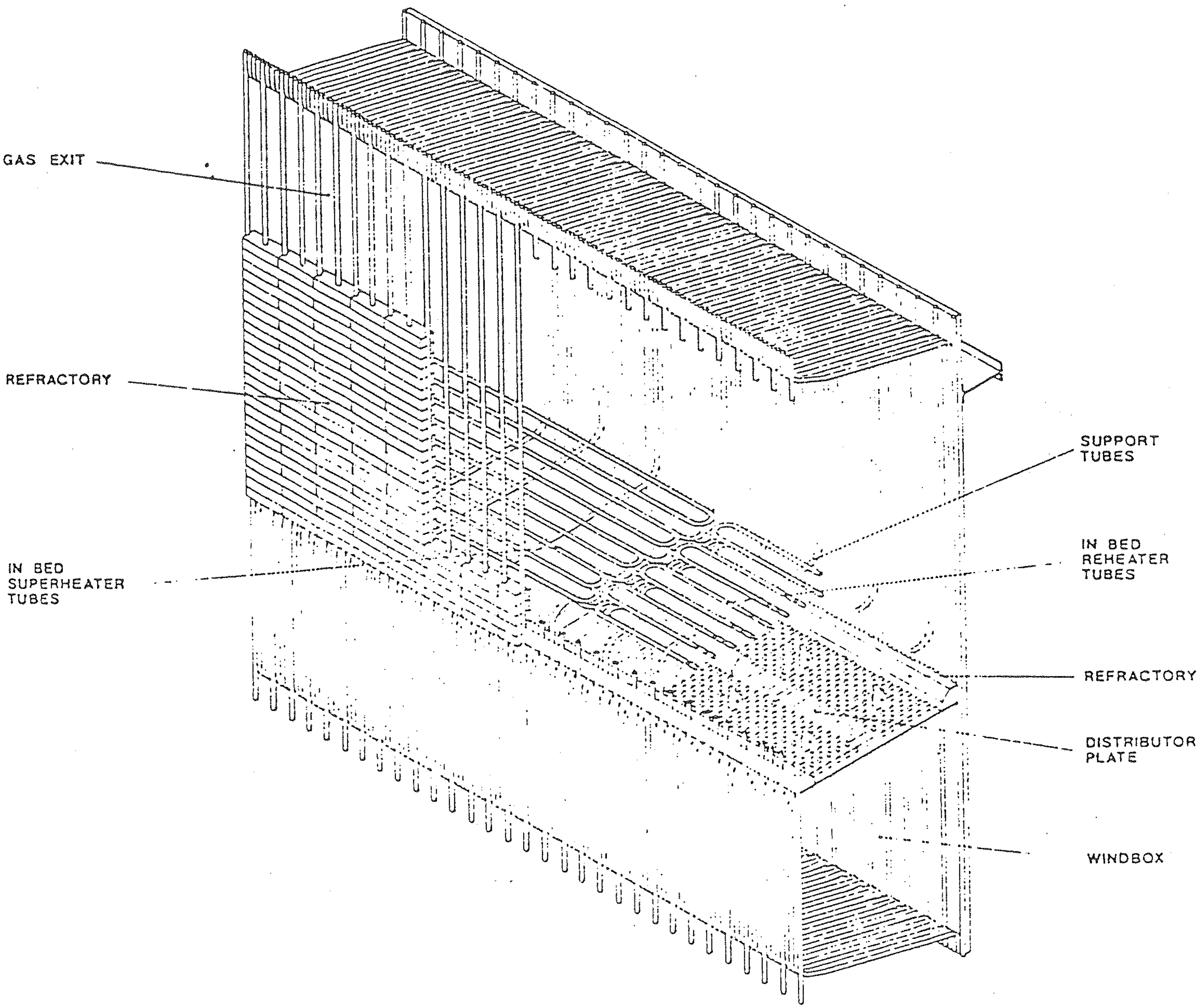


Figure 3

expansion problems.

An additional feature of the bed plate is that the air nozzles are so arranged within a low precast refractory wall section to encourage a higher fluidising velocity at the bottom of the bed. In practice this reduces the risk of segregation of the bed and assists fuel mixing.

By consideration of operating experience, bed geometry and feed system arrangement, individual underbed feed points were positioned to serve 16ft^2 of bed plan area.

COAL AND LIMESTONE FEED SYSTEM

A direct firing system is employed which is closely analogous to the conventional pulverised coal preparation and transport system designs commonly used on utility boilers, but with the mills acting as crushers.

Each bed is equipped with its own independent feed system and the boiler has been designed so that with a single feed system out of service, 100% MCR can still be maintained by over firing on the remaining beds.

From gravimetric type feeders coal is fed at a controlled rate into mills specifically designed to produce a product grading of ½" x 0. Graded limestone, ¼" x 0, is supplied to the mill outlet turret where it is mixed with the coal prior to being pneumatically transported to the bed. Hot air admitted to the crusher dries the coal and limestone and also serves as a transport medium. In addition to 6 way turret splitting, 4 way in line pipe splitters are provided, so that each mill serves the 24 coal feed points located in the bed.

