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Final Report

EVALUATION OF FREEBOARD PERFORMANCE IN A FLUIDIZED BED COMBUSTOR

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NOMENCLATURE

A_{Bed}	Inbed heat transfer area	m^2
A_{conv}	Convection heat transfer area	m^2
A_{loop}	Heat transfer test loop area	m^2
AF	Ash content in the fuel	fraction
A_r	Archimedes number $= \frac{d_p^3 \times g \times \rho_g (\rho_p - \rho_g)}{\mu^2}$	---
CFR	Coal feed rate	kg/h
CPW	Specific heat of water	kcal/kg-°C
CPASH	Specific heat of ash	kcal/kg-°C
d_p	Particle diameter (mean)	m
e	Emissivity	---
ES	Elutriated solids	kg/h
E	Voidage	---
f	Fraction of solids leaving the system	---
fBD	Fraction of the total solids in the drain	---
fCC	Fraction of the total solids in the cyclone catch	---
fMCC	Fraction of the total solids in the multiclone catch	---
fSC	Fraction of the total solids to the chimney	---
FWLOOP	Waterflow in freeboard test loop	kg/h
FWBED	Waterflow in bed coils	kg/h
FWCONV	Waterflow in convection coils	kg/h
H	Hydrogen in the fuel	fraction
HB	Enthalpy of dry flue gas at bed temperature (TB)	kcal/kg
HI	Enthalpy of dry flue gas at ambient temperature T1	kcal/kg
HO	Enthalpy of dry flue gas at outlet temperature TO	kcal/kg
HC	Calorific value of carbon	kcal/kg
HHV	High heat value of the fuel	kcal/kg
h_c	Convection coefficient component of h_o	kcal/h-m²-°C
h_o	Outside heat transfer coefficient	kcal/h-m²-°C

NOMENCLATURE (continued)

h_i	Inside heat transfer coefficient	kcal/h-m²-°C
h_r	Radiative component of h_o	kcal/h-m²-°C
k_g	Thermal conductivity of flue gas	kcal/m-h-°C
k_t	Thermal conductivity of tube material	kcal/m-h-°C
k_w	Thermal conductivity of water	kcal/m-h-°C
L	Height above the expanded bed height	m
$LMTD_{Bed}$	Log mean temperature difference in bed	°C
$LMTD_{FB}$	Log mean temperature difference in freeboard	°C
MF	Moisture in fuel	fraction
Nu	Nussell number $\left(= \frac{hc\ dp}{kg}\right)$	---
Pr	Prandtl number $\frac{(CPW)\mu_w}{k_w}$	---
QABS	Heat extracted from combustor	kcal/h
QBED	Heat absorbed by bed coils	kcal/h
QHTL	Heat absorbed by freeboard heat transfer test loop	kcal/h
QC	Heat in unburnt carbon	kcal/h
QCBD	Heat in unburnt carbon in bed drain	kcal/h
QCCC	Heat in unburnt carbon in cyclone catch	kcal/h
QCES	Heat in unburnt carbon in elutriated solids	kcal/h
QCRS	Heat in unburnt carbon in recycle solids	kcal/h
QCOAL	Heat input in coal	kcal/h
QCMCC	Heat in unburnt carbon in multiclone catch	kcal/h
QCONV	Heat absorbed by convection coils	kcal/h
QCSC	Heat in unburnt carbon in solids to chimney	kcal/h
QDFC	Heat in dry flue gas	kcal/h
QDFGIN	Heat in dry flue gas at freeboard inlet	kcal/h
QFBC	Heat released by freeboard combustion	kcal/h
QIN	Heat input	kcal/h
QINF	Heat in flue gas and solids at freeboard inlet	kcal/h

NOMENCLATURE (continued)

QMAIR	Heat in moisture in air	kcal/h
QMHF	Heat in moisture in fuel and moisture produced from hydrogen in fuel	kcal/h
QOUTF	Heat in flue gas solids at freeboard outlet	kcal/h
QSHES	Sensible heat in elutriated solids	kcal/h
QSHRS	Sensible heat in recycled solids	kcal/h
QSHS	Sensible heat of solids leaving FBC	kcal/h
QDFGOUT	Heat in dry flue gas at freeboard outlet	kcal/h
QMFGOUT	Heat in moisture in flue gas at freeboard outlet	kcal/h
QSHESOUT	Heat in elutriated solids at freeboard outlet	kcal/h
QMFGIN	Heat contributed by moisture at the freeboard inlet	kcal/h
QSHESIN	Heat in elutriated solids from bed entering freeboard	kcal/h
R_e	Reynolds number (VDP/μ)	---
r_i	Bed tube inside radius	m
r_o	Bed tube outside radius	m
TB	Bed temperature	°C
T1	Ambient air temperature	°C
TO	Outlet temperature	°C
TSO	Surface temperature of bed tubes (outside)	°C
TW1	Water inlet temperature	°C
TWO	Water outlet temperature	°C
U	Fluidization velocity	m/s
UC	Unburnt carbon in solids leaving the system	fraction
UBC	Total unburnt carbon	fraction
UCBD	Fraction of unburnt carbon in bed drain	fraction
UCCC	Fraction of unburnt carbon in cyclone catch	fraction
UCMCC	Fraction of unburnt carbon in multiclone catch	fraction
UCSC	Fraction of unburnt carbon in solids to chimney	fraction
U_o	Overall heat transfer coefficient in inbed coils	$kcal/h\text{-}m^2\text{-}°C$

NOMENCLATURE (continued)

U_{FB}	Overall heat transfer coefficient in free-board test loops	kcal/h-m²-°C
V	Velocity of water in the bed tube	m/s
WDFG	Weight of dry flue gas	kg/h
WMAIR	Weight of moisture in air in the flue gas	kg/h
WMHF	Weight of moisture in fuel and moisture produced from the hydrogen in fuel	kg/h
WMFG	Total moisture in the flue gas	kg/h
WRS	Weight of recycled solids	kg/h
β	Excess air coefficient	---
σ	Stefan-Boltzman's constant (4.876×10^{-8})	$kcal/m^2-h-°K^4$
ρ_g	Flue gas density	kg/m^3
ρ_p	Solids density	kg/m^3
ρ_w	Density of water	kg/m^3
μ_g	Viscosity of the flue gas	kg/m-s
μ_w	Viscosity of water	kg/m-s
η_c	Combustion efficiency	fraction

FOREWORD AND ACKNOWLEDGEMENTS

The United States Agency for International Development (USAID) and the Government of India (GOI) under the Alternative Energy Resources Development Project sponsored a joint project in fluidized bed combustion (FBC) technology. The Bharat Heavy Electricals Ltd (BHEL), Trichy, India, and the Oak Ridge National Laboratory (ORNL), were designated as the lead institutions for this project.

An experimental FBC research test facility was designed, erected and commissioned at BHEL, Trichy, to conduct experiments on the combustion of high-ash Indian coals and coal washery rejects. The test facility was designed to provide the necessary engineering and performance data for optimizing the design of large scale industrial and utility FBC boilers.

This report describes the project objectives, scope of work, schedule and milestones, the test facility and hardware, the tests carried out in the facility, and the test results. Potential applications of the test results to commercial FBC boiler design and operation are also summarized.

The authors acknowledge the financial assistance provided by USAID and BHEL. Special thanks are due to the K. Ramakrishnan, Executive Director, BHEL, Trichy and Mr. K.T.U. Malliah, General Manager, Industrial Power Products Division (IPPD), BHEL, Trichy for their invaluable assistance and support since the inception of the project. We are indebted to Dr. C. S. Daw, Engineering Technology Division, ORNL, for his many contributions during the design review, data analysis, and preparation of the final report. Mr. H. E. Trammell, former Director, Engineering Technology Division, ORNL, Mr. Robert Beckman, Chief, Office of Technology Development and Enterprise, and Mr. S. Padmanabhan, Project Officer, USAID, New Delhi, have provided essential administrative support. Dr. Gururaja, Director, Department of Non-Conventional Energy Sources (DNES), Government of India, and Mr. J. R. Meena, Project Officer, DNES, are also gratefully acknowledged for their continued interest and assistance. The assitance and encouragement provided by Dr. Daniel Bienstock, Pittsburgh Energy Technology Center, U.S. Department of Energy, USAID Program Manager, is gratefully acknowledged.

EXECUTIVE SUMMARY

Under the Alternative Energy Resources Development Project, the U.S. Agency for International Development (USAID) and the Government of India (GOI) entered into an agreement to sponsor research and development projects in coal and biomass conversion. In the coal conversion area, a collaborative research project in fluidized bed combustion (FBC) was initiated between the Bharat Heavy Electricals Ltd (BHEL), Trichy, India and the Oak Ridge National Laboratory (ORNL) in November 1983. As part of this project, an experimental FBC research test facility was designed and erected at the High Pressure Boiler Plant at BHEL, Trichy, to conduct experiments on the combustion of high-ash Indian coals and coal washery rejects. The facility was designed to provide maximum flexibility to test a broad range of calorific value fuels (2000-7300 kCal/kg) at different operating conditions. In addition, special design features such as underbed and overbed coal feeding, flyash reinjection, and adjustable "freeboard" height were incorporated in the design. Data on the combustion and heat transfer in the "freeboard" region of the combustor were of particular interest because of the lack of information on freeboard combustion, freeboard heat release, and heat transfer coefficient with respect to high-ash Indian coals. These data are critical for the design and scale-up of large FBC boilers.

The test facility consists of a 11-m high, 1 m × 1 m cross-section refractory lined combustor with the associated auxiliary systems (coal feeding, ash removal, air preheat and dust separation). Crushed, sized fuel is metered by gravimetric weigh belt feeders and is fed either underbed by pneumatic injection or overbed by a screw feeder. The bed material is a mixture of crushed refractory and bed ash, although there is provision to use limestone when burning high sulfur coals. Flyash collected in the downstream cyclones can be recycled into the combustor.

The maximum heat input to the combustor is 2.0 MW(t). The combustor is designed as a hot water generator at 10 kg/cm^2 and 170°C. Flexibility has been provided in the design by way of (1) a detachable side wall to insert and retract heat transfer surfaces in the main bed for specified bed heights (from 300 mm to 1300 mm), (2) lowering or raising the convective tube bank to vary the freeboard height (from 1000 mm to 6000 mm), (3) velocity turndown from 3.0 m to 1.0 m/s, (4) recycle of flyash from the primary and/or secondary cyclone, (5) provision for a waterwall test loop in the bed wall region, (6) heat transfer test loops at two locations in the freeboard, (7) overfire air injection, (8) continuous multipoint flue gas sampling and analysis, and (9) continuous monitoring, processing and display of data generated in the tests.

Three series of tests were conducted in the facility for a total of 600 h after about 300 h of shakedown testing. The tests were of long duration, typically lasting 40 to 50 h. The fuels tested include (1) high-ash (33-45%) sub-bituminous coal, (2) coal washery rejects containing 60-65% ash, and (3) a bowl-mill reject (50-55% ash).

Test series 1 consisted of approximately 200 h of tests in the once through (no flyash reinjection) underbed coal feed mode. Following these tests, a second series of tests were completed on the same fuels again with underbed feeding but with flyash reinjection. The last series of tests were performed in the overbed feed mode with and without flyash reinjection.

Performance data gathered in these tests included air/water flow rates, fuel feed rate, in-bed and freeboard temperatures at multiple locations, flue gas composition (CO, CO_2, O_2, SO_2, NO_x and hydrocarbons) along the combustor height, solid sample analysis from selected discharge locations, and dust loading at the combustor exit. These data were analyzed to compute the performance parameters such as combustion efficiency, in-bed and freeboard combustion, heat release in the bed and freeboard, carbon burn-up, heat transfer coefficient (bed and freeboard), bed retention and pollutant emissions.

The major accomplishments stemming from this collaborative work are summarized below:

(1) A state-of-the-art FBC research test facility was designed, erected and commissioned at BHEL, Trichy. The facility is now generating engineering data relevant to the design and operation of industrial FBC boilers up to 30 MW(e) in size and fired on high-ash content (up to 45%) coal, and coal washery rejects.

(2) Sufficient flexibility has been provided in this test facility to burn other fuels including high-sulfur coals, biomass and coal-water mixtures with minimum modifications.

(3) Operating problems associated with underbed/overbed fuel feed systems, flyash reinjection and ash removal specific to these high-ash fuels were identified and extensively analyzed. The experience gathered has resulted in establishing proper design and operational guidelines for these fuels.

(4) Testing and evaluation of the hardware (on-line flue gas analysis system, data acquisition system, gravimetric feeders, high pressure fan, gas sampling probes, elemental analyzer, adiabatic bomb calorimeter) supplied by USAID were completed and necessary hands-on experience obtained to successfully operate these equipment. The equipment expendables and spare parts needed for two years operation were also identified and procured.

(5) Combustion tests conducted on the high-ash, sub-bituminous coals clearly demonstrated that these coals are more reactive than Eastern, high-sulfur, sub-bituminous U.S. coals. Once through combustion efficiency for the Indian coals were in the range of 95-97% compared to 90-92% for U.S. coals. Apart from the coal reactivity, the low sulfur content (<1%) of Indian coals compared to the 3-5% sulfur U.S. coals, permits operation of the FBC at higher bed temperature (950°C compared to 850°C for U.S. coals).

Higher bed temperature is known to enhance the combustion efficiency. The combustion efficiency obtained with rejects was 85-90%.

(6) Similar to the U.S. experience, flyash reinjection improves combustion efficiency by 2-3%. However, the high-ash content limits the recycle ratio (ratio of flyash to coal) to a maximum of 2.0, beyond which the handling of the large quantities of high temperature ash poses severe problems.

(7) The sensible heat loss from the bed drain is substantial for these high-ash fuels. It is essential that this heat be recovered in large FBC units to improve the overall thermal efficiency of the boiler.

(8) Overbed feeding is a much simpler, easy to operate, and less prone to forced outages compared to underbed feeding. However, there is a 3-5% penalty in the combustion efficiency with overbed feeding because of the carbon carryover with the flyash.

(9) Freeboard combustion was around 6-9% when burning coal and 3-6% when burning washery rejects with underbed feeding. The values were higher for overbed feeding, typically 10-15% for coal and 5-8% for rejects. With flyash reinjection, freeboard combustion increased by at least 2% in all cases. Present FBC designs assume 10-15% freeboard combustion with underbed feeding and up to 30% for overbed feeding. These values are probably conservative and could be reduced. Reduction in freeboard combustion will translate to having less heat transfer surface in the freeboard region and less freeboard height both of which could favorably impact the cost of the boiler.

(10) Empirical correlations for predicting the in-bed and freeboard heat transfer coefficient in terms of the bed parameters have been developed.

(11) Sulfur oxide emissions were in the range of 190-500 ppm in most of the tests. The values were higher (700-1000 ppm) when firing rejects. NO_x emissions ranged from 160-420 ppm and showed an increasing trend with excess air at 900°C.

(12) Two seminars were organized in India in March 1988 in which the test results from the first series of tests were presented. A six member team of U.S. FBC experts attended these seminars and visited the test facility at Trichy.

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ABSTRACT

Under a cooperative agreement between the U.S. Agency for International Development (USAID) and the Government of India (GOI), a joint research project in fluidized bed combustion (FBC) was carried out by the Bharat Heavy Electricals Ltd. (BHEL), India, and the Oak Ridge National Laboratory (ORNL). The project was aimed at obtaining basic engineering data on the combustion of high-ash Indian coals (up to 45% ash), and coal washery rejects (up to 70% ash). Quantitative measurements of overall combustion efficiency, in-bed and freeboard combustion, in-bed heat transfer coefficient, freeboard heat transfer coefficient, flue gas composition and temperature profiles in the bed and freeboard were of particular interst.

A 1 m × 1 m cross section, 11.0-m high, refractory-lined FBC was erected at BHEL, Trichy. The combustor was designed as a hot water generator with a capacity of 90 t/h at 10 kg/cm^2 and 179°C. Tests were conducted on a sub-bituminous Indian coal (~38% ash) and a coal washery reject (65% ash), with and without flyash reinjection. Both underbed and overbed fuel feeding modes were tested in the facility. Three series of long-duration tests typically lasting 40 to 50 h were conducted in the facility for a total of 600 h after about 300 h of shakedown testing. Operational problems associated with underbed/overbed feeding, flyash reinjection and ash removal were identified.

The overall combustion efficiency obtained in the underbed tests was typically 95–97% for the high-ash coal and 85–90% for the washery rejects. With recycle, there was a 2–3% improvement in combustion efficiency. The freeboard combustion was estimated to be around 6–9% for the high-ash coal and 3–6% for the rejects. Freeboard combustion increased with increase in the ash recycle rate and fluidizing velocity. The maximum freeboard combustion obtained in the tests was 11% at a recycle ratio of 2.0.

The combustion efficiency was 3–5% lower with overboard feeding compared to underbed. In addition, the freeboard combustion was also higher (10–15%) in the overbed tests. Overbed feeding was simpler and less prone to forced outages compared to underbed.

The overall in-bed heat transfer coefficient measured in the bed was 193–200 kcal/m^2 h °C. The freeboard heat transfer coefficient ranged from 170 kcal/h m^2 h °C at just above the expanded bed to 50 kcal/h m^2 °C, at 1.6 m above the expanded bed. Empirical correlations for the in-bed and freeboard heat transfer coefficients were developed from the test data. Sulfur oxide, nitrogen oxides, and CO emissions from the combustor were found to be 400–670 ppm, 100–490 ppm, and 100–350 ppm, respectively. The SO_2 and NO_x values were much lower compared to high-sulfur U.S. coals. From an operational standpoint, the coal washery rejects required special attention in the handling of the high volume of ash generated during combustion.

1. INTRODUCTION

Fluidized bed combustion systems for firing high-ash coals and low-grade fuels are gaining wide acceptance in the industrial and utility sectors in India. These systems are viewed as the best current option for industrial heat and power generation and eventually for large scale utility power generation.

BHEL has the lead role in the development and commercialization of FBC technology in India. Several FBC boilers have been supplied by BHEL to industrial customers, and orders for many more are being executed. The largest industrial boiler in operation now is a 60 t/h steam unit operating at a paper mill. In the utility sector, the design for a 30 MWe FBC boiler has been completed and preliminary offers have been made to customers. Present FBC boiler designs are conservative due to lack of information on the combustion characteristics and the performance of high-ash fuels in large FBCs. In addition, the impact of fuel type on combustion efficiency and heat transfer in the "freeboard" region (region of the boiler from the top bed surface to the first row of the convective tube bank – see Fig. 1.1) is extremely important for selection of the proper boiler design.

Although the importance of the freeboard is well recognized by boiler designers, there is insufficient information available on the potential freeboard reactions. Some information is available from pilot plants and other test facilities (B&W/EPRI – 2 m × 2 m, TVA 20 MW AFBC pilot plant), but major uncertainties exist regarding freeboard heat release, heat transfer to the water walls and convection tube surfaces, freeboard solids inventory and particle size distribution, and freeboard solid/gas temperature differences. A broader data base is needed to develop reliable design and scale-up correlations. The data base should include the effect of such factors as size and configuration of the combustor and freeboard, the mode of fuel feeding (i.e. underbed vs overbed), recycle ratio, excess air, and overfire air.

The available data on freeboard heat-transfer and combustion is limited. Studies such as those by Wood et al. (1981), Byam et al.

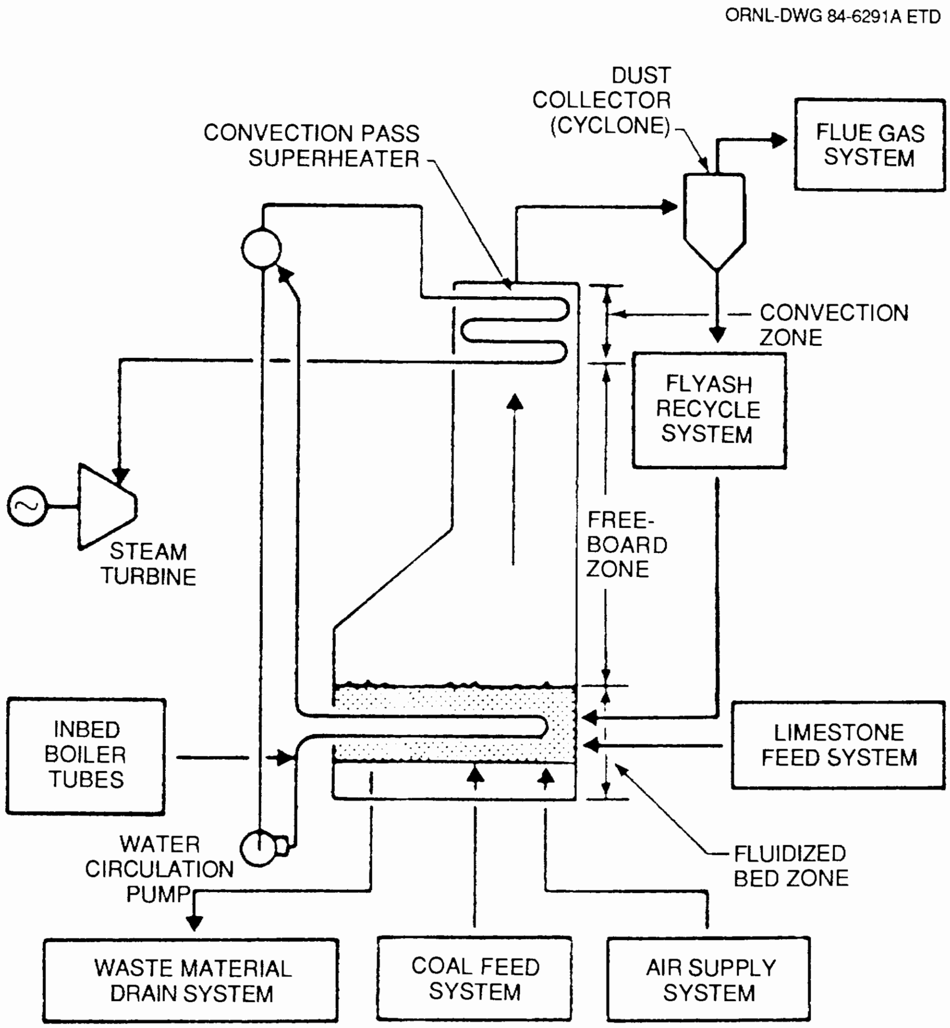

Fig. 1.1. Fluidized bed combustion boiler with major auxiliary systems.

(1981), George & Grace (1982), Xavier and Davidson (1981), Biyikli et al. (1983), Carson et al. (1987), Dixit et al. and Krishnan et al. (1983), provide some information for U.S. coals, but with respect to the high ash Indian coals there is virtually no information. BHEL has recognized the limitations of the available data in the literature because of the wide difference in the composition of Indian coals vis-a-vis other coals. Furthermore, since no sorbent is required with Indian coals (low sulfur) the bed depths are much shallower (300–500 mm) compared to the deep limestone beds (1200–1500 mm) used for the high sulfur U.S. coals. As would be expected, shallow beds exhibit an increased tendency toward freeboard combustion.

The purpose of this project was to perform a detailed investigation in the freeboard region. For this purpose, a 1 m × 1 m experimental FBC test facility was designed and instrumented to bridge the existing data gaps. In addition to the freeboard data, it was envisioned that the tests would shed light on the combustion characteristics of high-ash Indian coals and washery rejects, the effect of recycle on combustion efficiency, dust loading, heat generation and heat transfer rates in the bed and freeboard, and underbed vs overbed coal feed system performance. The test data in conjunction with the existing data base from the BHEL designed operating commercial FBC facilities would be used to develop design correlations for scale-up and performance prediction of FBC boilers up to 30 MW(e) capacity.

2. PROJECT DETAILS

The project design was completed during the first USAID-GOI Coal and Biomass Conversion Workshop which was held in New Delhi in November 1983. At this time, the specific objectives, scope of work, budget, schedule and milestone were prepared jointly by BHEL and ORNL. The project proposal was submitted to the USAID program manager from the Pittsburgh Energy Technology Center, U.S. Department of Energy and the GOI program manager from the Department of Nonconventional Energy Sources.

2.1 Objectives

The objectives of the project were as follows:

1. Design and construct a versatile FBC research test facility to conduct performance tests on high-ash content (40–65%) and low calorific value (2000 to 4000 kcal/kg) Indian coals.

2. Generate test data on combustion efficiency, heat release, heat transfer coefficient and pollutant emissions for these fuels under various operating conditions.

3. Estimate the 'inbed' and 'freeboard' combustion and heat transfer for these fuels at different test conditions.

4. Evaluate the effect of flyash reinjection on combustor operation and performance.

5. Test the operation/performance with underbed and overbed fuel feeding.

2.2 Scope of Work

The total cost of the project was shared by BHEL and USAID. The BHEL scope of work included the following:

- Engineering design of the test facility, fabrication of components and structures.

- Procurement of auxiliary equipment, instrumentation and control equipment.

- Erection of the test facility.

- Commissioning and shakedown testing.

- Operation of the facility (manpower and utilities).

- Infrastructure facilities and arrangements (air cooled condenser, pumps, chimney, coal handling and preparation, water treatment plant, chemical laboratory).

- Testing, data gathering, data analysis and report preparation.

The USAID scope of work included

- Providing non-indigenous equipment from the United States such as (1) on-line flue gas sampling and analysis system, calibration gases, flue gas sampling probes, heat traced lines, coal and limestone gravimetric feeders, data acquisition and analysis system, high head fan, adiabatic bomb calorimeter, fuel elemental analyzer, multisignal calibrator, and adequate spares and supplies for the above equipment for two years operation.

- Services of the ORNL staff member assigned for this project.

- Arranging visits of BHEL Engineers to United States for training courses on instruments, attendance at project review meetings and workshops, and site visits to FBC installations.

- Report preparation.

2.3 Budget

The total cost of the project was roughly U.S. $1.7 million. USAID contribution towards equipment, technical assistance, training and participation of BHEL engineers in the design review meetings, conferences and site visits to FBC installations in the United States, data analysis and report preparation was roughly one million dollars (see Appendix A). BHEL's contribution included engineering design of the test facility, indigenous equipment, fabrication, erection, commissioning, testing, data analysis and report preparation which was roughly 0.7 million dollars.

2.4 Project Schedule and Milestones

The project was initiated in November 1983. Design of the test facility and specifications for the equipment were completed between December 83 and March 1984. Extensive review of the design was conducted in the United States by FBC specialists associated with the Babcock and Wilcox Company, Combustion Engineering, the Tennessee Valley Authority, the Morgantown Energy Technology Center, the Electric Power Research Institute and the Massachusetts Institute of Technology. Modifications proposed by the reviewers were incorporated into the design. A major modification involved changing the supporting arrangement for the combustor from the earlier top-supported design to a bottom-supported design.

Purchase orders for the USAID supplied equipment and the indigenous equipment were released in October 1984. Material procurement (about 90 tonnes of steel plates, tubes and rolled products) for fabrication of the combustor, pressure parts and non-pressure parts and structures, fabrication of components, and the structural foundations were completed in November 1985. The erection of the combustor, auxiliary systems and ducting were completed in March 86 by a subcontractor. Precommissioning of the individual systems including the USAID supplied equipment were done during April 86—February 87. There were substantial delays in the delivery of the equipment from local suppliers since many of the equipment were not "off-the-shelf" items and had to be fabricated. In addition, the shipment of the equipment from the U.S., customs clearance formalities, and the need for training of BHEL engineers on these equipments contributed to further delays.

The first coal fire was performed in February 1987 followed by about 300 hours of shakedown tests, to cure the refractories and to fine tune the equipment.

Testing and data gathering commenced in June 1987. The first series of underbed tests (200 h) on high-ash coal and rejects were completed in September 1987. The facility was shutdown thereafter until January 1988 to perform several modifications to the combustor, induced draft fan, Roots blower and ash disposal system. Installation of the recycle system for the second series of tests was done at the same time the modifications were being carried out in the facility.

Recycle tests on the coal and washery rejects were completed in June 1988. After these tests, the facility was again shut down to install the overbed feed system. Overbed testing with and without fly-ash reinjection was completed in December 1988. Data analysis was conducted in parallel with the testing. During the first two series of tests, the Roots blower failed several times because of fabrication flaws. It was decided to procure a high head fan from the United States to replace the blower to ward off similar problems in the future. The facility is operating satisfactorily after these modifications and there are plans to test biomass fuels and coal-water mixtures in the facility. Some minimum modifications, especially in the fuel feed system will be required before these tests can start.

3. DESCRIPTION OF TEST FACILITY

The test facility is located in the Research and Development Complex of BHEL, Trichy along with the other existing FBC test rigs.

The existing peripheral facilities such as water treatment plant, condensate storage tank, air-cooled condensers, coal preparation, coal handling, chimney and other utilities are utilized for the test facility.

3.1 Layout

The facility consists of an 1 m × 1 m cross section, 11-m high refractory lined combustor. The total height of the combustor and supporting arrangement is 14.5 m in five levels starting from the ground level.

The combustion air and coal/flyash transport air are supplied by a Roots blower. The combustion gases pass through primary and secondary cyclones. The design allows recycle of flyash collected from the primary and secondary cyclones into the combustor as required. The flue gas from the secondary cyclone is vented to the atmosphere through an induced draft fan and chimney.

The coal from the coal preparation plant is loaded by front end loaders to the coal pit. An electrical hoist with bucket is used to elevate the coal to the bunker and is fed to the combustor. The coal flow rate is metered by gravimetric feeders placed below the bunkers. The spent bed material is drained continuously through an ash cooler and stored in bins.

The demineralized water required for the combustor is supplied from the existing condensate storage tank and pumped through the water circuits of the combustor. The hot water generated in the combustor is cooled in the existing air cooled condensers and returned to the condensate storage tank.

The control room measures approximately 8 m × 5 m and houses the combustion control system, on-line flue gas monitoring system, process instrumentation and control system and data acquisition system. The overall layout of the test facility is shown in Fig. 3.1.

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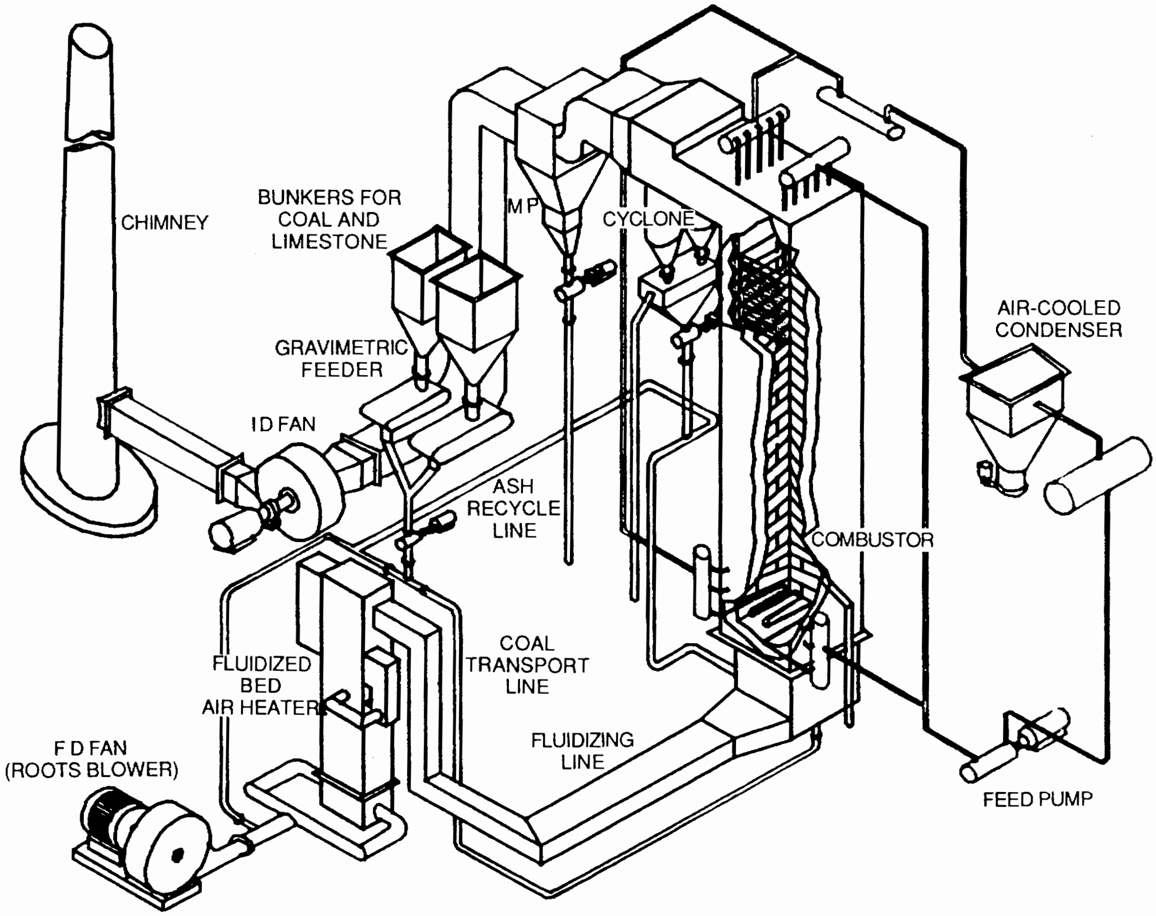

Fig. 3.1. Schematic of the FBC test facility.

