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Final Report

Coal conversion and biomass conversion: Volume 1: Final report on USAID [Agency for International Development]/GOI [Government of India] Alternate Energy Resources and Development Program

Kulkarni, A.; Saijuja, J.

30 Jun 1987

Viking Systems International, Pittsburgh, PA (USA)

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FINAL REPORT
ON USAID/GOI
ALTERNATE ENERGY
RESOURCES AND
DEVELOPMENT PROGRAM

COAL CONVERSION
AND
BIOMASS CONVERSION

VOLUME I

* * * * *

JUNE 30, 1987

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EXECUTIVE SUMMARY:

The United States Agency for International Development (AID), in joint collaboration with the Government of India (GOI), supported a research and development program in Alternate Energy Resources during the period March 1983 to June 1987. The primary emphasis of this program was to develop new and advanced coal and biomass conversion technologies for the efficient utilization of coal and biomass feedstocks in India. This final "summary" report is divided into two volumes. Volume I covers the program overview and coal projects and Volume II summarizes the accomplishments of the biomass projects.

In May of 1983, the Government of India, Department of Non-conventional Energy Sources (DNES) identified areas in coal and biomass conversion for joint collaboration that would enable the efficient utilization of domestic coal and biomass resources. To accelerate the development and commercialization of new technologies in the areas of interest, nine projects were selected for research and development.

Under a Participating Agency Service Agreement (PASA) with USAID, The Pittsburgh Energy Technology Center, (PETC) was responsible for the management and implementation of this joint U.S./India co-operative energy technology program. The role of PETC, is

discussed in Volume I, Section 2.0.

The six projects selected in the area of coal were:

- o Evaluation of the Freeboard Performance in a Fluidized-Bed Combustor
- o Scale-up of AFBC boilers
- o Rheology, Stability & Combustion of Coal-Water Slurries
- o Beneficiation of Fine Coal in Dense Medium Cyclones
- o Hot Gas Cleanup & Separation
- o Cold Gas Cleanup & Separation

The biomass conversion projects selected were:

- o Development of a Village-Level Gasifier Utilizing Charred Agricultural Residue - Project A
- o Utilization of Producer Gas in Small Engines (3-5 HP) - Project B
- o Development and Field Implementation of Wood-Based, Gasifier/Engine Systems (5-30 Hp) - Project C

Some of the projects, especially fluidized-bed combustion, coal preparation and the biomass projects were designed so as to provide a good technical database at the completion of the program through experimental investigations on demonstration units. This would permit the immediate application of the technology and possible commercialization. The project on scale-up of AFBC boilers was developed so as to finalize the design of the 30 MW(e) demonstration plant. Workplans for the other projects were developed with a view to allow long-term research and development

to be pursued. The management and implementation of the program is briefly discussed in Section 3.0, whereas the expenditures incurred on each project are outlined in Section 3.2.

During the course of the program, three workshops were held in India. The intent of each workshop was:

- to review the progress of the program during the year,
- to encourage U.S. specialists to discuss with their Indian counterparts the direction and future of the program,
- to assess the status of the individual projects through site visits to the facilities and address any concerns or anticipated problems in meeting the objectives of each of the collaborative projects, and
- to provide a forum for technical exchange between U.S. and Indian industry to understand the need for and availability of technology, products and services in the U.S and India in specific areas of interest in coal and biomass conversion.

During the implementation of the program, technical assistance was provided for each project by U.S. specialists with expertise in the respective technical areas. Several Indian engineers/scientists were trained in the use of sophisticated equipment/instruments supplied to each project from the U.S. The training programs involved site-visits to various private and public organisations to witness the operation of the systems of interest and obtain actual hands-on experience in the use of instruments/equipment. The engineers/ scientists also attended workshops/conferences in the U.S. to improve their understanding of the new advances in the technology areas of interest.

Photographs of some of the research test facilities erected under USAID/GOI sponsorship are presented in Figures I-IV. Detailed technical descriptions of these facilities, the test programs and other achievements of the projects are discussed under the accomplishments of individual coal and biomass projects. The technical accomplishments of the coal projects are presented in Section 5.0 of this document, whereas the accomplishments of the biomass projects are briefly reviewed in Section 6.0. Details pertaining to the accomplishments of the biomass projects are discussed in Volume II.

FIGURE I

FLUIDIZED-BED COMBUSTION
TEST FACILITY
AT BHEL (TRICHY)

FIGURE II

COAL PREPARATION
PILOT PLANT FACILITY
AT CFRI (DHANBAD)

FIGURE III

ERECTION OF
CWS-FLUIDIZED-BED
COMBUSTION TEST FACILITY
AT BHEL (TRICHY)

FIGURE IV

G-50 GASIFIER SYSTEM
INSTALLED ON THE FARM
AT VILLAGE JORH BY
JYOTI SOLAR ENERGY INSTITUTE

1.0 INTRODUCTION:

The United States Agency for International Development (AID), in joint collaboration with the Government of India (GOI), supported a research and development program in Alternate Energy Resources during the period March 1983 to June 1987. The primary emphasis of this R&D program was to develop new and advanced coal and biomass conversion technologies for the efficient utilization of coal and biomass feedstocks in India.

In May of 1983, the Government of India, Department of Non-conventional Energy Sources (DNES) identified areas in coal and biomass conversion for joint collaboration that would enable the efficient utilization of domestic coal and biomass resources. To accelerate the development and commercialization of new technologies in the areas of interest, nine projects were selected for research and development.

The six projects selected in the area of coal were:

- o Evaluation of the Freeboard Performance in a Fluidized-Bed Combustor
- o Scale-up of AFBC boilers
- o Rheology, Stability & Combustion of Coal-Water Slurries
- o Beneficiation of Fine Coal in Dense Medium Cyclones
- o Hot Gas Cleanup & Separation

- o Cold Gas Cleanup & Separation

The biomass conversion projects selected were:

- o Development of a Village-Level Gasifier Utilizing Charred Agricultural Residue - Project A
- o Utilization of Producer Gas in Small Engines (3-5 HP) - Project B
- o Development and Field Implementation of Wood-Based, Gasifier/Engine Systems (5-30 Hp) - Project C

This report summarizes the work performed on the coal and biomass projects through the period March 1983-March 1987. The report comprises of two volumes, Volume I outlines the accomplishments of the coal conversion projects whereas Volume II focuses on the biomass projects.

2.0 ROLE OF PITTSBURGH ENERGY TECHNOLOGY CENTER:

Under a Participating Agency Service Agreement (PASA) with AID, the Department of Energy, Pittsburgh Energy Technology Center (PETC), was responsible for managing and implementing this joint U.S./India co-operative energy technology program. The purpose of this agreement was also to obtain PETC's expertise in the areas of conversion and utilization of alternate energy resources. To meet the objectives of the program, PETC's scope of work included completion of several tasks in the areas of coal and biomass conversion technologies. These tasks are outlined below.

2.1 Coal Conversion Technologies:

- o Preparation of an implementation plan for projects identified in the areas of coal conversion
- o Submission of the plans to AID, detailing objectives, activities, outputs, budgets, management, technical responsibilities and schedule.
- o Providing a technical manager to coordinate the collaborative program and make periodical visits to India to participate in the design and implementation of the program.
- o Providing specialists in areas of laboratory expertise and programmatic interest for short-term advisory assignment in India.
- o Arranging for experts from Morgantown Energy Technology Center, Oak Ridge National Laboratory, Argonne National Laboratory or other DOE facilities to participate in the technical program and to visit India as required.
- o Facilitating contact between Indian participating organisations and U.S. private companies, research institutions, universities, associations, (e.g., EPRI), power companies (Florida Power and Light in coal/oil mixtures),

organization (e.g., TVA in fluidized bed combustion) in the five technical areas of the program and serve to further U.S. commercial interests where possible (i.e., licensing agreements).

- o Arranging for visits, and internships at institutions in the U.S. and for the participation of technical experts from these organizations in the exchange program to the maximum extent possible.
- o Procuring and providing equipment for research.

2.2 Biomass Conversion Technologies:

- o Preparation of implementation plans for the projects identified in the area of biomass conversion.
- o Submission of the plans to AID, detailing objectives, activities, outputs, budgets, management, technical responsibilities and schedule.
- o Providing a technical project manager experienced in small-scale gasifiers and who could make periodic visits to India to participate in the project design and implementation.
- o Sub-contracting technical organizations, such as Mitre or Battelle, who have experience in the design and operation of small-scale gasifiers for technical advise.
- o Providing technical publications and arranging technical visits and training for Indian engineers from participating Indian organisations at U.S. companies and sites.

3.0 MANAGEMENT AND IMPLEMENTATION OF THE PROGRAM:

The overall program was managed for the most part by Mr. Daniel Bienstock, Associate Deputy Director of the Pittsburgh Energy Technology Center. Final stages of the program were transferred to Dr. William C. Peters, Manager, PETC Office of Research and Technology Applications. Technical assistance in coal conversion technologies was provided by the following U.S. specialists.

Dr. R.P. Krishnan Oak Ridge National Laboratory	- Fluidized Bed Combustion
Dr. M. Ghate Morgantown Energy Technology Center	- Gas Cleanup & Separation
Dr. A. Kulkarni Viking Systems International	- Gas Cleanup & Separation
Mr. A. Deurbrouck Pittsburgh Energy Technology Center	- Coal Beneficiation
Mr. D. Bienstock Pittsburgh Energy Technology Center	- Coal-Water Slurries

The biomass specialists for the three projects included:

Mr. A. Talib Mitre Corporation	- Biomass Conversion
Dr. V. Flanigan University of Missouri	- Biomass Conversion
Dr. J. Goss University of California	- Biomass Conversion

These specialists visited India on short-term assignments during the course of the program to participate in project design and

implementation.

The implementation plans for each of the nine projects were developed at the First Workshop on Alternate Energy Resource Development held in New Delhi, November 7-11, 1982. The detailed technical and management workplans were approved by AID, Department of Science & Technology and DNES (GOI). The technical workplans described the scope of the research, development and demonstration activities under each of the selected projects, whereas the management plans described the overall management structure and schedule for the individual collaborative projects. The milestone charts in A1-A9 (Appendix A) summarize the scope of work and schedules for each of the individual projects. Since formal approval from DNES (GOI) for some projects was received as late as September 1984, it may be noted that these are revised schedules from the ones submitted to AID and GOI in January 1983.

3.1 Workshops on the Alternate Energy Resource Development Program:

Three workshops were held in India on the program between March 1983 and March 1987 on the following dates:

First Workshop	November 7-11, 1983 Taj Palace Hotel, New Delhi
Second Workshop	February 4-5, 1985 Maurya Sheraton, New Delhi
Third Workshop	December 5-7, 1985 Maurya Sheraton, New Delhi

The intent of each workshop was:

- to review the progress of the program during the year
- to encourage U.S. specialists to discuss with their Indian counterparts the direction and future of the program
- to assess the status of the individual projects through site visits to the facilities and address any concerns or anticipated problems in meeting the objectives of each of the collaborative projects, and
- to provide a forum for technical exchange between U.S. and Indian industry to understand the need for and availability of technology, products and services in the U.S and India in specific areas of interest in coal and biomass conversion

The workshop sessions included presentations by Indian scientists and engineers, U.S. specialists, and representatives from private organizations in the U.S. The trip reports submitted at the end of each workshop highlight the discussions held during the workshop and at the site-visits. The proceedings of the three workshops provide an in-depth status on each of the projects implemented and the presentations made by U.S. experts and specialists in the areas of coal and biomass conversions. The presentations by U.S. specialists highlighted the state-of-the-art technology in the U.S. and the focus of current research and development activities in the U.S. The trip reports and the proceedings are available through the National Technical Information Service (NTIS).

3.2 Site-Visits By Indian Engineers/Scientists To The US:

During the period August 1983 to May 1986, seventeen Indian engineers/scientists visited the U.S. under the coal program and six engineers visited the U.S. under the biomass segment. Their visits included site-visits to U.S. facilities actively involved in their respective areas of research to obtain either training and hands-on experience in the operation and maintenance of instruments, to participate in design review meetings, and technical discussions with experts in their field of interest, or to attend official technical conferences to update them on the current status of the technology and its future direction.

In addition to the above-mentioned activities, another facet of their visits, was to enable the young engineers to establish personal contacts with some of the best technical experts in the U.S. and open doors for independent communications and continued cooperation.

It must be noted that the various research laboratories in the U.S., both government and private facilities, actively cooperated during the course of the program in arranging these site-visits, and at no cost to the program. This was made possible because the Pittsburgh Energy Technology Center and the Morgantown Energy Technology Center, of the U.S. Department of Energy, have funded many of the ongoing U.S. research and development programs at these laboratories, as well as through the interpersonal relationships of the U.S. specialists and the industrial, university, and governmental project managers involved in the U.S. programs.

The facilities visited by the engineers/scientists are briefly outlined in Section 5.0. under the accomplishments of each project.

3.3 Expenditures On Individual Projects:

Total expenditures for the overall program were \$1,919,000. The summary cost-sheet is shown in Table 3.1. The largest expenditure categories, each of approximately 38% of the total funding were:

- o Equipment supplied to the Indian participating organizations (\$720,555), and
- o Technical R&D Contracts (\$728,064)

Almost \$100,000 was spent on training of Indian engineers in the US and for the Workshops held in India.

Individual project expenditures are shown in Table 3.2. The largest overall sub-project was the Freeboard Performance project. Equipment costs alone incurred on this project amounted to \$281,852 and expenditures on the training of Indian personnel were \$15,511. The remainder of the funding was spent on direct technical labor (Oakridge National Laboratory and Viking Systems International) travel and overhead. The detailed project breakdown for the Freeboard Performance sub-project is shown in Table 3.3. Similar cost breakdowns in terms of US personnel, travel, Indian

personnel and equipment are shown in Tables 3.4 to 3.11 for the other coal and biomass sub-projects.

TABLE 3.1: SUMMARY OF COST FOR PETC-PASA
(U.S. Dollars)

	Coal	Biomass	Sub-Total	Total	Percent
1. PETC				25,125	1.31
Salary	7,804	1,038	8,842	-	
Travel	13,750	2,042	15,792	-	
Other	120	379	499	-	
2. Equipment Shipped To India	564,569	155,986	720,555	720,555	37.55
3. Contracts				728,064	37.94
MITRE CORP.		264,241	264,241	-	
ORNL	340,008		340,008	-	
UNIV MISSOURI		57,462	57,462	-	
UNIV CALIF.		66,353	66,353	-	
4. Technical Support Service	198,525	122,865	321,389	321,389	16.75
5. Training Indian Engineers	77,503	22,357	99,860	99,860	5.20
6. Other -TVA	24,000		24,000	24,000	1.25
TOTAL:	\$ 1,226,278	692,722	1,919,000	1,919,000	100.00

TABLE 3.2: Individual Coal And Biomass Project Expenditures

PETC-PASA

COAL CONVERSION PROJECTS:

Freeboard Performance	\$ 684,600
Coal-Water Mixtures	76,492
Hot Gas Cleanup	162,229
AFB Boiler Scale-up	125,003
Coal Beneficiation	108,108
Cold Gas Cleanup	69,846

Sub-Total: \$ 1,226,278

BIOMASS CONVERSION PROJECTS:

Project A	232,667
Project B	225,219
Project C	234,836

Sub-Total: \$ 697,722

Total: \$ 1,919,000

TABLE 3.3: Evaluation of Freeboard Performance in a Fluidized Bed Combustor

ITEM	AMOUNT (\$)
Direct Labor	231,321
Travel	47,345
Training of Indian Personnel	15,511
Equipment	281,852
Overhead	96,589
Other	11,981
Sub-project Total:	684,600

TABLE 3.4: Scale-up of AFBC Boilers

ITEM	AMOUNT (\$)
Direct Labor	77,444
Travel	21,435
Training of Indian Personnel	4,438
Equipment	-
Overhead	20,832
Other	854
Sub-project Total:	125,003

TABLE 3.5: Rheology, Stability, and Combustion of Coal-Water Mixtures

ITEM	AMOUNT (\$)
Direct Labor	7,657
Travel	4,478
Training of Indian Personnel	3,496
Equipment	51,245
Overhead	8,937
Other	680
Sub-project Total:	76,492

TABLE 3.6: Hot Gas Cleanup and Separation

ITEM	AMOUNT (\$)
Direct Labor	6,303
Travel	6,075
Training of Indian Personnel	8,041
Equipment	132,399
Overhead	7,895
Other	1,517
Sub-project Total:	162,229

TABLE 3.7: Beneficiation of Fine Coal In Dense Medium Cyclones

ITEM	AMOUNT (\$)
Direct Labor	23,235
Travel	6,664
Training of Indian Personnel	3,221
Equipment	48,558
Overhead	25,427
Other	1,003
Sub-project Total:	108,108

TABLE 3.8: Cold Gas Cleanup and Separation

ITEM	AMOUNT (\$)
Direct Labor	5,390
Travel	3,076
Training of Indian Personnel	3,502
Equipment	50,516
Overhead	6,649
Other	712
Sub-project Total:	69,846

TABLE 3.9: Development of Village-Level Gasifier - Project A

ITEM	AMOUNT (\$)
Direct Labor	81,854
Travel	23,934
Training of Indian Personnel	6,933
Equipment	53,668
Overhead	60,137
Other	6,141
Sub-project Total:	232,667

TABLE 3.10: Utilization of Producer Gas in Small Engines - Project B

ITEM	AMOUNT (\$)
Direct Labor	81,854
Travel	23,934
Training of Indian Personnel	7,069
Equipment	46,084
Overhead	60,137
Other	6,141
Sub-project Total:	225,219

TABLE 3.11: Development and Field Implementation of Wood-based Gasifier/Engine Systems - Project C

ITEM	AMOUNT (\$)
Direct Labor	81,854
Travel	23,934
Training of Indian Personnel	6,537
Equipment	56,233
Overhead	60,137
Other	6,141
Sub-project Total:	234,836

4.0 COAL UTILIZATION IN INDIA:

In recent years, India has placed greater emphasis on domestic coal and biomass resources in meeting its energy needs. As a result of this policy, the need for new technologies and the efforts to accelerate their development have led to both independent projects and co-operative projects such as those implemented under the joint USAID/GOI Alternate Energy Resource Development Program.

4.1 Background:

In the commercial energy scenario in India, coal has come to occupy a pivotal position to meet national energy needs, and, in the years to come, dependence on coal is expected to increase considerably. Figure 4.1 illustrates the contribution of the major commercial energy sources to the country's energy supply. At present, 65% of the total energy in the country is generated by burning non-caking, high-ash coals in pulverized form. In addition, middlings and sinks available from the existing 17 coking-coal washeries are also consumed by thermal power stations. Altogether, about 30% of the coal produced in the country is being consumed for electric power generation. By 1990, with a target annual production of 240 million tons, 40-42% of the coal will be used by power stations.

While coal has traditionally been the largest source of commercial energy in the country, several factors have contributed to coal's

FIGURE 4.1: CONTRIBUTION OF
MAJOR COMMERCIAL
ENERGY SOURCES

increased utilization, the primary one being that it is the country's most abundant energy resource. The energy resources in India have been estimated at 114 billion tons of coal, 180 million tons of oil, and 70,000 MW of hydropower. Although it ranks tenth in the world's coal resources, the heating value of India's coal is small, with an average calorific value of 5000 kcal/kg, compared with the global coal resources estimated at approximately 12 trillion tons, with an average calorific value of 7000 kcal/kg. However, the bulk of the Indian coal resources lies within a relatively shallow depth of 300m from the surface and is mineable. This is important when one considers that only 6% of the world's coal is considered technically and economically mineable under present recovery conditions.

The second most important reason for using coal feedstocks is economics. In the early 1980's, India imported crude oil to supplement its indigenous production and meet its total annual oil requirements of 40 million tons. Imported crude oil constituted about 60% of the total oil needs during that time and consumed nearly 70% of the country's foreign exchange reserves, severely affecting the country's balance of payments.

Nearly \$6 billion were spent on the import of crude, and by the turn of the century this expenditure was expected to grow as oil requirements rose to more than 70 million tons annually to sustain rising energy consumption and to speed economic growth. Therefore, a massive program in offshore oil exploration was undertaken under

the direction of the Oil and Natural Gas Commission to unleash the potential sources of indigenous crude. Consequently, India has been able to achieve near self-sufficiency with respect to its crude requirements and at present imports only small quantities of diesel oil and kerosene.

While efforts are underway to increase the production of indigenous crude, India is nevertheless aware that its oil resources are limited. Also, from the standpoint of cost, coal is likely to remain the cheapest of the major energy resources. In fact at the time the joint USAID/GOI collaboration was being initiated in 1981, the cost of coal in India was among the lowest in the world with little government subsidy, as can be seen from Figure 4.2. Also, at present, with the global oil price at less than \$20 barrel, which translates into \$100/ton (coal equivalent), the cost of coal in India at \$13/ton compares very favorably. Additionally, any future increases in oil prices could make the balance of payment situation deteriorate further and lead to economic problems of serious proportions.