ASH COOLING SYSTEM

The bed drain system consists of a series of drains in each bed covering an approximate bed area of 100 ft^2/drain. Gravity drains are provided from each off-take point in the common ash let-down valve for each bed, which is operated from a pressure differential reading across the bed. Drains discharge directly into fluid bed ash coolers, the hot air from the coolers is returned upstream of mechanical collectors, thus recovering some heat in the regenerative air heaters. Coolers are equipped with water cooling surface which forms part of the feed water heating train.

START-UP SYSTEM

The bed start-up system is based on the use of oil fired burners to bring each bed up to a safe coal ignition temperature and to maintain that temperature during the start of coal firing until coal ignition is verified. In order to conserve oil, it is proposed that all beds are pre-heated by the injection of hot air into a static bed from in-duct burners , the maximum temperature of the air being fixed at 1300°F due to windbox metal temperature constraints.

Evaporative bed heat is supplemented by overbed burners at controlled firing rates to ensure adequate protection of in-bed surface.

Superheat/reheat bed light-up is carried out by in-duct burners only, the flow conditions to in-bed tubes being controlled throughout the light-up.

CONTROL SYSTEM

The control system for the boiler was developed from a combination of existing control techniques for fluid bed combustion together with a first principle approach to overall load control.

Previous experience had indicated that the ten fluid bed units in the boiler should be treated for control purposes as separate firing units. The fuel, air, combustion and temperature controls for each unit should be identical but independent.

The main boiler control scheme could then be designed as a supervisory system directing the ten FBC units to achieve the desired overall result.

To allow a reasonable understanding of the system it was therefore necessary to examine the process at two levels.

a the main boiler system relating fuel input to steam output and quantity

b the characteristics of an individual bed unit which relate fuel input to steam output via bed temperature.

BOILER INPUT/OUTPUT RELATIONSHIP

For control purposes the boiler may be regarded as a two input/two output system as shown in Figure 4, with the beds divided in two groups, the evaporator group and the superheater/reheater group.

Input 1 is fuel to evaporator beds producing energy output mainly in the form of steam flow with a smaller proportion of energy being delivered in the form of superheat and reheat duty in the steam as a result of hot gas flow provided to the convective superheating surfaces.

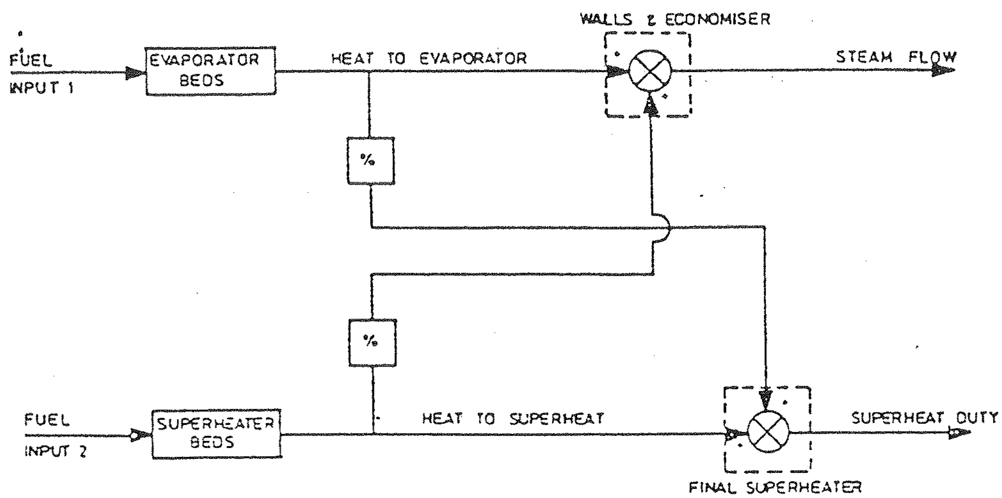
Input 2 is fuel to superheat/reheat beds producing energy output mainly in the form of superheat and reheat duty in the steam via both the in-bed superheat/reheat tubing and the convective surfaces. A small proportion of the fuel to this group delivers energy in the form of steam flow mainly via the hot gases passing over waterwalls and the economiser.

At 100% MCR conditions the energy conversion process results in the following approximate breakdown of duties.

	% Total Boiler Duty	Evaporative Beds	SH/RH Beds
SH/RH	51	6	45
Evaporative duty	49	19	30
Total boiler duty	100	25	75

Thus, for example, an increase of 1% in fuel to evaporator beds will create an increase of 0.8% in evaporative duty (steam flow rate) together with an increase of 0.2% in superheat/reheat duty. Conversely a change of 1% in fuel to SH/RH beds will create a change of 0.4% in steam flow together with a change of 0.6% in SH/RH duty.

Figure 4



Using the above data the final boiler control philosophy adopted was to meet any desired steam flow and steam temperature conditions by differential firing of the two bed groups, although each bed in a group would be operated at the common group conditions.

BOILER LOAD CONTROL

From the above relationship a load control scheme was devised whereby, for small changes, an error in steam flow generation was corrected by modulating the temperature of the evaporative beds via a feedback loop. Similarly, errors in the steam temperature in the superheater stages are corrected by regulating the temperature of the superheat beds.