3.2 Combustor

The fluidized bed combustor is a hot water generator of capacity 90 t/h at 10 kg/cm^2(a) pressure and 179°C (350°F). The cross sectional area of the combustor is 1 meter square (3.3 ft^2) and the combustor height is 11 m (35 ft) from the distributor plate. The combustor is supported at the bottom (see Fig. 3.2) and has the following features:

- variable bed height (300 to 1300 mm – 0.98 to 4.3 ft) – expanded bed height
- variable freeboard height (1000 to 6000 mm – 3.3 to 19.7 ft)
- variable inbed heat transfer surface
- refractory lined walls

ORNL-DWG 89-4699 ETD

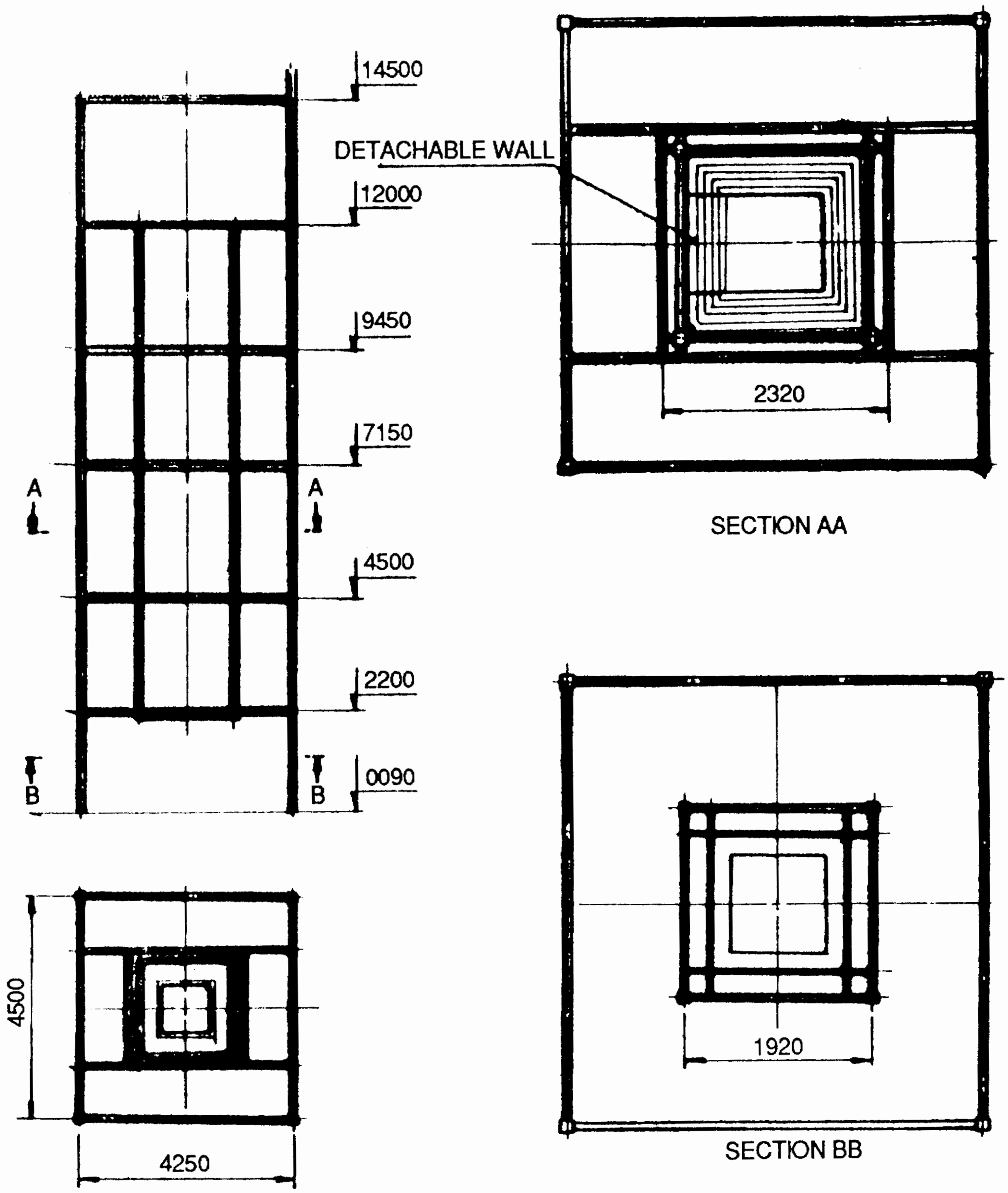

Fig. 3.2. Combustor suspension arrangement.

- heat transfer test loops at two elevations in the freeboard
- recycle of solids from primary and secondary cyclones into the main bed
- underbed/overbed coal feeding
- overfire air

The four sides of the bed and freeboard are refractory lined. One bed side wall is detachable and carries the inbed tube bundles. Tubes can be inserted or retracted through the detachable side wall (Fig. 3.3). Two water-cooled, instrumented heat transfer test loops are located in the freeboard (0.6 m and 1.6 m from the expanded bed surface) to measure the heat pickup in the freeboard region. Provisions have also been made for pressure, temperature, and flue gas sampling through the side walls. A horizontal convective tube bank is located at the freeboard exit. The convection section is 1.2 m in height and cools the flue gas to about 350°C (660°F) before it exits the combustor (Fig. 3.4). Fluidizing air is distributed with nozzles, and coal and recycled flyash are fed through individual nozzles attached to the distributor plate. An opening (108 mm) is provided in the distributor plate to drain the bed material. A manhole door is also located on one wall.

The wall refractory consists of a layer of fire brick 75 mm thick (3 in.) followed by five layers of light weight brick 350 mm thick (14 in.) and a seal plate, and finally covered with 100 mm (4 in.) thick mineral wool mattress and galvanized sheet covering (Fig. 3.5). The inbed tube bundle consist of three layers of tube bank. The tube size is 31.8 mm (1.25 in.) OD, 2.9 mm (0.1 in.) thick, and is constructed out of special alloy steel, SA 210 grade A1 material. The transverse pitch (ST) and longitudinal pitch (SL) are 96 mm (3.8 in.) and 106 mm (4.2 in.), respectively. The heat transfer test loops are made out of stainless steel tubes, 14 mm OD and 2.9 mm thickness. The surface in each loop is designed for equal heat absorption.

3.3 Supporting Structure

The test facility is bottom supported (Fig. 3.6). A computer program developed by BHEL was used to perform the detailed structural analysis. The main columns in the test facility are spaced at 4.5 m and 4.25 m. These columns support the main combustor and the five platforms. The major contribution to the load of 120 tonnes is from the 11-m tall refractory lined combustor.

3.4 Auxiliary Systems

This section describes the major auxiliary systems in the test facility.

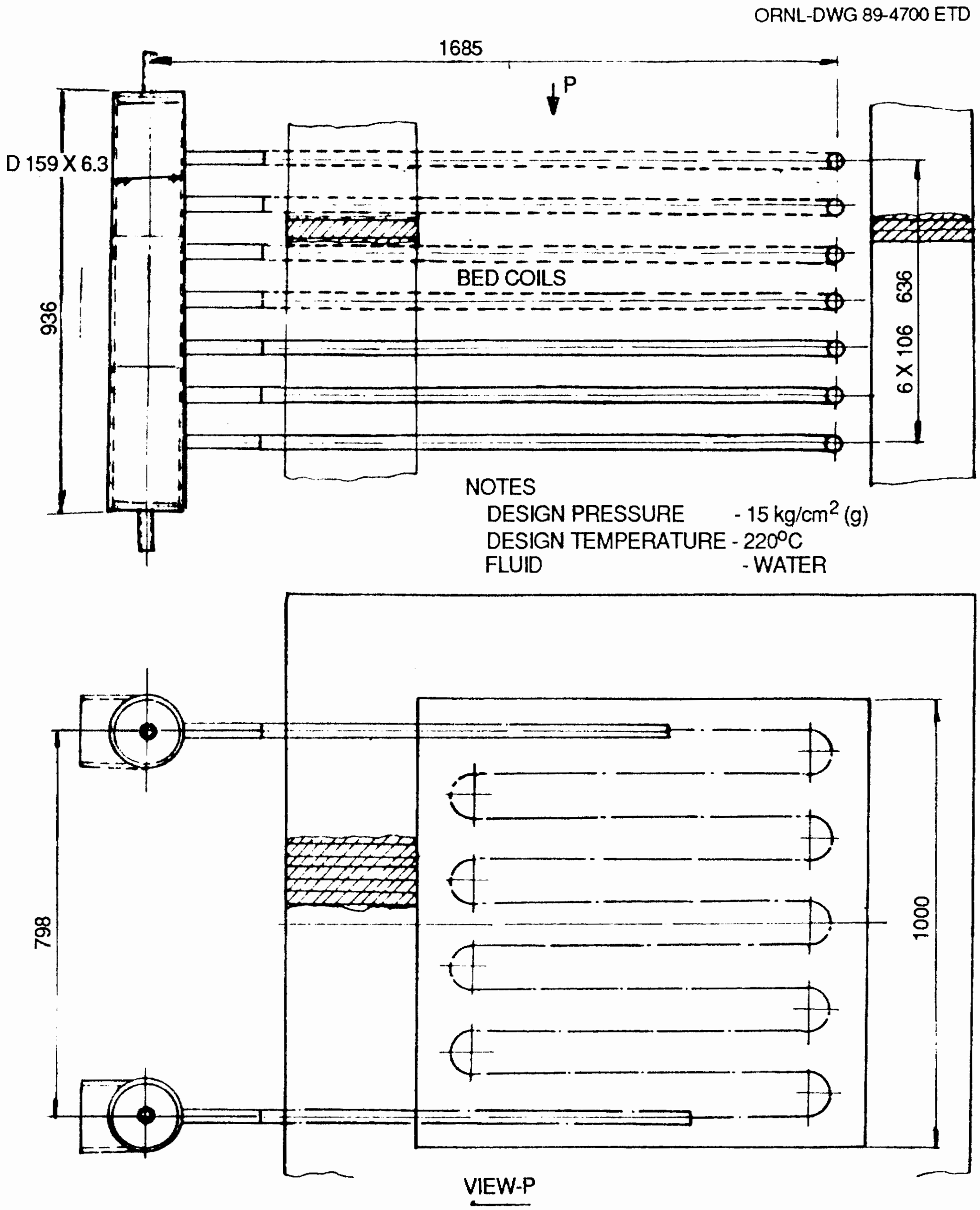

Fig. 3.3. Bed coils with headers.

ORNL-DWG 89-4701 ETD

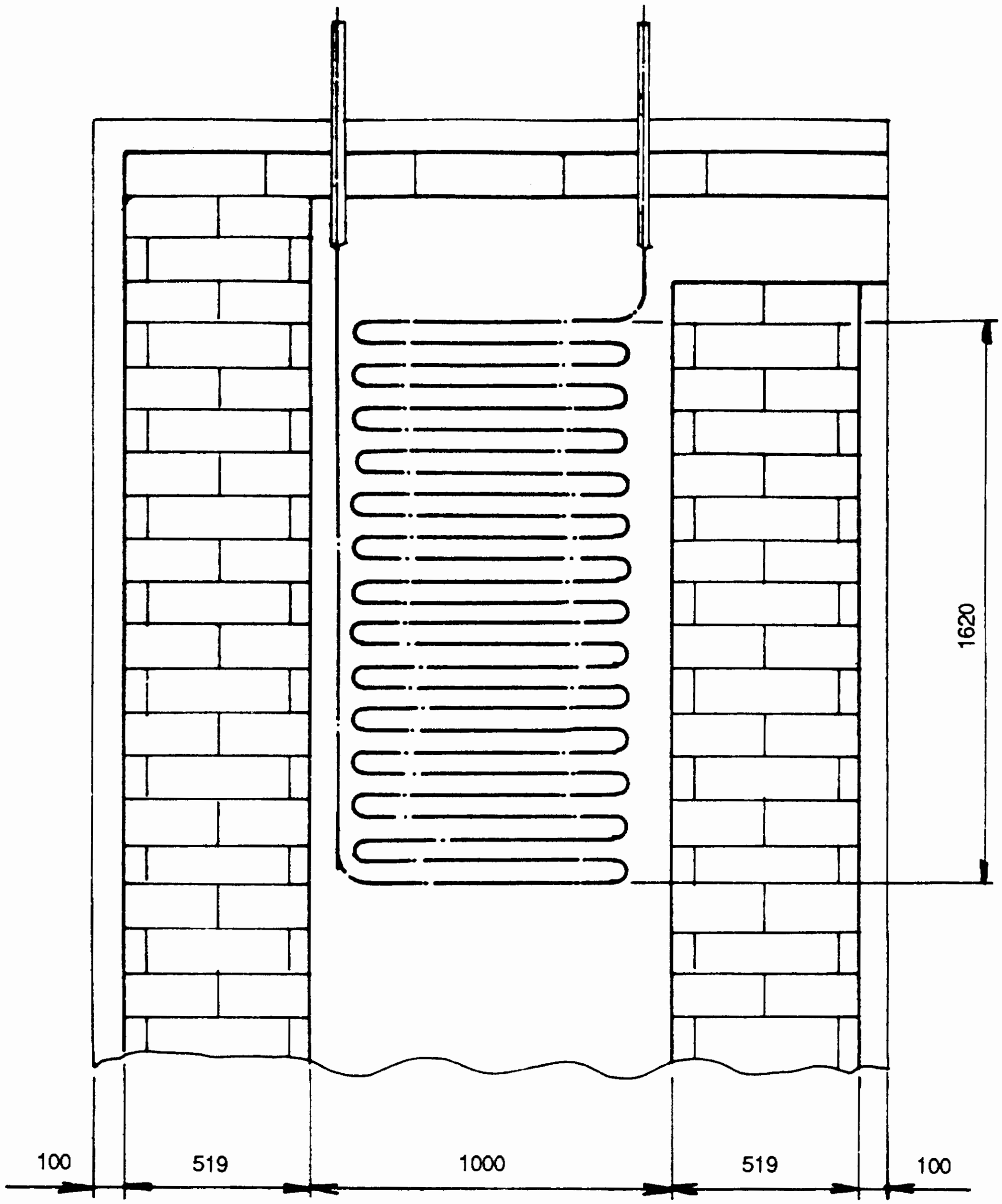

Fig. 3.4. Convection bundle.

ORNL-DWG 89-4702 ETD

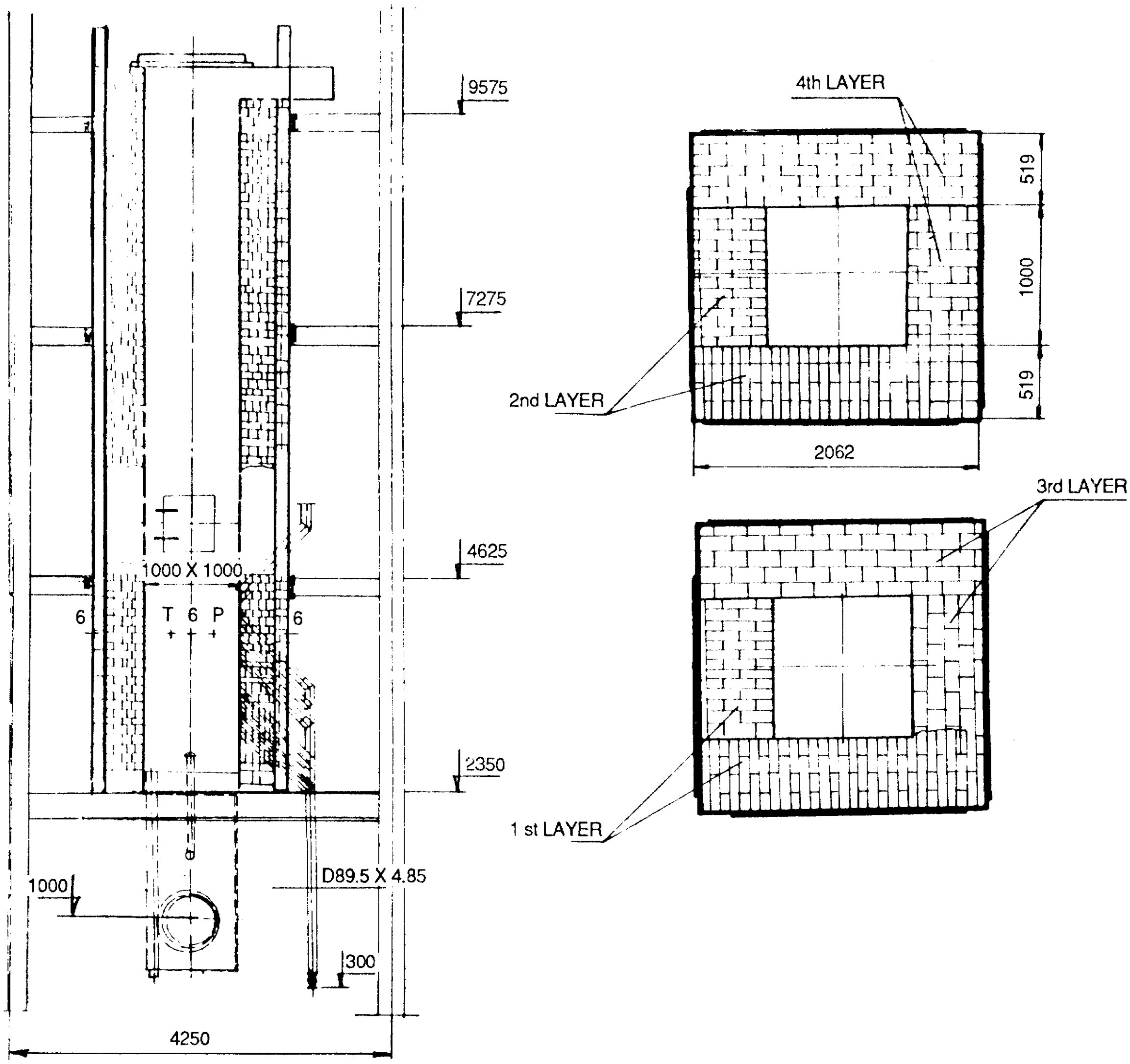

Fig. 3.5. Fluidized bed combustor.

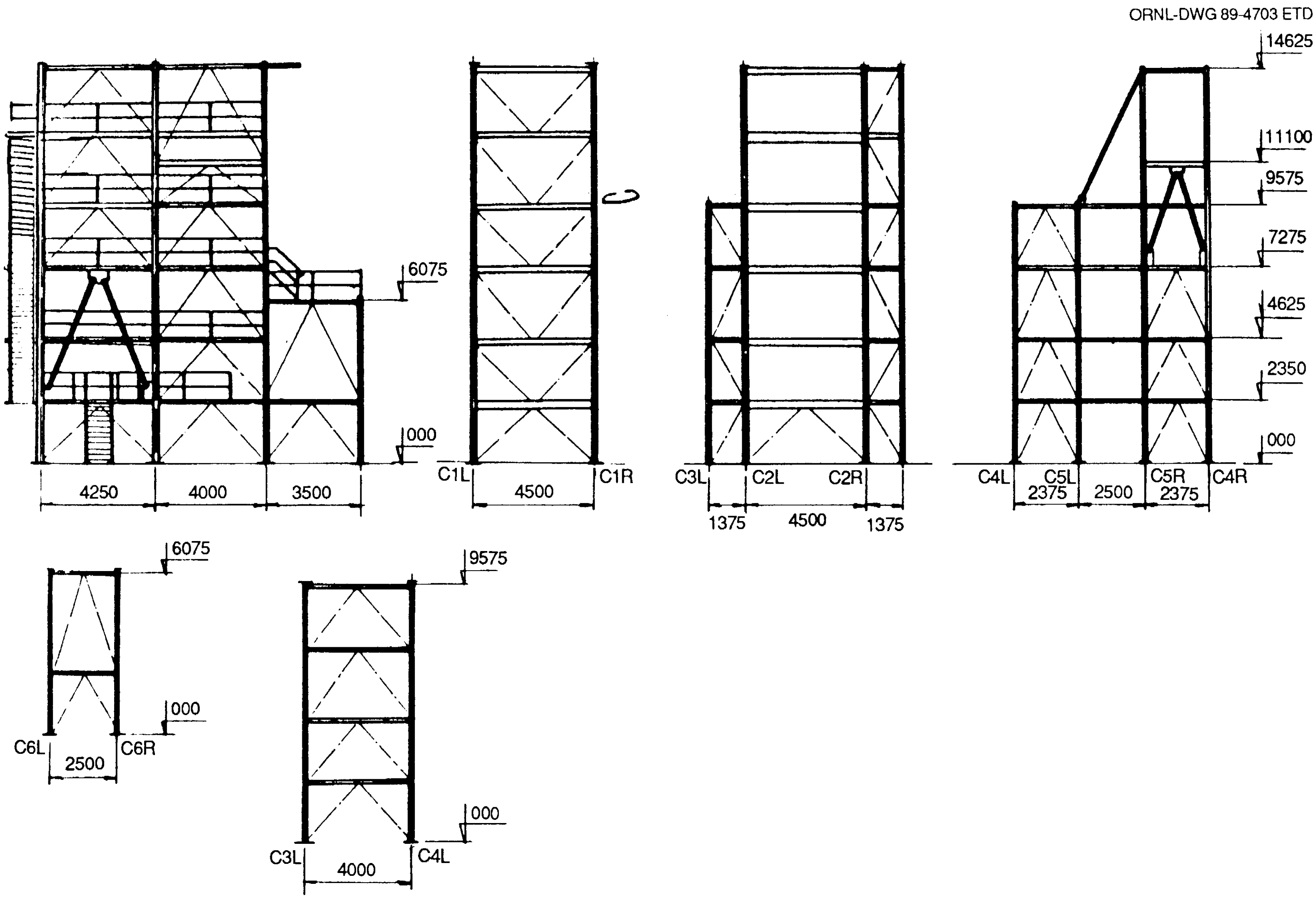

Fig. 3.6. Structural supports.

3.4.1 Coal and limestone feeding

The coal feed system is designed to permit either underbed or overbed feeding. In the underbed feeding mode, coal is discharged from the bunker to the gravimetric feeder. The coal is then pneumatically injected into the bed through the coal feed nozzle in the distributor plate. The pneumatic transport line is sized to permit the operation of the combustor with different fuels. Typical transport velocity in the feed line is 12 m/s (40 ft/s) for a solid-to-air ratio of up to 3.0.

In the overbed feeding mode, the coal is metered by the gravimetric feeder and then fed into the inlet line of the screw feeder. From the discharge end of the screw feeder the coal is dropped into the bed by gravity.

3.4.2 Ash removal and disposal

Spent bed material along with the bed ash have to be drained periodically from the bed to maintain the operating bed level. This is done by activating one of the several overflow tappings provided along the combustor side wall. Eight such tappings are provided to allow operation at various bed levels. Typically with Indian coals and rejects which are low in sulfur, a shallow bed is sufficient. The bed material is generally crushed refractory and ash since no sorbent (limestone) is required for sulfur capture. The design allows operation at bed heights ranging from 350 mm to 750 mm in 100 mm increments. For high sulfur coals which require deeper beds, and limestone as the bed material, the design permits operation at 1100 mm (3.6 ft), 1300 mm (4.3 ft) and 1500 mm (4.9 ft).

The overflow pipes are sized 88.9 mm (3.5 in.) OD and 7.9 mm thick (0.33 in.) (see Fig. 3.7). In addition to the overflow pipes, a bed drain pipe of 108 mm (4 in.) OD and 8 mm (0.3 in.) thickness is installed at the bottom of the bed to periodically drain the bed of "rocks", "shales", and other foreign material which may come with the fuel. These heavier material will tend to settle at the bottom and if allowed to collect will result in defluidization. The overflow pipe is connected to an ash-cooler (Fig. 3.8).

3.4.3 Flyash reinjection

The facility has provision for reinjecting the flyash collected in the ash overflow hoppers located below the primary cyclone. The overflow ensures that a constant level of flyash is maintained. Ash in the hopper enters a variable-speed rotary air lock feeder and is then pneumatically injected underbed through the feed nozzle. The recycle system is designed for recycling up to two times the coal feed rate. The line is 108 mm (4 in.) OD and 8 mm (0.3 in.) thick. Ash feed rate is estimated by the speed (rpm) of the feeder from the calibration curve. Typically, recycle flyash temperature is around 300°C (575°F).

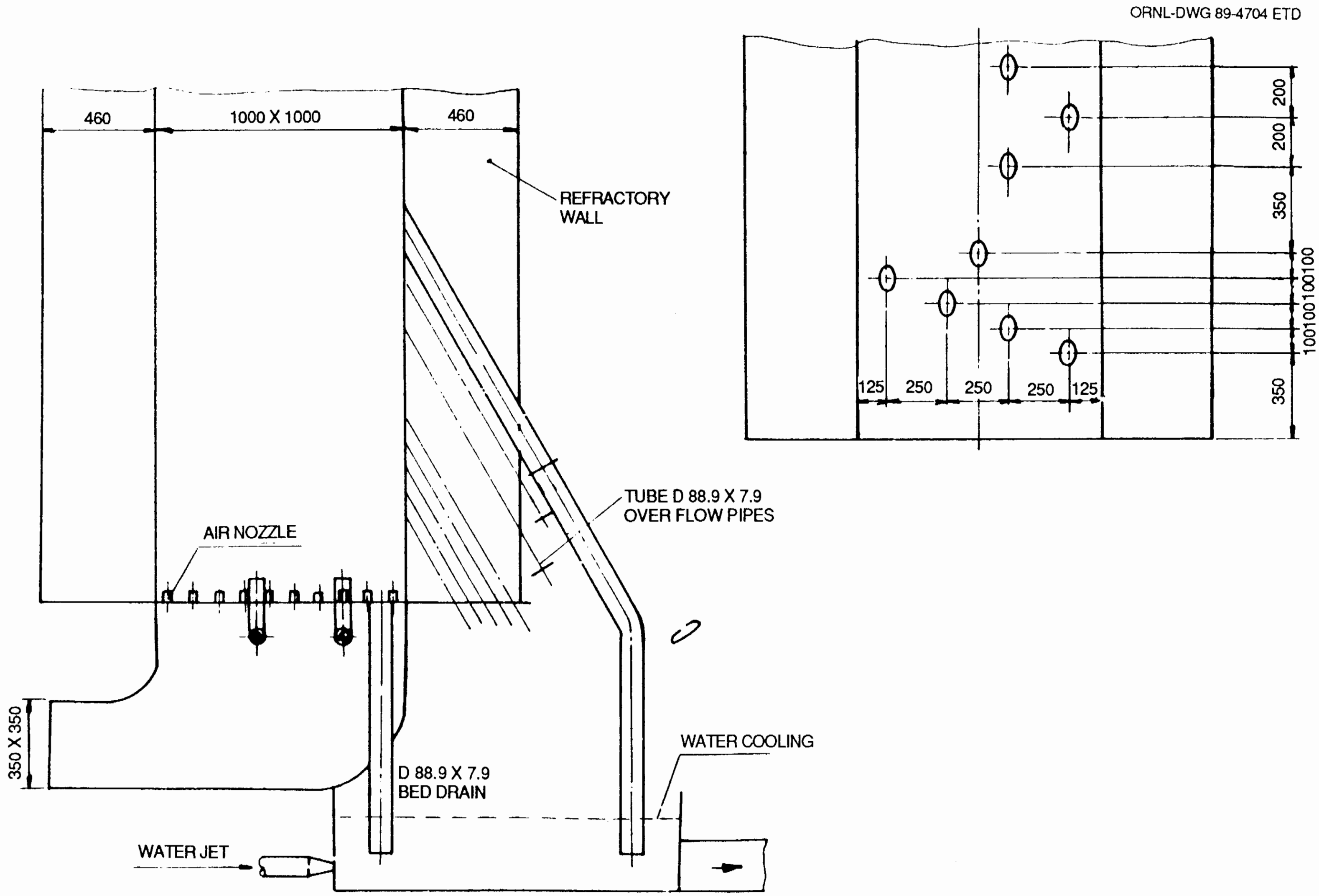

Fig. 3.7. Bed overflow system.

ORNL-DWG 89-4705 ETD

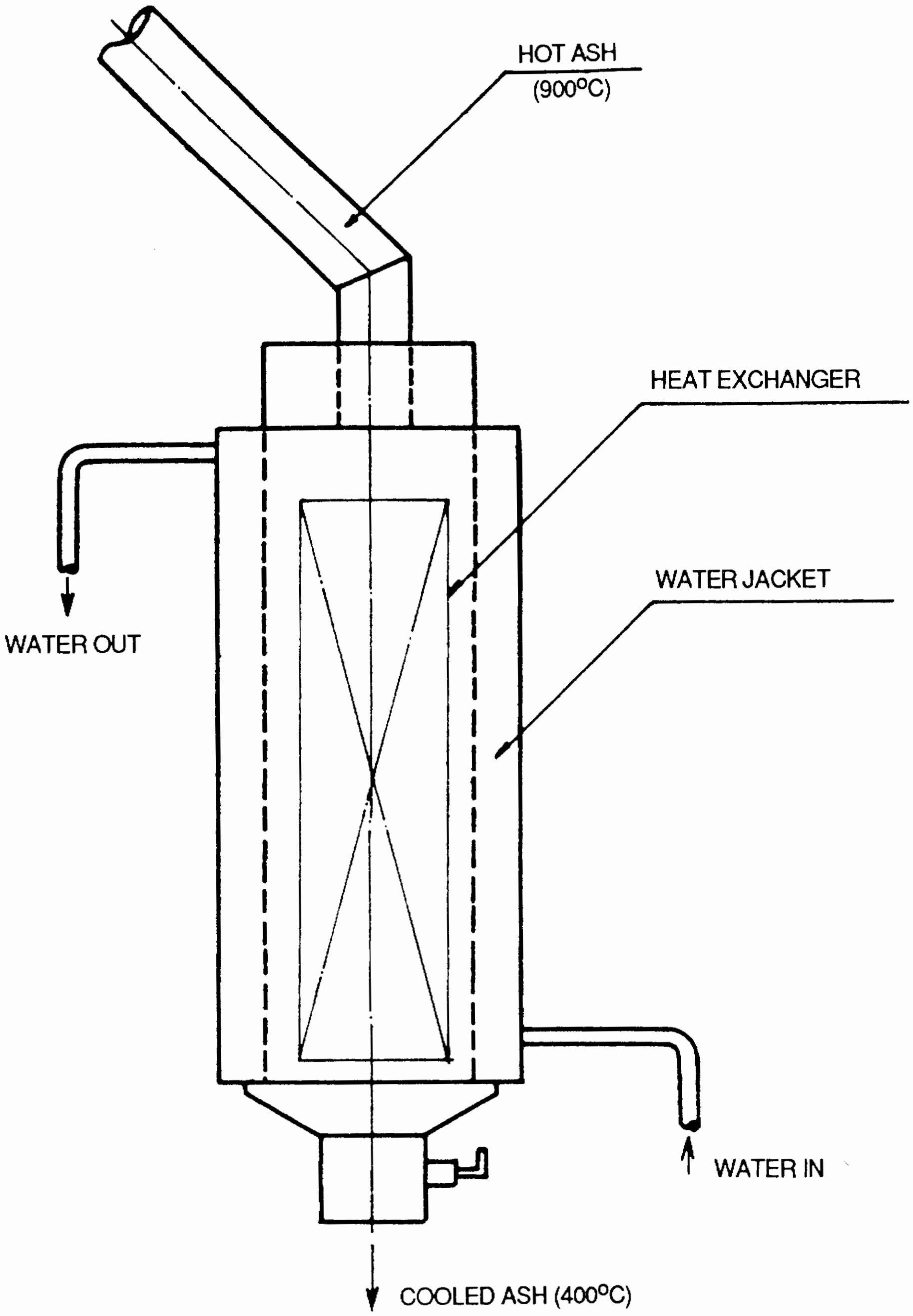

Fig. 3.8. Ash cooler.

3.4.4 Particulate removal

The particulate removal system is intended to separate the solid material (unburnt char, flyash and bed material) from the flue gas. Primary and secondary cyclones are located at the exit of the combustor. Primary cyclone catch is recycled to the bed. Flue gases enter the cyclones through 325 mm square (1.06 ft square) ducting. The design of the primary (twin) cyclones is based on the Stairmand design proportions (Usman 1975), yielding overall dimensions of 406 mm (1.33 ft) diameter and 1550 mm (5.08 ft) height (see Fig. 3.9). The cyclone is designed for a pressure drop of 100 mm (4 in.) water column (wc) and an inlet velocity of 20 m/s. The collection efficiency is 88.6% for particles in the size range 10 to 350 microns.

The flue gas leaving the primary twin cyclones passes through a secondary multiclone consisting of six cyclones in parallel flow arrangement (see Fig. 3.10). These cyclones are also of the Stairmand design and the overall collection efficiency is 70%. The particle size range is 10 to 20 microns. The overall dimensions of each of the cyclones are 219 mm (8.5 in.) OD and 824 mm (2.7 ft) height and the pressure drop is estimated to be 100 mm (4 in.) water column (wc). Multiclone discharge conditions are estimated to be 1.8 g/m^3 at 350°C (660°F).

3.4.5 Air/flue gas circuit

The combustor is designed for balanced draft operation in the freeboard. Fluidizing air is supplied by a Roots blower, and pneumatic transport air for coal, limestone, and recycle flyash is supplied by a tap line from the Roots blower. Air flows are metered by the segmental orifice in the fluidizing air line and the circular orifice plates in the transport lines. Flue gases flow through the freeboard, convection bank, and cyclone separators before being discharged through the chimney. The detailed dimensional drawing of the air/flue gas system is shown in Fig. 3.11 and a schematic of the system is shown in Fig. 3.12.

3.4.6 Water circuit

Feed water for the combustor is supplied from a demineralized (DM) water tank. At the start of the test, DM water is pumped to the condensate storage tank (CST) and stored. The required quantity of water is drained from the CST and pumped through the inbed tube bundle, convection bundle and heat transfer test loops. Three feed water pumps are provided. A schematic of the water circuit is shown in Fig. 3.13. Details are also provided in Fig. 3.14.

3.4.7 Air distributor

The nozzle-type air distributor has the flexibility to accommodate operation over a range of fluidization velocity (1.8 to 3.0 m/s), coal

ORNL-DWG 89-4706 ETD

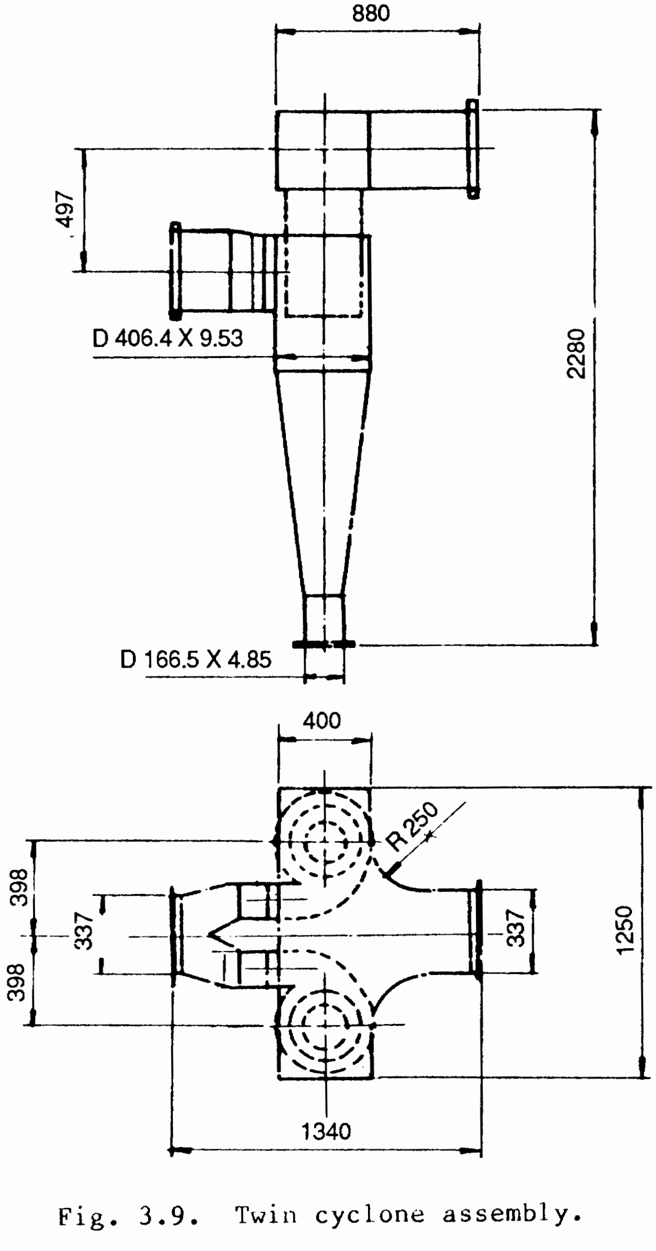

Fig. 3.9. Twin cyclone assembly.