Figure 4.3 illustrates the consumption trends of coal and oil in India from 1965 to 2000 to meet the country's fuel needs and sustain its rising energy consumption. It is clear that coal will continue to be the predominant energy source in the future, as it has been in the past. In the 10 years between 1973 and 1983, India increased its coal production from 77.23 to 130 million tons, representing an average annual growth rate of 5.25%. During this

FIGURE 4.2: COMPARISON OF COAL COSTS
IN INDIA
WITH EUROPEAN COUNTRIES

FIGURE 4.3: CONSUMPTION TRENDS OF COAL AND OIL IN INDIA

period, as much as \$4.9 billion was invested in the coal sector, with the anticipation that by the year 1990 the goal of 240 million tons of coal production could be achieved. An additional outlay of \$5.8 billion is planned to be invested in the coal sector so as to raise coal production to 400 millions tons annually by the end of the century.

To promote the use of high-ash Indian coals and the increased use of coal washery rejects in power plants, the application of efficient coal-based technologies and improvements in the efficiency and availability of existing coal-based power plants is needed.

4.2 Feasible Coal Technologies In The Indian Context:

Table 4.1 provides typical characteristics of a sub-bituminous Indian coal and coal washery rejects. Also tabulated are the characteristics of a typical sub-bituminous American Montana coal. Indian coals are very high in ash content but low in sulfur. Actually, the ash content of the coals mined in India varies anywhere from 24 to 45%. The ash content of coal washery rejects is even higher, close to 70%. Because of the high ash content of Indian coals, the introduction of newer coal technologies in India could be slow. World wide, the experience in using such high-ash coals as feedstocks is limited. The newer coal technologies -for instance, the fluidized-bed combustion technology developed in the United States have focused on reducing SO and NO

emissions.

Problems concerning ash have been very limited because of the low ash content of most raw U.S. coals. Consequently, the standard design practices used in the new coal technologies, such as those developed in the United States, may prove inadequate in the Indian context.

Table 4.1: Characteristics of sub-bituminous Indian and U.S. coal and coal-washery rejects.

Characteristic	Indian coal-washery rejects(%)	Sub-bituminous Indian coal (%)	Sub-bituminous U.S.(Montana) coal(%)
Carbon	25.60	51.70	65.3
Hydrogen	4.02	3.21	4.1
Nitrogen	0.90	0.87	1.0
Sulfur	0.30	0.49	0.8
Oxygen	1.40	8.69	17.1
Moisture	1.31	6.85	1.8
Ash	68.47	28.10	11.7
Kcal/kg (Btu/lb)	2410 (4338)	4892 (8805)	6047 (10,885)

4.2.1 Fluidized-Bed Combustion:

It is widely believed that the two most viable technologies for the utilization of high-ash coals are fluidized-bed combustion (FBC) and coal gasification for combined-cycle power generation. Bharat Heavy Electricals, Ltd. (BHEL), manufacturer of power generation

equipment in India, has successfully developed the FBC technology for industrial power generation and has commercialized the FBC boilers up to 150,000 lb/hr steam capacity. Although the application of FBC technology for industrial power generation has been proved, its entry into the utility sector has yet to mature.

Scaling-up of FBC boilers for utility application (up to 30 MWe) and the retrofitting of the aging stoker-fired boilers with FBC are the two immediate goals. The problems envisioned in large-scale FBC boilers in the handling of very high-ash coals are mainly in the areas of coal/ash handling, particulate separation from the flue gases, heat recovery from the spent bed material, erosion of the tube surfaces, and excessive carbon carryover in the elutriated fly ash. Special attention may be needed in the design of the combustor, the tube surfaces, the freeboard region, the cyclone separators, the coal feed system, and the ash-handling systems.

To obviate some of the scale-up and operating problems of conventional FBC boilers, variations in FBC boiler design and novel concepts such as the circulating fluidized-bed (CFB) boiler and the ignifluid boiler are also being studied because of the merits of the CFB boiler compared with the conventional AFB boiler for burning high-ash coals. While some of the claims for circulating fluidized-bed combustion (CFBC), such as simplicity in coal feeding, higher coal combustion efficiency, and easy turn-down for part-load operations, may be valid, the system has some serious technical limitations. First, the highly abrasive nature of ash, a

unique characteristic of Indian coals, could lead to serious erosion problems because of the high operating velocities. Second, the cyclone separators that go with the CFB boiler need to be of a special design (brick-lined, high-efficiency cyclones), which can add to capital and operating costs of the boiler. At present very little data are available on CFBC for high-ash coals, and the issues mentioned need to be resolved by actual tests in a pilot-scale CFB boiler. Investigations in this area have been initiated at BHEL.

4.2.2 Coal Gasification:

Coal gasification is a familiar technology in India. The experience gained from the operation of entrained-bed gasifiers at the coal-based fertilizer plants, among the largest in the world, has been good. These gasifiers supply synthesis gas for 900 tons/day ammonia plants. This has generated tremendous interest in other areas of gasification, such as combined-cycle gasification and other advanced power cycle systems. Development of pressurized fluidized-bed combustion, pressurized fluidized-bed gasification, and pressurized fixed-bed gasification is being actively pursued. To this end, a combined-cycle gasification demonstration plant of 6-MW(e) capacity is to be commissioned at Trichy in the summer of 1985. It is planned to retrofit the plant at a future date with a pressurized fluid-bed combustor for demonstration and testing purposes. However, the main concerns regarding the commercialization of the advanced power cycle technologies stem

from the lack of good gas clean-up and separation systems.

Contaminants from the above-mentioned processes not only pose environmental problems but also present economic difficulties that can affect the feasibility of the processes. While environmental concerns in India are not emphasised at present, concerns about the service life and materials of construction of the gas turbines, which are driven by the hot, pressurized, particulate-laden gases produced by combustion or gasification of coal are important. As Indian coals are low in sulfur ($<0.5\%$, coal basis, exception Assam coals), there is little need to develop technologies to remove sulfur because its corrosive effect on the material of construction will not be the controlling factor. Because of the high-ash content of the coals, however, particulate removal is of prime importance. Particles as small as 5-10 microns are known to erode the blades, making the turbine inoperable after a relatively short time and resulting in large operating costs, whereas particles smaller than 2 microns have a tendency to adhere to the surface upon impact and cause fouling of the stationary turbine cascade. Rates of erosion may be much greater with Indian coals than with other coals because of the highly abrasive nature of the fly ash. In addition, alkali salts composed mainly of sodium and potassium sulfates are corrosive and also shorten turbine life.

All these factors can lead to either large capital costs or large operating expenses, depending upon the materials of construction of the turbine impellers. Newer concepts, such as high-temperature,

high-pressure electrostatic precipitators; high-temperature, high-pressure baghouses; and granular-bed filters are receiving attention in an attempt to realize efficient gas clean-up systems.

4.2.3 Coal Beneficiation:

Coal beneficiation is another important area on which more attention is being focused in India. At present it is limited to coking-coal production. Considering the poor quality of coal supplied to the power plants, it has become clear that some degree of coal beneficiation is needed if conventional pulverized-fuel plants are to operate trouble-free and at high level availability. Availability of pulverized-fuel boilers is currently less than 50%. The problem stems from the poor-quality coal. Not only is the coal high in ash content (30-40% and higher), but it is also contaminated with dirt and shale from the overburden during mining operations. Silica in the coal varies from 7 to 15% on coal basis. The frequent problems plaguing the pulverized-fuel power plants include erosion of pulverized systems and induced-draft fans, clinkering and slagging in the boiler due to melting and fusion of bottom ash, stability of combustion, and handling and disposal of fly ash and bottom ash. Despite these "known" problems, the use of beneficiated coal in power plants has been limited, and steel plants receiving coals containing 17-18% ash consider themselves fortunate. Additionally, emissions of oxides of sulfur and nitrogen and of particulates are not controlled because of less stringent environmental regulations.

Beneficiated coals may be inevitable in the future especially when the four superthermal power plants, each of 2100-MW capacity, go into operation, as coals earmarked for these plants could have up to 45% ash content. Also, plants of this capacity are certain to increase the magnitude of emissions to alarming proportions and are expected to mandate stricter environmental regulations. The use of beneficiated coals, as opposed to run-of-mine coals, not only could improve the efficiency of existing power plants-on an average it is reported that the boiler efficiency increases 1% for every 10% reduction in ash content-but also would dramatically increase their availability because maintenance shutdowns would be reduced. Advanced coal beneficiation techniques, such as chemical demineralization, oil agglomeration and heavy dense medium cyclones are being considered.

4.2.4 Coal-Water Slurries:

It is also felt that development efforts in the area of coal beneficiation should be integrated with those of coal-water slurries. Making coal-water slurry fuel comparable with residual oil will require upgrading the low quality coals. The washability characteristics of Indian coals are generally very poor, since the mineral matter is finely disseminated within the coal matrix. While the washability indices of British, German, or American coals are in the range of 45-76, those of Indian coals are between 15 and 40, often making it difficult to reduce the ash content to less

than 50% of the original by conventional washing techniques without a substantial decrease in recovery.

While these problems may be serious and could make the use of coal-water slurries economically infeasible, development of coal-water slurries is being strongly emphasised because of their significant potential for replacing oil and gas used in boilers and furnaces, with minimum modifications and investment. The immediate application will be in industrial power generation, since in India thermal power generation is entirely based on coal feedstocks. Another area where its application is being considered is that of slurry transport of coal from the mines to the various utilities. The ever-increasing requirements of coal in various parts of the country have placed a tremendous burden on the country's major mode of transportation, the railways. Installation of pipelines for transport of coal has been proposed provided that direct combustion of transported slurry can be achieved. Consequently, studies on the development of a combustion system suitable for heavily laden coal-water slurry have been started, but it will be quite some time before substantial progress can be seen unless collaborative ventures are undertaken.

5.0 ACCOMPLISHMENTS OF THE COAL CONVERSION PROJECTS:

Some of the coal projects, especially fluidized-bed combustion, scale-up of AFBC boilers, and coal preparation were designed so as to provide a good technical database at the completion of the program. This would permit the immediate application of the technology and possible commercialization. Workplans for the other projects were developed with a view to allow long-term research and development to be pursued. This section briefly discusses the scope of work, the accomplishments of the individual projects and outlines the equipment supplied to the participating institutions to facilitate the implementation of the workplans.

5.1 EVALUATION OF FREEBOARD PERFORMANCE IN A FLUIDIZED-BED COMBUSTOR:

This project was implemented at Bharat Heavy Electricals Limited, Tiruchirrapali (Trichy).

5.1.1 Background:

Bharat Heavy Electricals, Ltd (BHEL), manufacturer of power generation equipment in India, has successfully developed the FBC technology for industrial power generation and has commercialized FBC boilers up to 150,000 lb/hr steam capacity. However, the application of FBC technology into the utility sector has yet to

mature. There are still developmental requirements that must be further evaluated before FBC can be commercialized for utility applications. Some of the areas are higher efficiency requirements, higher steam temperatures and pressures (compared to industrial power generation), unique load following and turn down requirements, high system availability, and compliance with stringent environmental emission standards. Presently in the U.S. there are three major FBC demonstration projects underway addressing these issues.

Controlled experiments in well instrumented bench scale/pilot scale test facilities are the key to obtaining the much needed engineering design data for these large systems. Two notable examples in the U.S. of intermediate scale FBC facilities that have been successively used for obtaining scale-up information are (1) the Babcock and Wilcox (B&W)/Electric Power Research Institute (EPRI) 0.81-m square cross section FBC test facility at the B&W Alliance Research Center, and (2) the Tennessee Valley Authority (TVA) 20-MW(e) AFBC pilot plant at the Shawnee steam plant at Paducah, Kentucky.

While the need for a well-instrumented, state-of-the-art FBC research test facility was recognized by BHEL as early as 1981, it was only in November 1983 that a decision was made to erect an FBC test facility at Trichy as one of the projects in this joint USAID)/GOI collaboration. The technical responsibility for the project was assigned to the Energy Systems Group (ESG), now the

Industrial Power Products Development (IPPD) Group at BHEL, Trichy, and the Oak Ridge National Laboratory (ORNL), Oak Ridge, USA. Subsequently, a 1m x 1m (3 ft. x 3 ft.) atmospheric fluidized bed combustion (AFBC) research test facility with the auxiliary systems was designed and erected at the high pressure boiler plant at Trichy. The project was specifically aimed at investigations of the combustion and heat transfer in a very specific region of the combustor known as the "freeboard region," i.e., the combustion space between the top of the fluidized bed and the first row of the convection tube surface. This region has a special significance in the design of FBC boilers since the performance of the boiler is much affected by the geometry, height, and amount of heat surface in the freeboard region. Very little information is available in this region of FBC boilers, particularly with high ash coals as used in India. Major uncertainties exist in the combustion rate, heat generation, heat transfer to the water walls, and convection tube surfaces, the solid particle inventory in the freeboard, the particle size distribution, and the solid/gas temperature in the freeboard. A broader data base is needed for developing reliable engineering correlations for design and scale up for large AFBCs. The data base should include the effect of such factors as size and configuration of the FBC and the freeboard, the mode of fuel feeding (i.e., underbed versus overbed), flyash reinjection into the combustor versus once through operation, the fresh coal to recycle flyash ratio, excess air and overfire air.

With the above goals in mind, the experimental test facility was designed to provide the maximum flexibility to conduct a series of tests related to both hardware and performance evaluation. The design fuels chosen consisted of a high ash (40-50 percent) Indian coal, coal washery rejects containing up to 70 percent ash, and a high sulfur (up to 4 percent) U.S. coal. The combustor was erected at Trichy after elaborate reviews and evaluations of the design by engineers from the U.S. associated with TVA, EPRI, Combustion Engineering, Babcock & Wilcox, Massachusetts Institute of Technology, and the Morgantown Energy Technology Center (METC). The test facility was instrumented with the state-of-the-art instruments from the U.S. capable of withstanding the hostile environment (ash) in the combustor and the downstream system due to the high ash content of the fuels tested. A brief description of the combustor and the auxiliary system is presented later in the report. Detailed information is available in the references listed at the end of the report.

Below the scope of the project, the current status, the equipment supplied by USAID for the test facility, and the training/site visits of BHEL engineers in the U.S. during the program are described.

5.1.2 Scope Of Work:

Under USAID/GOI sponsorship, the overall objective was to design,

construct, and operate a 1m square AFBC research test facility to evaluate the combustion and heat transfer in the freeboard region.

The test program was specifically designed to:

1. Gather performance and heat transfer data on freeboard combustion, heat release and heat transfer rates along the freeboard height.
2. Obtain data on dust loading and gas composition along the freeboard height.
3. Correlate the freeboard performance characteristics in terms of design and operating parameters.
4. Obtain combustion efficiency and carbon burn-up as a function of fuel type and size.
5. Obtain data on SO₂/NO_x emissions and sorbent utilization for different freeboard heights and operating conditions.

5.1.3 Project Approval:

The project was approved by the Department of Non Conventional Energy Sources (DNES), GOI shortly after the First workshop held in November 1983. Activities on the project commenced in January 1984 with the initiation of the engineering design of the test facility and specification of equipment jointly by BHEL and ORNL at Trichy.

5.1.4 Work Accomplished at BHEL (Trichy):

Table 5.1 lists the activities completed in chronological order

TABLE 5.1: PROJECT MILESTONES AND ACCOMPLISHMENTS

Item	Task Description	Current Status	Period of Activity and Completion Date	Remarks
1	Design of the combustor and auxiliary systems; specification of equipment	Completed	January '84 - March '84	BHEL and ORNL at Trichy
2	Documentation of the design, preparation of engineering drawings	Completed	April '84 - May '84	BHEL at Trichy
3	Review of the design document by FBC organizations in the U.S.; specification of USAID equipment for the test facility	Completed	June '84 - September '84	BHEL and ORNL in the U.S.
4	Revision of the design document and release of specifications for indigenous equipment for procurement	Completed	November '84 - March '85	BHEL and ORNL at Trichy
5.	Preparation of civil engineering foundation and structural supports drawings; design of the control room for the test facility	Completed	May '85 - August '85	BHEL at Trichy
6.	Site preparation, excavation and laying of raft foundation	Completed	August '85 - October '85	BHEL at Trichy

TABLE 5.1: (CONTINUED)

Item	Task Description	Current Status	Period of Activity and Completion Date	Remarks
7.	Preparation of manufacturing drawings and fabrication of the components	Completed	July '85 - November '85	BHEL at Trichy
8.	Erection of test facility	Completed	November '85 - March '86	BHEL and ORNL at Trichy
9	Light off ceremonies by Chairman, BHEL	Completed	April '86	BHEL at Trichy
42 10	Electrification, instrumentation and control (I&C) layout, and calibration of process control equipment, gas analyzers, gravimetric feeders and data acquisition system	Completed	May '86 - Jan. '87	BHEL and ORNL at Trichy and U.S. This activity was delayed due to delay in obtaining GOI clearance for shipping the calibration gases from the U.S. for the Beckman analyzers. There was also inordinate delays in obtaining the I&C equipment from local suppliers in India.
11	Precommissioning of boiler auxiliaries and preliminary shakedown testing	Completed	April '86 - August '86	BHEL and ORNL at Trichy
12	Testing, data gathering, and data analysis	In progress	January '87 - June '88	BHEL and ORNL at Trichy and U.S.

since the initiation of the project in November 1983.

Overview of Design, Fabrication, and Erection of the Test Facility:

Industrial Power Products Division (IPPD), BHEL, Trichy, took up the mechanical design of the test facility and the various subsystems. Preparation of manufacturing drawings were initiated after the review of and evaluation of the design by U.S. experts and subsequent modifications to the design. About seventy tons of plates, tubes, and rolled steel products were consumed in the fabrication of the combustor, pressure parts and non-pressure parts and supporting structures. Indigenous equipment (Roots blower, induced draft (ID) fan, rotary feeders, slurry pump, castable refractory, fire bricks), instrumentation and control equipment (pressure transmitters, thermocouples, coal/limestone feed indicators, flow meters, control/power cables, control switches for auxiliary equipment, strip chart recorders, and the instrumentation panel assembly) were ordered, inspected, and procured by the BHEL material management and procurement group.

The combustor, coal/limestone bunker, primary cyclone, and multiclone were fabricated at the R&D workshop attached to IPPD. Pressure part components (bed coils, convection coil, water wall and heat transfer test loops, external piping, and associated valves and fittings) were manufactured in the BHEL high pressure boiler plant shop. The fluidized bed air heater was manufactured

as a subcontract. Structural components (platform, beams, rafts, roof, etc.) were fabricated at the site and at the R&D workshop of IPPD.

Site preparation and excavation were initiated in August 1985 after the foundation and load drawings were released by the Civil Projects Group, BHEL, Trichy. A raft type foundation with twelve pedestals was adopted for the facility encompassing the combustor, FBC air preheater, multiclones, coal/limestone bunker, and gravimetric feeders. Individual foundations were provided for the Roots blower, ID fan, the slurry pump, and the duct supports. The main facility was housed under an asbestos roofing with appropriate side claddings.

The control room measuring 8 m x 5 m was erected as a separate building located 5 m from the main test facility. Special features of the control room include dust proof, noise proof, static proof, false ceiling, air conditioning, and tinted glass panels for visual observation of the combustor during operation. The control room houses the Beckman gas analysis system, the control and instrumentation panel and the Hewlett Packard Data Acquisition and Analysis System. The maintenance and service group of BHEL were responsible for the electrification, lighting, and air conditioning of the control room as well as the entire test facility.

A total of 120 tons of finished components for the test facility

and the subsystems were erected at the site. The erection was performed by S. K. S. Fabricators, Trichy, on a subcontract to BHEL.

5.1.5 AFBC Test Facility:

The test facility is located in the FBC complex at Trichy along with the other existing FBC test rigs. The site selected allowed the use of the existing peripheral facilities such as water treatment plant, condensate storage tank, air cooled condensers, coal preparation, coal handling, chimney and other utilities required for the operation. The system arrangement is shown in Figure 5.1. The total height of the combustor and supporting arrangement is 14.5 m with five floors starting with the ground level.

The combustion air and solids transport air are supplied by a Roots rotary blower. A coal-fired fluidized bed air heater will preheat the combustion air as needed. The combustion gases pass through primary and secondary cyclones (Figure 5.2). The design allows recycle of fly ash collected from the primary and the secondary cyclones into the combustor (Figure 5.3). Isokinetic dust sampling probes will be provided at the inlet and outlet of each of the primary and secondary cyclones. Space has been set aside for testing a baghouse in conjunction with the cyclones. The flue gases from the secondary cyclone are vented through an induced

FIGURE 5.1: GENERAL ARRANGEMENT OF FBC FACILITY

FIGURE 5.2: AIR AND FLUE GAS PATH

FIGURE 5.3: **ASH RECYCLE AND ASH DISPOSAL SYSTEM**

draft (ID) system to the chimney.