To improve stability and to allow large load changes to be made, a special feedforward or predictor algorithm was proposed. Stability will be improved by changing the temperature set point of one bed group to offset the disturbance anticipated from a change in the other group. For large changes in boiler output it will be necessary to change the number of beds in service. When this occurs the result will be that boiler output will be balanced at a new set of bed group temperatures. The main function of the predictor will be to make initial corrections trim. A general arrangement of this scheme is shown in Fig. 5.

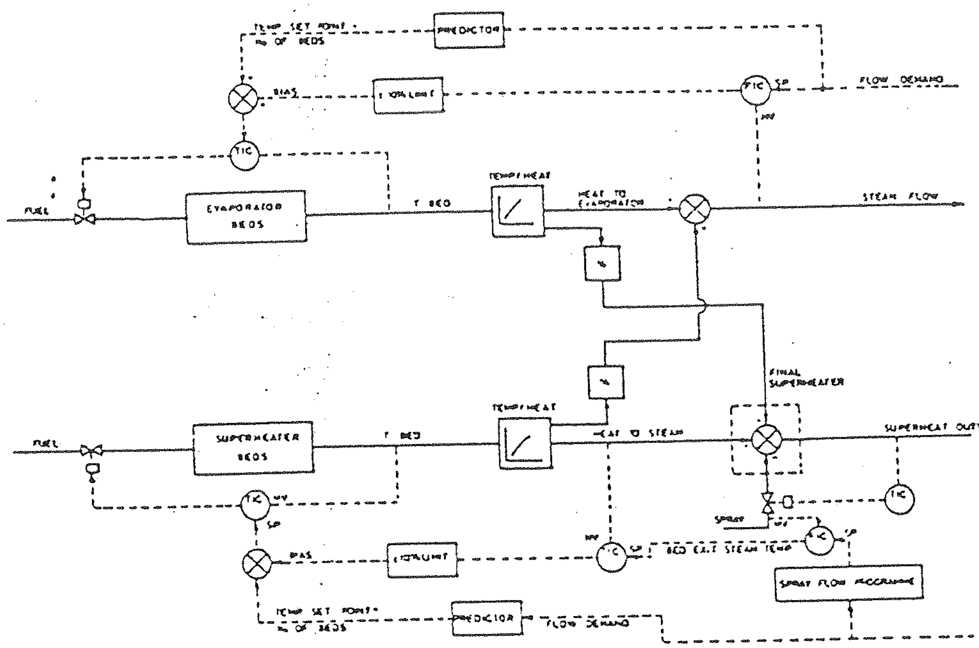
Having established a philosophy for boiler control, various studies were conducted to ensure that the components of the control scheme were capable of meeting its requirements. The first of these was to ensure that the individual bed units could be developed to operate reliably as a combustion system.

SINGLE BED UNIT

Each unit comprises a fluid bed with separate air flow controls, a coal crushing mill with weigh feeders for coal and limestone and a primary air system for conveying and drying duties at the mill. From previous experience controls were specified for each bed unit to provide automatic start-up, temperature controlled operation and shut-down.

The combustion process is normally maintained with 20% excess air and the bed operating in the range of 1400°F to 1650°F. Since there are a number of factors in the process which change the heat balance it has been found that the bed should always be operated under direct temperature control. The structure of the control system was therefore defined around the concept of a set of control

Figure 5



The combination of loops and sequences led to the choice of a microprocessor based unit controller for each bed.

CONTROL EQUIPMENT

With digital control indicated for each bed unit and extensive supervisory functions required for boiler load control it was decided to consider the use of a distributed digital system with adequate redundancy and security of back-up. Investigations showed that suitable equipment was obtainable from several large instrument manufacturers and so a scheme using a supervisory computer with 13 subsidiary microcomputers was devised. The system incorporates a central operator interface with redundant V.D.U. and keyboard workstations. Each unit controller includes a set of dedicated auto-manual back-up stations to allow manual override of any fluid bed operation whilst leaving the others on automatic control. Central equipment and unit controllers are all linked by a dual serial data highway.

SIMULATION

The performance and operability of the AFBC boiler were areas of concern for both TVA and FCCL. Two key parameters were identified for special investigation:

- Steady state turndown characteristics
- Transient response of a single bed.

The thermal performance of the individual operating/superheating sections of the system was investigated with the aid of NCB/FCCL's combustion models, in order to produce a set of turndown curves for part load operations. From these the best number of beds required to meet any given part load condition can be predicted together with their expected group temperatures. The study showed that area changing in the evaporative bed group could be avoided altogether over a load range of 32% to 100%. This was partly due to the use of sliding pressure operation of the boiler. Load following can be demonstrated in terms of temperature modulation of evaporative and superheat beds together with stepwise slumping or activation of individual superheat beds.

An extensive study of the transient behaviour of a single bed was carried out with the objectives of developing a stable bed temperature control system and predicting the repsonse rates to changes in set point and fuel feed rates.

A simple dynamic model of the heat balancing process was initially constructed on an analog