ORNL-DWG 89-4707 ETD

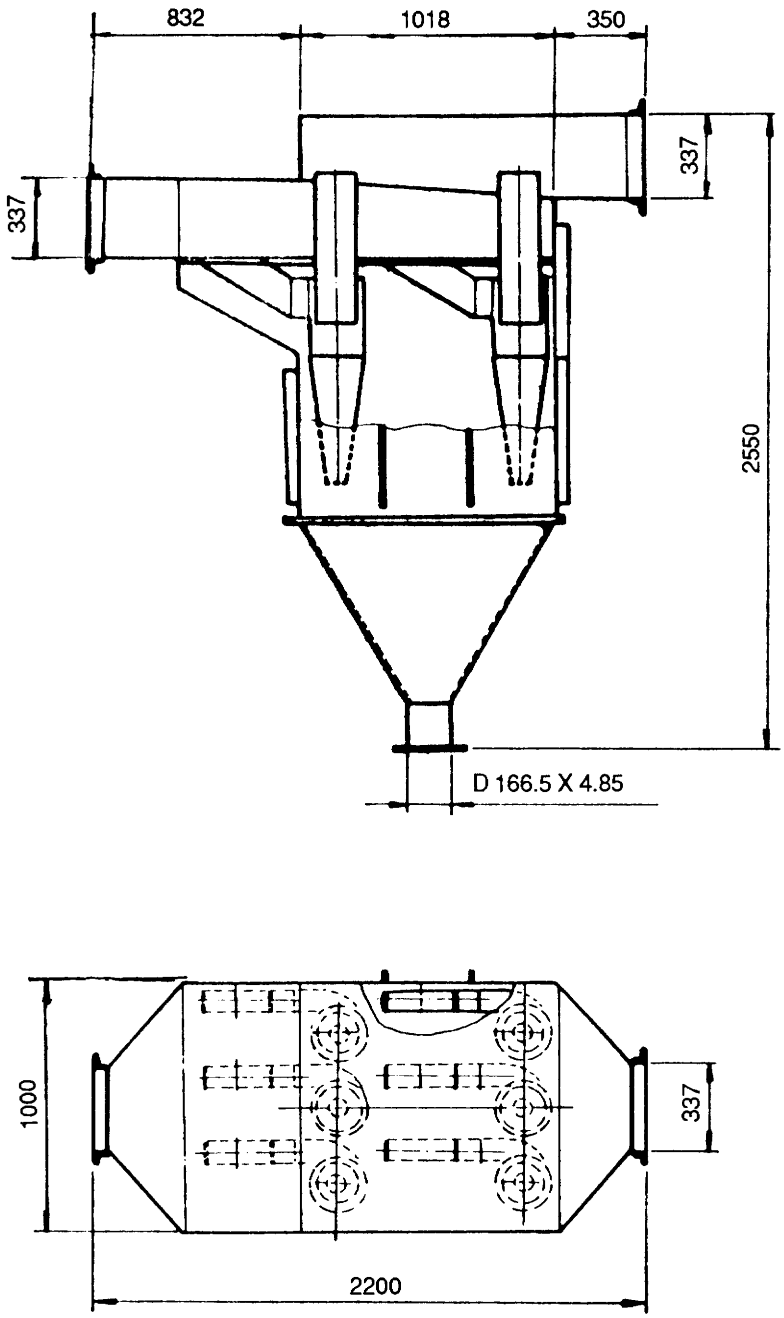

Fig. 3.10. Multiclone assembly.

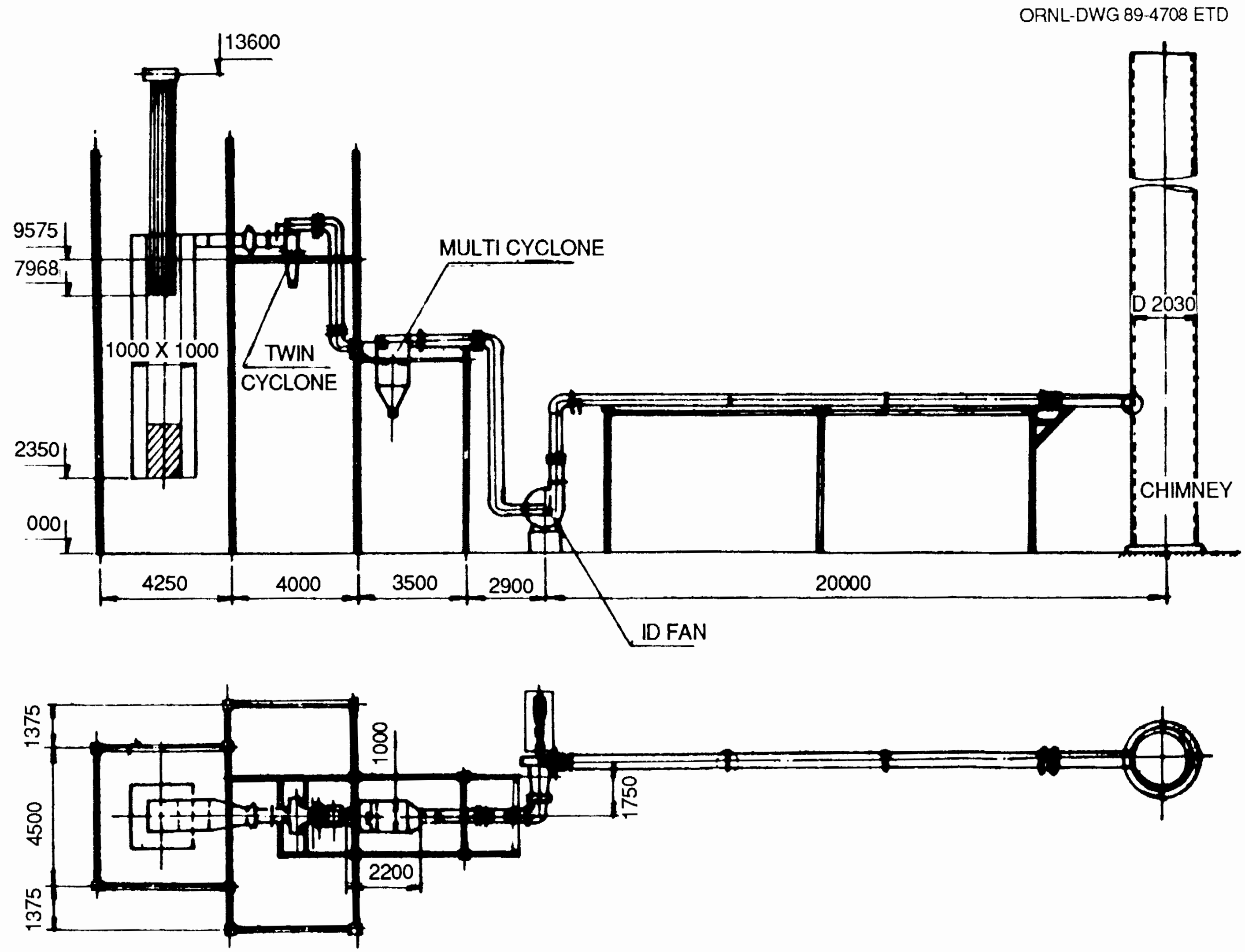

Fig. 3.11. Flue gas ducting.

ORNL-DWG 89-4709 ETD

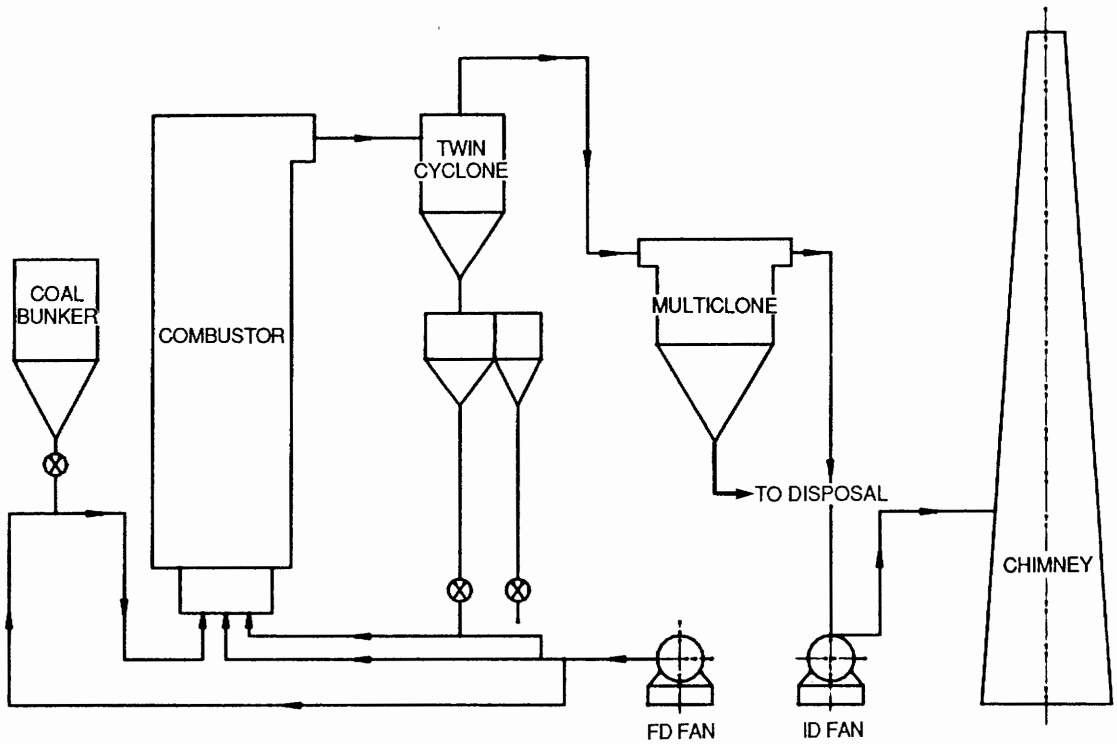

Fig. 3.12. Schematic of air and flue gas path.

ORNL-DWG 89-4710 ETD

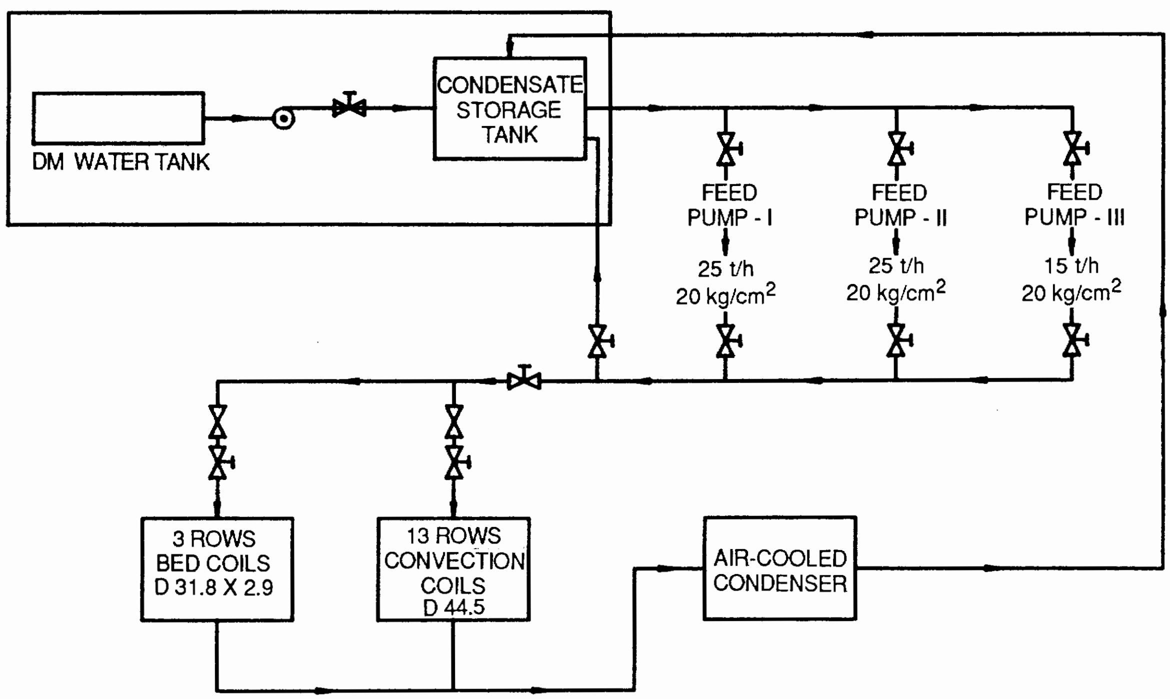

Fig. 3.13. Schematic of water circuit.

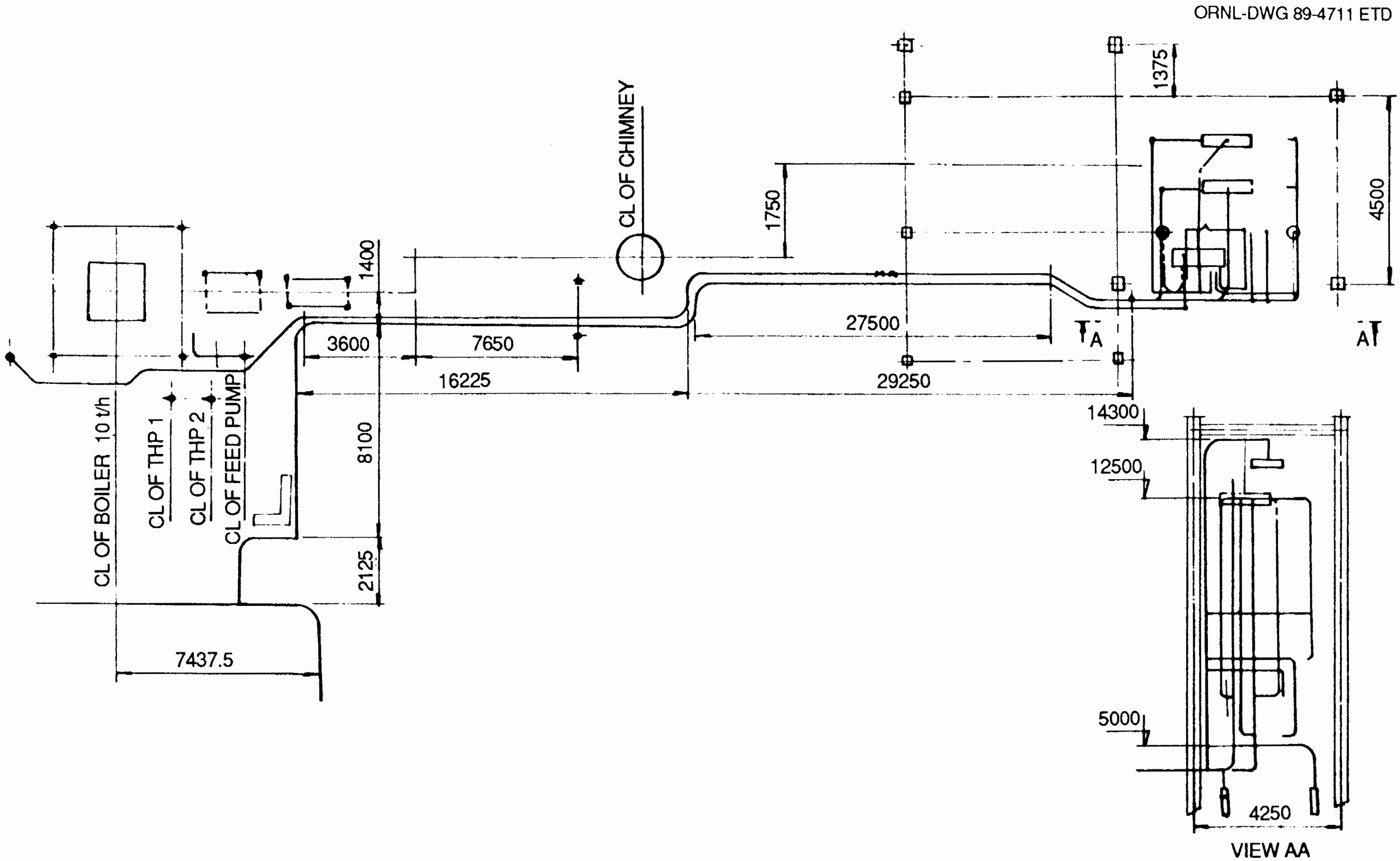

Fig. 3.14. External pipeline layout.

particle size (6 mm top size), flyash-to-coal recycle ratio (0.8 to 2.0), and temperature (ambient to 950°C). The construction material is carbon steel, and the overall distributor dimensions are 1150 mm (3.8 ft) square, 10 mm (0.39 in.) thickness with 62 nozzles. Figure 3.15 is a schematic of the distributor plate showing the locations of the various feed and drain pipes.

3.4.8 Instrumentation and controls

Conventional controls are used for controlling air-side pressure and temperature. Transport air and fluidizing air are regulated by dampers in the outlet ducting of the Roots blower. Water flow in the in-bed tube bundle, convection tube bundle, and freeboard heat transfer test loops are independently controlled. Air and water flows are continuously monitored and logged in the data acquisition system.

Temperatures in the bed, freeboard and convection zones are monitored with Chromel-Alumel (Cr-Al) thermocouples at selected locations through the ports located in the combustor walls. Coal feed rate is controlled by a gravimetric feeder. Flyash recycle rate is determined by setting the speed (rpm) of the ash feeder. Bottom ash drain is manually controlled by opening and closing the bottom drain intermittently.

3.4.9 Flue gas sampling system

Flue gas composition is continuously monitored with a Beckman gas analysis system designed for O_2, CO, CO_2, SO_x, NO_x and hydrocarbons. Each gas species analysis is recorded, displayed and fed into the data acquisition system. Individual characteristics of the gas analyzers are summarized:

Gas species	Model	Principle	Range
O_2	855	Paramagnetic	0-5, 10, 25, 50%
CO_2	864	Nondispersive infrared	0-5, 20%
CO	864	Nondispersive infrared	0-1000, 10,000 ppm
SO_x	865	Nondispersive infrared	0-2000, 10,000 ppm
NO_x	951 A	Chemiluminescense	0-10, 25, 100, 250, 1000, 2500, 10,000 ppm
HC	400	Flame ionization	0-15,000 ppm

The flue gas sampling system has multi-point sampling capability with built-in sample conditioning, back purging, heat-traced sample

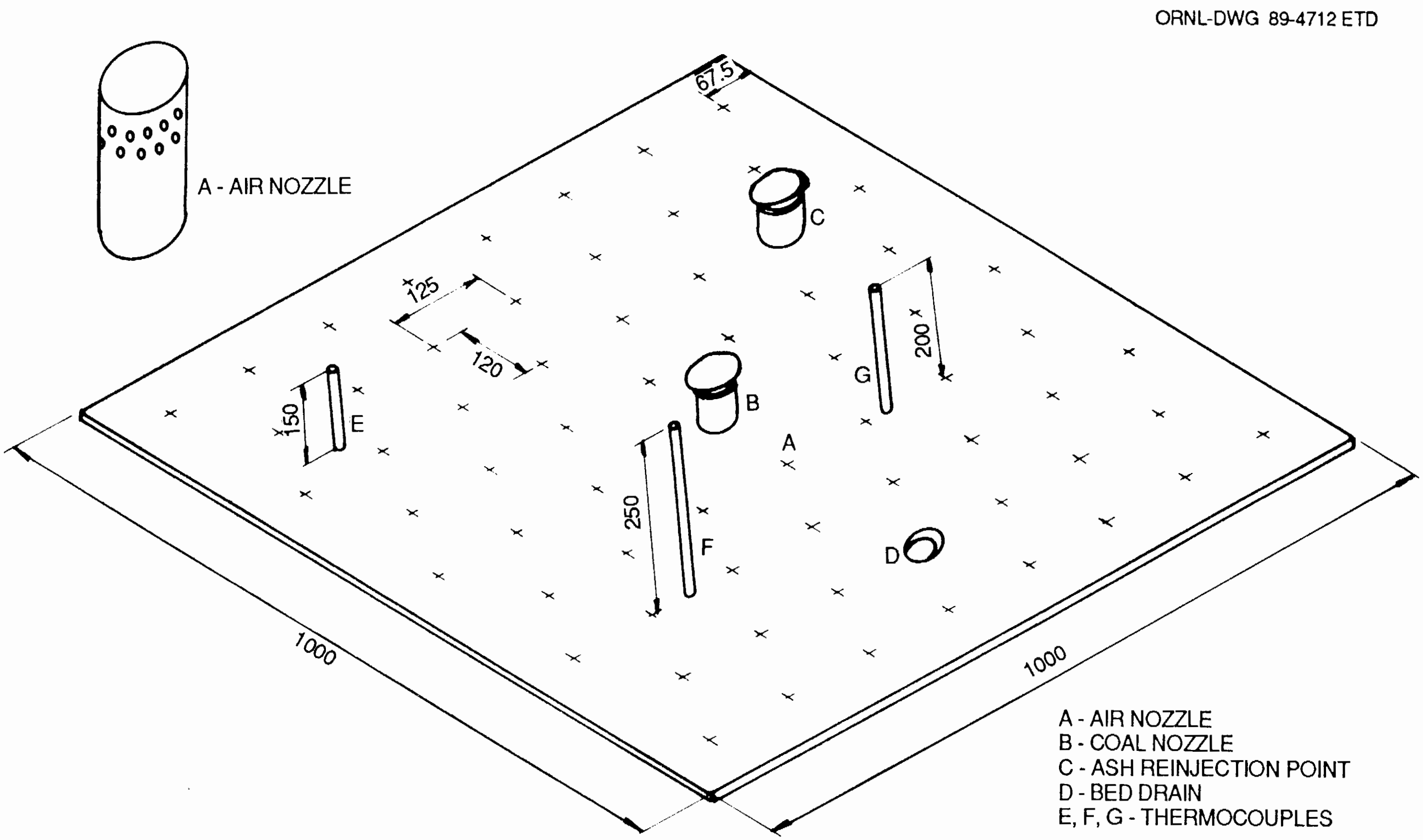

Fig. 3.15. Schematic of distributor plate showing the location of the coal, air and flyash feed nozzles, and thermocouples.

lines, and connections for span, zero and calibration gases. The gas sampling probes were specially designed and fabricated at ORNL for hot, dust-laden flue gas.

3.4.10 Data acquisition system

A Hewlett Packard Model 3054A gathers up to 1000 data points and can simultaneously process, display and transmit the data to the existing BHEL main frame computer. The data acquisition system consists of (1) color desk top computer, (2) data acquisition/control unit with extenders, (3) inkjet printer, (4) graphics plotter, (5) backup computer, plotter, printer, and (6) modem to transmit the data to the main frame ICL computer at BHEL.

4. PARTS SPECIFICATIONS

4.1 Pressure Parts

In this section details of the pressure part components of the combustor are furnished.

4.1.1 Feed water pump (three numbers)

Function	Circulate feed water through combustor
Capacity	25 t/h (two pumps) 15 t/h (one pump)
Normal pressure	10 kg/cm^2
Drive	Electric motor: 90 kW, 415V, 3 phase, 50 cycles/s

4.1.2 Convection bundle

Function	Cooling of the flue gas
Tube size	44.5 mm OD, 4 mm thick
Material	SA 210, Grade A1
Tube arrangement (pitch)	Transverse pitch (ST) 60 mm Longitudinal pitch (SL) 60.0 mm
Number of parallel paths	13

4.1.3 Bed bundle

Function	Extract heat from the bed and maintain the bed temperature
Tube size	31.8 mm OD, 2.9 mm thick
Material	SA 210 Grade A1
Tube arrangement (pitch)	ST 96 mm, SL 106 mm
Working pressure	10 kg/cm^2(g)
Number of parallel paths	3

4.2 Non-Pressure Parts

4.2.1 Air and flue gas ducting

Combustion air line	
Cross-section	340 mm square
Air flow rate	2100 Nm^3/h at maximum superficial velocity of 3 m/s
Temperature	ambient to 350°C
Material	carbon steel

Fuel transport air line	
Cross-section	108 mm OD pipe
Air flow rate	150 Nm^3/h
Temperature	ambient to 350°C
Material	carbon steel
Recycle Transport air line	
Cross-section	108 mm OD pipe
Air flow rate	400 Nm^3/h
Temperature	ambient to 350°C
Material	carbon steel
Flue gas ducting	
Cross-section	325 mm square
Flue gas flow rate	2750 Nm^3/h
Temperature	ambient to 350°C
Material	carbon steel

4.2.2 Roots blower/High head fan

Function	Supply combustion air, transport air and recycle air at elevated pressure
Capacity	5000 Nm^3/h (max) 2500 Nm^3/h (normal operation)
Temperature of air	30°C
Density	1.165 kg/m^3
Motor	70 HP, 965 RPM, 415V, 3 phase, 50 cycles/s
Control	manually operated valve

4.2.3 Induced draft fan

Function	Discharge the dust laden flue gas through chimney
Capacity	5000 Nm^3/h
Pressure	400 mm wc
Medium handled	flue gas (dust laden)
Flue gas density	0.53 kg/m^3
Temperature of flue gas	350°C
Flow control	inlet guide vane
Motor	squirrel cage induction motor, 30 kW, 1400 rpm, 415V, 3 phase, 50 cycles/s

4.2.4 Electric hoist

Function	Elevate coal to the bunker
Type of hoist	Trolley type hoist with bucket
Material to be handled	crushed coal
Size range of material	0–20 mm
Maximum lift (ground to bunker)	14 meters

Horizontal traverse (at top elevation)	5 meters
Bucket capacity (made of 8 mm plate and properly stiffened)	400 kg

4.2.5 Constant speed rotary feeders

Function	Feeding of coal to the pneumatic transport line
Feed rate	1500 kg/h (maximum)
Material handled	coal
Particle size	0–20 mm
Moisture in coal	10%
Temperature	ambient
Speed	10 rpm
Inlet and outlet opening	108 mm (4 in.)
Motor with gear box	1 kW, 415V, 3 phase, 50 cycles/s

4.2.6 Variable speed rotary air lock feeders

Function	Feeding of recycle flyash to pneumatic transport lines
Feed rate	1500 kg/h (maximum)
Material handled	Ash (collected from primary cyclone)
Bulk density	700 kg/m^3
Particle size	0–1.0 mm (maximum)
Temperature	500°C
Speed	2 to 10 rpm
Inlet and outlet opening	108 mm (4 in.)
Motor with gear box	1 kW, 415 V, 3 phase, 50 cycles/s.
Gap between motor and casing	0.10 mm
Cooling medium	water

4.2.7 Gravimetric coal/limestone feeders

Coal feeder

Function	Measure coal feed rate to the combustor
Capacity range	250–1000 kg/h
Material handled	coal
Particle size	0–20 mm
Bulk density	1200 kg/m^3
Moisture in coal	10% (max)
Temperature	ambient
Accuracy	±0.5%
Vendor	Merrick-USA
Model	950 DSC, 20 in. belt width

Drive	Electric motor, 0.25 HP
Other accessories	belt feeders, weight transducer system, digital control system, variable speed drive, knife gate valve

Limestone feeder

Function	Measure limestone feed rate to the combustor
Capacity range	25 kg/h–300 kg/h
Material handled	limestone
Particle size	0–5 mm
Bulk density	1360 kg/m^3
Moisture	5% (max)
Temperature	ambient
Accuracy	±0.5%
Vendor	Merrick-USA
Model	950 DSC, 12 in. belt width
Drive	Electric motor, 0.25 HP
Other accessories	Belt feeders, weight transducer system, digital feed control system, variable speed drive, knife gate valve

4.2.8 Overbed screw feeder

Function	Overbed feeding of coal-limestone mixture or coal to the combustor
Capacity	1000 kg/h
Material handled	coal
Particle size	0–20 mm
Speed range	constant speed
Length of horizontal traverse	3 m
Size of screw	220 mm OD, pitch 100 mm
Screw blade thickness	4 mm
Discharge opening	108 mm OD pipe

4.2.9 Primary cyclone

Function	Coarse dust separation from flue gas
Capacity	6800 m^3/h at 400°C
Number of cyclones	2
Diameter of cyclone	406 mm OD
Height of cyclone	1550 mm
Material of construction	corten steel
Pressure drop	100 mm (4 in.)
Collection efficiency	88.6%

4.2.10 Multiclone

Function	Fine dust separation from flue gas
Capacity	4800 m^3/h at 400°C
Number of cyclones	6
Diameter of cyclone	219 mm OD
Height of cyclone	824 mm
Pressure drop	100 mm (4 in.)
Collection efficiency	70%
Material of construction	corten steel

4.2.11 Air distributor plate

Function	Distribute the combustion air, and coal/recycle flyash into the bed, and support the weight of the bed material
Size of plate:	1150 mm square, 10 mm thickness
Type	Multi-nozzle
Ash recycle feed pipe	108 mm OD
Bed drain	108 mm OD
Coal feed pipe	108 mm OD
Pressure drop	100 mm water column at 2.5 m/s fluidization velocity

5. START UP AND OPERATING PROCEDURE

Start up of the combustor is achieved by igniting a layer of charcoal sprinkled with kerosene on the bed surface (Fig. 5.1). During start up, the bed material is a mixture of refractory and charcoal roughly in a 10 (refractory) to 1 (charcoal) ratio. A thin layer of charcoal is spread on the top of the bed material. Airflow through the bed is sequentially varied to sustain the combustion of charcoal and to uniformly mix the burning charcoal with the rest of the bed material. When the bed temperature exceeds the ignition temperature of the coal/reject (600–700°C), fuel feeding is initiated. Figure 5.2 depicts typical bed temperature rise during start-up. Usually, it takes about six hours for the refractory to heat up and the bed to stabilize.

After reaching steady state (bed temperature and freeboard temperature), the test parameters (fluidization velocity, excess air, and bed temperature) are set at the planned test conditions for four hours. During these four hours, test data are printed out at every 30 minute intervals. In addition, some critical bed measurements (water flow, water temperature, coal feed rate, air flow, and flue gas composition) are displayed every 2 minutes to monitor the operation and check for variation in these parameters. Ash discharge rates from the primary cyclones, multiclone, and bed overflow are measured at one hour intervals. A representative sample of the ash collected is sent to the laboratory for chemical analysis. At the end of four hours, the test conditions are changed to another set of velocity, excess air and bed temperature values and the procedure is repeated until all the planned test conditions are completed.

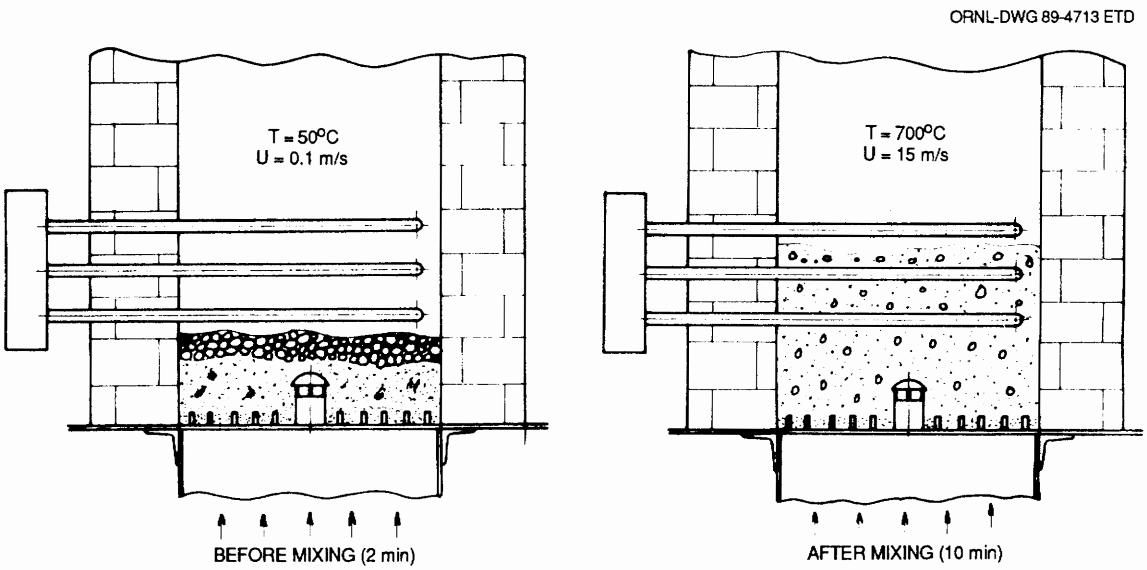

Fig. 5.1. Combustor before and after startup.

ORNL-DWG 89-4714 ETD

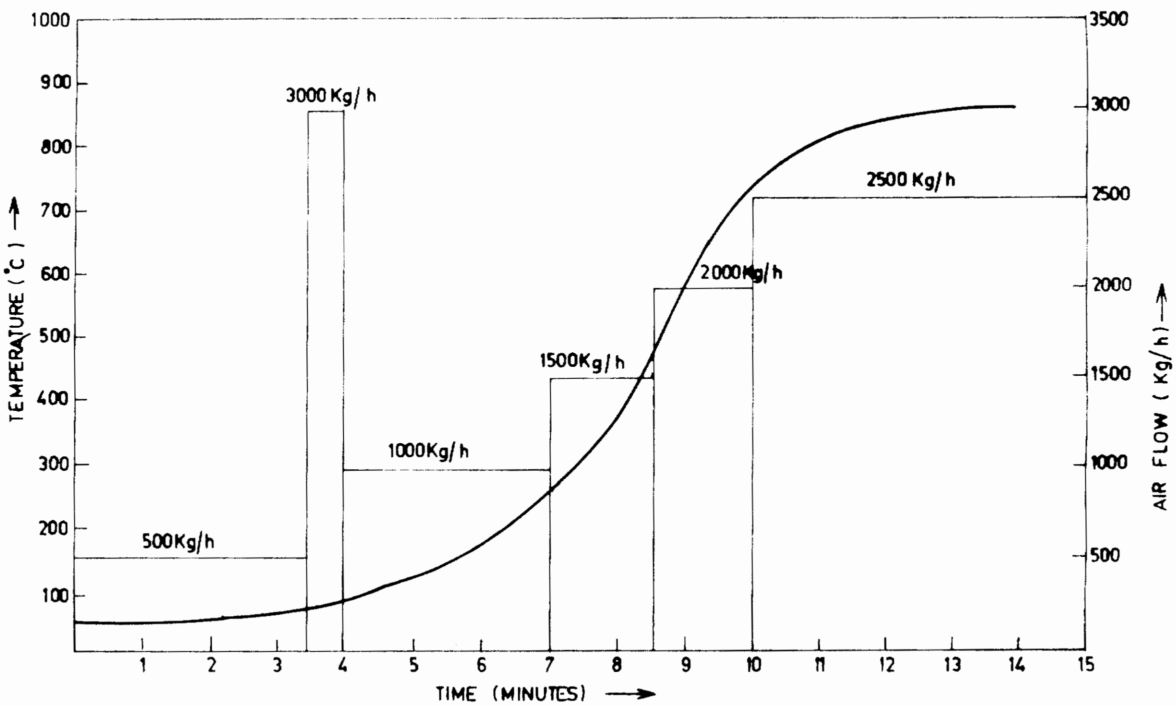

Fig. 5.2. Time-temperature-airflow characteristic during startup.