The coal from the preparation plant is loaded by front end loaders to the coal pit. An electrical hoist with bucket is used to elevate the coal/limestone to the respective bunkers.

Coal/limestone are metered by the gravimetric feeders before they are injected into the combustor. Both underbed pneumatic feeding and overbed feeding by a screw feeder are possible in the system (Figures 5.4 and 5.5).

The bed material (bed overflow) can be drained periodically or continuously, as the case may be through a rotary valve and stored in bins.

The demineralized water required for the unit is drawn from the existing condensate storage tank and pumped through the water circuit 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 (Figure 5.6).

The control room measures approximately 8 m x 5 m and houses the combustion control system, motor control system, instrumentation and data acquisition system.

Description of Fluidized-Bed Combustor:

The fluidized bed combustor shown in Figure 5.7 is a hot water

FIGURE 5.4:

COAL FEED SYSTEM

FIGURE 5.5: OVERBED FEEDING SYSTEM

FIGURE 5.6:

WATER COOLING AND EXTERNAL PIPELINES COOLING AND RECYCLING SYSTEM

generator of capacity 90 t/h at 10 kg/cm² pressure and 179 °C.

The cross-sectional area of the combustor is 1 m square (3.3 ft. square) and the maximum height is 11 m (36 ft) from the distributor plate. The combustor has the following features:

- o Variable bed height (300 mm to 1300 mm - 0.98 to 4.3 ft) - expanded bed height.
- o Variable freeboard height (1000 mm to 6000 mm - 3.3 ft to 19.7 ft).
- o Refractory lined freeboard walls.
- o Recycle of solids from primary and secondary cyclones into the main bed.
- o Underbed or overbed coal/sorbent feed.
- o Overfire air.

The four sides of the combustor up to 2000 mm (6.6 ft.) height from the distributor plate are refractory lined. One side wall is detachable. The detachable wall carries the inbed tube bundles. A provision is made to insert a water cooled test loop in the side opposite the detachable wall. The water cooled test loop consists of three 700 mm (2 ft.) length sections connected in series. The purpose of the water cooled test loop is to measure the heat pick up in the bed wall region.

Provision to measure the heat transfer to water cooled test loops at selected locations along the freeboard is also made in the design. The heat transfer measurements can be cross-checked by installing heat flux meters at the selected locations. The

FIGURE 5.7:

US AID/BHEL FLUIDIZED BED COMBUSTOR

horizontal convective tube bank is located at the exit of the freeboard. By raising or lowering the convection tube bank with an overhead chain block, the freeboard height can be varied in 1 m increments. The convection section in the combustor is 1.2 m in height and cools the flue gas to about 400 deg.C (750 F) before it exits the combustor.

The air distributor is a nozzle design. The coal/limestone mixture and recycled fly ash are fed through individual nozzles attached to the distributor plate. The distributor plate in turn is bolted to the windbox and can be dismantled easily by lowering the windbox. An opening is provided in the distributor plate to drain the bed material when required. Along the combustor side walls, provision is made for pressure, temperature, heat flux measurements, gas and solid sampling, overfire air and manhole doors for charging and removal of bed material.

Test Plan:

The combustor is designed to operate on three different coals, namely sub-bituminous high sulfur U.S. coal, a high volatile, high-ash Indian coal, and a 70% ash coal washery reject. The Indian coals and rejects are low in sulfur (less than 1%) and do not require any sorbent. The bed material in the case of the high sulfur U.S. coal is crushed, sized limestone; for the Indian coals and washery rejects crushed refractory and ash are used as bed material. The coal, sorbent (limestone) and crushed refractory

sizes will vary in the tests.

Other variables of interest are superficial velocity, expanded bed height, bed temperature, excess air, freeboard height, recycle ratio and coal/sorbent ratio. Effect of these variables on combustion efficiency, carbon utilization, heat release rates in the bed and freeboard, and the sorbent utilization will be studied.

5.1.6 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, coal and limestone gravimetric weigh belt feeders, and a Hewlett Packard (HP) computerized data acquisition system.

Beckman Gas Analysis System:

The flue gas analysis system consists of:

<u>Item</u>	<u>Emission Type</u>	<u>Mode</u>	<u>Model</u>	<u>Principle of Operation</u>	<u>Range</u>
01	O2-Oxygen	C	755	Paramagnetic	0-5, 10, 25, 50%
02	CO2-Carbon Dioxide	C	864	Nondispersive Infrared	0-5, 20%
03	CO-Carbon Monoxide	C	864	Nondispersive Infrared	0-1000, 10,000 ppm
04	SOx Sulfur Oxides	C	865	Nondispersive Infrared	0-2000, 10,000 ppm

05	NOx Nitrogen Oxides	C	951A	Chemiluminescence	0-10, 25, 100 250, 1000, 2500, 10,000
06	THC Total Hydrocarbons	C	400	Flame Ionization	0-15,000 ppm

C-Continuous

- Automatic sampling at three locations in the furnace have been provided.
- Sample conditioning, back purge system, heat tracing of sample line have been incorporated.
- Appropriate span and zero gases supplied by Beckman are used for accurate calibration.
- Gas sampling probes were designed and fabricated at ORNL and shipped to site.

Hewlett Packard Data Acquisition System

The data acquisition system consists of:

(1) 9836 CS	Color Desktop computers 80 character CRT, 572x390 Graphics, 640K Bytes RAM and Internal Disc Drives
(2) 3497 A	Data Acquisition/Control unit
(3) 3498 A	Extenders
(4) 2225 A	Thinkjet Printers
(5) 7475 A	Graphics 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

Merrick Coal/Limestone Gravimetric Weigh Belt Feeders

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

<u>No.</u>	<u>Size</u>	<u>Model</u>	<u>Purpose</u>	<u>Capacity</u>
01	20"	950 DSC	For Coal Feed	1000 kg/hr max.
02	12"	950 DSC	For Limestone Feed	2225-300 kg/hr
- 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%.				

5.1.7 Training And Site-Visits By Indian Engineers:

On this project, five BHEL engineers - M/s. A.V. Murthy, C. Bhakaran, S. Shanmugam, S. Sundarajan, and K.V. Seetharaman - visited the U.S. They participated in the design review meetings, workshops, and visited some of the major FBC installations in the U.S. Also during their visit, they were able to obtain hands-on experience in the operation and maintenance of the instruments at Beckman Industrial, Hewlett Packard and Merrick Corporation. 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 Georgetown University AFBC boiler plant, ORNL, the Electric Power Research Institute (EPRI), Hewlett Packard, Beckman Instruments and the Merrick Corporation.

One of the engineers also attended the International Energy Agency (IEA)-Grimethorpe Pressurized Fluidized Bed Combustion (PFBC) Lessons Learnt Workshop in St. Louis, July 15-18, 1984.

5.1.8 Reports/Publications Submitted By BHEL:

1. Evaluation of Freeboard Performance in Fluidized-Bed Combustor, Proceedings of the First USAID/GOI Workshop On Alternate Energy Resources And Development, R.P. Krishnan, November, 1983.
2. Evaluation of Freeboard Performance in Fluidized-Bed Combustor, Project Workplans and Proposal, December 1983.
3. Evaluation of Freeboard Performance in FBC, PETC FORM 81-B (1-80), US-DOE, USA, R. P. Krishnan, S. Chandrasekaran, et al., July 1985.
4. Evaluation of Freeboard Performance in AFBC, paper presented at the 8th International FBC Conference, Houston, Texas, USA, R. P. Krishnan, S. Chandrasekaran, et al., March 1985.
5. Evaluation of Freeboard Performance in a Fluidized Bed Combustor, Proceedings of the Second USAID/GOI Workshop On Alternate Energy Resources And Development, R.P.Krishnan, et al., Feb 4-6, 1985.
6. Evaluation of Freeboard Performance in Fluidized-Bed Combustor, Semi-Annual Report on USAID/GOI Coal And Biomass Projects of the Alternate Energy Resources And Development, June 1984.
7. Evaluation of Freeboard Performance in Fluidized-Bed Combustor, Semi-Annual Report on USAID/GOI Coal And Biomass Projects of the Alternate Energy Resources And Development, June 1985.
8. AFBC Test Facility for the Evaluation of Freeboard Performance, Proceedings of the Third USAID/GOI Workshop On Alternate Energy Resources And Development, S. Chandrasekaran, A. V. V. Murthy, R. P. Krishnan, December 5-7, 1985.

5.2 SCALE-UP OF AFBC BOILERS:

This project was implemented at Bharat Heavy Electricals Limited, Tiruchirrapalli (Trichy).

5.2.1 Background:

Atmospheric fluidized bed combustion (AFBC) boiler technology was introduced in India, a decade ago, by BHEL and its unique ability to burn a wide range of fuels (which include fuel oil of heating value 10000 kcal/kg down to coal washery rejects 1900 kcal/kg) and low grade fuels in an efficient and environmentally acceptable manner accounted for its rapid development. A large fraction of the estimated 112 billion tons of coal available in India is of poor quality (30 to 50% ash) and consequently the coal allocated to the power industry is an inferior variety. Conventional fired steam generators designed for good quality coal are unable to accept this quality deterioration without sacrificing the performance and availability. AFBC offers an excellent potential for the utilization of poor quality coal, washery middlings and rejects.

BHEL, in recent years, has commercialized the FBC technology for the capacity range of 10 to 60 t/h by building and operating a 45 t/h (99,200lb/h) FBC boiler for over 10,000 hours. BHEL has also developed a set of scaleup parameters to be used to build a utility

unit of 150 t/h (330,700 lb/h) and initiated the design of the unit.

5.2.2 Scope Of Work:

The objective of this project was to complete the proposed design of the 150 t/h unit including drawings and specifications, and submit it to the Tennessee Valley Authority, (TVA) U.S.A., through USAID for evaluation and verification for scaleup parameters.

BHEL was to select the parameters for the 30 MW(e) AFBC boiler based on typical customer requirements, configuration and the arrangement of the boiler and auxiliaries. BHEL would then prepare equipment lists, specifications of the equipment and arrangement drawings of the 30 MWe AFBC boiler.

TVA would evaluate the following items:

- The configuration and arrangement of the boiler.
- Equipment specifications and design of the boiler.

Also engineers from TVA would visit operating FBC boiler installations in India to gain first hand knowledge and also have technical discussions at Tirchy with project personnel. BHEL engineers would subsequently visit large AFBC boiler plants in the U.S. to acquire operational experience and also discuss with TVA the finalization of the 30 MW(e) design.

5.2.3 Project Approval:

The project was approved shortly after the First Workshop held in November 1983.

5.2.4 Work Accomplished At BHEL, (Trichy):

The proposal design with arrangement drawings and equipment specification prepared by BHEL were forwarded to TVA through USAID in December 1984. TVA had an inhouse review of the design and two TVA engineers had preliminary discussions with BHEL engineers at Tiruchi during February 1985. The comments of TVA were finalized during the visit of BHEL engineers to the U.S. in April 1985.

The following were TVA's comments.

- In view of the erosion experienced in the inclined inbed evaporator tubes at the operating installations in the U.S., TVA recommended horizontal evaporator coils with forced circulation.
- The bed temperature may be increased to 900^o C (from 850^o C) to improve combustion efficiency.
- Overbed feeding of coal may be considered to improve system

reliability.

- Two fans may be provided for forced draft, induced draft and primary air supply to improve boiler availability.
- A cooled distributor plate was recommended to avoid problems of warpage, leakage and erosion.
- The pressure drop across the air distributor is not to be less than 75 mm (3") WC during any condition of operation of the unit.
- As a followup action to this project, a proposal for the setting up of a 30 MWe demonstration project with part funding from USAID and BHEL was forwarded to USAID and also discussed with DNES, Government of India.
- Revisions of the original design were made to incorporate comments of TVA.

5.2.5 General Description of the FBC Steam Generator and Auxiliaries:

The following pages summarize the design of the 30 MW(e) steam generator and auxiliaries.

The steam generator is of the bottom supported non-reheat, natural circulation, fluidized bed semi-outdoor type unit designed

for firing coal.

The general arrangement of the boiler and auxiliaries, schemes of water and steam, air and gas are shown in the drawings Figures 5.8 to 5.10 respectively. The complete furnace section is of the welded wall type, arranged as a gas and pressure tight envelope. This eliminates the refractory material from the entire furnace wall section besides providing structural rigidity for the unit. The steam and water drum are conservatively designed and the bank tubes connect both the drums.

Part of the evaporating heating surface is located within the fluidized bed proper. The superheated steam system is in two sections. The first stage superheater is located at the furnace outlet section and the second stage superheater section is located within the fluidized bed proper to ensure the rated superheated steam temperatures. An interstage desuperheater is provided inbetween the two stages of superheaters to control the final steam temperature from the unit. The boiler is provided with a plain tube economizer fabricated from plain seamless steel tubes. The economizer will be arranged after the boiler bank section and enclosed by flue ducts. The boiler is provided with a tubular airpreheater as the last stage of heat recovery.

The coal feeding system consists of rotary airlock feeders and feed piping through which the crushed coal is pneumatically transported and fed to the fluidized bed.

FIGURE 5.8: GENERAL ARRANGEMENT OF
30 MWE AFBC BOILER

FIGURE 5.9: WATER AND STEAM FLOW SCHEMATIC

FIGURE 5.10: AIR AND GAS FLOW SCHEMATIC

The main boiler is of the bottom supported type and requires a simple concrete pier for support.

The boiler is provided with two forced draft fans for supplying the required air for fluidized combustion and two primary air fans for transporting the crushed coal to the fluidized bed. The boiler is equipped with two radial ID fans arranged after the dust collecting system.

An electrostatic precipitator is located before the ID fans to collect the flyash from the fluegas.

Boiler Pressure Parts System:

The boiler pressure parts system include economizer, circulation system including steam and water drums, boiler bank, downcomers, waterwalls and risers and superheater including the spray water control system. The details of these systems are as follows.

Economizer System:

The economizer system draws the feedwater through the feed pipes to the economizer inlet header. The economizer is located in a gas duct after the boiler bank tubes. It is a continuous loop, plain tube, drainable, horizontal and inline arrangement system. The feed water, after it is heated in the economizer, leaves the economizer

outlet header by the economizer links to the drum.

Circulation System:

The hot feed water from the economizer is discharged into the steam drum below the water level where it mixes with the recirculated water. The mixed water flows through the comparatively cooler bank tubes to the lower drum. In addition, the outermost boiler bank side wall tubes are specifically designed as downcomer sections to ensure adequate water flow to the lower water drum. In the boiler bank section the front rows of bank tubes (which are comparatively hotter) act as riser tubes and the rear rows of tubes act as downcomer tubes thus forming a circulation system within the boiler bank system.

The water from the water drum flows to the waterwall system lower headers, which act as the inlet to the furnace waterwall tubes. As the water rises up through the waterwall/bed evaporator tubes it gets converted partially into steam. The water-steam mixture, from the waterwall top headers, flow back to the drum through the riser tubes where the drum internals separate the steam and water; the saturated steam flows to the superheater section and the water flows back into the circulation system.

Superheater System:

The superheater system provided will include a first stage

superheater located at the furnace outlet, a second stage immersed in the fluidized bed and a desuperheating system in between the two stages for controlling the final superheat steam temperature.

The convection superheater located at the furnace outlet will be spaced, continuous loop, plain tubular type and would be hung from the furnace top.

The second stage superheater is located within the fluidized bed in three main segments. The startup segment has no superheater immersed in it. The inbed superheater arranged horizontally is supported by wall evaporator tubes.

For controlling the final superheated steam temperature at the rated value, over the control range of the boiler, a spray type desuperheater is provided in the steam connecting link between the two stages of superheat. This interstage desuperheater will be of a welded type with spray tubes and liners.

Design Parameters For Fluidized Bed Arrangement:

Based on the operating experience, the following basic parameters were adopted for the design of the AFBC boiler.

- Superficial fluidization velocity 2.5 m/s
- Average bed temperature 900°C

- Excess air (on fuel fed) 10%
- Combustion above bed (as % of heat input) 10%
- Average bed particle diameter 0.8 mm

The thermal design of two alternate configurations, a box and a bank tube were made. The bidrum bank tube design was selected as its height is considerably lower than that of the box arrangement and consequently affected substantial material savings.

Bed Surface Arrangement

The fluidized bed is arranged as a single bed of size 9.75 x 6.10 m. The bed is comprised of three main bed sections (2.43 x 6.1 m) in which the superheater surface and evaporator surface are immersed and a startup bed which has three sections (2.43 x 2.03 m) having only the evaporator surface immersed. During startup either of the end segments of the startup bed is initially actuated. Adjacent sections of the startup bed are then actuated and brought into service by feeding air and fuel. After sufficient steam flow has been established by the immersed evaporator sections of the startup bed, the main beds are actuated after ensuring that the inbed superheater surfaces are cooled by the steam already generated. The inbed horizontal superheater tubes are supported by the vertical evaporator tubes immersed in the bed by flexible connectors.

Windbox Arrangement

The windbox is divided into six compartments, three smaller compartments of size 2.43 x 2.03 m for startup and three main compartments of size 2.43 x 6.1 m. There is individual air ducting of each compartment, with a segmental orifice device in the air duct to monitor and control the airflow through each bed section. Adequate openings are provided in the airbox for the under fed coal pipes and the bottom ash discharge to traverse through. The whole windbox with all its attachments is hung from the side waterwall headers.

Distributor Plate Arrangement

In the first generation design, BHEL adopted a multi-orifice type distributor. Eventhough the fluidization performance was good, the long-term reliability after many startups was not very satisfactory. After testing several types of air distributors in a test rig, specially meant for this purpose, BHEL has evolved a water-cooled nozzle type distributor, finalized the material of construction and optimized the pitch of the nozzles, nozzle heights, hole size and the number of holes in the nozzle. With this design it has been possible to limit the distributor plate temperature very close to the inlet air temperature. This eliminates problems of overheating, high differential temperature and consequent warping of the plate.

The distributor plate load is directly transferred onto the

waterwalls. The design of the distributor plate includes an effective seal to the enclosure wall to prevent air bypass around the differential expansion caused by the temperature extremes that the plate is subjected to. Because of the inherent characteristics of the nozzle type design, a stagnant layer of bed always exists above the distributor plate protecting the plate against the hot bed temperature during boiler operation and also from the thermal shock that the plate would be subjected to during a unit trip, FD fan failure or load reduction and consequent segment slumping when the hot bed lands on the distributor plate.

Coal Feed System

The coal feed system draws the crushed coal of size 0 to 6 mm from the crushed coal bunker by gravity onto the rotary airlock feeders that help to feed coal against pressure. The coal discharged from the feeder is transported pneumatically to the fluidized bed through steel pipes. The air required for transportation of the coal is drawn from the forced draught fan and the pressure is boosted in the primary air fan before it is supplied to the air headers. Control valves on the headers regulate airflow through coal/air pipes. The fuel is then pneumatically conveyed to the coal splitter where the fuel is distributed and fed into the fluidized bed by underbed feedline. Individual air headers are provided for each compartment with necessary air measuring and control devices for shutoff if required. The rotary airlock coal feeder is a volumetric type of feeder which helps feed coal against

pressure, by effective sealing. A dynodrive mechanism which controls the eddy current flow helps regulate the speed of the rotary airlock feeder and hence the coal flow into the air-fuel lines. Each startup compartment is provided with one such coal feeder with a 1:13 line split, while each main bed section has two coal feeders with 1:4 line split each. Hence, there would be 33 coal feed points served by nine coal feeders. Adequate reserves have been built into the capacity of the coal feeders so as to maintain boiler load, even if a few of the feeders are out of service. Coal/air pipe bends are adequately lined up to prevent erosion. Systems to clear underfed coal pipe chokes have been incorporated to clear them during such an eventuality.

Bed-ash Letdown System

The bed-ash letdown system maintains the level of the fluidized bed which would otherwise swell to unmanageable proportions warranting a boiler shutdown. It also helps to drain the higher size material that do not fluidize or to drain the entire bed in case of an emergency.

Ash Overflow System

A major portion of the ash brought into the bed by the coal gets elutriated with the fluegas. However, the recycled flyash and the higher size ash that is retained need to be drained to maintain the bed level. Openings provided on the waterwalls, one per bed

segment, at the top of the bed with connecting pipes of required size help to drain this material by gravity. Submerged ash conveyors carry this quenched ash to the bed ash silo.

Under-bed Drain System

The under-bed drain system is essentially utilized to drain out the larger size fraction of the bed material that do not fluidize and settle to the bottom of the bed causing defluidization to set in. An airlock rotary valve which is motor operated and water cooled to handle the hot ash is provided at the outlet of the under bed drain pipe. The under bed drain pipe is sufficiently sized to drain off the entire mass of bed in case of emergency. By an indication of an unusually low temperature at the lower levels of the bed and a check of the bed pressure drop in that section, the onset of defluidization is detected and the under bed drain system is actuated to drain off the higher size fraction and restore normal operating conditions.

Draft System

The AFBC boiler has a balanced draft system with the two forced draft (FD) fans supplying the air for combustion and two induced draft (ID) fans sucking the hot gases out to maintain near atmospheric pressure in the combustion chamber. Two primary air (PA) fans boost a portion of the air leaving the FD fans and this air is utilized to transport the coal to the fluidized bed.

Tubular Airheater

Each boiler will be equipped with a tubular airheater with gas flow through the tubes and airflow outside the tubes. The size of the tube will generally be of 51 mm OD and of carbon steel. The end plates are approximately 25 mm thick and are of carbon steel material. The tube arrangements are staggered and the air side casing thickness shall be 4 mm. The airheater will be supported on necessary steel work and will be complete with all air/gas ducting, insulation and outer casing. A layer of refractory is provided above the tube sheets at entry and the airheater tubes are extended into this refractory layer to prevent erosion of the airheater tubes.

Dust Collecting System

An electrostatic precipitator is located after the tubular airheater and ahead of the ID fans to collect the ash from the fluegases before it leaves the stack. A four field EP with a specific collecting area of $118.5 \text{ m}^2/\text{m}^3/\text{sec}$ is provided to dedust the fluegases. The EP is sized for an outlet dust emission of $250 \text{ mg}/\text{Nm}^3$.

Controls and Instrumentation, Electrical for FBC Boilers

The instrumentation and controls for the boilers are generally based on the pneumatic system of measurement and controls to carry out the operation of the boiler efficiently both manually as well as on automatic controls.

All the instruments and controls for the FBC boiler are of pneumatic type. All temperature indicators are of analog type.

All remote indicating, recording and control instruments as well as the protective annunciation systems are mounted in a cubicle type control panel located inside the control room. The essential parameters such as pressure, temperature level and flow are indicated, recorded and controlled through the instruments and controllers mounted in the control panel. In addition, plant mounted local guages are also provided for local indication of pressure, level and temperature wherever required.

The automatic control system provided for the boiler is designed for efficient running of the boiler. The steam temperature control loop is also designed for maintaining the temperature within the guarantee limit. The control systems of the boilers can be divided under the following control loops.

Three Element Feed Control

This maintains the boiler drum level constant by computing feedwater flow and steam flow.

Steam Temperature Control

This takes care to maintain correct temperature outlet steam.

Furnace Draught Control

This maintains constant draught at the combustion chamber.

Combustion Control

This maintains constant pressure on the boiler by varying coal flow and air flow for optimum combustion efficiency.

5.2.6 Training And Site-Visits By Indian Engineers:

On this project Mr. S. Sundarajan was deputed to visit TVA facilities in Paducah, Kentucky and to review the design of the 30 MW(e) AFBC boiler. He also attended the conference on Fluidized-Bed Combustion in Florida and visited other FBC facilities in the US. The management team from BHEL, namely Dr. Y.P. Abbi and Dr. R. Vasudevan also visited the facilities at Paducah, Kentucky had discussions regarding the operation and experience of TVA on the 20 MW(e) demonstration plant.

5.2.7 Reports/Publications Submitted By BHRL (Trichy:)

1. **Scale-up Of AFBC Boilers**, Project Workplans and Proposal, December 1983.
2. **Scale-up of AFBC Boilers**, Proceedings of the Second USAID/GOI Workshop On Alternate Energy Resources And Development, K.M.V. Malarkkan, et al., Feb 4-6, 1985.
3. **Staus on AFBC Boiler Scale-up**, Semi-Annual Report on USAID/GOI Coal And Biomass Projects of the Alternate Energy Resources And Development, June 1984.
4. **Trip Report on Visit To US**, Sundarajan, S., April 1985.
5. **30 MW(e) AFBC Boiler Scale-up**, Semi-Annual Report on USAID/GOI Coal And Biomass Projects of the Alternate Energy Resources And Development, June 1985.
6. **30 MW(e) AFBC Demonstration Plant** Proceedings of the Third USAID/GOI Workshop On Alternate Energy Resources And Development, G. Vishwanathan, and S. Shanmugam, December 5-7, 1985.
7. **AFBC Boiler Scaleup**, Proceedings of the Third USAID/GOI Workshop On Alternate Energy Resources And Development, K.M.V. Malarkkan, S. Rajaram, G. Vishwanathan, and S. Sundarajan, December 5-7, 1985.
8. **Final Report on 30 MW(e) AFBC Boiler Scale-up**, April 15, 1987.

5.3 RHEOLOGY, STABILITY, AND COMBUSTION OF COAL-WATER MIXTURES:

This program was a joint effort between Bharat Heavy Electricals, Limited (BHEL), Tiruchirapalli (Trichy) and Central Fuel Research Institute (CFRI), Dhanbad.

5.3.1 Background:

Coal, besides its complex structure and heterogeneous nature, is solid in form and hence poses considerable problem in its mining, transportation, storage, distribution and combustion. Conversion of coal to liquid form would obviously eliminate some of the constraints and coal-liquid could be used with almost all the conveniences of conventional liquid fuels.

It is well-known that the chemical conversion of coal to oil via direct and indirect hydrogenation routes, the technology of which is largely established, is highly capital-intensive and involves severe environmental problems. One of the mid-term solutions is to transform coal in liquid form by suitably mixing it with an appropriate carrier liquid. On the basis of this concept, different types of coal-liquid mixtures -- viz., coal-oil, coal-methanol, coal-liquid CO, and coal-water mixtures -- fuels have assumed

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importance and are in various stages of development in several countries. Of all the coal-liquid mixtures presently being

developed, coal-water mixture (CWM) fuels appear to be economically most attractive.

The CWM fuel is essentially physical transformation of coal into fluid form with minimum quantity of water which practically acts as a carrier. CWM is a low-cost coal-based environmentally acceptable liquid fuel which can be stored, transported, pumped, atomized and burnt like conventional heavy liquid fuels. This fuel-form, when correctly prepared with low-ash demineralized coal, to an extent resembles petroleum-based residual fuel oil, and can be used as a substitute for it in existing oil-designed boilers with minimum alterations.

CWM is significantly different from ordinary coal-water slurry, which is generally used for long distance transportation of coal through pipeline. Transportation slurries are usually unstable and dilute, concentration of coal being about 50 weight per cent. The particle size of these slurries is coarse with top size up to 2.0 mm. They need dewatering and drying prior to their combustion.

CWM, despite its higher viscosity, has many advantages:

- o It is concentrated and can be burned directly without dewatering and drying.
- o It is non-settling and physically resembles heavy fuel oil; it can be stored, pumped, transported, atomized and burnt like heavy fuel oil.
- o It can be transported in laminar flow regime without any limitations of critical velocity and slope.

- o Its combustion characteristics are reportedly better compared with dry pulverized fuel, and can be used in coal-designed boilers without appreciable derating and any additional ash problem.
- o It is environmentally more acceptable as combustion of CWM generates less NO .

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In view of these attractive features, there is significant interest in many countries in the development of CWM fuel and suitable burner system for its combustion.

5.3.2 Relevance Of CWM In Indian Context:

The objective of CWM technology development mainly depends on the local conditions and the characteristics of coal available. In western countries and Japan, industrial and utility boilers are mainly oil-fired. The principal problem is to find a low-cost coal-based liquid fuel which could be used as a substitute for fuel oil in oil-designed boilers with minimum modification. The CWM fuel has been found to be remarkably suitable for this purpose. The ash content in coal should, however, be as low as possible (preferably below 3.0%), and the properties of CWM should be close to that of fuel oil. For this particular application, coal beneficiation is an integral part of CWM process and both are considered partner technologies.

The situation in India is, however, different; oil-fired utility boilers are very limited in India, and replacement of oil by CWM

does not have much relevance. Most of the industrial and utility boilers in the country use pulverized coal as fuel. Typical Indian coals are high in ash (20-35%) with poor washability characteristics. This is predominantly because of the difficulty in liberating the mineral matter which is generally intimately mixed with the physical structure of the coal particle. Under this peculiar situation, the development of technology for direct use of high-ash coal is one of the priority areas of R&D activities. This has resulted in the development of fluidized-bed combustion technology in which the ash content of coal is not of primary concern. Coal in the form of highly-loaded CWM would be a convenient feedstock, particularly for pressurized fluid-bed combustion and gasification. CWM, being liquid in form, could be relatively easily pressurized and fed to the unit without disturbing the system pressure.

Another aspect causing concern in the use of coal in India is its uneven location of reserves. The locations of major coal reserves are concentrated in the eastern parts of the country and, in consequence, availability of coal at the industrial centers at the western and southern parts of the country is hardly regular. Presently, coal is transported mainly by rail, which has reportedly reached a limiting point as to carrying additional coal, the quantum of which is sharply increasing with the rapid industrial growth. In the context of this background, it has been proposed to transport coal hydraulically through pipeline which, in general, has several overriding merits, viz., high operating factor,

immunity of inflation, economy of scale, low labor intensiveness and better environmental acceptability.

The two main methods for transporting coal through pipeline are in the form of traditional coarse coal-water slurry or concentrated CWM fuel. Coal-water transportation slurry, as mentioned earlier, cannot be directly used. It needs dewatering and drying, involving considerable consumption of thermal energy for use as pulverized fuel. CWM, on the other hand, can be directly burnt without dewatering and drying in coal-capable boilers with minor modifications. Hydraulic transport of coal in the form of concentrated CWM fuel has many distinct advantages over the traditional slurry:

- o Since CWM is largely non-settling, there is hardly any constraint as to critical velocity of the mixture and slope of pipeline. Velocity of CWM would be relatively low, and hence it would lead to less erosion of the pipeline. Size degradation of coal particles during transportation is also expected to be minimum.
- o No dewatering and thermal drying is required, making it possible to accommodate more fines in CWM.
- o Separation of particulates from water, effluent treatment and disposal is not involved.
- o Requirement of water is relatively low.
- o Stockpiling of pulverized coal is not involved. This might pose a serious problem with the typical Indian high-reactive non-coking coals.

These benefits could be achieved at the expense of a fraction of thermal energy of coal owing to the latent loss inside the boiler

for evaporation of water in CWM. The extent of this penalty obviously depends on the coal quality (calorific value) and its concentration in CWM.

The main constraint in transportation of highly-loaded CWM (coal concentration about 70%) through pipeline is its high viscosity (about 1000 cp) and difficulty in pumping (at higher velocity). Several alternatives could be considered for optimizing these factors to arrive at an acceptable option. One alternative approach would be transportation of about 90 % of coal in the form of slightly dilute CWM in order to have lower viscosity, the remaining part of the coal in dry form, mixing the two streams at the point of application to produce CWM of the desired concentration and characteristics.

Lastly, coal has a significant price advantage over other fossil fuels. The preliminary cost analysis indicates that the economics of CWM are attractive, particularly in the Indian context.

The typical costs of coal, CWM fuel and fuel oil are compared below:

<u>Fuel Type</u>	<u>Cost per Ton (Rs.)</u>	<u>Calorific Value GJ/Ton</u>	<u>Cost per GJ</u>
Coal	400.0	20.0	14.0
CWM	600.0	12.0	50.0
Fuel Oil	3000.0	40.0	87.0

1 US\$= Rs 12.75

It may be seen that the economic viability of CWM over fuel oil is very encouraging, the price differential of these two fuels being about Rs. 40.0 per GJ.

The CWM technology is relatively simple and most of the equipment, including process control instruments, is conventional. The details of cost for bulk-scale preparation of CWM under Indian conditions have not yet been analyzed. However, preliminary estimates show that the cost of equipment for a 500 t/day CWM preparation plant would be about Rs. 15 million. The capital cost of larger plants would have the usual benefit of capacity. If integrated with a coal-fired thermal power plant, the cost of a CWM manufacturing unit could be considerably less as some of the facilities, viz., coal handling, storage, crushing and other equipment for coal preparation are common to both processes.

In view of these attractive features, there is considerable interest in India to develop the technology for commercialization.

5.3.3 Scope Of Work:

In India, Central Fuel Research Institute (CFRI) and Bharat Heavy Electricals Limited (BHEL), Tiruchirapalli, have undertaken work in this emerging area. Under USAID/GOI sponsorship CFRI was concerned with the development of a process for the preparation of CWM with typical Indian coals, and characterization of the fuel. The development of burner and suitable combustion system was the

primary responsibility of BHEL.

Laboratory-scale studies were conducted at CFRI, to prepare coal-water mixtures using coal with and without beneficiation. The rheology and stability of these fuels were investigated as a function of the rank and type of coal, additives, and particle size distribution of coal. The milestone chart outlines the major activities undertaken by CFRI and their schedules as per project plans.

The combustion studies at BHEL, Trichy were to focus on the combustion and erosion characteristics of the CWM fuels, pressure drop and mixing studies to obtain data for scaleup of large scale CWM preparation equipment and the combustor.

5.3.4 Project Approval:

While the project was approved by AID upon submission of the project plans, the CFRI segment of the project received formal approval from DNES (GOI) in January 1984. BHEL received approval for its segment in September 1984.

5.3.5 Work Accomplished At CFRI:

At CFRI four types of experiments were conducted. These were laboratory-scale preparation, larger-scale batch preparation,

characterization and preliminary combustion tests of CWM.

Three types of coal were used in the preparation of CWM. These were coal samples of Samla seam (West Bengal), Baragolai (Assam) and Talcher (Orissa). The proximate and ultimate analyses of the coal samples are shown in Table 5.2, and particle size analysis in Table 5.3. The Baragolai coal had the highest calorific value with the lowest (6.0%) ash content. The volatile matter content of the coal was also high. The coal was, however, high in sulphur content. From particle size analysis it was observed that the particles less than 50 microns were much fewer in the Talcher coal sample as compared with that of other coals.

According to the standards of typical Indian coals, the Samla seam coal had a medium ash content (14%). Talcher coal represents typical high-ash Indian coal, the ash content being about 41.0%. This type of coal is generally used in pulverized-fuel-fired thermal power plants in India.

Coal samples were used without any beneficiation or pretreatment. Coals in most of the experiments were pulverized in a dry grinding mill. A few experiments were made in wet grinding in order to determine the effect of types of mills on the properties of CWM. For the size reduction of coal, dry grinding mill and sieving systems were used.

The additive systems used consisted essentially of a combination of

Table 5.2: Analysis of Coal Samples Used Experiments

Analysis, % (As received basis)	Coal Sample		
	Samla	Talcher	Baragolai* (Assam)
<u>PROXIMATE</u>			
Moisture	6.0	2.5	3.5
Ash	14.0	40.9	6.3
Volatile Matter	31.3	26.0	42.0
Fixed Carbon	48.7	30.6	48.2
	100.0	100.0	100.0
<u>CALORIFIC VALUE</u>			
Kcal/kg	6350.0	4140.0	7025.0
<u>ULTIMATE</u>			
Moisture	6.00	2.50	3.50
Ash	14.00	40.90	6.30
Carbon	64.44	43.13	69.70
Hydrogen	4.21	3.31	4.90
Sulphur	0.53	0.32	5.40
Nitrogen	1.79	1.02	1.40
Oxygen (by diff.)	9.03	8.82	8.80
	100.00	100.00	100.00
<u>PETROGRAPHIC</u>			
Vitrinite	74.2	60.0	89.8
Semivitrinite	1.8	-	1.3
Extinite	9.2	10.0	4.8
Inertinite	14.8	30.0	4.1
	100.0	100.0	100.0

*Hand-picked sample

a few chemical compounds in order to control the different properties of CWM. Some of the compounds were derived from coal. A number of additive systems were used for comparing their effectiveness. The additives used included Celex (magnesium salt of lignosulphonic acid), Lomar-D (sodium salt of alkylnapthalene sulphonic acid), and coal-derived stabilizers NC-1, NC-2, NC-3.

Ordinary process water as available in the laboratory was used in the preparation of CWM.

The following instruments were used for characterization of CWM

- o Haake Viscometer for Rheological Studies
- o Microtrac Particle Size Analyzer
- o Zeta-meter for measuring electrokinetic characteristics of coal particles
- o Standard sieves
- o Standard balance
- o Ovens for moisture determination
- o Glass apparatus for measuring stability and softness of pack (S.O.P.) of settled mass
- o Standard apparatus for proximate and ultimate analysis of feed coals.

For preliminary combustion tests, the existing 10 kg-coal-per-hour fluidized-bed unit was used. A flow diagram of the unit is shown in Figure 5.11. The unit was designed and operated for burning coal having a particle size less than 6 mm. It is provided with air preheater, coal hopper with screw feeder, internal cooling coil, dust-arresting systems, temperature and pressure measuring devices, and other accessories.

FIGURE 5.11: FLOW DIAGRAM FOR FLUID-BED COMBUSTION UNIT

The feed system of the unit was modified for introducing CWM. A feed-tank and a small gear pump were incorporated for this purpose. Other components of the unit remained unchanged for preliminary tests for the combustion of CWM fuels.

5.3.6 Results of Laboratory Experiments at CFRI:

The rheograms (effect of shear rate on shear stress) and graphical determination of flow consistency numbers and flow behavior indices were determined for CWM with three coals, under different conditions. The experimental results of the effects of the principal parameters listed below are presented and briefly discussed.

- o Coal type, concentrations and coal blends
- o Nature and concentrations of additives
- o Particle size consist
- o Temperature
- o Time of shearing at particular shear rate
- o Shear rate

Coal type, Concentration And Coal Blends:

Three coals, namely, Samla, Baragolai (Assam) and Talcher samples, and blends of Samla and Assam coals, were used for the preparation of CWM. The particle size consists for all the samples were below 100 mesh (150 microns), the size distributions for Samla and Assam coals were more or less identical, having about 90% below 300 mesh (50 microns). This fraction in Talcher coal was, however, below

10.0%.

The effects of concentrations of CWM with Samla and Assam coals, with no additive, on viscosity are shown in Figure 5.12. It can be seen in Figure 5.12 that the viscosities of CWM with Samla and Assam coals increased steeply beyond 54 and 60 weight per cent respectively. At 57 per cent concentration, the viscosities of CWM with Samla and Assam coals were 700 and 150 mPa.S respectively. This clearly shows that Assam coal was much superior to the other coal type (Samla) for coal-water dispersions. The specific reason for this remarkable performance of Assam coal could not be pinpointed. It has been reported that this coal sample contained certain clay materials which adversely affected the separation of fines for beneficiation by froth flotation techniques. The zeta-potential of Assam coal was higher (- 42 mv) compared to other coal samples (about -20mv). The zeta-potentials of different coal samples are presented in Table 5.4. The special clay matter in Assam coal might be responsible for this enhanced electrokinetic effect. The higher zeta-potential gave rise to relatively stronger repulsive forces between the coal particles causing better dispersion, less agglomeration, and lower viscosity of CWM. It may therefore be established that CWM prepared using Assam coal is particularly suitable for the preparation of CWM fuel.

Nature And Concentration Of Additives:

From experimental studies with Celex and Lomar-D, it was observed

FIGURE 5.12: EFFECT OF COAL CONCENTRATION ON CWM WITH SAMLA AND ASSAM COALS

Table 5.3: Size Analysis of Coal Samples

Particle Size less than	Coal Samples		
	Samla	Talcher	Assam
300 mesh (50 microns), %	93.0	6.3	94.0
200 mesh (75 microns), %	98.0	79.3	100.0
100 mesh (150 microns), %	100.00	97.9	100.0

Table 5.4: Zeta - Potentials of Coal Samples

Coal Samples	Zeta - Potential - mv
Samla	19.6
Talcher	21.0
Assam	42.4

that the optimum concentration of celex was 1.5 to 1.75 weight per cent of CWM. The results of the series of experiments reported here were conducted essentially to find the variation in viscosity of CWM with optimum concentration of celex with different concentrations of Samla, Assam and Talcher coals (ash 41%). The results are shown in Figures 5.12 and 5.13. The increase in viscosity of CWM with Samla and Assam coal concentrations with additive is shown in Figure 5.12, along with that of CWM without additives for comparison. Figure 5.13 shows the increase in viscosity of Talcher high-ash coal (ash 41.0%). The effect of additives in lowering the viscosity of CWM is apparent. This particular additive (celex) was also more specific for Assam coal. 60% CWM with Samla coal had the same viscosity (1300 mPa.S) as 70% CWM with Assam coal and the same concentration of celex. Although 60% CWM with Samla coal and 65% CWM with high-ash Talcher coal (Figure 5.13) had the same viscosity(1300 mPa.S), on the basis of concentration in terms of volume per cent, the performance of both coals was almost identical. The sp. gravity of Talcher coal was higher because of higher ash content against 14.0% for Samla coal.

The effects of blends of Samla and Assam coals, keeping the overall concentration constant at 60%, is shown in Figure 5.14. It may be seen that the favorable influence of Assam coal could be obtained even when it was blended with Samla coal to the extent of about 60.0%.