For each test condition the following parameters are kept constant: (1) size distribution of fuel feed, (2) bed height, (3) initial bed particle size distribution, (4) freeboard height, and (5) number of heat transfer coils immersed in the bed.

6. TEST VARIABLES

The combustor is designed to operate on three different coals: (1) sub-bituminous high-volatile, high-ash, low-sulfur coal; (2) 70% ash, coal washery reject; and (3) high-sulfur, sub-bituminous coal. The low sulfur coal and washery reject do not require any sorbent. The bed material for high sulfur coal is crushed, sized limestone. For low sulfur coal and washery reject, the bed material is crushed refractory and/or bed ash. The coal, limestone and crushed refractory sizes vary in the tests. Other test variables are fluidization velocity, bed temperature, excess air, recycle ratio, and mode of coal feeding (underbed/overbed). Table 1 depicts typical ranges for these variables.

Table 1. Range of test variables

Coal type		Coal washery reject	High ash/low sulfur coal
	C	25.60	51.7
	H	2.02	3.21
	N	0.90	0.87
	S	0.30	0.49
	O	1.40	8.68
	Moisture	1.31	6.85
	Ash	68.47	28.20
	HHV kcal/kg (Btu/lb)	2410 (4338)	4892 (8805)
Coal particle size		6 mm × 0 mm (1/4 in. × 0 in.)	
Bed material size			
Crushed refractory/ash		3 mm × 0 mm (1/8 in. × 0 in.) weighted average size 1000 microns	
Bed temperature, °C (°F)		800–950 (1472–1742)	
Superficial velocity, m/s (ft/s)		1.8–3.2 (5.0–10.4)	
Expanded bed height, mm (ft)		600 (2)	
Excess air, %		5–30	
Freeboard height, m (ft)		4.7 (15)	
Flyash recycle ratio		0.8 to 2.0	

7. TESTING AND OPERATING EXPERIENCE

Three series of tests were completed for a total duration of 600 hours following 300 hours of shakedown testing. The series 1 tests were done on a 40 to 45% ash content sub-bituminous Indian coal. The coal analysis is given along with the test data in Table B.1 in Appendix B. Tests were also done on a 60 to 65% ash content, low calorific value (2000 kcal/kg) coal washery reject. Analysis of the reject is also included in the test data in Tables B.4 and B.7 in Appendix B. The objectives of the series 1 tests were:

1. Obtain combustion and heat transfer data on the above fuels in the underbed, once-through (no flyash reinjection) mode

2. Select the optimum range for the bed parameters for subsequent tests

3. Establish the data analysis methodology for estimating the inbed and freeboard combustion, and heat transfer correlations for the inbed and the freeboard region.

Series II tests focused on the effect of flyash reinjection on the combustor operation and performance. The main purpose in conducting these tests was to get hands-on experience on the design and operation of the recycle system. This was the first facility designed in BHEL for recycle operation and the intent was to get necessary data and experience for implementation in future commercial boilers. Test data for Series II are given in Table B.1 in Appendix B.

Series III tests were specifically aimed at evaluating the performance of overbed coal feed system. Again, this design has not been implemented so far in BHEL commercial boilers, and therefore, it was decided to test this mode of feeding in the test facility. Although the overbed feed system was tested in a relatively small facility, the experience gained on the hardware, and the performance penalties measured with overbed feeding are directly applicable to large size FBCs. Data from the overbed feed tests are given in Table B.10 in Appendix B.

Initially, it was planned to vary bed temperature, superficial velocity and excess air keeping two of the three parameters constant and varying the third. However, this was not possible because of design constraints. The inbed tube surface had to be varied for each test condition in order to keep two of the three operating parameters constant. This was not practical and also time consuming because it would require shutting down the facility and allowing the bed to cool every time the tube surface had to be changed. Therefore, it was decided to vary the superficial velocity over the range 1.8 to 3.2 m/s and maintain the bed temperature between 875°C and 925°C and excess air between 10 to 30%. This combination was arrived at by performing trial runs on the fuels with three rows of tube bundles in the bed.

The major problem encountered in these series of tests was related to the high ash content of the fuel. During testing, the ash build-up in the combustor was rapid. Constant operator attention was needed to drain the ash by opening the bottom bed drain. This upset the bed height and resulted in drifting of the bed temperature, excess air and air flow in the bed. It took a long time to stabilize the bed each time the ash was drained. To circumvent this problem, a short six hour test was conducted with the rejects (which had the highest ash content) with the bed overflow pipe completely open and the bed drain closed over the entire duration of the test. The test was successful in that no defluidization tendency was observed and it was possible to maintain a constant bed height. Ash removal was also manageable. Subsequent tests were conducted in this manner and the bottom drain was used only when defluidization was suspected.

The multiclone was designed for four inches pressure drop. However, the pressure drop actually observed was much higher, close to 10 inches (water column). The higher pressure drop was partially due to much higher dust loading in the flue gas compared to what was used in the design of the multiclone. To reduce the pressure drop, the cyclone tube size had to be modified. Since the ID fan had sufficient reserve it was possible to operate the facility despite the high pressure drop in the multiclone.

The exit temperature of flue gas exceeded the design temperature (350°C) by 100°C. The reason for this is lower heat transfer coefficient in the convection section than what was used in the design of the convection bundle. The heat transfer coefficient in the convective section was estimated to be 13 to 16 kcal/h m^2°C under the test conditions.

Other problems encountered were mostly related to equipment failure. Some of the major problems are briefly discussed in the following paragraphs.

Roots blower. This is a twin lobe, positive displacement blower and is rated to supply both the combustion air and pneumatic transport air for coal and flyash reinjection. The solid-to-air ratio in the transport line was maintained below three. During the initial operation, the lobe-to-lobe clearance in the blower was observed to be inadequate. The blower had to be dismantled and the clearance adjusted to set it in operation. A silencer was also mounted to reduce the noise level. These remedies however did not solve the problem and the blower failed several times during the testing. Hence, a high head, single stage fan was ordered from the Buffalo Forge Co., USA to replace the Roots blower.

Induced draft fan. The ID fan was designed to operate at a maximum flue gas temperature of 350°C. During testing, the flue gas temperature consistently exceeded 350°C and at times it went up to 425°C. Exposure of the inlet guide vanes in the fan to these high temperature impaired their movement as testing progressed. The clearances had to be adjusted to free the motion of the vanes, and towards the end, the vanes had to entirely replaced. It was evident that the large quantity of ash in the fuel, and the high temperature of the ash, were the prime reasons for the failure of the ID fan. Special materials of construction (other than carbon steel) are worth considering in such applications.

Rotary feeders. The flyash collected in the twin cyclone flows through an intermediate bunker and into the rotary air lock feeder before it is injected pneumatically into the combustor. The temperature of flyash is around 450 to 500°C. The feeder is cooled by circulating water through the shaft and casing. The cooling was found to be insufficient and the thermal expansion caused by exposure to high temperature resulted in buckling of the shaft. Despite increasing the clearance between the stator and the rotor, and providing flexible material between the mating surfaces, the feeder failed. Eventually, a feeder designed for 900°C operation had to be installed to overcome this problem. Capacity of this high temperature feeder, however, was limited and the maximum ash/coal ratio that could be handled by this feeder was 2.0.

Flue gas analyzer. Gas sampling probes are provided at four elevations along the height of the combustor to draw gas samples for analysis. By positioning the solenoid valve located downstream of the sampling probes to a set position, it is possible to draw samples from any one of the four gas sampling probes. The gas probes are hollow, L-shaped, stainless steel probes containing a sintered metal filter inside the hollow vertical arm of the probe. The filters were procured from the Mott Co., USA.

The probe was designed and fabricated at ORNL. After one to two hours of operation, the probes plugged and there was no gas flow through the sampling line. The suction pump in the gas analyzer got overloaded and tripped. To overcome this problem, the stainless steel filters were replaced with COORS ceramic filters. The frequency of back-purging was also increased from once every 15 min to once every 5 min. At the end of each test, the probes were dismantled and the filters were cleaned in acid and caustic solutions as recommended by the manufacturer. Periodic cleaning and replacement of filters were found to be very important to keep the gas analyzer in operation. The oxygen and CO_2 measurements were cross-checked by Orsat readings once during each test condition.

There were several problems encountered as a result of foreign material (shale, tramp iron) entering along with the coal. Plugging occurred in the coal feedlines and the discharge lines from the coal bunker. Defluidization of the bed due to heavy foreign material accumulating at the bottom was also encountered. To detect defluidization, thermocouples were mounted vertically at selected locations on the distributor plate. Non-uniform bed temperature indicated that such defluidization had occurred.

8. DATA ANALYSIS AND TEST RESULTS

For each test condition, performance data were collected at one hour intervals over the four hour test run period. The data were checked for consistency and the best set of data were chosen for data analysis. Total material and heat balance were performed for each test condition. The data analysis methodology is described below.

8.1 Data Analysis

The combustion efficiency, η_C, is obtained from the total carbon loss in the system. Total carbon loss is determined by summing the carbon loss in the various streams leaving the combustor such as, bed over flow, bed drain, cyclone catch and multiclone catch. Any carbon not accounted for in these streams is assumed to be completely combusted. The computational equations are given below. For explanation of the symbols appearing in the equations the reader is referred to the nomenclature section.

$$\text{Combustion efficiency } (\eta_c) = \frac{UC \times f}{(1 - UC \times f)} \times AF \times \frac{HC}{HHV} \qquad (1)$$

where,

$$\underset{\text{(Unburnt carbon)}}{(UC \times f)} = \underset{\text{(Bed drain)}}{(UCBD \times fBD)} + \underset{\text{(Cyclone)}}{(UCCC \times fCC)} \qquad (2)$$

$$+ \underset{\text{(Multiclone)}}{(UCMCC \times fMCC)} + \underset{\text{(Chimney)}}{(UCSC \times fSC)}$$

Freeboard Combustion

Freeboard combustion is estimated by two ways;

1. from the bed heat balance (see Fig. 8.1)

2. from the heat balance over a control volume including both convection and freeboard (see Fig. 8.2) and cross checked against the total heat balance (see Fig. 8.3).

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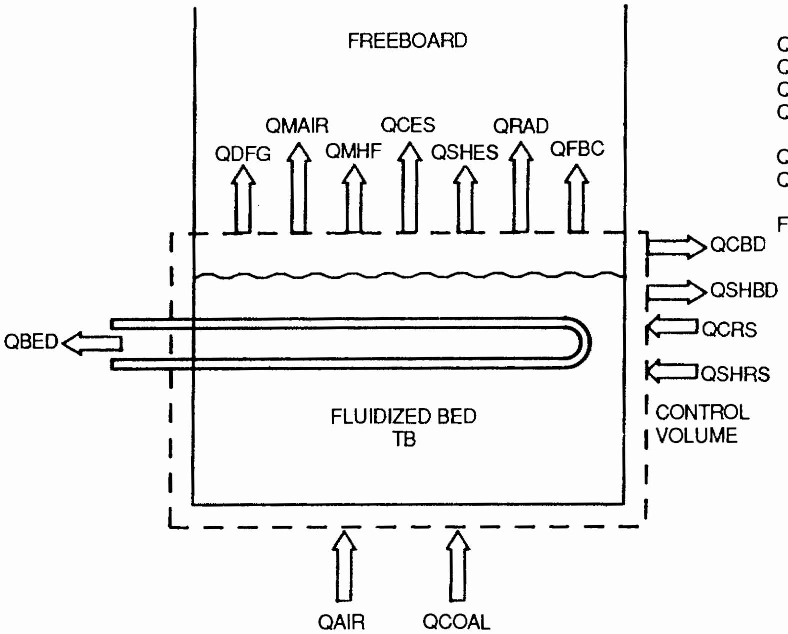

QIN = QCOAL + QSHRS + QAIR
QC = QCES + QCBD - QCRS
QSHS = QSHBD + QSHES
QIN = QDFG + QMAIR + QMHF + QC + QSHS + QRAD + QBED + QFBC
QRAD IS NEGLIGIBLE
QFBC = QIN - (QDFG + QMAIR + QMHF + QC + QSHS + QRAD + QBED)
FREEBOARD COMBUSTION (%) = QBFC/QCOAL X 100

Fig. 8.1. Estimation of freeboard combustion from bed heat balance.

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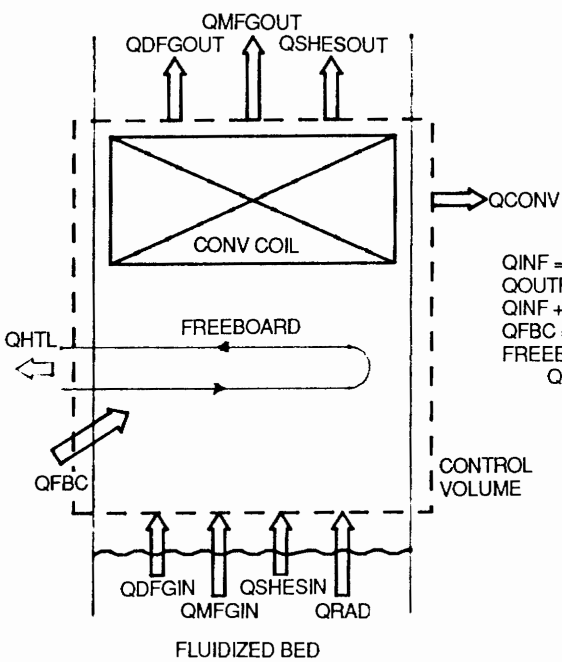

QINF = QDFGIN + OMFGIN + QSHESIN + QRAD
QOUTF = QDGFOUT + QMFGOUT + QSHESOUT
QINF + QFBC = QOUTF + QCONV + QHTL
QFBC = QOUTF + QCONV + QHTL = QINF
FREEBOARD COMBUSTION (%) = QFBC/QCOAL X 100

Fig. 8.2. Estimation of freeboard combustion from convection and freeboard heat balance.

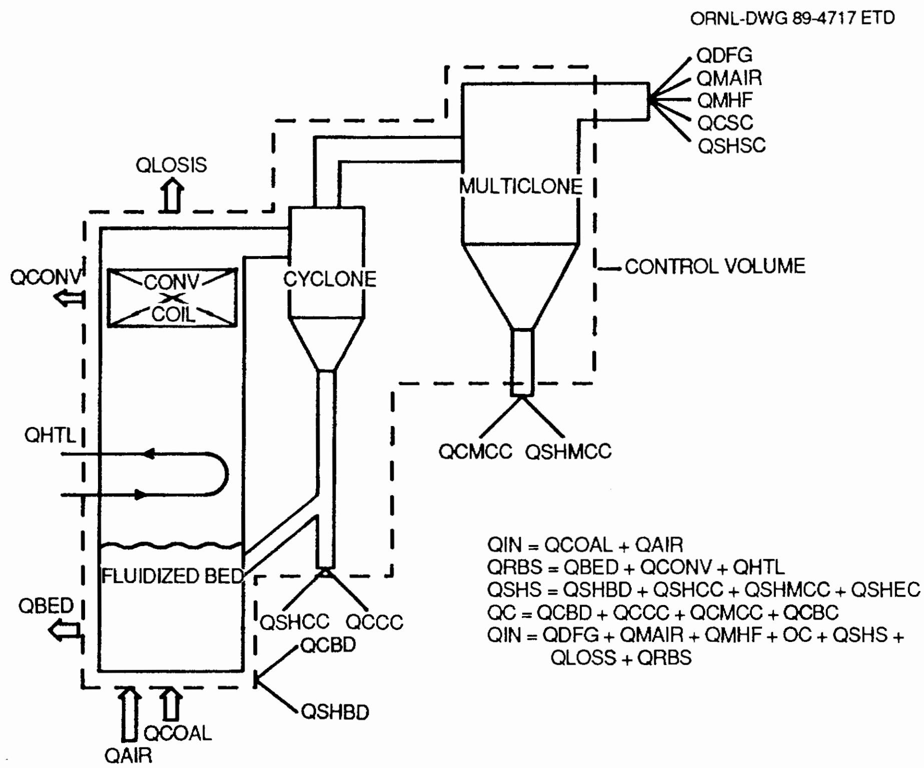

Fig. 8.3. Total heat balance.

1. Bed Heat Balance*

Heat Input = QIN = QCOAL + QSHRS (3)

Sensible heat in recycle solids = QSHRS = WRS × CPASH (TO − T1)

Heat in dry flue gas leaving bed = QDFG = WDFG (HB − H1)

Heat in moisture in the flue gas = QMAIR = WMAIR × 0.46 (TB − T1)

Heat in moisture from fuel = QMHF = WMHF [595.4 + 0.46 (TB − T1)]

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*Individual terms are referred to streams entering and leaving the bed section of FBC.

Sensible heat of solids leaving bed = QSHS = [CFR (AF + UBC) + WRS] × CPASH × (TB − T1)

Heat absorbed by bed coils = QBED = FWBED × CPW (TWO − TW1) × A_{Bed}

Heat released by freeboard combustion = QFBC = QIN − (QDFG + QMAIR + QMHF + QC + QSHS + QBED) (4)

$$\text{Freeboard combustion } (\%) = \frac{QFBC}{QCOAL} \times 100 \qquad (5)$$

2. Freeboard and Convection Heat Balance

Heat in flue gas and solids at freeboard inlet = QINF = QDFGIN + QMFGIN + QSHESIN

Heat in dry flue gas at freeboard inlet = QDFGIN = WDFG × HB

Heat in moisture in flue gas at freeboard inlet = QMFGIN = WMFG × 0.46 × TB

Heat in elutriated solids from bed surface entering freeboard = QSHESIN = ES × CPASH × TB

Elutriated solids = ES = CFR (AF − UBC) × (1 − fBD) + WRS

Heat in flue gas and solids at freeboard outlet = QOUTF = QDFGOUT + QMFGOUT + QSHESOUT

Heat in dry flue gas at freeboard outlet = QDFGOUT = WDFG × HO

Heat in moisture in flue gas at freeboard outlet = QMFGOUT = WMFG × 0.46 × TO

Heat in elutriated solids at freeboard outlet = QSHESOUT = ES × CPASH × TO

Weight of moisture in the flue gas $= WMFG = WMAIR + WMHF$

Heat released by freeboard combustion $= QFBC = (QOUTF - QINF) + QCONV + QHTL$ (6)

Freeboard combustion (%) $= \frac{QFBC}{QCOAL} \times 100$ (7)

Total Heat Balance*

Heat input in coal $= QCOAL = CFR \times HHV$

Heat in dry flue gas at combustor exit $= QDFG = WDFG\ (H0 - H1)$

Heat in moisture in flue gas at combustor exit $= QMAIR = WMAIR \times 0.46 \times (T0 - T1)$

Heat in moisture from fuel $= QMHF = WMHF\ [595.4 + 0.46\ (T0 - T1)]$

Weight of moisture in fuel and moisture from hydrogen in fuel $= WMHF = CFR\ (MF + 9H)$

Combustion efficiency $= \eta_c = \frac{(UC \times f)}{1 - (UC \times f)} \times AF \times \frac{HC}{HHV}$

Heat in unburnt carbon $= QC = QCOAL\ (1 - \eta_c)$

$$UC \times f = (UCBD \times fBD) + (UCCC \times fCC) + (UCMCC \times fMCC) + (UCSC \times fSC)$$

Total unburnt carbon $= UBC = \frac{(UC \times f)}{1 - (UC \times f)} \times AF$

---

*Individual terms are referred to streams entering and leaving the combustor.

Heat absorbed by bed coils = $QBED = FWBED \times CPW\ (TWO - TW1) \times A_{Bed}$

Heat absorbed by convection coils = $QCONV = FWCONV \times CPW\ (TWO - TW1) \times A_{Conv}$

Heat absorbed by heat transfer loops = $QHTL = FWHTC \times CPW\ (TWO - TW1) \times A_{loop}$

Sensible heat of solids leaving FBC = $QSHS = CFR\ (AF + UBC) \times [(fBD \times CPASH \times (TB - T1) + (fCC + fMCC + fCSC) \times CPASH\ (TO - T1)]$

Heat extracted from combustor = $QABS = QBED + QCONV + QHTL$

Heat in unburnt carbon = $QC = QCBD + QCCC + QCMCC + QCSC$

Heat in coal = $QCOAL = QDFG + QMAIR + QMHF + QC + QSHS + QABS$ (8)

Bed Heat Transfer Coefficient

The overall heat transfer coefficient U_o to the inbed tubes is calculated from

$$U_o = \frac{Q\ BED}{A_{Bed} \times (LMTD)_{Bed}} \tag{9}$$

$$Q\ BED = FWBED \times CPW \times (TWO - TW1)$$

The outside film coefficient, h_o, is given by

$$h_o = \frac{1}{\frac{1}{U_o} - \left[\frac{r_o}{k_t} \ln \frac{r_o}{r_i} + \frac{ro}{ri} \times \frac{1}{h_i}\right]} \tag{10}$$

The inside film coefficient, h_i, is given by

$$h_i = 0.023 \frac{k_w}{d_i} (Re)^{0.8} (Pr)^{0.4} \tag{11}$$

$$Re = \frac{V d_i \rho_w}{\mu_w} \tag{12}$$

$$Pr = \frac{(CPW)\ \mu}{k_w} \tag{13}$$

The outside film coefficient h_o is assumed to be the sum of the convection component, h_c, and the radiative component, h_r

$$h_o = h_c + h_r \tag{14}$$

There is no conclusive data on the radiation contribution to the overall heat transfer coefficient in fluidized beds. It is known however that small particles will contribute much less by way of radiation compared to large particles because of their low thermal mass.

In this study the radiative component is not neglected and is calculated from

$$h_r = \frac{(TB + 273)^4 - (TSO + 273)^4}{(TB - TSO)} \times \sigma \times e \tag{15}$$

Emissivity (e) of 0.8 is used based on published fluidized bed data. Based on this, h_r varies between 80 to 90 kcal/hr m²°C for the test conditions and accounts for approximately 30% of the overall heat transfer coefficient h_o. The convective component (h_c) is obtained by substracting h_r from the outside coefficient h_o.

Freeboard Heat Transfer Coefficient

Two heat transfer test loops were inserted in the freeboard (see Fig. 8.4) to study the heat transfer in the freeboard region. These loops were kept at 600 mm and 1600 mm from the expanded fluidized bed surface. These loops were specially designed to have 15 to 20°C rise between the inlet and outlet water temperature, and negligible drop in the flue gas temperature. The water flow was measured by a rotameter and the outlet and inlet temperatures were measured by RTDs. The gas temperature near the loops were measured by Cr-Al thermocouples.

All the tests were carried out with a constant expanded bed depth of 600 mm by maintaining a continuous overflow of the bed material. Tests were carried out with both overbed and underbed fuel feeding systems, with and without flyash recycle. The flyash recycle ratio was varied up to 2.0. The flyash was reinjected underbed pneumatically in both underbed and overbed feed tests.

The overall freeboard heat transfer coefficient UFB was calculated from

$$UFB = QFB/(A_{FB} \times LMTD_{FB}) \tag{16}$$

$$QFB = FWloop\ (TWO - TW1)_{loop} \times CPW \tag{17}$$

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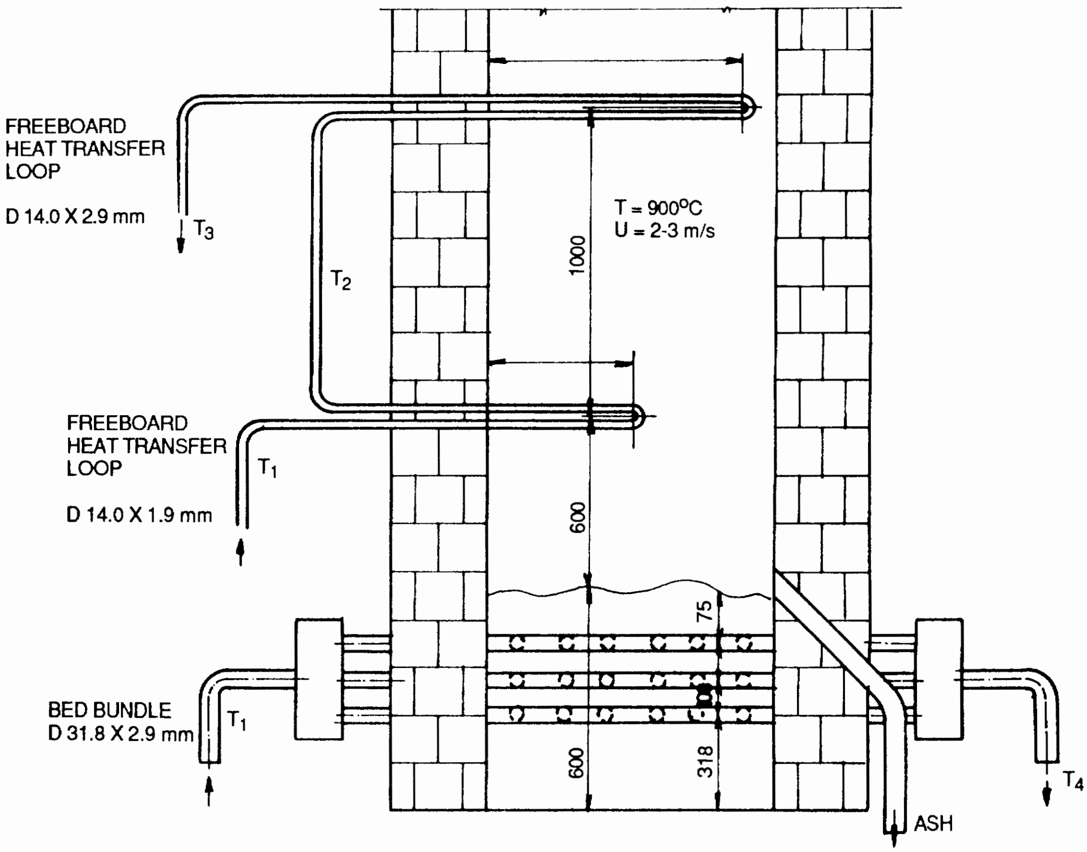

Fig. 8.4. Heat transfer test loops and bed bundle arrangement.

The freeboard heat transfer coefficients for loop 1 and loop 2 were independently calculated. These values were compared with U_0 calculated for the bed. The overall heat transfer coefficient was assumed to decrease in an exponential manner along the freeboard height starting from the expanded bed surface.

8.2 Test Results

The test matrix consisted of a total of sixty-one, 4-h duration tests. For each test condition, the bed particle size, fuel particle size, bed height, freeboard height, and the tube surface in the bed were maintained constant. The test variables were fuel type, fluidization velocity, mode of coal feeding, and the flyash recycle ratio. The coal feed rate was maintained constant in each test and the air flow rate was adjusted to obtain the required fluidization velocity. Once the required velocity was achieved, final adjustment to the coal feed rate was performed to maintain the excess air level within the selected test range. Prior to the actual commencement of data gathering, it was ascertained that the bed temperature, excess air and fluidization velocity held steady.

The following performance parameters were calculated for each set of data:

- overall combustion efficiency
- freeboard combustion
- inbed heat transfer coefficient
- freeboard heat transfer coefficient
- emissions

<u>Overall Combustion Efficiency</u>

The factors influencing the overall combustion efficiency in an FBC are: (1) loss of carbon in the elutriated solids (governed by bed carbon loading, bed particle size and fluidization velocity); loss of carbon in the overflow stream (which is determined by bed carbon loading and inerts feed rate); and (3) loss of carbon heating value due to CO formation.

The overall combustion efficiency was estimated by measuring the carbon lost in the elutriated flyash and the carbon lost in the bed overflow. CO emissions were insignificant in the tests to include in the combustion efficiency calculation. The ratio of the heat energy associated with the carbon lost in the two streams mentioned above to the heat energy in the feed coal is a measure of the combustion efficiency of the system.

$$\text{Combustion efficiency} = \frac{1 - (\text{carbon lost} \times \text{calorific value carbon})}{\text{heat energy in coal}}$$

The assumptions made in the above equation are

(a) all CO and hydrocarbons released during combustion burn and form CO_2

(b) all the hydrogen in the fuel is converted to water

The variation of combustion efficiency with fluidization velocity for high-ash coal and coal washery reject 1 is shown in Fig. 8.5. The trend exhibited is a decrease in combustion efficiency with fluidization velocity. The reason for this is the higher carbon loss due to elutriation as the velocity increases. The combustion efficiency for coal is in the range of 95–97% with underbed feeding, and 92–95% for overbed. With rejects, the combustion efficiency drops and is in the range 85–89%. The rejects are generally found to be less reactive than coal

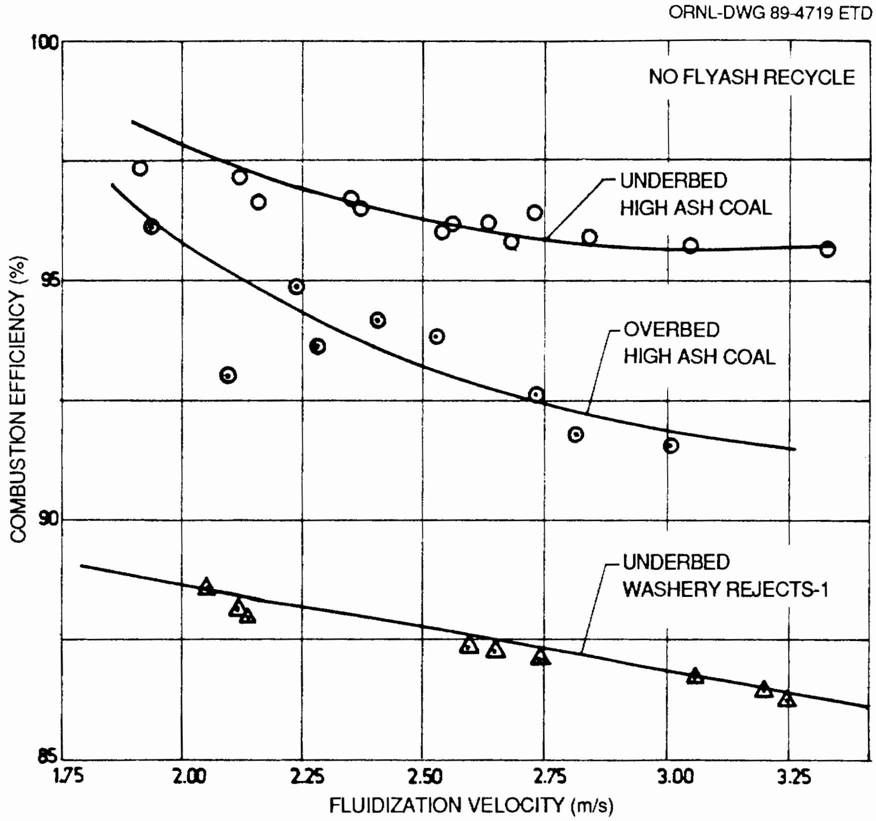

Fig. 8.5. Effect of fluidization velocity on combustion efficiency.

because of the higher inerts content in them (Anthony et al. 1988; Cao and Fang 1984). The heat loss in the flyash and bed drain were also higher for the rejects which will lower the combustion efficiency.

The once-through combustion efficiency obtained for Indian coals are much higher than those reported for most Eastern U.S. coals, which is typically 90–93% (Krishnan et al., 1983; Castleman, 1985). In the case of U.S. coals, the maximum temperature is limited to 850°C because this is the optimum temperature for sulfur retention. However, in the case of Indian coals, the bed temperature can be kept higher because of the low sulfur content. Higher temperatures are known to enhance the combustion efficiency. In the tests conducted, the highest bed temperature was 900°C.

Recycle tests were conducted with sub-bituminous, high-ash coal. In these tests, the recycle ratio was varied from 0.5 to 2.0 (flyash to coal ratio). Typically, the recycle stream temperature was 300–400°C. Test data are reported in Tables B.1 and B.10 (see Appendix B) and Figs. 8.6 and 8.7. A 2–3% improvement in combustion efficiency is indicated with flyash recycle for underbed (Fig. 8.6) and 4-5% for overbed feeding (Fig. 8.7). The maximum combustion efficiency obtained was

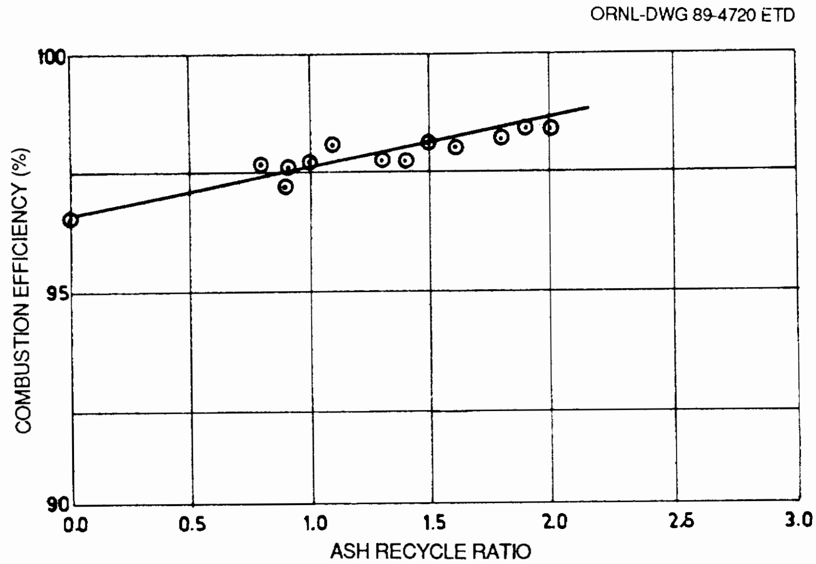

Fig. 8.6. Effect of recycle ratio on combustion efficiency with underbed feeding.

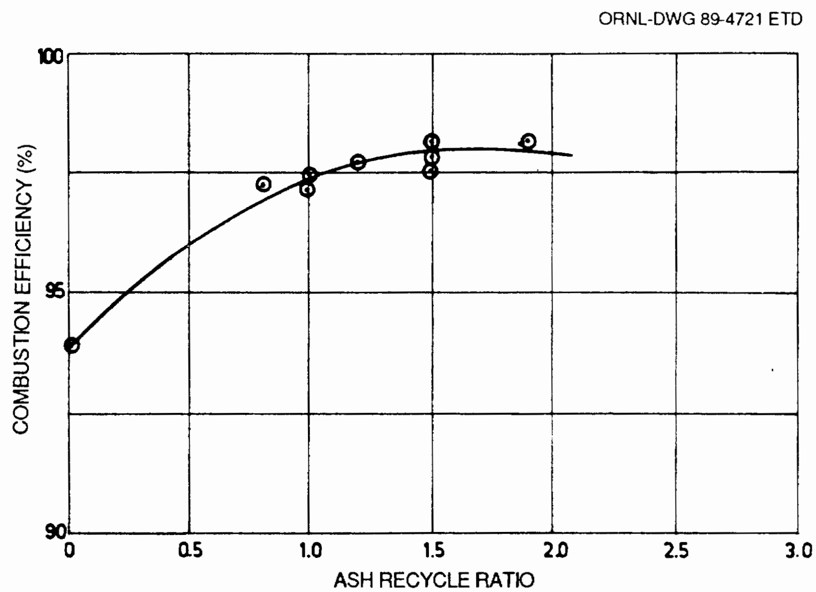

Fig. 8.7. Effect of recycle ratio on combustion efficiency with overbed feeding.

around 98.5% for underbed at a recycle ratio of 2.0. Other investigators have also observed a 2–3% improvement in combustion efficiency with recycle (Castleman, 1985; Bass, 1984; Valk et al., 1985) Attempts to conduct recycle tests on rejects of sufficient duration were not successful due to problems with ash handling.

Figures 8.8 and 8.9 compare the combustion efficiency with and without recycle for underbed and overbed feeding as a function of fluidization velocity. Recycle has a much more pronounced effect in the case of overbed, particularly at the higher velocities (Fig. 8.9). The trend observed is in agreement with the test results reported by others

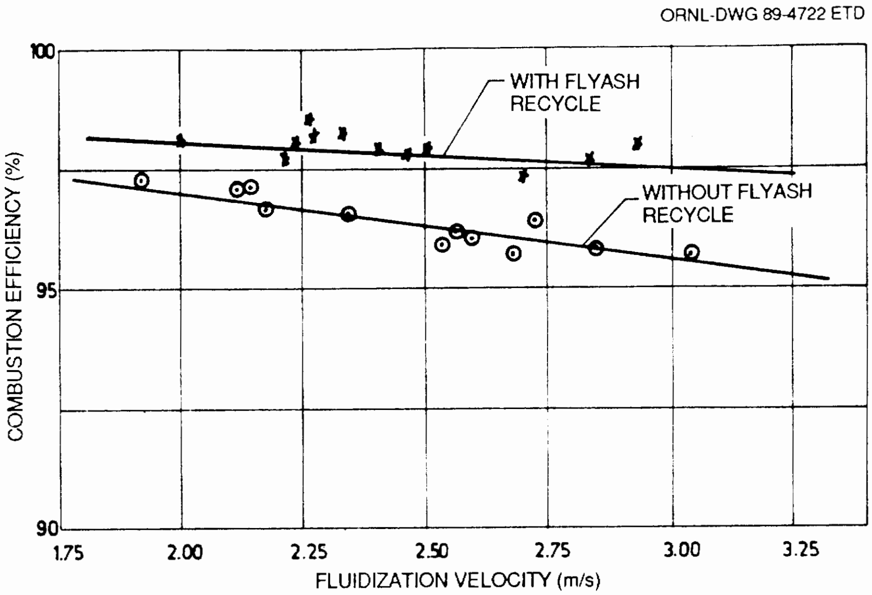

Fig. 8.8. Combustion efficiency with and without recycle with underbed feeding.

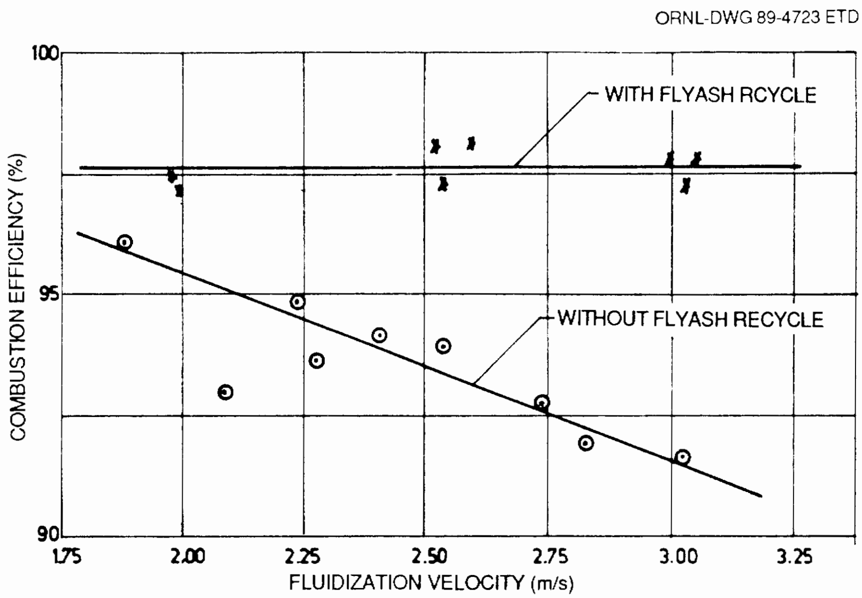

Fig. 8.9. Combustion efficiency with and without recycle with overbed feeding.

where overbed feed system resulted in lower combustion efficiency and recycling of flyash was very important in order to achieve high combustion efficiency (Castleman 1985; Carson 1988). In some cases, removal of the fines in the feed coal which have a tendency to partially burn and elutriate with the flyash, improved the combustion efficiency. This was also confirmed in one of the overbed feed tests in the facility, in which a double sieved washery reject was tested (see Table B.10, test runs 42 and 43, in Appendix B).

Freeboard Combustion

Freeboard combustion is reported here as a percentage of the total fuel heat input to the combustor released above the bed. Freeboard combustion is influenced, among other variables, by freeboard temperature, freeboard solids loading, fluidizing velocity, excess air and freeboard height.

The freeboard height was maintained at 4.7 m in all the tests. Freeboard combustion for the sub-bituminous coal with underbed feeding ranged from 6.0–9.0%, and for the rejects it was 3.5–5.5% (Fig. 8.10). For overbed fuel feeding, the values are higher and range from 10.0–16.0%, increasing fairly rapidly with fluidization velocity (see

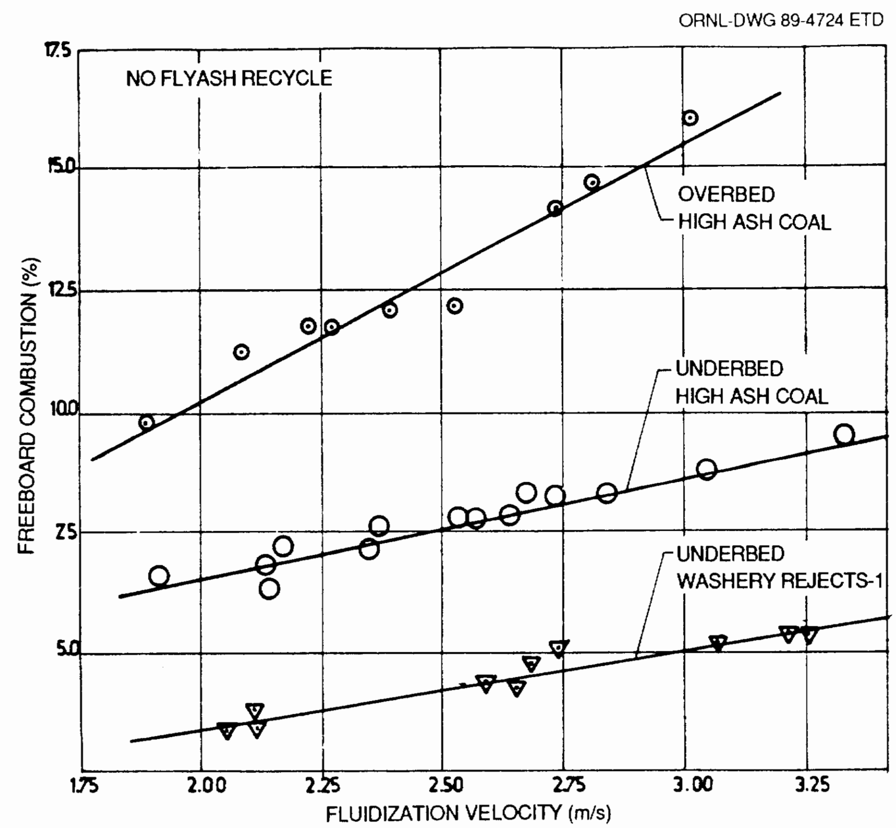

Fig. 8.10. Freeboard combustion versus fluidization velocity.

Fig. 8-10). In overbed feeding, the fuel is falling into the combustor by gravity from an elevation of 1 meter above the bed surface. During this process, substantial quantities of fines in the coal escape to the freeboard and burn, resulting in higher freeboard combustion.

Ideally, it will be advantageous if the combustion of the fuel takes place in the bed rather than in the freeboard. The heat transfer coefficient in the bed is much higher compared to the heat transfer coefficient in the freeboard, and consequently, the surface requirement for the boiler will be reduced if the combustion occurs in the bed. While it is not possible to completely eliminate freeboard combustion in FBC, it is desirable to minimize it by proper selection of the coal feed system design and the bed operating parameters.

One way to reduce freeboard combustion is by having a combination of underbed and overbed feed system, where the fines are fed underbed, and the larger coal particles overbed (Shimizu et al., 1985). The combustion efficiency improves in this design but the system configuration becomes complex. There is a trade off between performance and system complexity which has to be evaluated on a case by case basis.

The effect of flyash recycle on freeboard combustion is shown in Figs. 8.11–8.14. With recycle, the freeboard combustion increases for both underbed and overbed feeding. This is expected, since with recycle, the solids loading (char and flyash) in the freeboard increases. The observed trend is consistent with other experimental data from bench scale and pilot plant FBC which showed higher freeboard combustion with recyle (Rickman et al., 1979; Zimmerman et al., 1983; Krishnan et al., 1983). An important consideration in designing the freeboard is to ensure that the freeboard temperature is sufficiently high for the combustion of the char.

Heat-Transfer

The ability to predict heat transfer coefficients is essential for designing commercial FBC boilers. Empirical heat transfer correlations have been developed from FBC pilot plant data to aid in the design of FBC boilers. Thorough analysis of these correlations can be found in Grewal, 1981; Glicksman, 1980; Carson, 1985; and Divilio, 1986. Traditionally used correlations for the convection component of the inbed heat transfer coefficient are the Vreedenburg correlation (1958) and its modified versions (Andeen and Glicksman, 1976; Glicksman and Decker, 1979). Kantessaria and Jukkola (1983) found that the heat transfer data from the Great Lakes fluidized bed demonstration plant did not correlate with the traditional correlations. They developed the following relationship for the convection heat transfer coefficient.

$$Nu = 0.27\ (Ar)^{0.27} \tag{18}$$

$$Ar = \frac{D_\rho^3\ g\ \cdot\ \rho_p \cdot\ \rho_g}{\mu_g^2} \tag{19}$$

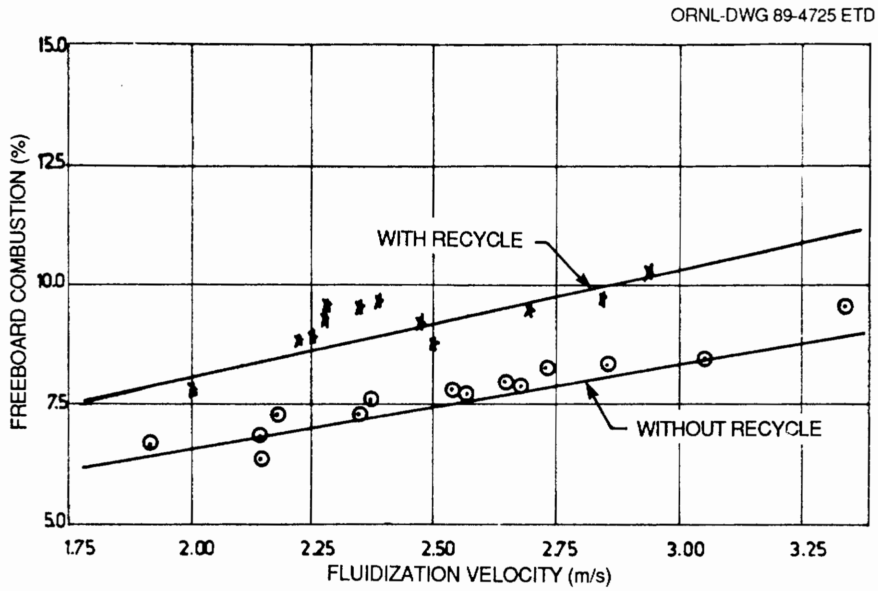

Fig. 8.11. Freeboard combustion versus fluidization velocity with and without flyash recycle and underbed feeding.

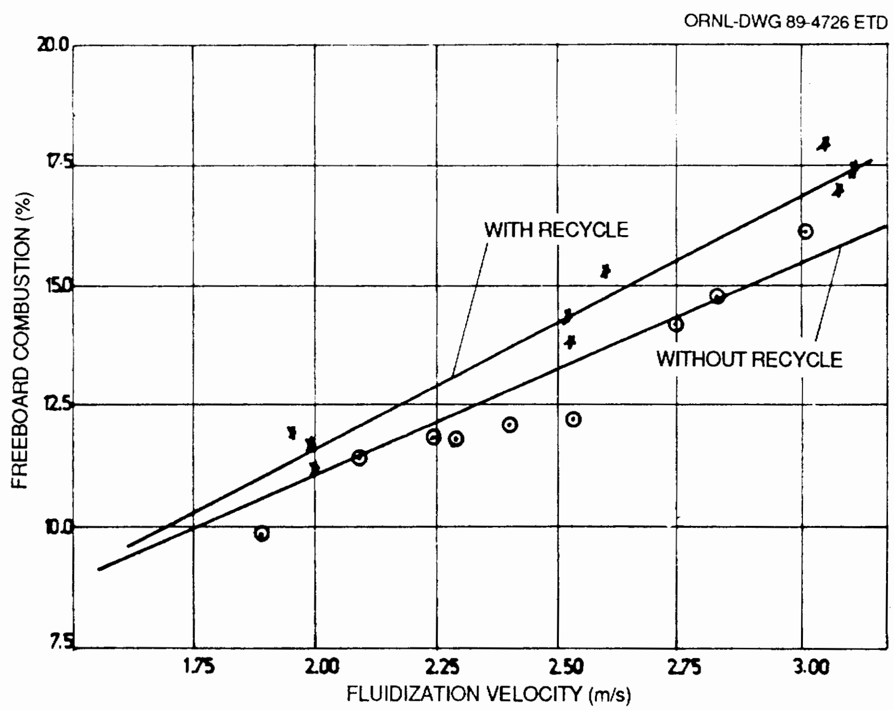

Fig. 8.12. Freeboard combustion versus fluidization velocity with and without flyash recycle and overbed feeding.

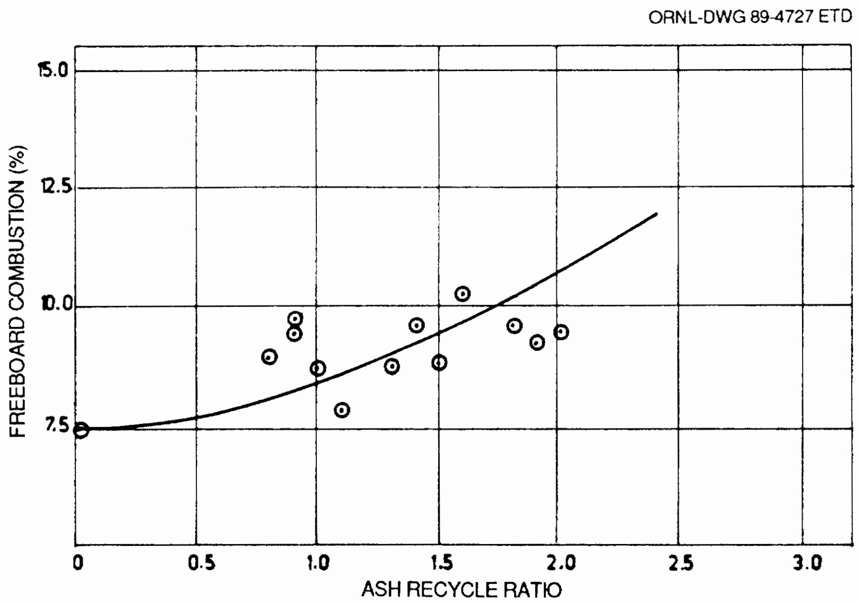

Fig. 8.13. Effect of flyash recycle ratio on freeboard combustion with underbed feeding.

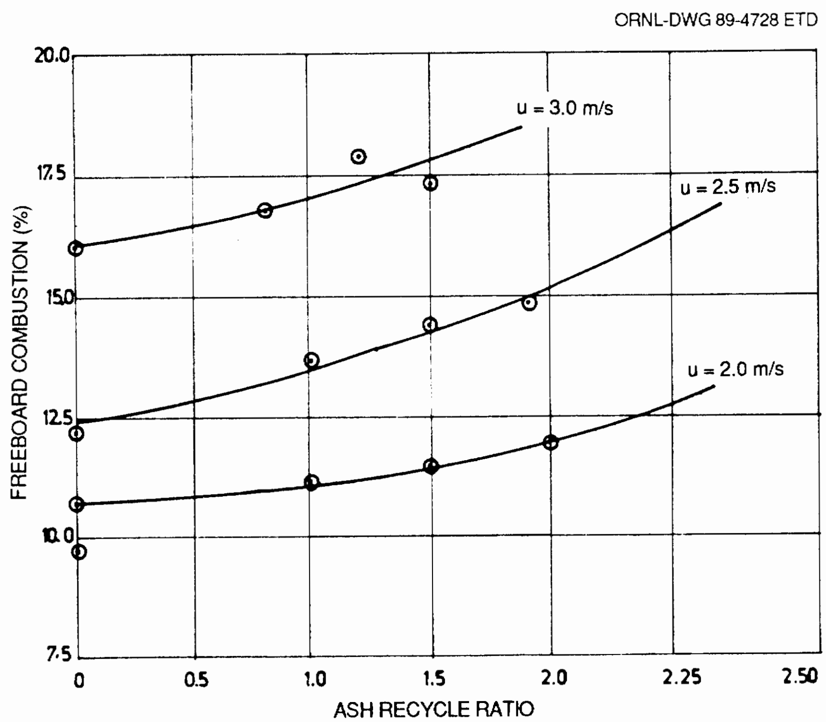

Fig. 8.14. Effect of flyash recycle ratio on freeboard combustion with overbed feeding.

Gelperin and Einstein (1969) proposed a similar correlation of the form

$$Nu = 0.63\ (Ar)^{0.22} \qquad (20)$$

The individual terms are defined in the nomenclature. Carson (1985) tested these correlations with the TVA 20 MW(e) pilot plant data and found that the correlations proposed by Kantessaria and Jukkola (1983) and Gelperin and Einstein (1969) are in line with the TVA 20 MW(e) heat transfer data with some modifications to the coefficients appearing in these correlations.

Figures 8.15 and 8.16 show the measured heat transfer coefficient and the heat transfer coefficient predicted using Kantesaria and Jukkola type correlation (Correlation 1) and the modified Vreedenburg type correlation (Correlation 2), respectively. The results indicate that both these correlations are satisfactory and predict the heat transfer coefficient in the test facility within ±6%.

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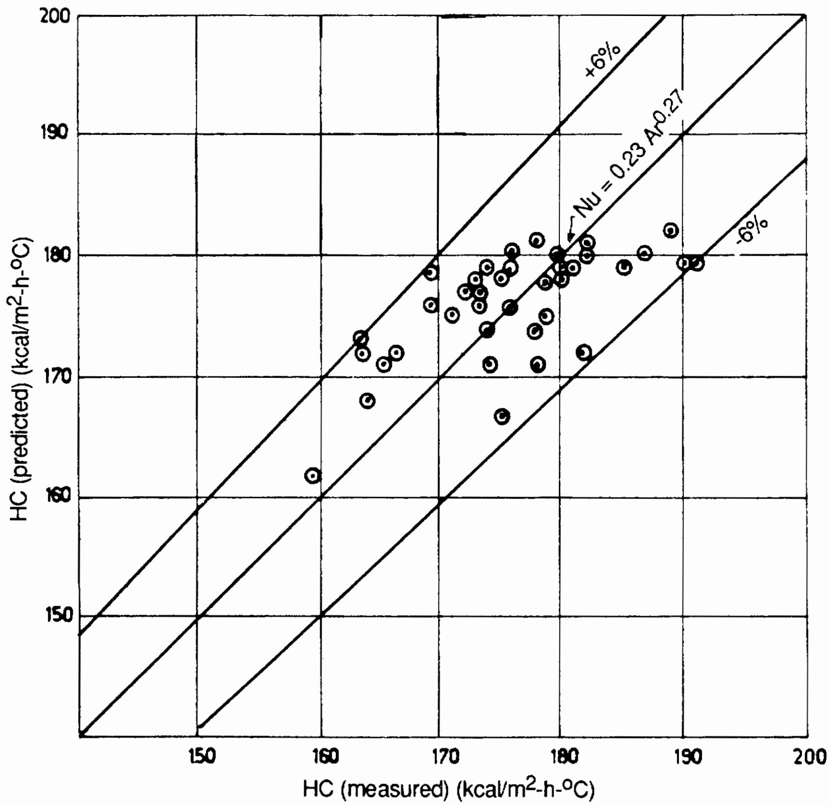

Fig. 8.15. Convective inbed heat transfer coefficient measured and predicted from correlation 1.

ORNL-DWG 89-4730 ETD

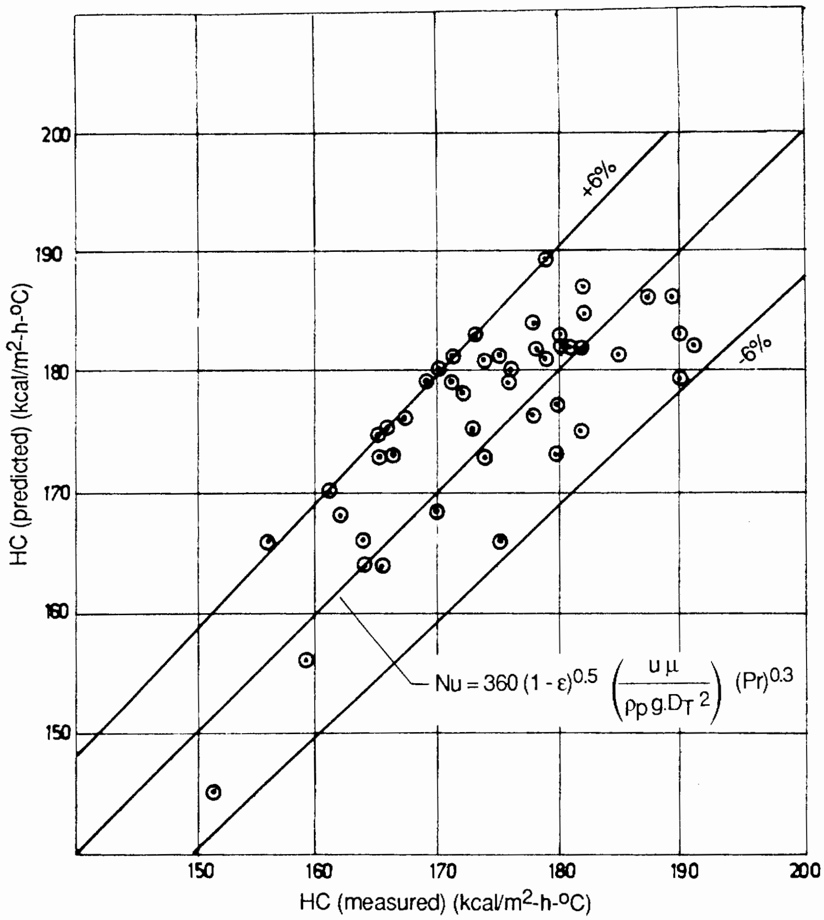

Fig. 8.16. Convective inbed heat transfer coefficient measured and predicted from correlation 2.

The gas side heat transfer coefficient for the bed, which is the sum of the convective (h_c) and radiative (h_r) components, was found to be in the range 193–300 kcal/h m²°C.

Freeboard Heat Transfer

The heat transfer coefficient in the freeboard decreases appreciably along the freeboard height (see Figs. 8.17–8.20). Heat transfer coefficients were measured at two locations in the freeboard. Location 1 represents a freeboard height of 600 mm above the expanded bed. Location 2 represents a freeboard height of 1600 mm above the expanded bed height.

With underbed feed, the heat transfer coefficient at location 1 is between 137 – 168 kcal/h-m²-°C. The values in the lower range (137–155) are for the "no recycle" tests (Fig. 8.17) and the higher values

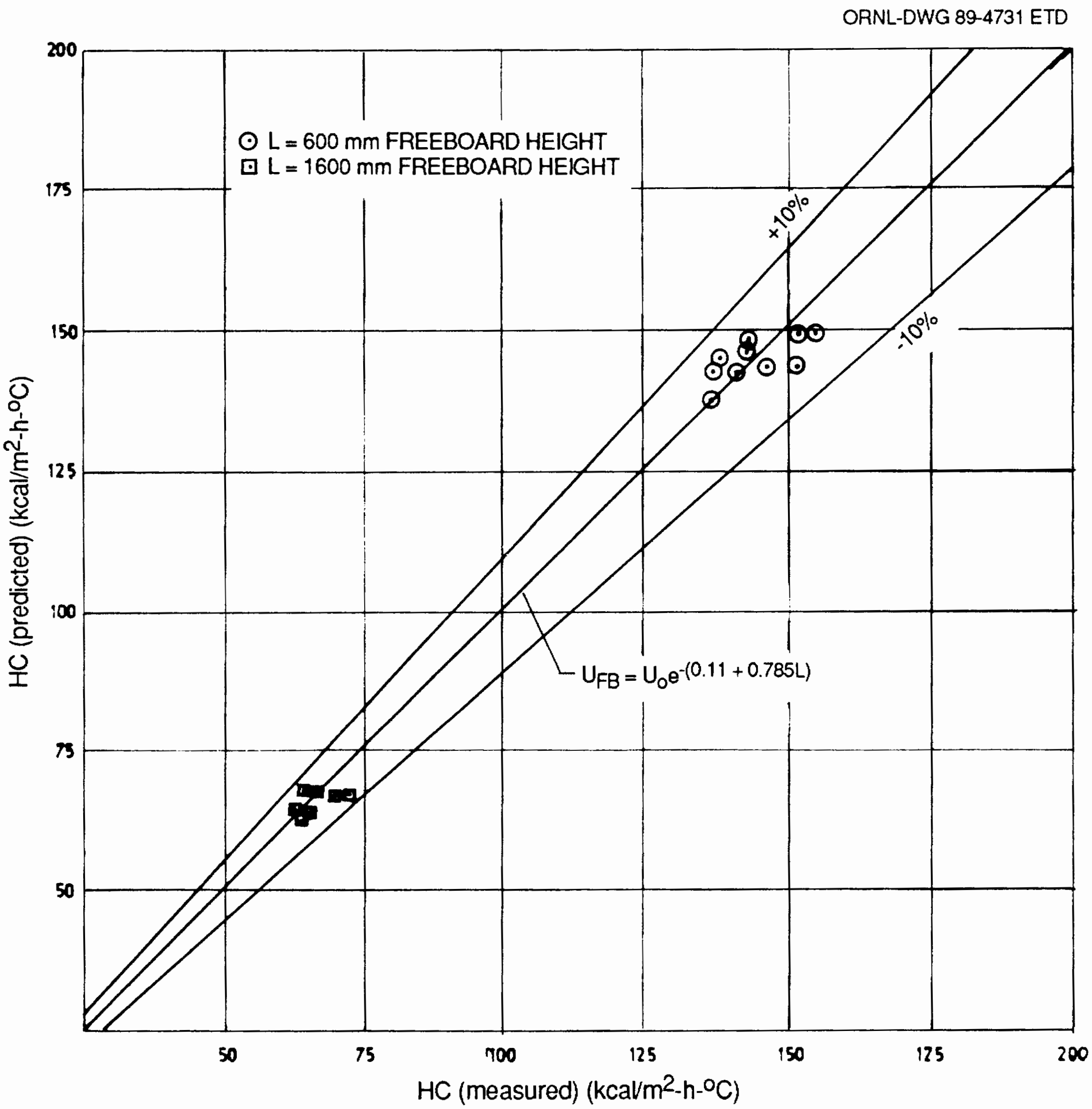

Fig. 8.17. Freeboard heat transfer coefficient measured and predicted for underbed feeding without flyash recycle.

ORNL-DWG 89-4732 ETD

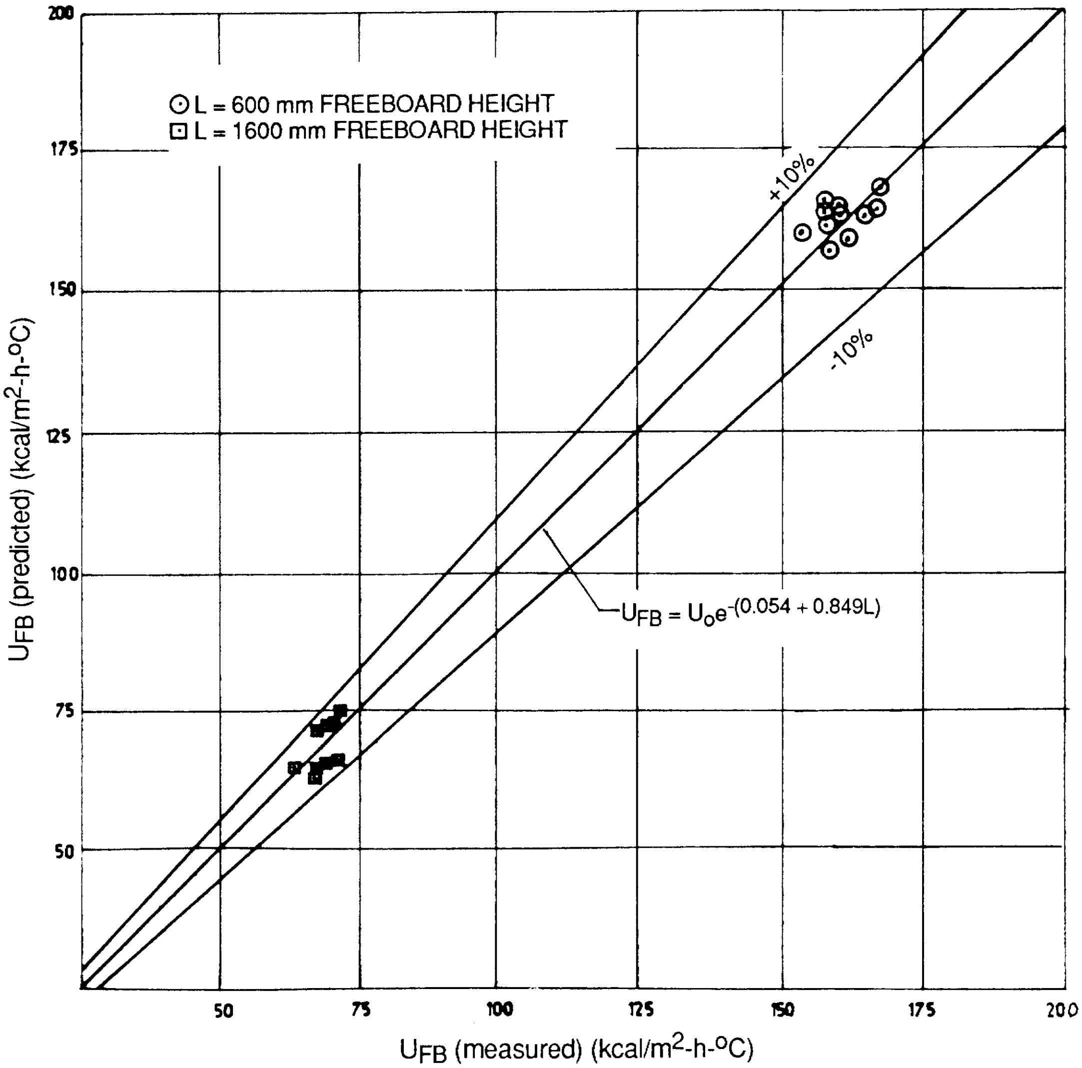

Fig. 8.18. Freeboard heat transfer coefficient measured and predicted for underbed feeding with flyash recycle.