The effects of concentrations of NC-1, NC-2 and NC-3 (added along

FIGURE

5.13: EFFECT OF COAL CONCENTRATION
ON VISCOSITY OF CWM
WITH TALCHER COAL

**FIGURE 5.14: EFFECT OF BLENDING IN CWM
SAMLA COAL WITH ASSAM COAL**

with celex) in CWM on the viscosity, stability and softness of pack (SOP) of the settled mass are shown in Figures 5.15, 5.16, and 5.17. At about 0.125% concentration of NC-1, when added along with 1.75% of celex, viscosity of 60% CWM with Talcher coal was minimum, while both stability and SOP were 100% (Figure 5.15). The effect of NC-1 on enhancing the stability was remarkable. There was no supernatant liquid at the surface of CWM with this system, showing that synergetic stability was satisfactory.

The effect of NC-2 as shown in Figure 5.16 was comparatively less predominant. The viscosity increased with a very small dose (0.025%) of the additive without any change in stability. Both stability and viscosity decreased with further increase in concentration of this additive. Figure 5.17 presents the effect of NC-3, which showed an increase in viscosity as well as stability. Its main function was found to be in stabilizing the suspension.

Particle Size Distribution:

In this series of experiments, two particle size consists -- coarse (150 to 75 microns) and fine (less than 50 microns) -- were mixed in different proportions in the preparation of 60% CWM. The objective of mixing two size fractions was to ensure bimodal distribution. The effects of particle size consists in CWM prepared with Samla and Assam coals were determined. The results are shown in Figure 5.18. The following observations were arrived at from these results:

FIGURE

5.15:

EFFECT OF ADDITIVE (Nc-1)
ON VISCOSITY, STABILITY
AND SOB OF 60% CWM
WITH TALCHER COAL

LEGEND:

Additive-Celex 1.75%

Temperature : 35°C

Particle Size: -100 B.S.S.

Shear Rate : 1024 sec⁻¹

FIGURE
5.16:

EFFECT OF ADDITIVE (Nc-2)
ON VISCOSITY, STABILITY
AND SOB OF 60% CWM
WITH TALCHER COAL

FIGURE

5.17: EFFECT OF ADDITIVE (Nc-3) ON VISCOSITY, STABILITY AND SOP OF 60% CWM WITH TALCHER COAL

LEGEND :

Additive-Celex 1.75%

Temperature : 35°C

Particle Size: -100 B.S.S.

Shear Rate : 1024 sec⁻¹

FIGURE 5.18: EFFECT OF PARTICLE SIZE CONSIST IN 60% CWM WITH SAMLA (ASH 14.0%) AND ASSAM (ASH 6.0%) COALS WITH ADDITIVE (CELEX 1.5%)

- o Viscosities (i.e., 100% coarse or fine particles) were higher for monomodal particle size distribution with both coal types.
- o Bimodal distributions with particular proportion of coarse and fine particles gave minimum viscosity with both coal samples.
- o Optimum proportion of size fractions was different for the coal samples studied. The ratios of coarse to fine for Samla and Assam coals were 50:50 and 30:70 respectively.
- o Optimum proportion of size fractions which gave lowest viscosity, also showed the highest dry packing density of the particles. The variation in dry packing density with the change in particle size consists of Samla coal is also shown in Figure 5.18.

These results would be useful for formulating methodologies for the preparation of CWM fuel in bulk scale.

Temperature:

The effects of temperature on the viscosity of 60% CWM prepared with Talcher coal and with four different additive systems, viz., celex, NC-1, NC-2 and NC-3 were determined. The viscosities were measured at four different temperatures, viz., 25, 30, 35 and

40 C. The results are shown in Figure 5.19. It was observed that the change in viscosity with temperature was very much dependent on the type of additives used. With some systems, viscosity increased with the temperature. The viscosity of CWM prepared with celex did not show any appreciable change with an increase in temperature. However, the viscosity was found to increase when NC-1 and NC-2

FIGURE
5.19:

EFFECT OF TEMPERATURE
ON VISCOSITY OF 60% CWM
WITH DIFFERENT ADDITIVES

LEGEND:

Coal : Talcher
Particle Size: -100 B.S.S.

were used as additives. With NC-3, the viscosity of CWM decreased up to 40 °C and thereafter showed a tendency to rise. The degree of variation in viscosity with temperature is believed to be closely related to the structure of CWM including additive - coal surface interaction.

Time Of Shearing:

In this series of experiments thixotropic characteristics of CWM with different concentrations of Talcher coal and 1.75% celex were determined. Typical thixotropic suspensions are time-dependent, i.e., exhibit a gradual decrease in viscosity at constant shear rate. The experimental results presented in Figure 5.20 show that the viscosities of CWM slurries with all the concentrations of coal studied initially decreased and after about 2 minutes of shear attained equilibrium and it remained almost constant. This suggests that the viscosities of the particular CWM system were practically time-independent and rheological properties would be largely governed by the Herschel-Bukley equation.

Shear Rate:

The effect of shear rate indicates more precisely the rheological properties of a suspension and hence is of considerable practical importance. Six series of experiments were conducted to establish this effect under different conditions of CWM suspensions.

FIGURE 5.20: EFFECT OF SHEARING TIME ON VISCOSITY OF CWM WITH DIFFERENT CONCENTRATIONS OF TALCHER COAL

LEGEND:

Additive-Celex 1.75%

Nc-1 0.15%

Temperature: 35°C

Effect of shear rate on the viscosity of CWM with three different concentrations of Talcher coal and additive (Figure 5.21).

Rheological characteristics of the above CWM (Figures 5.22 and 5.23).

Rheological characteristics of

60% CWM with Samla coal and additive (Figures 5.24 and 5.25)

65% CWM with Assam coal and additive (Figures 5.26 and 5.27)

60% CWM with blends of Samla and Assam coals (Figures 5.28 and 5.29)

57.8% CWM with Assam coal without additive (Figures 5.30 and 5.31)

The effect of shear rate on the viscosity of CWM with Talcher coal as presented in Figure 5.21, shows that the viscosity sharply

decreased with an increase in shear rate up to about 400 sec⁻¹ at all concentrations of coal. Thereafter, the viscosity remained more or less constant. With this particular CWM, the shear thinning or pseudoplastic properties were prominent up to that shear rate (400 sec⁻¹). The Herschel-Bukley constants, namely, flow consistency number (K) and flow behavior index (n), were determined. These characteristics along with yield stress of the CWM with Talcher coal at three different concentrations are shown in Table 5.5. At lower concentrations the flow index was 0.72 which increased to about 1.0 at a coal concentration of 65%. Yield stress also increased from 5 to 50 Pascals with an increase in coal concentrations. It was observed that the rheological

FIGURE 5.21: EFFECT OF SHEAR RATE ON VISCOSITY OF CWM WITH DIFFERENT CONCENTRATIONS OF TALCHER COAL

LEGEND:

Additive-Celex 1.75%
Nc-1 0.15%
Particle Size: -100 B.S.S.

FIGURE 5.22:

RHEOLOGICAL CHARACTERISTICS OF CWM
WITH DIFFERENT CONCENTRATIONS
OF TALCHER COAL

LEGEND:

Additive-Celex 1.75%

Nc-1 0.15%

Particle Size: -100 B.S.S.

(150 Microns)

FIGURE

5.23:

RHEOLOGICAL CHARACTERISTICS
OF CWM WITH TALCHER COAL

LEGEND:

Additive-Celex 1.75%

Nc-1 0.15%

Particle Size: -100 B.S.S.

FIGURE 5.24: RHEOLOGICAL CHARACTERISTICS
OF 60% CWM WITH SAMLA COAL

FIGURE 5.25:

RHEOLOGICAL CHARACTERISTICS
OF 60% CWM WITH SAMLA COAL

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LEGEND:

Yield Stress	Symbol	Pa
(1) -300 - 100%	○	15
(2) -300 - 40%	⊗	10
(3) -300 - 60%	△	12

FIGURE 5.26: RHEOLOGICAL CHARACTERISTICS
OF 65% CWM WITH ASSAM COAL

FIGURE 5.27: RHEOLOGICAL CHARACTERISTICS
OF 65% CWM WITH ASSAM COAL

FIGURE 5.28: RHEOLOGICAL CHARACTERISTICS
OF 60% CWM WITH BLEND OF
SAMLA AND ASSAM COALS

FIGURE 5.29: RHEOLOGICAL CHARACTERISTICS
OF 60% CWM WITH BLEND OF
SAMLA AND ASSAM COALS

FIGURE 5.30: RHEOLOGICAL CHARACTERISTICS
OF 57.8% CWM WITH ASSAM COAL

FIGURE 5.31: RHEOLOGICAL CHARACTERISTICS
OF 57.8% CWM WITH ASSAM COAL

Table 5.5: Yield Stress, Flow Consistency Number and Flow Behavior Index of CWM with Different Concentrations of Talcher

Coal Concentration In CWM %	Yield Stress Pascal	Flow Consistency Number K, Pascal	Flow Behavior Index n
60	5.0	0.15	0.72
62	25.0	0.30	0.85
65	50.0	0.70	1.05

Table 5.6: Yield Stress, Flow Consistency Number and Flow Behavior Index of 60% CWM with Different Size Consists of Samla Coal

Particle Size Consist: Ratio of Coarse (150 to 70 microns) to Fine (less than 50 microns)	Yield Stress Pascal	Flow Consistency Number K Pascal	Flow Behavior Index n
0 : 100	15	0.76	0.78
60 : 40	10	0.36	0.80
40 : 60	12	0.12	0.77

characteristics of CWM with this particular system changed from pseudoplastic to Bingham plastic with an increase in the concentration of coal.

The Hershey-Buckley constants for the other systems, namely, 60% CWM with Samla coal, 65% CWM with Assam coal, 60% CWM with Samla-Assam blend and 57.8% CWM with Assam coal (without additive) computed from Figures 5.23, 5.27, 5.29 and 5.31 are given in Tables 5.6, 5.7, 5.8 and 5.9 respectively.

It was observed that in all cases, CWM prepared with these coal samples and additive (celex) showed pseudoplastic properties with yield stress. The CWM slurry showed a tendency to behave like a Bingham plastic fluid under particular conditions which varied from system to system. For CWM with higher fractions of fine Samla coal particles, the flow behavior index was more than 0.70. On the other hand, CWM with Assam coal containing larger fractions of coarse particles showed similar behavior. This again demonstrates that the properties of CWM are very much case dependent and need to be established separately for each system.

5.3.7 Work Accomplished At BHEL, Trichy

A fluidized bed test facility and an atomized combustion test facility were designed, and fabricated. Erection of these facilities is in progress. Meanwhile, in an existing fluid-bed

Table 5.7: Yield Stress, Flow Consistency Number, and Flow Behavior Index 65% CWM with Different Particle Size Fractions of Assam Coal

Particle Size Consist: Ratio of Coarse (150 to 70 microns) to Fine (less than 50 microns)	Yield Stress Pascal	Flow Consistency Number K Pascal	Flow Behavior Index n
80 : 20	11.0	0.84	0.74
60 : 40	14.0	0.44	0.70
20 : 80	12.0	0.20	0.48

Table 5.8: Yield Stress, Flow Consistency Number and Flow Behavior Index of 60% CWM with Different Proportions of Samla - Assam Coal Blends

Proportion in Blend: Samla : Assam Coals	Yield Stress Pascal	Flow Consistency Number K	Flow Behavior Index n
60 : 40	16	0.26	0.73
40 : 60	8	0.19	0.67
20 : 80	6	0.12	0.57

Table 5.9: Yield Stress, Flow Consistency Number and Flow Behavior Index of 57.8% CWM with Different Particle Fractions of Assam Coal (without additive)

Particle Size Fractions: Ratio of Coarse (150 to 75 microns) to Fine (less than 75 microns)	Yield Stress Pascal	Flow Consistency Number K Pascal	Flow Behavior Index
60 : 40	2.4	0.60	0.80
40 : 60	7.0	0.05	0.40
20 : 80	8.0	0.12	0.48

test rig, slurries prepared out of washery tailings, spent wash from a distillery and a Kopers-Totzek gasifier exhaust char were successfully fired.

Fluidised Bed Test Facility:

A 0.5 m x 0.5 m fluidized bed test rig to fire coal water slurries was designed, fabricated and is being erected. This furnace has provision to test different feeding systems for CWS, like under bed and over bed feeding. To increase the residence time of sprayed particles which otherwise get ellutriated, part of the air can be introduced as over fire air tangentially in the 4 corners above the slurry admission point. As of June 1986, the following progress was reported on this facility:

- o Civil foundation work for fluidized bed combustor completed.
- o Water jacketed 0.5 m x 0.5 m fluidized bed combustor, structurals and platforms were fabricated. Structural columns were erected.
- o CWS preparation tank with Paddle mixer was fabricated and commissioned.
- o Slurry feeding system with pump, control and drain valves and water flushing line were fabricated.

Atomised Combustion Test Facility:

A test facility to burn 400 kg/hr of atomized CWS was designed, fabricated and is being erected. It has facilities for micronizing,

mixing, agitating and for preparation of the slurry. The following was the status on this facility as of June 1986.

- o Civil work and foundations for CWS preparation and storage tank, coal storage bunker, hot air ducting supports has been completed.
- o Civil foundation work for atomized CWS combustion furnace, pumps, and subsystems has been completed.
- o Design of CWS preparation and storage tanks and hot air ductings has been completed. Storage tank, preparation tank for CWS have been fabricated.
- o An air cooled furnace for atomized combustion of CWS has been fabricated.
- o Three types of atomizers (Y jet, an internal mix and an external mix types) have been fabricated.

Results Of Preliminary Tests At BHEL:

Slurry preparation and handling experiments at BHEL focused on the type and concentration of additives to be used for large-scale slurry preparation. Fifty different additives were tested and the additives which gave a minimum viscosity at a shear rate of 100

-1
sec were chosen for bulk slurry preparation and used in combustion tests. During these tests it was also found that

- o For most of the Indian coals non-ionic additives (hydroxide of a substituted phenyl polymer) at 0.1% by weight concentration were found to be adequate.
- o Bimodal distribution and a colloid content high enough to give a specific surface area greater then or equal to 125

m /cc gave better stability.

- o The samples of CWS were found to be stable for more than one week. The stability was monitored by keeping all the samples in tall, vertical, glass cylinders and determining the percentage of coal in the top layer. The densities of all the samples were found to remain constant for one week with marginal differences.
- o Some typical characteristics of the slurries are given below.

	Moisture %	Ash %	VM %	FC %	% Coal/char in slurry	Viscosity at 125 -1 sec shear rate
Korba West	8.9	49.0	18.3	23.8	60%	338.8
Swang Middlings	2.7	44.4	18.4	34.5	60%	314.6
Gasifier Char	2.2	81.1	3.2	13.5	76%	242.0

A slurry preparation and handling system consisting of a slurry storage and mixing tank, a closed loop pipe line with rubber lined pinch valves and a water flushing system was commissioned and tested. It was found that washery tailings, loaded up to 62% in the slurry could be handled trouble free.

Preliminary combustion tests determined that firing of the slurries in the available fluid-bed unit was possible. Some of the slurries fired successfully included:

- Slurry prepared from K-T Gasifier exhaust char of 1040 kcal/kg with coal to water ratio of 60 to 40, by spraying in the free board and feeding of coal into the bed. The quantity of coal and slurry were in equal proportion.

- Washery tailings from West Bokaro of 6488 kcal/kg CV with an ash content of 24% fired without any support coal.
- Spent wash sludge cakes from Trichy Distillates Ltd., (7.5% moisture, 47.4% ash, 45% volatiles and no fixed carbon) of 1540 kcal/kg calorific value was prepared as a slurry with solids to water ratio of 0.50. Slurry was fired by over head bed spraying and coal was fed into the bed for sustaining bed temperature. Slurry to coal feed ratio by weight was 1:1.

5.3.8 Equipment Supplied By USAID:

The following instruments/equipment were supplied under USAID/GOI sponsorship to BHEL on this project.

- o Brookfield viscometer for on line measurement
- o Haake Viscometer for viscosity characterization
- o Philadelphia mixer for slurry agitation and mixing
- o Wilden Diaphragm pump for slurry transfer
- o Kay-Ray density meter with mass flow multiplier
- o Ceramic tips for atomisers

CFRI received the following instruments:

- o Haake Viscometer for viscosity characterization
- o Microtrac Particle Size Analyzer

5.3.9 Training And Site-Visits By Indian Engineers:

Dr. M. Chakraborty, CFRI, principal investigator on this project visited PETC from March 6 to April 11 1984. At PETC, he focused on

the fundamental experimental studies on coal-water slurries and the use of state-of-the-art instruments used for characterization of the slurries. Similar instruments were provided to CFRI. He also attended the conference on "Newer Coal Technologies " from April 17-24 1985 held in Honolulu, Hawaii, along with the principal investigator Mr. K.M.V. Malarkkan from BHEL, Trichy.

Mr. T.K. Bhowmik an engineer from CFRI visited the US in January 1984 for a four-week period to undergo training at PETC in the area of slurry preparation, and use and operation of analytical instruments.

One engineer from BHEL visited CFRI, Dhanbad during the course of the program and was provided training in the following areas:

- o Use of instruments for CWS characterization.
- o Facility planning for large scale CWS preparation.
- o Details pertaining to the use of additives for slurry preparation.

5.3.10 Reports/Publications Submitted By CFRI And BHEL

1. Considerations for the Development of Coal-Water Mixtures as an Alternate Fuel Proceedings of the First USAID/GOI Workshop on Alternative Energy Resources and Development, Chakraborty, M., et.al., November 1983.
2. Coal-Water Slurry Combustion Technology- BHEL's Viewpoint in the

Indian Context Proceedings of the First USAID/GOI Workshop on Alternative Energy Resources and Development, Malarkkan, K.M.V., et. al., November 1983.

3. Rheology, Stability And Combustion of Coal-Water Mixtures, Project Workplans And Proposal, December, 1983.
4. Rheology, Stability, and Combustion of Coal-Water Slurries, Semiannual Report on Biomass and Coal Conversions Projects of USAID/GOI Alternative Energy Resources and Development Program, USDOE, Pittsburgh Energy Technology Center, Pittsburgh, PA, 15236, June 1984.
5. Coal-Water Mixtures Fuel and Preliminary Studies on its Rheological Characteristics, Proceedings of the Second USAID/GOI Workshop on Alternative Energy Resources and Development, Chakraborty, M., et.al., February 1985.
6. Coal-Water Slurry Combustion in Fluid-Beds- Prospects in India, Proceedings of the Second USAID/GOI Workshop on Alternative Energy Resources and Development, Malarkkan, K.M.V., et. al., February 1985.
7. Studies on Stability and Flowability of Coal-Water Mixtures (CWM Fuel) Proceedings of the Third USAID/GOI Workshop on Alternative Energy Resources and Development, Chakraborty, M., et.al., December 1985.
8. Development of Coal-Water Slurry Combustion Technology Progress in BHEL Proceedings of the Third USAID/GOI Workshop on Alternative Energy Resources and Development, Malarkkan, K.M.V., et. al., December 1985.
9. Coal Technology Development Activities In India, Conference on Newer Coal Technologies: Implications for Energy and Development Policies in Asia and the Pacific, Chakraborty,M., April 17-24 1985.]

5.4 HOT GAS CLEANUP AND SEPARATION:

This project was implemented at Bharat Heavy Electricals Limited (BHEL) Corporate Research and Development facility in Hyderabad.

5.4.1 Background:

Development and testing of hot gas cleanup and separation systems has been identified to be a priority area in coal conversion technology, at BHEL, because of the interest in commercialization of coal based combined cycle plants for power generation. Systems for coal gasification as well as combustion under pressure are being developed for testing in the combined cycle mode. After a study of various gasification systems in the light of existing state of the art, developmental time required and appropriateness for adoption to the Indian scene, BHEL selected a moving bed gasifier based combined cycle plant for the purpose of technology development and demonstration. The plant capacity selected was 6.2 MWe. This plant is presently undergoing pre-commissioning tests. After tests with the moving bed gasifier based combined cycle plant are completed, it is planned to operate this facility with a pressurized fluidized bed combustor and also a pressurized fluidized bed gasifier. During this stage of development hot gas cleanup systems, namely, high temperature, high pressure (HTHP)

particulate separation systems are planned to be introduced for testing in the combined cycle mode.