ORNL-DWG 89-4733 ETD

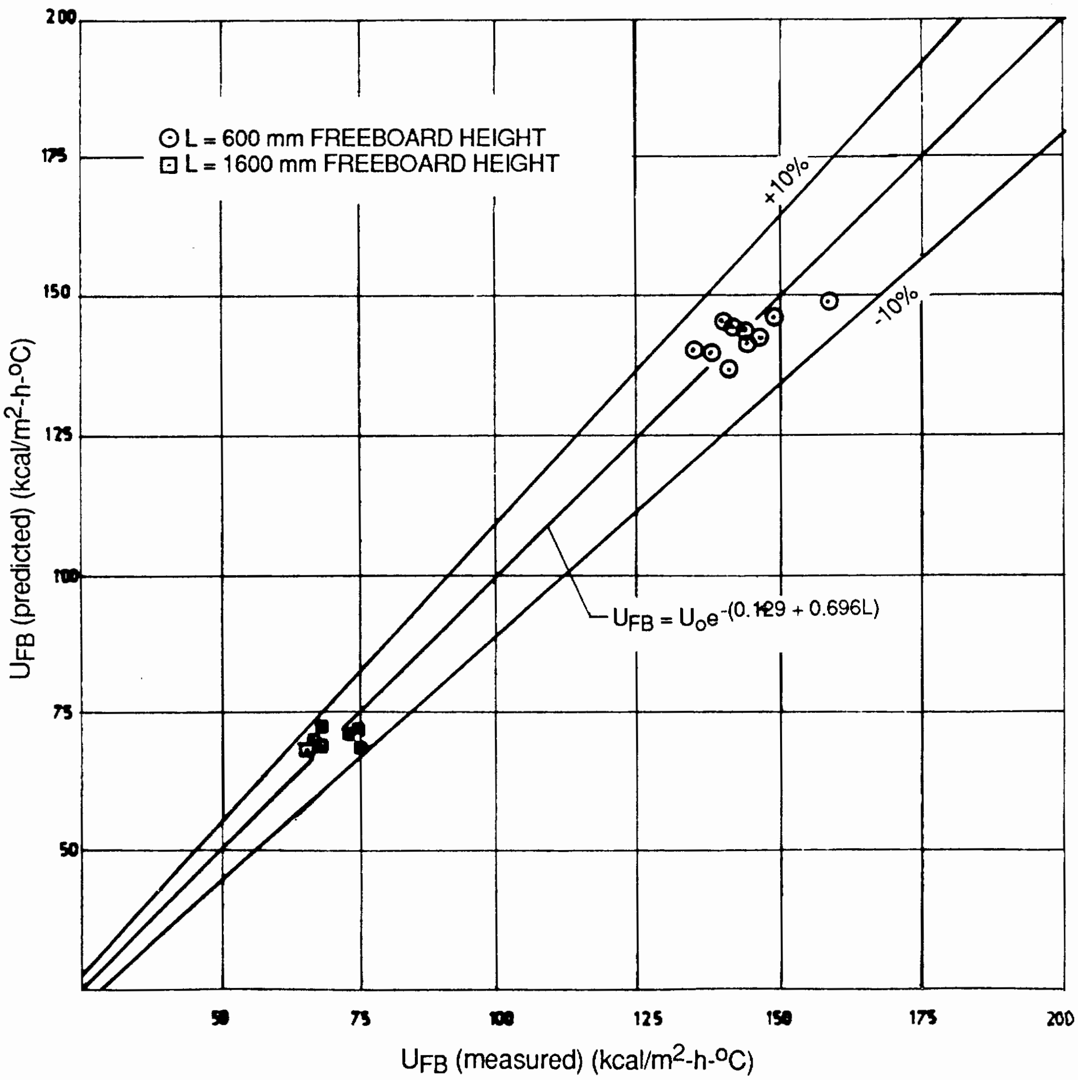

Fig. 8.19. Freeboard heat transfer coefficient measured and predicted for overbed feeding without flyash recycle.

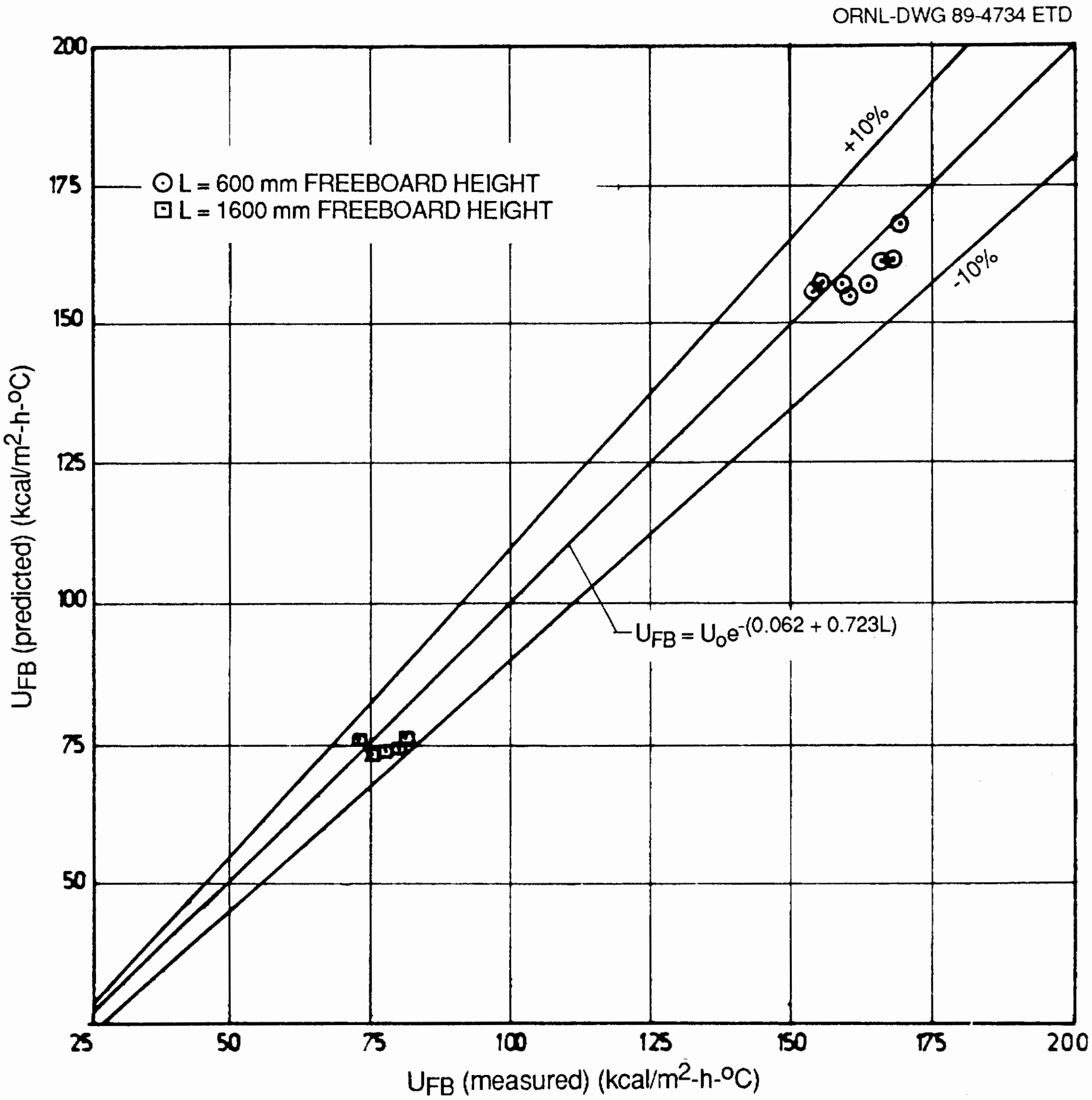

Fig. 8.20. Freeboard heat transfer coefficient measured and predicted for overbed feeding with flyash recycle.

(155–168) correspond to recycle operation (Fig. 8.18). The coefficient decreases drastically at location 2 and is between 63–75. At this location, the recycle had very little effect on the heat transfer coefficient.

In the overbed feed tests, the heat transfer coefficients were similar to the coefficients obtained in the underbed test (see Figs. 8.19 and 8.20). The range was 135–170 Kcal/hr-m^2°C at location 1 and 65–80 Kcal/h-m^2°C at location 2. With recycle, there is a marginal improvement in the heat transfer at both locations.

Figure 8.21 shows a comparison of the freeboard heat transfer coefficient obtained under different test conditions as a function of freeboard height. An exponential decay type correlation of the form

$$\frac{U_{fb}}{V_o} = e^{-(C_1 + C_2 L)} \tag{21}$$

fits the data within ±10%. The heat transfer coefficient measured in the test facility are generally higher than what has been reported elsewhere (Modrak, 1982).

Emissions

NO_x and SO_2 emissions (the major pollutants) were found to be within the U.S. Environmental Protection Agency (EPA) limits (1.2 lbs/million Btu for SO_2, and 0.6 lbs/million Btu for NO_x). NO_x emissions ranged from 200–400 ppm (0.3–0.6 lbs/million Btu) for coal with underbed feeding and 90–300 for overbed feeding without recycle (see Fig. 8.22). In both cases, NO_x increased with excess air. With recycle, the NO_x decreased slightly for both underbed and overbed (see Fig. 8.23).

ORNL-DWG 89-4735 ETD

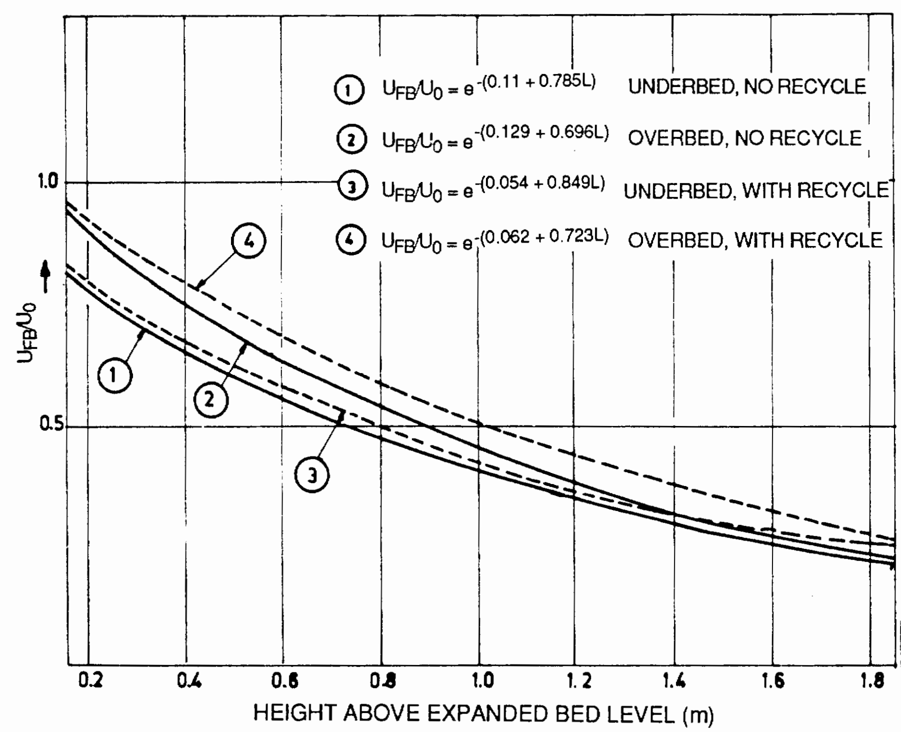

Fig. 8.21. Comparison of freeboard heat transfer coefficient obtained at various test conditions.

ORNL-DWG 89-4736 ETD

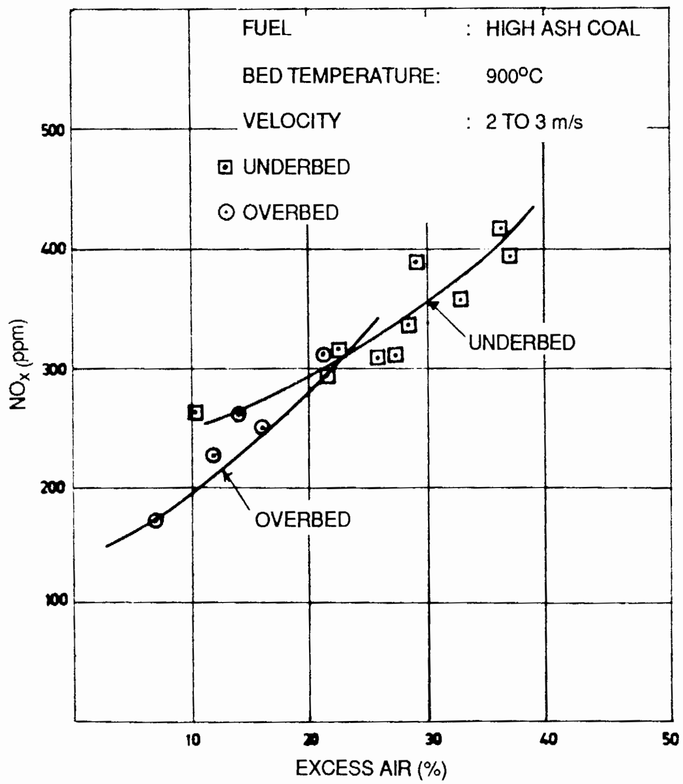

Fig. 8.22. Nitrogen oxide emission versus excess air without flyash recycle.

ORNL-DWG 89-4737 ETD

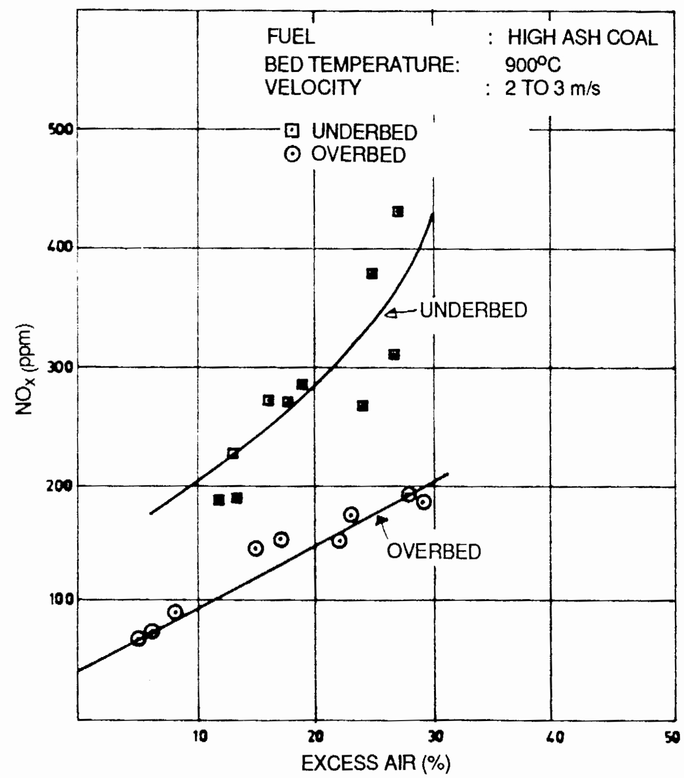

Fig. 8.23. Nitrogen oxide emission versus excess air with flyash recycle.

Sulfur oxide emission varied appreciably with both fuel type and operating conditions. The underbed tests with coal produced the least amount of SO_2, 200–500 ppm (0.4–1.1 lbs/million BTU), compared to the overbed tests where the emission ranged from 300–1000 ppm (see Appendix B). Flyash recycling increased the SO_2 emissions in both cases. Higher SO_2 emission with recycle could result from the combustion of the unburnt char during recycle.

As expected, the combustion of mill rejects which had a sulfur content of 0.58%, compared to a sulfur content of 0.4% for coal, resulted in higher SO_2 emissions (700–1070 ppm).

CO Emission

CO emissions at the various test conditions are shown in Fig. 8.24 as a function of excess air. As expected, CO emissions are higher for overbed. Increasing the excess air caused the CO levels to drop in both cases. Flyash recycling made a significant difference in CO emissions, particularly in the overbed tests. CO emissions generally decreased in the recycle tests.

ORNL-DWG 89-4738 ETD

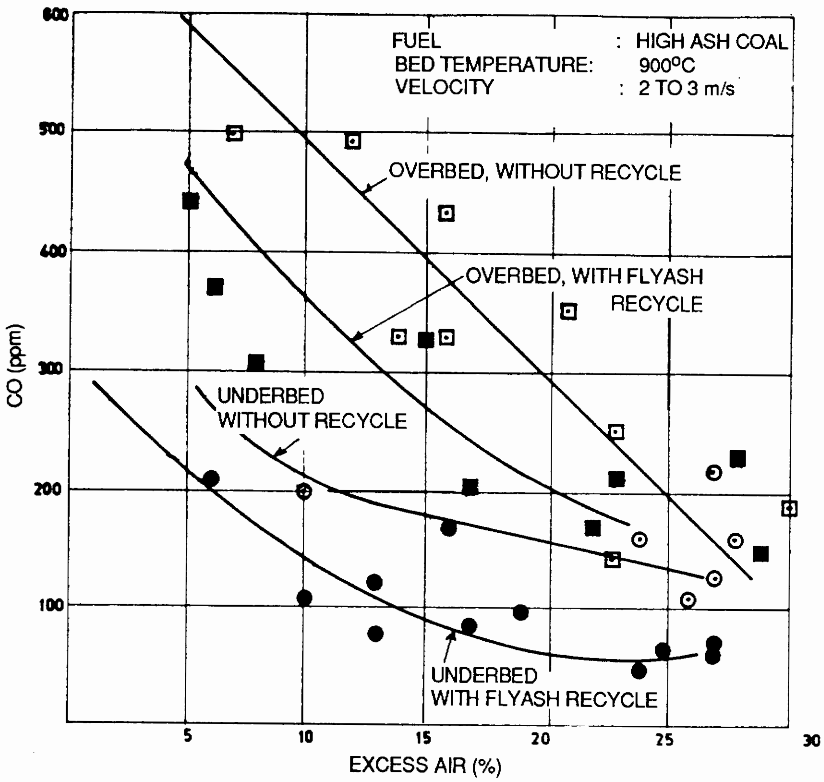

Fig. 8.24. Carbon monoxide emission versus excess air.

Bed Retention

Bed retention is a measure of the ash in the coal that is retained in the bed. This is an important parameter in the FBC system design, since the ash handling system has to be sized according to the amount of ash that is retained in the bed.

With the high-ash Indian coals, accurate prediction of bed retention is much more important compared to low-ash coals. Bed retention measured under the various test conditions are plotted in Fig. 8.25 for underbed feeding and Fig. 8.26 for overbed feeding. With overbed feeding, the bed retention was much higher, 12–25% compared to 7–15% for underbed. With recycling, bed retention increased in both cases.

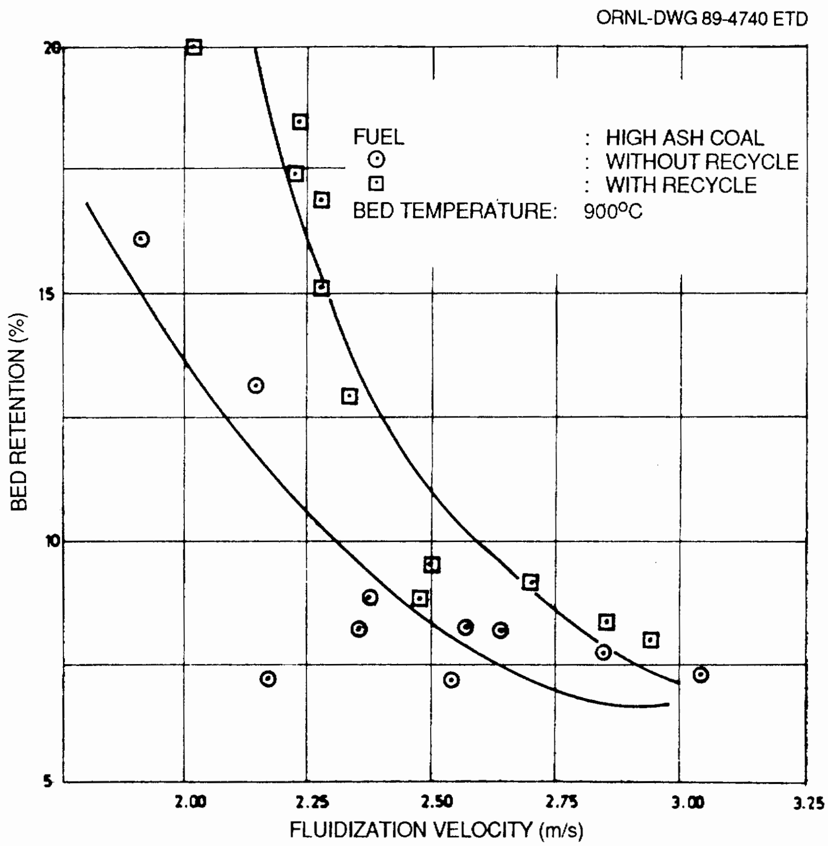

Fig. 8.25. Bed retention versus fluidization velocity with underbed feeding.

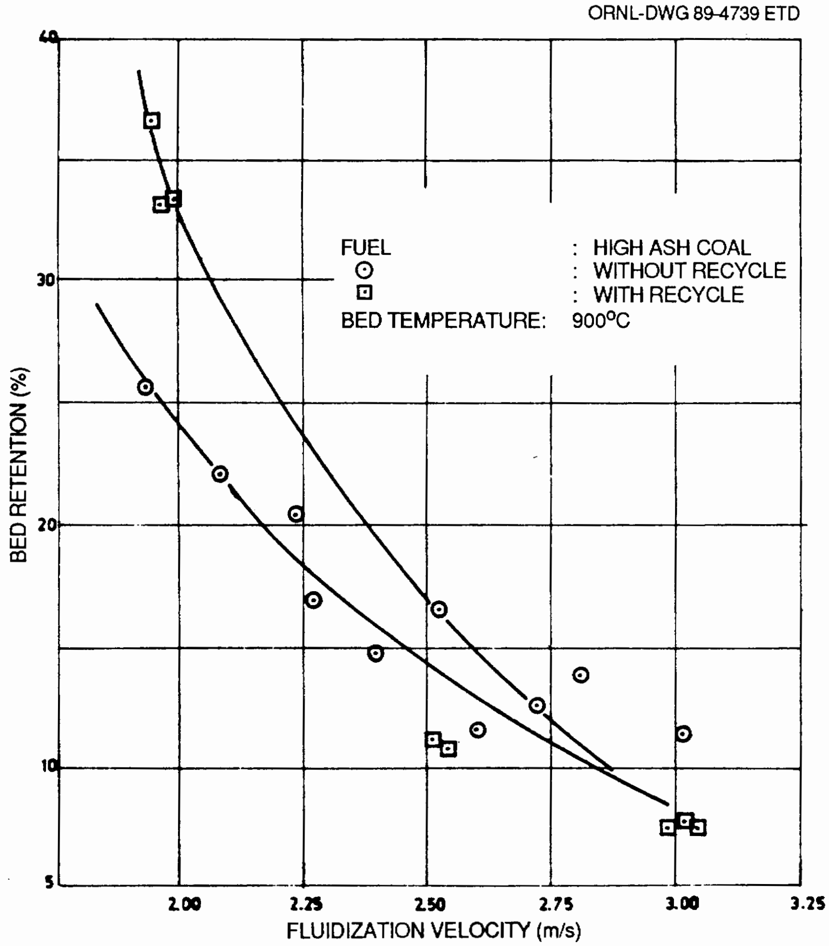

Fig. 8.26. Bed retention versus fluidization velocity with overbed feeding.

9. APPLICATION OF TEST RESULTS TO LARGE FBCS

The FBC research test facility has served as a valuable developmental tool in establishing the performance characteristics of the FBC process and equipment for the combustion of high ash content fuels. The experience gained during the 1000 hrs of operation including the analytical results obtained from 600 hrs of testing has defined the range of combustion performance parameters for the fuels and identified the engineering problems that need to be addressed for commercial applications. Significant results from the operation and testing that bear relevance to the design and operation of large FBC's are highlighted below.

1. Despite the high ash content of Indian coals, it is possible to achieve high combustion efficiency of the order of 95 to 97%, provided the bed temperature is maintained at around 900°C and excess air levels between 15 to 20%.

2. Flyash reinjection further enhances the combustion efficiency by 2 to 3% depending on the fuel composition, and the recycle ratio. A recycle ratio of 2.0 appears adequate to achieve 98% combustion efficiency with coal.

3. Freeboard combustion is strongly influenced by the fuel type, fuel size distribution, fluidization velocity and mode of fuel feeding. Overbed feeding results in higher freeboard combustion compared to underbed feeding. Based on the limited hours of testing, the freeboard combustion is 10-15% for overbed and 6-10% for underbed feeding. Currently FBC boilers are designed for 10-15% freeboard combustion with underbed feeding and 40% ash coal. It is estimated that a 2% reduction in freeboard combustion would result in a net reduction of up to 10% in the total heat transfer surface in the boiler. This is likely to reduce the overall boiler cost by 3-5% for boilers above 15 MW(e) in size.

4. Overbed feeding is simpler, easy to operate, less prone to forced outages, and has higher tolerance for moisture in coal compared to underbed feeding. It should be considered for large boilers. The performance penalty associated with overbed feeding is 3-5% in combustion efficiency compared to underbed. Freeboard combustion is higher in overbed feeding, and consequently, the tube surface requirement in the freeboard will be higher. Minimizing the fines content in the coal results in less freeboard combustion and less carbon loss from the system. Overall, overbed feeding with flyash reinjection appears attractive for large scale FBCs.

5. From the temperature profile and heat release rates measured in the freeboard, it appears that a 3 meter freeboard height with underbed feeding is reasonable over the range of variables tested. For overbed feeding, the freeboard height can be increased by an additional one meter, provided the fines content in the coal is limited to 20% less than 1.0 mm.

6. Heat transfer coefficient correlations developed for the bed and the freeboard region can be used to optimize surface requirement in FBC boilers.

7. Emissions of SO_x and NO_x are well below the U.S. EPA limits.

8. When burning washery rejects with high ash content, adequate attention should be given to handling and disposal of ash from the system.

10. CONCLUSIONS AND RECOMMENDATIONS

Utilization of high ash coal and coal washery rejects in FBC systems up to 30 MWe size is possible with the present data base available in India. No major technological constraints are foreseen for this technology for even larger sizes [up to 60 MW(e)]. Optimization of combustor design, selection of proper fuel feed system, implementation of flyash recycle, and careful attention to the engineering design of the ash disposal system are key to the successful operation and performance of large FBC boilers.

It is recommended that future testing in the FBC research facility include the following

- testing of larger size coal and rejects (up to 12 mm), high sulfur coal and lignites
- evaluate performance of various ash cooling system designs
- testing of coal-water slurries and biomass fuels
- corrosion/erosion evaluation of tube surfaces in the combustor through long duration testing
- developing a performance prediction model for FBC boiler design.

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Appendix A

USAID EXPENDITURES, EQUIPMENT SPECIFICATIONS, TRAINING, SITE-VISITS OF BHEL ENGINEERS, AND PROJECT PUBLICATIONS

Table A.1. Summary of project expenditures

	Amount ($)
U.S. technical assistance	366,214
Travel	72,235
Equipment and accessories shipped to BHEL	412,872
Training of BHEL engineers in United States	39,248
Subcontracts (TVA, Northern States Power Co, Colorado-Ute, Electric Power Research Institute, Combustion Engineering)	23,015
Workshops, conferences, report preparation, publications, etc.	11,981
Overhead	135,167
Total	1,060,732

Equipment Supplied by USAID:

The major equipment and instruments supplied for this project by USAID include a complete Beckman flue gas analysis system, gas sampling probes, heat-traced sample lines, coal and limestone gravimetric weigh belt feeders, a Hewlett Packard (HP) computerized data acquisition system, a Buffalo Forge high-pressure blower, an Andersen stack sampling system, a SuperCal multisignal calibrator, a Parr adiabatic calorimeter, a Leco elemental analyzer, and a vacuum pump.

I. Beckmann Gas Analysis System

The flue gas analysis system consists of:

Item	Emission Type	Mode	Model	Principle of Operation	Range
01	O_2-oxygen	C	755	Paramagnetic	0-5, 10, 25, 50%
02	CO_2-carbon dioxide	C	864	Nondispersive Infrared	0-5, 20%
03	CO-carbon monoxide	C	864	Nondispersive infrared	0-1000, 10,000 ppm
04	SO_2 sulfur oxides	C	865	Nondispersive infrared	0-2000, 10,000 ppm
05	NOx-nitrogen oxides	C	951A	Chemiluminescence	0-10, 25, 250, 1000, 10,000 ppm
06	THC total hydrocarbons	C	400	Flame ionization	0-15,000 ppm

C-Continuous

- Automatic sampling at three locations in the furnace.
- Sample conditioning, back purge system, and heat traced sample lines.
- Appropriate span and zero gases supplied by Beckman for accurte calibration.
- Gas sampling probes were designed and fabricated at ORNL and shipped to site.

Cost: $173,072 (including freight, spares, and supplies)

II. Merrick Coal/Limestone Gravimetric Weigh Belt Feeders

The coal/limestone feeders were procured from Merrick Corporation having the following capacities:

No.	Size	Model	Purpose	Capacity
01	20"	950 DSC	Coal feeding	1000 kg/h max.
02	12"	950 DSC	Limestone feeding	225-300 kg/h

- Accessories include self contained belt feeders, weight transducer systems, digital feed control systems, variable speed drive, total enclosure, manual knife gate valve.
- The system accuracy is 0.5%.

Cost: $33,180 (including freight and spares)

III. Hewlett Packard Data Acquisition System

The data acquisition system consists of:

(1) 9836 CS Color Desktop computer, 80 character CRT, 572 × 390 Graphics, 640K Bytes RAM and Internal Disc Drives

(2) 3497 A Data acquisition/control unit

(3) 3498 A Extenders

(4) 2225 A Inkjet Printers

(5) 7475 A Graphic Plotters

(6) 9816 S Backup Computer, 805 Large Keyboard 630, 3 1/2" Disc Drives, 512 K Bytes Ram

(7) 9121 D Dual disc drive

(8) 3497 A Relay Multiplexers

(9) Expansion kit (Memory board and accessories)

(10) COMLINK-3 Modem to transmit signal to the main ICL computer at BHEL

Cost: 75,600 (including freight, spares, and supplies)

IV. Buffalo Forge Co. High-Pressure Blower

Buffalo Forge size 55-2 type R blower, single width, single inlet, arrangement 1, V-belt driven, SKF spindle bearings, 46 3/4 in. diameter wheel, 3 3/16 in. diameter shaft with shaft seal, 1/4 in. housing butterfly valve at inlet, horizontal top discharge, clockwise rotation, extra motor sheave and belt for low pressure rating, belt guard, and inlet silencer to maintain noise level around 90 db. Blower is rated for:

(1) 3500 cfm, 120 in. water column static pressure, 100°F ambient air temperature and 0.0709 lb/ft^3 clean air density
(2) 3500 cfm, 60 in. water column static pressure, 100°F ambient air temperature and 0.0709 lb/ft^3 clean air density.

Three phase, 415–440 V, 50 Hz power supply. Motor and blower are mounted on sliding rails.

Spares

Belts, shaft, fan wheel, and spindle bearings

Cost: $52,347 (including freight and spares)

V. Andersen Co. Stack Sampling System

Andersen stack sampling system based on EPA method 5, No. 90-900-1 with 1 extra set of glassware (No. 90-402), two alundum thimble filter holders (D-01021), twelve alundum thimbles (D-1022098) with gaskets, two each gooseneck nozzles (D-1023, D-1024, and D-1025), three extra sets of gaskets (D-1028), pitot tips (D-3930-1), filter assembly kit for 4 in. filter, and 1/2 in. NPT × 5/8 in. compression adaptor.

Cost: $14,078 (including freight, spares, and supplies)

VI. SuperCal Multisignal Calibrator/Indicator

SuperCal multisignal (volts, mV, mA, frequency, thermocouple), Model CL6000-200 calibrator/indicator for 220 volts, 50 Hz, power supply with Ni-Cd battery pack (CL-6012), external battery charger (CL 6009), test leads (CL 6013), fuse pack (CL-6014), carrying case (CL-6011), extra desktop charger (CL-6235), spare battery pack (CL-6012), RTD simulator model (CL-6030, digital pressure gage (DPG-600G-30), and extra test leads, fuses and operator manuals.

Cost: $4086 (including freight and spares)

VII. Parr Instruments Adiabatic Bomb Calorimeter

Model 1252, System II oxygen bomb calorimeter consisting of 1241 adiabatic bomb calorimeter with 1108 oxygen bomb; 1720 calorimeter controller with 1755 printer; 1108 oxygen bomb (extra); 391 DD calorimeter bucket (extra); 1541 water heater; 1551 water cooler; 1562 closed circuit style bucket filter; 1841 autocharge; 1249 spare parts kit; 2811 pellet press with 1/2 in. punch and die set; 3601 gelatin capsules; 362C printer paper for 1755; 264C printer ribbon for 1755; 1249 spare parts kit (extra); and A38A bomb heat support stand (extra).

Cost: $20,811 (including freight, spares, and supplies)

VIII. LECO Corporation Elemental Analyzer

Model CHN-600 automatic determinator for carbon, hydrogen, and nitrogen in organics with Model No. 785-600 determinator, control console (No. 786-500), LB-80 electronic balance (No. 600—900) supplies for 5000 analyses, and manufacturer recommended spares for two years trouble-free operation.

Cost: $38,578 (including freight, spares, and supplies)

IX. Air Dimensions Inc. Diaphragm Pump

Dia-Vac gaseous, single-head, stainless steel casing, neoprene coated teflon diaphragm pump, standard direct drive, 1/3 HP motor operated on 115V, 50 Hz for use in the Beckman gas analysis system.

Cost: $1,120 (including freight)

Training and Site-visits of BHEL Engineers

On this project, eleven BHEL engineers (A. V. Vasudevamurthy, S. Shanmugam, C. Baskaran, S. Sundararajan, K. V. Seetharaman,

R. Jayaprakash Narayanan, S. V. Srinivasan, M. Rajavel, P. Vasudevan, S. Anatharamakrishnan, and J. Anthony) visited the United States. They participated in the test facility design review meetings, workshops, and visited several FBC installations in the United States. During their visit, they were also able to obtain hands-on experience in the operation and maintenance of the instruments at Beckman Industrial, Hewlett Packard, Instrument Society of America Training School, Merrick Corporation, and the Instrumentation and Controls Division, Oak Ridge National Laboratory. The organizations and sites visited include the Pittsburgh Energy Technology Center (PETC), the Morgantown Energy Technology Center (METC), the Babcock and Wilcox Co. (B&W), Combustion Engineering (CE), the Tennessee Valley Authority (TVA), the TVA 20 MW AFBC pilot plant, the TVA 160 MW AFBC demonstration plant (under construction), the Northern States Power Co. (NSP) 125 MW AFBC boiler retrofit, the Georgetown University AFBC boiler plant, the Colorado-Ute circulating fluidized bed (CFBC) utility boiler, the Keeler/Dorr-Oliver Quaker State Oil Refinery Corporation, FBC boiler, the Gilberton Power Co. CFBC boiler, the Pyropower Corporation, the Electric Power Research Institute (EPRI), Hewlett Packard, Beckman Instruments, Buffalo Forge, Peabody Co., and the Denver Equipment Co.

One engineer attended the International Energy Agency (IEA) – Grimethorpe Pressurized Fluidized Bed Combustion (PFBC) Lessons Learned Workshop in St. Louis, Missouri, July 15–18, 1989. Mr. J. Anthony, BHEL, presented a paper on the FBC freeboard project in the Tenth International FBC Conference, San Francisco, California, April 30–May 3, 1989.

Project Reports and Publications

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Appendix B

TEST DATA

Table B.1. Test data on high-ash coal with underbed feeding with and without flyash recycle, test series 1 through 26

S.No.	Description	01	02	03	04	05	06	07
01	Fuel[a]	1	1	1	1	1	1	1
02	Fuel feeding[b]	1	1	1	1	1	1	1
03	Ash reinjection, kg/h	360	480	720	540	540	300	0
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	900	884	870	881	883	872	894
07	Bed temp -2, °C	906	892	877	880	876	865	876
08	Bed temp -3, °C	897	887	872	879	876	865	872
09	Bed temp -4, °C	897	887	889	879	876	878	873
10	Bed temp -5, °C	909	907	889	889	885	879	893
11	Freeboard temp -1, °C	917	923	909	904	895	886	909
12	Freeboard temp -2, °C	887	936	947	918	901	888	931
13	Freeboard temp -3, °C	847	925	937	908	890	876	917
14	Freeboard temp -4, °C	749	826	907	813	791	779	816
15	Comb exit temp, °C	460	470	510	480	484	492	476
16	Coal feed rate, kg/h	406.5	370.0	363.5	365.5	352.0	358.8	330.0
17	Total air flow, m^3/h	2679	2201	2274	2382	2250	2521	2400
18	Fluegas analysis, O_2, %	3.9	2.0	2.3	3.2	2.8	4.4	4.2
19	Fluegas analysis, CO_2, %	15.6	17.3	17.1	16.2	16.6	15.2	15.3
20	Fluegas analysis, CO, ppm	450	82	425	400	176	76	109
21	Fluegas analysis, NOx, ppm	273	193	230	282	277	314	308
22	Fluegas analysis, SOx, ppm	316	341	395	230	245	294	485
23	Fluegas analysis, HC, ppm	-	-	-	0.86	1.06	0.06	0.03
24	Heat extracted from bed coils, Mkcal/h	0.60	0.60	0.58	0.61	0.59	0.59	0.60
25	Heat extracted in convection coils, Mkcal/h	0.59	0.50	0.51	0.53	0.48	0.47	0.41

[a]1. High ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.1 (continued)

S.No.	Description	01	02	03	04	05	06	07
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.84	5.11	4.76	4.58	4.87	4.87	4.52
27	Heat extracted in test loop 2, 10^3 x kcal/h	3.98	4.55	4.28	4.18	4.23	4.16	4.27
28	Coal analysis: C, %	42.28	42.28	43.49	43.41	43.41	43.72	46.32
29	Coal analysis: H, %	2.41	2.41	2.48	2.47	2.47	2.49	2.63
30	Coal analysis: N, %	1.05	1.05	1.08	1.08	1.08	1.08	1.15
31	Coal analysis: S, %	0.57	0.57	0.59	0.59	0.59	0.59	0.62
32	Coal analysis: O_2, %	9.40	9.40	9.67	9.65	9.65	9.72	10.27
33	Coal analysis: Ash, %	37.5	37.5	35.30	35.5	35.5	35.20	31.40
34	Coal analysis: Moist, %	6.60	6.80	7.40	7.30	7.30	7.20	7.70
35	Coal analysis: HHV, kcal/kg	4057	4057	4154	4150	4150	4192	4400
36	Bed particle size, microns	693	621	656	636	636	669	669
37	Air temp, °C	42	40	39	50	48	42	41
38	Combustibles in bed material, %	1.20	0.80	1.00	1.40	1.20	1.30	1.67
39	Combustibles in cyclone catch, %	3.90	3.70	3.00	3.90	3.30	3.40	7.80
40	Combustibles in multi-clone catch, %	3.80	3.10	2.30	2.80	2.40	3.30	4.80
41	Avg. bed temp, °C	900	888	877	881	878	870	880
42	Max. freeboard temp, °C	917	936	947	918	901	888	931
43	Fluidization Vel, m/s	2.69	2.22	2.27	2.37	2.24	2.47	2.37
44	Excess air, %	24	12	13	19	16	27	26
45	Freeboard combustion, %	9.5	8.8	9.5	9.6	8.9	9.0	7.6
46	Combustion efficiency, %	96.87	97.73	98.36	97.65	98.17	97.79	96.53
47	Carbon burn up, %	96.03	97.30	98.06	97.21	97.84	97.37	95.91
48	Dust concentration, g/Nm^3	221	317	427	326	343	196	49
49	Flue gas flow rate, kg/h	2928	2428	2506	2613	2473	2750	2400
50	Material drained from bed, kg/h	13.96	24.17	21.63	14.00	23.06	10.87	9.15

Table B.1 (continued)

S.No.	Description	01	02	03	04	05	06	07
51	Material drained from cyclone, kg/h	84.74	58.19	45.99	76.14	55.38	50.19	32.35
52	Material drained from multiclone, kg/h	54.49	56.39	60.69	39.61	46.52	65.23	43.16
53	Bed retention, %	9.11	17.42	16.86	10.79	18.45	8.61	8.83

Table B.1 (continued)

S.No.	Description	08	09	10	11	12	13	14
01	Fuel[a]	1	1	1	1	1	1	1
02	Fuel feeding[b]	1	1	1	1	1	1	1
03	Ash reinjection, kg/h	0	0	0	0	0	360	720
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	902	883	880	880	901	903	899
07	Bed temp -2, °C	891	876	878	882	903	904	903
08	Bed temp -3, °C	887	878	882	877	899	912	910
09	Bed temp -4, °C	887	880	880	881	900	908	902
10	Bed temp -5, °C	904	891	882	880	902	924	922
11	Freeboard temp -1, °C	908	897	887	885	888	933	933
12	Freeboard temp -2, °C	896	882	908	890	895	951	949
13	Freeboard temp -3, °C	881	867	902	910	930	943	950
14	Freeboard temp -4, °C	787	773	820	810	825	828	835
15	Comb exit temp, °C	488	480	480	480	460	498	521
16	Coal feed rate, kg/h	373.0	342.0	325.0	384.0	412.2	416.2	435.2
17	Total air flow, m^3/h	2549	2374	2156	2679	3038	2808	2909
18	Fluegas analysis, O_2, %	4.3	4.5	3.6	5.1	5.6	4.3	4.1
19	Fluegas analysis, CO_2, %	15.2	15.1	15.9	14.5	14.0	15.2	15.4
20	Fluegas analysis, CO, ppm	123	160	-	-	-	87	76
21	Fluegas analysis, NOx, ppm	307	335	300	360	400	439	379
22	Fluegas analysis, SOx, ppm	350	310	300	-	-	191	-
23	Fluegas analysis, HC, ppm	-	-	-	-	-	11.07	19.48
24	Heat extracted from bed coils, Mkcal/h	0.61	0.58	0.59	0.60	0.60	0.59	0.58
25	Heat extracted in convection coils, Mkcal/h	0.45	0.41	0.36	0.47	0.57	0.56	0.64

[a] 1. High ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b] 1. Underbed, 2. Overbed.

Table B.1 (continued)

S.No.	Description	08	09	10	11	12	13	14
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.59	4.50	4.25	4.31	4.23	4.78	4.89
27	Heat extracted in test loop 2, 10^3 x kcal/h	4.24	3.76	3.84	3.93	3.97	4.38	3.95
28	Coal analysis: C, %	43.57	43.57	43.57	42.28	43.57	42.20	42.20
29	Coal analysis: H, %	2.48	2.48	2.48	2.41	2.48	2.40	2.40
30	Coal analysis: N, %	1.08	1.08	1.08	1.05	1.08	1.05	1.05
31	Coal analysis: S, %	0.59	0.59	0.59	0.57	0.59	0.57	0.57
32	Coal analysis: O_2, %	9.68	9.68	9.68	9.40	9.68	9.38	9.38
33	Coal analysis: Ash, %	35.20	35.20	35.20	37.50	35.30	37.50	37.50
34	Coal analysis: Moist, %	7.40	7.40	7.40	6.80	7.30	6.90	6.90
35	Coal analysis: HHV, kcal/kg	4150	4150	4150	4057	4157	4050	4050
36	Bed particle size, microns	681	647	647	684	731	709	709
37	Air temp, °C	40.00	39.00	39.00	40.00	41.00	41.00	37.50
38	Combustibles in bed material, %	1.37	1.67	1.31	1.50	1.87	1.35	1.50
39	Combustibles in cyclone catch, %	7.00	5.30	5.10	5.70	6.90	3.70	3.40
40	Combustibles in multi-clone catch, %	4.20	4.40	2.90	4.50	5.27	2.54	1.05
41	Avg. bed temp, °C	890	880	880	880	901	907	904
42	Max. freeboard temp, °C	908	897	908	910	930	951	950
43	Fluidization Vel, m/s	2.54	2.35	2.14	2.64	3.04	2.84	2.94
44	Excess air, %	27	28	21	33	37	27	25
45	Freeboard combustion, %	7.8	7.2	6.4	8.0	8.5	9.7	10.4
46	Combustion efficiency, %	95.96	96.60	97.29	96.12	95.69	97.62	98.05
47	Carbon burn up, %	95.23	95.98	96.80	95.38	94.90	97.16	97.68
48	Dust concentration, g/Nm^3	57	55	58	59	52	213	359
49	Fluegas flow rate, kg/h	2549	2590	2362	2911	3295	3063	3178
50	Material drained from bed, kg/h	9.45	9.87	15.1	11.81	12.37	12.88	13.96

Table B.1 (continued)

S.No.	Description	08	09	10	11	12	13	14
51	Material drained from cyclone, kg/h	73.79	74.64	58.06	83.81	84.10	87.6	84.50
52	Material drained from multiclone, kg/h	48.05	35.87	41.24	48.78	49.04	55.59	65.64
53	Bed retention, %	7.2	8.2	13.2	8.2	7.3	8.25	8.0

Table B.1 (continued)

S.No.	Description	15	16	17	18	19	20	21
01	Fuel[a]	1	1	1	1	1	1	1
02	Fuel feeding[b]	1	1	1	1	1	1	1
03	Ash reinjection, kg/h	720	360	360	660	0	0	0
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	898	913	909	899	889	902	914
07	Bed temp -2, °C	904	919	914	900	883	897	910
08	Bed temp -3, °C	910	924	919	898	890	907	918
09	Bed temp -4, °C	903	915	910	902	876	887	899
10	Bed temp -5, °C	922	946	932	905	902	921	932
11	Freeboard temp -1, °C	935	936	951	920	913	927	937
12	Freeboard temp -2, °C	923	955	951	925	922	936	947
13	Freeboard temp -3, °C	915	957	952	930	910	929	935
14	Freeboard temp -4, °C	806	843	835	840	798	822	824
15	Comb exit temp, °C	503	502	508	499	477	488	491
16	Coal feed rate, kg/h	375.2	378.2	331.1	371.1	328.1	402.1	374.1
17	Total air flow, m^3/h	2220	2433	1941	2309	2160	2845	2521
18	Fluegas analysis, O_2, %	1.8	2.9	1.1	2.2	3.6	5.4	4.5
19	Fluegas analysis, CO_2, %	17.6	16.5	18.2	17.2	15.9	14.2	15.0
20	Fluegas analysis, CO, ppm	103	87	213	80	-	-	-
21	Fluegas analysis, NOx, ppm	299	272	212	189	318	417	386
22	Fluegas analysis, SOx, ppm	127	581	354	201	426	503	461
23	Fluegas analysis, HC, ppm	6.89	4.77	7.20	4.84	11.62	0.04	4.75
24	Heat extracted from bed coils, Mkcal/h	0.57	0.58	0.58	0.57	0.57	0.59	0.58
25	Heat extracted in convection coils, Mkcal/h	0.56	0.53	0.41	0.52	0.39	0.51	0.55

[a]1. High ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.1 (continued)

S.No.	Description	15	16	17	18	19	20	21
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.81	4.79	4.92	5.09	4.13	4.09	4.11
27	Heat extracted in test loop 2, 10^3 x kcal/h	3.80	4.14	3.95	3.76	3.87	3.85	3.89
28	Coal analysis: C, %	42.2	43.49	43.49	43.49	43.49	42.28	42.28
29	Coal analysis: H, %	2.40	2.48	2.48	2.48	2.48	2.41	2.41
30	Coal analysis: N, %	1.05	1.08	1.08	1.08	1.08	1.05	1.05
31	Coal analysis: S, %	0.57	0.59	0.59	0.59	0.59	0.57	0.57
32	Coal analysis: O_2, %	9.38	9.67	9.67	9.67	9.67	9.40	9.40
33	Coal analysis: Ash, %	37.50	35.50	35.50	35.50	35.50	37.50	37.50
34	Coal analysis: Moist, %	6.90	7.20	7.20	7.20	7.20	6.80	6.80
35	Coal analysis: HHV, kcal/kg	4050	4150	4150	4150	4150	4060	4060
36	Bed particle size, microns	999	628	896	771	670	728	867
37	Air temp, °C	33.3	33.3	33.3	35.3	33.6	34.8	34.0
38	Combustibles in bed material, %	1.00	1.20	1.00	0.91	0.85	1.60	1.20
39	Combustibles in cyclone catch, %	2.70	2.40	3.60	3.02	6.50	6.60	6.00
40	Combustibles in multi-clone catch, %	1.69	4.20	2.36	2.30	2.48	3.26	2.39
41	Avg. bed temp, °C	904	918	914	899	887	902	914
42	Max. freeboard temp, °C	935	957	952	930	913	936	947
43	Fluidization Vel, m/s	2.27	2.50	2.01	2.34	2.16	2.85	2.56
44	Excess air, %	10	17	6	13	22	36	29
45	Freeboard combustion, %	9.4	8.8	7.8	9.6	7.2	8.4	7.7
46	Combustion efficiency, %	98.54	97.78	98.22	98.29	96.56	95.91	96.16
47	Carbon burn up, %	98.26	97.38	97.90	97.98	95.43	95.13	95.43
48	Dust concentration, g/Nm^3	444	233	273	394	56	58	67
49	Fluegas flow rate, kg/h	2452	2672	2151	2545	2366	3088	2748
50	Material drained from bed, kg/h	21.11	12.62	23.51	17.13	13.63	11.49	11.45

Table B.1 (continued)

S.No.	Description	15	16	17	18	19	20	21
51	Material drained from cyclone, kg/h	45.73	60.15	40.76	54.67	71.28	93.50	91.96
52	Material drained from multiclone, kg/h	72.87	61.49	53.77	59.94	31.56	44.79	50.91
53	Bed retention, %	15.00	9.40	20.00	13.00	7.20	7.67	8.16

Table B.1 (continued)

S.No.	Description	22	23	24	25	26
01	Fuel[a]	1	1	1	1	1
02	Fuel feeding[b]	1	1	1	1	1
03	Ash reinjection, kg/h	0	0	0	0	0
04	Fuel top size, mm	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600
06	Bed temp -1, °C	906	891	879	858	908
07	Bed temp -2, °C	901	886	873	847	901
08	Bed temp -3, °C	916	878	881	878	920
09	Bed temp -4, °C	888	906	886	862	906
10	Bed temp -5, °C	929	893	874	862	900
11	Freeboard temp -1, °C	943	900	880	870	825
12	Freeboard temp -2, °C	978	925	900	875	948
13	Freeboard temp -3, °C	961	935	910	888	940
14	Freeboard temp -4, °C	847	845	800	780	850
15	Comb exit temp, °C	504	525	511	526	544
16	Coal feed rate, kg/h	319.8	396.0	330.0	415.0	476.0
17	Total air flow, m^3/h	1864	2443	1916	2463	2940
18	Fluegas analysis, O_2, %	1.7	4.8	3.6	5.3	5.4
19	Fluegas analysis, CO_2, %	17.6	14.8	15.9	14.3	14.3
20	Fluegas analysis, CO, ppm	200	-	-	-	-
21	Fluegas analysis, NOx, ppm	263	390	300	360	380
22	Fluegas analysis, SOx, ppm	451	500	280	390	460
23	Fluegas analysis, HC, ppm	6.18	3.00	2.10	0.80	6.40
24	Heat extracted from bed coils, Mkcal/h	0.60	0.59	0.56	0.56	0.57
25	Heat extracted in convection coils, Mkcal/h	0.32	0.48	0.36	0.44	0.58

[a] 1. High ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b] 1. Underbed, 2. Overbed.

Table B.1 (continued)

S.No.	Description	22	23	24	25	26
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.44	-	-	-	-
27	Heat extracted in test loop 2, 10^3 x kcal/h	4.12	-	-	-	-
28	Coal analysis: C, %	42.28	42.38	42.28	40.69	41.67
29	Coal analysis: H, %	2.41	2.51	2.41	2.32	2.38
30	Coal analysis: N, %	1.05	1.05	1.05	1.01	1.03
31	Coal analysis: S, %	0.57	0.57	0.57	0.55	0.56
32	Coal analysis: O_2, %	9.40	9.40	9.40	9.04	9.26
33	Coal analysis: Ash, %	37.50	37.70	38.00	38.40	38.60
34	Coal analysis: Moist, %	6.8	6.4	6.3	8.0	6.5
35	Coal analysis: HHV, kcal/kg	4060	3970	3992	3704	3774
36	Bed particle size, microns	702	769	803	873	849
37	Air temp, °C	33.00	44.45	38.92	40.26	45.04
38	Combustibles in bed material, %	0.80	0.70	0.40	0.70	0.60
39	Combustibles in cyclone catch, %	4.60	5.40	4.40	5.80	5.80
40	Combustibles in multi-clone catch, %	3.24	3.10	4.00	3.60	4.20
41	Avg. bed temp, °C	907	891	879	858	909
42	Max. freeboard temp, °C	978	935	910	888	948
43	Fluidization Vel, m/s	1.91	2.73	2.13	2.68	3.33
44	Excess air, %	10	31	23	33	35
45	Freeboard combustion, %	6.6	8.3	6.8	8.4	9.5
46	Combustion efficiency, %	97.39	96.53	97.22	95.78	95.68
47	Carbon burn up, %	96.89	95.97	96.76	95.24	95.15
48	Dust concentration, g/Nm^3	63	60	55	64	62
49	Fluegas flow rate, kg/h	2060	2690	2122	2720	3235
50	Material drained from bed, kg/h	19.43	11.90	26.9	11.2	12.9

Table B.1 (continued)

S.No.	Description	22	23	24	25	26
51	Material drained from cyclone, kg/h	47.97	52.60	67.50	102	118
52	Material drained from multiclone, kg/h	52.53	24.80	33.00	46.20	53.30
53	Bed retention, %	16.2	8.0	19.9	7.0	7.0

Table B.2. Heat and material balance for test series 1 through 26

S.No.	Description	01	02	03	04	05	06	07
01	Heat input, Mkcal/h	1.66	1.50	1.51	1.52	1.46	1.50	1.45
02	Heat in dry fluegas, Mkcal/h	0.28	0.24	0.28	0.26	0.25	0.29	0.27
03	Heat in moisture (air) Mkcal/h	0.01	0.01	0.01	0.01	0.01	0.01	0.01
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.08	0.08	0.08	0.08	0.08	0.08	0.08
05	Heat in unburnt carbon, Mkcal/h	0.05	0.03	0.02	0.04	0.03	0.03	0.06
06	Heat in ash, Mkcal/h	0.02	0.02	0.02	0.02	0.01	0.01	0.01
07	Heat absorbed in water, Mkcal/h	1.17	1.11	1.11	1.16	1.08	1.07	1.02
08	Air, kg/h	2679	2201	2274	2882	2250	2521	2400
09	Fuel, kg/h	408.5	370.0	363.5	365.5	352.0	358.8	330.0
10	Fluegas, kg/h	2928	2428	2506	2613	2423	2750	2620
11	Bed ash, kg/h	13.96	24.17	21.63	14.00	23.06	10.87	9.15
12	Cyclone ash, kg/h	84.74	58.19	45.99	76.14	55.38	50.19	52.35
13	Multiclone ash, kg/h	54.49	56.39	60.69	39.61	46.52	65.23	43.14

Table B.2 (continued)

S.No.	Description	08	09	10	11	12	13	14
01	Heat input, Mkcal/h	1.55	1.42	1.35	1.56	1.71	1.68	1.76
02	Heat in dry fluegas, Mkcal/h	0.29	0.27	0.24	0.30	0.32	0.33	0.36
03	Heat in moisture (air) Mkcal/h	0.01	0.01	0.01	0.01	0.02	0.02	0.02
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.08	0.08	0.07	0.09	0.09	0.09	0.10
05	Heat in unburnt carbon, Mkcal/h	0.06	0.05	0.04	0.06	0.07	0.04	0.04
06	Heat in ash, Mkcal/h	0.01	0.01	0.01	0.02	0.02	0.02	0.02
07	Heat absorbed in water, Mkcal/h	1.08	1.00	0.97	1.08	1.18	1.16	1.24
08	Air, kg/h	2549	2374	2156	2679	3038	2808	2908
09	Fuel, kg/h	373.0	342.0	325.0	384.0	412.2	416.2	435.2
10	Fluegas, kg/h	2783	2590	2362	2911	3295	3063	3177
11	Bed ash, kg/h	9.45	9.87	15.1	11.81	12.37	12.88	13.06
12	Cyclone ash, kg/h	73.79	74.64	58.06	83.81	84.1	87.6	84.5
13	Multiclone ash, kg/h	48.05	35.87	41.24	48.38	49.04	55.59	65.64

Table B.2 (continued)

S.No.	Description	15	16	17	18	19	20	21
01	Heat input, Mkcal/h	1.52	1.57	1.37	1.54	1.36	1.63	1.52
02	Heat in dry fluegas, Mkcal/h	0.27	0.29	0.24	0.27	0.24	0.33	0.29
03	Heat in moisture (air) Mkcal/h	0.01	0.01	0.01	0.01	0.01	0.02	0.01
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.09	0.09	0.08	0.09	0.08	0.09	0.08
05	Heat in unburnt carbon, Mkcal/h	0.02	0.04	0.03	0.03	0.05	0.06	0.06
06	Heat in ash, Mkcal/h	0.02	0.02	0.01	0.01	0.01	0.02	0.02
07	Heat absorbed in water, Mkcal/h	1.13	1.12	1.00	1.12	0.97	1.11	1.04
08	Air, kg/h	2220	2433	1941	2309	2160	2845	2521
09	Fuel, kg/h	375.2	378.2	331.1	371.1	328.1	402.1	374.1
10	Fluegas, kg/h	2452	2672	2151	2545	2365	3088	2748
11	Bed ash, kg/h	21.11	12.62	23.51	17.13	13.63	11.49	11.45
12	Cyclone ash, kg/h	45.73	60.15	40.26	54.67	71.28	93.50	91.96
13	Multiclone ash, kg/h	73.87	61.49	53.77	59.94	31.56	44.79	50.91

Table B.2 (continued)

S.No.	Description	22	23	24	25	26
01	Heat input, Mkcal/h	1.30	1.57	1.32	1.54	1.80
02	Heat in dry fluegas, Mkcal/h	0.22	0.33	0.27	0.35	0.44
03	Heat in moisture (air) Mkcal/h	0.01	0.01	0.01	0.01	0.01
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.07	0.09	0.07	0.10	0.10
05	Heat in unburnt carbon, Mkcal/h	0.03	0.05	0.04	0.06	0.08
06	Heat in ash, Mkcal/h	0.01	0.02	0.01	0.02	0.02
07	Heat absorbed in water, Mkcal/h	0.93	1.07	0.92	1.00	1.15
08	Air, kg/h	1864	2443	1916	2463	2940
09	Fuel, kg/h	319.8	396.0	330.0	415.0	476.0
10	Fluegas, kg/h	2060	2690	2122	2720	3235
11	Bed ash, kg/h	19.63	11.90	24.90	11.20	12.90
12	Cyclone ash, kg/h	47.97	92.60	67.50	102.0	118.0
13	Multiclone ash, kg/h	52.53	44.80	33.00	46.20	53.30

Table B.3. Size distribution of bed particles
for test series 1 through 26

S.No.	Sieve size (mm)	01	02	03	04	05	06	07
01	-6.000 + 4.000	0.0	0.0	1.1	2.5	2.9	1.8	1.8
02	-4.000 + 2.800	0.8	0.3	6.3	4.2	4.2	4.1	4.1
03	-2.800 + 2.000	1.8	1.9	6.0	2.5	2.5	4.2	4.2
04	-2.000 + 1.400	9.2	9.1	17.0	10.5	10.5	12.9	12.9
05	-1.400 + 1.000	12.7	12.4	16.6	13.8	13.8	11.0	11.0
06	-1.000 + 0.700	36.3	27.9	28.3	22.5	22.5	23.8	23.8
07	-0.700 + 0.500	30.6	37.5	18.7	30.2	30.2	25.7	25.7
08	-0.500 + 0.250	8.0	8.2	4.0	12.2	12.2	15.2	15.2
09	-0.250 + 0.180	0.1	0.6	0.1	0.3	0.3	0.2	0.2
10	-0.180 + 0.125	0.1	0.8	0.1	0.4	0.4	0.2	0.2
11	-0.125 + 0.063	0.1	1.2	0.5	0.2	0.2	0.5	0.5
12	-0.063 + 0.000	0.3	0.1	1.3	0.7	0.7	0.4	0.4
13	Avg. particle size (microns)	693	621	656	636	636	669	669

Table B.3 (continued)

S.No.	Sieve size (mm)	08	09	10	11	12	13	14
01	-6.000 + 4.000	1.3	1.3	1.3	0.0	0.0	0.7	0.7
02	-4.000 + 2.800	4.3	2.3	2.3	0.8	0.8	2.5	2.5
03	-2.800 + 2.000	3.3	3.3	3.3	1.8	1.8	4.0	4.0
04	-2.000 + 1.400	7.4	7.4	7.4	9.2	9.2	10.5	10.5
05	-1.400 + 1.000	10.5	13.5	13.5	12.4	13.4	20.3	20.3
06	-1.000 + 0.700	29.5	26.9	26.9	36.3	36.3	32.7	32.7
07	-0.700 + 0.500	26.0	26.0	26.0	30.6	30.6	22.6	22.6
08	-0.500 + 0.250	15.8	15.8	15.8	8.0	7.5	4.3	4.3
09	-0.250 + 0.180	0.9	2.9	2.9	0.2	0.1	1.1	1.1
10	-0.180 + 0.125	0.4	0.4	0.4	0.2	0.1	0.4	0.4
11	-0.125 + 0.063	0.1	0.1	0.1	0.2	0.1	0.5	0.5
12	-0.063 + 0.000	0.1	0.1	0.1	0.3	0.1	0.4	0.4
13	Avg. particle size (microns)	681	647	647	684	731	709	709

Table B.3 (continued)

S.No.	Sieve size (mm)	15	16	17	18	19	20	21
01	-6.000 + 4.000	2.5	0.1	1.5	4.6	4.7	2.9	1.0
02	-4.000 + 2.800	2.8	1.6	3.7	4.5	4.5	2.3	3.1
03	-2.800 + 2.000	8.3	4.1	4.0	4.0	0.5	2.5	3.8
04	-2.000 + 1.400	17.5	12.5	12.3	14.5	11.3	14.6	17.5
05	-1.400 + 1.000	20.3	14.3	27.4	15.7	14.4	16.8	19.8
06	-1.000 + 0.700	35.4	30.2	35.8	22.7	21.0	22.9	33.4
07	-0.700 + 0.500	11.6	22.6	11.8	20.7	23.0	27.5	18.7
08	-0.500 + 0.250	1.5	12.4	6.6	12.6	19.9	7.8	1.7
09	-0.250 + 0.180	0.1	0.8	0.5	0.6	0.6	0.4	0.4
10	-0.180 + 0.125	0.1	0.5	0.2	0.1	0.1	0.1	0.3
11	-0.125 + 0.063	0.1	0.4	0.1	0.1	0.1	0.1	0.2
12	-0.063 + 0.000	0.0	0.5	0.1	0.1	0.1	0.1	0.1
13	Avg. particle size (microns)	990	628	896	771	670	728	867

Table B.3 (continued)

S.No.	Sieve size (mm)	22	23	24	25	26
01	-6.000 + 4.000	1.5	0.6	0.4	2.0	1.05
02	-4.000 + 2.800	10.7	2.9	5.0	6.1	8.1
03	-2.800 + 2.000	7.2	3.2	5.0	6.3	2.3
04	-2.000 + 1.400	5.8	16.9	18.2	17.2	18.1
05	-1.400 + 1.000	12.2	15.2	15.2	16.2	18.5
06	-1.000 + 0.700	17.0	26.1	22.5	24.6	21.2
07	-0.700 + 0.500	22.2	26.4	21.2	20.2	21.0
08	-0.500 + 0.250	22.6	10.3	12.1	7.0	8.7
09	-0.250 + 0.180	0.4	0.1	0.1	0.1	0.1
10	-0.180 + 0.125	0.2	0.1	0.1	0.1	0.15
11	-0.125 + 0.063	0.1	0.1	0.1	0.1	0.1
12	-0.063 + 0.000	0.1	0.1	0.1	0.1	0.1
13	Avg. particle size (microns)	702	769	803	873	849

Table B.4. Test data on high-ash coal washery reject-1 with underbed feeding, without flyash recycle, test series 27 through 36

S.No.	Description	27	28	29	30	31	32	33
01	Fuel[a]	2	2	2	2	2	2	2
02	Fuel feeding[b]	1	1	1	1	1	1	1
03	Ash reinjection, kg/h	0	0	0	0	0	0	0
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	896	903	871	891	876	910	883
07	Bed temp -2, °C	901	905	873	889	878	904	880
08	Bed temp -3, °C	905	902	873	895	878	908	875
09	Bed temp -4, °C	909	905	872	891	880	909	878
10	Bed temp -5, °C	900	902	870	889	885	905	875
11	Freeboard temp -1, °C	906	910	880	895	890	910	885
12	Freeboard temp -2, °C	910	915	890	905	900	915	910
13	Freeboard temp -3, °C	920	922	895	915	910	925	905
14	Freeboard temp -4, °C	830	830	790	810	825	835	815
15	Comb exit temp, °C	512	491	471	481	475	518	502
16	Coal feed rate, kg/h	1011.0	890.0	765	798	680	915	894
17	Total air flow, m^3/h	3145	2589	2123	2572	2050	3010	2752
18	Fluegas analysis, O_2, %	3.0	1.6	1.0	2.9	1.4	3.9	2.7
19	Fluegas analysis, CO_2, %	16.1	17.4	18.0	16.2	17.6	15.3	16.4
20	Fluegas analysis, CO, ppm	-	-	-	-	-	-	-
21	Fluegas analysis, NOx, ppm	-	-	-	-	-	-	-
22	Fluegas analysis, SOx, ppm	-	-	-	-	-	-	-
23	Fluegas analysis, HC, ppm	-	-	-	-	-	-	-
24	Heat extracted from bed coils, Mkcal/h	0.59	0.59	0.56	0.57	0.56	0.59	0.57
25	Heat extracted in convection coils, Mkcal/h	0.55	0.47	0.37	0.46	0.36	0.54	0.47

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.4 (continued)

S.No.	Description	27	28	29	30	31	32	33
26	Heat extracted in test loop 1, $10^3 \times$ kcal/h	-	-	-	-	-	-	-
27	Heat extracted in test loop 2, $10^3 \times$ kcal/h	-	-	-	-	-	-	-
28	Coal analysis: C, %	23.36	23.36	22.87	24.19	24.19	23.57	23.36
29	Coal analysis: H, %	1.73	1.73	1.69	1.79	1.79	1.75	1.73
30	Coal analysis: N, %	0.58	0.58	0.57	0.60	0.60	0.59	0.58
31	Coal analysis: S, %	0.30	0.30	0.29	0.31	0.31	0.30	0.30
32	Coal analysis: O_2, %	7.73	7.73	7.57	8.01	8.01	7.80	7.73
33	Coal analysis: Ash, %	65.40	65.40	65.90	64.30	64.30	65.20	65.40
34	Coal analysis: Moist, %	0.90	0.90	1.10	0.80	0.80	0.80	0.90
35	Coal analysis: HHV, kcal/kg	2050	2050	2016	2188	2188	2180	2050
36	Bed particle size, microns	729	740	764	745	778	745	740
37	Air temp, °C	45.00	36.70	43.4	41.5	36.2	39.4	40.0
38	Combustibles in bed material, %	0.60	0.90	0.9	1.3	0.6	0.85	0.60
39	Combustibles in cyclone catch, %	6.50	5.00	6.0	5.8	6.7	6.5	6.0
40	Combustibles in multi-clone catch, %	7.20	9.10	7.1	8.7	5.6	7.5	7.5
41	Avg. bed temp, °C	903	903	872	892	878	908	879
42	Max. freeboard temp, °C	920	922	895	915	910	925	910
43	Fluidization Vel, m/s	3.20	2.65	2.12	2.59	2.05	3.06	2.74
44	Excess air, %	18.0	9.0	6.0	17.0	8.0	24.0	16.0
45	Freeboard combustion, %	5.5	4.3	3.6	4.4	3.4	5.1	5.0
46	Combustion efficiency, %	86.48	87.38	88.06	87.43	88.73	86.80	87.11
47	Carbon burn up, %	85.29	86.27	86.95	85.90	87.36	84.86	85.98
48	Dust concentration, g/Nm^3	177	185	177	164	172	170	177
49	Fluegas flow rate, kg/h	3460	2868	2361	2830	2272	3296	3032
50	Material drained from bed, kg/h	188	173	181	153	136	164	170

Table B.4 (continued)

S.No.	Description	27	28	29	30	31	32	33
51	Material drained from cyclone, kg/h	314	282	248	257	195	288	288
52	Material drained from multiclone, kg/h	160	127	75	106	107	145	133
53	Bed retention, %	28.4	29.7	35.9	29.9	31.0	27.5	29.1

Table B.4 (continued)

S.No.	Description	34	35	36
01	Fuel[a]	2	2	2
02	Fuel feeding[b]	1	1	1
03	Ash reinjection, kg/h	0	0	0
04	Fuel top size, mm	6	6	6
05	Expanded bed height, mm	600	600	600
06	Bed temp -1, °C	884	898	858
07	Bed temp -2, °C	880	895	862
08	Bed temp -3, °C	883	900	856
09	Bed temp -4, °C	889	899	856
10	Bed temp -5, °C	887	898	856
11	Freeboard temp -1, °C	900	900	860
12	Freeboard temp -2, °C	922	905	860
13	Freeboard temp -3, °C	920	918	876
14	Freeboard temp -4, °C	830	825	785
15	Comb exit temp, °C	512	491	437
16	Coal feed rate, kg/h	985	890	750
17	Total air flow, m^3/h	2910	2330	1913
18	Fluegas analysis, O_2, %	4.0	1.7	1.4
19	Fluegas analysis, CO_2, %	15.1	17.2	18.0
20	Fluegas analysis, CO, ppm	-	-	-
21	Fluegas analysis, NOx, ppm	-	-	-
22	Fluegas analysis, SOx, ppm	-	-	-
23	Fluegas analysis, HC, ppm	-	-	-
24	Heat extracted from bed coils, Mkcal/h	0.55	0.58	0.55
25	Heat extracted in convection coils, Mkcal/h	0.56	0.49	0.39