Identification of gas cleanup and separation requirements is mandatory not only to meet near term and future gas turbine specifications but also for the development of efficient HTHP particulate separation systems applicable to coal based combined cycle plants. A great deal of uncertainty exists in this area due to lack of operational data and because present specifications are based on premium fuels only. The approach to the problem of HTHP particulate separation has been generally towards extending application of existing particulate separation devices to withstand the HTHP environment. Though seemingly simple, the approach is compounded by such factors as the unknown performance of these devices in HTHP conditions, lack of adequate particulate sampling technology, equipment reliability, and need to develop special auxiliary hardware. Also, there is the need to study the effect of alkali metals on equipment as well as the physical nature of the ash concerned. Further, reliable operation of gas turbines is related to particulate loading and its size distribution and the chemical composition of the gas it expands. From the available literature on these aspects as well as blade erosion and deposition dependence on particle size, it appears certain that the earlier specifications of dust loading for gas turbines cannot be applicable for their use in combined cycle generation of power from coal. The cleaning systems may be able to remove dust fractions of larger sizes almost completely and as such more of the fine dust

may be permitted in the expansion gas. Since such fine dusts do not contribute much to erosion, future specifications are likely to permit higher dust loadings, but these specifications will most likely include an allowable size distribution of the dust. Since the selection and evaluation of the dust separation devices depend to a large extent on the particulate loading and the particle size distribution, the need for experimental data is necessary to successfully design and operate these systems with confidence.

Theoretical studies and experimental work were initiated at BHEL to address the HTHP particulate separation problem prior to initiation of this project. These studies took into consideration the experimental data on various designs of cyclones, which were completed at BHEL in a test loop during 1982-1984. From this study there were indications that "cyclone only" systems may be sufficient for gas turbine protection, though not sufficient for meeting projected environmental requirements.

Because of the many uncertainties that presently exist in this area, BHEL decided to evaluate the performance of HTHP particulate separation devices by setting up a well instrumented test facility. The goal of this facility is to provide a comprehensive evaluation of contending systems from the point of view of their performance with respect to gas turbine tolerance, environmental standards, reliability and cost.

5.4.2 Scope Of Work:

Under the sponsorship of USAID/GOI, technical assistance from the US was to be provided to BHEL in the setting up of a well instrumented high temperature, high pressure test facility to evaluate hot gas cleanup devices for use in combined cycle power generation.

BHEL, Corporate R&D would be responsible for the design of the test facility, fabrication of systems and subsystems, instrument specifications, and identification, design and fabrication of a HTHP device for testing upon completion of the test facility in March 1987. The milestone chart outlines the major activities and their schedules as per project plans.

5.4.3 Project Approval:

The project was approved by DNES (GOI) in July 1984.

5.4.4 Work Accomplished At BHEL, Hyderabad:

Indian engineers from BHEL were first acquainted with the state of the art technology in the US in the field of gas cleaning in conventional pulverized-fuel fired boilers and combined cycle power plants through site-visits to various facilities in the U.S. and

discussions with U.S.technical experts in this area.

Upon a thorough review and evaluation of the various HTHP control devices, namely, granular-bed filters, electrostatic precipitators, ceramic crossflow filters and baghouses, BHEL identified the granular-bed filter (GBF) as the first HTHP device that should be designed fabricated and tested. The decision was based on factors such as technical merit, material of construction, simplicity of design, availability of raw materials, the experience of US organizations with various devices and the extent of their development in the US, development time required and appropriateness for application on a commercial scale.

The HTHP facility was designed and detailed engineering drawings prepared for the fabrication of various systems, and auxiliary equipment, structures, and control room and facility layout. A brief description of the facility is addressed later. Presently, erection of the facility is underway. The specific accomplishments of the project are summarized below:

- o The process design of GBF and auxiliary systems was started in July 1984 on approval of the project and completed by December 1984.
- o Documentation of process design and preparation of preliminary instrument specifications was started in January 1985 and completed in March 1985. Detailed instrument specifications were completed by June 1985.
- o Detailed mechanical design, analysis and preparation of fabrication drawings for GBF design was initiated in July 1985 and completed in November 1985 using HK-40 for GBF internals. However, the work had to be redone during January 1986 through

March 1986 to incorporate changes in material and expansion provisions for internals, as the fabrication offers received based on the previous design were technically unacceptable. Fabrication sub-contract for GBF was finalized in November 1986.

- o Detailed mechanical designs of auxiliary systems- cyclone II, ash lock, bag filter and recirculation loop including the disengagement vessel- have been completed. The bag filter fabrication was sub-contracted and is expected at the site by March 1987. The fabrication of the remaining equipment has also been sub-contracted.
- o Procurement of instruments by BHEL was initiated in July 1985. Most of the instruments in BHEL's scope have been received at the site. The instruments /equipment supplied from the US were received at the facility in November 1986.
- o Design and erection of structures has been completed.

Erection of equipment was expected to start by early 1987. However design and fabrication changes in the GBF and the delay in start-up of the PFBC operation, has led to postponing the commissioning of the test facility to the end of 1987.

Preliminary Recirculation Loop Tests:

A full scale model of the recirculation loop was fabricated and installed in the last quarter of 1985. Several experiments have been conducted since then using dry sieved sand. The recirculation loop design parameters have been verified and it has been possible to obtain close control over the rate of recirculation. Further tests have been planned with 2 mm alumina spheres which is the material that will be used in the GBF.

Test Plan:

Detailed test plans and ranges of process variables have also been prepared. In brief the testing will focus on the following major aspects:

- i. Performance evaluation of the GBF by variation of operating parameters in selected ranges on either side of design points;
- ii. Data collection and evaluation to establish design correlations to optimize the major design parameters of the system;
- iii. Design verifications of the media recirculation loop, from experimental data.
- iv. Long duration runs to prove the operational reliability of the system.

5.4.5 HTHP Particulate Separation Test Facility:

The granular-bed filter to be tested will be mounted at the downstream end of the pressurized fluid-bed combustor at BHEL (Figure 5.32). The 422 mm I.D. pressurized fluid bed combustor capable of burning up to 300 Kg/hr coal at a pressure of 5 atm and operating at 850-900 °C bed temperature will provide hot flue gases for testing the Granular Bed Filter. The PFB plant consists of a pressurized combustor with in-bed heat transfer tubes which help to extract a major part of the heat released in the combustor. The combustor is provided with an overflow ash discharge system to control bed height consisting of an overflow

FIGURE 5.32: PFBC PROCESS SCHEMATIC

ash tube and ash fluidizer with a slurry ash discharge system. The ash fluidizer controls bed level and can be used to control the ash carry over from the combustor.

The combustor exit gases will be routed to the GBF through two cyclones in series. The process flowsheet is shown in Figure 5.33. Particle collection is accomplished in the GBF by causing the particle laden gas to move radially inward in cross-flow through an annulus of granular collecting materials, which in the present case are 2 mm alumina spheres. The granular solids are in fact a moving bed and the media recirculation is achieved by a pneumatic transport system. It is expected that the dust particles deposited on the granules during the filtration process will be separated during the transportation period. The pneumatic air is then routed through a secondary conventional cleaning system and then vented out. Two different designs of filter elements both having an outside diameter of 528 mm and an overall filter bed thickness of 200 mm are under fabrication for tests in sequence. The specifications of the filter elements are given in Table 5.10. A provision has been made in the design for varying the effective filter height to obtain superficial velocities in the range of 0.38 to 0.76 m/s. The pressure vessel will be adequately lined with refractory and insulation to obtain a shell temperature of around 180 C.

The recirculation and cleaning of the dirty media will be carried

TABLE 5.10
FILTER ELEMENT(I) PARAMETERS

PARAMETER	I	II	III
SUPERFICIAL VELOCITY M/S	0.36	0.50	0.76
FILTER ID M	0.10	0.10	0.10
FILTER OD M	0.528	0.528	0.528
FILTER HEIGHT M	0.50	0.36	0.24
SURFACE AREA M ²	0.83	0.60	0.40

FIGURE 5.33:
HT HP PARTICULATE SEPARATION PROCESS FLOW SCHEMATIC

out by means of a pneumatic transport system (Figure 5.34). For a given inlet dust load, the pressure drop across the filter bed is a function of the dust load carried out by the media, which increases over the height of the filter element. The published information and experimental data point to an optimum dust loading in the filter media in the range of 3.5 to 7 gms/kg of filter media, for pressure drop to be maintained in the desired range. This forms the basis of designing the recirculation rate of granules and the air supply required to operate the system. The control over the recirculation rate will be achieved by means of a non-mechanical valve in the recirculation line. The dirty media flows down the down comer, up the lift line before being carried into the disengagement vessel from where the media falls back into the element. The dust gets elutriated and gets separated in a bag house. The solids circulation loop design is based on choking velocity correlations and the design ensures that the lift line operating velocity is maintained above the calculated choking velocity.

The continuous logging of various process parameters like temperature, flow, pressure, level, weight and gas composition and on-line reduction of the data into respective engineering units will be conducted using a HP 3407A data acquisition system. Data acquisition and control unit are coupled to a HP 9816 computer. The other peripherals are a HP 7475A graphics plotter and an inkjet printer.

PRESSURE LOSS ESTIMATES (N/m^2)

$$\Delta P_1 \text{ (L-VALVE)} = 1049 \text{ N/m}^2 \text{ (107 mm H}_2\text{O)}$$

$$\Delta P_2 \text{ (LIFT LINE)} = 3069 \text{ N/m}^2 \text{ (313 mm H}_2\text{O)}$$

$$\Delta P_3 \text{ (DISENGAGEMENT VESSEL)} = 3099 \text{ N/m}^2 \text{ (316 mm H}_2\text{O)}$$

$$\Delta P_4 \text{ (UPPER MEDIA LEG)} = 2942 \text{ N/m}^2 \text{ (300 mm H}_2\text{O)}$$

$$\Delta P_{\text{TOTAL}} = 10159 \text{ N/m}^2 \text{ (1035 mm H}_2\text{O)}$$

MEDIA CIRCULATION RATE = 306 Kg/hr

TEMPERATURE = 250°C

SYSTEM PRESSURE = 5 ata

GAS VELOCITY IN LIFT LINE = 12 m/s

L-VALVE AERATION FLOW = 12 $\frac{\text{Am}^3}{\text{Hr}}$ (MAX.) AVERAGE

TRANSPORT AIR $\approx 40 \frac{\text{Am}^3}{\text{Hr}}$

FIGURE 5.34:

SOLID RECIRCULATION LOOP

The gas analysis will be performed using a Beckman gas analyzer system. It has six individual analyzers mounted on a common panel for monitoring CO_2 , CO , O_2 , SO_2 , NO_2 and H_2O . The flue gas composition will be monitored at the exit of the PFB combustor, and the GBF.

A Kay-Ray model 4760 Gamma continuous level system will be used for monitoring the level of filter media in the upper down comer of the recirculation loop. This consists of a Cs-137 sealed source and a detector followed by a level transmitter.

The particulate sampling and analysis will be conducted using microfiber filters and cascade impactors. The dust sampling schematic is shown in Figure 5.35 and the process instrumentation and control diagram is shown in Figure 5.36.

These instruments will be located in the control room being constructed at the project site specifically for this project.

5.4.6 Equipment Supplied By USAID:

The following instruments/equipment were supplied from the U.S. to BHEL, Hyderabad under USAID/GOI sponsorship.

- o Hewlett Packard Data Acquisition System

FIGURE 5.35: DUST SAMPLING SCHEMATIC

- o Beckman Instruments Gas Analysis System
- o Kay-Ray Non-intrusive Level Monitoring Meter for Solids

5.4.7 Training and Site-Visits By Indian Engineers:

Mr. R.S. Rangan, principal investigator on this project visited the US for a two-week period from September 15 to September 30 1984. During his stay he visited the facilities at METC, PETC, Combustion Power, Research Cottrell, Denver Research Institute, Institute of Gas Technology (IGT), Westinghouse Electric (R&D) Center, and Accurex Corporation to discuss and review the status of hot gas cleanup systems under development in the US. This visit led to the selection and prioritization of the systems to be employed for testing at BHEL.

Mr. R.S. Rangan and Mr. Shankar Chakravarti also visited the US for a four-week period in May 1986 to obtain training at the NYU high temperature, high pressure gas cleanup facility in the areas of operation and use of instrumentation for data collection and reduction.

5.4.8 Reports/Publications Submitted by BHEL, Hyderabad

1. Status of Hot Gas Cleanup During PFBC And AFBC, Proceedings of the First USAID/GOI Workshop on Alternate Energy Resources And Development, November, 1983.
2. Hot Gas Separation And Clean-up, Project Workplans and Proposal,

December 1983

3. Hot Gas Separation And Clean-up, Semi-Annual Report on Biomass And Coal Conversion Projects of the Alternate Energy Resources And Development Program, June, 1984.
4. Trip report on visits to U.S. Organizations Working on Hot Gas Clean-up, October 1984.
5. Hot Gas Clean up - BHEL's programme on Granular Bed Filter, Proceedings of the Second USAID/GOI Workshop on Alternate Energy Resources And Development, February 1985.
6. High-Temperature and High-Pressure Particulate Separation Test Facility, Design And Specification Report, March 1985.
7. Hot Gas Clean up - BHEL's programme on Granular Bed Filter, Proceedings of the Third USAID/GOI Workshop on Alternate Energy Resources And Development, December 1985.
8. Appendix to Report on HTHP particulate separation test facility, March 1985.
9. Hot Gas Separation And Clean-up, Quaterly Status Report on Biomass And Coal Conversion Projects of the Alternate Energy Resources And Development Program, July 1985.
10. Trip Report on Training at NYU-PFB Facility, April 1986.
11. High-Temperature, High-Pressure Particulate Separation Test Facility , Final Report, December 1986.

5.5 BENEFICIATION OF FINE COAL IN DENSE MEDIUM CYCLONES:

This project was implemented at the Central Fuels Research Institute (CFRI), Dhanbad.

5.5.1 Background:

The drift nature of the coal seams of the major Indian coal basins has resulted in the fine dissemination of mineral matter throughout the coal substance. The intergrown dirt necessitates crushing the virgin coal into small sizes in order to release the dirt which results in excessive production of fines. These fines pose enormous problems during handling, beneficiation, dewatering, water clarification, drying, heavy medium regeneration, etc. During beneficiation the low differential in specific gravity between coal and extraneous matter leads to a large percentage of near gravity materials (NGM) as much as 70 to 80 percent in some cases. This causes considerable migration of "sinks" in "floats" and "floats" in "sinks". Additionally, in India other problems associated during coal preparation include wide fluctuations of ash content of coal seams, small production of majority of the mines needing construction of central washeries, and progressive deterioration of the quality and washability characteristics of the feed to washeries. On account of these factors, coal preparation

plants in India need more sophisticated designs and hence are 30 to 40 percent more expensive than those in other countries.

Washability studies done on Indian coals in the early forties concluded that the Indian coals were not amenable to techno-economic beneficiation. Subsequent washability studies conducted under the aegis of the Fuel Research Committee and at the Central Fuel Research Institute established feasibility of beneficiating Indian coals, though in general, the washability characteristics of Indian coals were found to vary from difficult to very difficult.

Since 1950 the Central Fuel Research Institute has been engaged in R&D activities covering various aspects of coal preparation, namely evaluation of the washability characteristics of Indian coals, development of suitable techniques for their effective beneficiation, upgrading and dewatering of fine coal, properties of heavy medium suspensions and application of H.M. cyclones for the preparation of Indian coals. CFRI has also played a major role in the planning of all the public sector washeries which were set up during the last 3 decades. During the period 1951-1983, seventeen washeries were set up with aggregate throughput capacity of about 29 million tons per annum.

The coking coal reserves in India are concentrated in the Jharia coal field. The upper seams are comparatively better in quality and washing characteristics as compared to the lower seams. The yield

of clean coal from lower seam coals is poor with high yield of middlings when washed. However, when crushed to smaller sizes, the yield of clean coal increases with decrease in the yield of middlings. The middlings release considerable percentage of clean coal on crushing to very fine size (less than 0.1 mm). For fine and ultrafine coal beneficiation, processes like oleoflotation, oil agglomeration and chemical demineralization have been developed at the Central Fuel Research Institute. Oleoflotation and oil agglomeration processes permit easy dewatering of cleaned product in addition to efficient beneficiation. Chemical demineralization gives high order of refinement with practically no loss of carbon.

Static heavy medium coal cleaning processes are effective for comparatively coarser size coal having bottom size around 6 mm. Below this size, the separation becomes progressively ineffective due to large settling time taken by the particles in the viscous heavy medium. Gravity processes other than static heavy medium are also not effective for cleaning such small size particles particularly those having inferior cleaning characteristics. Heavy medium cyclone washers using centrifugal force instead of gravity hold much promise to beneficiate smaller size coal with high capacity and efficiency.

At the Central Fuels Research Institute, Dhanbad, studies on the applicability of heavy medium cyclone have established the suitability of heavy medium cyclones for beneficiating Indian coals. So far heavy medium cyclones have been installed in 13

commercial coal washeries in India having total throughput capacity of about 3500 tons per hour. Heavy medium cyclones are in very common use today. However, there is a trend towards increasing both the top size of feed as well as to feed the cyclones with zero size particles.

The major limitation in conventional heavy medium cyclone washers is their inability to accept particles finer than 0.5 mm which tend to contaminate the separating medium. Generally the fines below 0.5 mm in coals crushed to 10/6 mm remain in the range of 20 to 40%. It has been found that most of the fines consist of intergrown particles of vitrinites and inertinites which do not respond properly to flotation and as a consequence considerable amounts of coal particles get lost along with flotation tailings.

With the progressive depletion of easy and medium washable coals in India it has become imperative to utilize inferior quality coals for production of metallurgical coke. However, due to the inferior cleaning characteristics in Indian coking coals, the yield of clean coal obtained on washing, is unsatisfactory. In order to augment the yield of clean coal, the coal needs to be crushed to comparatively finer size prior to beneficiation. But with the finer crushing of the coals, the problem of beneficiation increases. Since dense medium cyclones appear to provide a means for dealing with small size coals which are difficult to wash, as reported in many studies conducted in both the US and Europe, there is considerable interest in the development and application of dense

medium cyclones for washing Indian coals after crushing to finer size with the aim of augmenting the recovery of clean coal to meet the progressive demand of metallurgical coke from the Iron and Steel Industry.

5.5.2 Scope Of Work:

Under USAID/GOI sponsorship the development of dense medium cyclones for beneficiation of fine coal was implemented at CFRI. The milestone chart Figure A5 outlines the major activities to be undertaken by CFRI and their schedules as per project plans.

Upon completion of the visit to the US (PETC) by a CFRI scientist, the following experimental program was developed to evaluate the beneficiation of fine coal using dense medium cyclones.

- o The following sizes of coal sizes were to be investigated
 - 9- 28 mesh (ASTM)
 - 28-100 mesh (ASTM)
 - 100-200 mesh (ASTM)
 - 28-200 mesh (ASTM)
- o Two fine size magnetites would be used as separating media namely, 100 % below 30 micron with high percentage of below 5 micron 95% through 325 mesh (ASTM)
- o An 8" diameter cyclone having rubber or ceramic lining would be used initially. In the future, 4" and 6" diameter cyclones would be considered, if necessary. The cyclone overflow, apex and inlet size would be 3", 2 1/2" and 1 1/2" respectively. The cyclones would be placed horizontally, maintaining a
 - o 5 angle of the slant side of the cone with the horizontal. The inlet pressure to the cyclone would be

maintained at 10 psi. Higher pressures 20-30 psi would also be tried depending on the availability of a centrifugal pump.

- o The specific gravity of medium would be 1.40, aimed at 1.45-1.55 sp.gr of separation (cut). The pulp ratio would be 1:4 and 1:6, that is approximately 20% and 14% coal by weight respectively.

5.5.3 Project Approval:

There was considerable delay in starting the project as the administrative approval of the project from the Government of India was received in September 1984.

5.5.4 Work Accomplished At CFRI:

After obtaining the approval, action was taken for the placement of orders for various items of equipment required for setting up the pilot plant. The installation of the pilot plant was completed in November 1985. The "Microtrac" particle size analyzer and Sweco Screening apparatus as received from the U.S. were installed and optimized. Between February 1986 and May 1986 (4 months) extensive testing operations as per the program were executed.

Coal Preparation Pilot Plant Facility:

The flowsheet of the pilot plant installed at CFRI is shown in Figure 5.37. The facility shown in Figure 5.37A comprises of

Flow Sheet of D.M. Cyclone Set up
At C.F.R.I., India.
USAID - GOI Project.

FIGURE 5.37

FIGURE 5.37A

the following:

- i) Structure of three floors.
- ii) Wilfley centrifugal slurry pump constructed of Ni-hard cast iron, capacity 300 gals/min, head 110 ft. of water.
- iii) 8" diameter rubber lined dense medium cyclone from the Heyl Patterson Company.
- iv) Pulp tank for storing mixture of dense medium (ground magnetite-in water) and the fine coal to be treated; capacity 120 gallons, MS construction.
- v) Two movable sample collectors.
- vi) Two sample receivers.
- vii) Pipe lines, pressure guage, etc.