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.4 (continued)

S.No.	Description	34	35	36
26	Heat extracted in test loop 1, 10^3 x kcal/h	-	-	-
27	Heat extracted in test loop 2, 10^3 x kcal/h	-	-	-
28	Coal analysis: C, %	23.36	23.36	22.87
29	Coal analysis: H, %	1.73	1.73	1.69
30	Coal analysis: N, %	0.58	0.58	0.57
31	Coal analysis: S, %	0.30	0.30	0.29
32	Coal analysis: O_2, %	7.73	7.73	7.57
33	Coal analysis: Ash, %	65.40	65.40	65.9
34	Coal analysis: Moist, %	0.90	0.90	1.1
35	Coal analysis: HHV, kcal/kg	2050	2050	2016
36	Bed particle size, microns	820	832	847
37	Air temp, °C	44.95	36.72	43.41
38	Combustibles in bed material, %	0.90	0.90	0.9
39	Combustibles in cyclone catch, %	6.4	5.0	6.0
40	Combustibles in multi-clone catch, %	7.2	9.1	7.1
41	Avg. bed temp, °C	884	898	858
42	Max. freeboard temp, °C	922	918	876
43	Fluidization Vel, m/s	3.25	2.67	2.21
44	Excess air, %	26.0	10.0	9.0
45	Freeboard combustion, %	5.3	4.9	3.5
46	Combustion efficiency, %	86.36	87.40	87.98
47	Carbon burn up, %	85.17	86.29	86.87
48	Dust concentration, g/Nm^3	167	183	172
49	Fluegas flow rate, kg/h	3251	2638	2174
50	Material drained from bed, kg/h	183	174	177

Table B.4 (continued)

S.No.	Description	34	35	36
51	Material drained from cyclone, kg/h	306	282	232
52	Material drained from multiclone, kg/h	155	127	85
53	Bed retention, %	28.4	29.8	35.9

Table B.5. Heat and material balance for test series 27 through 36

S.No.	Description	27	28	29	30	31	32	33
01	Heat input, Mkcal/h	2.07	1.82	1.54	1.75	1.49	1.99	1.83
02	Heat in dry fluegas, Mkcal/h	0.37	0.30	0.23	0.29	0.23	0.37	0.32
03	Heat in moisture (air) Mkcal/h	0.02	0.01	0.01	0.01	0.01	0.02	0.02
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.13	0.11	0.10	0.11	0.09	0.12	0.12
05	Heat in unburnt carbon, Mkcal/h	0.28	0.23	0.18	0.22	0.17	0.26	0.24
06	Heat in ash, Mkcal/h	0.10	0.09	0.07	0.08	0.06	0.09	0.09
07	Heat absorbed in water, Mkcal/h	1.16	1.07	0.94	1.03	0.92	0.13	1.05
08	Air, kg/h	3145	2589	2123	2572	2050	3010	2752
09	Fuel, kg/h	1011.0	890.0	765	798	680	915	894
10	Fluegas, kg/h	3460	2868	2361	2830	2272	3296	3032
11	Bed ash, kg/h	188.0	173.0	181	153	136	164	170
12	Cyclone ash, kg/h	314.0	282.0	248	257	195	288	282
13	Multiclone ash, kg/h	160.0	127.0	75	103	107	145	133

Table B.5 (continued)

S.No.	Description	34	35	36
01	Heat input, Mkcal/h	2.02	1.82	1.51
02	Heat in dry fluegas, Mkcal/h	0.40	0.29	0.21
03	Heat in moisture (air) Mkcal/h	0.02	0.02	0.01
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.12	0.12	0.1
05	Heat in unburnt carbon, Mkcal/h	0.28	0.23	0.18
06	Heat in ash, Mkcal/h	0.09	0.09	0.07
07	Heat absorbed in water, Mkcal/h	1.11	1.07	0.94
08	Air, kg/h	2910	2330	1914
09	Fuel, kg/h	985	890	750
10	Fluegas, kg/h	3251	2638	2174
11	Bed ash, kg/h	183	174	177
12	Cyclone ash, kg/h	306	282	232
13	Multiclone ash, kg/h	155	127	85

Table B.6. Size distribution of bed particles for test series 27 through 36

S.No.	Sieve size (mm)	27	28	29	30	31	32	33
01	-6.000 + 4.000	1.4	1.8	1.0	1.05	0.8	0.6	0.5
02	-4.000 + 2.800	5.8	5.9	6.0	7.0	2.2	8.1	5.0
03	-2.800 + 2.000	5.5	8.2	6.7	4.7	5.5	3.5	5.15
04	-2.000 + 1.400	15.8	20.1	20.5	13.5	21.5	25.0	24.1
05	-1.400 + 1.000	15.0	12.0	16.3	15.3	14.8	14.0	19.0
06	-1.000 + 0.700	22.5	19.0	22.5	23.2	23.25	20.0	20.0
07	-0.700 + 0.500	23.0	22.8	20.7	19.5	20.6	17.5	16.3
08	-0.500 + 0.250	10.4	7.5	5.9	15.25	10.8	9.1	5.0
09	-0.250 + 0.180	0.1	1.1	0.0	0.2	0.3	1.1	2.1
10	-0.180 + 0.125	0.1	1.2	0.2	0.15	0.1	0.3	2.5
11	-0.125 + 0.063	0.2	0.25	0.15	0.15	0.2	0.6	0.15
12	-0.063 + 0.000	0.2	0.15	0.05	0.0	0.05	0.2	0.2
13	Avg. particle size (microns)	729	740	764	745	778	745	740

Table B.6 (continued)

S.No.	Sieve size (mm)	34	35	36
01	-6.000 + 4.000	1.4	1.8	0.8
02	-4.000 + 2.800	8.8	10.9	7.2
03	-2.800 + 2.000	7.5	8.2	5.5
04	-2.000 + 1.400	15.8	20.1	21.4
05	-1.400 + 1.000	15.0	12.0	14.8
06	-1.000 + 0.700	22.5	19.0	23.25
07	-0.700 + 0.500	23.0	19.8	20.6
08	-0.500 + 0.250	5.4	7.5	5.8
09	-0.250 + 0.180	0.1	0.1	0.3
10	-0.180 + 0.125	0.1	0.2	0.1
11	-0.125 + 0.063	0.2	0.25	0.2
12	-0.063 + 0.000	0.2	0.15	0.05
13	Avg. particle size (microns)	820	832	847

Table B.7. Test data on coal washery rejects and mill rejects for test series 37 through 43

S.No.	Description	37	38	39	40	41	42	43
01	Fuel[a]	4	4	4	3	3	2	2
02	Fuel feeding[b]	1	1	1	1	1	2	2
03	Ash reinjection, kg/h	720	0	720	0	0	0	0
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	918	909	907	846	837	894	896
07	Bed temp -2, °C	919	909	908	862	848	891	921
08	Bed temp -3, °C	917	911	908	867	844	889	913
09	Bed temp -4, °C	910	910	907	864	843	894	918
10	Bed temp -5, °C	930	926	907	881	860	897	913
11	Freeboard temp -1, °C	945	932	932	898	868	897	924
12	Freeboard temp -2, °C	950	946	957	880	845	856	899
13	Freeboard temp -3, °C	954	938	984	850	824	713	819
14	Freeboard temp -4, °C	854	833	891	774	756	721	760
15	Comb exit temp, °C	530	530	510	473	454	450	487
16	Coal feed rate, kg/h	740	640	560	756	695	865	950
17	Total air flow, m^3/h	2801	2876	2272	2759	2252	2692	3002
18	Fluegas analysis, O_2, %	3.0	4.8	3.4	5.0	3.9	4.1	4.3
19	Fluegas analysis, CO_2, %	16.8	15.1	16.4	14.4	15.5	15.0	14.8
20	Fluegas analysis, CO, ppm	350	136	400	140	181	101	112
21	Fluegas analysis, NOx, ppm	300	204	82	352	219	495	521
22	Fluegas analysis, SOx, ppm	800	695	1068	186	176	318	379
23	Fluegas analysis, HC, ppm	5	0.23	12.9	-	1.12	1.24	1.70
24	Heat extracted from bed coils, Mkcal/h	0.62	0.59	0.60	0.51	0.53	0.53	0.53
25	Heat extracted in convection coils, Mkcal/h	0.60	0.47	0.53	0.45	0.36	0.57	0.62

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.7 (continued)

S.No.	Description	37	38	39	40	41	42	43
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.93	4.75	5.01	4.89	4.68	5.23	4.58
27	Heat extracted in test loop 2, 10^3 x kcal/h	4.49	4.26	4.59	4.09	4.03	2.59	2.73
28	Coal analysis: C, %	27.26	29.61	29.68	24.29	23.53	23.36	23.36
29	Coal analysis: H, %	1.55	1.68	1.68	1.38	1.34	1.73	1.73
30	Coal analysis: N, %	0.67	0.73	0.73	0.6	0.58	0.58	0.58
31	Coal analysis: S, %	0.37	0.40	0.40	0.33	0.32	0.30	0.30
32	Coal analysis: O_2, %	8.45	9.18	9.20	5.40	5.23	7.73	7.73
33	Coal analysis: Ash, %	58.7	54.9	55.7	66.1	67.1	65.4	65.40
34	Coal analysis: Moist, %	3.0	3.5	2.6	1.9	1.9	1.9	0.9
35	Coal analysis: HHV, kcal/kg	2548	2698	2995	2188	2150	2050	2050
36	Bed particle size, microns	729	792	725	1078	892	1308	986
37	Air temp, °C	38.4	36.4	40.22	38.63	36.2	36.20	36.2
38	Combustibles in bed material, %	0.50	0.55	1.1	1.2	1.0	1.0	1.0
39	Combustibles in cyclone catch, %	3.85	5.75	7.0	5.3	7.0	4.56	4.06
40	Combustibles in multi-clone catch, %	4.1	4.55	6.0	6.2	8.6	4.59	3.88
41	Avg. bed temp, °C	916	910	908	860	843	892	918
42	Max. freeboard temp, °C	954	946	984	898	868	897	921
43	Fluidization Vel, m/s	2.89	2.93	2.32	2.66	2.15	3.02	3.43
44	Excess air, %	18.0	31.0	20.0	33.0	24.0	26.0	27.0
45	Freeboard combustion, %	7.1	5.5	6.5	5.0	4.0	4.8	5.8
46	Combustion efficiency, %	94.51	92.92	92.25	87.85	86.77	91.17	91.73
47	Carbon burn up, %	93.14	92.00	90.30	86.46	85.01	90.29	91.00
48	Dust concentration, g/Nm^3	428	101	480	180	146	144	153
49	Fluegas flow rate, kg/h	3094	3150	2504	2991	2456	2991	3331
50	Material drained from bed, kg/h	133	105	103	89	190	198	186

Table B.7 (continued)

S.No.	Description	37	38	39	40	41	42	43
51	Material drained from cyclone, kg/h	229	230	166	318	267	283	342
52	Material drained from multiclone, kg/h	73	16	43	92	98	85	93
53	Bed retention, %	30.5	30.0	33.0	17.8	40.7	35.0	30

Table B.8. Heat and material balance for test series 37 through 43

S.No.	Description	37	38	39	40	41	42	43
01	Heat input, Mkcal/h	1.89	1.73	1.68	1.65	1.49	1.77	1.95
02	Heat in dry fluegas, Mkcal/h	0.36	0.36	0.27	0.30	0.24	0.28	0.41
03	Heat in moisture (air) Mkcal/h	0.02	0.02	0.01	0.01	0.01	0.02	0.02
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.1	0.1	0.08	0.09	0.08	0.12	0.12
05	Heat in unburnt carbon, Mkcal/h	0.10	0.12	0.13	0.20	0.20	0.16	0.16
06	Heat in ash, Mkcal/h	0.07	0.06	0.05	0.06	0.07	0.09	0.09
07	Heat absorbed in water, Mkcal/h	1.23	1.07	1.13	0.98	0.90	0.10	1.15
08	Air, kg/h	2801	2876	2272	2759	2252	2692	3002
09	Fuel, kg/h	740	640	560	756	695	865	950
10	Fluegas, kg/h	3094	3150	2504	2991	2456	2991	3331
11	Bed ash, kg/h	133	105	103	89	190	198	186
12	Cyclone ash, kg/h	229	230	166	318	267	283	342
13	Multiclone ash, kg/h	73	16	43	92	98	85	93

Table B.9. Size distribution of bed particles, test series 37 through 43

S.No.	Sieve size (mm)	37	38	39	40	41	42	43
01	-6.000 + 4.000	1.4	0.8	0.7	5.0	6.3	7.6	3.0
02	-4.000 + 2.800	8.8	4.2	4.7	13.9	9.8	31.2	20.4
03	-2.800 + 2.000	7.5	5.4	6.4	11.2	7.7	17.2	17.6
04	-2.000 + 1.400	15.8	13.7	16.3	21.5	18.3	18.6	24.5
05	-1.400 + 1.000	15.0	13.9	13.9	13.0	12.1	8.2	11.3
06	-1.000 + 0.700	-	29.10	23.40	18.90	22.40	8.80	13.6
07	-0.700 + 0.500	23.0	27.9	24.9	12.7	13.0	4.6	4.9
08	-0.500 + 0.250	5.4	3.9	8.6	3.3	10.1	2.1	2.3
09	-0.250 + 0.180	0.1	0.1	0.1	0.1	0.1	0.4	0.7
10	-0.180 + 0.125	0.1	0.1	0.1	0.1	0.2	0.5	0.7
11	-0.125 + 0.063	0.2	0.3	0.4	0.2	0.1	0.7	0.4
12	-0.063 + 0.000	0.2	0.2	0.5	0.1	0.2	0.1	0.6
13	Avg. particle size (microns)	729	792	725	1078	892	1308	986

Table B.10. Test data on high-ash coal with overbed feeding with and without flyash recycle, test series 44 through 61

S.No.	Description	44	45	46	47	48	49	50
01	Fuel[a]	1	1	1	1	1	1	1
02	Fuel feeding[b]	2	2	2	2	2	2	2
03	Ash reinjection, kg/h	0	0	0	0	0	0	0
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	915	936	938	877	902	878	922
07	Bed temp -2, °C	896	912	908	842	895	853	907
08	Bed temp -3, °C	903	920	919	842	875	856	897
09	Bed temp -4, °C	900	917	916	856	880	856	897
10	Bed temp -5, °C	903	917	915	858	878	860	879
11	Freeboard temp -1, °C	924	923	943	904	913	932	913
12	Freeboard temp -2, °C	977	985	984	972	972	958	956
13	Freeboard temp -3, °C	1035	1033	1030	1002	1017	1041	1025
14	Freeboard temp -4, °C	932	927	920	894	905	920	915
15	Comb exit temp, °C	593	593	571	564	568	595	557
16	Coal feed rate, kg/h	458	458	366	360	308	468	421
17	Total air flow, m^3/h	2786	2651	2198	2156	1863	3100	2489
18	Fluegas analysis, O_2, %	3.5	2.7	2.2	3.7	1.2	4.7	3.8
19	Fluegas analysis, CO_2, %	15.8	16.6	17.0	15.7	18.0	14.8	15.6
20	Fluegas analysis, CO, ppm	1750	327	496	248	498	187	140
21	Fluegas analysis, NOx, ppm	310	308	224	260	169	291	275
22	Fluegas analysis, SOx, ppm	742	689	998	635	841	266	502
23	Fluegas analysis, HC, ppm	–	–	–	–	–	–	–
24	Heat extracted from bed coils, Mkcal/h	0.60	0.61	0.60	0.56	0.56	0.54	0.57
25	Heat extracted in convection coils, Mkcal/h	0.56	0.53	0.40	0.38	0.31	0.57	0.49

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.10 (continued)

S.No.	Description	44	45	46	47	48	49	50
26	Heat extracted in test loop 1, $10^3 \times$ kcal/h	4.79	4.57	4.45	4.11	4.13	4.14	3.94
27	Heat extracted in test loop 2, $10^3 \times$ kcal/h	4.43	4.85	4.73	4.83	4.15	4.54	4.19
28	Coal analysis: C, %	42.67	42.00	44.42	41.01	45.55	43.23	39.82
29	Coal analysis: H, %	2.43	2.39	2.53	2.34	2.60	2.46	2.27
30	Coal analysis: N, %	1.06	1.04	1.10	1.02	1.13	1.07	0.99
31	Coal analysis: S, %	0.58	0.57	0.80	0.55	0.62	0.58	0.56
32	Coal analysis: 02, %	9.48	9.34	9.87	9.11	10.12	9.61	8.85
33	Coal analysis: Ash, %	38.28	37.62	34.57	39.24	33.63	36.92	40.47
34	Coal analysis: Moist, %	5.5	7.04	6.91	6.73	6.36	6.12	7.1
35	Coal analysis: HHV, kcal/kg	4100	4024	4300	4024	4150	4024	3900
36	Bed particle size, microns	887	823	897	800	897	823	845
37	Air temp, °C	42.91	39.53	37.40	35.87	44.26	44.97	34.42
38	Combustibles in bed material, %	0.64	0.73	0.69	0.39	0.40	0.69	0.62
39	Combustibles in cyclone catch, %	11.37	10.09	10.69	10.37	7.39	11.43	8.10
40	Combustibles in multi-clone catch, %	11.37	10.09	10.65	10.37	7.39	11.43	8.10
41	Avg. bed temp, °C	903	921	920	854	888	860	906
42	Max. freeboard temp, °C	1035	1033	1030	1002	1017	1041	1025
43	Fluidization Vel, m/s	2.82	2.74	2.27	2.09	1.88	3.01	253
44	Excess air, %	21.0	16.0	12.0	23.0	7.0	30.0	23.0
45	Freeboard combustion, %	14.7	14.1	11.8	11.4	9.9	16.0	12.2
46	Combustion efficiency, %	91.76	92.63	93.62	93.00	96.12	91.61	93.85
47	Carbon burn up, %	90.18	91.25	92.34	91.48	95.61	90.32	92.53
48	Dust concentration, g/Nm^3	64	67	56	60.4	48	59	67.00
49	Fluegas flow rate, kg/h	3050	2919	2425	2365	2061	3375	2727
50	Material drained from bed, kg/h	24.6	21.9	21.5	31.1	26.39	20.1	28.5

Table B.10 (continued)

S.No.	Description	44	45	46	47	48	49	50
51	Material drained from cyclone, kg/h	151	150.4	105	110.2	77.19	152.7	141.8
52	Material drained from multiclone, kg/h	-	-	-	0	0	-	-
53	Bed retention, %	14	12.7	17.0	22.0	25.48	11.6	16.7

Table B.10 (continued)

S.No.	Description	51	52	53	54	55	56	57
01	Fuel[a]	1	1	1	1	1	1	1
02	Fuel feeding[b]	2	2	2	2	2	2	2
03	Ash reinjection, kg/h	0	0	360	540	720	720	540
04	Fuel top size, mm	6	6	6	6	6	6	6
05	Expanded bed height, mm	600	600	600	600	600	600	600
06	Bed temp -1, °C	915	931	885	868	888	905	895
07	Bed temp -2, °C	886	897	898	885	906	926	912
08	Bed temp -3, °C	886	896	872	855	874	885	904
09	Bed temp -4, °C	916	897	882	861	881	898	891
10	Bed temp -5, °C	885	887	883	880	882	911	896
11	Freeboard temp -1, °C	908	918	902	914	915	947	929
12	Freeboard temp -2, °C	960	963	940	952	971	997	985
13	Freeboard temp -3, °C	1003	1006	908	947	1016	1017	977
14	Freeboard temp -4, °C	899	896	870	870	899	903	873
15	Comb exit temp, °C	567	577	540	543	561	537	543
16	Coal feed rate, kg/h	371	393	447	450	464	375	356
17	Total air flow, m^3/h	2209	2359	3057	3076	3059	2573	2492
18	Fluegas analysis, O_2, %	2.4	2.7	4.5	4.4	3.8	2.5	2.9
19	Fluegas analysis, CO_2, %	16.9	16.6	15.0	15.2	15.6	16.8	16.5
20	Fluegas analysis, CO, ppm	324	428	155	235	217	330	-
21	Fluegas analysis, NOx, ppm	262	256	186	195	178	150	155
22	Fluegas analysis, SOx, ppm	478	702	612	563	554	600	416
23	Fluegas analysis, HC, ppm	-	-	30.02	16.68	70	43	9
24	Heat extracted from bed coils, Mkcal/h	0.57	0.58	0.55	0.54	0.56	0.57	0.56
25	Heat extracted in convection coils, Mkcal/h	0.42	0.47	0.68	0.71	0.75	0.65	0.57

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.10 (continued)

S.No.	Description	51	52	53	54	55	56	57
26	Heat extracted in test loop 1, 10^3 x kcal/h	4.03	4.35	4.67	4.70	4.56	4.78	4.88
27	Heat extracted in test loop 2, 10^3 x kcal/h	4.25	4.62	4.65	4.67	5.08	4.82	4.89
28	Coal analysis: C, %	42.75	42.75	42.43	42.43	42.43	47.29	47.29
29	Coal analysis: H, %	2.44	2.44	2.42	2.42	2.42	2.69	2.69
30	Coal analysis: N, %	1.06	1.06	1.05	1.05	1.05	1.17	1.17
31	Coal analysis: S, %	0.58	0.58	0.57	0.57	0.57	0.64	0.64
32	Coal analysis: O_2, %	9.5	9.5	9.43	9.43	9.43	10.51	10.51
33	Coal analysis: Ash, %	37.13	37.13	38.40	38.40	38.40	32.0	32.0
34	Coal analysis: Moist, %	6.55	6.55	5.70	5.70	5.70	5.70	5.7
35	Coal analysis: HHV, kcal/kg	4050	4050	4122	4122	4122	4590	4590
36	Bed particle size, microns	872	904	772	933	743	1033	990
37	Air temp, °C	33.41	34.29	35.11	35.67	35.56	34.54	36.38
38	Combustibles in bed material, %	0.68	0.89	0.50	1.1	0.3	0.9	0.7
39	Combustibles in cyclone catch, %	7.97	8.5	4.3	3.5	3.7	4.4	4.4
40	Combustibles in multi-clone catch, %	7.97	8.5	2.7	1.9	2.1	1.6	1.9
41	Avg. bed temp, °C	901	905	884	867	887	904	900
42	Max. freeboard temp, °C	1003	1006	940	952	1016	1017	977
43	Fluidization Vel, m/s	2.24	2.40	3.02	3.00	3.05	2.60	2.52
44	Excess air, %	14.0	16.0	29.0	28.0	23.0	15.0	17.0
45	Freeboard combustion, %	11.8	12.0	16.7	17.9	17.3	14.9	14.4
46	Combustion efficiency, %	94.88	94.11	97.21	97.72	97.71	97.05	98.06
47	Carbon burn up, %	93.99	93.08	96.64	97.25	97.26	97.66	97.66
48	Dust concentration, g/Nm^3	58.24	62.0	200	270	343	379	304
49	Fluegas flow rate, kg/h	2433	2595	3326	3348	3340	2874	2730
50	Material drained from bed, kg/h	28.3	21.6	13.4	12.9	13.5	14.3	12.6

Table B.10 (continued)

S.No.	Description	51	52	53	54	55	56	57
51	Material drained from cyclone, kg/h	109.6	124.4	113.2	119.3	111	78.3	71.8
52	Material drained from multiclone, kg/h	-	-	45	40.3	54	27.3	29.5
53	Bed retention, %	20.6	14.8	7.8	7.5	7.6	11.9	11.1

Table B.10 (continued)

S.No.	Description	58	59	60	61
01	Fuel[a]	1	1	1	1
02	Fuel feeding[b]	2	2	2	2
03	Ash reinjection, kg/h	360	360	540	720
04	Fuel top size, mm	6	6	6	6
05	Expanded bed height, mm	600	600	600	600
06	Bed temp -1, °C	896	906	896	893
07	Bed temp -2, °C	908	903	889	894
08	Bed temp -3, °C	878	888	891	886
09	Bed temp -4, °C	896	905	893	899
10	Bed temp -5, °C	883	895	890	899
11	Freeboard temp -1, °C	896	924	921	938
12	Freeboard temp -2, °C	956	1032	1034	1056
13	Freeboard temp -3, °C	960	1085	1153	1235
14	Freeboard temp -4, °C	873	905	927	987
15	Comb exit temp, °C	539	548	550	594
16	Coal feed rate, kg/h	351	353	359	358
17	Total air flow, m^3/h	2531	1945	1945	1918
18	Fluegas analysis, O_2, %	3.6	1.4	1.0	0.8
19	Fluegas analysis, CO_2, %	15.8	17.9	18.3	18.4
20	Fluegas analysis, CO, ppm	175	309	370	440
21	Fluegas analysis, NOx, ppm	158	93	79	67
22	Fluegas analysis, SOx, ppm	674	778	930	1093
23	Fluegas analysis, HC, ppm	20	65	134	224
24	Heat extracted from bed coils, Mkcal/h	0.56	0.56	0.56	0.54
25	Heat extracted in convection coils, Mkcal/h	0.53	0.40	0.44	0.43

[a]1. High-ash coal, 2. Washery rejects-1, 3. Washery rejects-2, 4. Mill rejects.

[b]1. Underbed, 2. Overbed.

Table B.10 (continued)

S.No.	Description	58	59	60	61
26	Heat extracted in test loop 1, 10^3 x kcal/h	5.00	5.89	6.60	5.54
27	Heat extracted in test loop 2, 10^3 x kcal/h	4.88	5.29	6.59	6.37
28	Coal analysis: C, %	47.29	40.68	40.68	40.68
29	Coal analysis: H, %	2.69	2.32	2.32	2.32
30	Coal analysis: N, %	1.17	1.01	1.01	1.01
31	Coal analysis: S, %	0.64	0.55	0.55	0.55
32	Coal analysis: O_2, %	10.51	9.04	9.04	9.04
33	Coal analysis: Ash, %	32.0	41.5	41.5	41.5
34	Coal analysis: Moist, %	5.7	4.9	4.9	4.9
35	Coal analysis: HHV, kcal/kg	4590	3950	3950	3950
36	Bed particle size, microns	916	926	980	952
37	Air temp, °C	38.95	34.98	33.63	32.92
38	Combustibles in bed material, %	0.7	0.7	0.9	0.9
39	Combustibles in cyclone catch, %	5.6	4.8	3.9	4.1
40	Combustibles in multi-clone catch, %	2.7	2.9	3.5	3.5
41	Avg. bed temp, °C	895	901	892	894
42	Max. freeboard temp, °C	960	1084	1153	1235
43	Fluidization Vel, m/s	2.53	1.98	1.97	1.95
44	Excess air, %	22.0	8.0	6.0	5.0
45	Freeboard combustion, %	13.8	11.1	11.5	11.9
46	Combustion efficiency, %	97.33	97.37	97.33	97.57
47	Carbon burn up, %	96.78	96.84	97.03	97.08
48	Dust concentration, g/Nm^3	216	276	383	496
49	Fluegas flow rate, kg/h	2765	2147	2151	2123
50	Material drained from bed, kg/h	12.0	49	49.1	54.6

Table B.10 (continued)

S.No.	Description	58	59	60	61
51	Material drained from cyclone, kg/h	79.0	64	68.5	59.7
52	Material drained from multiclone, kg/h	21	33.5	31.3	34.3
53	Bed retention, %	10.7	33.1	33.0	36.7

Table B.11. Heat and material balance for test series 44 through 61

S.No.	Description	44	45	46	47	48	49	50
01	Heat input, Mkcal/h	1.88	1.82	1.57	1.47	1.30	1.88	1.64
02	Heat in dry fluegas, Mkcal/h	0.40	0.38	0.30	0.30	0.25	0.44	0.33
03	Heat in moisture (air) Mkcal/h	0.02	0.02	0.02	0.01	0.01	0.02	0.02
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.11	0.11	0.09	0.08	0.08	0.11	0.09
05	Heat in unburnt carbon, Mkcal/h	0.15	0.14	0.10	0.11	0.05	0.16	0.10
06	Heat in ash, Mkcal/h	0.03	0.03	0.02	0.02	0.02	0.02	0.03
07	Heat absorbed in water, Mkcal/h	1.17	1.15	1.05	0.95	0.88	1.13	1.07
08	Air, kg/h	2788	2650	2198	2156	1863	3100	2488
09	Fuel, kg/h	458	458	366	360	308	468	421
10	Fluegas, kg/h	3050	2919	2425	2365	2061	3375	2727
11	Bed ash, kg/h	25.0	21.9	21.51	31.1	26.39	20.10	28.5
12	Cyclone ash, kg/h	151	150.4	105.0	110.2	77.19	152.7	141.8
13	Multiclone ash, kg/h	-	-	-	-	-	-	-

Table B.11 (continued)

S.No.	Description	51	52	53	54	55	56	57
01	Heat input, Mkcal/h	1.50	1.59	1.84	1.85	1.91	1.72	1.63
02	Heat in dry fluegas, Mkcal/h	0.30	0.33	0.39	0.40	0.41	0.33	0.32
03	Heat in moisture (air) Mkcal/h	0.02	0.02	0.02	0.02	0.02	0.02	0.02
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.09	0.09	0.10	0.10	0.11	0.09	0.09
05	Heat in unburnt carbon, Mkcal/h	0.08	0.08	0.05	0.04	0.04	0.03	0.03
06	Heat in ash, Mkcal/h	0.02	0.02	0.02	0.02	0.02	0.02	0.02
07	Heat absorbed in water, Mkcal/h	1.00	1.06	1.25	1.26	1.32	1.23	1.15
08	Air, kg/h	2409	2359	3057	3076	3059	2573	2492
09	Fuel, kg/h	371	393	447	449.5	464	375	356
10	Fluegas, kg/h	2433	2595	3326	3347	3340	2824	2730
11	Bed ash, kg/h	28.3	21.6	13.4	12.9	13.5	14.3	12.7
12	Cyclone ash, kg/h	109.4	124.4	113.7	119.3	111	78.3	71.8
13	Multiclone ash, kg/h	-	-	45.0	40.3	40.0	27.3	29.5

Table B.11 (continued)

S.No.	Description	58	59	60	61
01	Heat input, Mkcal/h	1.61	1.39	1.42	1.41
02	Heat in dry fluegas, Mkcal/h	0.32	0.26	0.26	0.28
03	Heat in moisture (air) Mkcal/h	0.02	0.01	0.01	0.01
04	Heat from moisture and hydrogen in fuel, Mkcal/h	0.08	0.07	0.08	0.08
05	Heat in unburnt carbon, Mkcal/h	0.04	0.04	0.03	0.03
06	Heat in ash, Mkcal/h	0.01	0.02	0.02	0.03
07	Heat absorbed in water, Mkcal/h	1.1	0.97	1.01	0.98
08	Air, kg/h	2531	1945	1945	1918
09	Fuel, kg/h	351	353	359	358
10	Fluegas, kg/h	2764	2147	2151	2123
11	Bed ash, kg/h	12.0	49.0	49.1	54.6
12	Cyclone ash, kg/h	79.0	64.0	685	59.7
13	Multiclone ash, kg/h	21.0	33.0	31.3	34.7

Table B.12. Size distribution of bed particles for test series 44 through 61

S.No.	Sieve size (mm)	44	45	46	47	48	49	50
01	-6.000 + 4.000	0.1	1.9	7.2	5.5	7.2	1.9	5.4
02	-4.000 + 2.800	2.1	5.5	10.0	3.9	10.0	5.5	15.0
03	-2.800 + 2.000	3.5	4.6	8.9	4.8	8.9	4.6	13.6
04	-2.000 + 1.400	20.0	18.8	7.8	10.0	7.8	18.8	7.3
05	-1.400 + 1.000	20.4	19.7	10.9	11.6	10.9	19.7	9.0
06	-1.000 + 0.700	30.6	26.6	27.8	27.5	27.8	26.6	11.9
07	-0.700 + 0.500	21.1	16.5	20.5	30.7	20.5	16.5	20.9
08	-0.500 + 0.250	2.0	2.9	6.5	5.5	6.5	2.9	16.5
09	-0.250 + 0.180	0.0	2.0	0.1	0.1	0.1	2.0	0.1
10	-0.180 + 0.125	0.0	1.3	0.1	0.1	0.1	1.3	0.1
11	-0.125 + 0.063	0.1	0.1	0.1	0.2	0.1	0.1	0.1
12	-0.063 + 0.000	0.1	0.1	0.1	0.1	0.1	0.1	0.1
13	Avg. particle size (microns)	887	823	807	800	897	823	845

Table B.12 (continued)

S.No.	Sieve size (mm)	51	52	53	54	55	56	57
01	-6.000 + 4.000	2.5	1.7	0.9	1.3	0.6	1.9	1.6
02	-4.000 + 2.800	8.6	18.4	2.2	11.8	1.9	12.3	9.7
03	-2.800 + 2.000	8.8	16.5	2.5	11.9	2.6	11.7	11.1
04	-2.000 + 1.400	16.8	24.5	12.3	25.2	11.3	26.8	25.4
05	-1.400 + 1.000	12.4	14.6	15.3	14.6	14.7	15.6	15.7
06	-1.000 + 0.700	21.0	16.8	30.1	18.2	31.3	18.4	21.0
07	-0.700 + 0.500	21.1	10.8	29.9	13.1	30.6	10.8	12.7
08	-0.500 + 0.250	8.2	9.9	6.3	2.8	6.4	1.7	2.1
09	-0.250 + 0.180	0.2	0.1	0.1	0.1	0.1	0.1	0.1
10	-0.180 + 0.125	0.2	0.2	0.1	0.2	0.1	0.1	0.1
11	-0.125 + 0.063	0.1	0.2	0.1	0.2	0.1	0.3	0.2
12	-0.063 + 0.000	0.1	0.3	0.1	0.5	0.2	0.3	0.3
13	Avg. particle size (microns)	872	904	772	933	743	1033	990

Table B.12 (continued)

S.No.	Sieve size (mm)	58	59	60	61
01	-6.000 + 4.000	2.2	1.0	2.7	1.7
02	-4.000 + 2.800	9.8	5.7	17.6	12.5
03	-2.800 + 2.000	8.4	6.4	12.9	10.1
04	-2.000 + 1.400	20.5	22.0	25.1	19.6
05	-1.400 + 1.000	14.7	17.3	14.0	12.4
06	-1.000 + 0.700	20.2	25.1	16.0	19.0
07	-0.700 + 0.500	18.4	18.3	9.1	18.6
08	-0.500 + 0.250	5.2	3.8	1.5	5.6
09	-0.250 + 0.180	0.1	0.1	0.1	0.1
10	-0.180 + 0.125	0.1	0.1	0.1	0.1
11	-0.125 + 0.063	0.2	0.1	0.2	0.2
12	-0.063 + 0.000	0.2	0.1	0.7	0.11
13	Avg. particle size (microns)	914	926	980	952

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