In order to maintain and vary the feed pressure up to 30 psi, a high capacity centrifugal slurry pump powered with 50 HP motor was installed. The pump is provided with a 6" diameter suction inlet and a 4" diameter delivery outlet. The feed pressure can be adjusted by controlling the valve in the slurry by-pass line, between the delivery pipe of the pump and slurry storage tank and also by adjusting the valve provided in the cyclone feed pipe.

The 8" diameter Heyl Patterson cyclone with a 14° cone angle as received from the U.S. in already assembled condition was used in most of the tests. The diameter of the overflow apex was 2 1/2" and 2" for the inlet orifices. The cyclone was placed horizontally maintaining the 5° angle of the slant side of the cone with the horizontal.

However, in one series of tests, the cyclone inlet and outlet orifices were changed to 3 1/2" (overflow), 2 1/2" (apex) and 1 1/2" (inlet). Preliminary tests revealed appreciable size degradation of coal feed during circulation of the coal medium slurry in the circuit. Therefore, care was taken to collect the sample within the brief period after the addition of coal in the circulating medium, allowing around 2 minutes for good mixing. Probable error values (E_p) have been considered as the basic criterion for assessing the performance of the cyclone in all the cases.

Characteristics Of Raw Coal And Magnetite:

A typical high ash coking coal sample having inferior cleaning characteristics from the Jharia coalfield, seam #10 was used for the entire study. The washability results on whole coal crushed separately to 13 mm and 9 mesh B.S. are presented in Table 5.11 and Figure 5.38. It may be observed that the increase in clean coal yield varies from 6-10% when crushed to 9 mesh B.S. However, the coal fines below 200 mesh B.S. were not included as the studies on D.M. cyclone are limited to plus 200 mesh B.S. size coal. The screen analyses of the crushed samples are presented in Table 5.12.

It may be observed that due to the hard nature of Indian coals, the percentage of fines below 200 mesh is quite low and, therefore,

TABLE 5.11

Washability Characteristics of Coal Crushed Separately

Sp. Gravity	Crushed to 13 mm and Screened at 200 mesh B.S. (13 mm - 200 mesh B.S.)			Crushed to 9 mesh and Screened at 200 mesh B.S. (9 mesh - 200 mesh)			Cleans Ash %	Raw Coal Crushed to 13 mm % Yield (13mm-200 mesh bas.)	Raw Coal Crushed to 9 mesh BS % Yld. (on 9-200 mesh basis)	% Increase In Yield
	Cum. Wt. %	Cur. Ash %	% NGM (+ 0.10SG)	Cum. Wt. %	Cum. Ash %	% NGM (+ 0.10SG)				
1.30	3.9	1.8	-	3.5	1.6	-	15	45.5	55.5	10.0
1.40	15.0	6.5	35.3	17.8	6.0	34.7	16	49.5	59.2	9.7
1.50	39.2	13.7	48.0	38.2	11.2	36.0	17	54.5	63.5	9.0
1.60	63.0	18.8	36.9	53.8	14.6	23.8	18	59.5	66.5	7.0
1.70	76.1	21.5	17.9	62.0	16.8	23.6	19	63.8	69.8	6.0
1.80	80.9	22.6	7.6	77.4	21.5	21.8				
	100.0	31.3	-	100.0	31.9	-				

Table 5.12: Screen Analysis of Raw Coal Crushed Separately

Size	Crushed to 13 mm		Crushed to 9 mesh B.S.	
	Wt. %	Ash %	Wt. %	Ash %
13 mm - 9 mesh B.S.	66.78	33.8	-	-
9-30 mesh B.S.	18.67	26.4	55.08	34.1
30-100 mesh B.S.	9.18	23.9	23.41	27.6
100-200 mesh B.S.	2.40	29.0	5.68	28.9
Below 200 mesh B.S.	2.97	34.4	15.83	30.2

FIGURE 5.38:

WASHABILITY CURVES OF RAW COAL CRUSHED SEPARATELY TO 13mm AND 9 MESH B. S.

high proportions of coal (9 mesh to 200 mesh B.S.) were available for treatment in the D.M. cyclone.

The ground magnetite as available for use in commercial coal washeries, was of a coarser nature. In order to make this magnetite suitable for the study, attempts were made for further size reduction by dry grinding in ball mill allowing different grinding periods and different ball loading. But due to the hard nature of Indian magnetite, the material could not be ground to a very fine size, namely 100% below 30 micron with a high percentage below 5 micron as stipulated in the plan program. The other size, i.e. 95% below 325 size ASTM (350 mesh B.S.), could be well achieved and all the tests were carried out with this grind of magnetite. The screen analysis of the as received magnetite and that after further grinding are presented in Table 5.13. Some other properties of the magnetite are also shown in the same table. The specific gravity vs stability is presented in Figure 5.39.

5.5.5 Results of the Experimental Investigations:

The experimental results reported by CFRI are briefly presented in this section.

Effect of Feed Inlet Pressure on Performance of Cyclone:

The influence of pressure was studied on two different size ranges

Table 5.13: Screen Analysis of Magnetite

Size (In microns)	Magnetite (As received) % passing	Magnetite (After grinding in ball mill) % passing
300	100.0	100.0
212	100.0	100.0
150	100.0	100.0
106	100.0	100.0
75	100.0	100.0
53	97.6	99.9
38	96.5	99.7
27	89.5	96.1
19	72.6	87.6
13	56.9	75.9
9.4	39.0	61.0
6.6	25.0	44.1
4.7	17.6	34.6
3.3	10.5	23.7
2.4	5.5	14.6

B. Density of magnetite powder - 4.2 gm/cc

C. Magnetite concentration:

Magnetics % - 81.8

Non-magnetics % - 18.2

D. Stability index of suspension at 1.45 sp.gr. - 91.6

E. Viscosity of suspension at 1.45 sp.gr. - 4.8 cp

FIGURE 5.39

of coal feed viz. 9-100 mesh B.S., and 9-200 mesh B.S. at feed pressure 5 psi, 15 psi and 30 psi. The pulp ratio was maintained at 6:1 (medium to coal ratio by weight). The results of the two series of tests are presented in Tables 5.14 and 5.14A and also in Figures 5.40 and 5.40A.

From the results shown in Table 5.14A, it was observed that with the increase of feed inlet pressure of the circulating slurry from 5 psi to 30 psi, the sp.gr. of separation as well as the probable error values have progressively increased. With the increase of pressure viz. 5 psi, 15 psi and 30 psi, the corresponding figures of sp.gr. of separation are 1.436, 1.453 and 1.481, whereas the probable error values are 0.015, 0.022 and 0.027 respectively. The performance with feed size 9-100 mesh B.S. at pressures between 5 and 30 psi is satisfactory. The throughout capacity, however, increases with the increase in pressure.

The results of tests with feed size 9-200 mesh B.S. are shown in Table 5.14A. The tests were undertaken at the same operating pressure and medium to coal ratio. In this case also, the same trend in performance, i.e. the gradual increase of sp.gr. of separation and the probable error values with the increase of feed inlet pressure, was noted. With the inclusion of the fines fraction 100-200 mesh in the feed, the deterioration in the performance of the cyclone was all the more prominent. With the gradual increase of pressure, the changes in the sp.gr. differential were also more pronounced. Therefore, the inclusion of fines below 100 mesh and

Table 5.14: Effect of Feed Inlet Pressure on Performance of Cyclone

Test No: DMC/2			
Size of Feed Coal	9-100 mesh B.S.		
<u>Orifice dia., inch</u>			
Overflow	2 1/2	2 1/2	2 1/2
Apex	2	2	2
Inlet	2	2	2
Inlet pressure, psi	5	15	30
Medium coal to ratio	6:1	6:1	6:1
Feed medium sp. gravity	1.37	1.37	1.37
Medium plus coal sp.gr.	1.42	1.42	1.42
Feed coal ash %	33.8	33.8	33.8
Clean coal yield %	26.4	30.3	34.1
Clean coal ash %	11.0	11.6	12.6
Sink yield %	73.6	69.7	65.9
Sink ash %	42.8	44.3	45.7
Sp.gr. of separation	1.436	1.453	1.481
Probable error	0.015	0.022	0.027
Sp.gr. differential	0.066	0.083	0.161
Feed coal, tph	3.11	5.30	8.30
Coal in slurry (Wt. %)	14.3	14.3	14.3

Table 5.14A: Effect of Feed Inlet Pressure on Performance of Cyclone

Test No: DMC/3

Size of Feed Coal	9-200 mesh B.S.		
<u>Orifice dia., inch</u>			
Overflow	2 1/2	2 1/2	2 1/2
Apex	2	2	2
Inlet	2	2	2
Inlet pressure, psi	5	15	30
Medium coal to ratio	6:1	6:1	6:1
Feed medium sp.gr.	1.550	1.550	1.550
Overflow medium sp.gr.	1.390	1.350	1.330
Underflow medium sp.gr.	2.030	2.220	2.330
U'flow - O'flow	0.640	0.870	1.000
Medium plus coal sp.gr.	1.600	1.600	1.600
Feed coal ash %	29.7	30.3	30.1
Clean coal yield %	77.2	77.7	75.5
Clean coal ash %	20.0	20.8	20.3
Sink yield %	22.8	22.3	24.5
Sink ash %	62.6	63.3	60.3
Sp.gr. of separation	1.719	1.741	1.780
Probable error	0.024	0.040	0.055
Sp.gr. differential	0.169	0.191	0.230
Feed coal, tph	3.25	5.60	8.68
Coal in slurry (Wt. %)	14.3	14.3	14.3

EFFECT OF FEED INLET PRESSURE ON PERFORMANCE

FIGURE 5.40

EFFECT OF FEED INLET PRESSURE ON PERFORMANCE

FIGURE 5.40A

operation at high pressure viz. 30 psi in particular, leads to some adverse effects on the performance of the cyclone. However, in this case too, the overall performance was satisfactory, the E_p values being in the range of 0.024-0.055.

Effect of Pulp Ratio on Performance at Different Feed

Pressure:

Another series of tests were carried out keeping the same size consists of the feed, i.e. 9-200 mesh in which the medium to coal ratio was changed from 6:1 to 4:1. The results are shown in Table 5.15 and Figure 5.41. Deterioration in the performance of cyclone is observed due to higher concentration of coal in the slurry. The probable error values vary between 0.042 and 0.078 with the increase of pressure from 5 psi to 30 psi. However, the performance of the cyclone up to feed pressure of 15 psi was satisfactory.

Effect of Feed of Various Size Grading on Performance of

Cyclone:

In this case, tests were conducted separately at pulp ratios 6:1 and 4:1 keeping the same medium density and feed inlet pressure of 15 psi. The results are shown in Tables 5.16 and 5.16A and in Figures 5.42 and 5.42A on feed sizes 9-30 mesh, 30-100 mesh, 100-200 mesh and 30-200 mesh. Gradual deterioration in the performance of the cyclone with finer sizes of feed is evident in

Table 5.15: Effect of Pulp Ratio on Performance at Different Feed Pressures

Test No: DMC/5A				
Size of Feed Coal	9-200 mesh B.S.			
<u>Orifice dia., inch</u>				
Overflow	2 1/2	2 1/2	2 1/2	
Apex	2	2	2	
Inlet	2	2	2	
Inlet pressure, psi	5	15	30	
Medium to coal ratio	4:1	4:1	4:1	
Feed medium sp.gr.	1.450	1.450	1.450	
Medium plus coal sp.gr.	1.520	1.520	1.520	
Feed coal ash %	31.0	28.9	29.2	
Clean coal yield %	63.5	77.7	70.9	
Clean coal ash %	20.5	19.3	19.3	
Sink yield %	31.5	22.3	29.1	
Sink ash %	53.8	62.3	53.3	
Sp.gr. of separation	1.662	1.747	1.678	
Probable error	0.042	0.052	0.078	
Sp.gr. differential	0.212	0.297	0.228	
Feed coal, tph	4.32	7.44	11.54	
Coal in slurry (Wt. %)	20.0	20.0	20.0

EFFECT OF PULP RATIO ON PERFORMANCE AT DIFFERENT PRESSURE.

FIGURE 5.41

Table 5.16: Effect of Feed of Various Size Grading on Performance of Cyclone

Test No: DMC/4				
Size of Feed Coal	9-30 mesh B.S.	30-100 mesh B.S.	100-200 mesh B.S.	30-200 mesh B.S.
<u>Orifice dia., inch</u>				
Overflow	2 1/2	2 1/2	2 1/2	2 1/2
Apex	2	2	2	2
Inlet	2	2	2	2
Inlet Pressure, psi	15	15	15	15
Medium to coal ratio	6:1	6:1	6:1	6:1
Feed medium sp.gr.	1.450	1.450	1.450	1.450
Medium plus coal sp.gr.	1.500	1.500	1.500	1.500
Feed coal ash %	27.5	32.5	33.1	32.6
Clean coal yield %	65.9	67.9	74.3	69.1
Clean coal ash %	13.8	17.6	20.0	18.0
Sink yield %	34.1	32.1	25.7	30.9
Sink ash %	54.0	64.0	71.0	65.2
Sp.gr. of separation	1.626	1.695	1.975	1.703
Probable error	0.035	0.054	0.113	0.068
Sp.gr. differential	0.176	0.245	0.525	0.253
Coal in slurry (Wt. %)	14.3	14.3	14.3	14.3

Table 5.16A: Effect of Feed of Various Size Grading on Performance of Cyclone at Different Pulp Ratio

Test No: DMC/5				
Size of Feed Coal	9-30 mesh B.S.	30-100 mesh B.S.	100-200 mesh B.S.	30-200 mesh B.S.
<u>Orifice dia., inch</u>				
Overflow	2 1/2	2 1/2	2 1/2	2 1/2
Apex	2	2	2	2
Inlet	2	2	2	2
Inlet pressure, psi	15	15	15	15
Medium to coal ratio	4:1	4:1	4:1	4:1
Feed medium sp.gr.	1.450	1.450	1.450	1.450
Medium plus coal sp.gr.	1.520	1.520	1.520	1.520
Feed coal yield %	28.5	28.7	31.7	29.2
Clean coal yield %	73.6	84.5	78.1	83.2
Clean coal ash %	16.6	22.6	21.2	22.3
Sink yield %	26.4	15.5	21.9	16.8
Sink ash %	61.8	62.0	69.2	63.4
Sp.gr. of separation	1.722	1.790	2.064	1.832
Probable error	0.036	0.068	0.128	0.104
Sp.gr. differential	0.272	0.340	0.614	0.382
Coal in slurry (Wt. %)	20.0	20.0	20.0	20.0

FIGURE 5.42

FIGURE 5.42A

both the cases. With the increase in coal concentration, the performance further deteriorated. In the case of feed size 100-200 mesh, the probable error values were higher than 0.11 with very high figures of sp.gr. differential, i.e. 0.525 (Table 5.16) and 0.614 (Table 5.16A).

Influence of Cyclone Parameters on the Performance of the Cyclone:

Earlier tests were conducted with cyclone parameters namely overflow, apex and inlet orifices of diameters of 2 1/2", 2" and 2" respectively as may be noted in Tables 5.14 to 5.16A. During the present series of tests, the same parameters were changed to 3 1/2", 2 1/2" and 1 1/2" respectively and the results are presented in Table 5.17 and Figure 5.43. The tests were conducted at three different feed pressures viz. 5 psi, 15 psi and 30 psi keeping pulp ratio at 4:1. The comparative study indicated no appreciable change in the performance but a remarkable increase in the capacity of the cyclone is observed when overflow and Apex orifices of larger diameters and inlet orifices of smaller diameters are used.

Results of Tests in 6" Diameter Cyclone:

As indicated in the program, a few tests were conducted in a 6" diameter cyclone to study the performance at various operating conditions. The 6" diameter cyclone set up already existed at the Institute. The following tests were carried out:

Table 5.17: Influence of Cyclone Parameters on Performance of Cyclone

Test No: DMC/6			
Size of Feed Coal	9-200 mesh B.S.		
<u>Orifice dia., inch</u>			
Overflow	3 1/2	3 1/2	3 1/2
Apex	2 1/2	2 1/2	2 1/2
Inlet	1 1/2	1 1/2	1 1/2
Inlet pressure, psi	5	15	30
Medium to coal ratio	4:1	4:1	4:1
Feed medium sp.gr.	1.420	1.420	1.420
Overflow medium sp.gr.	1.20	1.21	1.23
Underflow medium sp.gr.	1.80	1.98	2.22
U'flow - O'flow	0.60	0.77	0.99
Medium plus coal sp.gr.	1.48	1.48	1.48
Feed coal ash %	34.2	34.0	32.2
Clean coal yield %	55.1	67.5	75.0
Clean coal ash %	22.2	23.5	23.0
Sink yield %	44.9	32.5	25.0
Sink ash %	48.9	55.8	59.8
Sp.gr. of separation	1.637	1.709	1.747
Probable error	0.049	0.056	0.086
Sp.gr. differential	0.217	0.289	0.327
Feed coal, tph	9.59	12.15	19.18
Coal in slurry (Wt. %)	20.0	20.0	20.0

INFLUENCE OF CYCLONE PARAMETERS ON PERFORMANCE

FIGURE 5.43

KUSUNDA X SEAM
RAW COAL CRUSHED TO 2 mm
SIZE : 2 - 0.5 mm

FIGURE 5.44

BLOCK - II, O.C.P.
RAW COAL CRUSHED TO 2mm
SIZE : 2 - 0.5 mm

FIGURE 5.45

BLOCK - II, O.C.P.
 RAW COAL CRUSHED TO 2mm
 SIZE 0.5 - 0.15 mm

FIGURE 5.46

KUSUNDA X SEAM
RAW COAL CRUSHED TO 2mm
SIZE: 2 - 0.5 mm

FIGURE 5.47

BLOCK - II, O. C. P.
RAW COAL CRUSHED TO 2mm
SIZE : 2 - 0.5mm

FIGURE 5.48

BLOCK - II, O.C.P.
RAW COAL CRUSHED TO 2mm
SIZE: 0.5 - 0.15 mm

FIGURE 5.49

- i) Separation of 2 mm-0.5 mm size of feed at 5, 10, 15 and 20 psi using high ash coal
- ii) Separation of 2 mm-0.5 mm size of feed at 5, 10, 15 and 20 psi using medium ash coking coal
- iii) Separation of 0.5mm-0.15 mm size feed at 5, 10, 15 and 20 psi.

The results are presented in Table 5.18. The curves showing washability characteristics of the feed coal and the partition curves are given in Figures 5.44-5.49. It was observed that at around 10 psi feed pressure, the E value was low.

P

Results of Tests in 8" Diameter Cyclone:

This investigation indicates that beneficiation of Indian coking coals having difficult cleaning characteristics (when crushed to fine size, i.e. 9 mesh) by a dense medium cyclone may lead to a high order of performance resulting in higher yield of clean coal when compared to recoveries obtained in cases of coarser crushing.

Indian coals being of a hard nature, when crushed to fine size, a major portion of coal feed lies within the size range 9-200 mesh B.S. which may be conveniently treated in a dense medium cyclone to achieve good recoveries of clean coal with stipulated ash content.

Fine grinding of magnetite namely 95% below 350 mesh B.S., has been found effective in improving the sharpness of separation when fine

TABLE 5.18

Performance Criteria of D.M. Cyclone Tests**

Details of Sample	Feed Size mm	Ash %	Feed Pressure Lb/sq in	S.G. of Suspension	S.G. of Separation	E P	Organic Eff.*	Cleans		Sinks	
								Wt %	Ash %	Wt %	Ash %
Kusunda x seam	2-0.5	40.0	5	1.45	1.648	0.041	74.0	43.8	20.6	56.2	55.1
coal crushed	"	"	10	"	1.820	0.065	88.9	59.1	23.0	40.9	64.6
to below 2 mm	"	"	15	"	1.896	0.072	93.0	67.0	24.9	33.0	70.7
	"	"	20	"	1.990	0.075	82.4	61.0	25.6	39.0	62.5
Block II OCP	2-0.5	29.8	5	1.35	1.500	0.034	97.0	32.0	13.2	68.0	37.6
	"	"	10	"	1.549	0.030	86.2	43.1	17.4	56.9	40.2
	"	"	15	"	1.620	0.055	89.4	55.4	19.5	44.6	42.6
	"	"	20	"	1.700	0.044	92.0	71.0	22.4	29.0	47.9
-do-	0.5-0.15	24.6	5	1.35	1.779	0.096	98.2	85.5	20.1	14.5	51.2
	"	"	10	"	1.840	0.055	99.5	89.6	21.0	10.4	55.6
	"	"	15	"	1.905	0.117	97.5	89.3	21.7	10.7	57.2
	"	"	20	"	1.944	0.111	99.5	93.6	22.3	6.4	58.4

*On reconstituted feed basis

**6" dia. cyclone, 20° cone angle, feed inlet aperture 1½",
overflow aperture 1½", apex aperture 15/16"

size of coal is treated. The sharpness of separation is quite high even after inclusion of fines up to 200 mesh B.S. in the feed at operating pressure up to 15 psi. With finer size grading of feed, higher gravity of separation for same sp.gr. of suspension with higher imperfection in separation is clearly observed. Although, increase in coal concentration in the feed enhances the capacity, it deteriorates the performance of the cyclone to some extent.

However, in order to ascertain the optimum down limit of the feed size of coal, the operating pressure, the pulp ratio of the slurry and, in particular, the cyclone parameters, extensive tests need to be carried out in the dense medium cyclones aiming at high efficiency of performance and recovery of clean coal to achieve higher washing economy.

5.5.6 Equipment Supplied By USAID:

The following equipment was supplied to CFRI under USAID/GOI sponsorship.

- o Microtrac Particle Size Analyzer (Leeds & Northrup)
- o Heyl and Patterson Cyclones
- o Sweco Screens (R.P. Hoppe)

5.5.7 Training And Site-Visits By Indian Engineers/Scientists:

Mr. A.K. Chakravarti visited the US for four-week period in January 1984. During his stay he visited the coal preparation facilities at PETC, and EPRI (Homer City). He also visited Iowa State University, Roberts & Schaefer Company, Dravo Engineers, Pittsburgh to discuss and acquaint himself with the advances in coal preparation and coal beneficiation in the US.

He also participated in the Engineering Foundation Conference on "Impact of Coal Quality on Downstream Processes" held in Chicago.

5.3.8 Reports/Publications Submitted by CFRI, Dhanbad

1. The Status of Coal Cleaning in India, Proceedings of the First USAID/GOI Workshop on Alternative Energy Resources and Development, November 1983.
2. Beneficiation of Fine Coal In Dense Medium Cyclones, Project Workplans And Proposal, December, 1983.
3. Trip Report on Visit To US , February 1984.
4. Staus Report on Coal Beneficiation, Semiannual Report on Biomass and Coal Conversions Projects of USAID/GOI Alternative Energy Resources and Development Program, USDOE, Pittsburgh Energy Technology Center, Pittsburgh, PA, 15236, June 1984.
5. Beneficiation of Difficult Cleaning Coking Coal, Proceedings of the Second USAID/GOI Workshop on Alternative Energy Resources and Development, February 1985.
6. Studies In Relation To Beneficiation Of Small Coal In Dense Medium Cyclone Proceedings of the Third USAID/GOI Workshop on Alternative Energy Resources and Development, Chakraborty, M., et.al., December 1985.

7. Beneficiation of Fine Coal In Dense Medium Cyclone Final Report ,
June 1986.

5.6 COLD GAS SEPARATION AND CLEANUP:

This project was implemented at Regional Research Laboratory (RRLH) Hyderabad.

5.6.1 Background:

Gasification of coal is an important method for processing coal. A one ton/hour fixed-bed pressure gasification plant installed at Regional Research Laboratory, Hyderabad is undergoing extensive testing. The gas obtained with oxygen-steam contains CO_2 ,

H_2 , CO , CH_4 and impurities such as H_2S and sulfur

containing organics. Depending upon the gasification process, tars and particulate matter are also present in the product gas. For most applications CO_2 , H_2S , sulfur compounds and

particulate matter have to be removed, whether it is for combined cycle generation of power or for synthesis purposes like FT synthesis, SNG, methanol, or oxo-synthesis. The current practice of wet scrubbing with water or other liquids is not thermally efficient and is energy intensive when compared to the separation process based on the adsorptive or membrane permeative techniques. This present facility has a hot potash wash system to remove CO_2 and H_2S .

Gas cleaning by adsorptive techniques may have advantages over wet cleaning methods. The gas need not be cooled to ambient temperatures and the problem of handling or disposal of liquid effluents may be eliminated.

In view of the attractive features of adsorptive and permeation membrane techniques, there is considerable interest in the development of these techniques in India.

5.6.2 Scope Of Work:

Under USAID/GOI sponsorship the cold gas cleanup and separation project implemented at Regional Research Laboratory, Hyderabad (RRLH) was undertaken with a view to allow long-term research and development to be pursued in the areas of adsorption and membrane separation for cleaning gaseous effluents from coal gasification processes.

The scope of work included exchange of scientific information and visits by Indian scientists/engineers to the United States of America to acquaint themselves with gas separation and clean up techniques practiced in the US, focusing primarily on adsorptive gas separation and gas/solid contacting techniques to remove particulate matter. A critical review of the technology status was to be prepared so as to define a research plan for processing gas

produced during the gasification of the high-ash Indian coals. Based on their conclusions a bench scale unit would be designed and fabricated to carry out exploratory and process development studies to optimize gas separation methods to separate particulates, acid gases like carbon dioxide, hydrogen sulphide and organic sulfur compounds.

5.6.3 Project Approval:

The project was approved by DNES (GOI) in April 1984 and commencement of the project was rescheduled to begin July 1984.

5.6.4 Work Accomplished At RRLH:

A detailed literature review was conducted on gas clean up with specific reference to removal of impurities like hydrogen sulphide and other sulphur compounds and carbon dioxide and particulate matter. Reports received from the US were also used in the review.

A two-phase program was prepared for exploratory laboratory-scale studies for the separation of such impurities from the crude gas stream of the coal gasification pilot plant at RRLH, adopting chemical absorption, adsorption and membrane permeative separation techniques. In the first phase, simulated gas mixtures containing gaseous impurities would be used and during the second phase, gas

from the in-house coal gasification pilot plant would be used. In the latter case, particulate matter and tar would be removed first before feeding to adsorbents.

During the visit of US specialists to India, the scope of work in the project was discussed in detail. Based on these discussions, the scope was modified to include removal of acid gases like carbon dioxide and hydrogen sulfide and other sulphur compounds like mercaptans, carbon oxysulphide, carbondisulphide. Aspects pertaining to the removal of particulate matter were deleted. Furthermore, studies on removal of acidic gases were to be restricted in the initial stages to adsorptive and membrane permeative separation techniques.

A bench-scale experimental set up was installed for adsorptive gas cleaning. The unit has undergone preliminary testing. The adsorption column is made of stainless steel tube, 27 mm i.d. and 700 mm long. It has a filter at the top and a SS wire-mesh screen as bed support at the bottom. A pressure gauge mounted on the column indicates the system pressure and four thermocouples embedded along the length of the reactor measure the bed temperature. The system has facilities for mixing cylinder gases, rotameters, steam generation, etc. The spent bed can be regenerated either with steam or with nitrogen gas. An electrically heated steam generator with safety valve and pressure gauge is installed to supply the steam required for countercurrent regeneration of the bed.

A membrane separation set up has also been designed and installed for the initial studies using pure gas mixtures, using some of the commercially available membranes. The membrane permeative cell of 10" x 7" size was fabricated from two stainless steel plates of 1 1/2" thick. Installation of both units with necessary piping, fittings, valves, etc., is complete except for the gas chromatograph. Testing of the unit is in progress. The schematic flow diagram of the set up is shown in Figure 5.50.

Some preliminary experiments have been conducted with N :
2

H (60:40) mixtures for studying the equilibrium adsorption
2

characteristics using activated carbon at atmospheric pressure.

Initially, the inlet gas composition was estimated and the outlet composition was analyzed at regular intervals of 15 minutes using an Orsat gas analysis apparatus. A few experiments were also conducted on the unit using activated carbon made from coconut char using binary gas mixtures such as CO + H₂, H₂ + N₂, etc.

There was no provision for analysis of trace quantities of gas. Orsat gas analysis was not useful as it was time consuming and not accurate to detect and estimate any component in less than 0.1% concentration. It was felt that continuous monitoring of the feed and product gas analysis is essential.

The adsorption characteristics in all these experiments could not

FIGURE 5.50: EXPERIMENTAL SETUP FOR GASCLEANUP STUDIES

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be established due to the following reasons:

- o Analysis of more number of samples collected at smaller intervals of time is required and this could not be done as it needs quick and precise estimations in a short time.
- o The inlet composition of the gas mixture from the cylinder was found to vary continuously. This necessitated simultaneous analysis of inlet and outlet gas streams.
- o The gas flow rate was found to vary with time and use of a mass flow controller was found necessary.

The first two problems can be overcome by using a gas chromatograph for analysis.

5.6.5 Equipment Supplied By USAID:

The following instruments/equipment were supplied from the US to RRLH under USAID/GOI sponsorship.

- o Hewlett Packard Gas Chromatograph
- o Pressure Regulators
- o Mass Flowmeters
- o Swagelok Fittings
- o Stainless Tubing
- o Molecular Sieves
- o Celgard Membranes (Samples)

5.6.6 Training and Site-Visits By Indian Engineers:

Mr S.N. Reddy visited the US for a three-week period in August 1985 to acquaint himself with the state-of-the-art technologies developed in the areas of adsorption and membrane separation in the US. He had discussions and review meetings with US specialists at premier institutions in the US and made site-visits to their facilities. The institutions he visited included METC, IGT-Chicago, NBS-Colorado, Lawrence Berkeley Laboratory- San Francisco, Battelle Pacific Laboratory- Seattle, State University of New York, Buffalo and Stanford Research Institute.

5.6.7 Reports/Publications Submitted By RRLH:

1. Cold Gas Cleanup And Separation, Project Workplans And Proposal, December 1983.
2. Gas Cleanup - A Review, Proceedings of the Second USAID/GOI Workshop on Alternate Energy Resources And Development, February 1985.
3. Some Recent Trends in Cold Gas Cleanup, Proceedings of the Third USAID/GOI Workshop on Alternate Energy Resources And Development, December 1986.
4. Progress Report On Cold Gas Cleanup And Separation, Semi-Annual Report Biomass And Coal Conversion Projects of the USAID/GOI Alternate Energy Resources And Development Program, June 1985.
5. Trip Report of Visit to US by S.N. Reddy, September 1985.
6. Consolidated Performance Report for the Period 1983-1986 January 1987.

6.0 VOLUME II - BIOMASS PROJECTS OVERVIEW:

6.1 Background:

6.1.1 Development and Field Testing of Small Biomass Gasifier-Engine Systems:

As part of an overall effort to reduce the dependence on imported oil, the Government of India and the United States Agency for International Development (USAID) have recently completed a three year collaborative research and development program. The overall objective of this program was to develop and implement alternative energy technologies in India. A major component of this program involved development and field testing of biomass conversion technologies that can significantly decrease India's dependence on imported oil. Based on the availability of biomass resources and their potential for substitution of significant imported oil, the agricultural sector was considered the most viable candidate for application of biomass conversion technology. For example, millions of small farms in India are presently irrigated by diesel-oil-powered irrigation pumps. These dispersed diesel irrigation pumps can potentially be fueled by producer gas (i.e., a low calorie fuel gas) obtained from gasifying biomass feedstocks. The most common size of these diesel engine-operated pumps falls between 5 and 30

horsepower (hp). Because of this tremendous market potential, the biomass conversion component of the collaborative program was designed primarily to develop and field test small gasifier-engine systems.

6.1.2 Gasifier-Based Irrigation System:

A gasifier-based irrigation system was investigated. The major components of this system are:

- o Gasifier
- o Gas Cleanup
- o Modified diesel engine
- o Centrifugal water pump

The gasifier, under partial oxidizing conditions, converts solid biomass fuels into raw producer gas, a mixture of gases containing carbon monoxide and hydrogen as the primary combustible constituents. The producer gas is then cooled and cleaned to remove particulate matter and condensable organic compounds. These unit operations are normally accomplished in the gas cleanup subsystem using a combination of cyclone and wet scrubbers. A final filtering step is included to ensure the removal of fine particulates and organic mist that could be detrimental to the diesel engine along with small quantities of pilot diesel fuel. The engine is directly coupled to a centrifugal pump that lifts the irrigation water. As such, no modifications are required for the water pump operation.

In order to carry out the design, development, and field testing of a specific biomass gasifier-based irrigation system, the following three projects were initiated in India:

Project A: Development of a village-level gasifier for irrigation pumps, based on charred agricultural residue.

Project B: Utilization of producer gas in small horsepower diesel engines

Project C: Development and field implementation of small wood-based gasifier engine systems

6.2 Project Teams and Implementation Strategy:

The technical work of these projects was conducted under direct supervision of Indian engineers and scientists from participating institutions. In addition, U.S. specialists in biomass gasification were closely involved in the design, development, and implementation of the three biomass projects. The U.S. project team consisted of the MITRE Corporation, the University of California at Davis (UCD), and the University of Missouri at Rolla (UMR). The MITRE Corporation, Mclean, Virginia, under a contract with PETC, provided the technical and management support to the biomass conversion component. The biomass gasification specialists from the Department of Agricultural Engineering, UCD, and the Department of Mechanical Engineering, UMR, served as technical advisors to the three projects.

The United States Project Team:

- o Developed a phased implementation strategy for the three projects
- o Conducted performance tests and developed operating and maintenance procedures for the U.S. test gasifiers to be used for Projects A and B
- o Provided special analytical equipment and instrumentation to facilitate data monitoring and acquisition
- o Designed a four week intensive hands-on training program for the selected Indian engineers from the three projects
- o Trained six Indian engineers in the operation and maintenance, including data acquisition, of small biomass gasifier-engine systems
- o Assisted in the design and implementation of laboratory and field test procedures
- o Assisted in the evaluation and documentation of laboratory and field performance data

The Indian Project Team:

The Indian project teams were led by individual principal investigators; each team consisted of chemical, mechanical, and civil engineers, and technicians. Specifically, Projects A and B were carried out in the chemical and mechanical engineering departments, respectively, of the Indian Institute of Technology (IIT), New Delhi. Project C was carried out by the Jyoti Solar Energy Institute (JSEI), Vallabh Vidyanagar, Gujarat. Considering the diversity of biomass resources available in India, Projects A and B were focused on using agricultural wastes such as corncobs, peanut hulls, and cotton refuse as the primary feedstocks. Project

C, on the other hand, used wood chips as the primary feedstock.

To highlight the results of laboratory and field testing efforts completed under this collaborative program, comparative performance data for the systems developed under Projects C and A and B are given in Tables 6.1 and 6.2, respectively. As shown in Table 6.1, the G-55 model gasifier-engine system developed under Project C exhibited similar laboratory and field performance. The average diesel fuel replacement was about 70 percent, whereas the overall thermal efficiency of the system was about 7.0 percent. The extent of diesel fuel replacement was estimated as percent reduction in diesel fuel consumption when compared with the full load diesel-only operation. The overall system thermal efficiency was estimated by dividing the net energy output in the pumped water with total energy content of the biomass and diesel fuel consumed. The overall thermal efficiency of the system was primarily reduced because of the inefficient centrifugal pumps used in India for lifting irrigation water. The system efficiency based on engine brake power (i.e., torque) was estimated to be about 15 percent.

A phased implementation strategy was used. This strategy was developed to facilitate the design and development, laboratory, and field testing, and personnel training phases, with each phase approximately twelve months long. Phase I was devoted to tasks relating to project design and development and preliminary equipment testing. During Phase 2, tasks pertaining to the fabrication and short-term testing of field trial gasifier-engine

TABLE 6.1

COMPARATIVE SYSTEM PERFORMANCE: GASIFIER-ENGINE SYSTEM
DEVELOPED UNDER PROJECT C
(G-55 Model)

Performance Parameter	Laboratory	Field
Total time of operation (hrs)	70	400
Average wood consumption (kg/hr)	3.5	3.5
Average diesel consumption (l/hr)	0.33	0.33
Average gas temperature at the gasifier outlet (°C)	200	200
Average gas/air mixture temperature (°C)	35	35
Average total pressure drop across the gas cleanup system (mm H ₂ O)	63	63
Average pump discharge (l/sec)	15.3	12.5
Total head (m)	9.6	11.86*
Water power (kW)	1.44	1.46*
Engine BHP (kW)	3.2	3.2
Diesel fuel replacement (%)	70	70
Overall thermal efficiency (%)	6.8	7.0

*Calculated values

TABLE 6.2

COMPARATIVE SYSTEM PERFORMANCE: GASIFIER-ENGINE
SYSTEM DEVELOPED UNDER PROJECTS A AND B

Performance Parameter	Laboratory	Field
Total time of operation (hrs)	50	100
Average wood consumption (kg/hr)	2.5	2.25
Average diesel consumption (l/hr)	0.46	0.444
Average gas temperature at the gasifier outlet ($^{\circ}$ C)	350	350
Average gas/air mixture temperature ($^{\circ}$ C)	35	35
Average total pressure drop across the gas cleanup system (mm H ₂ O)	60	59
Average pump discharge (l/sec)	12.75	13.89
Total head (m)	9.96	11.37*
Water power (kW)	1.245	1.55*
Engine BHP (kW)	2.5	3.1
Diesel fuel replacement (%)	58	63.5
Overall thermal efficiency (%)	5.7	7.40

*Calculated values

systems were carried out. Phase 3 was devoted to carrying out tasks relating to long-term field testing, operator training, and documentation.

6.3 Major Accomplishments:

The major accomplishments of both the Indian and United States project teams during the course of this three-year collaborative program are highlighted below:

Projects A and B

- o Designed and fabricated a small gasifier and gas cleanup subsystem suitable for converting preprocessed agricultural residue into producer gas
- o Conducted laboratory tests to obtain performance data on gasifier and gas cleanup subsystems
- o Designed, fabricated, and tested different engine intake systems for producer gas dual-fuel operation
- o Quantified the performance of the selected intake system with respect to maximum diesel fuel replacement and overall engine thermal efficiency
- o Conducted laboratory tests to quantify the performance of the integrated gasifier-diesel engine pumpset system
- o Completed over 100 hours of field performance data for the integrated system
- o Evaluated the laboratory and field performance data for the integrated system

Project C

- o Conducted short- and long-term laboratory tests on small, wood-based gasifier and dual-fuel diesel engine pumpset systems
- o Modified the design of the gasifier and gas cleanup systems

The field performance of the system, as measured by the diesel fuel replacement and overall thermal efficiency, developed under Projects A and B (see Table 6.2) was better than that achieved during the laboratory testing. The significant improvement observed in the overall thermal efficiency during the field operations has resulted from the use of a new diesel engine pumpset as opposed to an old set used in the laboratory tests.

6.4 Conclusions Concerning Small Gasifier-Engine Systems In India:

The two small gasifier-engine systems developed and tested under this collaborative program proved that technically sound small-scale, simple gas producer (i.e., gasifier) engine systems can be developed. The long-term (over 1000 hours for both models G-50 and G-55 gasifiers) field tests under Project C also established that these systems, after proper training, can be independently operated by local farmers, and that the operation and maintenance of such a system does not require excessive time inputs from the farmer.

For possible wide scale implementation of this technology, it is recommended that extensive field testing of at least 25 units be carried out to optimize the design in order to:

- o Improve overall thermal efficiency
- o Improve the design of hardware to provide economical operating life accepted by the operator and manufacturer at the local and industrial levels

o Determine the acceptable range of biomass fuels and their availability

o Determine the socio-economic and political impacts of wide-scale adaption of this technology at the farm level

The recommended additional work must be conducted in a total systems approach, integrating all the required expertise to quantify the socio-economic benefits and to develop a strategy for wide-scale implementation of this technology in India.

APPENDIX A

**FIGURE A1: EVALUATION OF FREE BOARD PERFORMANCE
IN A FLUIDIZED BED COMBUSTOR**

FIGURE A2: AFB BOILER SCALE UP

FIGURE A3: SCHEDULE OF MAJOR ACTIVITIES

1984

1985

1986

FIGURE A4: HOT GAS CLEAN UP - MILESTONE CHART

FIGURE A5: COAL BENEFACATION PROGRAM - MILESTONE CHART

FIGURE A6: COLD GAS CLEAN UP AND SEPARATION - MILESTONE CHART

NOTE: The subscript numbers refer to the Phase of the Project.

LEGEND

- ▲ Start of Task
- ▼ End of Task
- Continuation of Task
- U.S. Visits to India - Coordination and Monitoring
- Annual Workshop
- Formal Request for Indian Visits to U.S.
- Indian Visits to U.S.
- ◆ Expected delivery of Procured Equipment from the U.S.

FIGURE A7: PROPOSED SCHEDULE FOR PROJECT A

NOTE: The subscript numbers refer to the Phase of the Project.

LEGEND

- ▲ Start of Task
- ▼ End of Task
- Continuation of Task
- U.S. Visits to India - Coordination and Monitoring
- Annual Workshop
- Formal Request for Indian Visits to U.S.
- Indian Visits to U.S.
- ◆ Expected Delivery of Procured Equipment

FIGURE A8: PROPOSED SCHEDULE FOR PROJECT B

NOTE: The subscript numbers refer to the Phase of the Project.

LEGEND

- ▲ Start of Task
- ▼ End of Task
- Continuation of Task
- U.S. Visits to India - Coordination and Monitoring
- Formal Request for Indian Visits to U. S.
- Indian Visits to U.S.
- ◆ Expected Delivery of Procured Equipment
- Annual Workshop

FIGURE A9: PROPOSED SCHEDULE FOR PROJECT C